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Snow and albedo climate change impacts across the United States Northern Great Plains

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Abstract

In areas with a seasonal snowpack, a warmer climate would cause less snowfall, a shallower snowpack and a change in the timing of snowmelt. Trends in temperature, precipitation (total and as snow), days with precipitation and snow, and winter albedo were investigated over the 60 year period from 1951 to 2010 for 20 meteorological stations across the Northern Great Plains. This is an area where snow accumulation is shallow but persistent for most of the winter (November through March). The most consistent trends were minimum temperature and days with precipitation, which both increased at a majority of the stations. The modeled winter albedo decreased at more stations than where it increased. There were substantial spatial variability in the climate trends. For most variables, the period of record used influenced the magnitude and sign of the significant trends.

1 Introduction

While global annual temperatures have increased by 0.74 °C in the past century and 1.3 °C in the past 50 years, these temperature increases are not consistent across the globe (IPCC, 2007). In some locations rates of change are increasing faster than the global average, and increases are not uniform for annual maximum and minimum temperatures. Trends in annual minimum temperatures are important to snowpack properties. Snowfall and snowpack trends are an important issue in semi-arid to arid climates where water demand already surpasses supply (Stewart, 2009).

An overall warmer climate would yield less snowfall, shallower snowpack, and a change in the timing of the snowmelt (Stewart, 2009). The Western US has already seen earlier snowmelt and peak discharge in snow dominated river systems of up to 20 days earlier (Stewart, 2009). The Western US has also seen widespread declines in springtime snow water equivalent (SWE) from 1925 to 2000 (Mote et al., 2005).

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There has also been a decrease in precipitation as snow across the Western US (Knowles et al., 2006). Decreases are amplified when the average wintertime temperatures remain around 0 °C (Knowles et al., 2006). The ratio of precipitation as snow has also been decreasing across the Northeastern US and the contiguous US region (Huntington et al., 2004; Feng and Hu, 2007, respectively). Over some of the previously studied regions, there has been both an overall decrease in the amount of snowfall and an increase in the amount of annual precipitation. These trends are correlated to winter temperature increases and are a cause for concern as snow cover acts a control for summer soil-water storage and without long periods of snow cover, crop lands like those found across the Northern Great Plains will become drier (Feng and Hu, 2007; Stewart, 2009).

Changes in the amount of precipitation as snowfall and the number of days with snowfall are both important to the water and energy budget of an area. Seasonal snow cover is an important part of the energy budget due to its low thermal conductivity and high albedo (Stewart, 2009). Reductions in overall amount of precipitation as snow would likely lower the depth of the snowpack and possibly decrease the persistence of snowcover which would decrease the overall winter albedo. This would increase the absorption of incoming solar radiation. A reduction in the number of days with snow would decrease the amount of fresh snow and therefore decrease the overall albedo of the snowpack resulting in an increase in the amount of radiation that is absorbed.

The objectives of this paper are to determine (1) if the amount of precipitation falling as snow is changing, (2) if the number of days with snowfall is changing, and (3) if these changes impact modeled albedo over the winter period, which defined as November through March. Annual precipitation and temperature changes will also be evaluated. This investigation will also focus on two stations in close proximity to one another to examine small-scale spatial changes and the influence of length of record.

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2 Data

For this work the Northern Great Plains (NGP) area is defined as western parts of Kansas, Nebraska and South Dakota as well as the eastern parts of Colorado and Wyoming (Fig. 1). This area represents a transition from the more water abundant East to the more arid region bordering the Front Range of the Rocky Mountains, and as such plays an important role in crop production in the US (http://www.globalchange.gov/). Snowpack accumulation is shallow but persistent for most of the winter. The Köppen–Geiger classification for the area is mostly semi-arid (BSK) with small parts of the humid continental (DFA) classification (Peel et al., 2007).

Twenty stations (Fig. 1) were identified for this region that had less than 30 % of all years excluded due to missing data, where missing years were those with more than 14 days of missing data (Reek et al., 1992). The stations were located from 39.4 to 44.7° N latitude and 99.8 to 105° W longitude with elevation ranging from 733 to 1880 m a.s.l. Daily data, including maximum temperature, minimum temperature, precipitation, and snowfall, were retrieved for the period from 1951 to 2010 from the National Climatic Data Center (www.ncdc.noaa.gov), and summarized for the annual analysis.

3 Methods

For each station, the annual average maximum and minimum temperature were calculated for each year in °C. The total precipitation (mm) and snowfall (mm), from precipitation as snow, as well as the number of days with precipitation and snow were also calculated for each year (Huntington et al., 2004). The amount of precipitation as snow was the total daily precipitation when snowfall was observed. Air temperature was not used as a threshold between rain and snow, as this varies based on climate (Fassnacht and Soulis, 2002; Fassnacht et al., 2013).

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No difference was made between rain and snow where the snowfall melted before being measured (Huntington et al., 2004). This means that snowfall that fell and melted before it was measured was counted as rainfall. This study does not take into consideration days that may have had mixed precipitation (where both rain and solid precipitation fall in the same day). This will overestimate the amount of snowfall since it includes days with both rain and snow entirely as snowfall. However, since precipitation gauges are less efficient at measuring snowfall than rainfall there is an error both underestimating and overestimating the total amount of snowfall. There was no attempt made to quantify the error caused by the assumptions in this study (see Huntington et al., 2004; Knowles et al., 2006). While trends have been observed in wind speed (e.g., Hoover et al., 2014), it was assumed these were limited across the study domain and that there was no trend in the amount of undercatch. In particular, wind induced undercatch (e.g., Yang et al., 1998) was not computed since wind data were not available. Similar assumptions have been applied to studies in other regions with similar climate such as Mongolia (Fassnacht et al., 2011).

Various snow albedo (α_s) models have been created with different data requirements. The simplest models are a three linear segment shallow snowpack model (Gray and Landine, 1987) and a first order decay model (Verseghy, 1991) originally derived by the US Army Corps of Engineers (1956). Other models exist, such as the sub-model used in the CROCUS snow model, where α_s varies as a function of wavelength for three spectral bands and snow particle size (Brun et al., 1992; Vionnet et al., 2012). The Greuell and Konzelmann (1994) formulation considers the density of snow and the interaction of snow and ice albedos. The SNICAR albedo model (Flanner and Zender, 2005; Flanner et al., 2007) further considers surface temperature and near-surface temperature gradients (Flanner and Zender, 2006) to simulate changes in snow particle size and shape. However, only precipitation, snowfall, snow on the ground, and temperature data were available at a daily time step for this current study, thus the simple α_s decay model was used to determine trends.

Daily albedo was modeled over the winter period (November through March) using meteorological data (temperature, precipitation, and snow on the ground). Since observations of albedo and surface characteristics were not available, a time variant first order decay model was used. This model takes the form:

$$\alpha_s(t) = [\alpha_s(t-1) - \alpha_{s\text{-min}}]e^{-k\Delta t} + \alpha_{s\text{-min}}, \quad (1)$$

where $\alpha_s(t)$ and $\alpha_s(t-1)$ are the albedo at the current and previous time step, t, $\alpha_{s\text{-min}}$ is the minimum allowable albedo, k is a decay coefficient, and Δt is the time step (Verseghy, 1991). This model is incorporated into the Canadian Land Surface Scheme (Verseghy, 1991) to model snow conditions (Brown et al., 2006). In this paper, the decay (0.01 per hour converted to a daily rate) used by Verseghy (1991) was implemented. It uses three conditions: (1) for fresh snow $\alpha_s(t)$ is set at 0.84, (2) for dry snow (no melt), $\alpha_s(t)$ decays to an $\alpha_{s\text{-min}}$ of 0.70, and (3) for melting snow, $\alpha_s(t)$ decays to an $\alpha_{s\text{-min}}$ of 0.50. Fresh snow was considered to reset the albedo when at least 2.54 cm of snowfall was observed over a day. When no snow was present, a soil albedo of 0.20 was used.

The significance of each climatological trend was determined using the Mann–Kendall test (Gilbert, 1987). This is a robust non-parametric test that does not assume a specific distribution of the data nor is it influenced by extreme values/outliers or missing values. For all stations, trends were analyzed from the entire period of record (1951 to 2010). For the Sterling, Colorado and Kimball, Nebraska stations, the periods from 1951 to 1980 and from 1981 to 2010 were also investigated to see if there was a difference in the changes in trends over a shorter time period (Venable et al., 2012). When a trend was significant, the rate of the change was estimated using the Sen's slope estimator, which is the median slope of all pairs analyzed, giving the overall rate of change. For this analysis the MAKESENS macro developed for Excel spreadsheets was used (Salmi et al., 2002) to identify trends at both the $p < 0.05$ and $p < 0.10$ level.

Trends are often computed to assess regional climate patterns. The Regional Kendall Test (RKT of Helsel and Frans, 2006) combines a number of stations in close proximity to estimate the Mann–Kendall significance and Sen's slope rate of change. Since Clow

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(2010) used RKT to assess trends for station groups over 10s to 100s of km in the mountain of Colorado, it is also used here as the terrain in the NGP is less complex than in the mountains and the climate should be less varying.

4 Results

Average annual maximum (T_{max}) and minimum (T_{min}) temperatures varied by less than 4 °C, ranging from 14.3 to 19.2 and −0.5 to 3.2 °C, respectively, while annual total precipitation (P) varied by almost four-fold from 277 to 1016 mm and precipitation as snow (P as snow) by six-fold from 46 to 349 mm annually (Fig. 1). The range in numbers of days with precipitation (P days) and snowfall (snow days) varied similarly, but the average modeled winter albedo only varied from 0.53 to 0.6 (Fig. 1).

Climate trends were generally spatially variable with warming of minimum temperatures and more days with precipitation illustrating the most consistent trends across the 20 stations (Figs. 2 and 3). Minimum temperatures increased at 9 stations averaging 2.74 °C century^{-1}, with significant T_{min} cooling only at Kimball. Eleven stations saw an average increase of 28.3 days with precipitation per century while only Alliance had fewer precipitation days. T_{max} trends were fewer (4 significant and 2 less significant), with four warming and two cooling. Precipitation totals increased at four locations by an average of 182 mm century^{-1} and decreased at one. Changes in the amount of precipitation as snow are more prevalent with seven stations increasing by an average of 103 mm century^{-1} and five decreasing by an average of 78 mm century^{-1}. Four stations had more snow days by an average of 16.6 century^{-1}, while seven saw an average of 23.2 fewer snow days per century. Alliance was the only station with a decrease in both P and snow days, and these were the largest changes. Albedo increased at four stations by an average of 6.6 % century^{-1} and decreased at seven stations by an average of 8.6 % century^{-1}.

There are some identifiable spatial patterns in the climate trends. For example, in the southwest parts of the NGP T_{max} and/or T_{min} increased at most stations (Fig. 3), but

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there was a decrease in T_{max} at Torrington and in T_{min} at Kimball, respectively. Other spatially coherent areas included increasing P totals and days with P in the east, and increasing P as snow, days with P and days with snow in the southeast, with some corresponding increases in albedo. However, adjacent stations showed decreasing snow and some decreasing albedo. In the north and north-west parts, snow days and albedo decreased, while the further north (Belle Fourche) and south (Sterling), an increase in winter albedo was estimated (Fig. 3).

Significant trends were observed with the RKT for T_{max} (rate of 0.625 °C century^{-1}), T_{min} (rate of 1.17 °C century^{-1}), P amount (rate of 105.3 mm century^{-1}), and days with P (rate of 15.6 century^{-1}), while days with snow decrease (rate of −1.82 century^{-1}) and albedo decreases (−0.007 century^{-1}) were only significant at the $p < 0.10$ level (Figs. 2 and 3). These were similar to the averages of the individual stations. The RKT trends in P as snow were not significant (Fig. 2).

Sterling in northeast Colorado and Kimball in southwest Nebraska are 73 km apart with an elevation difference of 380 m (highlighted in Figs. 2 and 3). Opposite trends in winter albedo were estimated (Fig. 4d), in part as a function of differences in temperature (Fig. 4a), precipitation as snow (Fig. 4b), and days with precipitation and snow (Fig. 4c).

5 Discussion

The RKT trends showed increases for four variables (at $p < 0.05$ level) and decreasing trends ($p < 0.10$ level) for two variables (Fig. 2) that were similar to the averages of the individual stations. However, since these were regional trends, they tended to be much less than what was observed at individual stations as no systematic trends were observed across the entire domain (Fig. 3). Considering the relative terrain homogeneity of the study domain, high levels of spatial and temporal variability suggest a need for further study to better understand climate change across the NGP (Hudson et al., 1983). In a similar terrain and climate, the variability in temperature trends was extensive over a study of eastern Colorado (Pielke et al., 2002). For example, Fort Collins and Fort Morgan saw both significant increases in T_{max} and T_{min}, while Kimball saw less significant increase in T_{max} but a decrease in T_{min} (Figs. 2 and 3). This highlights the importance of considering the scale of analysis. It is possible that a small increase in the winter temperatures can affect snowfall amounts (Fassnacht et al., 2013). The average annual minimum temperatures for almost all stations in this study remain warmer than freezing (approx. −5 to 10 °C). Studies have shown that the Northern Great Plains is one of the regions of the US experiencing increased temperatures as well as a decrease in the amount of annual snowfall (Knowles et al., 2006). There has also been a decrease in the ratio of snowfall to rainfall in these regions (Knowles et al., 2006). Feng and Hu (2007) reported a decrease in the ratio of precipitation as snow at stations in the Northern Great Plains, however only three of the stations used in this study showed such as decrease (i.e., Harrison, Kimball, Yuma). Previous work (Feng and Hu, 2007) also found an overall decrease in the amount of snowfall and an increase in total precipitation, however, this study found more variability regardless of an overall trend in the decrease or increase of snowfall or precipitation.

The length and period of record examined also influences the rates of change and significance (Venable et al., 2012). There was little consistency in the trends over the two 30 year periods (Fig. 5). Of the seven variables, only T_{min} at Kimball was significantly getting cooler for all time periods (Fig. 5b). Conversely there was strong cooling of T_{max} early in the period of record but overall there was a weaker degree of warming at Kimball. Similarly, at Sterling, P as snow decreased for the first 30 years then increased, yielding a less significant increase overall (Fig. 5). This result may illustrate cyclical trends that become highlighted when analyzing shorter time periods (Chen and Grasby, 2009).

Albedo is correlated to snowfall amounts (for example, explained variance of 42 and 45 % for Kimball and Sterling), but albedo is more strongly correlated to days with snow (explained variance of 62 and 81 % at the focus sites). This stronger relation is due to the high albedo of fresh snow. While previous studies (e.g., Huntington et al., 2004;

Knowles et al., 2006; Feng and Hu, 2007) examined changes in the amount of precipitation as snow, and others examined changes to snow covered area and duration of snow cover (e.g., Brown and Mote, 2009; McCabe and Wolock, 2010), a quantification of changes in the days with precipitation and days with snow are important for understanding changes to albedo. It is thus recommended that days with snow be computed as an additional indicator of climate change.

There are limitations in the Verseghy (1991) albedo model since the decrease in α_s is a function of time and air temperature that dictates the state (accumulating or melting) of the snowpack. From the one available dataset at the time, Flanner and Zender (2006) illustrated that the default albedo decay coefficient used by Verseghy (1991) was too stringent; a slower decrease in albedo computed using a smaller decay ($k < 0.01\,\mathrm{h}^{-1}$) would yield a higher winter albedo when snow was present. Other models, however, could not be used, as snow specific data were not available for the 60 year period of analysis. Such data include snow particle size or shape, the density of snow, surface temperature and near-surface temperature gradients. This paper illustrates the influence of changing amounts of snow and the occurrence of snowfall using the available meteorological data. The latter variable has not been shown in the literature yet.

In the future, more snow data will be available from in situ and remote sensing sources that will allow for the use of more physically-based albedo estimates and model. Additional information to improve snow albedo estimates will include the presence of light absorbing particulates, such as black carbon, dust, and needle litter in forested regions (Flanner et al., 2007; Painter et al., 2007; Boon, 2009). Each of these constituents can play a relevant role in lowering the snow albedo.

6 Conclusions

The amount of precipitation falling as snow is changing at a majority of the stations analyzed. Trends derived from the Regional Kendall Test for all twenty stations showed

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the dominant trends among the stations but not the local variability. There were more stations with a decrease in the days with snow than an increase.

The number of days with snowfall was most important in the modeling of albedo, while the amount of precipitation as snow was less important. Albedo trends mirrored the direction of number of snow days trends at most stations, with albedo decreasing significantly at 7 stations and increasing at 4 others. This affects the winter energy balance.

Temperatures are warming at some of the sites. However, climate trends are not consistent over space or over different time periods, illustrating the relevance of the scale of analysis. There is substantial spatial variability in trends across the study domain, with opposite trends in nearby stations. The period of analysis also influence the significance and rates of change.

Author contributions. S. R. Fassnacht and M. L. Cherry designed the study. M. L. Cherry performed most of the analysis and wrote a partial draft as part of her B.S. thesis. S. R. Fassnacht wrote the first full draft and created all the figures. N. B. H. Venable completed writing the manuscript and added relevant literature citations.

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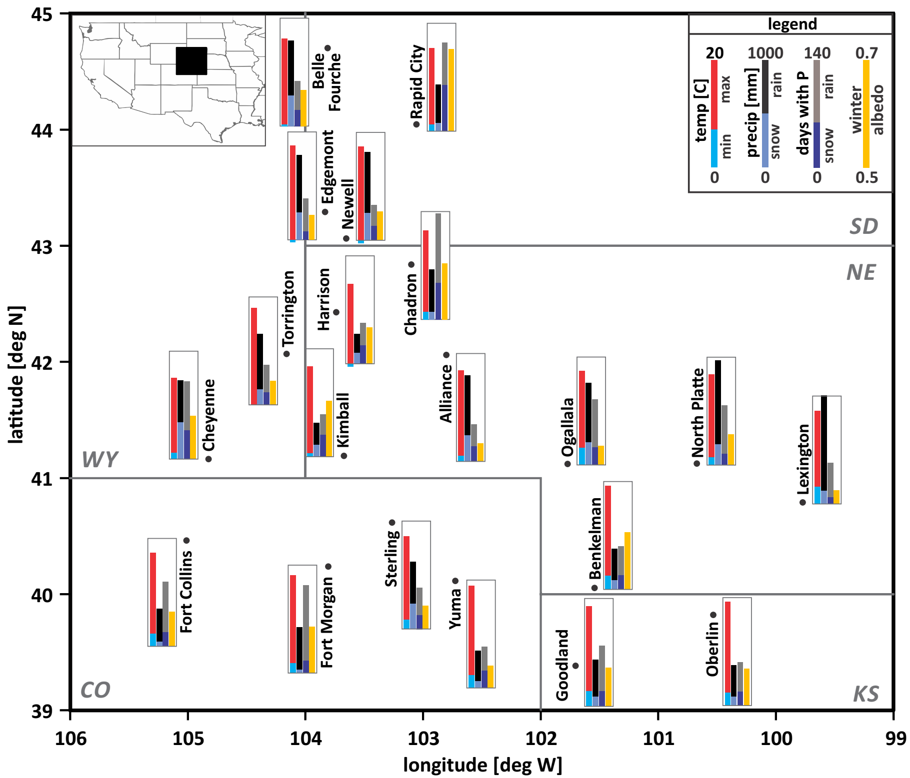

Figure 1. Location map and average climate from 1951 through 2010 for the 20 study stations in the Northern Great Plains. The annual climate summary includes the temperature (temp) as daily maximum (max) and minimum (min), precipitation (precip) as the sum of rain and snow shown separately, days with precipitation (days with *P*) as the sum of days with rain and days with snow shown separately, and the winter albedo. The precipitation as snow is the amount of precipitation when fresh snow was observed, as defined by Huntington et al. (2004); the days with snow are the days when fresh snow was observed. The winter albedo is modeled.

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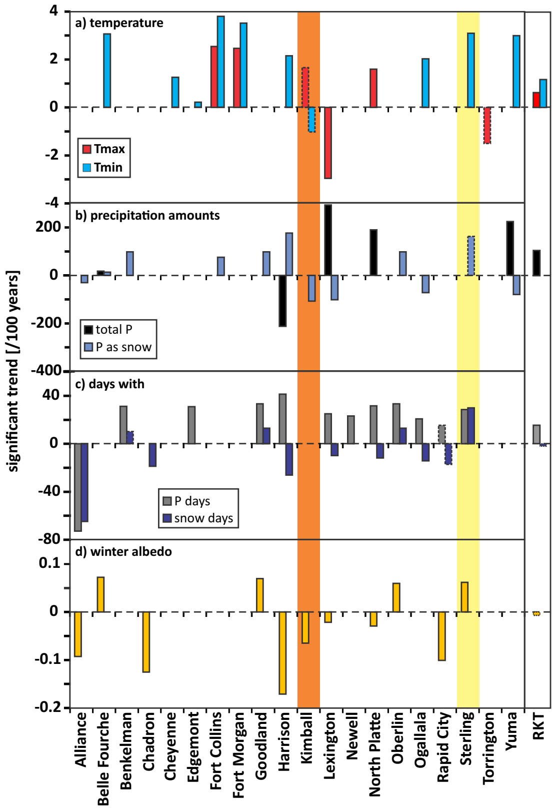

Figure 2. Significant climatic trends at the 20 stations and for the seven variables summarized in Fig. 1 for the period from 1951 through 2010 shown per century. Significant trends are presented at the $p < 0.05$ level, except for trends shown with a dashed border which are at the $p < 0.10$ level. Trends from the Regional Kendall Test (RKT) are shown at the right. The Sterling, Colorado (yellow) and Kimball, Nebraska (orange) stations are highlighted as they are subsequently compared in Figs. 4 and 5.

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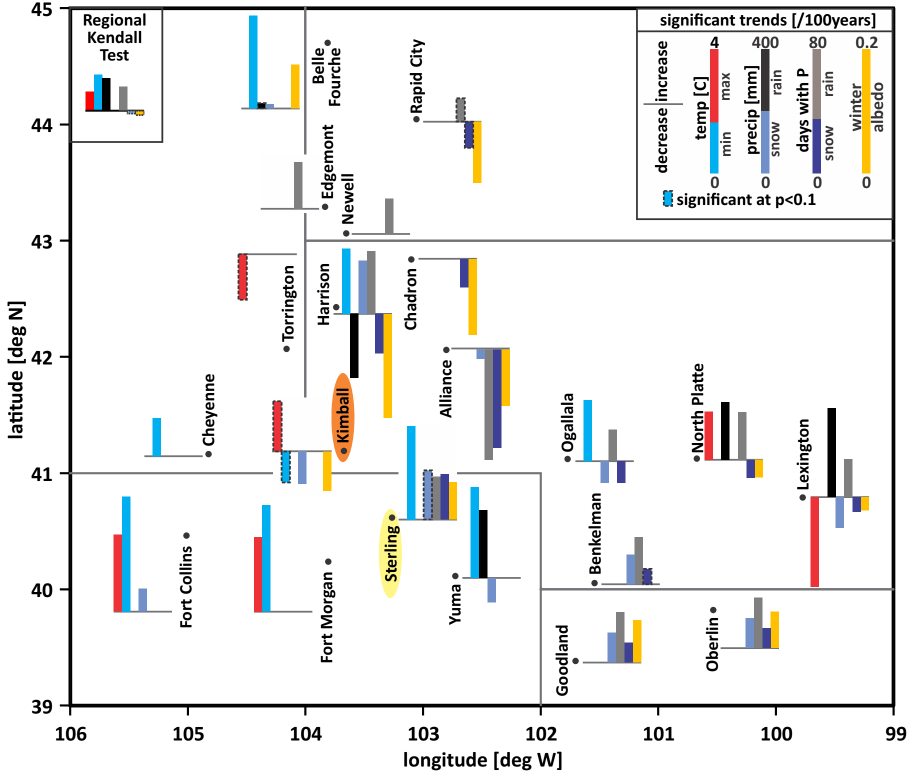

Figure 3. The spatial distribution of the climatic trends at the $p < 0.05$ level for the period from 1951 through 2010 shown per century. Trends shown with a dashed border are at the $p < 0.10$ level. Significant RKT trends are shown in the top left. Sterling and Kimball stations are highlighted.

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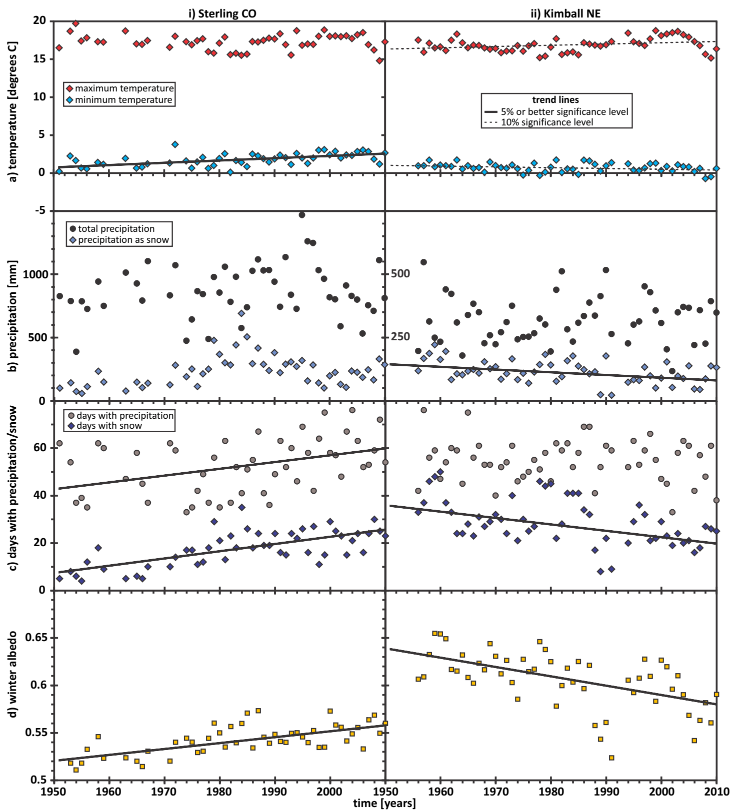

Figure 4. Time series of climate at the neighbouring **(i)** Sterling, Colorado and **(ii)** Kimball, Nebraska meteorological stations, illustrating **(a)** temperature (annual maximum and minimum), **(b)** total annual precipitation and precipitation as snow, **(c)** days with precipitation and days with snow, and **(d)** winter albedo. Significant trends are shown as solid lines for the $p < 0.05$ level and as dashed lines for the $p < 0.10$ level. The Kimball station is 73 km northwest of the Sterling station.

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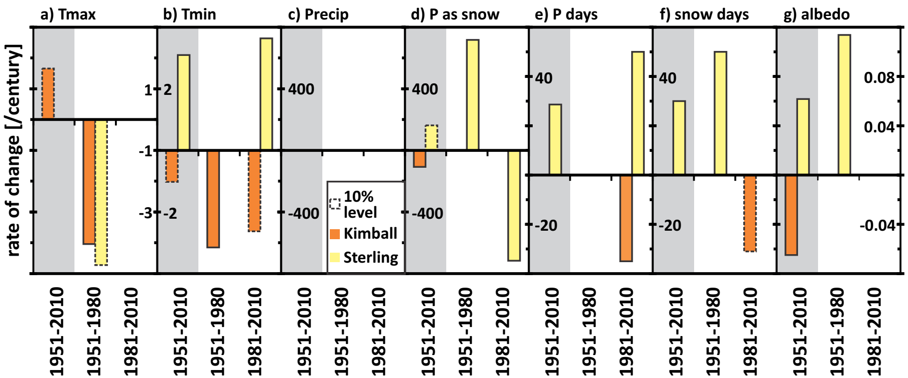

Figure 5. Significant rates of change for the seven variables **(a–g)** for the two focus stations over varying lengths of record (60 years: 1951–2010 and 30 years: 1951–1980, 1981–2010). There were no significant precipitation trends **(c)**.

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