Dear Dr. Marsh and the editorial board,

I would like to thank the anonymous reviewers for their insightful comments. Below we have outline how the reviewers' comments have been addressed.

Regards,
Steven R. Fassnacht

Anonymous Referee #1

> This paper was interesting to read, and the content is appropriate for The Cryosphere. However, before I would recommend acceptance for publication, I suggest that some substantial changes be made. The authors are interested in assessing whether there have been changes in precipitation falling as snow and the number of days with snow. They include the impact on the modeled albedo in the objectives, but there isn't really sufficient justification provided.
An additional has been made to the abstract to clarify the possible impacts of a changing climate on the snowpack. Further, we have added text in the Introduction to explain why albedo changes and differences are important.

> The paper has not been set up to show why there would be an interest in the modeled albedo without tying it back to climate change or regional resource interests.
As per the previous comment, several references have been made to work by Qu and Hall (2006) and Painter et al., (2007, 2010) to put albedo into context. Additional comments have been added to the discussion.

> I suggest that the authors start by citing some studies that have looked at climate or temperature changes in the region, and include a short reference to global trends.
Several references have been added to present the snow cover changes and possible albedo feedback changes across both the Northern Hemisphere and the Northern Great Plains area. We feel it is more important to focus on snow-based changes than global climate change.

> The connection between snowfall and water storage has been well made. Albedo could be brought in through the fact that changes in albedo contribute to the snow albedo feedback and act as a positive feedback in the climate system. Without regional albedo observations during the period of record employed here, a practical albedo model was chosen to estimate the changes that may be associated with the changes in temperature and snowfall.
ok.

> P3333 – Line 22-23: As stated above, it is not immediately obvious why the modeled albedo is a concern. Up to this point, the authors are discussing effects of climate change, namely trends in temperature, precipitation and specifically snowfall on the size of the winter snowpack, and the possible implications of reductions in the winter snowpack on water availability.
A paragraph has been added earlier in the Introduction to explain why we care about snow albedo. We have previously assumed that this was obvious and we needed to state this early in the paper.
> P3336 – Line13: On what was the snowpack albedo refreshment threshold based? Verseghy

(1991) does not specify a value of new snow that is required to refresh the snowpack albedo to 0.84. Until CLASS (Canadian Land Surface Scheme) version 3.0, the albedo refreshment threshold was time-step dependent, (1.4E-6 based on the snowfall rate in m/s (of depth, not SWE), which works out to 2.52 mm depth with a 30 minute time step and 1.26 mm depth with a 15 minute time step; see Langlois et al., 2014). The albedo refreshment threshold in CLASS was changed to 5 mm in a time step (see Langlois et al., 2014 who used CLASS 3.5) and was no longer dependent on the length of the time step. In CLASS version 3.6 the albedo refreshment threshold was reduced to 0.1 mm depth in a time step. The authors should not be required to follow the albedo refreshment threshold used in any version of CLASS, but their text implies that Verseghy (1991) is the basis of the value used. In fact, the value employed by the authors is larger than the largest value ever employed in CLASS. I acknowledge that one is based on a model time step and the other on a daily total. There should be some explanation or justification for the source of the threshold employed, and possibly a sensitivity test if the value is uncertain.
The CLASS model was not used, only the albedo decay model presented by Verseghy (1991). The above was summarized in the text. The text relating to resetting the albedo for fresh snow has been modified to read: "Fresh snow was considered to reset the albedo to 0.84 when at least 2.54 cm of snowfall was observed over a day, since this was the resolution of fresh snow depth measurements (1 inch)."

> P3336 – Line 14: A 'soil albedo' of 0.20 is going to remove any spatial variability in albedo that is not snowpack dependent, and will bias the effect of assessed snowpack related trends on albedo, depending on the bias of 0.2 compared with the average snow-free albedo at each location. This should be discussed or acknowledged.
This is now presented in the discussion: "The constant soil albedo of 0.2 can create problems when snow free conditions persist in the winter months. In the Community Land Model version 4.0, the albedo of soil is a function of color, wetness, and wavelength, such that it can vary between 0.04 in the visible for saturated dark soil to 0.61 in the near infrared for dry, light soil (Oleson et al., 2013). The identification of soils and vegetation at the 20 stations was not undertaken."

> P3337 – Line 10: I suspect that the variability in winter albedo has been underestimated significantly. While the landscape is prairie, and most vegetation types still present in winter (e.g. crop stubble, dead grass [ignoring trees]), would be buried by snowpacks of say 10-20 cm, there would be variability in how efficiently various species are buried, depending in part on whether they are bent flat or remain upright. I don't see this as a fatal flaw in the paper, but there should be some discussion about the applicability to bare ground and easily buried surfaces (i.e. true regional trends are not being simulated, but rather trends at sites likely represented by weather stations).
This is possible and a discussion has been added: "For the Northern Great Plains, the winter albedo of snow free areas will vary over space, but not necessarily over time due to the dormant nature of the vegetation. In the prairie regions, the grasses can be up to 50 cm tall yet will lie down during snow accumulation yielding 10 to 20 cm high vegetation. Thus 10 to 20 cm of snow is required to completely cover such vegetation. However, the dataset used herein are collected at airports and near towns with grass areas that are landscaped, thus the vegetation is only 3 to 5 cm high allow it to be buried much quicker than native, non-landscaped prairie vegetation. Formulations do exist to consider the burial of vegetation by snow (e.g., Wang and Zeng, 2009),

but this is beyond the scope of this paper."

We have added the NARR albedo dataset which was thought to be a good comparison, but the problem is scaling from the point (station) to spatial (32 km resolution) dataset with imhomogeneities in the latter. Also, the latter uses a simple version of the albedo equation used in this work.

P3337 – Lines 18-20: The abstract indicates that a warming would result in less snowfall, but either this is not the case, or stations with cooling have obscured this. Can the authors test this using only stations showing warming?
The abstract was changed to state that warming could rather than would result in less snowfall. What is observed is actually the opposite; with warming, especially Tmin, precipitation as snow and the number of days with snow both increase.

P3338 – Lines 20-26: It may be difficult to assess some trends without looking at whether spatial differences in actual albedo, changes in albedo, elevation differences and possibly changing weather patterns had any effect. I acknowledge that doing this may be too cumbersome here but the authors may want to add to their discussion of the difficulty.
We are not sure what the reviewer is asking here. There are some elevation differences but those are small, at least regionally.

Also, were the instrument histories of the stations assessed to determine whether any instrument types were changed or locations moved slightly. Such actions can have a large effect on the ability to detect trends. A simple statement of the latter will do.
As per the detailed comments from reviewer 2, we have added information about the specific stations used, in particular a description of station moves.

P3339 – Lines 17-25: The two periods of analysis meet relatively close to the well documented change in global temperature trends, which showed cooling from the 1940s –1970s and warming thereafter. The authors may be seeing a global trend on top of the local or regional trend. This should be mentioned. These trends offer much to explain the changes in days with snow, precipitation as snow and albedo (Figure 5). In broad not necessarily consistent terms, there was more cooling from 1951-1980 and more warming from 1981-2010, and 1951-1980 showed more precipitation as snow, more snow days and a higher albedo.
Good point. This has been added.

P3339 - Lines 26-29: Also, a bare surface with one large snowfall late in a given time period will have a very low average albedo.
Not necessarily. It depends on when the snow falls during the day.

The 'days with snow' appears to be calculated as days with snowfall. If days with snow on the ground has not been calculated, could this be added? It may be more significant as it integrates the effects of snowfall and melting.
Throughout the document the phrase "days with snow" was changed to "days with snowfall." Both snowfall and snow on the ground amounts are measured. When there was snow on the ground, days with observed snowfall reset the albedo (see above), using the amount of

precipitation of snow distinction defined by Huntington et al. (2004).

P3340 - Lines 10-12: The meaning of ‘stringent’ is not clear to me. Do the authors mean too static or not flexible enough? Was a slower albedo decay and a higher albedo desired? If so, why?
This should have said “too large,” and thus albedo decayed too quickly.

Minor comments and errors:
P3332 - Line 10: “There was substantial variability. . ..”
changed.

P3332 - Line 16: Did the authors mean to state that “In some locations rates of change are increasing faster than the global average”? A temperature increase can be expressed as a rate of change (C/Time), or one can state that in a given location, temperatures are increasing faster than the global average. An increase in the rate of change implies the rate of change of the slope or the derivative, but I don’t think this was what the authors intended to express.
This sentence should have read: “In some locations temperatures rates of change are increasing faster warming much more than the global average, ...”

P3332 - Line 18 and P3334 – Lines 19-20: I suspect that trends in daily maximum and minimum temperatures would be important for snowpack properties, as these would affect phases changes and metamorphism. I am curious about why average annual minimum and maximum temperatures were used rather than the average maximum and minimum temperatures over the defined winter period of each year. Other indices, such as the number of days with the maximum or minimum temperature below 0 C may also be useful.
Good point. However, here we used annual temperatures as they can be compared to other studies.

P3332 - Line 21: “. . ., a shallower snowpack. . .”
Changed.

P3332 - Line 21-22: I agree with this statement as applied to the US northern great plains where there is a seasonal snowpack, but in a colder environment with a longer winter, a warming climate may bring more snowfall. I would qualify the sentence by including the region of interest.
“In non-polar regions” was added, and it was further stated that “an overall warmer climate could yield ...” rather than “would yield ...”

P3334 – Line 22-23: This method of calculating snow would overestimate the snow amount. If the number of days with air temperatures just above 0 C (days likely to have mixed or transitional precipitation) shows a trend, then this will bias the fractional snow calculation. (i.e. if the number of days with air temperatures say in the range of 0-5 C increased, then this method will bias the trend in snowfall high, whereas if the number of such days has decreased, it will bias the trend in snowfall low. The authors do a decent job of explaining their rationale for this choice of method so no change in methodology is requested.

Some of the snow could be mixed phase precipitation, but if it was still snow in the morning when the daily measurement was made, it was all considered snow. Conversely if it melted between when it fell and when the measurement was made, it was considered rain. This should not be systematically incorrect; not other data were available.

P3335 – Line 1: This sentence is awkward. I would reword it as: "We did not attempt to correct for snowfall that melted before being measured."
changed

P3338 – Lines 5-8: This sentence is awkward.
This was reworded.

P3338 – Line 26: 'to understand better'
"for further study" was deleted.

P3339 – Line 2: '. . . saw significant increases in both Tmax and Tmin'
changed.

P3339 - Lines 7-9: Studies have shown that the NGP is experiencing increasing temperatures and decreases in annual snowfall, but this study shows more increases in snowfall. Sample bias?
"The results presented herein include an additional 10 years of data and illustrate less consistency in changes to the amount of snowfall."

P3339 – Line 13: '. . . such a decrease. . .'
"s" deleted in "as"

Some figures are hard to read, If a figure is wider than a single column, I suggest that it be increased to the usable width on the page within the margins.
I will work with the copy-editor on this.

Review #2 comments – "Snow and albedo climate change impacts across the United States Northern Great Plains by Fassnacht et al.

> This paper analyzes trends in physical climate variables as well as estimated (derived) albedo for 20 stations across the Northern Great Plains with (nearly) serially complete records for the 60-year period 1951 through 2010. The most robust trends were increases in daily minimum temperature and days with precipitation. Other variables, including albedo, had less consistent trends.

Trends in albedo were computed at 11 stations, 7 decreasing and 4 increasing.

> While the paper does not represent breakthrough science, it does make a modest contribution to the regional understanding of climate change in the cold regions of the U.S., and eventually should be publishable. However, I think the authors need to be sent back to do more analysis, and improve the presentation. With respect to the latter, I find the figures very hard to follow. While their attempt to include multiple variables and the spatial location of stations on single plots is clever, I also find it nearly impossible to digest – information overload. The way many

authors have presented this kind of information that works well is with bubble diagrams, which provides a much better sense of the combination of spatial structure, trend direction, and magnitude. It does require separate plots for each variable. My suggestion is to replace Figures 1-3 with such plots (multi-panel of course). There are various ways of doing this; one is to use the size of the bubble to reflect the strength of the trend, with color (typically red and blue) indicating the trend magnitude, and solid vs open circles for statistically significant vs not.
We agree that Figure 1 has much information, but feel that it puts the climatological similarities and differences into spatial perspective. Figure 2 and 3 each show the same information to illustrate the magnitude and direction of change (Figure 2) and the spatial distribution of change (Figure 3).

> My major technical concern is that the paper doesn't investigate the cause for spatial anomalies. The Sterling vs. Kimball comparison is interesting, but the authors don't offer any explanation as to why the trends are so different. My suspicion is that changes in station location, conditions, and/or instrumentation may have played a role. Presumably the 20 stations are in the NCDC Cooperative Observer network. There is a metadata archive for these stations, which the authors should review carefully. It is not necessarily the case that stations have been in the same location even if the station number hasn't changed. I have seen presentations by Kelly Redmond that have highlighted horrors in these station records where the station has moved, but the same station ID was retained (his examples are in the West, where station moves often mean changes in elevation, and hence spurious temperature trends – that won't be so much the case in the Great Plains, but other local factors may well be responsible for some of the apparent trends). In the case of precipitation, and the snow part in particular, minor changes in station location can easily change wind patterns, and hence snow undercatch, and even if the station location is unchanged, construction of buildings, growing or removal of trees, and so on can have a major effect. Also, there is the issue of time of observation. Nothing is said in the paper about observation time, which has changed in many cases and can introduce spurious trends. NCDC has a time of observation file for all of these stations (the authors may want to talk to Pasha Groisman who is an expert on these matters).
We have explored the metadata for all 20 stations. These stations were selected since they had a long continuous record from 1951 through 2010 with few missing years of data. The metadata for all stations was explored and the distance that stations were moved has been summarized. This is also presented in the discussion. It should also be noted that the Northern Great Plains are relatively flat and thus any change in elevation from a station move is negligible. For example, the Goodland station was moved about 500 meters, but it remained at the airport so the change in elevation could be assumed to be only in the order of meters.

> Conspicuously missing from the methods section is any discussion of how the observations were taken. In part, this should include a summary of gauge type and time of observation (and any changes therein), but also how solid precipitation was recorded. Many (perhaps all) of these stations are manually observed once per day, and with snow in particular, how is this collected? Is the presence of snow via manual observation of snow depth, which then is annotated and the total (liquid) precipitation total ascribed to snow rather than rain over the previous 24 hours? And whatever the protocol is, has it remained the same over the 60-year period?
The presence of snow was determined as fresh snowfall. This was used to reset the albedo of snow. The presence of snow on the ground was used to confine albedo to snow-based or soil.

> Again, I think a discussion with Pasha Groisman would be worthwhile. Incidentally, I am surprised that I don't see any reference to his work on similar topics.
Good point. We have added citations to Groisman talking about station moves and their implications.

> I also have to wonder why the authors didn't use stations in the Hydroclimatic Network (HCN), for which some quality control has been done. Some of these stations no doubt are in HCN, but others may well not be, and if so why not? Were they not included (in HCN) because of quality control issues.
Nine of the 20 stations are part of the US HCN. The metadata for all stations was explored and the distance that stations were moved has been summarized. This is also presented in the discussion.

> Finally, although not conclusive, changes in snow albedo, if present, would be important. The authors note the limitations of the USACE decay algorithm, and I understand that there is no viable alternative over such a long period. Given that the computed albedos are a function of several measured variables, I think the authors should analyze trends in the contributing variables, and then show which trends are most responsible for the observed trends (this is different from the partitioning of variance, which they do discuss). It may also be that in the case of stations with no significant trend, this is resulting from cancellation of trends in the driving variables, and this should be noted as well.
This has been added to the dicussion.

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 ~~w~~could cause less snowfall, a shallower snowpack and a change in the timing of snowmelt, all which could reduce the winter albedo and yield an increase in net shortwave radiation. 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 was~~ere~~ substantial spatial variability in the climate trends. For most variables, the period of record used influenced the magnitude and sign of the significant trends.

Keywords: trends, temperature, precipitation, snow, albedo

1 INTRODUCTION

While global annual temperatures have increased by 0.74 °C in the past century and 1.3 degrees °C in the past 50 years, these temperature increases are not consistent across the globe (IPCC, 2007). In some locations temperatures ~~rates of change~~ are ~~increasing faster~~ warming much more 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).

In non-polar regions, a~~A~~n overall warmer climate c~~w~~ould yield less snowfall, a shallower snowpack, and a change in the timing of the snowmelt (Stewart, 2009). The Western United States has already seen earlier snowmelt and peak discharge in snow dominated river systems of up to 20 days earlier (Stewart, 2009). The Western United States has also seen widespread declines in springtime snow water equivalent (SWE) from 1925 to 2000 (Mote et al., 2005).

Numerous studies have examined ~~the~~ snow cover and its variability across the Northern Hemisphere, with most highlighting a decrease over the period of record. Station data for North American has shown that the end date of snow cover has not changed from 1980 to 2006, although ~~some~~ temperatures at some stations have been warming in~~for~~ the same region (Peng et al., 2013). Using up to eight sources, including station and modeled data, the March and April snow cover extent (SCE) were constant or slightly decreasing from about 1960 to the early 1980s, then ~~a~~ decreased through the 1980s, followed by an increase in the early 1990s (Brown and Mote, 2011). After that time the March SCE was relatively stable through 2010 but was decreasing in April (Brown and Mote, 2011).

There has also been a decrease in precipitation as snow across the Western United States (Knowles et al., 2006). Decreases are amplified when the average wintertime temperatures remain around 0 degrees Celsius (Knowles et al., 2006). The ratio of precipitation as snow has also been decreasing across the Northeastern United States and the contiguous United States 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). Be~~Somewhere be~~tween 90-120 snow covered days occur in the Northern Great Plains, with a thin maximum SWE of between 20-40 mm. Using a number of climate models, the largest future decrease is in snow covered days, which is much more than maximum SWE (Brown and Mote, 2009).

Seasonal snow cover is an important part of the energy budget due to its low thermal conductivity and high albedo (Stewart, 2009). Similarly, the snow albedo feedback is a concept used in climate models to define the atmospheric energy balance from the change in solar radiation due to the change in snowpack albedo (Qu and Hall, 2006). Reductions in the albedo of a snowpack surface, such as due to the presence of dust, can drastically increase rate of melt and for deep snowpack results in snow-free conditions a month or more earlier than clean snow conditions (e.g., Painter et al., 2007). The increased absorption of solar radiation due to ~~a~~ decreased albedo is much more important in the melting of snow than the small increases in longwave radiation due to temperature increases (Painter et al., 2010).

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 sh~~w~~ould~~ likely~~ lower the depth of the snowpack and could possibly decrease the persistence of snowcover which ~~w~~could decrease the overall winter albedo. The decreased albedo ~~is~~ would increase the absorption of~~the~~ incoming solar radiation. A reduction in the number of days with snowfall would also reduce the amount of fresh snow and therefore reduce 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 is 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.

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 (Figure 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 United States <*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 (Figure 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 degrees north latitude and 99.8 to 105 degrees longitude with elevation ranging from 733 to 1880 meters above sea level. 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 (NCDC) <*www.ncdc.noaa.gov*>, and summarized for the annual analysis.

The stations were all part of the NCDC cooperative (COOP) network. Often such stations are moved, especially over a long period of record, such as the 60 years examined here (e.g., Groisman and Legates 1994; Groisman et al. 1996; Peterson et al., 1998). Such moves can create~~d~~ discontinuities. As such, nine of the stations (denoted by an asterisk in Figures 1-3) are~~were~~ part of the US Historical Climatology Network (USHCN) and~~that~~ are considered a high quality data set of basic meteorological variables (Menne et al., 2015). The station metadata were reviewed to examine station moves and thus possible discontinuities in the record. All nine of the USHCN stations were moved over the 60-~~-~~year period of investigation but these moves were usually less than several kilometers. Three of the remaining stations (Chadron, North Platte, and Yuma) were not moved and thus are considered consistent. Six stations (Belle Fourche, Benkelman, Goodland, Lexington, Newell and Ogallala) were moved less than 0.5 km and most only 150 m. Edgemont was moved in 2009 at the end of the period of investigation, thus this move was not considered to bias the trend analysis. Some of the station moves appeared to be back to or in close proximity of previous locations. This appears to be the case for Sterling that was moved in 1983 and back in 2004.

3 METHODS

For each station, the annual average maximum and minimum temperature were calculated for each year in degrees Celsius. 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).

We did not attempt to correct for snowfall that melted before being measured ~~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 exemplified by 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~~is~~ 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:

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

where $\alpha_{s(t)}$ and $\alpha_{s(t-1)}$ are the albedo at the current and previous time step, t, α_{s-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. Using the same albedo model as that used in~~in~~ the Canadian Land Surface Scheme, Langlois et al. (2014) proposed a threshold of 0.5 cm to reset the albedo to 0.84. Herein, f~~F~~resh snow was considered to reset the albedo to 0.84 when at least 2.54 cm of snowfall was observed over a day, since this was the resolution of fresh snow depth measurements (1 inch). 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.

To further investigate changes at these two locations over the latter~~er~~ 30-~~-~~year period,~~s,~~ the North American Regional Reanalysis (NARR) data were also evaluated. Monthly data were acquired from the NARR dataset from the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from~~at~~ their website <http://www.esrl.noaa.gov/psd/> (Mesinger et al., 2006). The NARR data are a combination of modeled (the National Center for Environmental Prediction Eta model) and assimilated (Regional Data Assimilation System, RDAS) station data at a spatial resolution of 32 km available for the period from 1979 to present. The point values from the two comparison stations (Sterling and Kimball) were extracted by location. The yearly summary by calendar year for air temperature and precipitation, and the period from November to March for the~~rom~~ albedo dataset were~~as~~ tested using~~for~~ trend analysis.

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

4 RESULTS

Average annual maximum (Tmax) and minimum (Tmin) 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 (Figure 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 (Figure 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 (Figures 2 and 3). Minimum temperatures increased at 9 stations averaging 2.74 degrees Celsius per century, with significant Tmin 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. Tmax 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 per century 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 per century and five decreasing by an average of 78 mm per century. Four stations had more snow days by an average of 16.6 per century, 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% per century and decreased at seven stations by an average of 8.6% per century.

There are some identifiable spatial patterns in the climate trends. For example, in the southwest parts of the NGP Tmax and/or Tmin increased at most stations (Figure 3), but there was a decrease in Tmax at Torrington and in Tmin 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 snowfall 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 areas~~parts~~, snow days and albedo decreased, but ~~while the further north~~ ~~(~~Belle Fourche data showed the opposite trend. In the ~~) and~~ south at ~~, (~~Sterling, Goodland and Oberlin, ~~), an increase in~~ the modeled winter albedo ~~was estimated~~ increased (Figure 3).

Significant trends were observed with the RKT for Tmax (rate of 0.625 deg C/100 years), Tmin (rate of 1.17 deg C/100 years, P amount (rate of 105.3 mm/100years), and days with P (rate of 15.6 /100 years), while days with snowfall decreases (rate of -1.82 /100 years) and albedo decreases (-0.007 /100 years) were only significant at the p<0.10 level (Figures 2 and 3).

These were similar to the averages of the individual stations. The RKT trends in P as snow were not significant (Figure 2). The magnitude of regional trends tended to be much less than what was observed at individual stations and~~s~~ no systematic trends were observed across the entire domain (Figure 3).

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

Average temperature trends were similar for the station and NARR data (Table 1), however~~while~~ total precipitation was decreasing from the station data yet increasing from the NARR data. Precipitation as snow was decreasing at twice and more than 10 times the rate for the station data compared to the NARR data at Kimball and Sterling, respectively. Albedo trends were of opposite sign and different magnitudes between the two datasets. The minimum station temperature and average NARR temperature trends at Sterling were significant; no other variable had a significant trend for both the station and NARR datasets (Table 1).

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 (Figure 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 and~~s~~ no systematic trends were observed across the entire domain (Figure 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 stations (Pielke et al., 2002). For example, Fort Collins and Fort Morgan saw ~~both~~ significant increases in both Tmax and Tmin, while Kimball saw less significant increase in Tmax but a decrease in Tmin (Figure 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 above freezing (approx. -5 to 10 degrees C). Previous s~~S~~tudies have shown that the Northern Great Plains is one of the regions of the United States experiencing increased temperatures as well as a decrease in the amount of annual snowfall (Knowles et al., 2006). The results presented herein include an additional 10 years of data and illustrate less consistency in changes to the amount of snowfall. 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 a~~s~~ 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.

There is some correlation between trends of the different variables, which could be relevant to albedo as some of them are used in the model. For example, there is a weak correlation between days with snow and maximum or minimum temperature with 19% of the variance explained when all 20 trends are used. However, few stations see significant trends among a number of different variables (Figure 2). For example, seven stations had significant trends in amount of precipitation as snow and minimum temperature, with 24% of the variance explained. Trends in temperature and precipitation amounts (total and as snow) were not correlated to albedo trends (see Figure 2).

The length and period of record examined also influences the rates of change and the level of significance (Venable et al., 2012). There was little consistency in the trends over the two 30-year periods (Figure 5). Of the seven variables, only Tmin at Kimball was significantly getting cooler for all time periods (Figure 5b). Conversely there was strong cooling of Tmax 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 (Figure 5). This result may illustrate cyclical trends that become highlighted when analyzing shorter time periods (Chen and Grasby, 2009). These trends also somewhat mirror global patterns of cooling from the 1940s to mid-1970s and warming thereafter.

Most of the stations did move over the 60 years of data collection, as explained in the Study Site section. Stations moves can cause time series discontinuity (Groisman and Legates, 1994; Peterson et al., 1998). While the Sterling station did move about 1.6 km twice (1983 and 2004), these potential discontinuities are not present in the time series (Figure 4i). There was a third move in 2010 of about 100 m. There was no indication of changes to~~in~~ the time of observation ~~time~~ at this station, as that has also been shown to cause discontinuity in time series (Groisman and Legates, 1994; Peterson et al., 1998). It should also be noted that the Northern Great Plains are relatively flat and thus any change in elevation from a station move is negligible. For example, the Goodland station was moved about 500 meters, but it remained at the airport so the change in elevation could be assumed to be only in the order of meters.

In climate change modeling efforts based on data for the northern prairies in Canada, snow cover duration was less sensitive to temperature changes than in other regions (Brown and Mote, 2009), but trend analyses from the Northern Great Plains for 1910-1993 show high variability in seasonal snow cover durations. Wintertime increases in snow cover duration were linked with significant increases in seasonal snowfall amounts, though no significant changes were seen in total precipitation (Hughes and Robinson, 1996).

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 snowfall (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 snowfall are important for understanding changes to albedo.

Snow-albedo feedbacks are enhanced by increasing air temperatures and increasing total solar radiation as occurs in springtime. Hernández-Henríquez et al. (2015) found generally low magnitude, variably increasing and decreasing fractions of time that mid-latitude sites (such as the NGP) were snow covered, but conclude that snow cover extent~~d~~ trends in late spring and early summer have the greatest impact on the snow-albedo feedback and surface radiation budget input, particularly at higher latitudes. It is thus recommended that days with snowfall be computed as an additional indicator of climate change and that seasonal analysis, particularly of spring datasets be conducted in spatially and temporally variable snow covered regions like the NGP. While the arctic, especially in sea ice regions, and the mountains of the western U.S., show an increase in the energy balance for snow and ice covered regions, there is a possible negative trend for the Northern Great Plains area (Flanner et al., 2011).

The NARR dataset was evaluated as it includes albedo data for the second 30-year period of analysis. However, the trends in albedo were of opposite sign and different magnitude (Table 1), and~~but~~ no trends were significant. There was greater interannual variability in the NARR albedo than the station data, but the NARR winter albedo (averaging about 0.31 for the 32 km pixels about each site) is much less than the modeled station albedo (averaging 0.59 at Kimball and 0.55 at Sterling). For the Northern Great Plains, the maximum surface albedo from the dataset compiled by Robinson and Kukla (1985) was from 0.71 to 0.80; these data are used to model the NARR dataset. The maximum surface albedo was derived at a 1 degree (latitude and longitude) resolution from satellite data; there can be~~ a~~ large differences between point measurements of albedo and satellite-based estimates~~d~~ due to inhomogeneities such as partial snow cover (Arola et al., 2003). The low values of albedo modeled during snow conditions is consistent among numerous climate/land surface models, even in non-forested areas where the canopy does not need to be considered (Qu and Hall, 2007). Further, the decrease is surface albedo is much more dominated by the melting and thus disappearance of snow, rather than snow~~the~~ metamorphism and the addition of meltwater to the surface of the snowpack (Qu and Hall, 2007). New additions to the snow albedo model in the land surface scheme used to generate the NARR dataset employ~~uses~~ a modification of the albedo decay model presented in equation 1 (Livneh et al., 2010).

The constant soil albedo of 0.2 can create problems when snow free conditions persist in the winter months. In the Community Land Model version 4.0, the albedo of soil is a function of color, wetness, and wavelength, such that it can vary between 0.04 in the visible for saturated dark soil to 0.61 in the near infrared for dry, light soil (Oleson et al., 2013). The identification of soils and vegetation at the 20 stations was not undertaken.

For the Northern Great Plains, the winter albedo of snow free areas will vary over space, but not necessarily over time due to the dormant nature of the vegetation. In the prairie regions, the grasses can be up to 50 cm tall yet will lie down during snow accumulation yielding 10 to 20 cm high vegetation. Thus 10 to 20 cm of snow is required to completely cover such vegetation. However, the dataset used herein are collected at airports and near towns with grass areas that are landscaped, thus the vegetation is only 3 to 5 cm high allow it to be buried much quicker than native, non-landscaped prairie vegetation. Formulations do exist to consider the burial of vegetation by snow (e.g., Wang and Zeng, 2009), but this is beyond the scope of this paper.

Using simple snow albedo models is not uncommon; recently the European Centre for Medium-Range Weather Forecasts (ECMWF) was using the snow albedo model presented herein for melting conditions and a linear model for non-melting conditions, based on the Météo-France climate model (Douville et al., 1995). 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~~large; a slower decrease in albedo computed using a smaller decay ($k <$ 0.01 /h) 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 CONCLUSION

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 the dominant trends among the stations but not the local variability. There were more stations with a decrease in the days with snowfall 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 influences the significance and rates of change.

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Table 1. Comparison of the trends per century from 1981 through 2010 for station and North American Regional Reanalysis (NARR) datasets at Kimball and Sterling. The trend with a plus sign indicates a significant trend at the $p<0.10$ level and an asterisk is at the $p<0.05$ level.

	Kimball		Sterling	
	station	NARR	station	NARR
maximum temperature (^{o}C)	3.74		3.26	
average temperature (^{o}C)		2.26		4.33*
minimum temperature (^{o}C)	-2.63+		3.64*	
total precipitation (mm)	-185	57.6	-268	64.7
precipitation as snow (mm)	-97.6	-48.9	-716*	-61.5
albedo (unitless)	-0.075	0.002	0.038	-0.129

List of Figures

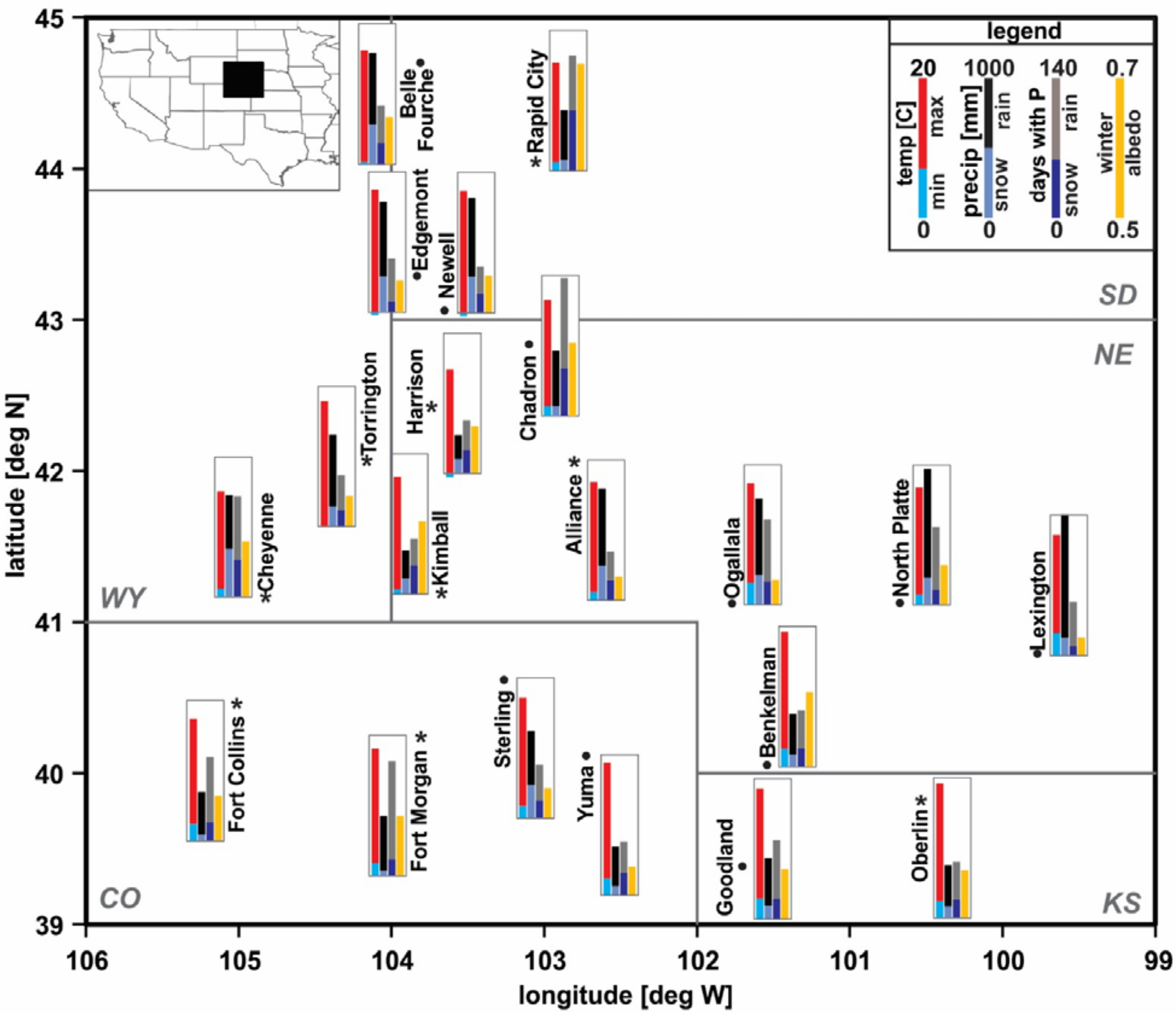
1. Location map and average climate from 1951 through 2010 for the 20 study stations in the Northern Great Plains. The annual climate summary includes the temperature (temp) as daily maximum (max) and minimum (min), precipitation (precip) as the sum of rain and snow shown separately, days with precipitation (days with P) as the sum of days with rain and days with snowfall 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 snowfall are the days when fresh snow was observed. The winter albedo is modeled. The nine stations that are part of the U.S. Historical Climate Network (HCN) are identified with an asterisk.

2. Significant climatic trends at the 20 stations and for the seven variables summarized in Figure 1 for the period from 1951 through 2010 are 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 Figures 4 and 5. The nine stations that are part of the U.S. Historical Climate Network (HCN) are identified with an asterisk.

3. The spatial distribution of the climatic trends at the $p<0.05$ level for the period from 1951 through 2010 are 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.

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 snowfall, 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.

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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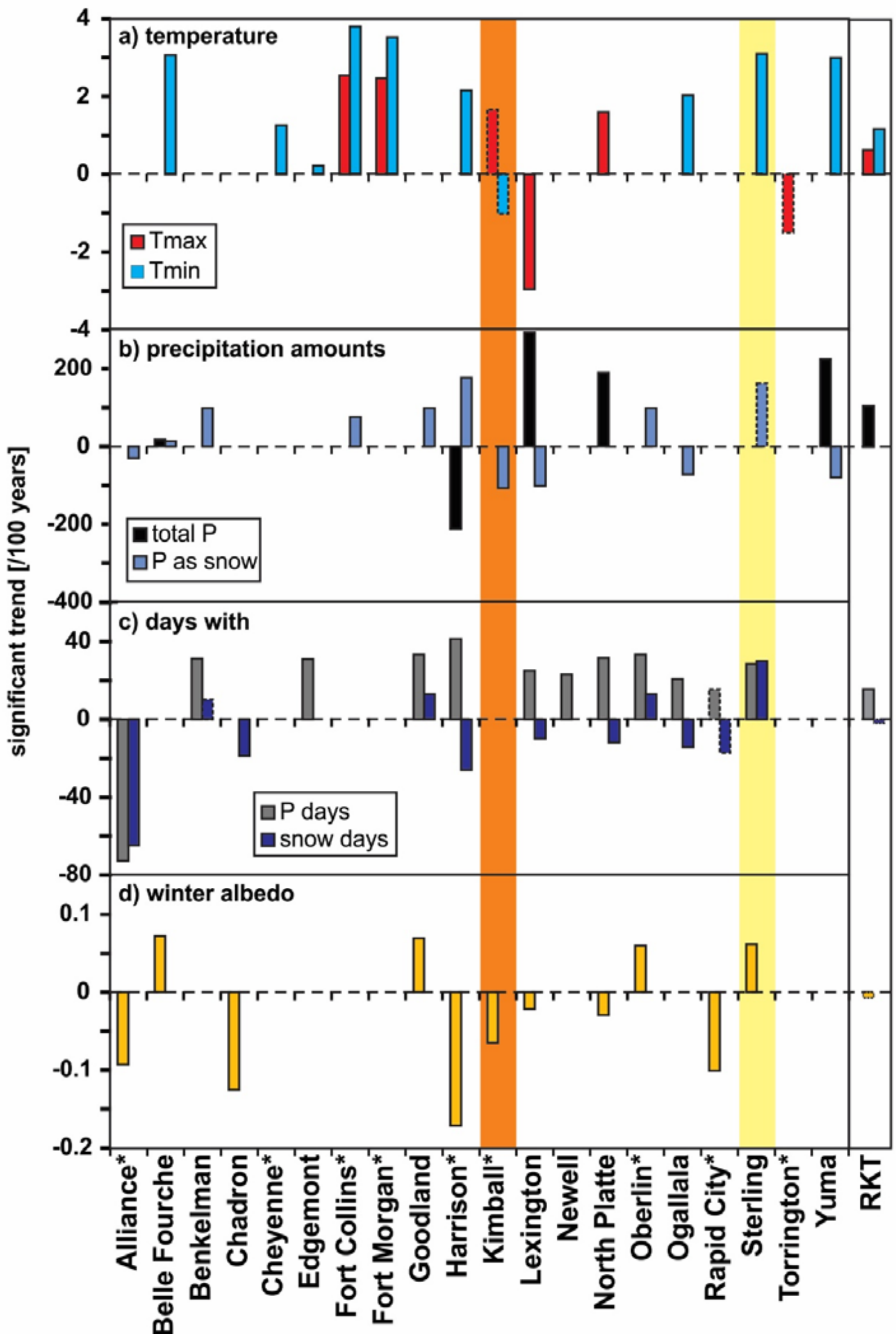
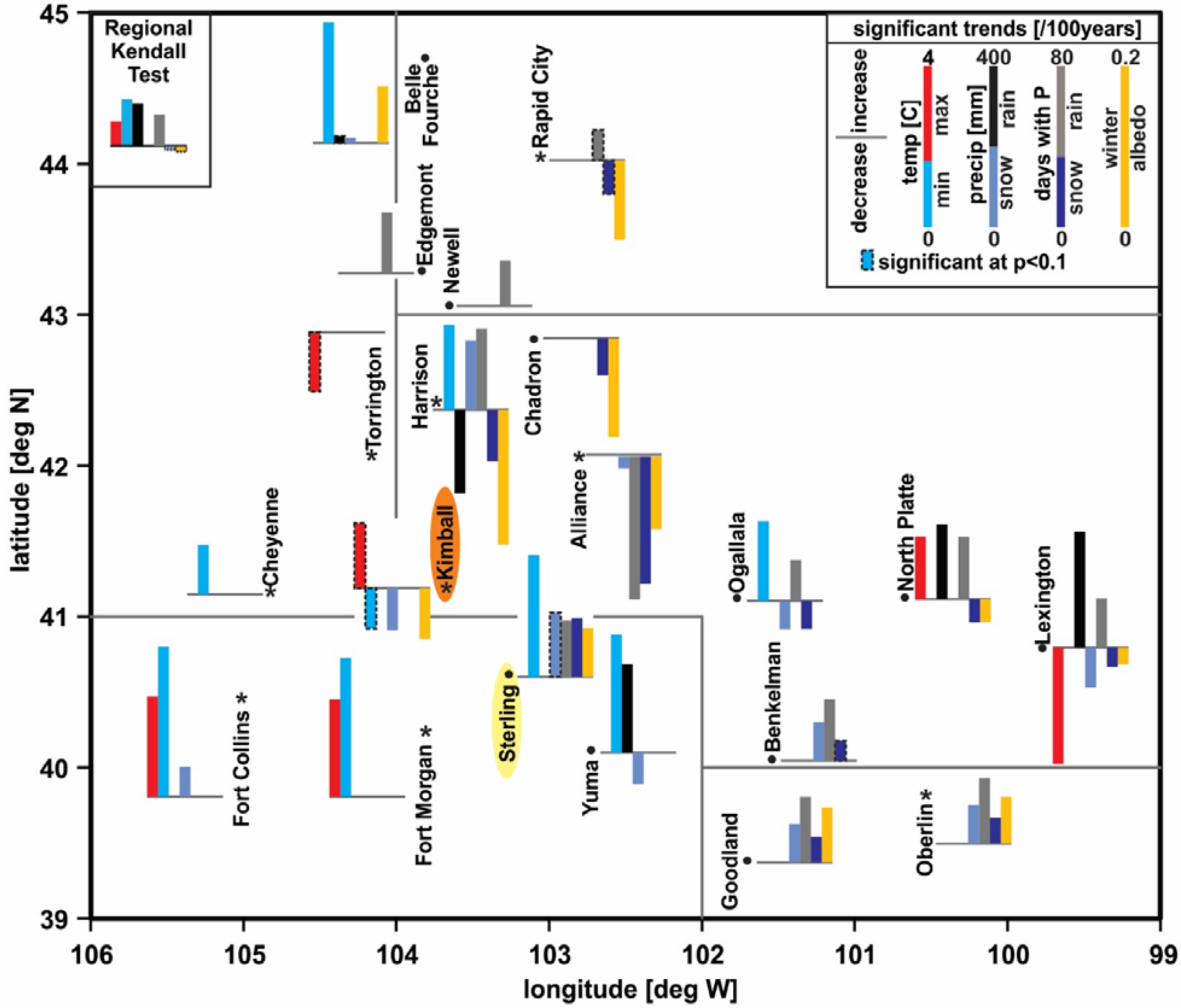


Figure 2. Significant climatic trends at the 20 stations and for the seven variables summarized in Figure 1 for the period from 1951 through 2010 are shown per century. Significant trends are presented at the p<0.05 level, except for trends shown with a dashed border, which are at the p<0.10 level. Trends 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 Figures 4 and 5. The nine stations that are part of the U.S. Historical Climate Network (HCN) are identified with an asterisk.



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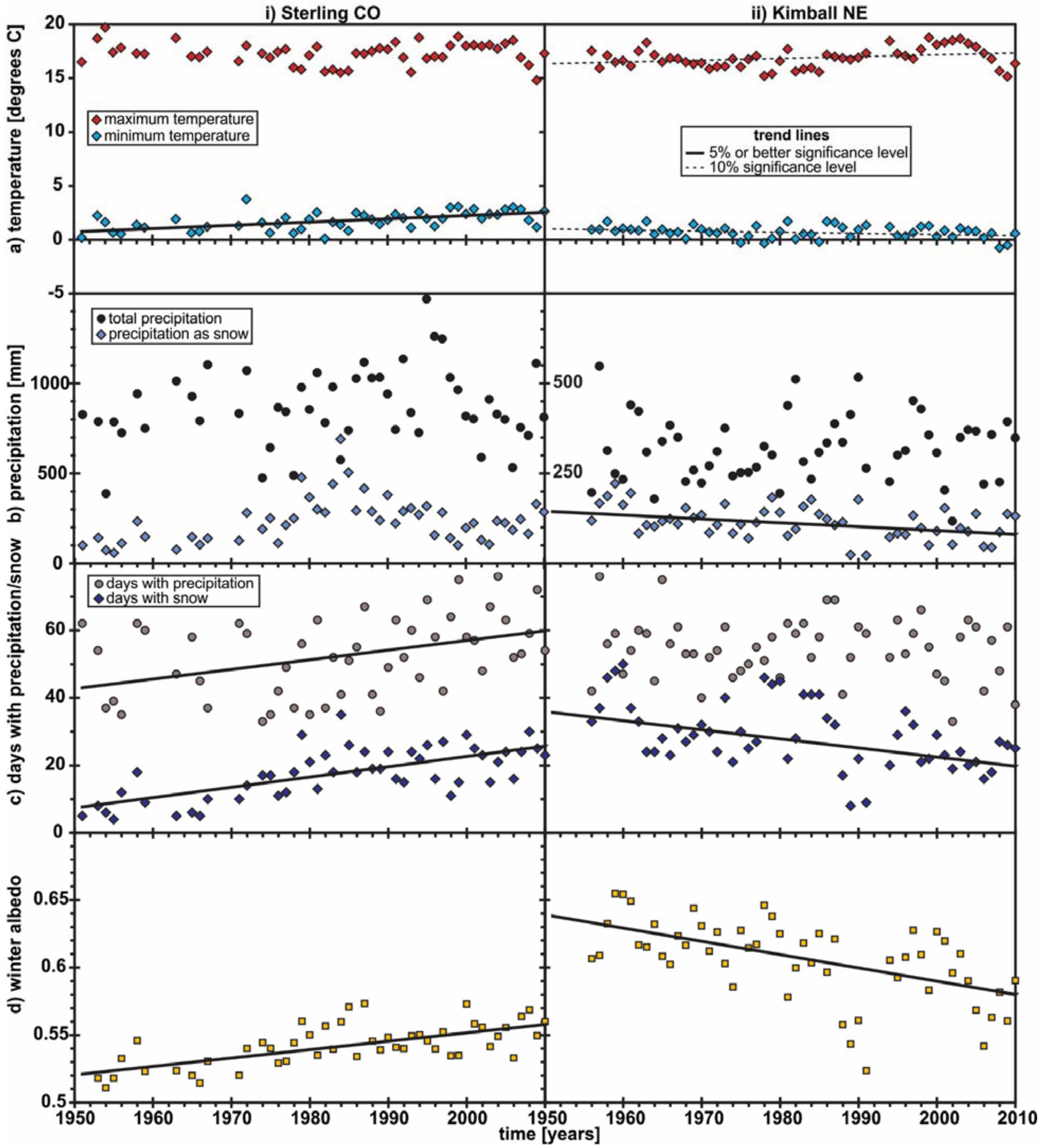

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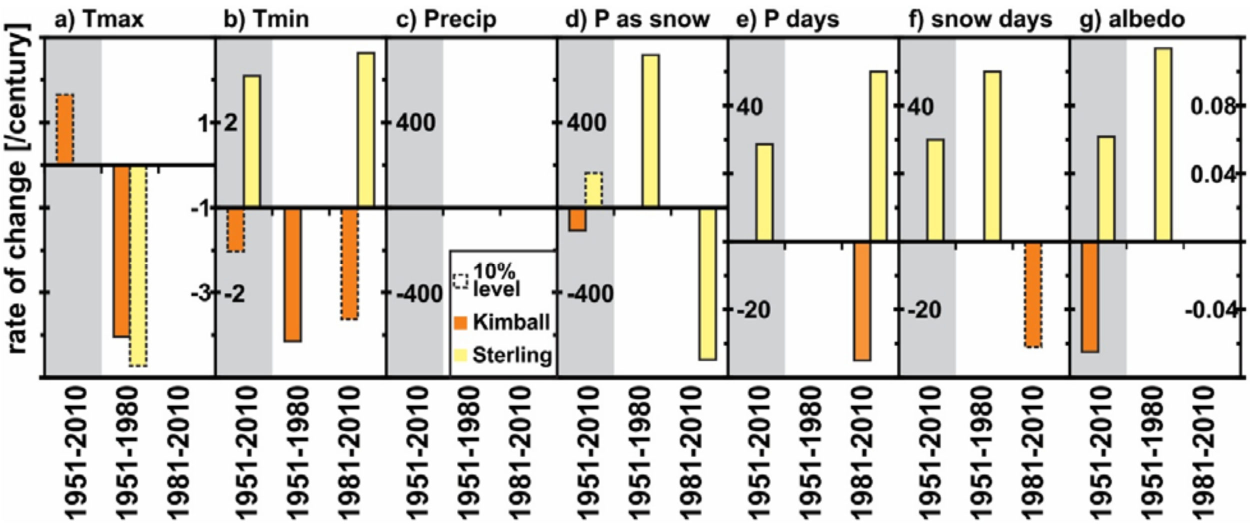

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