CLIMATE CHANGE IN MONTANA

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ABSTRACT

Records from climatological stations having approximately 100 years of record and snow courses with approximately 75 years of record were analyzed to determine how temperatures, precipitation, and snowpack have changed over the past 100 years. Only stations that were not moved, that have been measured using the same methods and those that had a substantially complete data set were analyzed. A minimum of missing records were estimated to develop a complete monthly data set.

Many Montana snow courses have been measured since the mid 1930's. Three snow courses that were established in Glacier National Park (GNP) in 1922 are still being measured on May 1. Only the April 1 (May 1 for GNP) snow water equivalent (SWE) for snow courses that have been measured manually since the 1930's and have not been relocated were analyzed. Reduction in manual measurements due to implementation of the SNOTEL network has eliminated most of the early-season manual surveys and most of the snow courses that were co-located with SNOTEL sites. There were 24 snow courses in Montana with about 70 years of record that were analyzed. Trend analysis indicates an average of about 15 percent decrease in April 1 snow water equivalent. However, three snow courses in Glacier National Park that have been measured for over 80 years show an upward trend of about 4 percent over the 70 year period and a 13 percent increase for the 83 year record. Part of the explanation of decreasing snow packs might be related to increasing tree canopy cover. Those that are located in more open areas show less of a decrease than those located in more timbered stands.

There were 15 climatological stations in Montana and two in Northwest Wyoming that met the selection criteria where temperature was analyzed. Trend analysis for these 17 stations showed the average annual temperature has increased about 1.4^0 C over the past 100 years. None of the stations show any acceleration of temperature increases in the more recent years suggesting that increases may be more natural than man caused. The trend of annual precipitation at 20 stations (four in Northwest Wyoming) showed an increase of about two percent over the last 100 years. However, some stations showed increases while others showed decreases. Again, there does not appear to be different rates of change in recent years compared to earlier years. Annual and seasonal variability may be more significant than small annual changes over long time periods. For example, it is not uncommon for annual precipitation to vary between 40 and 160 percent of average and annual temperatures to vary 3^0 C above or below average.

INTRODUCTION

Montana is very fortunate that Joe Caprio, former State Climatologist, electronically entered many of the pre-1948 climatological records into the National Weather Service (NWS) database. When the NWS first computerized their climatological records, they started with the 1948 records. Records collected prior to 1948 were not entered electronically. To do a similar study in most other states would require extensive amount of work just to get the records into electronic form since most have not entered pre-1948 data. Also, many states have sharpened the cutters on the snow samplers or have adjusted the number of snow samples at the snow courses without going back and adjusting prior records of snow water equivalent (SWE) to reflect these changes. This makes analyzing long term records to determine climatic change almost impossible. In order to accurately determine climatic change, it was necessary to use data from climatic stations that had not been moved over their period of record and where data collection method was uniform over that record. This eliminated many locations where early records were located downtown and the station was subsequently moved to the airport without any concurrent record. Also eliminated were stations where manual measurements were replaced by automated equipment such as Automatic Surface Observation System (ASOS) stations and those stations with significant amount of missing records. For snow courses, only those that were measured manually throughout their entire record and those that had not been relocated without obtaining parallel records between an old location and new

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location were considered. Sites where snow survey telemetry system (SNOTEL) replaced manual snow courses were not considered since small changes in collection methods might imply climate changes that were really just changes in data collection methods or equipment. Also, many states used stainless steel snow pillows in the early phases of SNOTEL and then replaced them with hypalon snow pillows without determining or adjusting for the compatibility of records between these two sensors.

INTRODUCTION

Climatological stations and snow courses analyzed were all located within Montana and in Yellowstone and Grand Teton National Parks in northwest Wyoming. Climatological sites that were selected had approximately 100 years of record that was collected in a consisted manner at the same location. This eliminated stations where the instrumentation was moved from the downtown area to the airport, where manual measurements were replaced by automated equipment and locations that had significant amount of missing record. Snow courses that were selected had about 70 years of records that were collected by consistent methods at the same location. Only the April 1 snow water equivalent was analyzed except for the Saint Mary's snow courses in Glacier National Park where snow measurements have been made only on May 1. This eliminated sites where the manual snow course measurement was replaced by SNOTEL sites, where the snow course was relocated without having parallel records between the locations, where the snow sampler cutter was modified (sharpened) without adjusting prior records (Farnes et. al. 1983) or where the number of sample points on the snow course were reduced without adjusting prior records.

METHODS

Monthly climatological data for the average temperature and total precipitation was obtained from databases maintained by the Natural Resources and Conservation Service (NRCS), Western Region Climate Center (WRCC), NWS, and older hard-copy summaries prepared by NWS. Station histories from NWS and WRCC were consulted to determine which stations were not moved any significant distance over the period of record. . April I SWE data was obtained from the NRCS database. Monthly data was put into an EXCEL spreadsheet and missing data was estimated using correlations with adjacent stations. Five-year moving averages were calculated for average annual and seasonal temperatures, annual and seasonal precipitation, and April 1 SWE. Five-year moving averages were used to better observe the trends that might be masked by plotting annual values. Trends over the period of record were determined using the trend line obtained from the EXCEL program. The change over 100 years was obtained by extending the trend line to cover a 100 year period for climatological stations and for the snow course SWE.

RESULTS AND DISCUSSION

Trends for average annual temperature at 16 of the climatological stations are shown in Figure 1. From the trends obtained using the Montana and Northwest Wyoming data, it does not appear that there was any acceleration in the rate of change in more recent years over that which has been going on over the past 100 years. This appears to suggest that the increasing temperatures were more natural than man-caused. Table 1 provides a comparison of temperature change by climatological station. Two of the stations with the longest records were looked at seasonally. Winter (October through March), spring (April through June) and summer (July through September) temperature trends for Bozeman in Southwest Montana and Yellowstone Park (Mammoth) near the Montana border in Northwest Wyoming are shown in Figure 3. It appears that winters were warming at a greater rate than either spring or summer temperatures (Figure 3). All temperature analysis was based on data from valley stations and should not be interpreted to represent similar temperature trends in higher elevations. Further analysis of mountain temperatures may be possible by comparing valley trends with data from SNOTEL sites over the past 20-30 years. However, there is not a strong correlation between mountain and valley precipitation or temperature. A comparison of the 1971-2000 average annual temperatures between city and airport stations for eight locations, indicate the average annual temperature at the airport was 0.6 to 1.4 ^{0}C colder than at the city (Bozeman 1.4; Billings 0.8; Dillon 0.6; Glasgow 1.1; Havre 1.4; Kalispell 1.2; Livingston 0.9; and Miles City 0.6). The statewide average for these eight stations was 1.0 ^{0}C. If the current climatic trends continue (warming about 1.4 ^{0}C

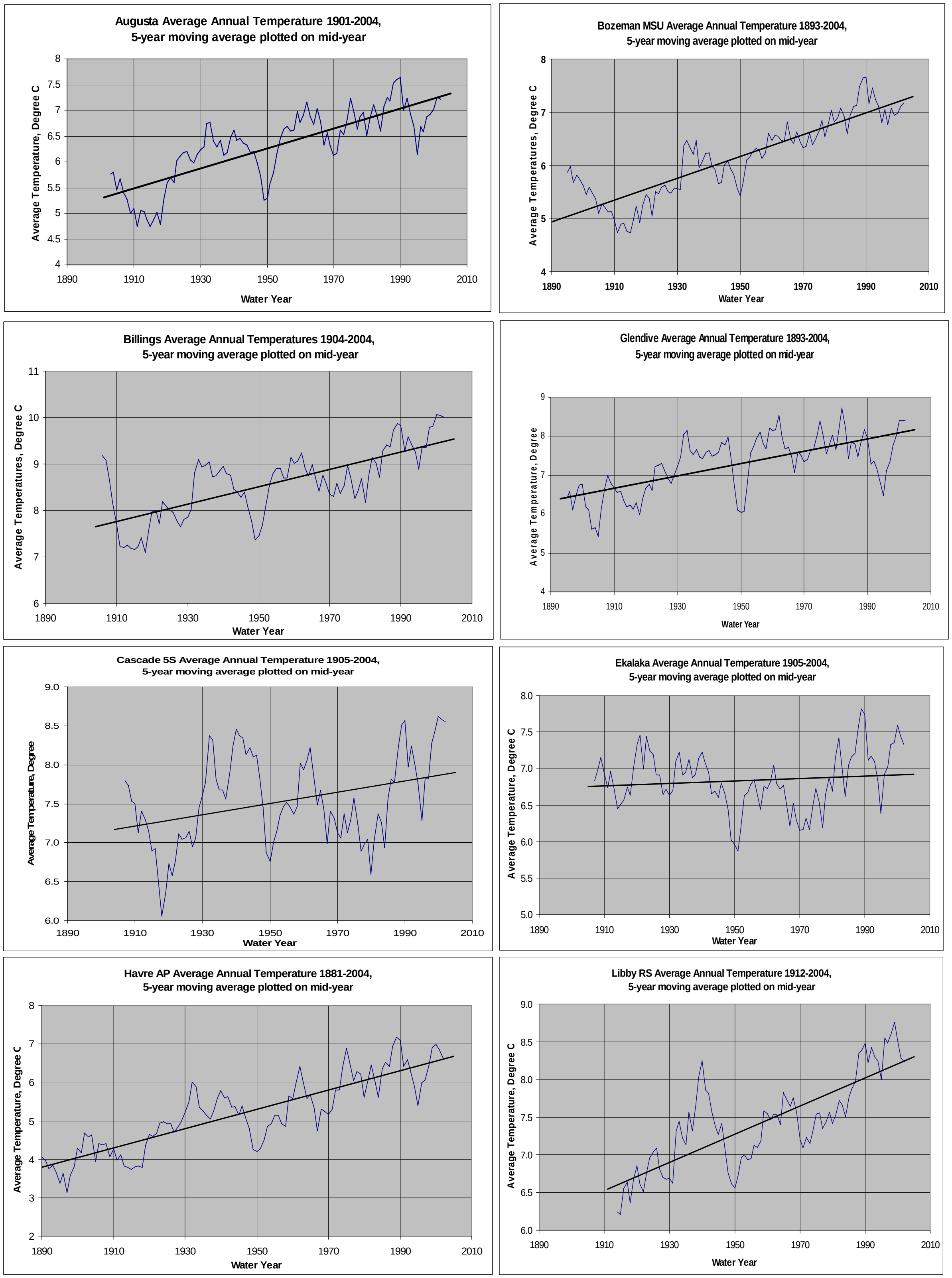

Figure 1. Five-year moving average of annual temperature for climatological stations in Montana and Northwest Wyoming with trend line.

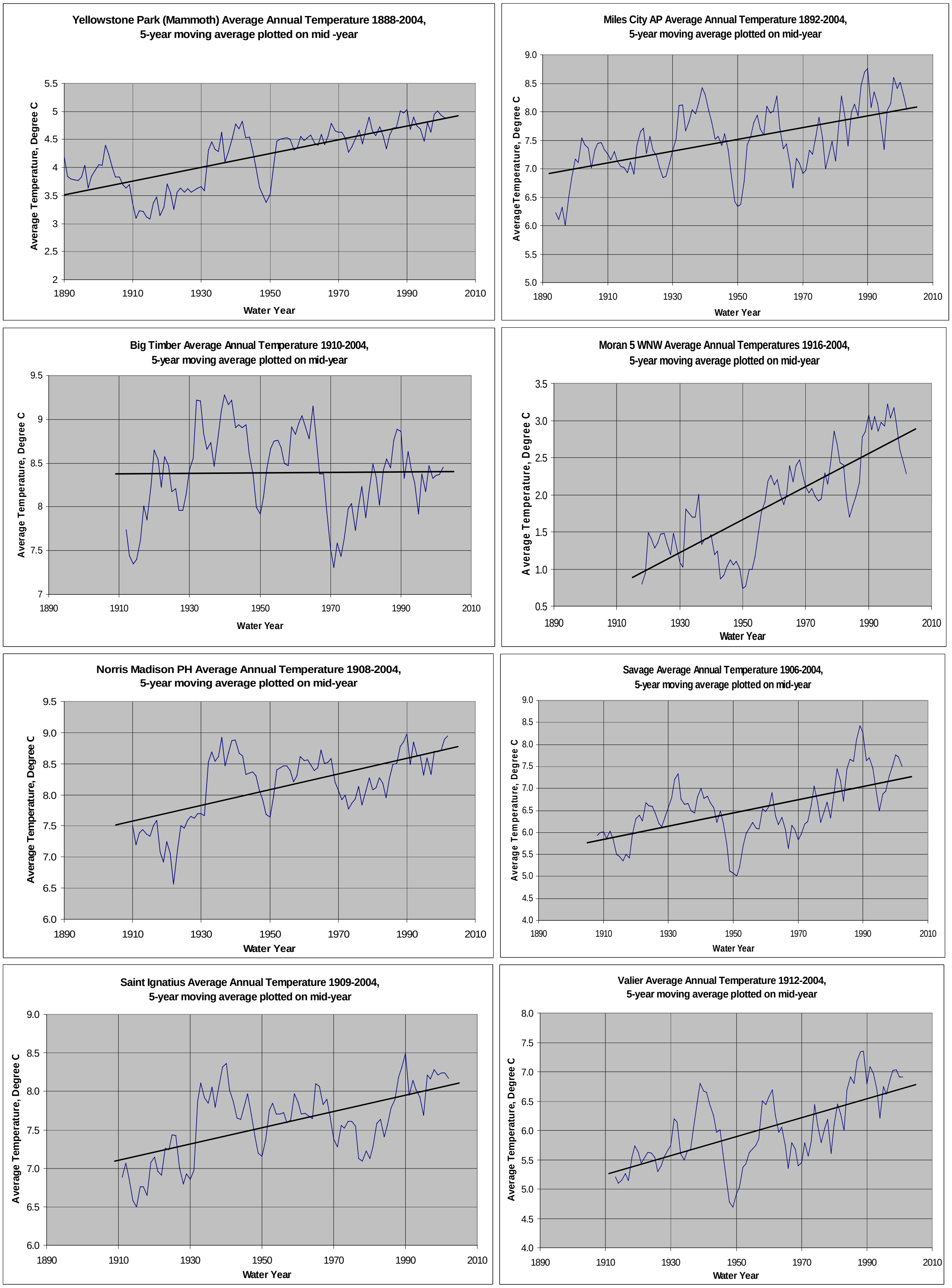

Figure 1 (cont.). Five-year moving average of annual temperature for climatological station in Montana and Northwest Wyoming with trend line.

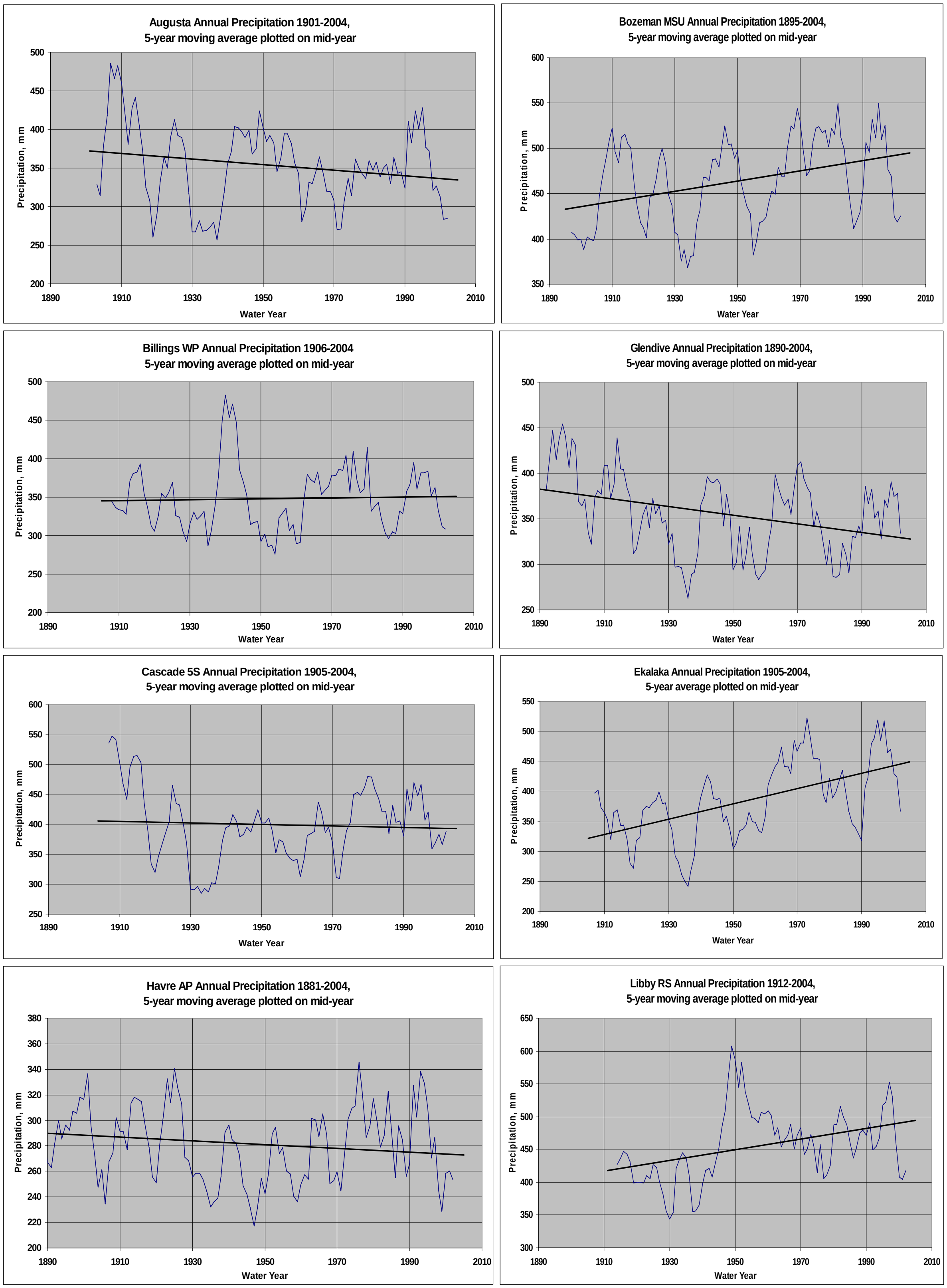

Figure 2. Five-year moving average of annual precipitation for climatological stations in Montana and Northwest Wyoming with trend line.

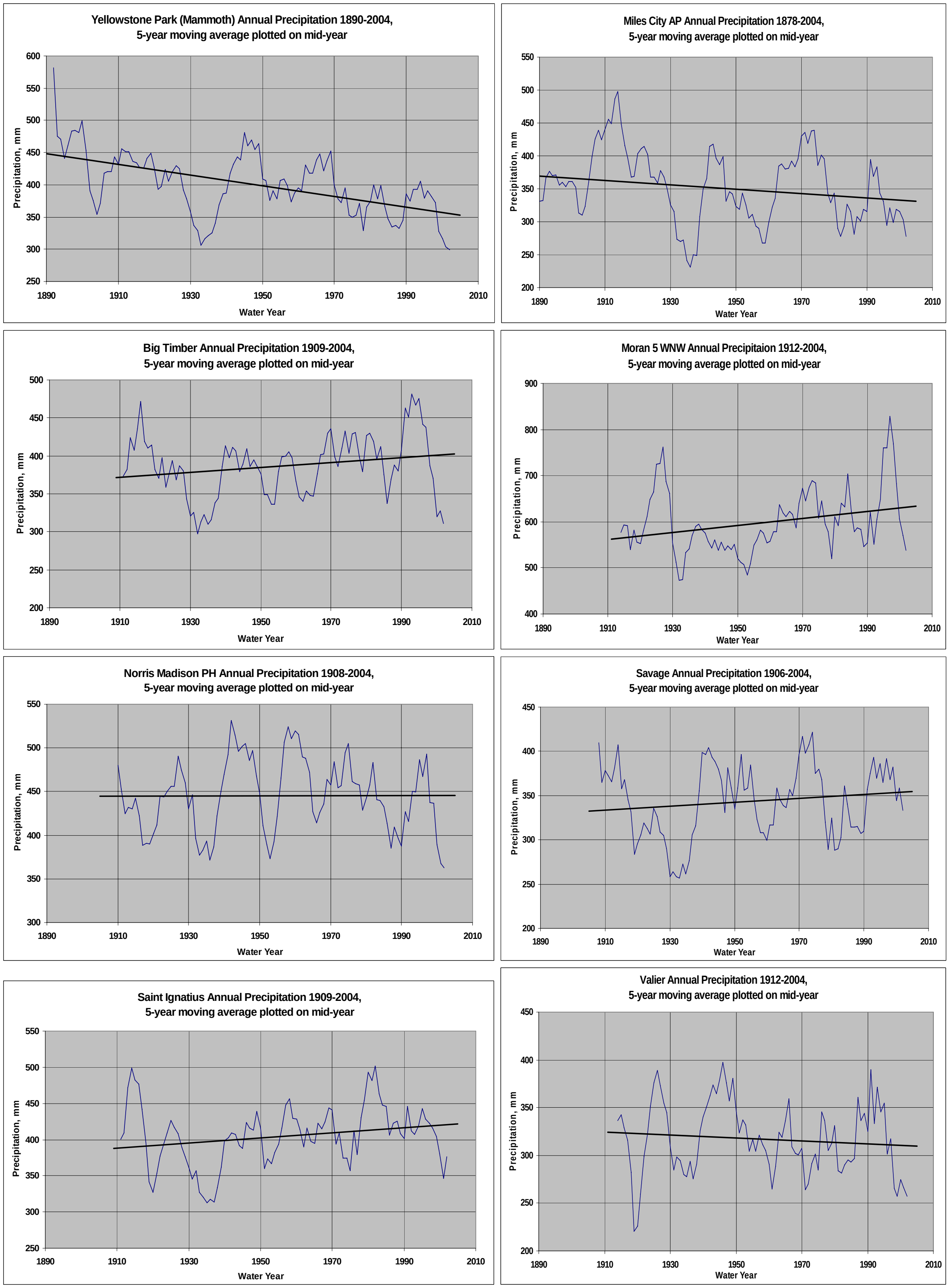

Figure 2 (cont.). Five-year moving average of annual precipitation for climatological stations in Montana and Northwest Wyoming with trend line.

Table 1. Change in average annual temperature and annual precipitation over past 100 years for climatological stations in Montana and Northwest Wyoming taken from difference in trend line between 1890 and 1990.

Station	Period of Record	Temperature, ^{0}C Change over 100 yrs.		Period of Record	Precipitation, mm Change over 100 yrs.
East Continental Divide					
Anaconda				1906-2004	1
Augusta	1901-2004	2.0		1901-2004	-35
Big Timber	1940-2004	0.0		1909-2004	30
Billings Water Plant	1904-2004	1.8		1906-2004	5
Bozeman MSU	1893-2004	2.1		1895-2004	55
Cascade 5 S	1905-2004	0.6		1905-2004	-20
Dillon WMCE	1896-2004	0.4		1896-2004	-205
Ekalaka	1905-2004	0.1		1905-2004	125
Fairfield				1908-2004	31
Fort Assiniboine				1918-2004	41
Glendive	1893-2004	1.6		1890-2004	-45
Havre AP	1881-2004	2.5		1881-2004	-14
Holter Dam				1904-2004	-60
Lake Yellowstone*				1905-2004	-5
Miles City AP	1892-2004	1.0		1878-2004	-35
Norris Madison P H	1906-2004	1.3		1908-2004	0
Savage	1906-2004	1.4		1906-2004	20
Valier	1912-2004	1.6		1912-2004	-15
Virginia City				1917-2004	114
Yellowstone Park (Mammoth)*	1888-2004	1.3		1890-2004	-80
Average East Divide	14	1.3		20	-1
West Continental Divide					
Jackson*				1921-2004	2
Libby RS	1912-2004	1.8		1912-2004	17
Moran 5 WNW*	1916-2004	2.3		1912-2004	13
Saint Ignatius	1909-2004	1.0		1909-2004	10
Average West Divide	3	1.7		4	11
Average Statewide	17	1.4		24	1

- Station in Northwest Wyoming

over the next 100 years), this would suggest that the temperature at the airports 70 years from now, might be similar to that currently being experienced at the nearby valley (city) locations.

Procedures used by the NWS/NOAA to determine average monthly and annual temperatures need t review. For stations with a complete 30 year record, the reported averages were different than the average obtained from the original published data. For many Montana stations, the 1971-2000 average annual temperature reported by the NWS was 0.6 to 0.8 ^{0}C lower than that obtained by averaging the actual data. This implies that the current average annual temperatures were that much warmer compared to average than they really were.

Trends for annual precipitation at 16 of the climatological stations are shown in Figure 2. Table 1 provides a summary of annual precipitation changes over the past 100 years. Seasonal trends for precipitation at two stations (Bozeman and Mammoth) are shown in Figure 4. Winters were generally becoming drier while spring precipitation was about the same and summer precipitation was increasing (Figure 4).

Trends for April 1 SWE (May 1 at Saint Mary's) at 10 of the snow courses are shown in Figure 5. Data for all of the snow courses analyzed is summarized in Table 2. The snow course analysis (Figure 5 and Table 2) could imply drier and warmer winters or it could be result of increased interception of snow from tree growth. In Montana, most of the snow courses are located in small, protected openings within forest stands. Through time, the tree growth encroaches into the area where snow interception increases and the snowpack accumulation on the ground is reduced. Table 2 shows the percent canopy obtained using the Photocanopyometer (Codd 1959). Most

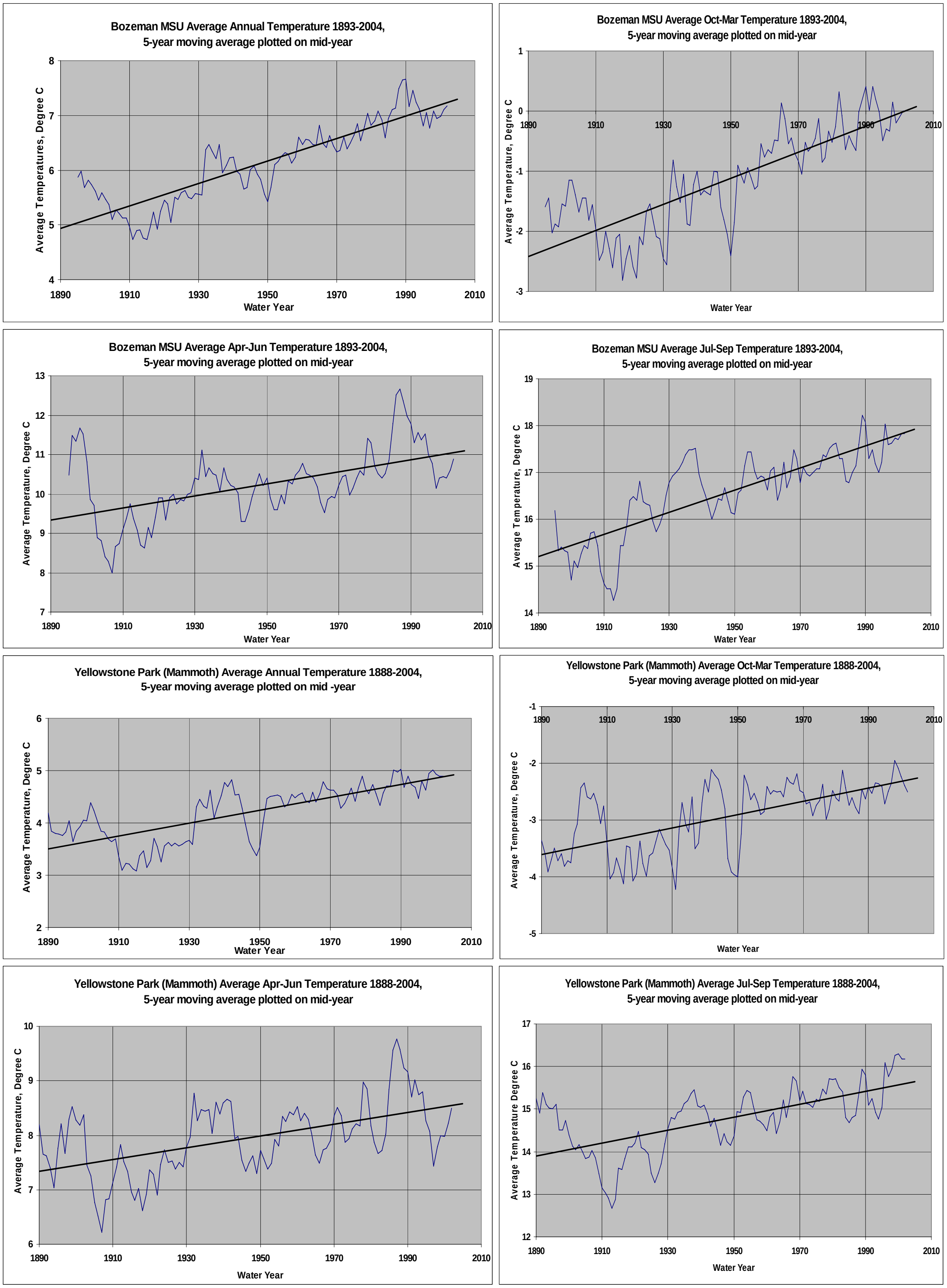

Figure 3. Five-year moving average of seasonal temperatures for climatological stations in Montana (Bozeman) and Northwest Wyoming (Mammoth) with trend line.

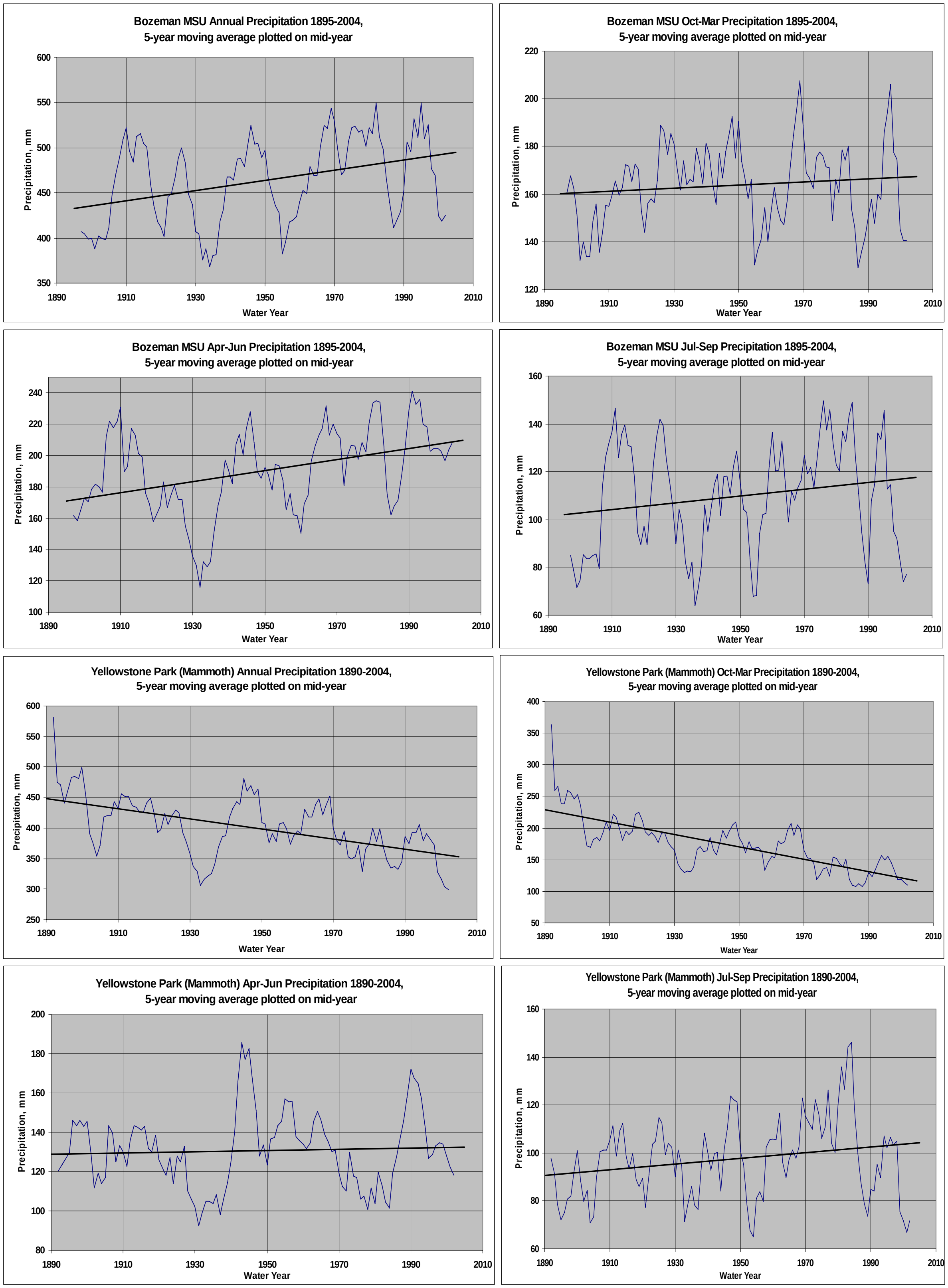

Figure 4. Five-year moving average of seasonal precipitation for climatological stations in Montana (Bozeman) and Northwest Wyoming (Mammoth) with trend line.

Table 2. Change in snow water equivalent over past 100 years based on difference in the trend line between 1930 and 2000 and pro-rated to estimate the change over 100 years of record.

Station	Period of Record	April 1 SWE, mm Change 1930-2000	April 1 SWE, mm Change over 100 Yrs.	April 1 SWE, mm 1971-2000 Avg.	Percent Change	Percent Canopy
East of Continental Divide						
Crevice Mountain	1935-2004	-15	-21	274	-8	8
Crystal Lake	1939-2004	10	14	343	4	4
Devils Slide	1935-2004	-51	-73	521	-14	30
Elk Horn Springs	1935-2004	-3	-4	231	-2	43
Goat Mountain	1934-2004	-36	-51	246	-21	
Hebgen Dam	1934-2004	-28	-40	305	-13	16
Kings Hill	1934-2004	3	4	348	1	35
New World	1939-2004	-28	-40	371	-11	0
Pipestone Pass	1938-2004	-26	-37	145	-26	44
Porcupine	1938-2004	-2	-3	185	-2	36
Stemple Pass	1934-2004	-28	-40	259	-15	66
Twenty-One Mile	1937-2004	-56	-80	429	-19	42
Average East of Divide	12		-31	305	-10	
West of Continental Divide						
Baree Creek	1937-2004	-218	-312	1095	-28	10
Big Creek	1941-2004	-138	-197	1110	-18	
Gibbons Pass	1936-2004	-58	-83	577	-14	36
Hoodoo Creek	1937-2004	-295	-422	1113	-38	19
Marias Pass	1934-2004	-76	-109	427	-25	47
North Fork Jocko	1941-2004	-180	-257	1090	-24	19
Red Mountain	1937-2004	-58	-83	478	-17	21
Skalkaho Summit	1937-2004	-40	-57	630	-9	6
Slide Rock Mountain	1937-2004	-84	-120	394	-30	66
Storm Lake	1939-2004	-93	-133	338	-39	7
Stuart Mountain	1936-2004	31	44	820	5	7
Weasel Divide	1937-2004	-33	-47	836	-6	13
Average West of Divide	12		-148	742	-20	
Hudson Bay Drainage						
Average 3 Saint Mary's courses*	1922-2004	86	122	889	14	26
Statewide Average	25		-81	538	-15	

• Iceberg Lake, Mount Allen and Piegan Pass.

Percent canopy was obtained mostly in the 1970's using the Photocanopyometer (Codd 1959).

of the observations were take in the 1970's. It is possible to redo these observations at each of the sampling points for the snow courses shown in Table 2 to confirm how much change there has been in canopy growth which can then be related to change in the snow interception. Only the difference between the change related to interception and total change in the SWE should be attributed to climate change.

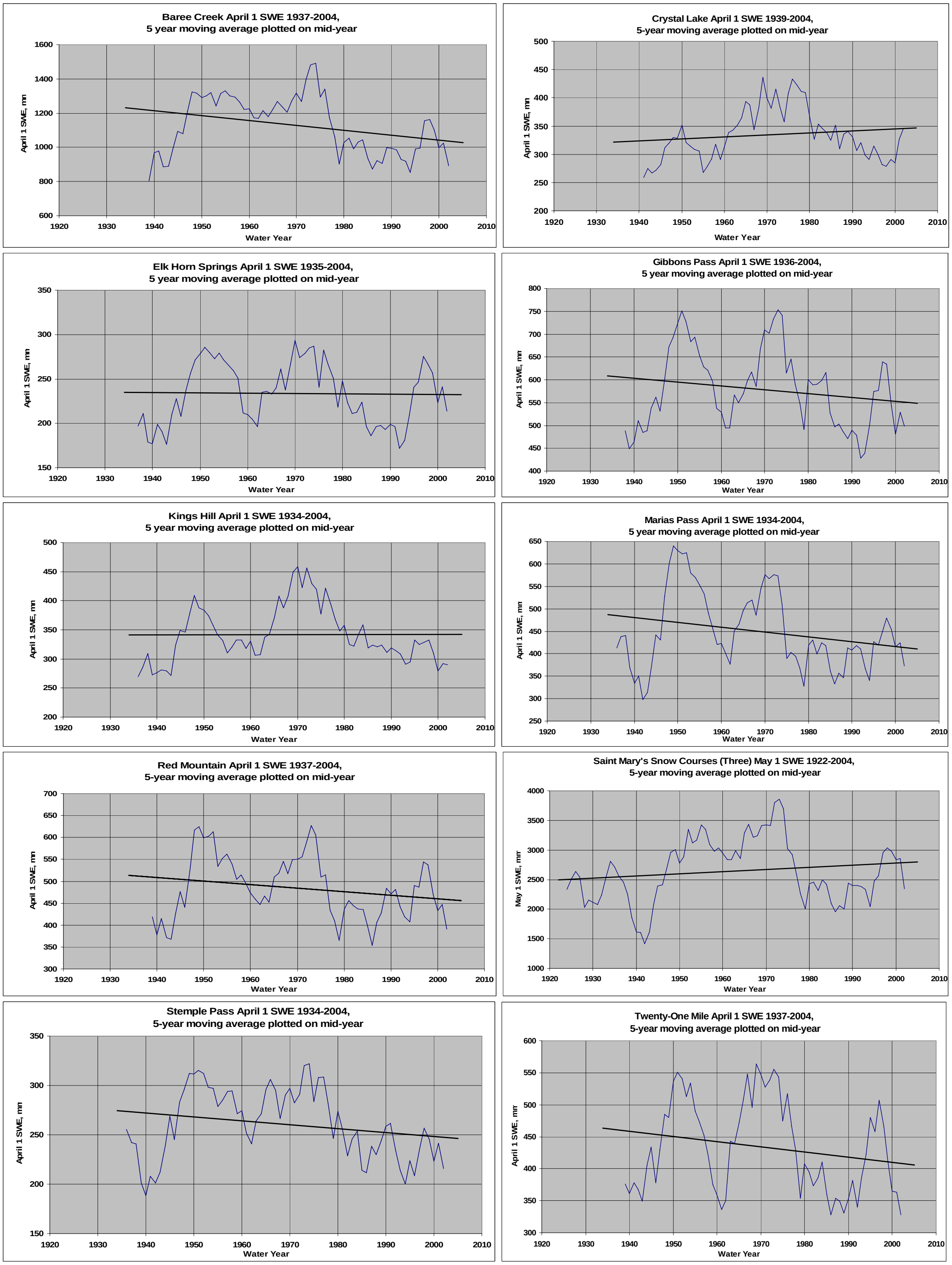

Figure 5. Five-year moving average of April 1 snow water equivalent (May 1 for Saint Mary's) for Montana snow courses with trend line.

MANAGEMENT IMPLICATIONS

Currently, there is considerable discussion relative to global warming and its impacts. In many cases, the climatological data being used to present the situation has not been screened for reliability and accuracy nor has the entire period of record been used. It is difficult and time consuming to go through the daily records, estimate missing records or correct erroneous records, and evaluate station changes for its period of record but this needs to be done in order to obtain an accurate assessment. In many cases, the records obtained from computer files are analyzed without making any effort to determine if such records are complete and accurate. Analysis from these unverified records can present erroneous results and implications that may not be valid. In many cases, it appears there is a great desire to show that global warming is all man-caused and will create a negative influence on all plant and animal life on the planet. If global warming is predominately a natural progression as it appears to be using the Montana data, then spending large sums of money and time trying to slow the effects of supposedly man-induced changes may not have any significant effect on the warming trends. Possibly this money should be shifted to programs that determine how best to live with the increasing temperature trends. Efforts to reduce pollutants going into the atmosphere should be continued but should not be tied to stopping or reducing the rate of climate (temperature) change.

CONCLUSIONS

Data from selected stations in Montana and Northwest Wyoming that have been screened for reliable and consistent records suggests that there has been a warming of annual average temperature of about 1.4 ^{0}C over the past 100 years. The data also suggests that there has not been any significant acceleration in the rate of change in more recent years. It appears that temperatures have been changing over thousands of years as some areas that are now being farmed or occupied were buried under 500-1000 meters of ice around 15,000 years ago. With the present rate of change, in about 70 years the temperatures at local airports will be similar to today's temperature at the nearby downtown locations. More effort needs to be put into validating existing climatic records used to evaluate climate change to present a truer picture of what has occurred. Greater effort in terms of funding and research needs to be directed toward learning how to co-exist with the changing climate rather than trying to figuring out ways to modify these changes. Many responses previously thought to be related to photoperiods are actually responses to temperature. Most species of plants, fish, birds, and animals respond to temperature rather than calendar dates. Changes in dates of phenological stages (plants), spawning and migration (fish), nesting (birds), and migration to summer range (animals in response to plant phenology) to name a few, are all triggered by or determined by temperature. During warmer years, these responses will be advanced while during years having cooler temperature, these responses will be delayed. As temperatures warm, it should come as no surprise that the time of these responses should advance. However, it is not just one response that is advanced with warming temperatures but all responses that are related to those temperatures. For example, when birds next earlier, the trees, plants, and insects also respond earlier.

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EVALUATION OF ENHANCEMENTS TO THE SNOWMELT RUNOFF MODEL

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ABSTRACT

As part of a larger effort to develop tools for improved short-term (1-2 week) streamflow forecasting in snowmelt-dominated basins, the Snowmelt Runoff Model (SRM) is used to simulate and forecast streamflow in the Big Wood River basin, Idaho. Several enhancements to SRM will be evaluated: a) a new method to estimate degree-days; b) new techniques used to assign and temporally update model parameters (degree-day factor and runoff coefficients) that make use of data from SNOTEL sites located within the basin and; c) the incorporation of relative humidity and wind speed data into a new (optional) model module designed to improve model performance during rain-on-snow events. Model results will be evaluated to determine the usefulness of these enhancements.

INTRODUCTION

In the Western United States, water supplies are often derived from runoff due to snowmelt. Thus knowledge of the timing and rate of snowmelt is crucial for decision-makers in federal and state agencies, as well as citizens whose livelihoods are directly affected by water availability (for example, farmers and tourism operators). Also as the region's population increases, bringing more industry, there is and will be ever-increasing demands on water resources. Consequently, the objective of this project is to develop a prediction system for short-term streamflow forecasts in the mountainous regions of the Western United States.

Snowmelt runoff may be simulated using either an energy balance approach or a temperature index (degree-day) approach (Singh and Singh, 2001). Energy balance models are physically correct, but demand a lot of data that is often not readily available. Conceptually-based, degree-day models, on the other hand, lack the complexity of energy-balance models and often rely on commonly available input variables, which make them suitable candidates for operational implementation. These models, however, are not without limitations. Degree-day models often use model parameters to simplify hydrologic processes and often ignore the physics behind them. Because of this, there is a desire to include more detail (complexity) in these models, yet maintain their operational feasibility.

This paper is focused on several enhancements to the Snowmelt Runoff Model (SRM), which are designed to optimize model efficiency and to aid in its operational implementation. These enhancements include: 1) the incorporation of relative humidity and wind speed data to increase model accuracy during rain-on-snow events (i.e. condensation melt), 2) the use of SNOwpack TELemetry (SNOTEL) data to assign and update model parameters, and 3) the use of an alternate scheme to estimate daily average temperature.

STUDY AREA

The Big Wood River Basin (Figure 1), located in south-central Idaho, has an elevation range of 250 to 3,630 meters. It's rugged, mountainous landscape and the fact that approximately 50% of the basin's total annual precipitation falls in the form of snow during the winter months, make it a suitable area for the study of snowmelt runoff. Our study area is limited to a subsection of the basin (~1,625 km^2) located upstream of Magic Reservoir. This is important because the model is set up to simulate natural flow, not controlled flow.

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