Climate change in ski resorts of the West

Final report

Abstract:

This final report presents the analysis of a research project on climate change in western North American ski resorts. With meteorological data for a chosen set of 10 ski resorts, it is investigated how temperature and snowfall have varied between 1901 and 2019 due to climate change. The discussion shows increasing temperatures in each location which can be associated with human-caused climate change. Snowfall conditions are affected by changing temperatures, but the two variables are shown to be not linearly correlated as several other factors influence snowfall as well. It can be concluded that coastal ski resorts are hit particularly hard by climate change in terms of beneficial conditions for the ski industry compared to continental ski resorts in western North America.

Introduction:

During the late 20th and the 21st century, reports of unprecedented changes in our environment have been accumulating and raising concerns not only in scientific communities but among the public as well, with the most noticeable change being globally increasing temperatures. Global warming is increasing temperatures at an exponential scale and can be primarily attributed to human caused emission of greenhouse gases such as carbon dioxide, methane and nitrous oxides (IPCC, 2013). Consequences of the warming

climate are projected to be catastrophic and affect biologic systems over the entire globe (Lenton et al., 2019).

The North American ski industry is an established touristic and cultural asset of the western continent. All around the Rocky Mountain Range, numerous ski areas count on winterly snowfall and cold temperatures to operate a successful winter season. Facing progressively fast climate change it must be asked: How are North American ski resorts affected by changing climatic conditions and are they sustainable in the future? Are there general trends in changing temperatures or snowfall that could affect all ski resorts?

My research aims to determine how ski resorts in western North America are affected by recent climate change with the help of climatic data from several western ski resorts. Global trends show rising temperatures and a common rise in precipitation over most regions (Fischer and Knutti, 2015). Regional climates, however, might respond different individually to changing global climatic processes. With my research, I expect to observe rising temperatures in at least the last 50 years across all datasets with mixed results in changing snowfall amounts. Since snow highly depends on the prevailing temperature level, I expect to see declining snowfall levels in warmer ski resorts close to the Pacific Coast and perhaps even higher snowfall levels in the colder continental resorts. Generally, it will be interesting to see if observations differentiate between ski resorts at the coast and ski resorts in the interior of the continent.

Materials and Methods:

For my analysis, I exclusively used weather and climate data from ClimateBC (climatebc.ca) and ClimateNA (climatena.ca). These applications are provided by Dr. Wang from UBC in cooperation with Dr. Gamann, Dr. Spittlehouse and Dr. Carroll. The U.S. Department of

Agriculture provides official spatial climate data sets at a scale of around 800 x 800 m grids from an extensive weather station network on the entire continent (National Resources Conservation Service). This data can be interpolated with the PRISM (Parameter-elevation Relationships on Independent Slopes Model) method in order to create climatic maps and calculate values for locations without weather stations. Using the interpolated PRISM data, the two applications by Dr. Wang et al. downscale the climatic data in order to obtain climatic data for any location on the North American continent. ClimateNA provides researchers with many variables such us temperatures, precipitation, evaporation, solar radiation, humidity, and many more for any chosen location. The datasets range from 1901 to the year 2019 and provide yearly, seasonal, and monthly data.

For my analysis, I decided to specifically investigate the variables concerning temperature and snowfall in order to answer my research questions. The first and main dataset analyzed was from Whistler Blackcomb ski hill in British Columbia. With help of the python interface JupyterLab, the data was cleaned, sliced, and sorted in order to enable an investigation of the temperature and snowfall data.

In the following step, the processed data was used to generate several exploratory graphs of the variables of interest that could show how the ski season was affected by changing climatic conditions. Primarily, monthly and seasonal snowfall data was plotted over time and compared to monthly temperature data at the investigated locations between 1901-2019. After successfully analyzing the climatic data at the location of Whistler Blackcomb, a ski hill north of Vancouver in British Columbia, I proceeded to conduct the same analysis for 9 other ski resorts along western Canada and the western United States.

Finally, the visualization software Tableau was used to put the results together into one dashboard summarizing findings from all 10 ski resorts shown in *Figure 1.*

Figure 1: The 10 analyzed ski resorts along the West Coast, the Interior United States and Canada.

Results:

In Whistler, the mean temperature during the winter season has been rising constantly since the mid-20th century as shown in *Figure 2*. The used seasonal data is calculated with data from December to February. The grey shading represents the difference between the warmest and the coldest temperature during the respective season. It can hence be seen that the average temperature increases by about 2°C in 60 years and that the range of values between maximum and minimum temperature decreases.

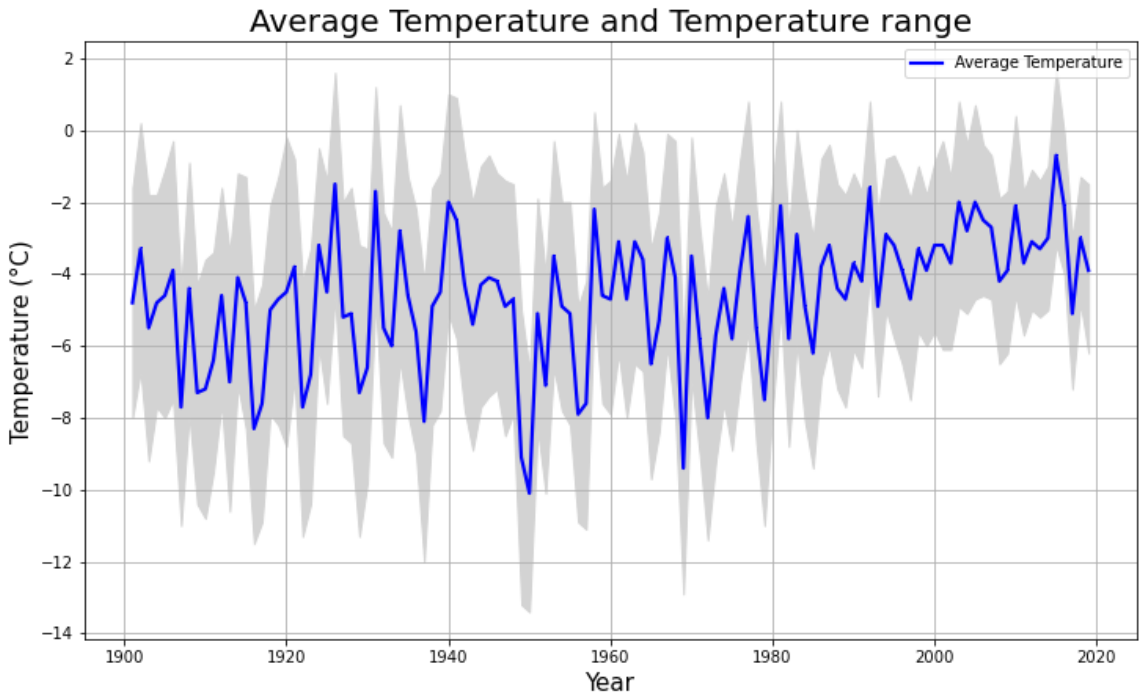

Figure 2: Average seasonal winter temperature and the difference between maximum and minimum temperature at Whistler Blackcomb between 1901-2019.

Snowfall levels in Whistler have increased during the middle of the 20th century, before experiencing a steep decline between 1960 and 2019, almost cutting average snowfall in half during that time. *Figure 3* shows the historic trends for mean seasonal snowfall levels in the investigated time period with a polynomial trendline highlighting the described changes in snowfall levels.

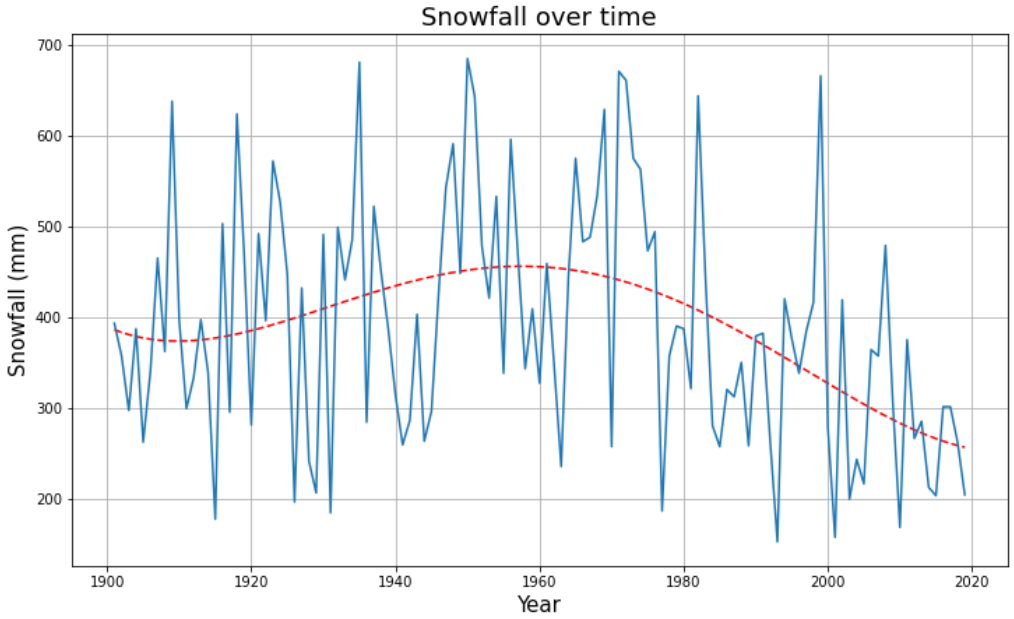

Figure 3: Seasonal snowfall levels in blue and the polynomial trendline of 4th degree in red at Whistler Blackcomb between 1901 and 2019.

The monthly plotted snowfall and temperature data matches the seasonal graphs as can be seen in the Appendix. Detailed seasonal and monthly graphs for each ski resort are attached in *Appendix 1.1.-1.10.*

Figure 4 analyzes the monthly distributions of snowfall over three intermediate periods of 40 years. The graphed violin plots serve to detect consistently high or low snowfall levels in a particular month over the selected time periods in order to separate changes in the early, middle, and late season. The figure shows a tendency towards lower snowfall levels during the month of February in recent times, otherwise there are no major changes in monthly snowfall distribution between the three investigated time periods.

Parallel to the analysis of temperature and snowfall data in Whistler, the other 9 ski resorts were investigated in the same manner with the detailed results for each of the 10 analyzed ski resorts found in the Appendices.

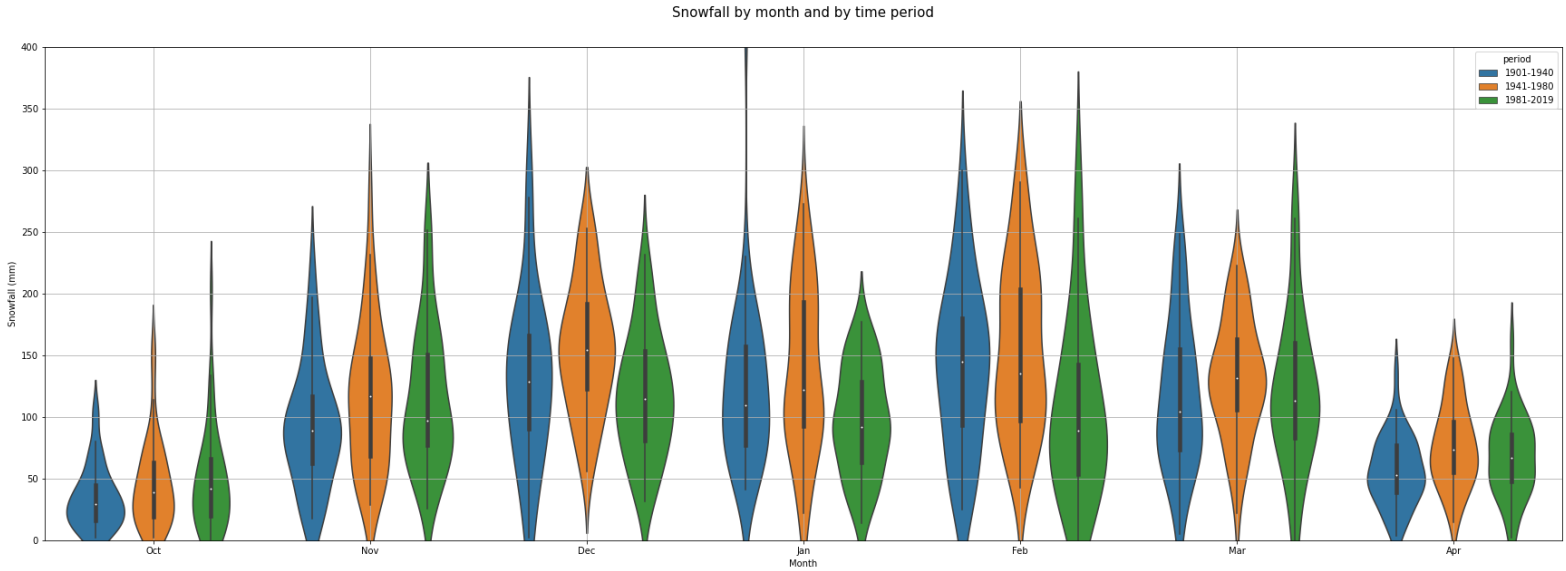

Figure 4: Monthly plotted snowfall distributions during the time periods 1901-1940 (blue), 1941-1980 (orange) and 1981-2019 (green). A larger print of the graph can be found in *Appendix 1.10*

The consistent rise in temperatures and the individual changes in snowfall patterns are discussed and explained in the following 'Discussion' chapter.

Discussion:

All ski resorts show the expected rise in temperature, especially in the most recent period. The rising temperatures in the ski resorts are very consistent with the globally rising temperatures (Global warming index, 2020). Consequently, most of the ski resorts show a slight warming or stagnating temperatures in the earlier 20th century and rapid warming since the 1960s. The baseline temperatures at coastal ski resorts, heavily influenced and regulated by the Pacific Ocean, are generally higher than the temperatures at ski resorts further east in the continent (see *Figure 1* for a Map of the ski resorts). Due to the rising temperatures, especially Mount Baker, is coming close to averaging temperatures above freezing even during the winter months.

The analysis of snowfall levels presents less coherent results across the different datasets. Many ski resorts show little variation or no clear trend in snowfall levels across the investigated time period. There is no general rise or decline in snowfall for either coastal or continental ski resorts. However, the resorts experiencing stronger recent declines in snowfall levels, Mount Washington, Mount Baker and Whistler Blackcomb are all located along the west coast. The resorts with recently increasing snowfall levels, Big Sky and Vail, are both located further east in the Rocky Mountain range.

Naturally, there are more influencing geophysical and climatic factors involved in the amount of snowfall in each location than just temperature data. However, the data analysis indicates that the ski resorts with lower baseline temperatures experience a less substantial decrease in snowfall due to global warming than the ski resorts which are subject to initially higher temperatures. This can be explained by two factors: primarily, rising temperatures increase the chance for precipitation to fall as rain instead of snow. Besides other undesirable effects on the skiing conditions, this negatively affects all ski resorts due to less

available snow and inferior snow conditions (Scott and McBoyle, 2006). The second effect affects snowfall in a different manner. For each additional °C of air temperature, saturated air contains 7% more humidity (Coumou and Rahmstorf, 2012). This additional moisture can result in higher precipitation as additional snowfall if the temperatures are low enough. This effect could explain the increase in snowfall in Big Sky for example where rising temperatures are met with increasing snowfall.

The analysis of the monthly snowfall distribution across all 10 analyzed resorts indicate the most recent decreases in snowfall to happen mainly in the late season. Especially in February, most ski resorts show slightly lower common snowfall levels in the last time period (1981-2019) than previously. This development is coherent with global climate research which has been observing shortening of the winter season and reduced snow cover mainly due to early spring season (Comiso and Hall, 2014).

Conclusions:

Rising temperatures are the most indicative sign of global warming and climate change and they are shown to affect all investigated ski resorts. Mean winter temperatures have risen by more than 3°C in less than 100 years in several locations. This results in important environmental changes in all aspects of the winter season. A large part of these changes will come into full effect in the future.

With rising temperatures everywhere, a decrease in snowfall could be intuitively expected as well. This, however, is not the case in the investigated ski resorts. There are indicators for deteriorating snow conditions in several locations, but a general trend cannot be determined from this project. It appears coastal ski resorts, subject to higher temperatures,

are the first to suffer from less snow. Some continental resorts could even benefit from increased snowfall in the intermediate run.

In conclusion, the gained data shows that atmospheric conditions in ski resorts are undoubtedly changing, often more rapid in recent decades compared to the previous century.

Primarily coastal ski resorts are critically affected by changes due to stronger declines in snowfall and temperatures increasing close to the melting point.

More uncertainties arise when trying to answer why regional climates are changing in the observed way.

Admittedly, the analyzed data is overall not strong enough to paint a clear picture as to how exactly the geophysical location of the ski resort and the respective changes in temperature affects snowfall in the future. Factors other than temperature measurements, such as changing mid-latitude cyclone paths, changing oceanic oscillations and atmospheric feedback effects will have to be taken into account to give a more precise answer as to why and how snowfall patterns are and will be changing in western North America.

Despite mentioned limitations of the project, the way this preliminary ski resort analysis is set up, it will be easy to analyze many more locations in the future. This can be used to draw effective conclusions onto which regions are particularly affected by a warming climate and which suffer most from declining snowfall as well as what developments can be expected for ski resorts in similar locations in the future.

References:

Comiso, J.C & Hall, D.K. (2014). Climate trends in the Arctic as observed from space. *WIREs Climate Change 2014,* 5:389-409. doi: 10.1002/wcc.277.

Coumou, D. & Rahmstorf, S. (2012). A decade of weather extremes. *Nature Climate Change,* 2, 491-496. doi: 10.1038/nclimate1452.

Fischer, E.M. & Knutti, R. (2015). Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nature Climate Change,* 5, 560-564. doi: 10.1038/nclimate2617.

Global Warming Index (updated November 2020). *Human-induced warming.* Accessed 30 November 2020. Retrieved from https://www.globalwarmingindex.org/

IPCC (2013). Climate Change 2013: The physical science basis. *Contribution of Working Group 1 to the Fifth Assessment report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, US.

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. & Schellnhuber, H.J. (2019). Climate tipping points – too risky to bet against. *Nature, 575, 592-595, doi:*

Le Page, M. (2018). Climate change is happening, but how fast? This is what we really know. *New Scientist, Environment,* 12.12.2018.

National Resources Conservation Service. *Climate data.* United States Department of Agriculture. (Accessed December 01 2020). Retrieved from https://www.wcc.nrcs.usda.gov/climate/

Scott, D. & McBoyle, G. (2006). Climate change adaptation in the ski industry. *Mitigation and adaptation strategies for global change*, 12, 8. doi:10.1007/s11027-006-9071-4

Appendix

1.1 Big Sky:

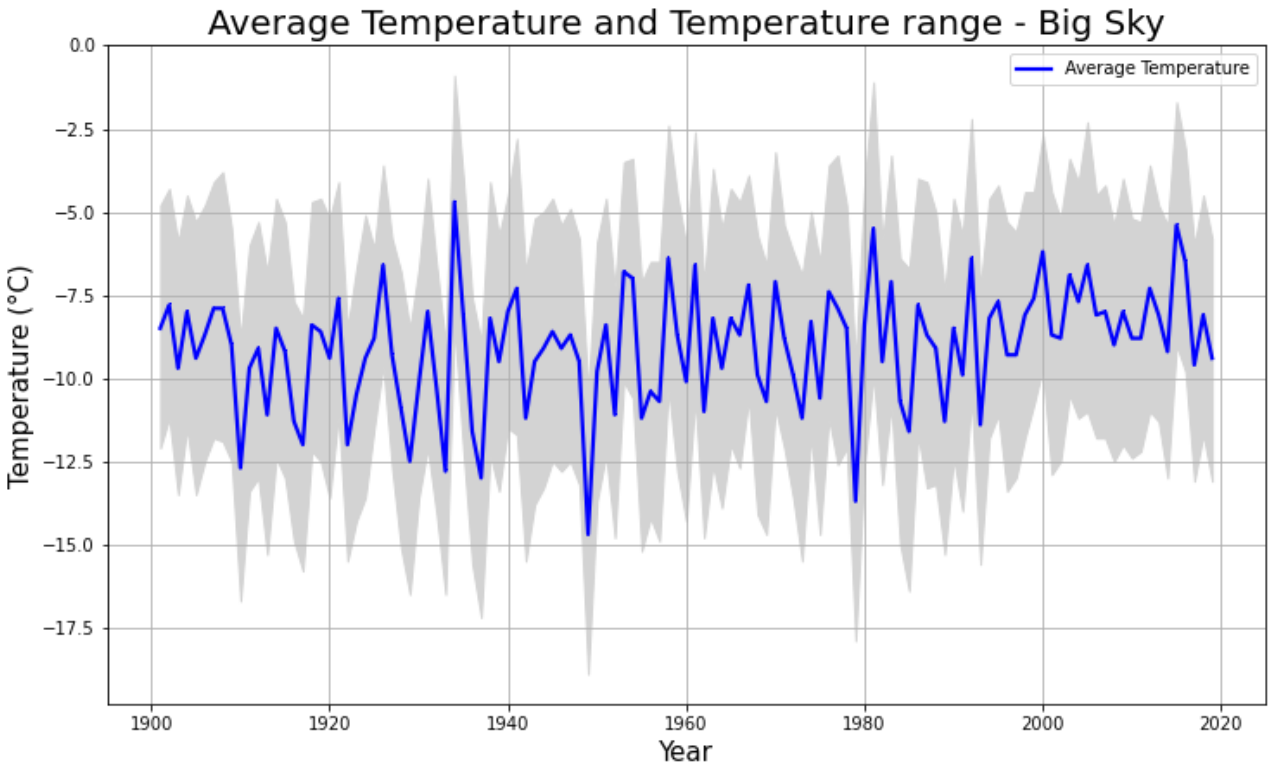

Figure A.1.1.1: Seasonal temperatures show a steady increase since around 1960.

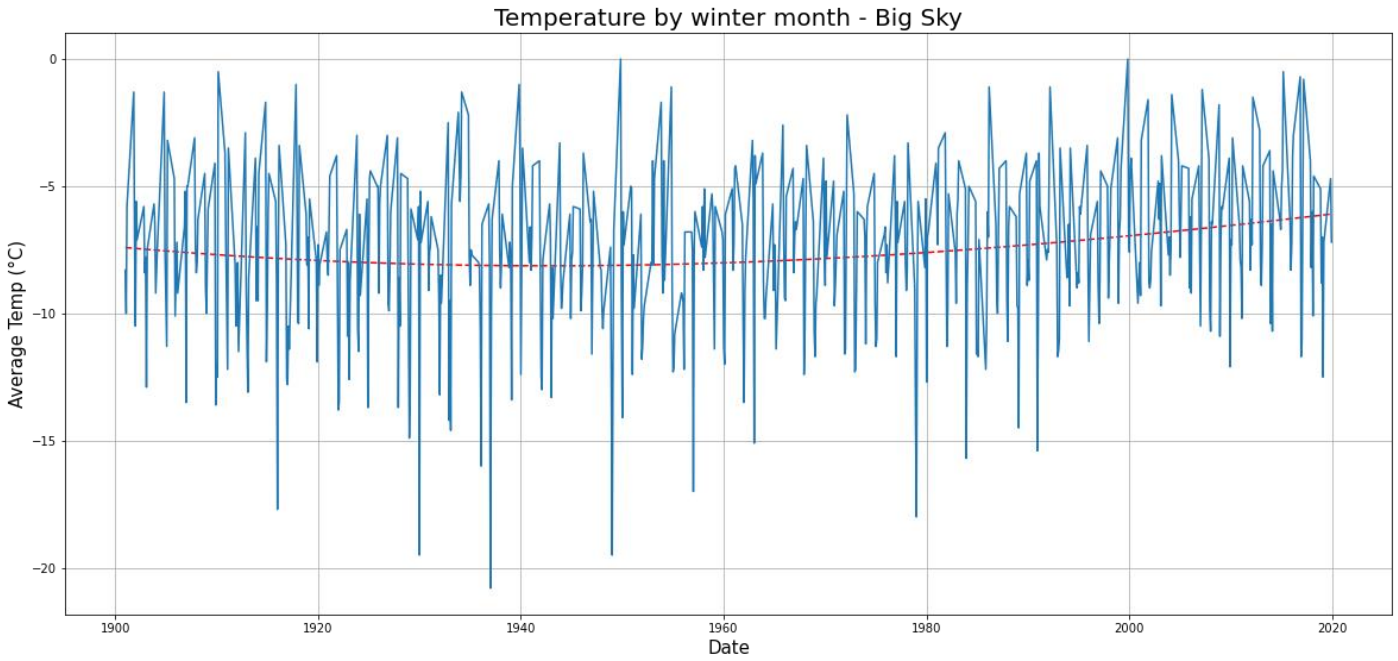

Figure A.1.1.2: Monthly winter temperatures

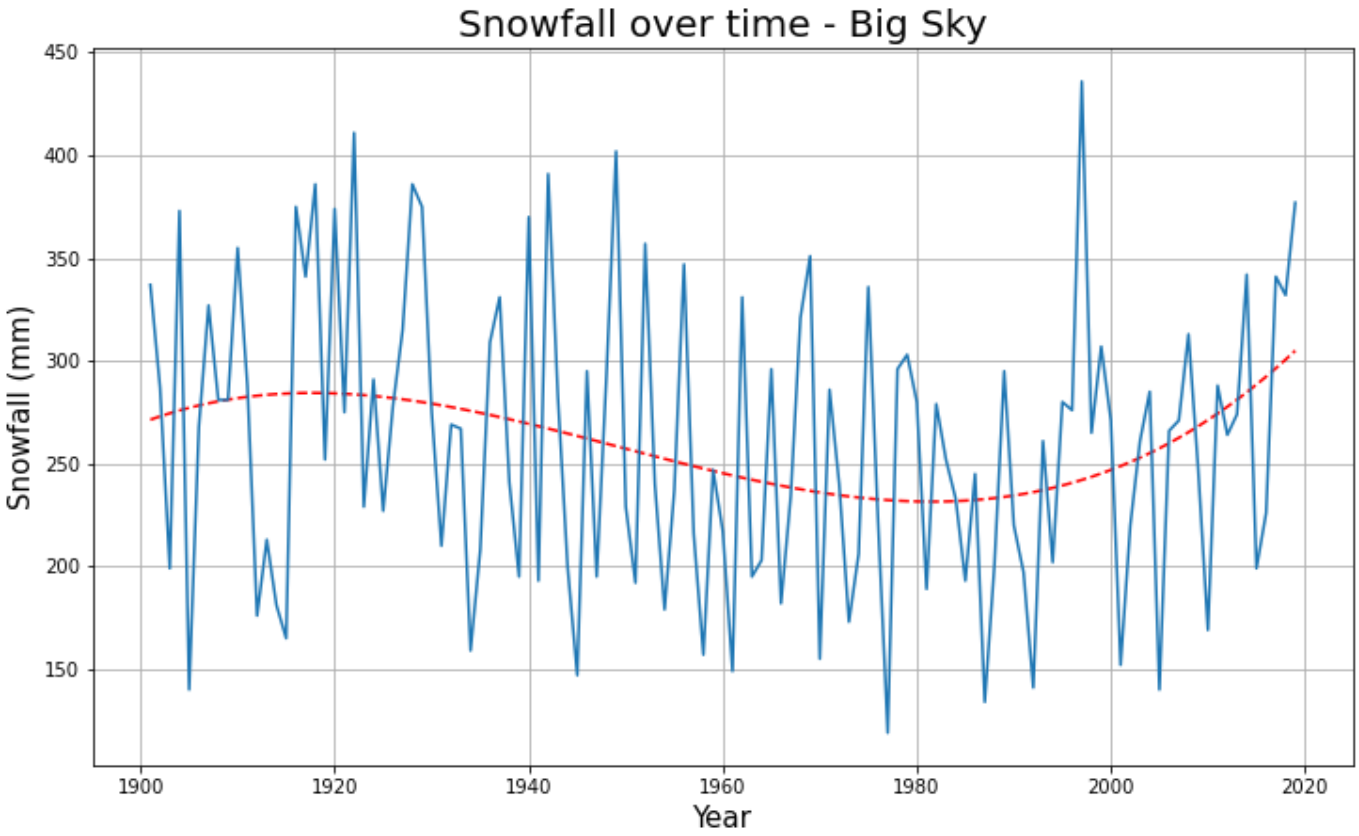

Figure A.1.1.3: Seasonal snowfall data shows a strong increase in the 21st century

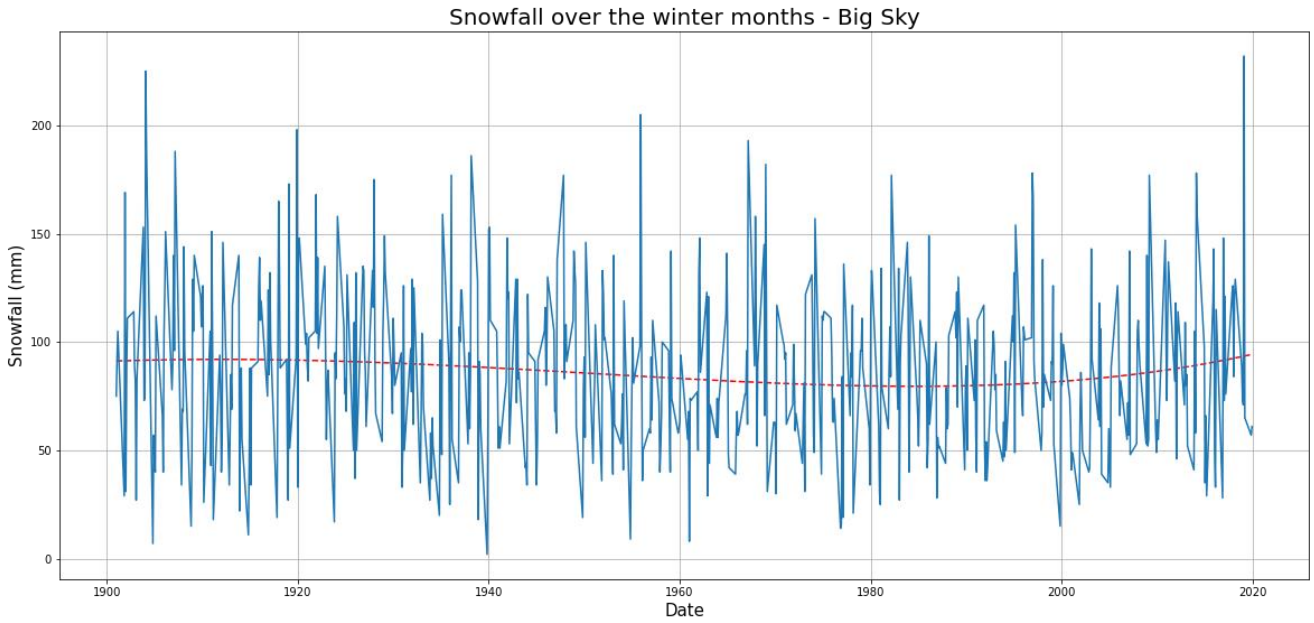

Figure A.1.1.4: Monthly snowfall data

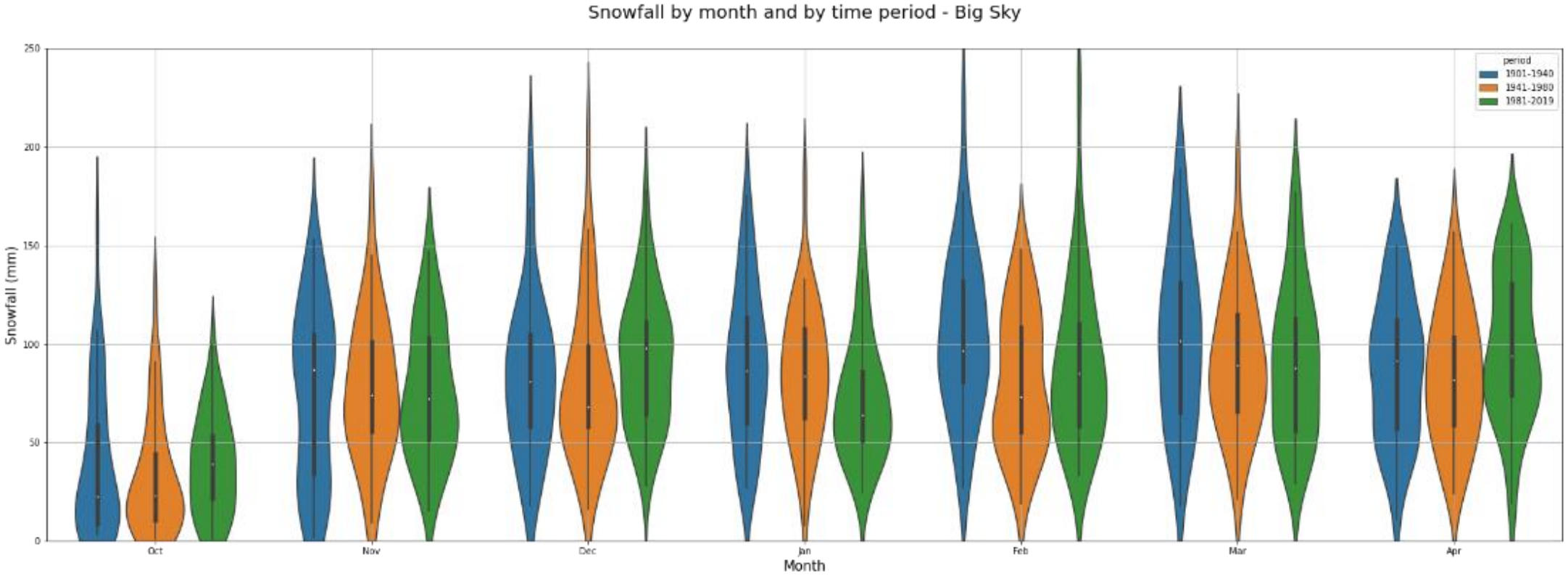

Figure A.1.1.5: Snowfall distributions by month and by time period. Period 1901-1940 in blue, 1941-1980 in orange and 1981-2019 in green. Slight tendencies towards generally lower levels in recent January and February snowfall levels

1.2 Big White:

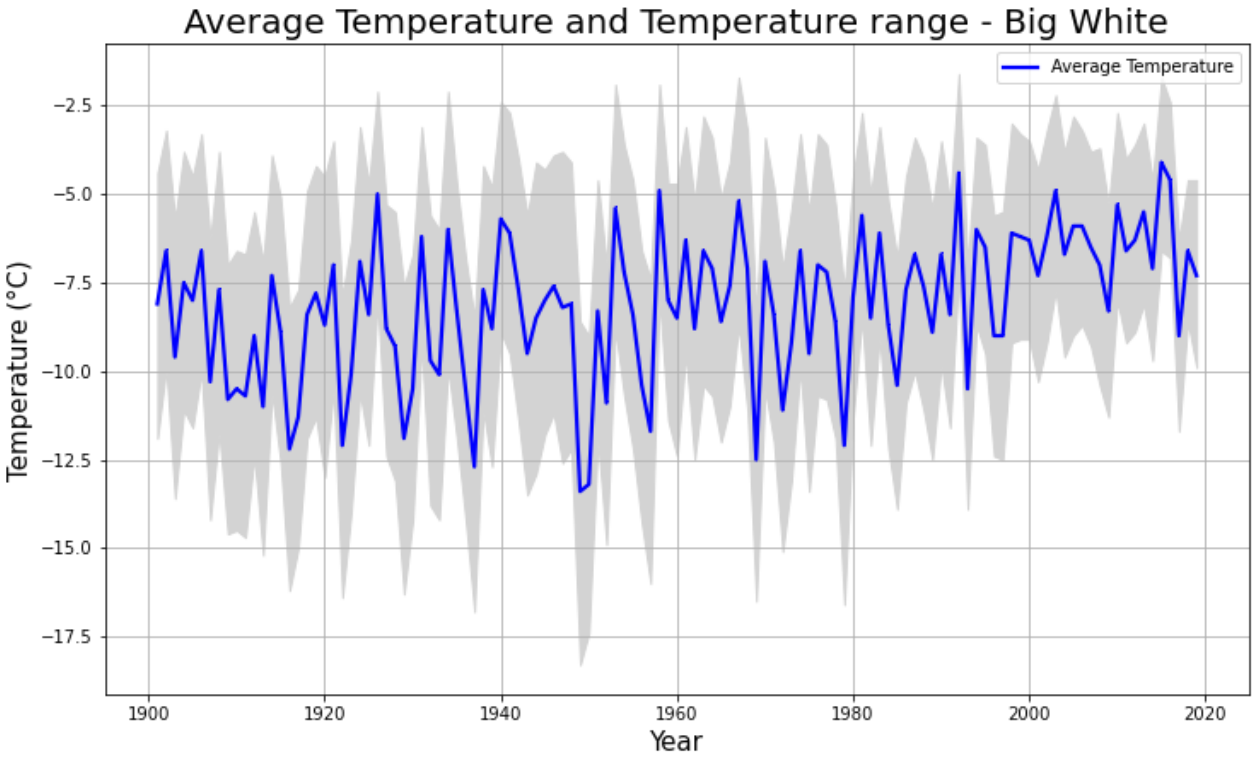

Figure A.1.2.1: Seasonal temperatures show a steady increase since around 1950.

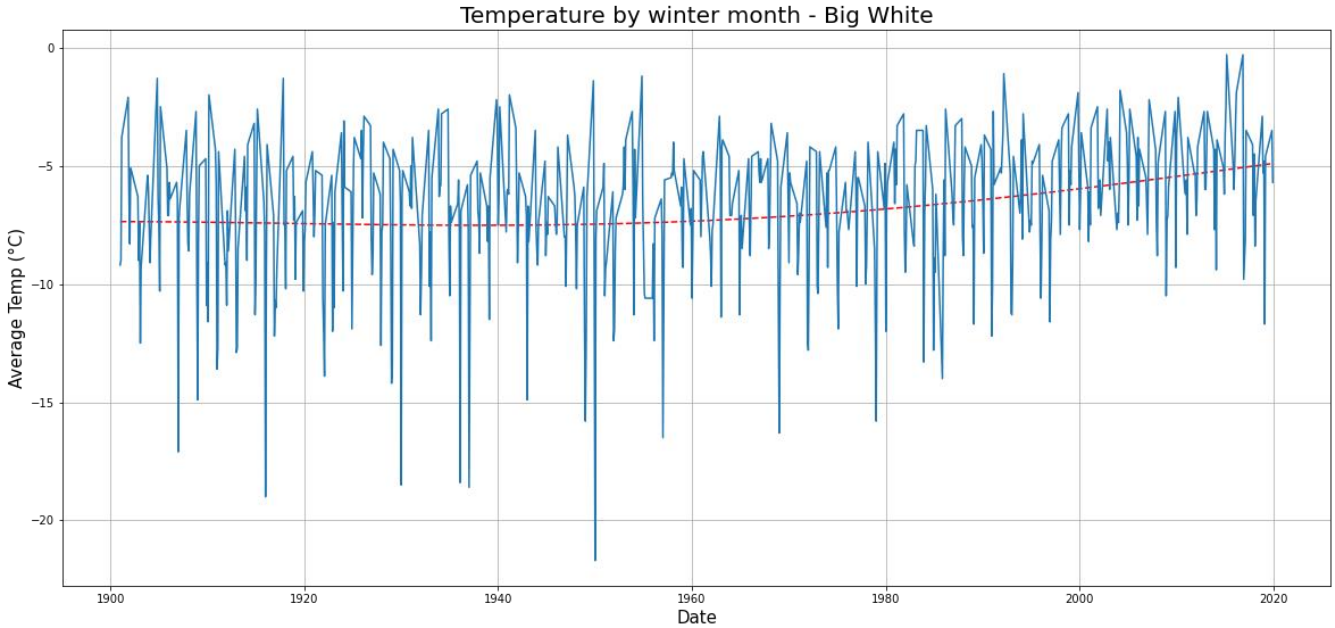

Figure A.1.2.2: Monthly winter temperatures

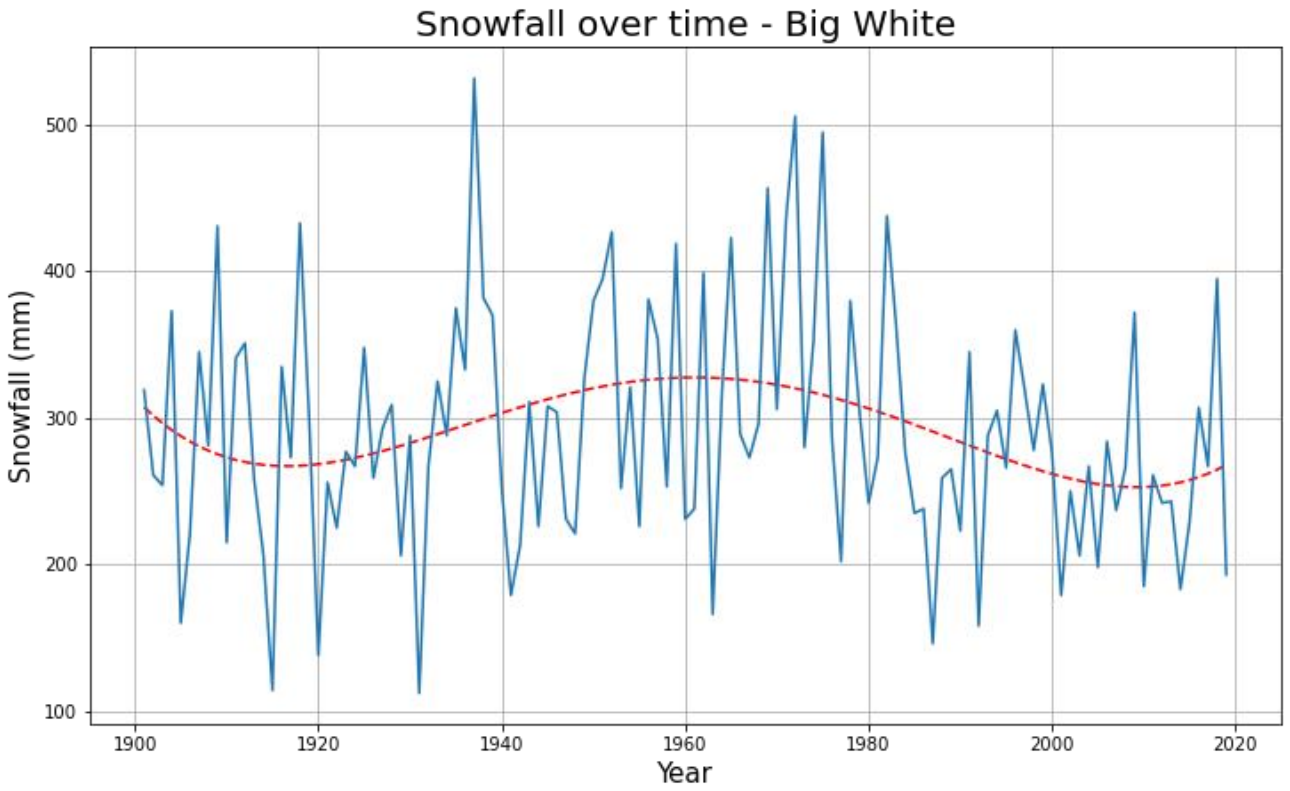

Figure A.1.2.3: Seasonal snowfall data oscillates with highest values in the mid-20st century.

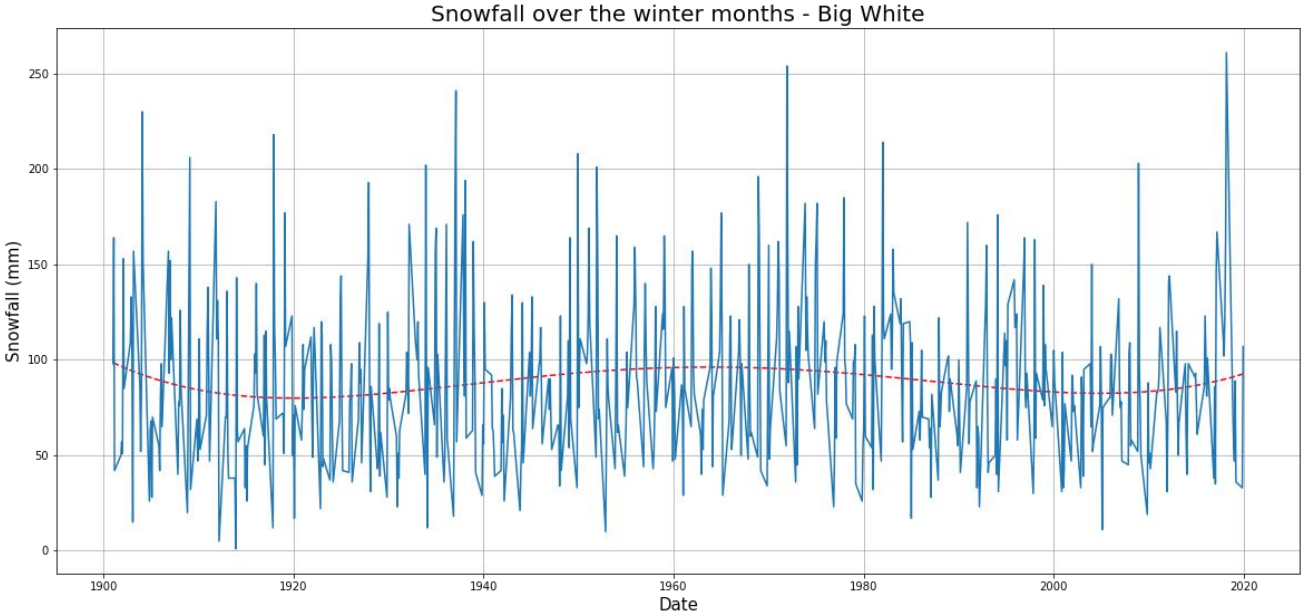

Figure A.1.2.4: Monthly snowfall data

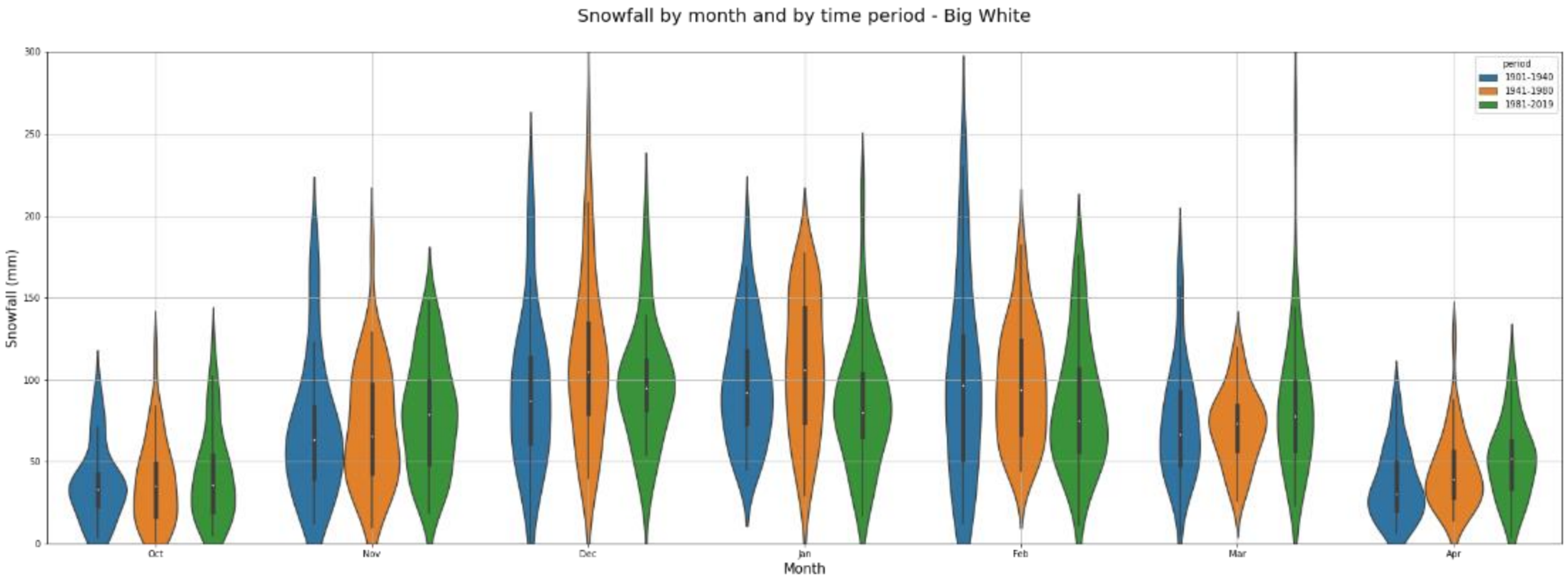

Figure A.1.2.5: Snowfall distributions by month and by time period. Period 1901-1940 in blue, 1941-1980 in orange and 1981-2019 in green. Slight tendencies towards generally lower levels in recent February snowfall.

1.3 Jackson Hole:

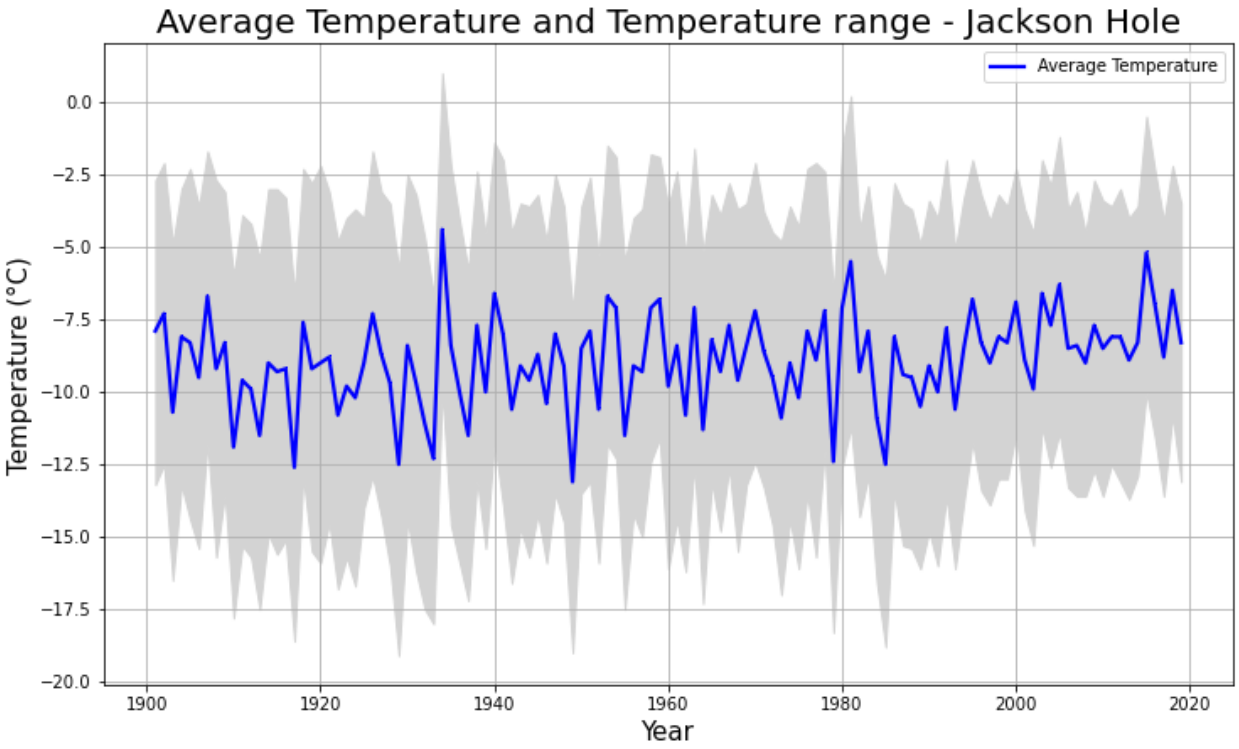

Figure A.1.3.1: Seasonal temperatures show a sligt increase since around 1980.

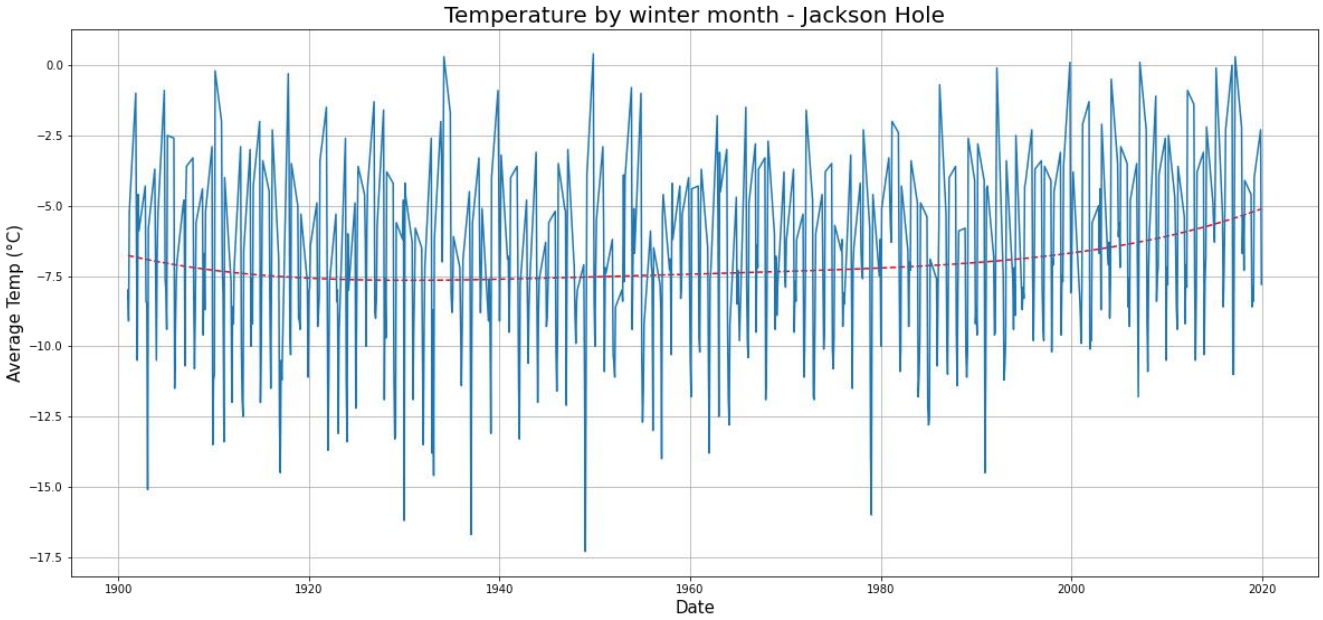

Figure A.1.3.2: Monthly winter temperatures

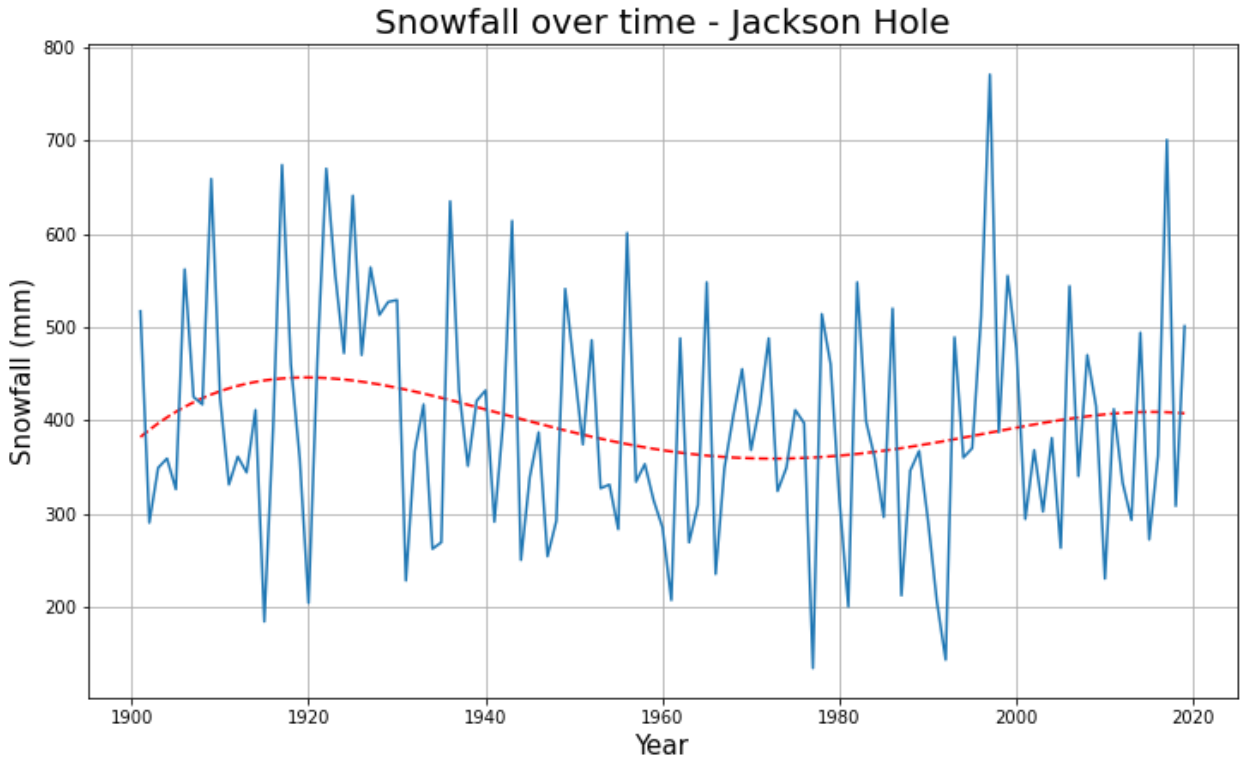

Figure A.1.3.3: Seasonal snowfall data remains relatively steady.

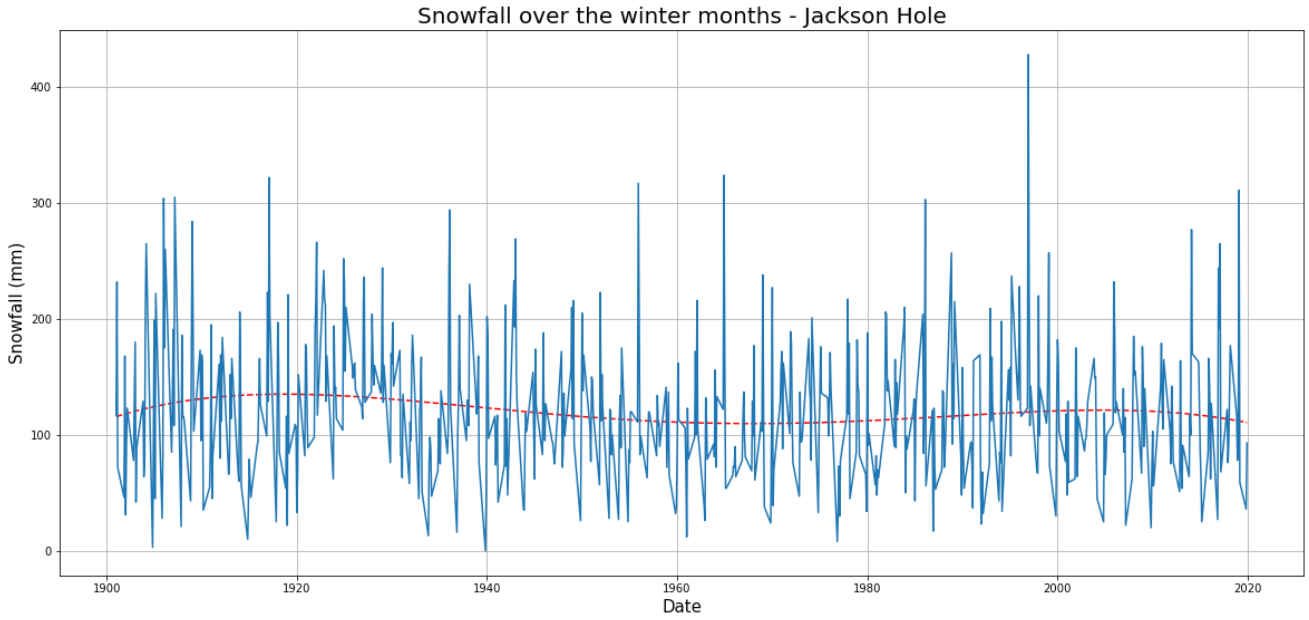

Figure A.1.3.4: Monthly snowfall data

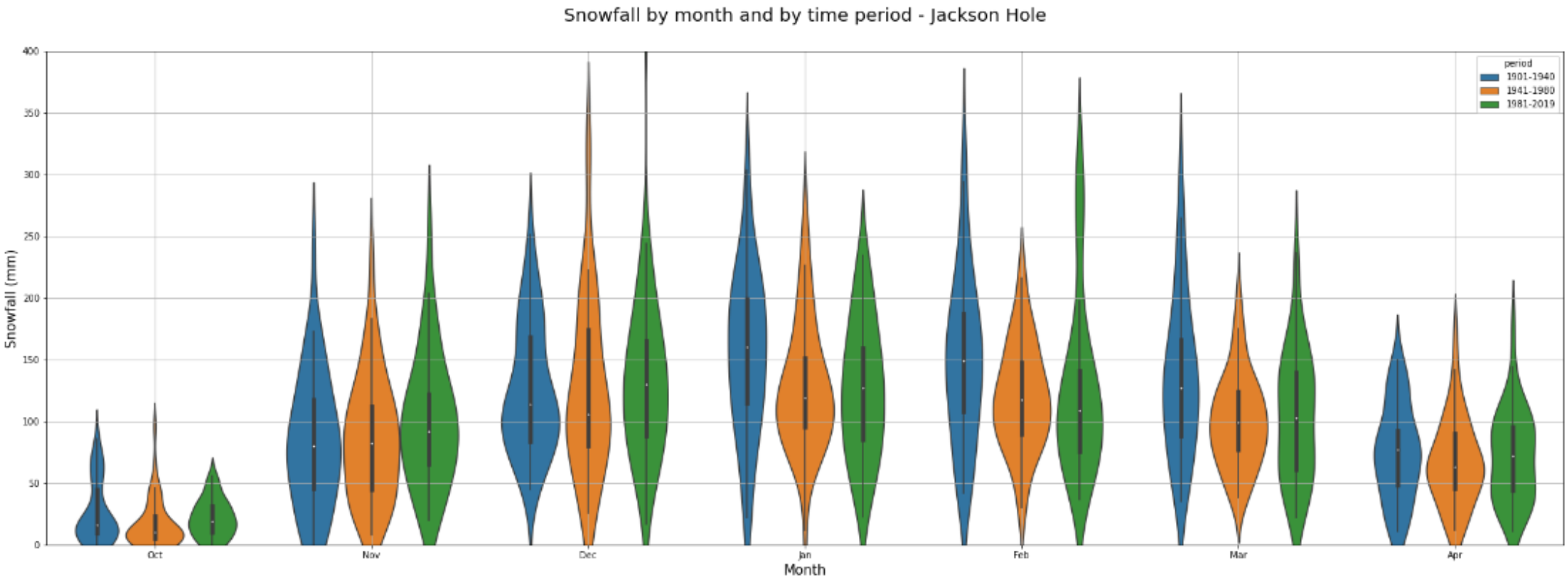

Figure A.1.3.5: Snowfall distributions by month and by time period. Period 1901-1940 in blue, 1941-1980 in orange and 1981-2019 in green. Slight tendencies towards generally lower levels in recent February snowfall.

1.4 Lake Louise:

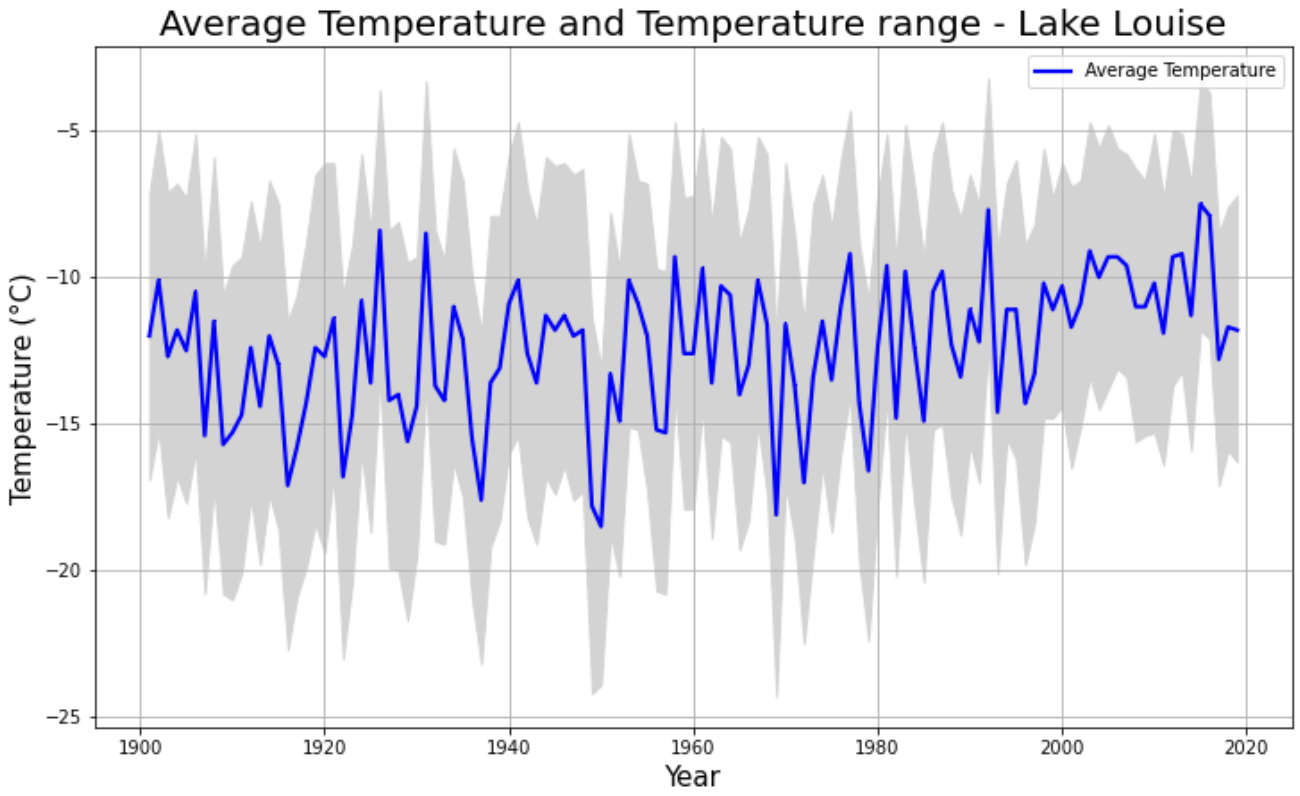

Figure A.1.4.1: Seasonal temperatures show a steady increase since the early 20th century.

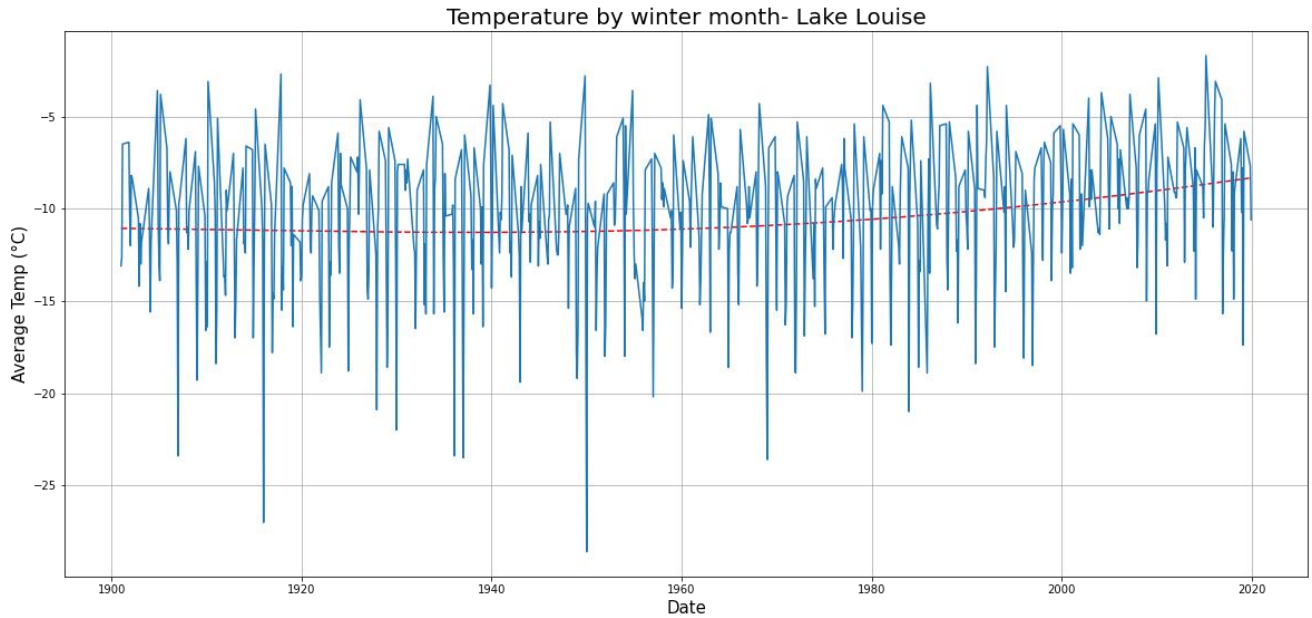

Figure A.1.4.2: Monthly winter temperatures

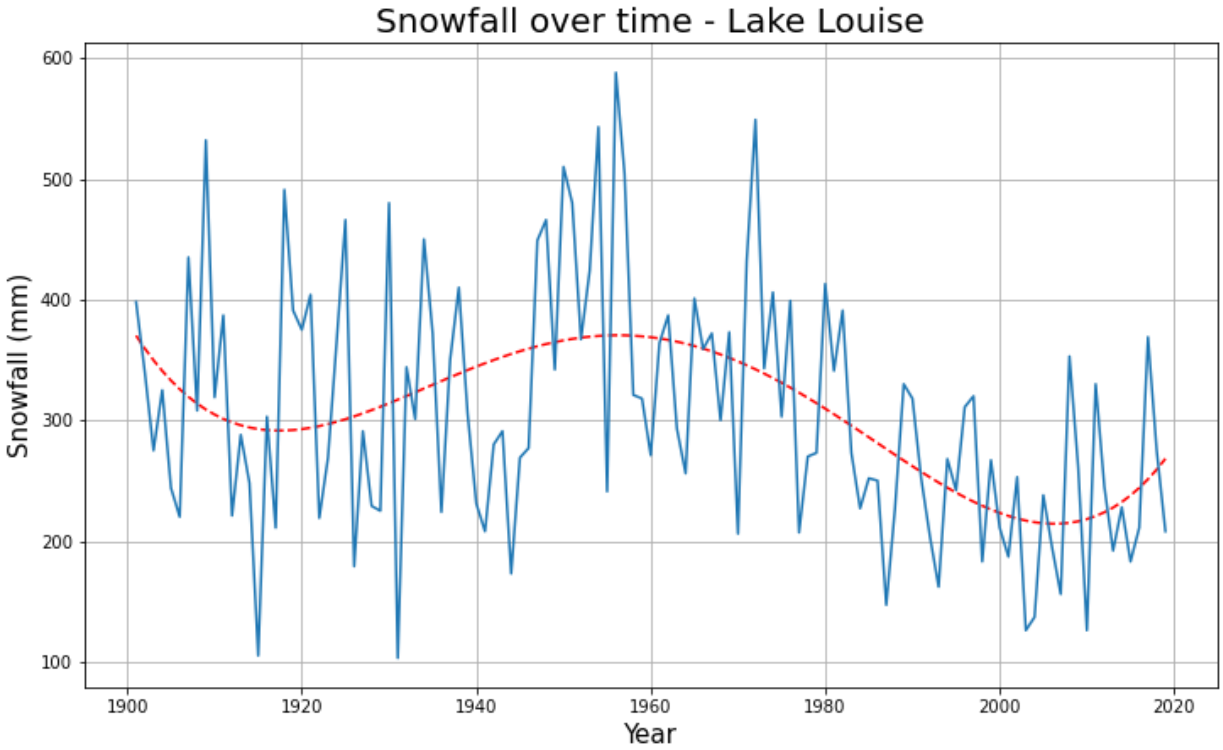

Figure A.1.4.3: Seasonal snowfall data shows a strong decrease in the later 20th century with a possible slight increase in the most recent data.

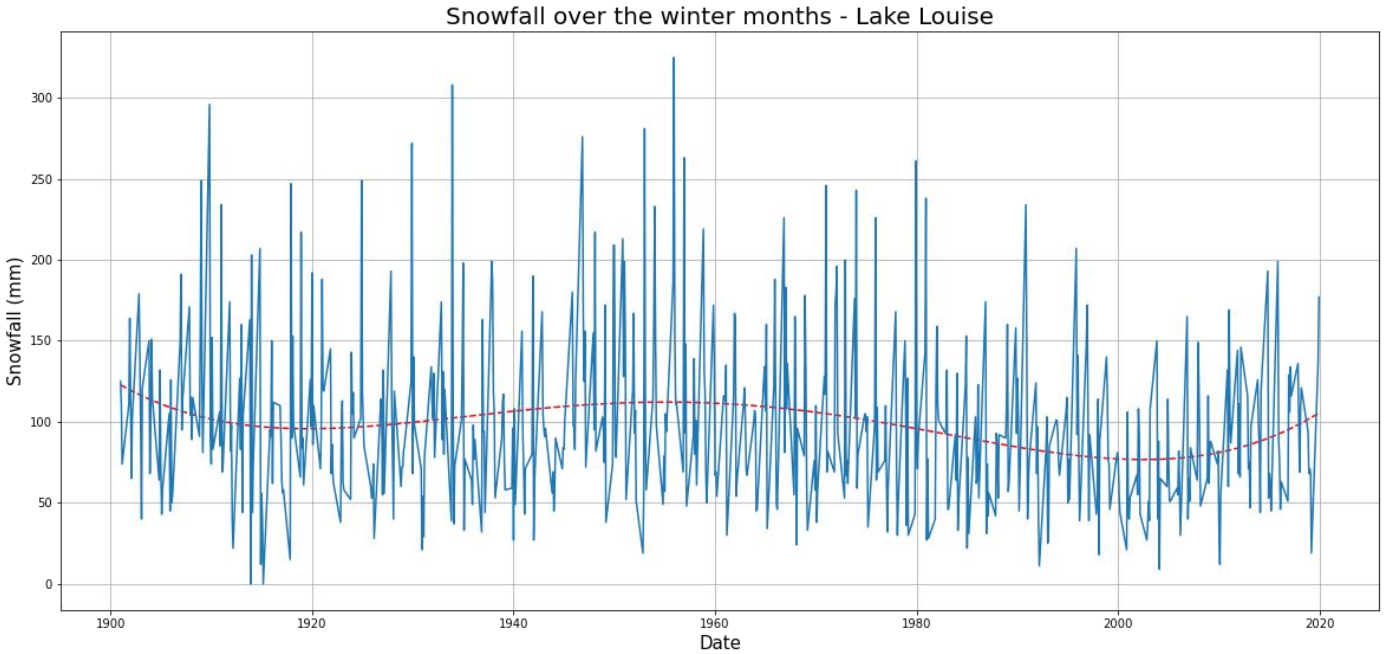

Figure A.1.4.4: Monthly snowfall data

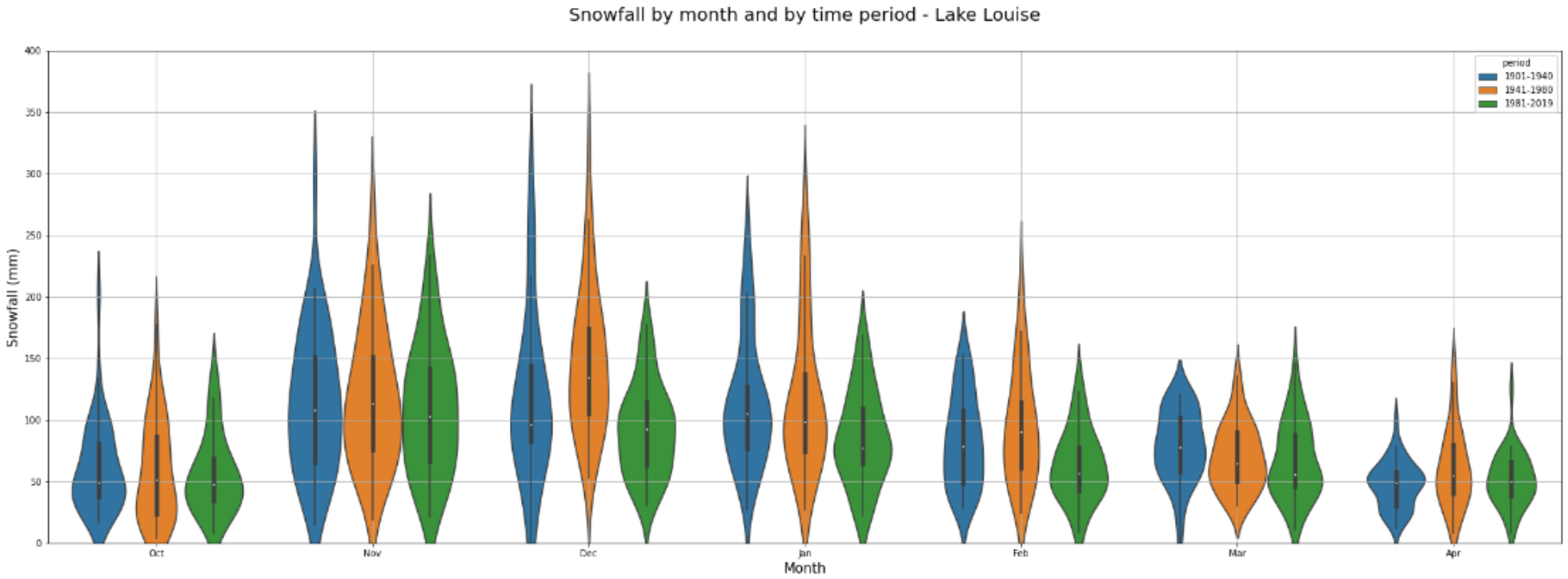

Figure A.1.4.5: Snowfall distributions by month and by time period. Period 1901-1940 in blue, 1941-1980 in orange and 1981-2019 in green. Slight tendencies towards generally lower levels in all months.

1.5 Mammoth Mountain:

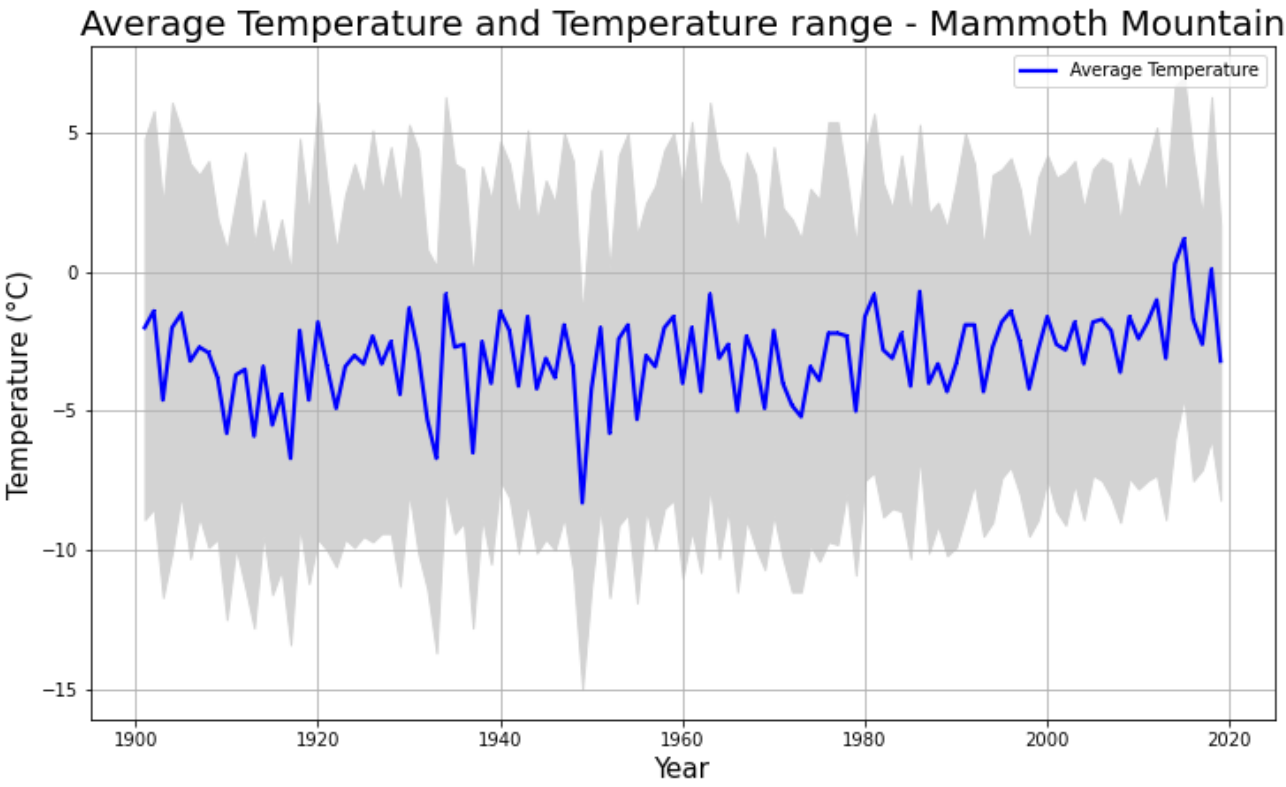

Figure A.1.5.1: Seasonal temperatures show a steady increase since the early 20th century.

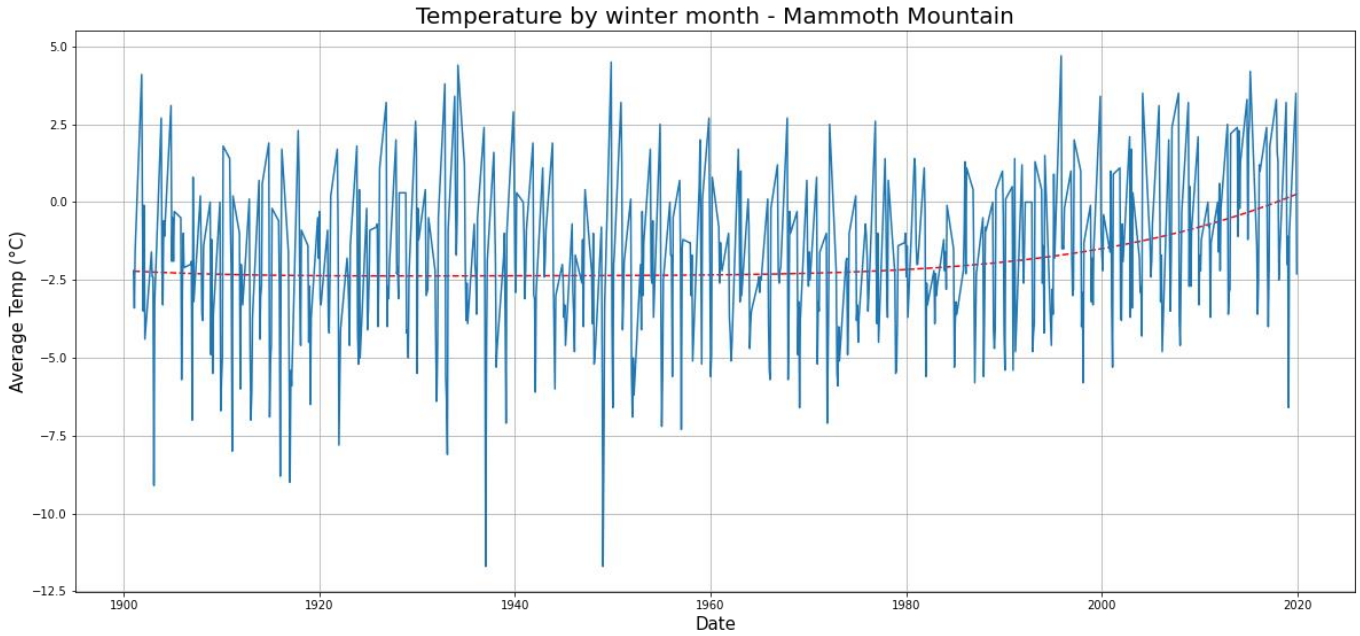

Figure A.1.2.2: Monthly winter temperatures

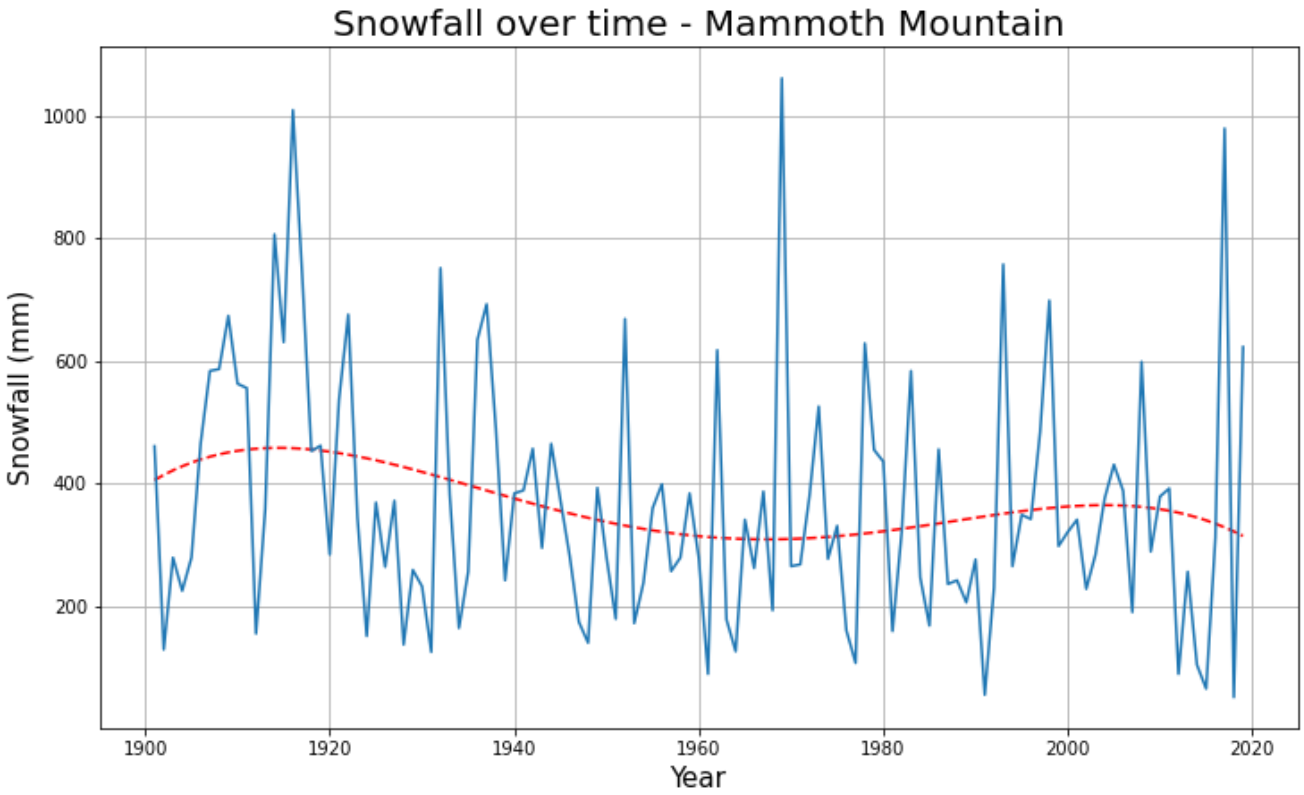

Figure A.1.5.3: Seasonal snowfall data remains relatively steady during the later 20th century.

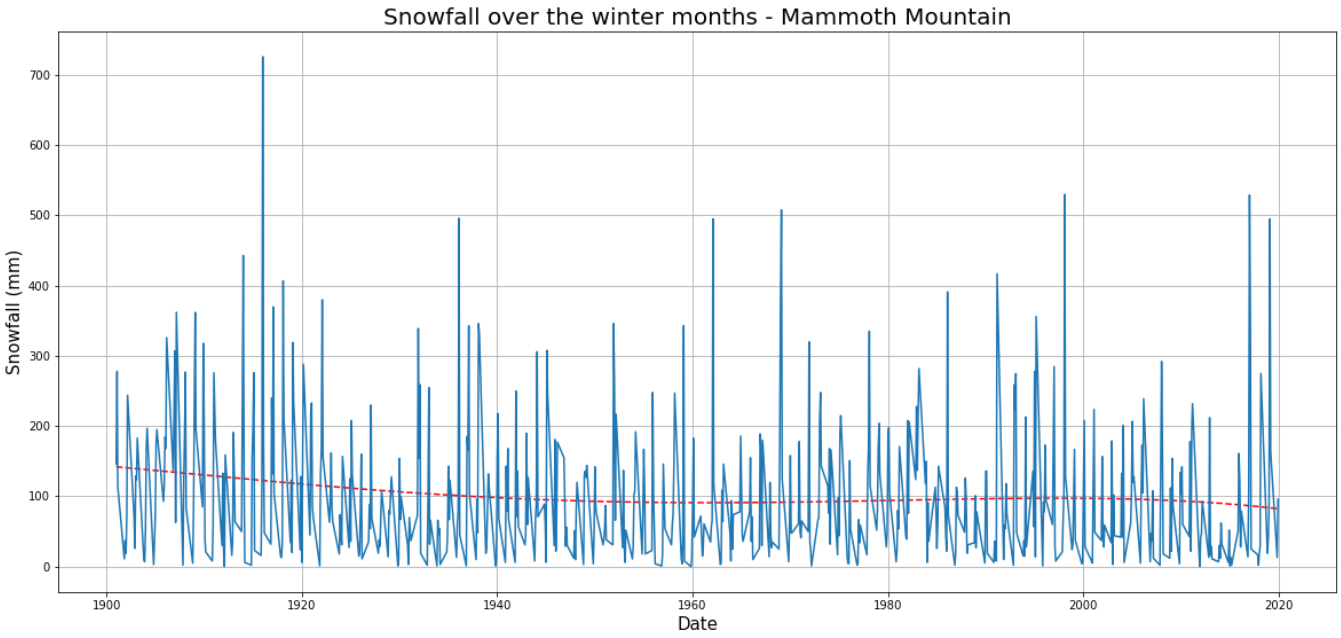

Figure A.1.5.4: Monthly snowfall data

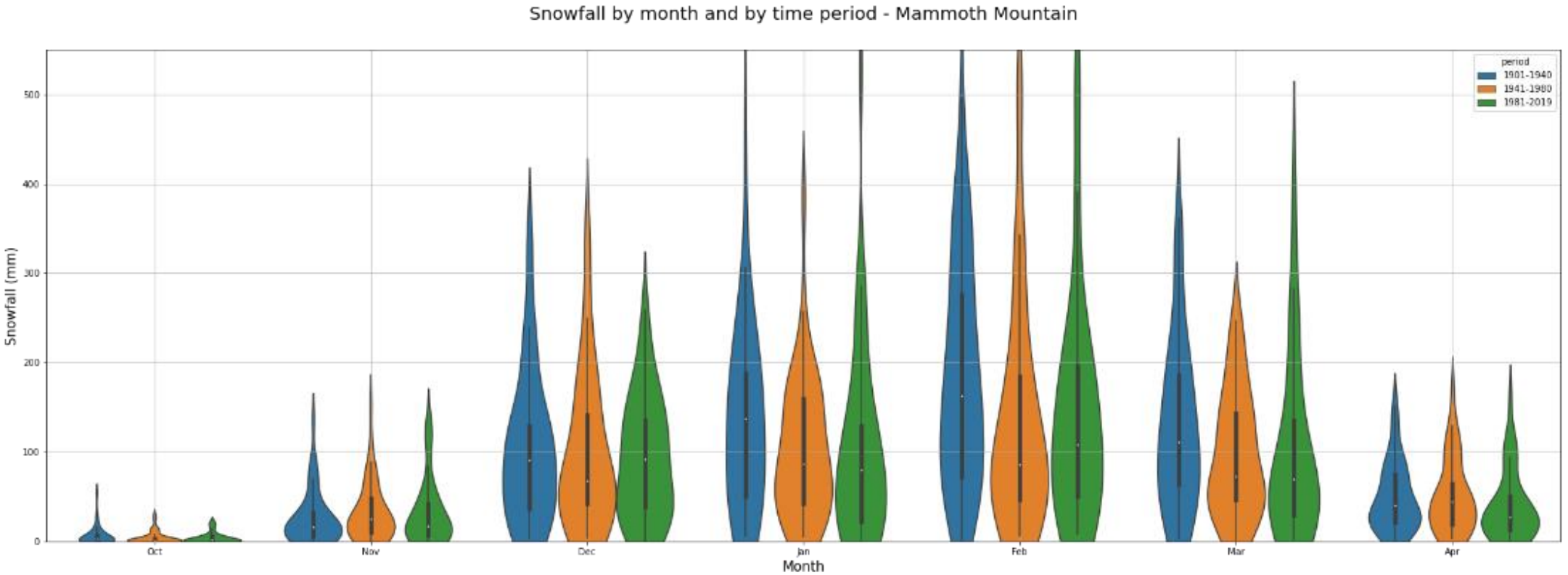

Figure A.1.5.5: Snowfall distributions by month and by time period. Period 1901-1940 in blue, 1941-1980 in orange and 1981-2019 in green. Slight tendencies towards generally lower levels in recent January snowfall.

1.6 Mount Washington:

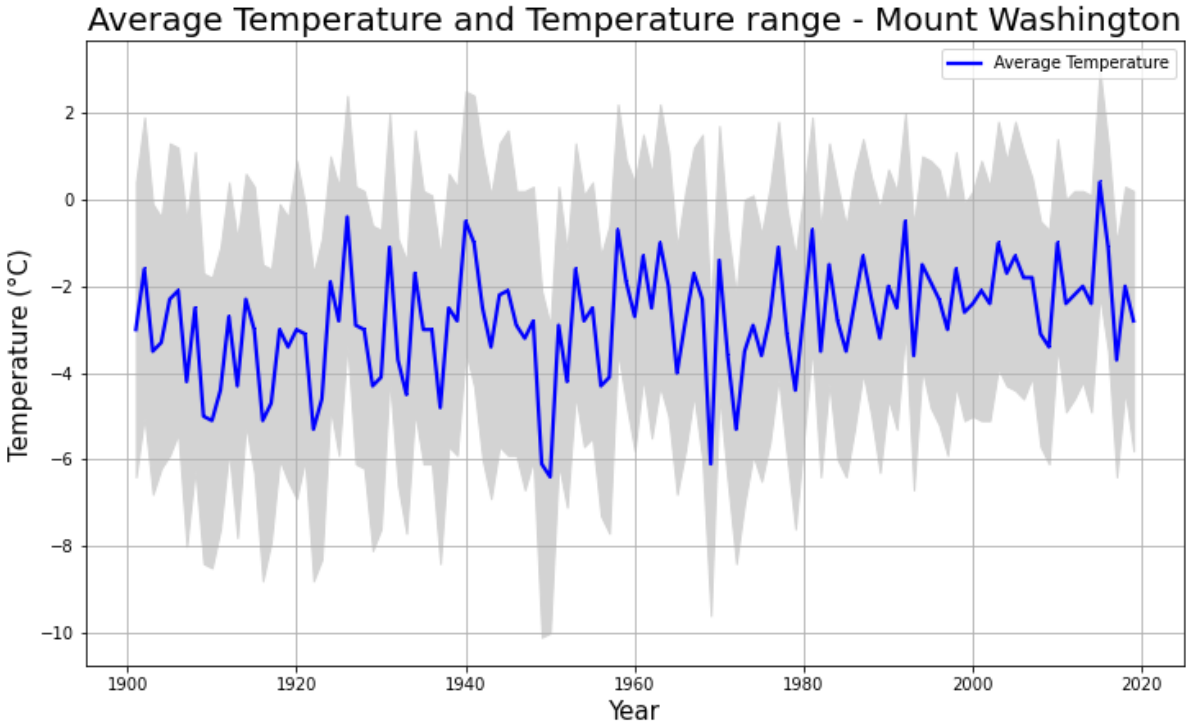

Figure A.1.6.1: Seasonal temperatures show a slight, but steady increase over the entire data.

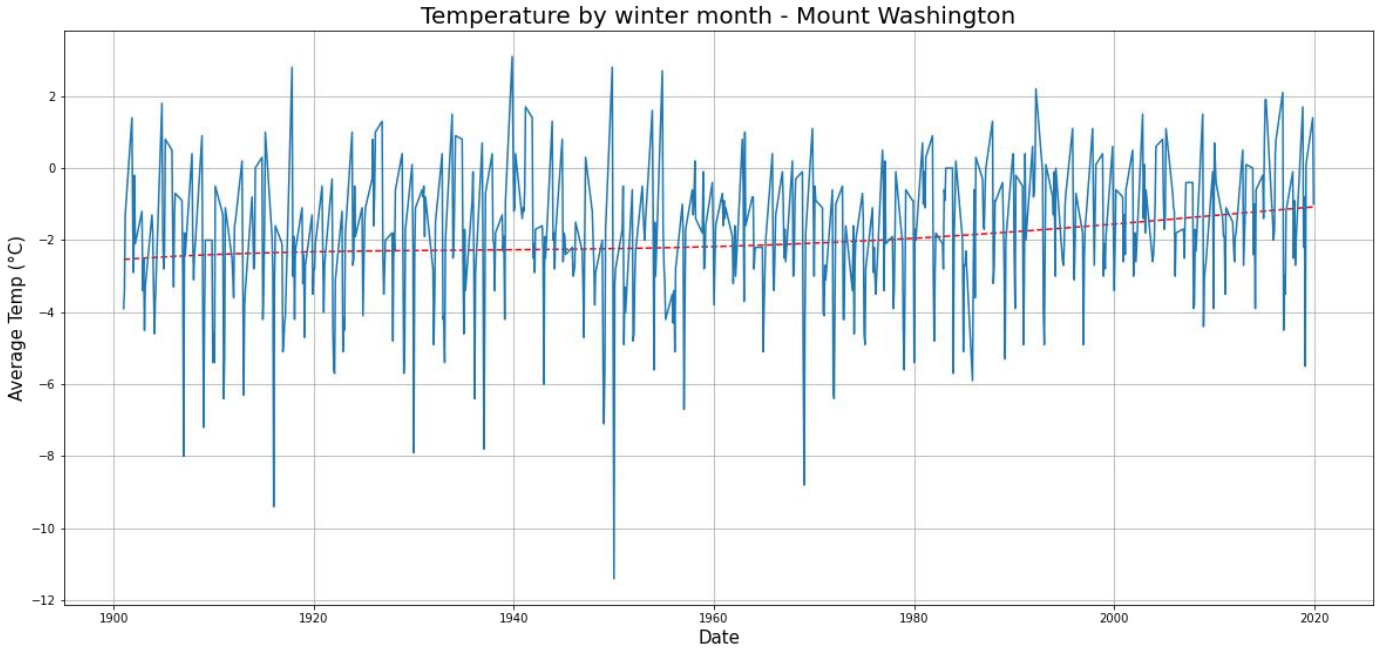

Figure A.1.6.2: Monthly winter temperatures

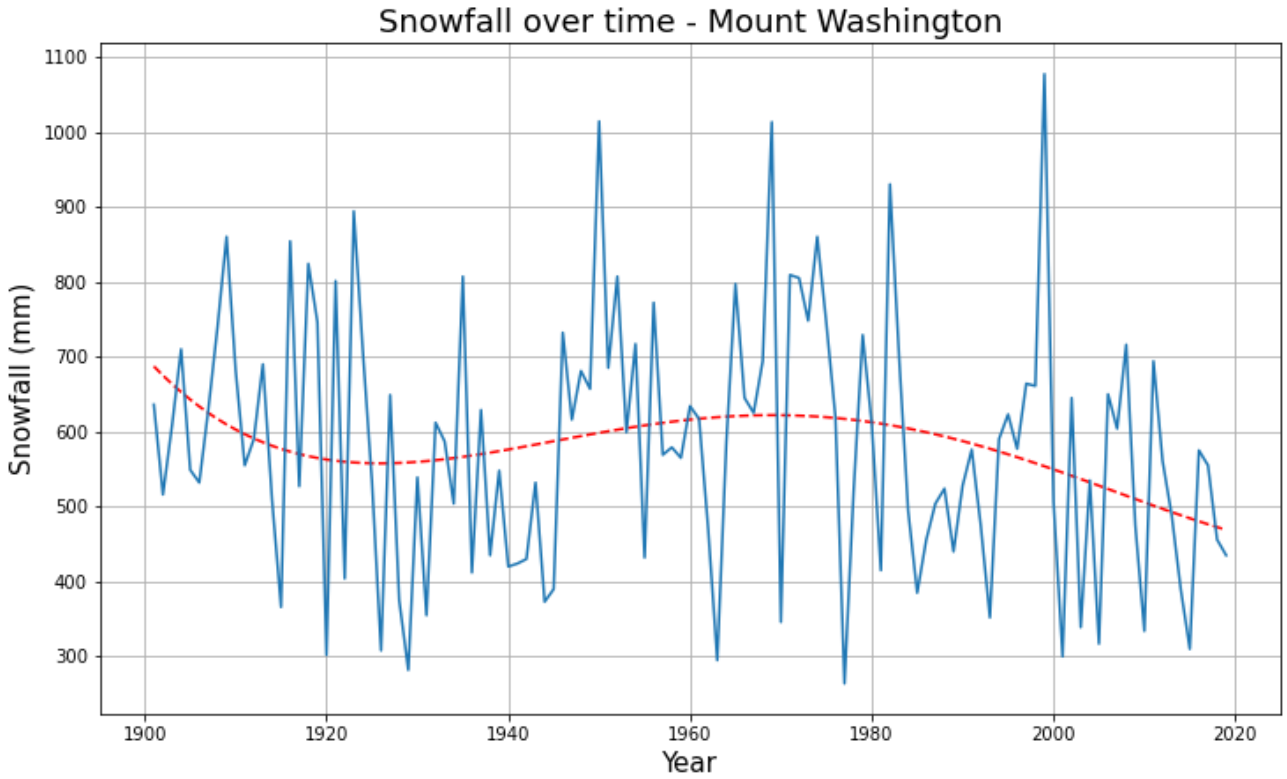

Figure A.1.6.3: Seasonal snowfall data shows a significant recent dip in snowfall since around 1980.

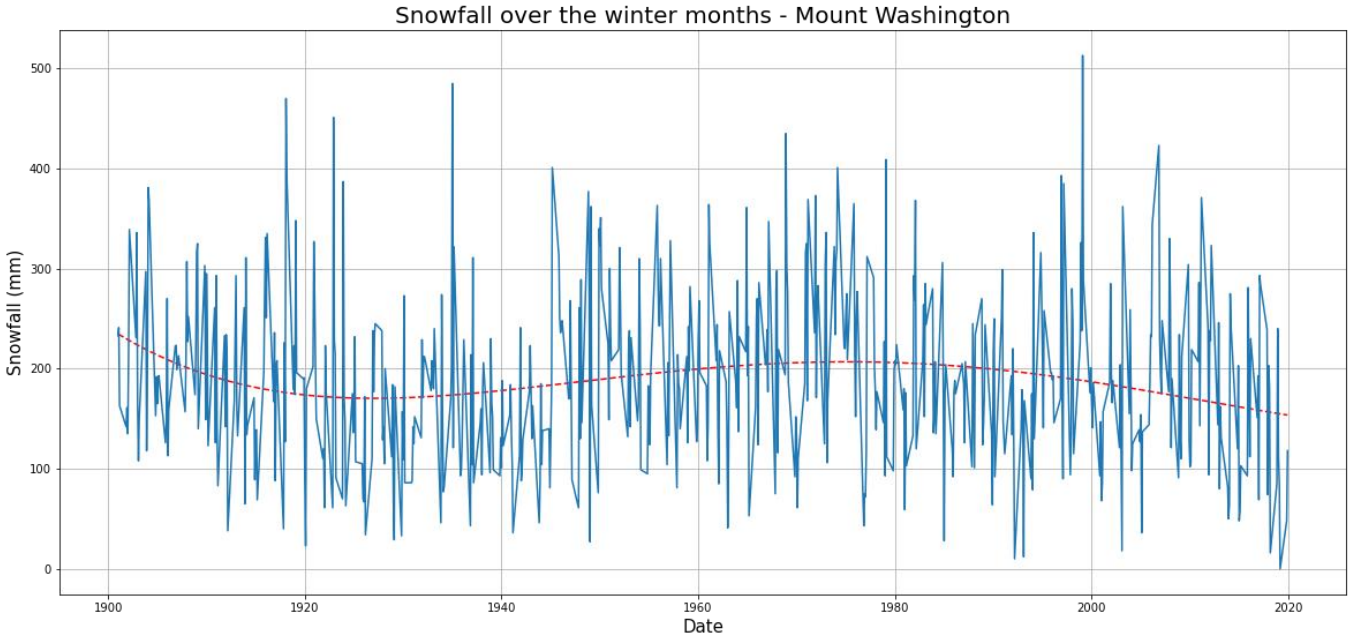

Figure A.1.6.4: Monthly snowfall data

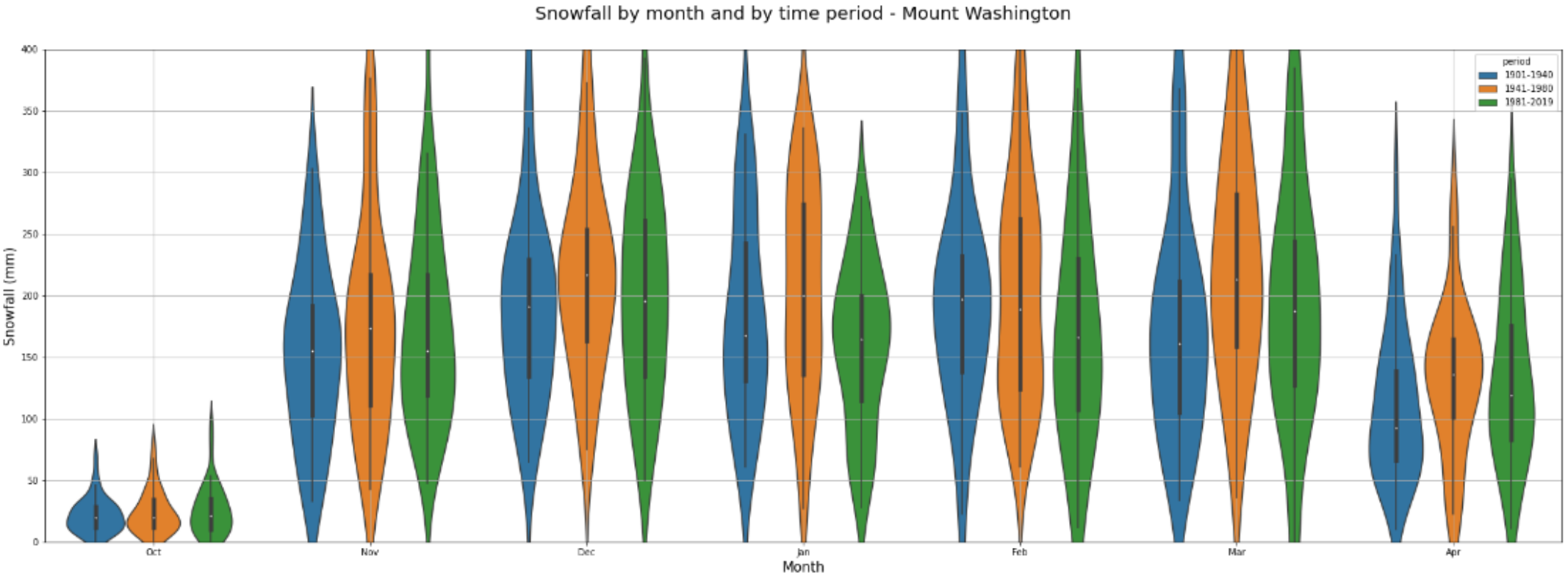

Figure A.1.6.5: Snowfall distributions by month and by time period. Period 1901-1940 in blue, 1941-1980 in orange and 1981-2019 in green. Slight tendencies towards lower levels in recent February snowfall levels.

1.7 Mount Baker:

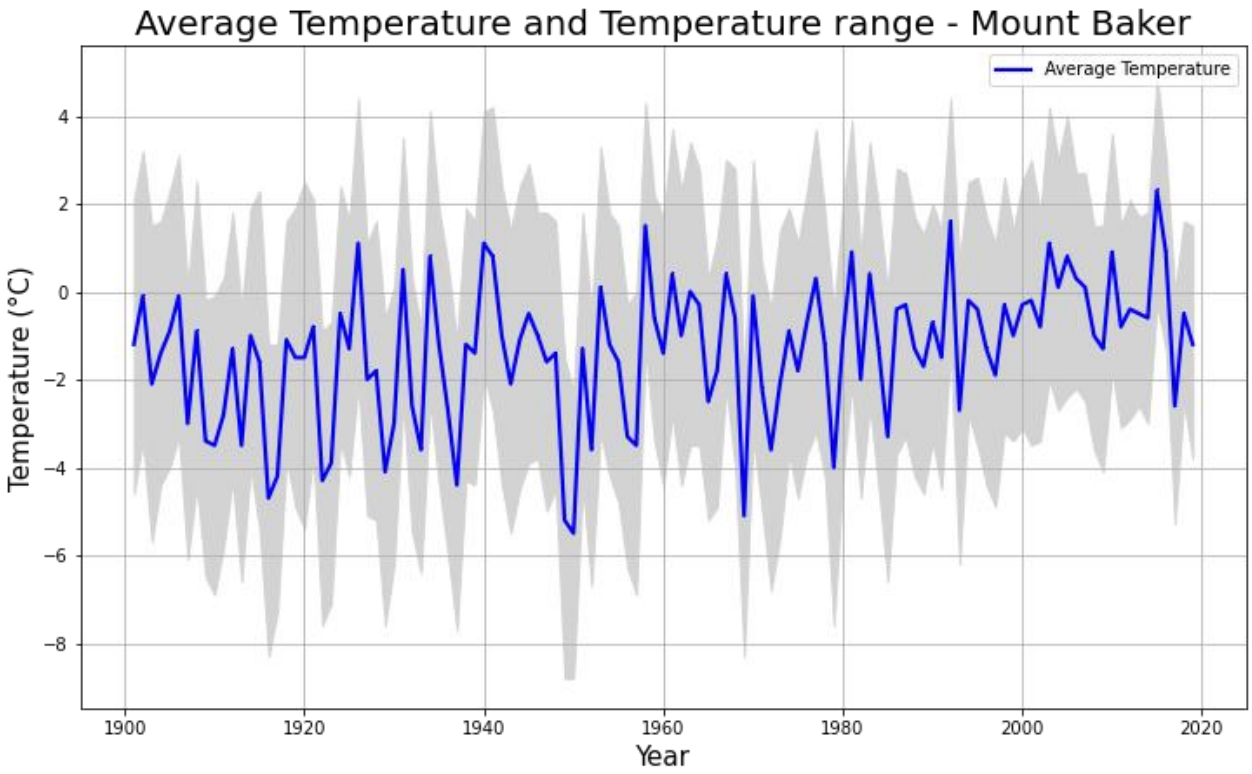

Figure A.1.7.1: Seasonal temperatures show a steady increase since 1910.

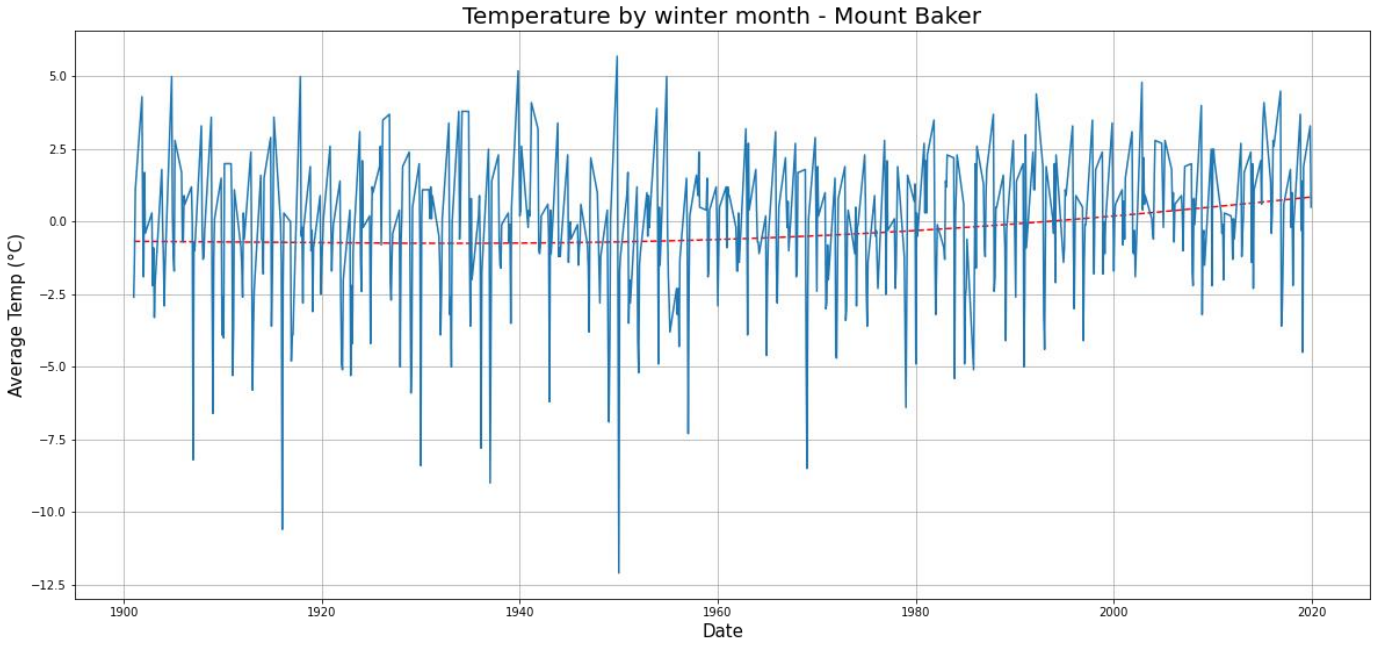

Figure A.1.7.2: Monthly winter temperatures

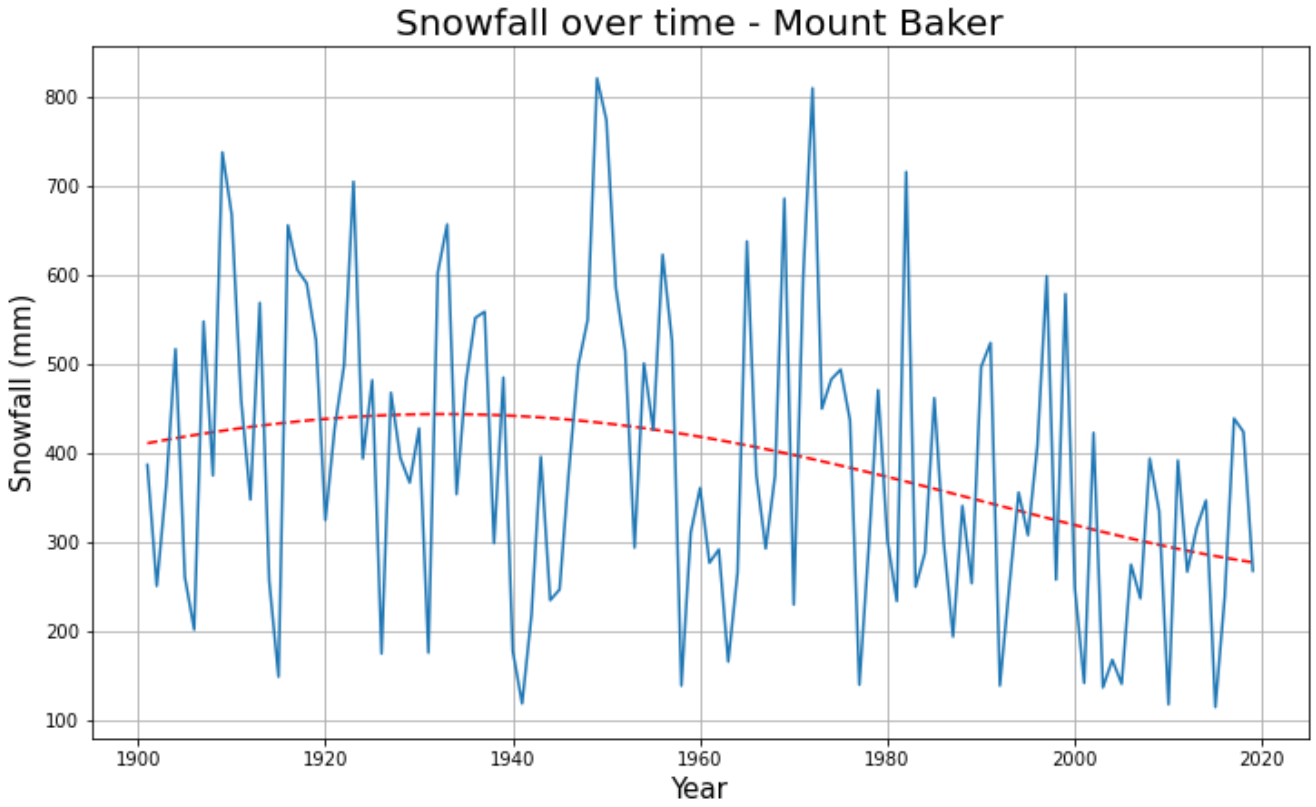

Figure A.1.7.3: Seasonal snowfall data shows decreasing snowfall levels since 1940.

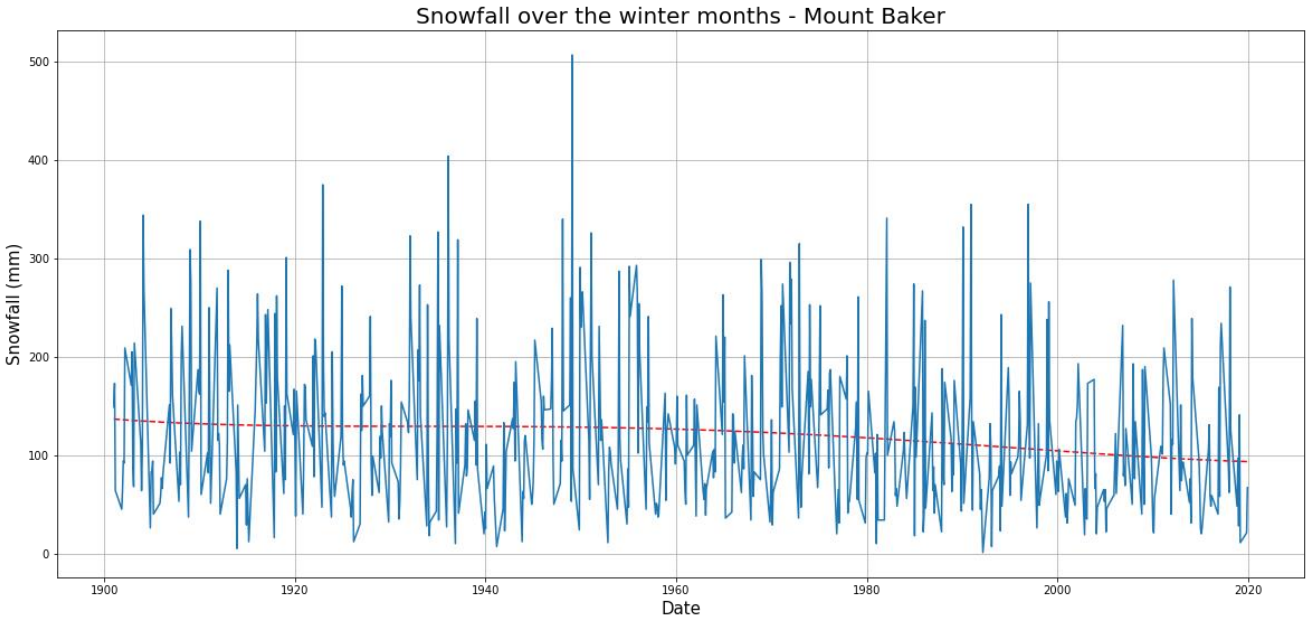

Figure A.1.7.4: Monthly snowfall data

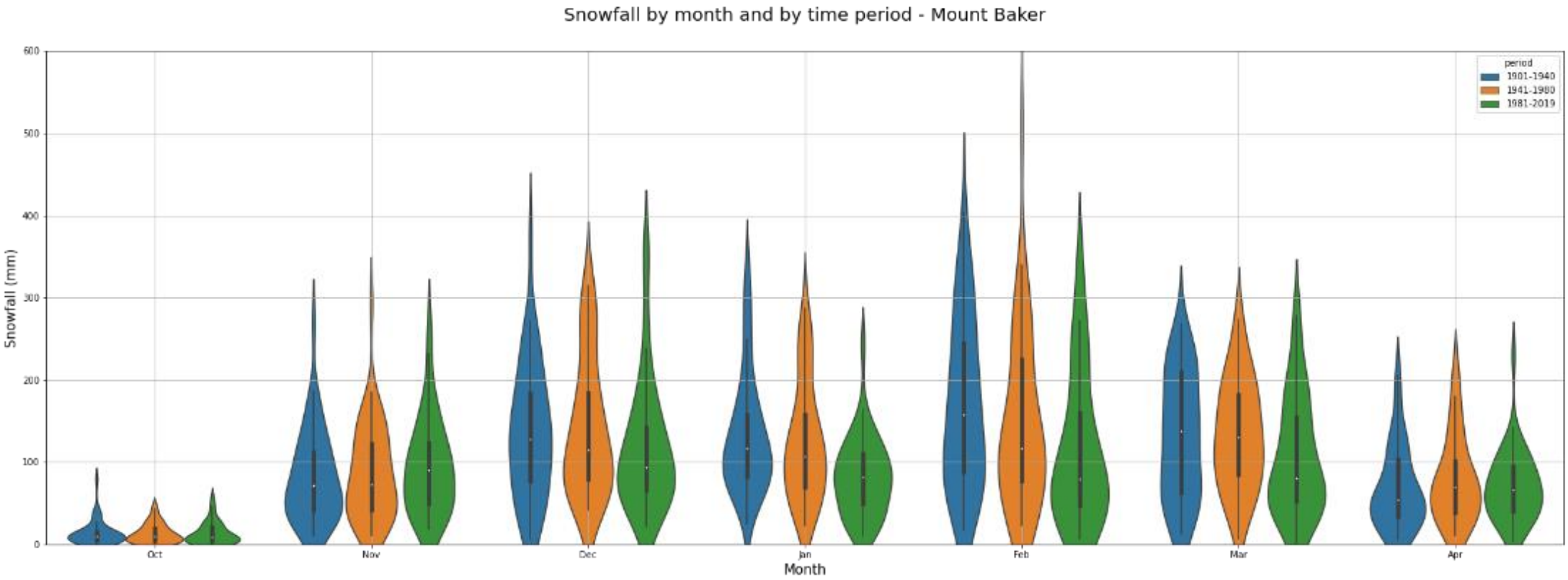

Figure A.1.7.5: Snowfall distributions by month and by time period. Period 1901-1940 in blue, 1941-1980 in orange and 1981-2019 in green. Slight tendencies towards generally lower levels in recent January, February, and March snowfall.

1.8 Mount Hood:

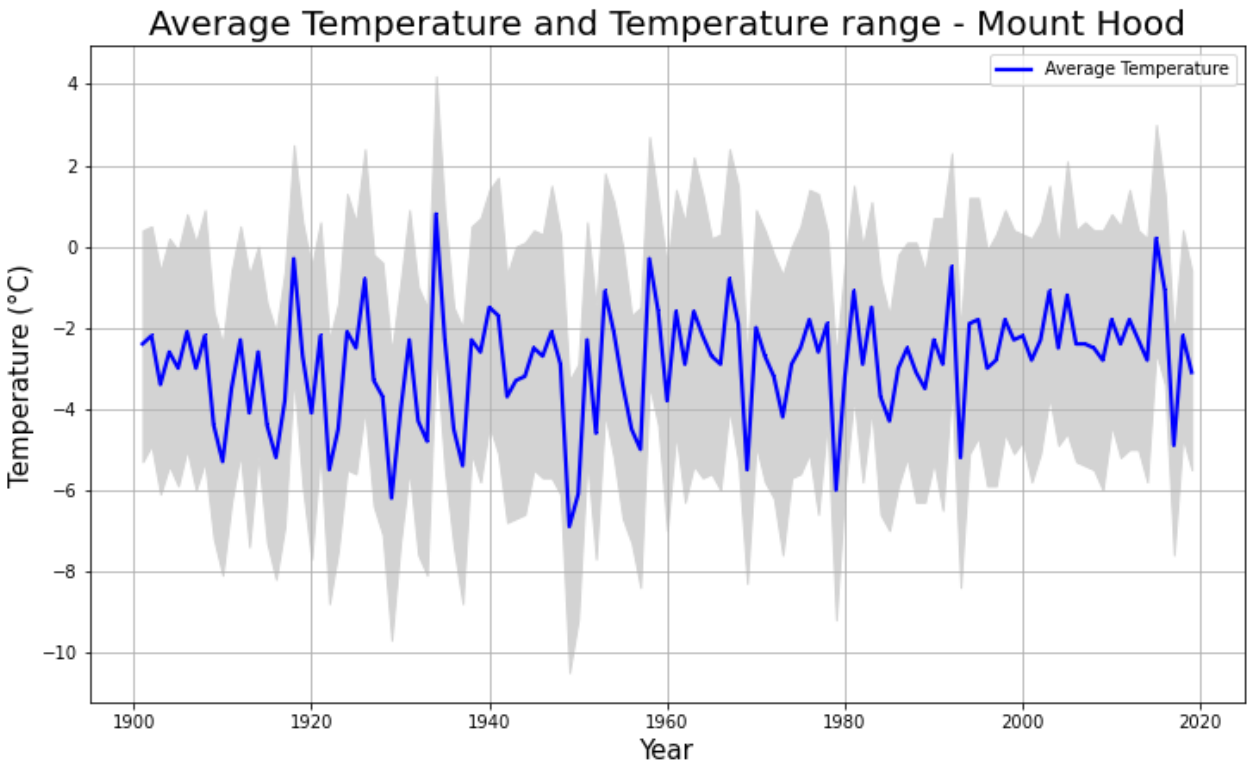

Figure A.1.8.1: Seasonal temperatures remain relatively steady with a slight increase in the last 40 years.

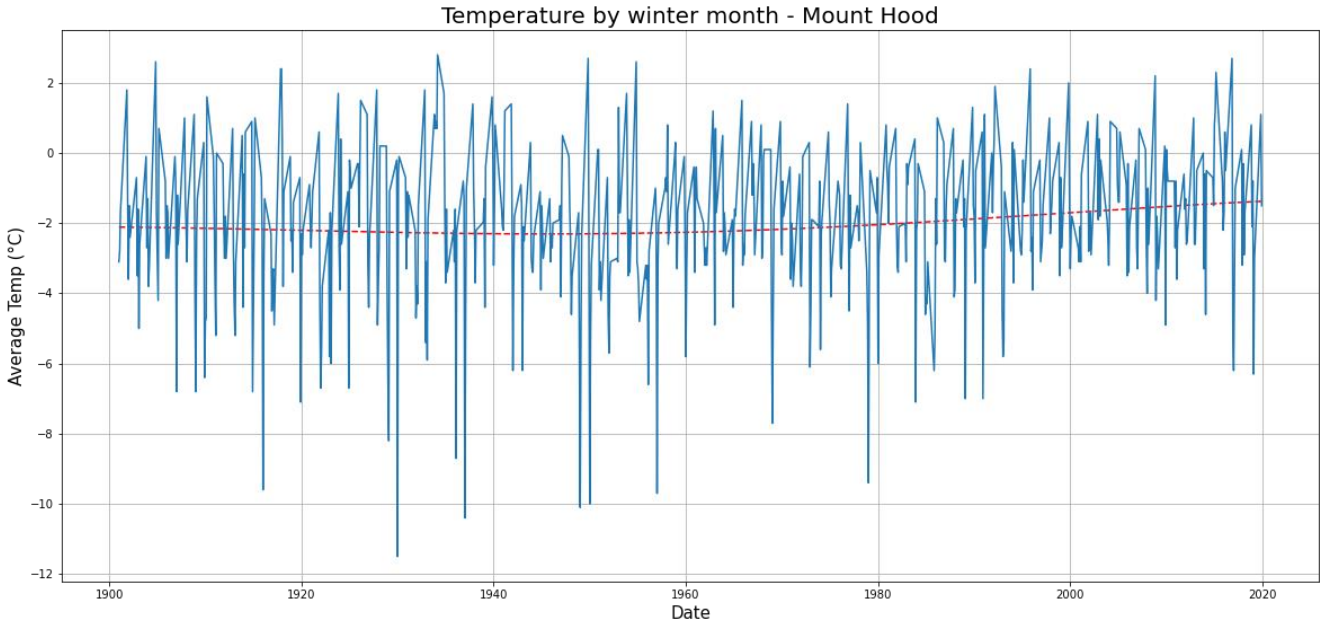

Figure A.1.8.2: Monthly winter temperatures

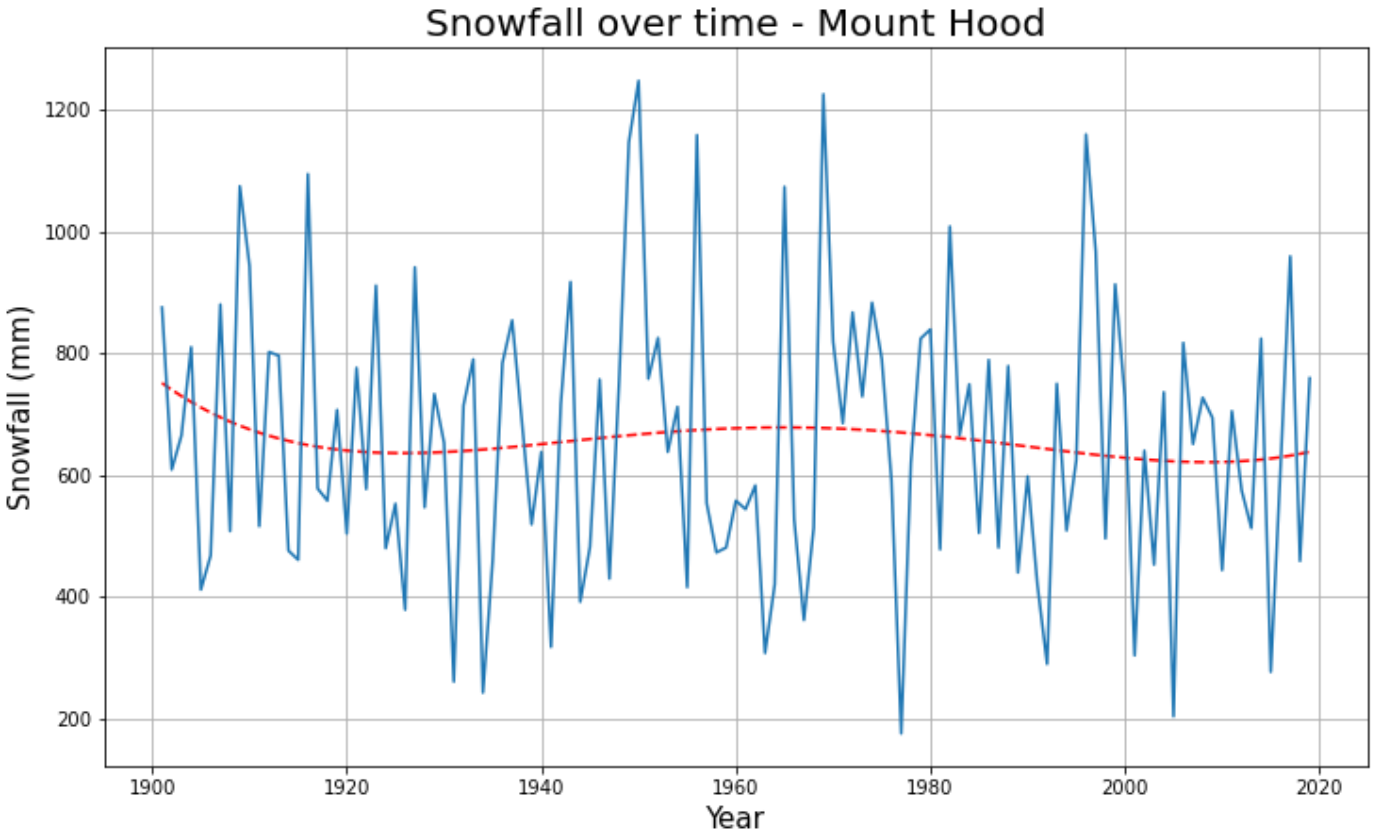

Figure A.1.8.3: Seasonal snowfall data indicates stable snowfall levels.

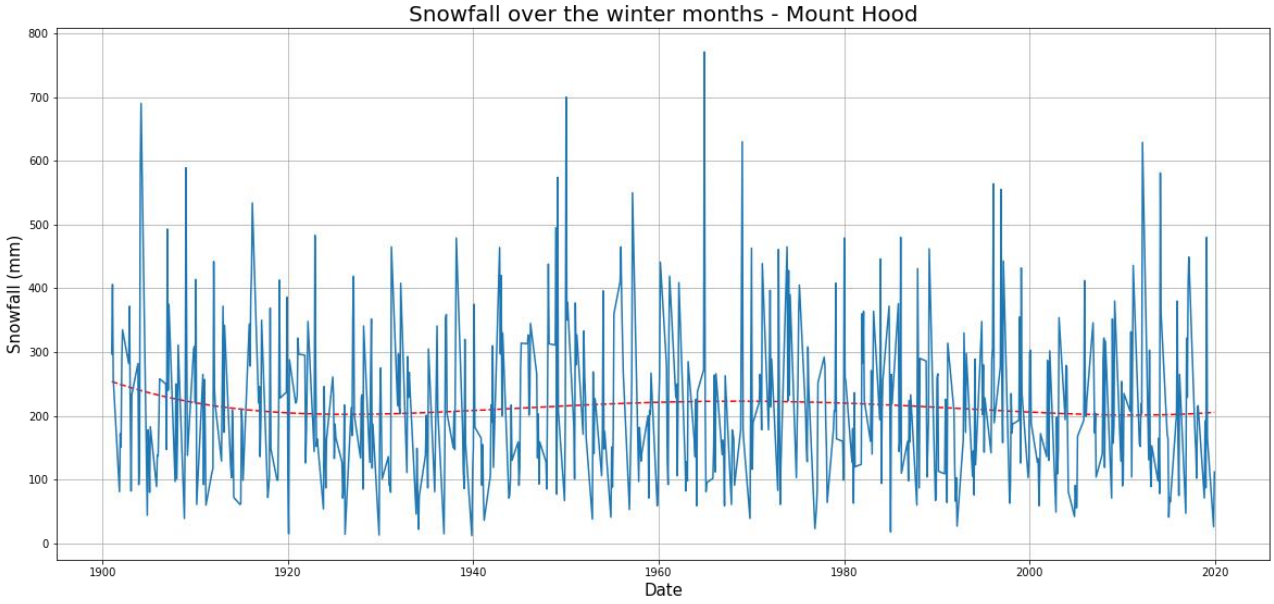

Figure A.1.8.4: Monthly snowfall data

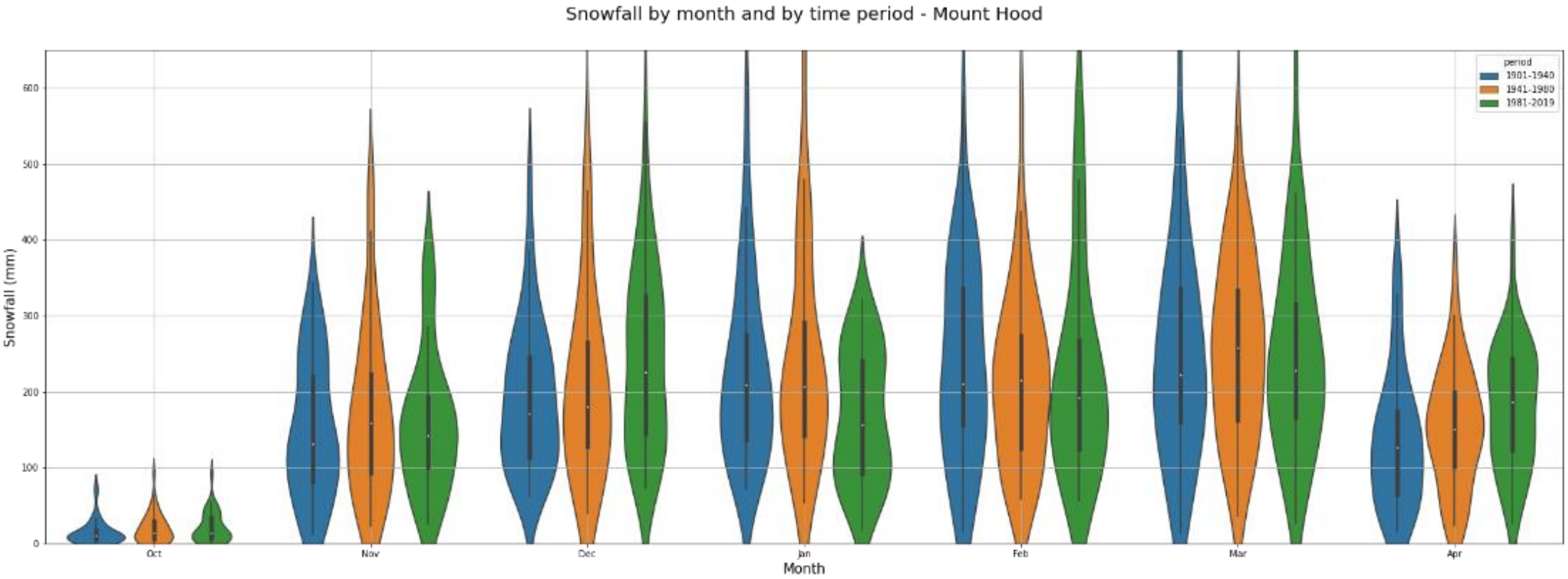

Figure A.1.8.5: Snowfall distributions by month and by time period. Period 1901-1940 in blue, 1941-1980 in orange and 1981-2019 in green. Slight tendencies towards generally lower levels in recent February snowfall levels and higher levels in April.

1.9 Vail:

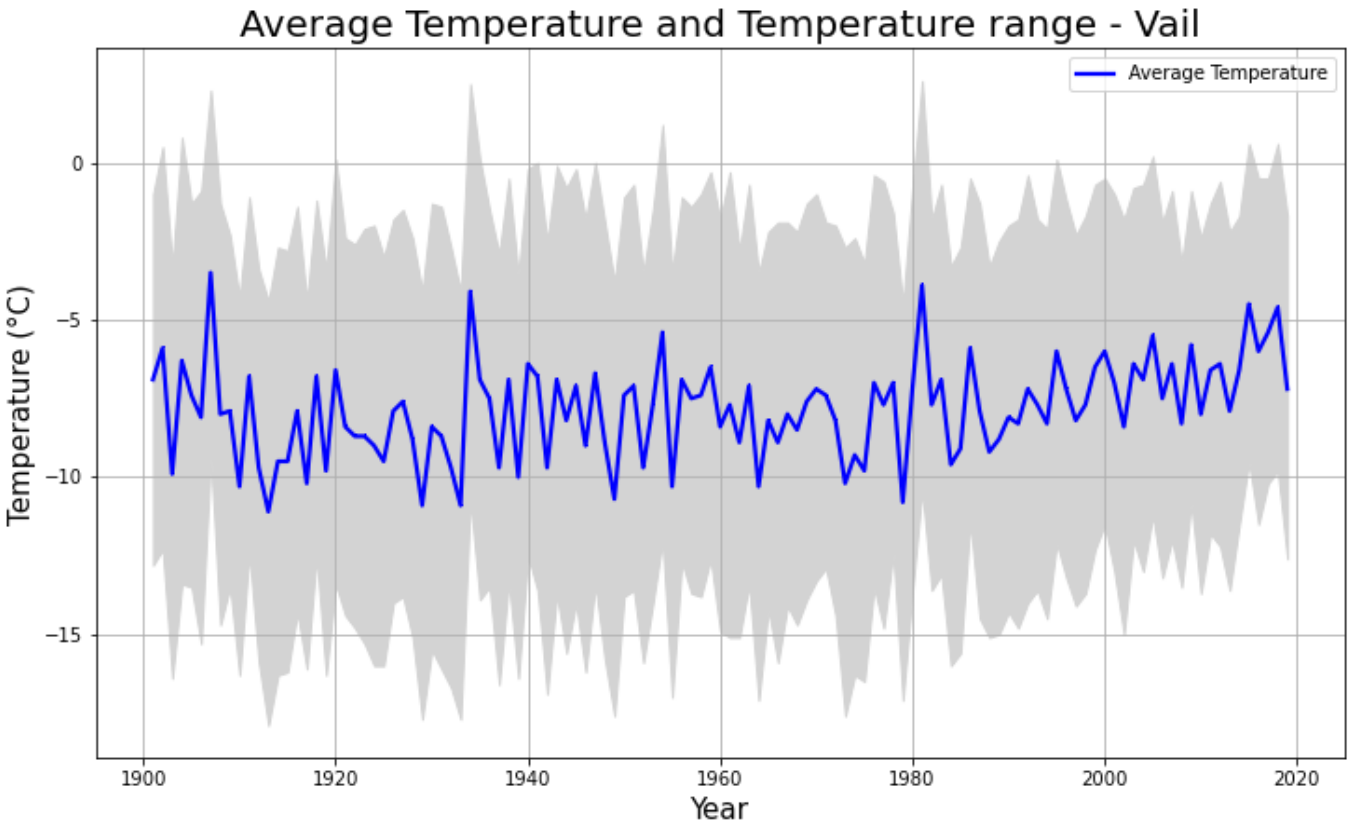

Figure A.1.9.1: Seasonal temperatures show a steady increase since around 1960.

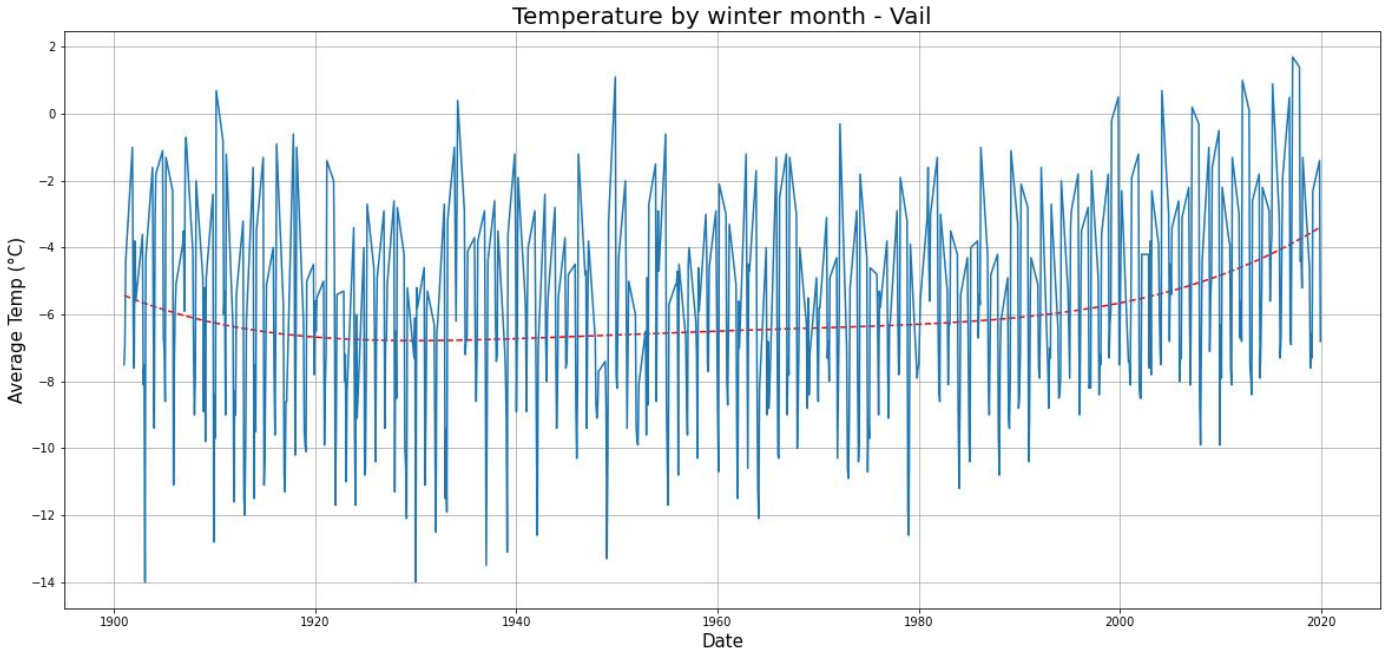

Figure A.1.9.2: Monthly winter temperatures indicate a much faster increase in temperatures recently

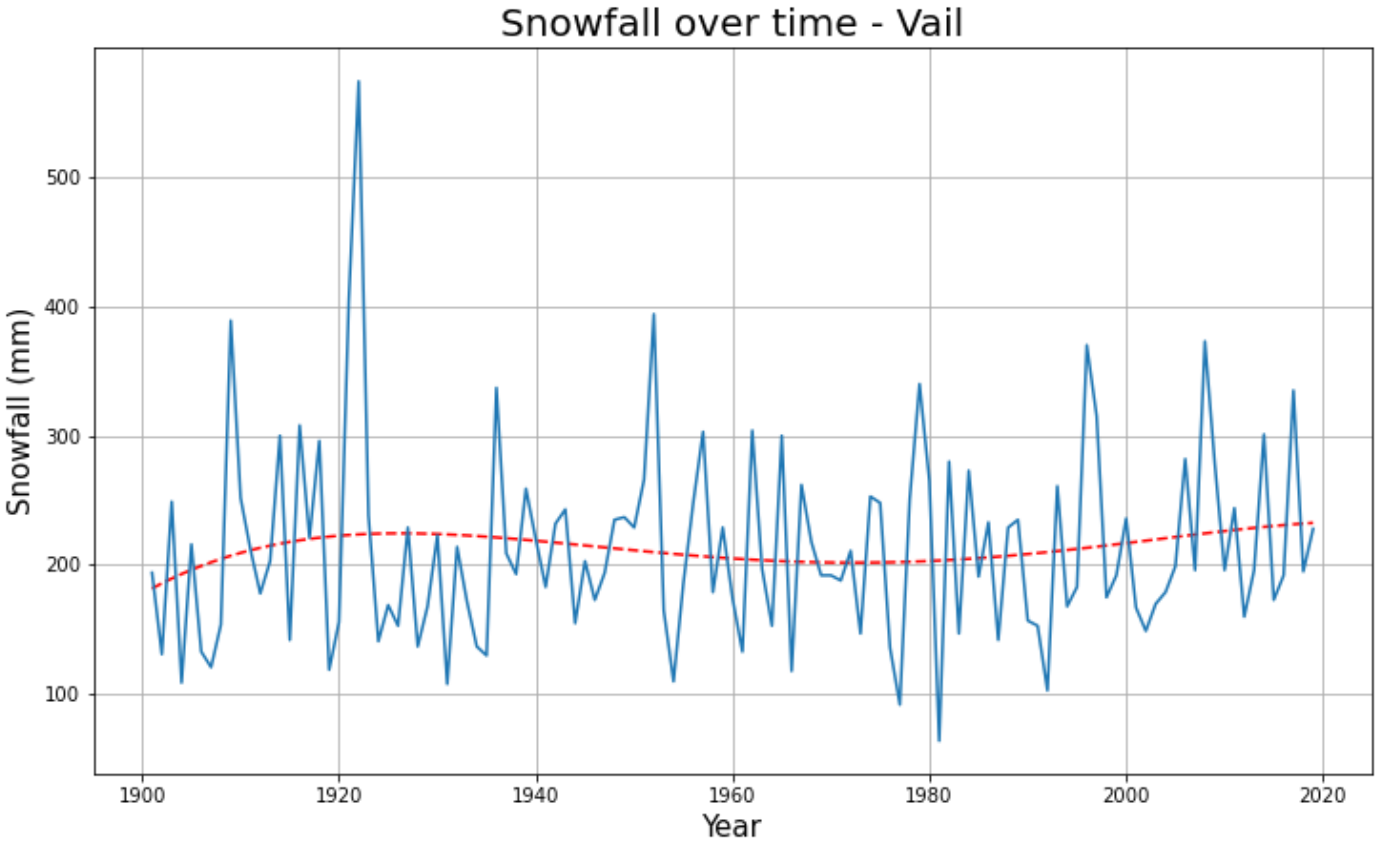

Figure A.1.9.3: Seasonal snowfall remains relatively steady with a recent slight increase.

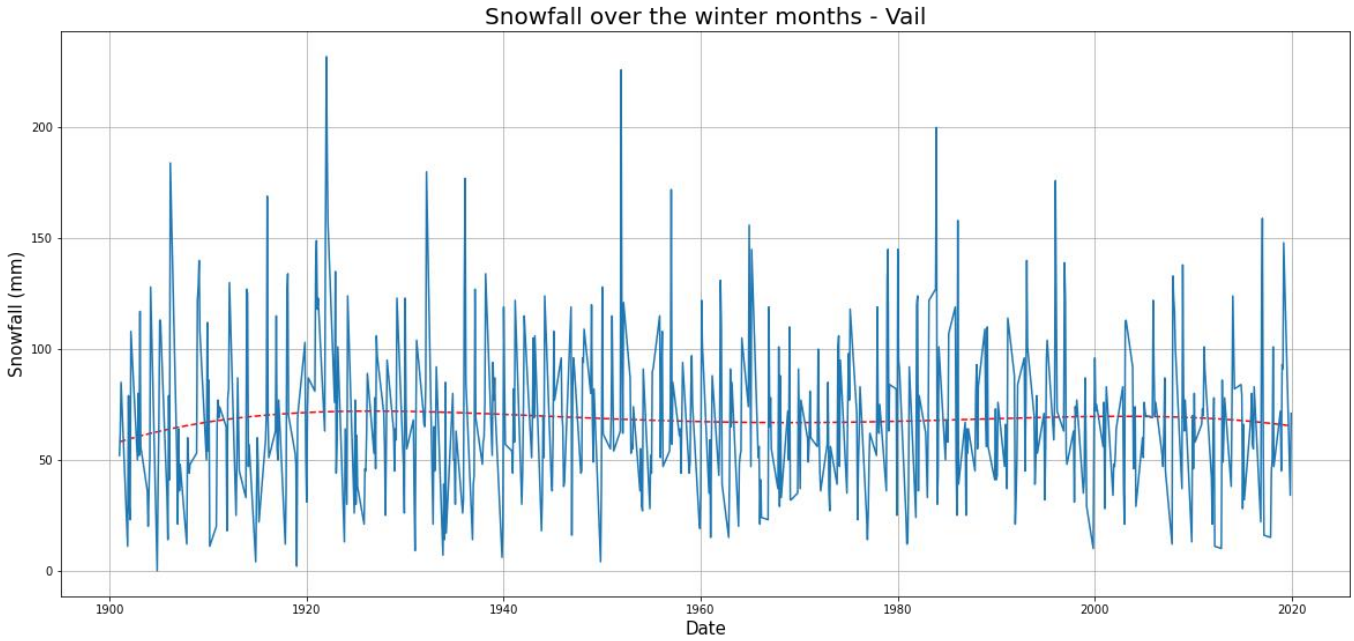

Figure A.1.9.4: Monthly snowfall data

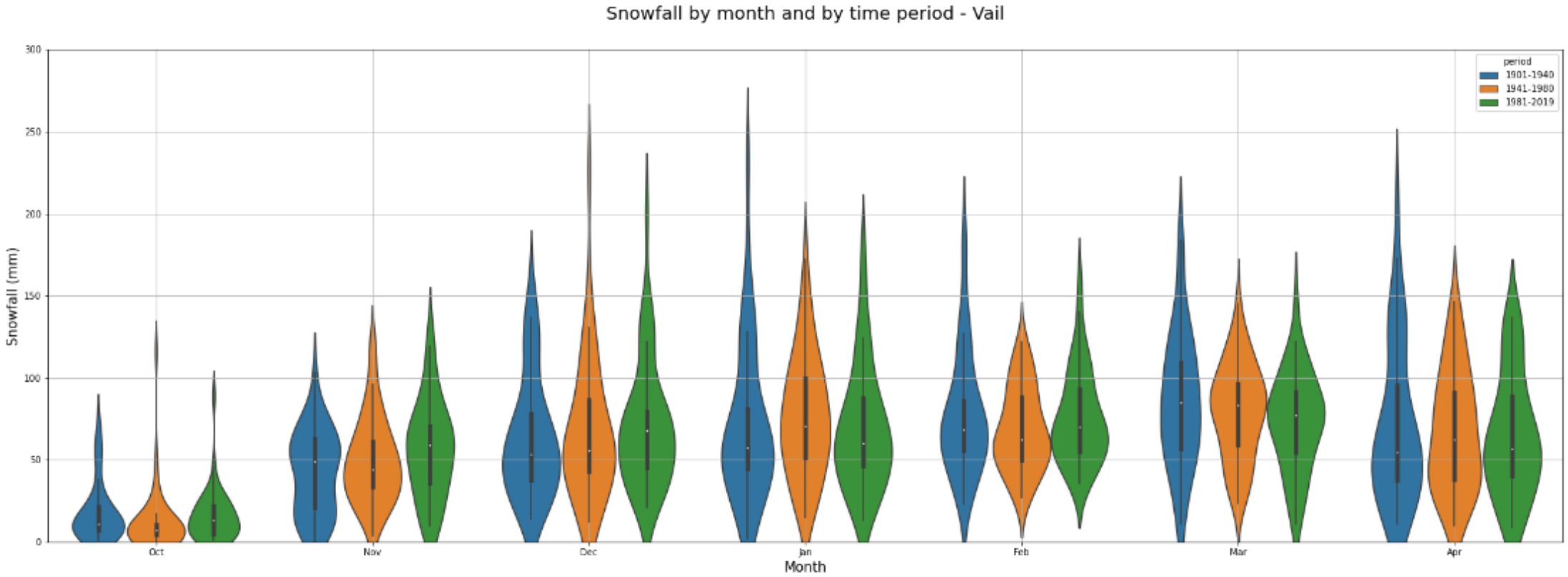

Figure A.1.9.5: Snowfall distributions by month and by time period. Period 1901-1940 in blue, 1941-1980 in orange and 1981-2019 in green. No major changes can be observed.

1.10 Whistler Blackcomb:

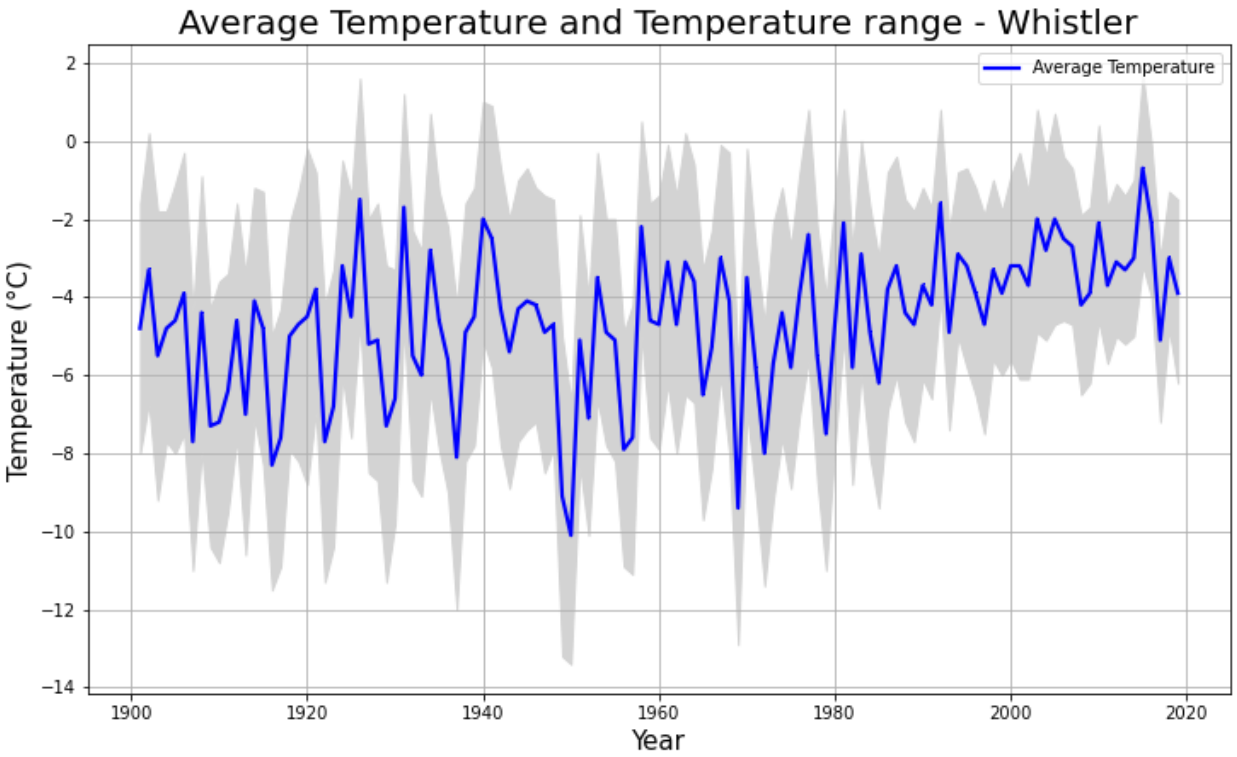

Figure A.1.10.1: Seasonal temperatures show a strong increase since around 1960.

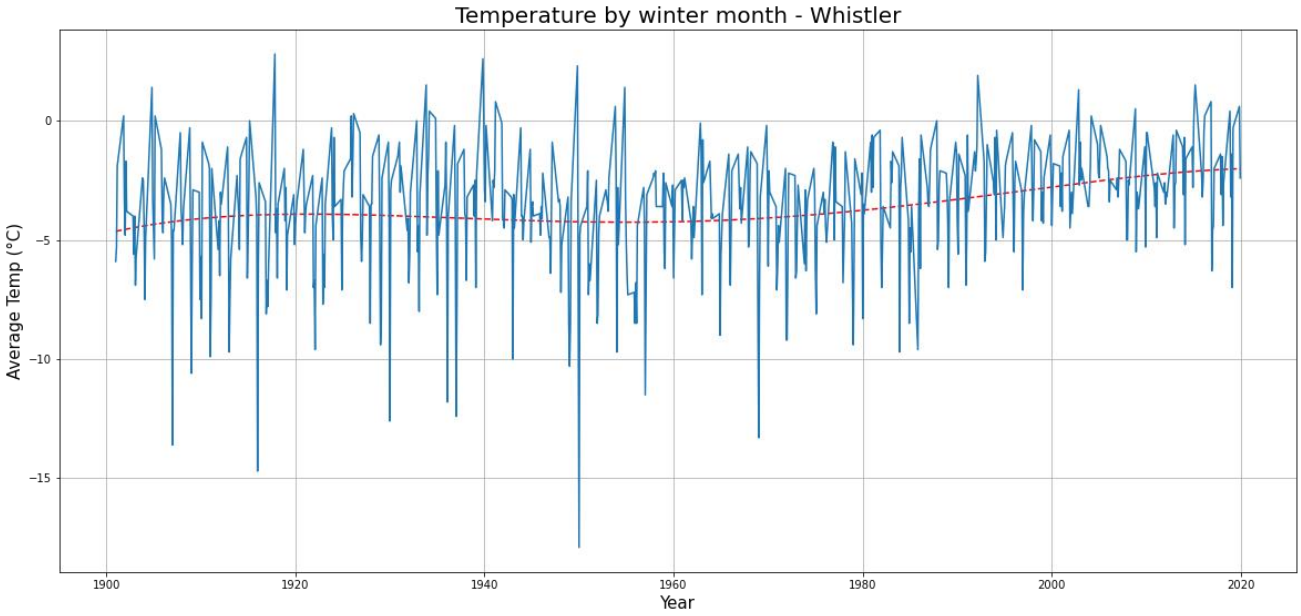

Figure A.1.10.2: Monthly winter temperatures

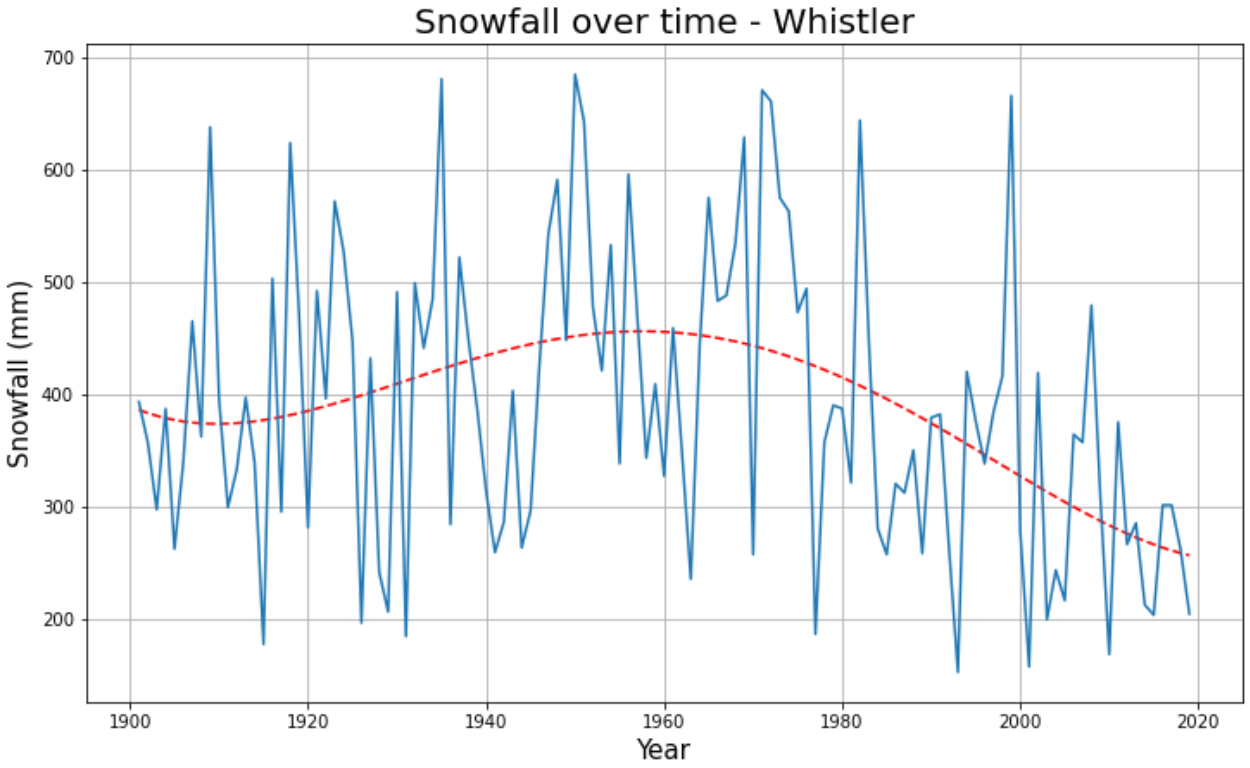

Figure A.1.10.3: Seasonal snowfall data shows a strong decrease since the mid-20th century.

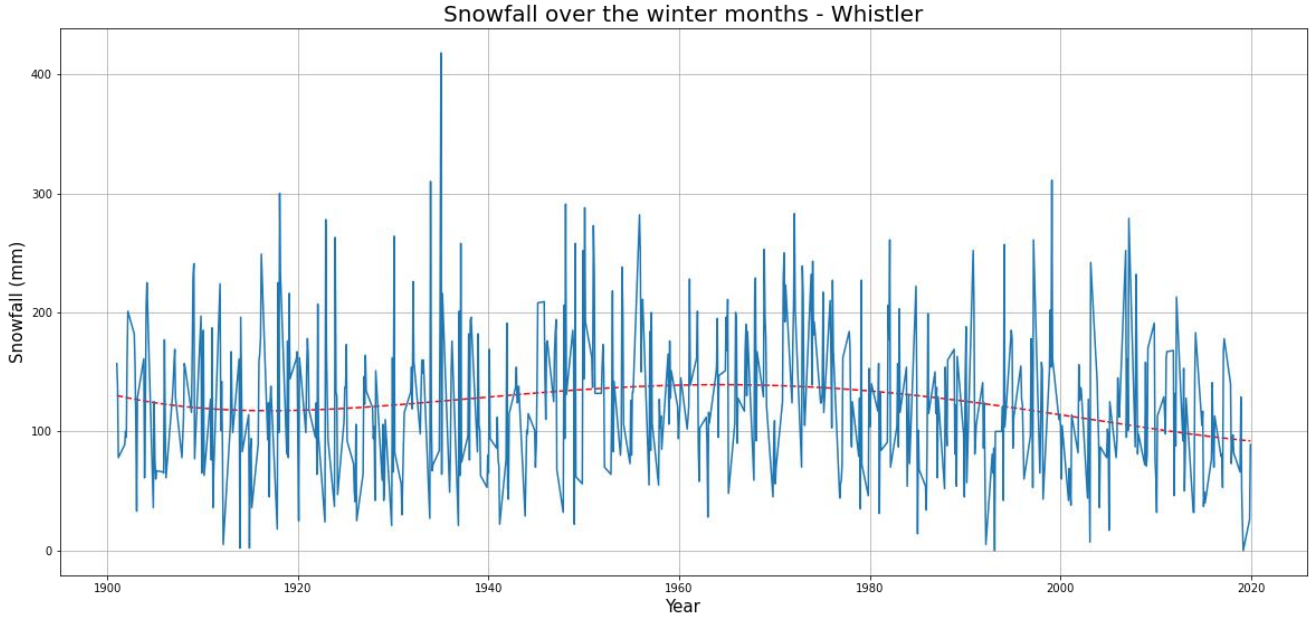

Figure A.1.10.4: Monthly snowfall data

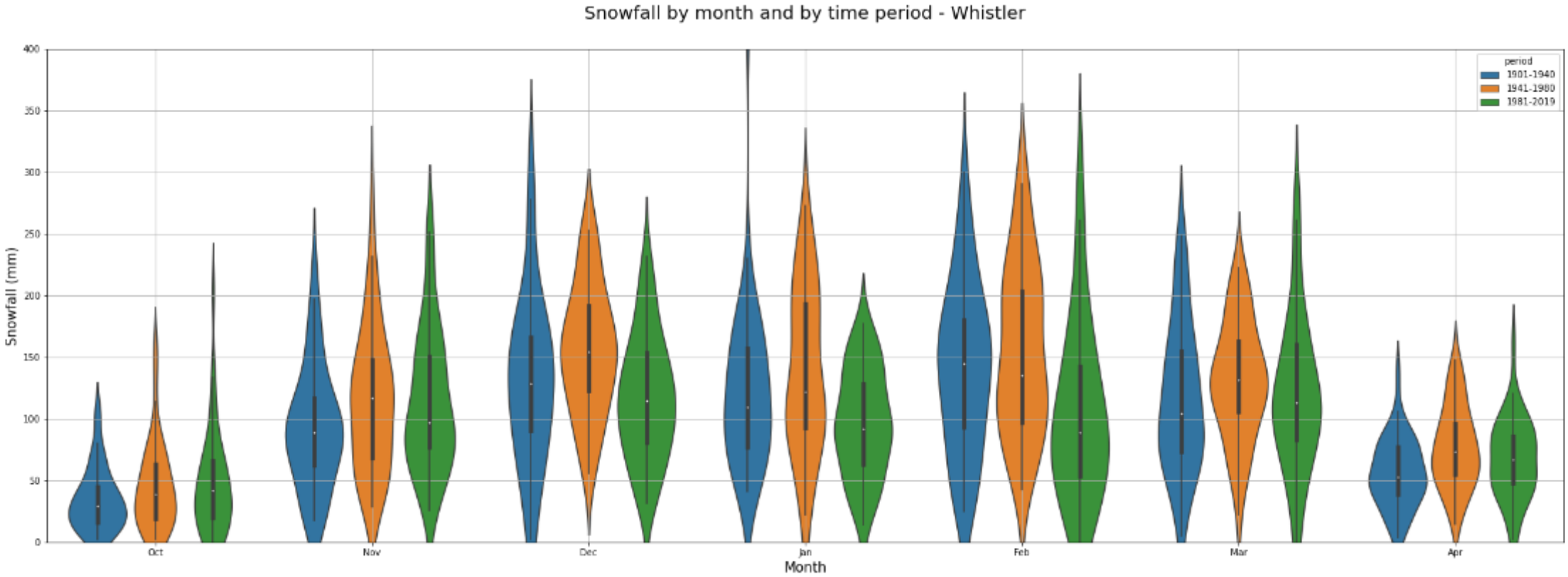

Figure A.1.10.5: Snowfall distributions by month and by time period. Period 1901-1940 in blue, 1941-1980 in orange and 1981-2019 in green. Slight tendencies towards generally lower levels in recent February snowfall levels.