CHARACTERIZING TEMPERATURE AND PRECIPITATION TRENDS ACROSS IDAHO

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Abstract
This study used the Daymet daily surface weather dataset to determine various annual weather trends across Idaho between 1980 and 2022. The weather variables include minimum and maximum temperature, precipitation, and snow water equivalence. Using temperature data, non-contiguous annual frost-free days and growing degree days were calculated. Trends were closely examined across two specific regions of the state; the central Idaho Rocky Mountains and the Snake River Plain. Using correlation analyses, F-tests, and ANOVA tests, significant trends were identified and reported in this paper. Overall, temperature and temperature-derived variables showed the greatest change with annual mean minimum temperature exhibiting a strong increase between 1980 and 2022. These trends suggest numerous cascading effects to Idaho's environment and agricultural economy.

Keywords: *Idaho, climate, weather*

Introduction
Effective natural resource management depends upon numerous factors including consideration of weather conditions (e.g., temperature and precipitation) and climate trends. To fully characterize trends requires a lengthy dataset ideally spanning a century or more. These data are not readily available for most of the planet however, due to a number of reasons including: (1) weather stations did not exist throughout the entire time period, (2) records were lost or destroyed, (3) instrumentation and measurement devices have changed resulting in unacceptable data uncertainty and inconsistencies, along with other considerations and concerns. As a result, weather and climate studies with acceptable spatial (e.g., $1km^2$) and temporal resolution (e.g., daily) are often limited to only relatively recent records.

This study sought to characterize temperature and precipitation trends across the state of Idaho in the western United States. The time period of this study spanned 1980-2022 which is a direct result of weather data availability, continuity, and resolution. The specific dataset identified for this study is the Daymet[1] daily surface weather dataset (Thornton et al 2022) which provided temperature minimum (Tmin in degree Celsius), temperature maximum (Tmax in degree Celsius), Precipitation (Precip in mm/day), and snow water equivalent (SWE in kg/m^2).

Because weather events do not recognize state boundaries, the extent of the study area included all 8-digit hydrologic unit watersheds (n = 93) intersecting the state of Idaho (**Figure 1**). This is particularly important when considering precipitation and snow events, subsequent runoff, and hydrologic cycling.

[1] https://daymet.ornl.gov/

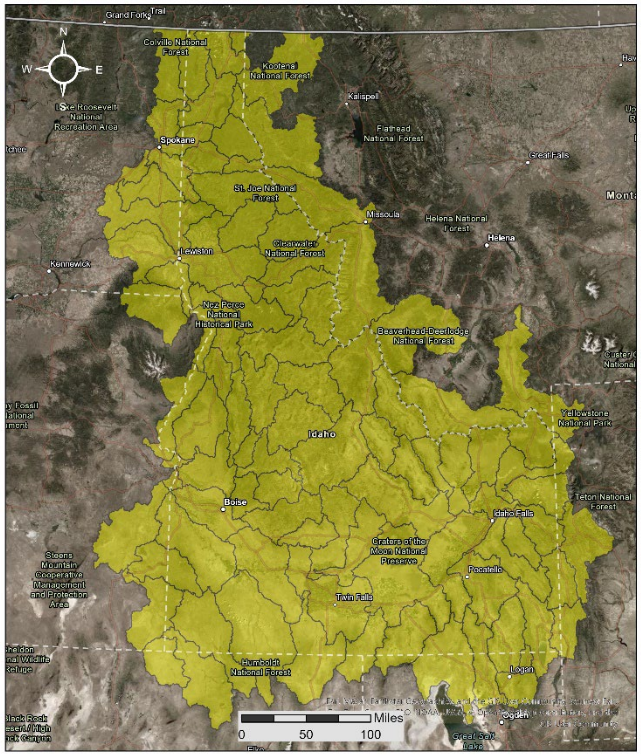

Figure 1. The Idaho study area and 8-digit hydrologic unit code watershed polygons (n = 93)

The goal of this study was to not only assemble useful weather datasets, but to explore multi-decadal trends within these data, and from these results make careful projections of possible future conditions to support natural resource managers and decision makers with reliable spatiotemporal data and information.

Methods

Daymet data for North America were downloaded in NetCDF (*.nc) file format which is not directly supported and ready for immediate use in nearly any modern software application. To make these data useful, we found it best to export these files into a common spatial data raster format like TIF. This was done using the GDAL utility in Idrisi Terrset, resulting in 365 raster layers for each year and each data product (e.g., Tmin). These data were then inspected to ensure correct georeferencing and overall data consistency. Upon completion of this review, data were batch exported from Idrisi raster format (*.RST) to TIF file format.

The TIF files were opened in ArcGIS Pro where the spatial reference system was defined as Lambert Conformal Conic (Daymet) and each layer was then clipped to the Idaho study area. Each daily TIF file had a spatial resolution of 1 km^2 (1000 x 1000 meter pixels) and was named following the convention of [Data Product]_YYYYJJJ.tif; where Data Product was either Tmin, Tmax, Precip, or SWE, YYYY was the year (e.g., 1980), and JJJ was the numeric Julian date ranging from 001 through 365. Leap years were processed following the same protocol used by the original Daymet dataset.

During initial data visualization and exploration, it was noted that early (1980-1990) temperature data appeared visually different from later data (e.g., 1990-2022). This possible error/anomaly was explored through a careful validation before any further analysis was begun. To do this, daily Idaho weather station data was downloaded from the National Centers for Environmental Information (NCEI) for the years 1980 through 1990. Of the 397 NCEI weather stations located in Idaho, 66 were operational between 1980 and 1990 and only 40 provided accurate point locations and temperature data. These stations were used to calculate annual mean Tmin and Tmax for each weather station. This was compared to the corresponding annual mean Tmin and Tmax for the Daymet pixel within which the weather station was located. Running ANOVA for Tmin showed no difference between the NCEI weather station data and the Daymet data (P = 0.673) while ANOVA for Tmax indicated a difference (P = 0.019). However, the F-statistic (5.54) was less than F-critical (6.71) suggesting the sample size may not be sufficient to conclusively make this determination (**Table 1**). Daily comparisons were then made and ANOVA results showed no difference between NCEI weather station data and Daymet values (P = 0.581 Tmin and P = 0.974 Tmax). It is noted that some differences were found and a perfect agreement did not exist nor was it expected. This can be attributed in part to some errors in interpolation and extrapolation processing of the original Daymet data but is also attributable to legitimate differences between a weather station instrument and the corresponding Daymet pixel value for the same time period. To expound, each weather station effectively represents a point observation of weather conditions at a specific latitude and longitude location. To arrive at a correct daily minimum and daily maximum temperature depends upon the frequency of data observations and is assumed to be sufficient to capture these values. These statistics represent Tmin and Tmax at one point location. In contrast, Daymet data effectively represents an area observation of weather conditions across a $1km^2$ pixel. In mountainous areas it is very common for temperatures (and precipitation) to vary somewhat dramatically across an elevational gradient (Pepin et al., 2022) and in the case of this study, elevation differences within a 500-meter radius of sampled weather stations ranged up to 563 meters (e.g., NCEI weather station USR0000ISFK). Using these results as well as the uncertainty quantification reported by Thornton et al (2021) confirms the Daymet dataset provides reliable data well suited to this study.

Table 1. Validation results comparing Daymet temperature data with analogous NCEI weather station data between 1980 and 1990.

VARIABLE	GRAND MEAN		P-VALUE	PEARSON
	NCEI	Daymet		CORRELATION
Annual Mean Tmin	-1.3	-1.4	0.673	0.919
Annual Mean Tmax	14.2	13.6	0.019	0.892

From the primary weather variables (Tmin and Tmax) two secondary derivatives were produced; Frost-Free Days (FFD) and Growing Degree Days (GDD). FFD was simply a count of daily instances where Tmin > 0° Celsius on a pixel-by-pixel basis. This calculation was accomplished using the Greater Than tool and Raster Iterator within ArcGIS Pro's Model Builder. The annual sum of these Boolean layers became the FFD layer for each year (NOTE: The FFD model used in this study does not require continuity of frost-free days). These FFD data were used as the foundation for growing degree days calculations. For this study, a base temperature of 0° Celsius was used with all calculations following Nugent (n.d.) (NOTE: daily data where Tmin < 0° C were excluded from GDD calculation).

The summary raster layers provided data values for each $1km^2$ pixel across the entire Idaho study area and gave a general overview of temperature, precipitation, snow water equivalent, frost-free days, and growing degree days over time. To more readily enable use of these data, a space-time data cube was created using the multidimensional mosaic dataset in ArcGIS Pro. These time-aware data were then saved in Cloud Raster Format (CRF)[2] and temporal profiles extracted using 8-digit hydrologic unit code watershed polygons (HUC08) with the Zonal Statistics tools in ArcGIS Pro.

There are 93 HUC08 polygons within the study area. This paper selected and reports results for seven of those watersheds; four henceforth referred to as High Country Watersheds and three referred to as Snake River Plain watersheds (**Table 2** and **Figure 2**). These watersheds were selected to represent a (1) contiguous mountainous region and (2) lower elevation region with minimal topographic relief.

[2] CRF data are available from https://giscenter.isu.edu/research/Techpg/NSF_ICREWS/results.htm

Table 2. Topographic characteristics of the seven watersheds selected for this study.

REGION	HUC 08	AREA (km^2)	ELEVATION SUMMARY (meters)				
			MIN	MAX	RANGE	MEAN	MEDIAN
High Country	17060201	6,279	1,408	3,605	2,197	2,309	2,303
High Country	17060203	4,719	918	3,347	2,429	1,974	2,015
High Country	17060205	3,890	1,221	3,184	1,963	2,197	2,206
High Country	17060206	3,563	918	3,099	2,181	2,120	2,163
Snake River Plain	17040201	1,413	1,430	2,161	731	1,506	1,476
Snake River Plain	17040206	5,593	1,308	2,667	1,359	1,494	1,457
Snake River Plain	17040209	8,702	1,242	2,832	1,590	1,454	1,400

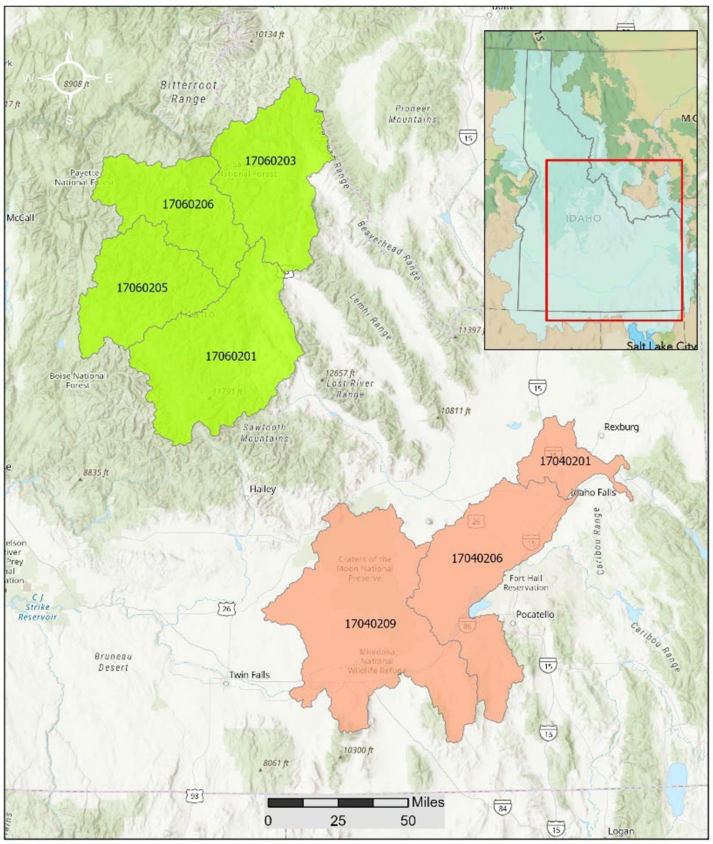

Figure 2. Seven watersheds were selected to serve as case study regions, four were considered high country watersheds (green) and three Snake River Plain watersheds (orange).

The tabular results of zonal statistics analysis were exported to Microsoft Excel for data visualization and further analysis. This included linear trend calculation and a determination of confidence based upon regression analysis and F-test.

Results and Discussion

Four primary annual weather variable trends were explored across both High Country and Snake River Plain watersheds; minimum temperature (Tmin), maximum temperature (Tmax), precipitation (Precip), and snow water equivalence (SWE). In most instances, annual mean temperatures have been increasing since 1980 with more prominent rate of increase seen in the High Country watersheds. Precipitation (both Precip and SWE) exhibit a declining trend over the same time period (**Figure 3**).

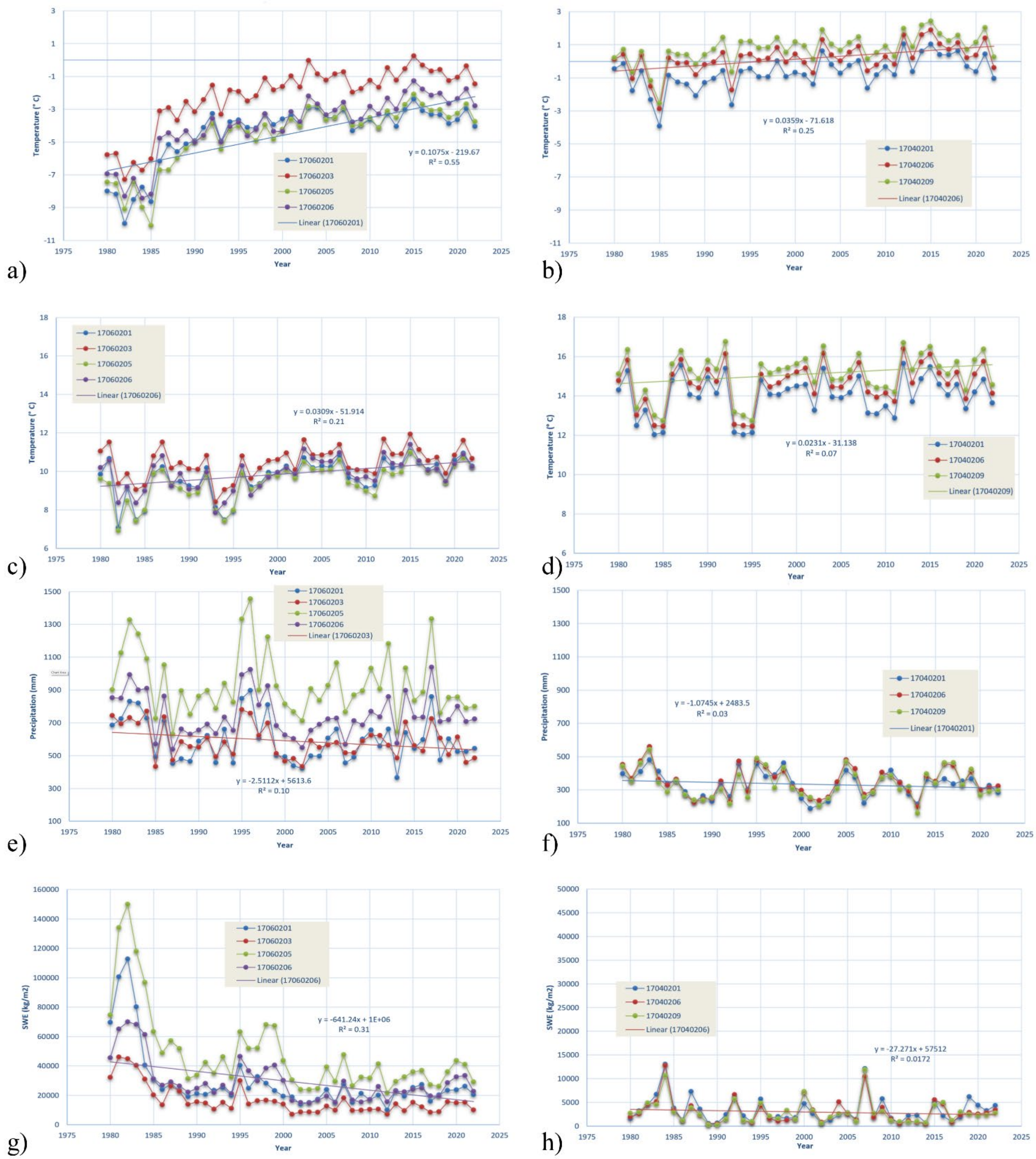

Figure 3. Annual trend of four primary weather variables across High Country watersheds (left) and Snake River Plain watersheds (right). Tmin (a and b), Tmax (c and d) show an overall increasing trend while Precip (e and f) and SWE (g and h) show a decreasing trend. The linear regression equation and R^2 values are for a single watershed and are given to illustrate general trend. NOTE: The Y-axis for SWE graphs (g and h) are not identical simply because of the extreme difference in SWE values observed between these regions.

Two secondary annual weather trends were also explored; frost-free days (FFD) and growing degree days (GDD). Secondary variables are those derived from primary variables and not provided directly by the Daymet dataset. Each of these weather variables exhibit an increasing trend between 1980 and 2022 (**Figure 4**).

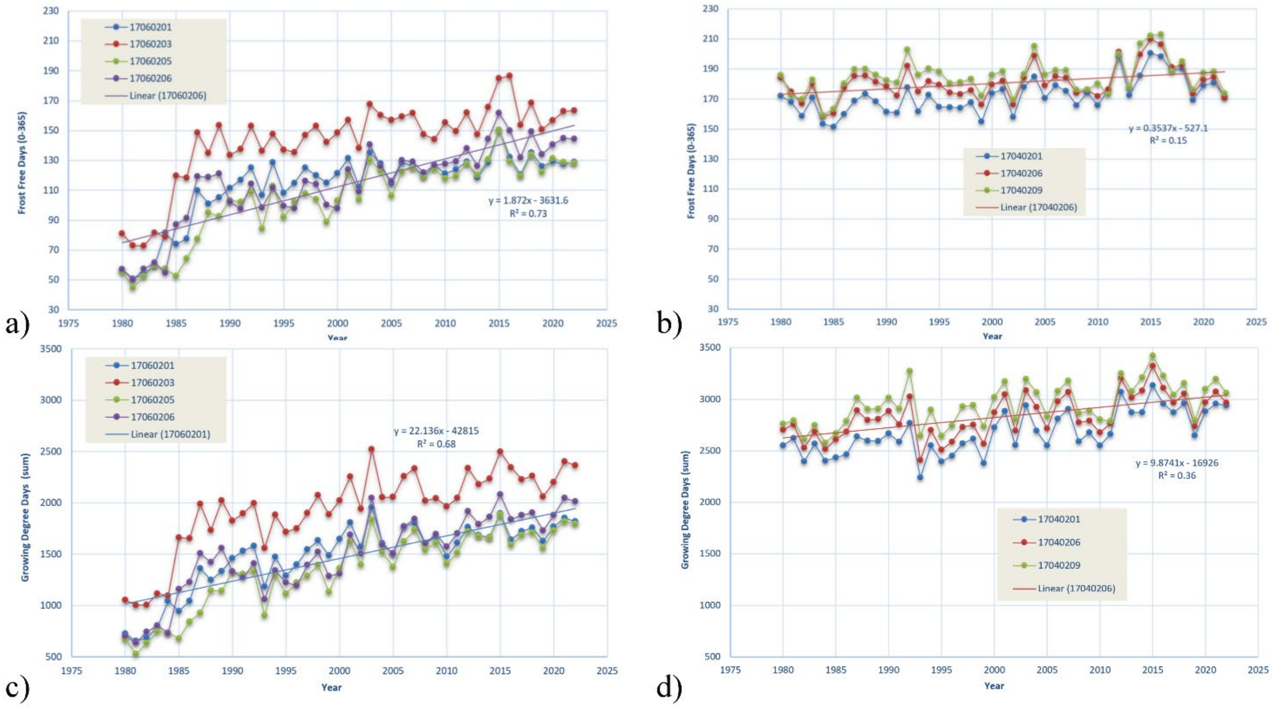

Figure 4. Annual trend of two secondary weather variables across High Country watersheds (left) and Snake River Plain watersheds (right). Both FFD (a and b) and GDD (c and d) show an overall increase over time and more or less, agreement with one another. However, GDD is increasing more rapidly due to increasing trends of Tmax. The linear regression equation and R^2 values are for a single watershed and are given to illustrate general trend.

To better understand the reliability of these trends a number of statistics were closely examined and tested. These are the R^2 for linear trend lines, the adjusted R^2 for goodness of fit, and F-test of regression residuals (**Tables 2 and 3**).

Table 3. Results of statistical analysis of weather trends explored in this study for High Country watersheds.

VARIABLE	R^2	Adjusted R^2	F-test P-value
Mean Tmin	0.51	0.51	< 0.001
Mean Tmax	0.20	0.20	< 0.001
Sum Precip	0.02	0.01	0.064
Sum SWE	0.24	0.23	< 0.001
Sum FFD	0.52	0.51	< 0.001
Sum GDD	0.53	0.53	< 0.001

Table 4. Results of statistical analysis of weather trends explored in this study for Snake River Plain watersheds.

VARIABLE	R^2	Adjusted R^2	F-test P-value
Mean Tmin	0.20	0.20	< 0.001
Mean Tmax	0.05	0.04	0.012
Sum Precip	0.01	0.00	0.208
Sum SWE	0.02	0.01	0.133
Sum FFD	0.17	0.16	< 0.001
Sum GDD	0.30	0.30	< 0.001

While intriguing trends exist for each of the variables examined in this study, one must recall that correlation does not necessarily infer causality. In this case, due to large residuals in these data and interannual variability, the results of statistical analyses suggest several trends are not reliable and should not be considered indicative or predictive of future conditions. These are: annual precipitation in both High Country and Snake River Plain watersheds as well as Tmax and SWE across the Snake River Plain watersheds.

However, nearly all trends of annual weather variables for High Country watersheds (five of six or 83%) were significant and can be considered reliable. In contrast, only half of the weather variable trends for Snake River Plain watersheds were significant. This suggests an effect of elevation and topography (**Table 2**) which agrees well with reports from other studies exploring elevation dependent warming (EDW) (Pepin et al. 2022) and its effect on biodiversity (Parmesan 2006), snowpack (Lopez-Moreno 2005), and reservoirs of freshwater (Viviroli et al. 2011).

Looking more closely at only the significant trends established across High Country watersheds reveals the majority are temperature or temperature-derived variables with Tmin showing the strongest significant trend. Assuming those trends are indeed reliable and will continue to follow a roughly linear progression in the future, one can forecast future conditions based upon past conditions. This is typically done with confidence where the time period forecast forward does not exceed the time period for which the trend was established. In this study, forecasting 40 years forward is reasonable because it is based upon a single time step of roughly 40 years (1980-2022). The results of this forecast show a continued increase in annual Tmin, Tmax, FFD and GDD (**Table 5**).

Table 5. Forecast for significant temperature and temperature-derived weather variables for High Country watersheds. Note the forecast Tmax conditions show very little change relative to changes in Tmin.

VARIABLE	2030	2040	2050	2060
Mean Tmin	-1.4	-0.4	0.7	1.8
Mean Tmax	10.8	11.1	11.4	11.7
Sum FFD	169	187	206	225
Sum GDD	2121	2342	2564	2785

It is interesting to note that based upon existing trends –which may not continue to follow current linearity—by the year 2050, mean annual minimum temperatures will not fall below freezing. That does not suggest an absolute absence of freezing temperatures or elimination of winter snow, but rather the mean annual minimum temperature will not fall below zero. For this to occur, an increase in winter minimum temperatures would need to take place. As a result, frost free days are forecast to increase to over seven months by the year 2060.

Ecologically these changes could have numerous repercussions. For instance, Aspen (*Populus tremuloides*) would be detrimentally impacted if winter snowpack declines (Mote et. al. 2005 and 2018). In turn, Juniper (*Juniperus spp.*) could invade the areas left vacant by Aspen and increase its distribution (Miller et al., 2000) but only if water availability is sufficient to encourage juniper recruitment (Lu et al., 2021).

The frequency and extent of wildfires may also be impacted if the trends demonstrated in this study continue. On one hand, a longer growing season (i.e., increased FFD) with increased growing degree days would lengthen the fire season in Idaho. However, decreased precipitation and potentially increased drought would effectively reduce vegetation biomass production and potentially decrease fuel loads and fuel continuity. In the latter scenario, the extent or size of wildfires would likely decline.

Even with a longer growing season, Idaho's large agricultural economy would likely see a net negative impact if rising temperatures and declining precipitation and snowpack come to fruition. These trends would ultimately reduce the availability of water for irrigation and increase the occurrence and severity of drought.

It should be clear that none of the trends explored in this study definitively assure future conditions in Idaho. Weather and climate are complex with an abundance of nonlinearities and interactive variables. As a result, a relatively large change in one variable (e.g., Tmin) does not translate to the same change in another variable (e.g., Tmax). Addition research and more sophisticated modeling is required to better understand and forecast these important environmental variables. In addition, future research will explore intra-annual variability within winter and growing seasons.

Conclusions

Collectively, these trends suggest --for at least the watersheds explored in this study-- mean annual temperatures are increasing resulting in extended frost-free days (FFD) and longer growing seasons along with an increase in growing degree days (GDD). However, with annual precipitation and snow water equivalence declining the net effect may be one of increased plant stress during the growing season and more frequent drought conditions across these regions. In speculation, these trends could cause numerous ecological changes impacting Idaho's ecosystems and agricultural economy. The reader is cautioned that none of the trends or forecast conditions presented in this paper are probable, but rather only possible.

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