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Nationwide Climate Assessment of Canadian Viticulture Utilizing Google Earth Engine

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Abstract

Across the global viticultural industry, shifting climate patterns are driving the development of new wine-growing regions. Canadian viticulture could benefit as short growing seasons and freezing winters limit the viability of wine production. Since the late 1800s, global temperatures have risen about 1.1°C and trends of key climactic indicators like temperature and precipitation have pushed poleward. In the primary Canadian growing regions of Ontario, Quebec, Nova Scotia, and British Columbia, shifts in climate may open the wine-growing regions to new opportunities with new varietals, but with some risks. This research topic looks to provide a nationwide climate assessment of Canadian viticulture utilizing *Google Earth Engine* (GEE) to understand how shifting temperature and precipitation gradients may impact the Canadian wine industry.

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Chapter 1: Canadian Wine Industry Background

1.1 Introduction

Wine was first produced around the current-day Southern Caucus region (Estreicher, 2017). The presence of wine can be traced back to the Neolithic period and has been produced in some rudimentary form well before the creation of writing (Estreicher, 2017). Modern wine grapes, the *Vitis vinifera* varietal, are derived from *Vitis vinifera sylvestris* (Estreicher, 2017). Wine as a beverage has lasted through the ages and remains a beloved beverage of choice for many today.

Wine production can only happen within particular climate conditions, with grapes susceptible to extreme climate shifts (Jones et al., 2022). With wine quality, profile, colours, and flavour varying with growing regions and climates, shifting climates pose a risk to wine-producing regions worldwide. This research hopes to add to a growing research base by assessing future climatic scenarios of Canada's four primary growing regions.

1.2 Background

1.2.1 Canadian Wine: A Brief History

The history of wine production in Canada is both controversial and dubious in its origins. On his supposed landing at present-day L'Anse aux Meadows about 1,000 years ago, Leif Erikson, the Norse explorer, declared the land as Vineland, possibly due to the presence of native grapes (Wallace, 2009; Phillips, 2017). Oral history in other provinces, such as Quebec, has Jacques Cartier discovering native varietals *Vitis riparia* on his arrival (Outreville, 2010). Later, French varietals, *Vitis vinifera*, were thought to have been first planted by Samuel de Champlain (Outreville, 2010). The first 250 years of wine production history in Canada is spotty at best, but the provenance of wine in Canada is undoubtedly more profound than one may expect (Phillips, 2017).

The first commercial winery in Canada is believed to have been in Cooksville, Ontario, around the 1860s (Jarrell, 2019). Initial cultivation of grapes in Canada utilized native grape varietals within the *Vitis labrusca* species (Hope-Ross, 2006). Between the 1930s and the 1970s, shifting demand among Canadian consumers for higher quality wines led to a shift amongst wine producers from native varietals towards the French *Vitis vinifera* and hybrids that could persist in short growing seasons (Hope-Ross, 2006; Phillips, 2017).

While other regions around the country continue to emerge as potential viticultural locations, the four provinces of Ontario, Quebec, Nova Scotia, and British Columbia remain the central players in Canadian wine production (Hope-Ross, 2006). There are an estimated 800 wineries across Canada, generating roughly $9 billion CAD of economic activity (Mignone, 2022; Rimerman, 2017). Canada remains a minor player in the global wine landscape, but only time will tell if and how that will change.

Wine production in Canada is limited by relatively short growing seasons and frigid winters (Jobin-Poirier et al., 2019). Canadian winters pose a significant risk to viticulture. The *Vitis* varieties (**Table 1**) that characterize Canadian wine production are generally cold hardy varietals, including Riesling or Cabernet Franc, or hybrids of native North American and French varietals such as Marquette and Frontenac (Shaw, 2016). Climactic factors dictate the varietal type within the various Canadian growing provinces (Shultze & Sabbatini, 2019). The industry has primarily abandoned wine production utilizing native *Labrusca* varietals (Phillips, 2017; Lerfino-Blanchford, 2020).

Growing Province	**Growing Season**	**Dormancy Season**	**Examples of Common Varietals**	**Source**
Ontario	April 1st – October 31st	November 1st – March 31st	Chardonnay, Pinot Gris, Riesling, Cabernet Sauvignon	*Hewer & Gough, 2019*
Nova Scotia			Chardonnay, Pinot Noir, L'Acadie Blanc, Riesling	*Robicheau et al., 2018; Lewis, n.d.; Messiga et al., 2015*
British Columbia			Cabernet Sauvignon, Chardonnay, Pinot Noir, Sauvignon Blanc	*Beech & Hewer, 2021*
Quebec			Sainte-Croix, Vandal Cliché, Marechal Foch, Frontenac	*Outreville, 2010*

Table 1: Common Wine Grape Varietals By Province.

1.2.2 Canadian Ice Wine

Canada is one of the largest producers of ice wine globally (Cliff et al., 2001). Ice wine is a sweet wine typically categorized as a dessert wine because of its sugar levels (Musabelliu, 2013). It has its supposed beginnings in ancient Rome, but other accounts have placed Germany as the birthplace (Musabelliu, 2013). The two provinces associated with Canadian ice wine production are Ontario, the largest producer, and British Columbia (Cliff et al., 2001: Ierfino-Blachford, 2020). However, most Canadian wine regions can produce ice wine (Pickering, 2006). Ice wine production requires freezing temperatures beginning in late fall and early winter (Cliff et al., 2001: Ierfino-Blachford, 2020). The varietals of Vidal and Riesling are commonly used in ice wine production as thicker skins help better protect grapes from freezing temperatures (Cliff et al., 2001). Harvest typically occurs in Ontario between December and January, while British Columbia typically begins in November (Pickering, 2006).

The uniqueness of ice wine lies in the characteristics of the grapes and the production. Harvesting grapes at or below -8°C maintains water crystallization within the grapes, resulting in a wine that is higher in sugar concentration and acidity (Pickering, 2006; Cliff et al., 2001). Optimal temperatures for icewine production lie between -10°C and -12°C (Shaw & Cyr, 2010). Canada is ideal for icewine production as the warm summers allow grapes to ripen, and the freezing winters crystallize the water within the grapes allowing for the appropriate sugar ratios needed (Simone et al., 2015; Shaw & Cyr, 2010).

As the name suggests, ice wine needs extremely cold conditions. Given the likely warming trend because of changing climate, already limited ice wine production areas may become smaller. Warmer winter climates may push ice wine harvest closer to the first months of the new year and increase the risk of lowering quality or ability to harvest due to storms, frost damage, or failure to maintain a temperature below -8 °C (Byres et al., 2015). As one of the few wines producing nations with ice wine production, alterations in the growing climate may threaten future production ability.

1.2.3 Ontario

Ontario wine production primarily exists within three primary appellations, 1) Niagara Peninsula, 2) Prince Edward County, and 3) Lake Erie North Shore/Pelee Island (Shaw, 2016) (**Figure 1**). Most wineries sit between 41° and 44° North (VQA Ontario, 2022). Amongst all the wine regions in Canada, the regions of Ontario account for the most significant production of wine (Rimerman, 2017). There are roughly 180 wineries within the province, totalling almost 7,000 hectares (Hewer & Gough, 2020; Phillips, 2017). Ontario's size and proximity to Lake Ontario and Lake Erie provide suitable growing areas for cool-climate wines with various soil types, meso-climates, and topographies (Shaw, 2016). Common varietals found in Ontario are primarily European varietals, including Chardonnay, Riesling, and Pinot Noir (Hewer & Gough, 2019).

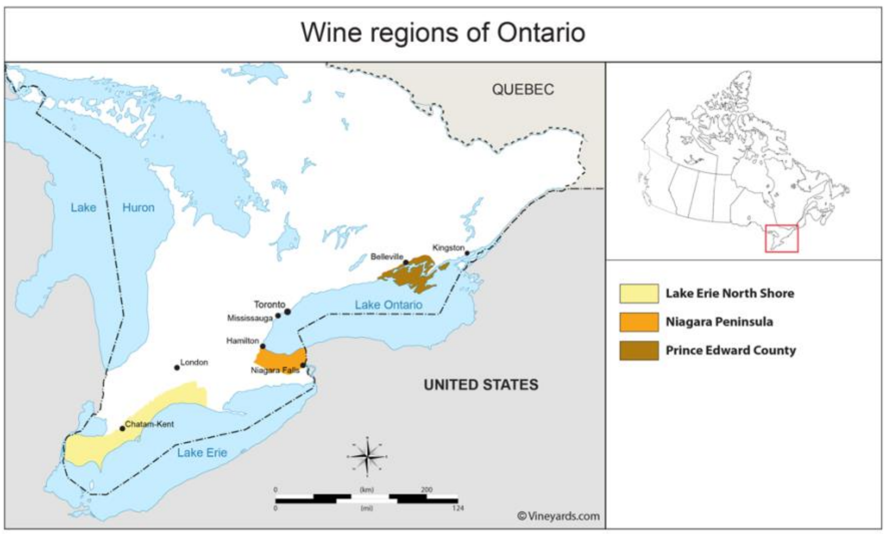


Figure 1*:* Wine Growing Regions of Ontario

Source: ("Wine Map of Canada", n.d.)

Wine growing in Ontario traditionally has been limited by both climate and geography. The cold, harsh winters of southern Ontario made it extremely difficult to grow grape varietals that require longer, warmer growing seasons (Phillips, 2017). Furthermore, the domination of the Canadian Shield and boreal forests provide a geographical limit to wine growing provincially (Phillips, 2017). The three wine-growing regions are all located along large lakes, with Niagara and Prince Edward County adjacent to Lake Ontario and Lake Erie North Shore/Pelee taking the name of the lake it sits beside (Phillips, 2017). These large bodies of water help provide ideal growing climates (**Table 2)** as they regulate temperature, providing cool breezes over vineyards in the summers and a heating effect in the winter (Phillips, 2017).

Growing Area	Temperature Range	Yearly Precipitation Sum	Frost Free Period	Growing Degree Days (Above 10°C)
Niagara Peninsula	-4.1°C – 22.2°C	947.5mm	165 Days	1590
Prince Edward County	-.6°C – 20.6°C	948mm	158 Days	1303.1
Lake Erie North Shore	-3°C – 23.2°C	906mm	155 Days	1649.4

Table 2: Ontario Wine Growing Regions Generalized Climate (Environment Canada 2023; Farmer's Almanac, 2023)

Lake Ontario and Lake Erie are critical in helping to provide ideal growing conditions as they help to moderate the climate, given the variability of Ontario's weather (Phillips, 2017). The water bodies help to moderate both temperature and precipitation (Phillips, 2017). Given these lakes' sheer size and depth, they do not freeze over entirely in the winter; thus, the water tends to be warmer than the surrounding environment. The warmer winter air coming off these lakes helps to protect vineyards from winter frost. In the summer, the colder water helps to cool the overlying air masses and, in turn, provides a cooler climate within the viticultural regions (Shaw, 2016**).** The lakes' moderating services reduce vine stress and help to ensure a successful yearly harvest (Shaw, 2016). The temperature range across these three regions is large as Ontario can experience sustained winter temperatures below -20°C and sustained summer temperatures above 30°C. Precipitation very much follows similar trends, with some years having higher or lower rates of precipitation when compared to climate averages (Shaw, 2016). General growing seasons, sometimes described as the period between the last and first frost, also vary, with Lake Erie North Shore having the shortest and the Niagara Peninsula the longest.

1.2.4 British Columbia

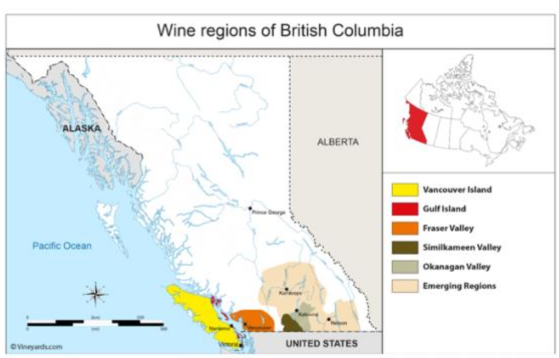


Figure 2: Wine Growing Regions of British Columbia

Source: ("Wine Map of Canada", n.d.)

British Columbia is the second largest Canadian wine producer after Ontario (Hewer & Gough, 2021). Five wine appellations exist within the province (**Figure 2**) 1) Vancouver Island, 2) the Gulf Islands, 3) Similkameen Valley, 4) Okanagan, and 5) Fraser Valley ("Wines of British", 2017). Much of the production remains above the latitude of 49°, like other global wine regions like Champagne in France or Germany ("Wines of British", 2017). There is an estimated 4,130 hectares of vineyards within the province ("Wines of British", 2017). The bulk of the wine production within British Columbia is from the Okanagan Valley (Cartier, 2014). The wine regions of BC are highly variable due to the province's location and topography. British Columbia is alongside the Pacific Ocean. As a result of location, air masses full of moisture undergo orographic lifting by the Rockies, and cool, dry air falls on the leeward side over wine regions like the Okanagan and Fraser Valley ("Wines of British", 2017). This phenomenon has created various wine-producing regions with different climates (**Table 3**), some characterized by relatively dry, almost desert-like conditions, while others with high yearly precipitation rates.

Growing Area	Temperature Range	Yearly Precipitation Sum	Frost Free Period	Growing Degree Days (Above 10°C)
Vancouver Island	3.1°C – 17.4°C	1163.5mm	206 Days	805
Gulf Islands	4.1°C – 17.2°C	1528mm	140 Days	823
Fraser Valley	3.3°C – 18.8°C	1667.5mm	207 Days	1127.1
Okanagan Valley	-2.3°C – 20.4°C	414mm	201 Days	1191.5
Similkameen Valley	-5°C – 17.9°C	346.9mm	116 Days	838.9

Table 3: British Columbia Wine Growing Regions Generalized Climate (Environment Canada, 2023; Farmer's Almanac, 2023)

Like other provinces in Canada, British Columbia has a growing season sandwiched between cold winters, with the season starting in April and ending in October. Regions within the mountains, including the Okanagan and Similkameen Valleys, can experience deep freezing events that can reach as low as -25°C (Rayne & Forest, 2016, as cited in Hewer & Gough, 2021). Diurnal temperature swings are common, sometimes changing 30°C within a day ("Wines of British," 2017). The varietals grown reflect the conditions. The typical wine grape varietals found in British Columbia include Chardonnay, Muller-Thurgau, Gruner Veltliner, Pinot Noir, and Merlot, to name a few. Varieties, such as those listed, can succeed in shorter growing seasons with highly variable climate conditions (Beech & Hewer, 2021).

1.2.5 Quebec

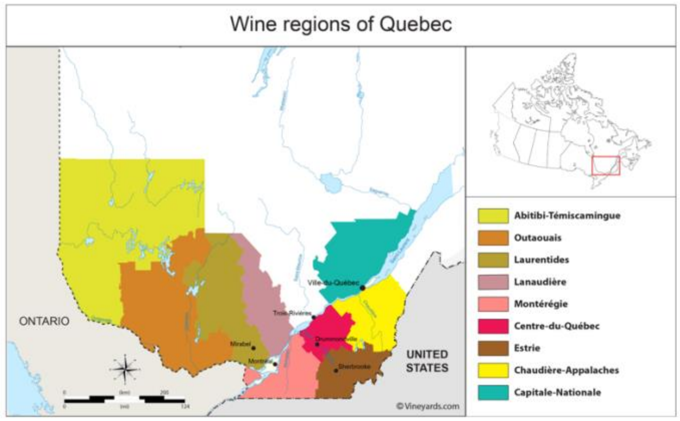


Figure 3: Wine Growing Regions of Quebec
Source: ("Wine Map of Canada", n.d.)

Quebec wine tradition stretches back centuries (Outreville, 2010). With roughly fifty wineries in-province, Quebec is Canada's third largest wine producer (Outreville, 2010). The Quebec wine industry supposedly began south of the St. Lawrence River (Outreville, 2010). While having a rich tradition in wine, the commercial Quebec wine industry is only about 40 years old, as the first licenses to sell were only granted in early 1985 (Outreville, 2010). The 150 wineries produce many varietals not generally grown in the rest of Canada, including several *Vitis labrusca* varietals such as Marechal Foch, Sainte-Croix, and Seyval Blanc (Lord-Tarte, 2012). Most of the wine production within the province comes from 3 places, 1) Montérégie, 2) the Eastern Townships, and 3) the Capitale-Nationale (Lord-Tarte, 2012). The remaining wine comes from regions such as Lanaudière, Centre-du-Quebec, Outaouais, and Bas-Saint-Laurent (**Figure 3**) (Lord-Tarte, 2012).

Growing Area	Temperature Range	Yearly Precipitation Sum	Frost Free Period	Growing Degree Days (Above 10°C)
Montérégie	-9.7°C – 21.2°C	1000.3mm	165 Days	1260
Eastern Townships	-10.9°C – 19.6°C	1087.8mm	115 Days	1047
Capitale-Nationale	-12.8°C – 19.3°C	1189.7mm	145 Days	896.7
Lanaudière	-11.6°C – 20.9°C	1119.3mm	144 Days	1175

Centre-du-Quebec	-10.2°C – 20.9°C	1113.5mm	152 Days	1214.8
Outaouais	-12.6°C – 19.3°C	939.9mm	118 Days	988.8
Abititi-Temiscamingue	-16.1°C – 17.3°C	975.9mm	76 Days	723.3
Laurentides	-11.5°C – 19.8°C	1076.7mm	144 Days	1062.4
Bas-Saint-Laurent	-11.8°C - 19°C	1140.7mm	132 Days	899.5

Table 4: Quebec Wine Growing Regions Generalized Climate (Environment Canada, 2023; Farmers Almanac, 2023)

Most wineries in Quebec remain small in production, mainly due to most wine regions lying just north of 45°N (Jones, 2012b). While other wine-growing provinces have more northerly wine production areas, like in the case of British Columbia, Quebec lacks large water bodies to help regulate temperatures within the appellations (Jones, 2012b). Quebec winters are particularly problematic as there is little in the way of protecting vines from freeze damage (Jones, 2012b). Growing seasons in Quebec can be shorter than in other viticultural provinces, sometimes starting in early May and ending in September (Jones, 2012b). Frigid winters and late-onset frost remain a challenge for the cultivation of wine grapes in Quebec (Jones, 2012b).

1.2.6 Nova Scotia

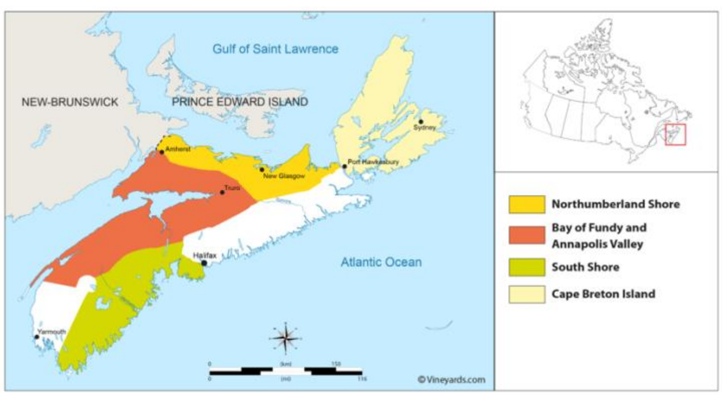


Figure 4: Wine Growing Regions of Nova Scotia

Source: (“Wine Map of Canada”, n.d.)

Nova Scotia is the smallest wine region in Canada. There are four primary growing areas within Nova Scotia, 1) Northumberland Shore, 2) Annapolis Valley, 3) South Shore, and 4) Cape

Breton Island (**Figure 4**). Much like the three other wine-producing provinces, the history of grape cultivation and, ultimately, wine production is traced back to the early colonizers of the province. As the story goes, French colonizer, Louis Hebert planted the first vines in Bear River ("The Rich History," 2021). The first wine production facilities started to pop up in the 1980s, but it took almost two decades for wine production to become commercially viable as new vines needed time mature and fruit ("The Rich History," 2021). The most famous wine-growing region in Nova Scotia is the Annapolis Valley, where wine producers have won national awards for vintages. Both native and imported grape varietals are found within this province. Common white varietals include L'Acadie Blanc, and Seyval Blanc, while common red varietals found include Marechal Foch and Leon Millot ("Nova Scotia," 2022).

Growing Area	Temperature Range	Yearly Precipitation Sum	Frost Free Period	Growing Degree Days (Above 10°C)
Annapolis Valley	-6.9°C – 18.4°C	1183.1mm	125 Days	861.5
Northumberland Shore	-6.2°C – 19.3°C	1232.2mm	149 Days	889
South Shore	-5.2°C - 19°C	1535.7mm	119 Days	978.8
Cape Breton Island	-5.4°C – 17.9°C	1517.2mm	149 Days	781.7

Table 5: Nova Scotia Wine Growing Regions Generalized Climate (Environment Canada, 2023; Farmer's Almanac, 2023)

The uniqueness of Nova Scotia's wine region lies in the province's geography. A peninsula protruding into the Atlantic Ocean, most vineyards within the province are rarely further than 20km from the Ocean ("Nova Scotia," 2022). The Atlantic Ocean hugely influences the province's seasonality and climate (**Table 5**) ("Nova Scotia," 2022). The Ocean helps to moderate temperatures, especially in the summer, and to cool the nights ("Our Region," n.d.). The province's proximity to the Ocean contributes to the high yearly precipitation and substantial temperature swings creating such risk for frost in the spring and early summer months (Wright & Franklin, 2022).

1.3 Climate Change & the Canadian Wine Industry

According to the latest 2023 Climate Change Report from the Intergovernmental Panel on Climate Change (IPCC), global surface temperature increase is occurring at the highest rate within the last 2000 years (IPCC, 2023). Since the late 1800s, global temperatures have risen about 1.1°C (NASA, n.d.ab). According to the 2022 Global Climate Report released by the National Oceanic and Atmospheric Association (NOAA), average global temperatures between 2014 and 2022 saw year-over-year increases ("NOAA", 2022; "NOAA", 2023). A study by Jones & Schultz (2016) found that average temperatures were rising within cool climate regions, and average temperatures were rising .17°C per decade. With viticulture so tied to temperature, shifts in temperature can also lead to shifts in growing regions (Mozell & Thach, 2014). Current temperature trends have increased warming in the northern latitudes, in and around nations like Canada (Mozell & Thach, 2014).

Like temperature, precipitation patterns are moving toward the poles (Mozell & Thach, 2014). Countries in the northern latitudes, like Canada, are becoming wetter, while sub-tropical and tropical nations are experiencing drier conditions (Trenberth et al., 2007). Concurrently, higher temperatures increase the moisture retention of air masses, increasing rates of surface water evaporation (Trenberth, 2011). The drought-like conditions by high rates of evaporation are especially problematic in the event of extreme rainfall (Trenberth, 2011). Above-average rainfall in hard, dry soil may cause flash flooding as water cannot percolate as quickly into the soil.

Climate changes are problematic as grapes are susceptible (Jones et al., 2022). Alongside some risk, climate change may benefit the Canadian wine industry. Higher temperatures have caused a shift northward of ideal viticultural climates, and the wine-growing regions of Canada may experience bud bursts earlier in the season as spring temperatures arrive earlier (Comte et al., 2023; Fraga et al., 2013). Longer growing seasons with more extended frost-free periods would allow wine producers to cultivate varietals that do not need to be as cold-resistant as the varietals currently grown (Jobin-Poirier et al., 2019). Varietals typically associated with warmer regions, such as Cabernet Sauvignon or Grenache, may have some potential here in Canada as growing climates become more suitable (Schultze & Sabbatini, 2019).

Chapter 2: Literature Review

2.1 *Introduction*

Sourcing academic literature highlighting the interconnections of climate change and Canadian viticulture was challenging. The lack of academic sources directly reflects the relative newness of the commercialization of Canadian wine. This section will review the connections between climate change and viticulture found in academic sources. Sources focusing on climate change in the Canadian viticultural context will be of principal concern. However, relevant discussion topics within the international wine industry will also be considered.

Online search engines like google scholar and digital libraries like JSTOR were used to search for relevant articles and scholarly publications. Queries within journals such as, but not limited to, the *Journal of Wine Research* and the *International Journal of Wine Research* yielded some essential articles. All journals were considered in the search for sources. A general Google search using terms including but not limited to "climate change AND Canadian viticulture" or "impacts of climate change on Canadian wine industry" were used to broaden the search. In addition, growing provinces like Ontario and British Columbia have organizations such as the *Ontario Wine Council* or the *BC Wine Institute* that help promote the wine industry province-wide through the facilitation and dissemination of knowledge and information (Doloreux & Frigon, 2019). Publications from relevant provincial and private organizations helped to supplement research from academic resources.

2.2 Cool Climate Viticulture

Across the global viticultural regions, the ideal temperature range for wine production is between 12°C and 22°C (Jones & Schultz, 2016). Temperatures for cool-climate wine are generally accepted to be between 13°C -15°C (Schultze & Sabbatini, 2019; Jones & Schultz, 2016). Wine-growing regions within these cool-climatic zones tend to occupy the higher latitudes, with examples including Canada, Germany, and Switzerland (Jones & Schultz, 2016). The wine varietals of cool-climate zones reflect the short growing season, typically less than seven months, and include Riesling, Gewurztraminer, and Pinot Noir (Jones & Schultz, 2016). Generally, white varietals do better in cool climates than reds due to the growing season length needed for reds to develop and mature (Schultze & Sabbatini, 2019).

With short growing seasons and long winters, site selection is important in wine production in cold climates (Kemp et al., 2019). With such a short growing season, it is in the best interest of winemakers to select locations that will ensure successful growth and can be found in areas with bodies of water helping to moderate temperatures or south-facing slopes (Phillips, 2017; Kemp et al., 2019). Furthermore, adequate sites can help protect from the problematic late-onset frost typical of cool climate regions (Ryan, 2019; Schultze & Sabbatini, 2019). With the many limiting factors of cool-climate production, winemakers must adequately assess the conditions of the many microclimates they may operate in and choose grape varietals accordingly (Kemp et al., 2019).

Within cool-climate regions, warm and sunny summers benefit grape production, but the extreme cold of winter can threaten future harvests (Han et al., 2021; Kemp et al., 2019). To help ensure harvest success, winemakers within cool-climate regions can use several strategies to prevent vine damage through the winter. First and foremost, winter damage prevention can be done through adequate site selection (Kemp et al., 2019). From a physical measure, many wine producers will attempt to cover trimmed-back grapevine trunks with soil, straw, geotextile blankets, or even snow (Svyantek et al., 2020). To mitigate against late-onset frost in the spring, some wineries have begun to use an innovative fan to help draw back down rising warm air while others remain traditional and light a series of torches amongst the vines (Phillips, 2017).

2.3 Temperature, Precipitation & Phenology

A phrase found frequently in literature was, "Wine is grown, not made (Nicholas, 2015)." This phrase refers to the belief in the industry that the quality of grapes determines the quality of wine, and the actual production and fermentation of wine does little to influence quality or profile (Nicholas. 2015). The concept of "terroir" is closely associated with this belief. Terroir refers to land containing a series of biotic and abiotic interactions (i.e., soil, topography, temperature, precipitation, biodiversity), in which these interactions lend themselves to the development of inherent characteristics in the resulting viticultural harvest (Droulia & Charalampopoulos, 2022; Malheiro et al., 2010; Mayer, 2013; Sgubin et al., 2022).

Growing conditions must meet precise thresholds for viticultural success. The most critical climactic variables to the development of a high-quality terroir are temperature and precipitation (Hannah et al., 2013; Droulia & Charalampopoulos, 2022; Verdugo-Vasquez et al., 2015; Reis et al., 2021). Climatic terroirs vary globally, with wines from different regions characteristically reflecting the conditions in which they were grown. With changing temperature and precipitation patterns occurring within viticultural regions, the alteration of wine grape phenology is of primary concern. Grape phenology is a term that concerns itself with the lifecycle of the grapevine in response to climactic fluctuations (Malheiro et al., 2013; Biasi et al., 2019; Winkler et al., 1975). Vegetative and reproductive developmental cycles are the two primary cycles within grape phenology (Giese, 2020). Wine grape phenology generally lasts two years, with new vine growth remaining in a vegetative state in year one and fruiting in the second year (Giese, 2020). In the second year of phenology, vines will typically go through four stages, 1) bud burst, 2) flowering, 3) veraison, and 4) maturity (Cameron et al., 2022; Teslić, 2018). The movement from one stage to another varies seasonally, with temperature being the primary driving force (Cameron et al., 2022).

Prior to the bud burst, grapes remain in a state of dormancy (Campbell, 2019). As days shorten and the winter chill comes along at the end of October or early December, consistent freezing temperatures result in the high production of abscisic acid (Campbell, 2019). High concentrations of abscisic acids in grapes suppress growth, sugars become starches, and leaves fall (Campbell, 2019; eVineyard, 2018). The water within the vines binds to the sugars and proteins, creating a cryoprotective layer that will protect the cells from extreme freezing temperatures (eVineyard, 2018). The interactions of these internal processes cause vines to enter a deep dormant state known as the endo-dormant phase (Campbell, 2019; Trefethen Vineyards, 2020). Different grape varietals require different temperatures to enter the dormant phase (Campbell, 2019). Vines must spend a certain amount of time in a state of dormancy and the length of the dormant period will vary depending on the grape varietal (eVineyard, 2018). Below-freezing temperatures are not required for vines to remain dormant but lower temperatures will, however, help improve the vines' hardiness to cold (eVineyard, 2018).

Following the endo-dormancy phase, the vines will enter eco-dormancy (eVineyard, 2018; Campbell, 2019). The transition from the endo-dormancy phase to the eco-dormancy phase occurs when dormancy requirements are met (Campbell, 2019). In the eco-dormant stage, unfavourable climactic variables like cold temperatures and shorter day lengths keep vines from budding (eVineyard, 2018). The onset of warmer springtime temperatures and longer days helps to induce the grapes out of their cold-induced dormant period (Schultze & Sabbatini, 2019). Budburst occurs when spring temperatures remain consistently above 10°C, with other factors like sunlight and growth hormones also thought to have a role (Malheiro et al., 2013; Verdugo-Vasquez et al., 2015). In the bud burst phase, the energy stores help form new buds that swell, and new shoots will become new leaves (Trefethen Vineyards, 2020; Teslić, 2018). In the northern hemisphere, bud burst typically occurs between late February to April, depending on the region (Teslić, 2018). In comparison, bud bursts in the southern hemisphere occur between August and October (Teslić, 2018).

Studies have shown that grapevines will begin flowering upon prolonged exposure to ideal temperatures and levels of solar radiation (Vasconcelos et al., 2009; Buttrose, 1969, as cited in Teslić, 2018). Tell-tale morphological features of the flowering stage on vines are the inflorescence clusters (Teslić, 2018). The flowering stage will continue onto the veraison and maturity stages throughout the summer, where the fruit will develop and ripen on the vine until it is ready to harvest (Trefethen Vineyards, 2020). Following harvest, the cycle will repeat as a growing season ends and winter approaches.

2.4 Climate Alteration & Phenological Impacts

Growing seasons for cool climate viticulture, like that in Canada, should range from April to October, with average ideal temperatures sitting between 13° and 15° Celsius (Schultze & Sabbatini, 2019; Holland & Smit, 2013; Hewer & Brunette, 2020; Jones & Schultz, 2016). This temperature range varies slightly between articles, with others suggesting a more appropriate range of 12° to 22° Celsius (Jones & Schultz, 2016). There must also be enough precipitation to help facilitate grape development at the start of the growing season (Droulia & Charalampopoulos, 2022; Hewer & Brunette, 2020; Jobin-Poirier et al., 2019). Enough rain must be present to prevent desiccation of newly formed buds from high temperatures; inversely, too much rain may result in fungal growth and pest introduction at the beginning of the growth season (Jobin-Poirier et al., 2019; Fraga et al., 2013). Throughout most of the literature cited, many authors emphasized the importance of ranges. Regionally, temperature and precipitation regimes varied. Some years were warmer or wetter than others, and some were colder and drier, but these values still fell within a normal range of climactic values for the specific region (Malheiro et al., 2013; Jones et al., 2005; Dinu et al., 2021; Jones & Davis, 2000).

With warming temperatures globally, phenology is shifting (Jones et al., 2022). Several European studies have found earlier phenological cycles. In Alsace, Duchene & Schneider (2005, as cited in Ryan, 2019) found bud burst and flowering occurred 15 days earlier in 2003 than in 1965. The phenological shift between 1965 and 2003 is due to a significant temperature increase (Duchene & Schneider, 2005, as cited in Ryan, 2019). Duchene & Schneider (2005, as cited in Ryan, 2019) found a temperature increase of almost 2°C in the 30 years between 1965 and 2003. Similar patterns are occurring in other French regions, like Bordeaux (Jones & Davis, 2000, as cited in Holland & Smit, 2013). In Bordeaux, between 1952 and 1997, harvest occurred 13 days earlier (Jones & Davis, 2000). Given the linkage of phenology and climate established by Jones & Davis (2000), a greater frequency of warmer days can lead to shorter interval periods between bud burst and harvesting. Given the prevalence of studies indicating shifts in phenological cycles amongst European viticulture linked to shifting temperatures, it is only reasonable that shifting temperatures may also alter the phenological cycles of Canadian grown grapes.

Changing climate also will influence precipitation patterns. Viticulturally, rainfall at the beginning of the wine season is ideal as it aids in bud development and bud burst (Jobin-Poirier et al., 2019; Fraga et al., 2013). However, sustained rainfall late in the growing season can alter the quality of the final wine and increase the risk of disease (Jones & Davis, 2000). A Holland and Smit (2013) study assessed climactic change in the Ontario growing region of Prince Edward County between 1987 and 2011. They found that in the study period defined, there was an increasing trend of precipitation, especially in the summer months. Dry summers are preferable, as mentioned prior, and wine growers expressed this sentiment in the region (Holland & Smit, 2013). The increasing rainfall trend could prove problematic as increased rainfall, particularly later in the growing season, is attributed to pest introduction and poor grape quality (Jones & Davis, 2000).

2.5 Climate Alteration and Wine Quality Alteration

The global wine industry relies heavily on quality indicators to sell wine. Moreover, wine regions are associated with certain wine qualities, colours, and characteristics. These qualities are so important to wine producers that the development and implementation of appellation of origin labels restrict how and where certain wines can be made, what claims producers can publicly make about production, and even the words used on the bottle label. The most common example is the use of the name *Champagne* or the *Denominazione di Origine Controllata e Garantita (DOCG)* label found on Italian wine bottles. Canada has similar programs implemented provincially, but they have no legal backing.

Climate alteration within wine regions impacts phenological timing and the wine's physical characteristics. Climatic variables, such as temperature, help give the wine its inherent characteristics. Characteristics of wine include flavour, acidity, sugar level, and colour, amongst others (Nicholas, 2015). The change in any of these characteristics not only changes the wine but also changes commercial viability. Of high importance are acidity and sugar levels (Nicholas, 2015). Wine producers often use sugar and acidity levels to indicate grape ripeness and when to harvest for optimal results (Gambetta & Kurtural, 2021).

Discussed in several papers is the potential for wine colour to change. The biosynthesis of the pigment responsible for wine coloration, anthocyanin, relies on temperature and light exposure (Mori et al., 2007; Gambetta & Kurtural, 2021). However, higher temperatures are enough to cause a decrease in the production of this pigment, whereas low-temperature increase production (Mori et al., 2007). For red wine, this may mean rich red wines may become lighter in a higher temperature climate (Mori et al., 2007).

Depending on the region, increasing temperatures may allow Canadian wine producers to harvest grapes at a preferred time. A paper by Gambetta & Kurtural (2021) demonstrated that increasing temperatures within the Napa and Bordeaux wine-growing regions enabled wine producers to leave grapes on the vine if the fruit was not ripe enough. In wine-producing nations like Canada, short growing seasons limit the ability of winemakers to leave the grapes on the vine. The longer fruits are left on the vine later in the growing season, the higher the risk for damage or poor harvests from cold temperatures or frost (Byres et al., 2015). As observed in Napa and Bordeaux, longer growing seasons may ripen grapes at an increased rate and afford producers more time when deciding harvest dates (Gambetta & Kurtural, 2021).

2.6 Growing Degree Days

Within the wine industry, growing degree days is a real buzzword. In many cases, the suitability of a region for grape cultivation is measured in growing degree days. Growing degree days (GDD) describe the accumulation of near-surface heat throughout a growing season (“Growing Degree,” n.d.). The base temperature threshold for GDD is 10°C (“Growing Degree”, n.d.). GDD is calculated using the formula:

$$GDD = \frac{(T_{Cutoff} + T_{Min})}{2} - T_{base}$$

Source: (Fraisse & Paula-Moraes, 2018)

GDD was developed by French scientist Rene A. F. de Réaumur in the late 1790s (Fraisse & Paula-Moraes, 2018). The GDD concept is used frequently across many agricultural sectors. Similarly, wine producers use GDD to estimate what grapes are suitable across different landscapes of varying climates (Fraisse & Paula-Moraes, 2018). According to Winker et al. (1975), a GDD value of 1390 and above provides for the most suitable grape growing conditions ("Growing Degree, n.d.). In a Canadian context, an alteration in climate favouring increasing temperatures can further open the Canadian wine industry to new varietal imports.

2.7 Late Onset Frost

Wine production in Canada typically occurs in the frost-free period between the last frost in spring and the first frost of fall (Shaw, 2016). Frost is a common phenomenon known by wine producers. A paper by Shaw (2016) evaluated various climate variables, including frost. Between 1970 and 2015 alone, all three wine-growing areas in Ontario, Prince Edward County, Niagara Peninsula, and Lake Erie North Shore, experienced at least one frost event each year (Shaw, 2016). March, April, and May in Canada can be particularly unforgiving as a sustained period of warm temperatures can be followed by a deep freeze. Deep freeze can cause winterkill (Shaw, 2016). Once vines leave the endo-dormancy phase, they cannot adapt to sudden cold temperatures (Shaw, 2016; Comte et al., 2023). Some wine regions can have large portions of the upcoming year's harvest lost entirely due to frost (Shaw, 2016).

There are two kinds of frost, radiative and advective (Shaw, 2016; Willwerth, 2014). Radiative frosts occur when longwave radiation can escape from the land surface layer, allowing for a drop in near-surface temperature (Willwerth, 2016). The second, advective frost, occurs when a colder and denser airmass pushes warm air up, creating near-surface temperatures conducive to frost development (Willwerth, 2014; Shaw, 2016). When the water within vines' cellular and intra-cellular spaces freezes, it can damage tissue, hamper wine quality, or even cause vine loss (Willwerth, 2014). Some methods used to try and combat frosts include large fans blowing warm air onto the vines or even contained fires being lit throughout vineyards to heat the surrounding air (Bongiorno, 2023).

2.8 New Opportunities for Canadian Wine

Shifts in climate may be beneficial for Canadian viticulture as the lengthening of growing seasons may allow for the introduction of new varietals that require longer growing seasons and extended periods of frost-free days (Jones & Shultz, 2020; Jobin-Poirier et al., 2019). Moreover, aside from new varietals, Shaw (1999) found that Canadian winemakers continue to establish themselves in regions outside the traditional wine-growing areas. Establishing wine-growing regions can be found alongside the shores of Lake Huron in Ontario and new areas within the Okanagan in British Columbia.

Currently, roughly 70% of global wine production comes from the European continent (Cardell et al., 2019; Santos et al., 2020; Fraga et al., 2013). Unsurprisingly, the top three global producers of wine are Italy, Spain, and France (Santos et al., 2020). According to Cardell et al. (2019), European wine regions are expected to experience temperatures higher than acceptable thresholds for some traditional varietals under several climate scenarios. Higher temperatures can reduce the quality of European wines produced, but also production as higher temperatures stress vines (Cardell et al., 2019). The patterns identified by Cardell et al. (2019) also follow patterns established in papers like Hannah et al. (2013, as cited in Sgubin et al., 2022; Ryan, 2019) and Sgubin et al. (2022). Hannah et al. (2013, as cited in Sgubin et al., 2022; Ryan, 2019) performed a climate suitability analysis across Europe and applied two Representative Concentration Pathways (RCPs), 4.5 and 8.5. In both concentration pathways, viticultural areas decreased between 25% - 73% in RCP8.5 and 19% - 62% in RCP4.5 (Hannah et al., 2013, as cited in Sgubin et al., 2022; Ryan, 2019). Sgubin et al. (2022) showed similar patterns but not as extreme as those demonstrated by Hannah et al. (2013). In Sgubin et al. (2022), in a suitability analysis utilizing General Circulation Models (GCMs) comparing the historical baseline (1980-2009) to RCP4.5 and RCP8.5, it was found that suitability was lost at a more gradual rate. With RCP4.5 by the mid-century, most suitable areas remain, gradually shifting northward by the end of the century (Sgubin et al., 2022). Similarly, with RCP8.5, Sgubin et al. (2022) found that almost 90% of suitable wine regions would exist in the central regions of Europe like Germany or Austria, and traditional wine-growing areas like central and southern Italy would prove unsuitable by the end of the century. Sgubin et al. (2022) suspect that suitable European wine-growing regions by the end of the century will firmly be encased between the latitudes of 44°N and 56°N with many of the traditional wine producers like Italy, Spain, and parts of France now unsuitable for wine production. With traditional wine-growing regions slowly becoming more unsuitable, the long-term outlook for Canadian wine is promising. Increasing capacity for Canadian wine production may allow for the opportunity to fill market gaps as traditional European terroirs lose viticultural capabilities due to altering growing climates.

2.9 Research Gaps & Shortcomings

A research piece by Doloreux & Frigon (2019) addressed some of the reasons behind the supposed gap in research within the Canadian wine industry. Through exploring "innovation modes," loosely defined as how wine-related firms develop new approaches, Doloreux & Frigon (2019) determine that innovation development within Canadian wine firms varies highly. Capacities for developing new research and innovation depend on each province's industry size and institutional structure (Doloreux & Frigon, 2019). Ontario and British Columbia contain most wine-related firms within Canada (Doloreux & Frigon, 2019). These two provinces also are home to two university-affiliated research centres, the *Wine Research Centre* at the University of British Columbia and the *Cool Climate Oenology and Viticultural Institute* at Brock University. It also happens that Ontario and British Columbia are the two most significant wine producers in Canada. The complexities associated with innovative development require ongoing interactions between actors of different expertise, with some provinces having more capacity for these interactions than others (Doloreux & Frigon, 2019).

Chapter 3: Study Area & Materials

3.1 Study Areas

This climatic assessment will focus on the four central wine-growing provinces across Canada. The four provinces (**Figures 5-8**), Ontario, British Columbia, Quebec, and Nova Scotia, will have their wine-growing appellations assessed for near-surface temperature (NST) and precipitation trends to understand future near-surface temperature and precipitation conditions. Understanding what future scenarios could help understand if the Canadian wine industry has the potential to grow in new ways.

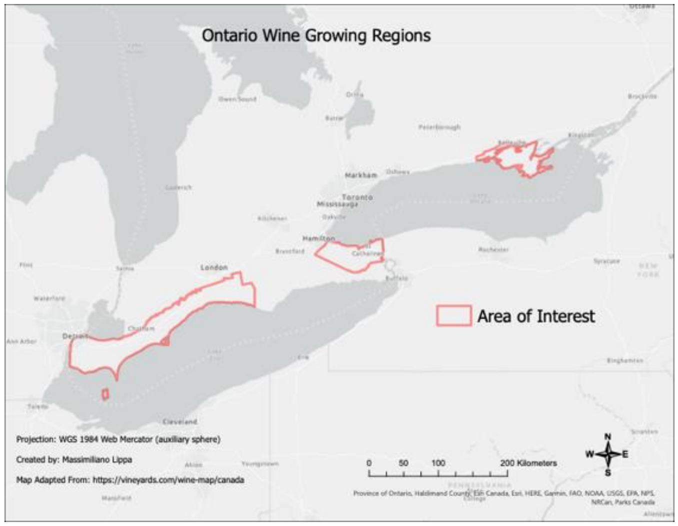


Figure 5: Areas of Interest Within Ontario

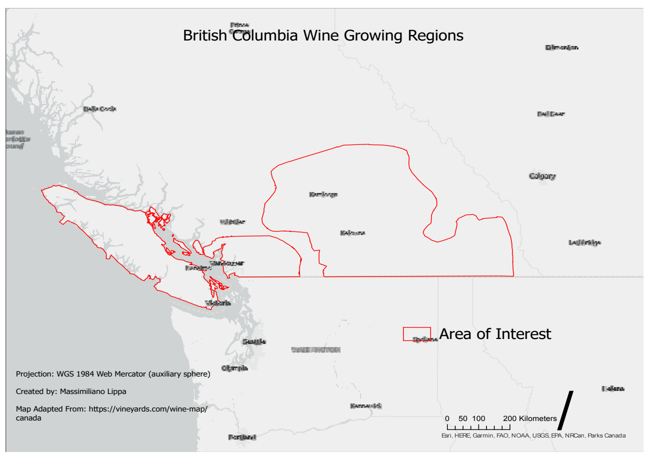


Figure 6: Areas of Interest Within British Columbia

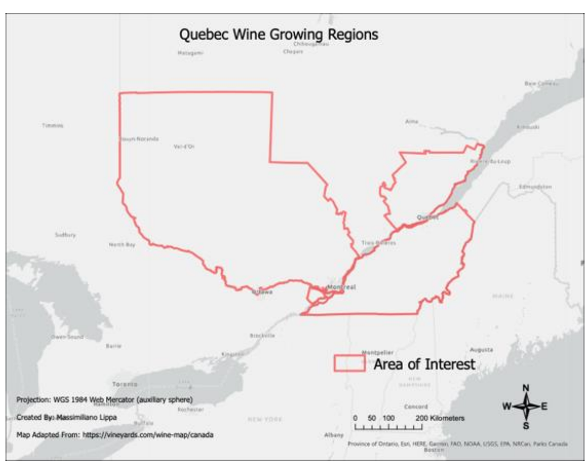


Figure 7: Primary Wine Growing Regions of Quebec

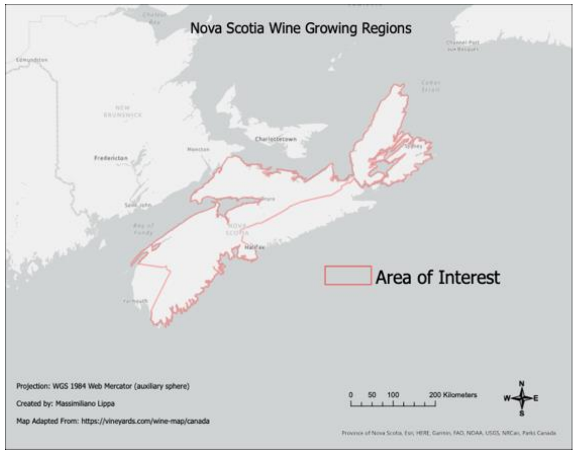


Figure 8: Primary Wine Growing Regions of Nova Scotia

3.2 Materials

3.2.1 Wine Region Boundaries Files

To begin analyzing our regions of interest, boundaries needed to be defined. Parsing through various open-source databases, Ontario was the only wine-growing province with government provided shapefiles of the smaller individual wine-growing regions. For Quebec, British Columbia, and Nova Scotia, maps were modified from *Vineyards.com* and uploaded into ArcGIS Pro. Maps from this website proved helpful because wine-growing areas within each province were well-defined and current. Utilizing the georeferencing tool, the maps, in the form of raster layers, were assigned a spatial reference of WGS1984 (World Geodetic System 1984). This spatial reference was chosen as it was the default needed to upload the completed layer files to *Google Earth Engine*. Once the digital map file was overlaid and aligned with our base map, polygons were created to border the wine-growing areas of interest with the *Create Polygon Features*, specifically with the tracing function. Once polygons were created, they were converted into shapefiles and exported into Earth Engine.

3.2.2 Google Earth Engine

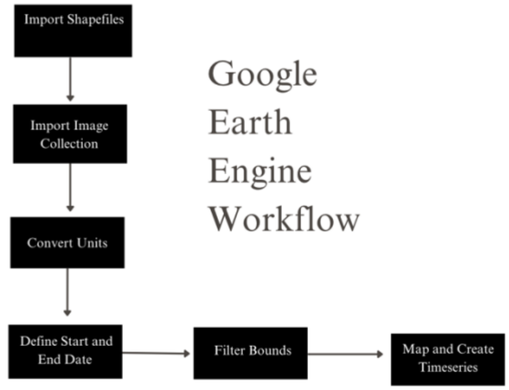


Figure 9: Workflow of *Google Earth Engine*

Near-surface temperature and precipitation data could be filtered within specified boundaries with the boundary layers imported from *ArcGIS Pro*. This research used *Google Earth Engine* (GEE) to help visualize the variation in NST and precipitation. *Google Earth Engine* is a cloud-based system that allows users to process, analyze, and store geospatial data (Mutanga & Kumar, 2019). GEE's open-source usage was an important aspect (Mutanga & Kumar, 2019). GEE allows researchers to continually create and analyze trends or patterns in their fields of interest (Mutanga & Kumar, 2019). With open access to a series of satellite data (ex. MODIS, Landsat, and NOAA AVHRR), variables such as land surface temperature, precipitation, and many other could be visualized along a spatial and temporal gradient in our region of interest (Mutanga & Kumar, 2019; Kumar & Mutanga, 2018; Yu, 2022). GEE is incredibly advantageous because it allows researchers to use a Java-enabled Application Programming Interface (API) (Yu, 2022). Java codes can then be transferred and shared with other GEE users for reproduction (Yu, 2022).

3.2.3 ArcGIS Pro

ArcGIS Pro is a geographic information systems (GIS) application that helps visualize data in 2D and 3D formats (De Gorostizaga-Moxon, 2021). The 64-bit application is part of a family of GIS software systems created by the *Environmental Systems Research Institute* (ESRI). For this thesis, *ArcGIS Pro* was used for creating maps. The bulk of spatial visualization of NST and precipitation was done using GEE.

3.2.4 ERA5

The *ERA5* dataset is used to understand historical average near-surface temperatures within our study areas. The *ERA5* dataset is provided by the *Copernicus Climate Change Service* and the *European Centre for Medium-Range Weather Forecasts* (ECMWF). *ERA5* is a climate reanalysis tool that validates satellite-derived data to terrestrial weather stations to create long-term datasets (Copernicus, 2019).The specific package used in GEE is the *ERA5 Monthly Aggregates*. This package provides a monthly value across 9 bands of accessible data dating from 1979 to 2020. In this thesis research, the band evaluated was "*mean_2m_air_temperature*," with a resolution of 27,830m. Near-surface temperature refers to temperatures predicted to occur 2 meters above the ground. Across the data provided, *ERA5* provides an hourly forecast using data assimilation in which previous forecasts are updated with the newly available information to provide an updated forecast (Copernicus, 2019).

3.2.5 CHIRPS

For wine-growing regions of Canada, precipitation is another crucial variable whose future impacts must be considered. The *Climate Hazards Group Infrared Precipitation with Stations* (CHIRPS) dataset provides long-term precipitation data from 1981 (Funk et al., 2015). *CHIRPS* precipitation data provides a high resolution, 0.5°- degree, grid system from 50°S - 50°N, at 5,566m (Funk et al., 2015). Three components support the *CHIRPS* precipitation dataset, 1) the *Climate Hazards group Precipitation Climatology* (CHPclim), 2) the satellite-fed *Climate Hazards Group Infrared Precipitation*, 3) and global weather station data (Funk et al., 2015). The three components feed into the more extensive *CHIRPS* database (**Figure 10**).

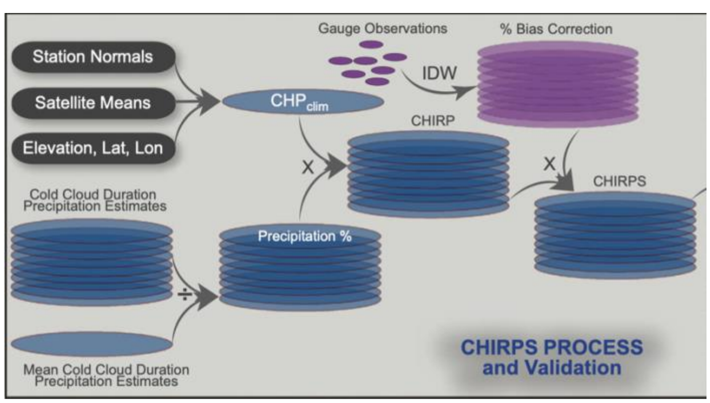


Figure 10: CHIRPS Dataset Input and Outputs

Source: (Funk et al., 2015)

Precipitation values within the *CHIRPS* dataset are available in three forms, 1) daily, 2) monthly, and 3) pentad (Funk et al., 2015). Pentadal values were used to analyze precipitation within viticultural regions of Canada. Pentadal values are aggregated 5-day precipitation estimates, with six pentads each month (Funk et al., 2015). *CHIRPS* was the precipitation dataset of choice due to the variety of scales it could provide and the high resolution (Paredes-Trejo et al., 2021).

3.2.6 NEX-GDDP-CMIP6

The *NEX-GDDP-CMIP6* dataset is composed of an aggregation of downscaled climate scenarios derived from General Circulation Models (GCMs) (NASA, n.d.c). The creation of the *NEX-GDP-CMIP6* dataset was done under the *Coupled Model Intercomparison Project Phase 6*, hence the abbreviated name *CMIP6* (NASA, n.d.c). Helping to support the *Sixth Assessment Report of the Intergovernmental Panel on Climate Change, CMIP6* ultimately set out to provide globally available, high-resolution projected climate change impacts considering local topography and climate (NASA, n.d.c).

The bands "*pr*" for precipitation and "*tas*" for daily near-surface temperature were selected. The resolution used for the analysis was the standard 27,830m in GEE. Moreover, within *CMIP6* datasets, specific climate models could be selected for projected data collection. As this research focuses on Canada's boundaries, the Canadian-developed *Canadian Earth System Model Version 5* (CanESM5) was selected to run future precipitation and near-surface temperature projections up to 2100. *CanESM5*, like various other models, was developed to highlight historical climate variability and future project scenarios up to the end of the 21st century (Swart et al., 2019). The lower resolution of *CanESM5* allows this model to produce projections of larger areas (Swart et al., 2019). The lower resolution of *NASA-GDDP-CMIP6* made it inadequate to use this dataset in place of *ERA5* and *CHIRPS* in determining a baseline climatic condition. Baseline conditions at higher resolutions were preferred for data visualization in Earth Engine. The ability to spatially analyze data covering large areas proved especially useful as some wine-growing areas, especially in places like British Columbia and Nova Scotia, covered large portions of the respective provinces.

3.2.7 TerraClimate

TerraClimate is a gridded dataset of terrestrial climate data (Abatzoglou et al., 2018). Data for *TerraClimate* is derived from interpolated climate normals from the *WorldClim* dataset (Abatzoglou et al., 2018). *TerraClimate* was used only to map precipitation over British Columbia for 1999-2019 because *CHIRPS* data was limited to the British Columbia wine regions. It would have been preferred to use *CHIRPS* data for each of the four provinces, but since there was not, another data source was needed. A monthly climate dataset covering 1958-2019, the University of California Merced provided the TerraClimate used in this research ("TerraClimate," n.d.). The resolution of the *TerraClimate* dataset is roughly 4km ("TerraClimate," n.d.). The band used for this dataset was "*pr*" and considered cumulative precipitation.

3.2.8 Canadian Climate Normals

The *Canadian Climate Normals* were used as a validation tool for our *CHIRPS*, *ERA5*, *TerraClimate*, and *CMIP6* datasets. Environment Canada publish *Canadian Climate Normals* to help provide an overview of climate variability across Canada. Climate Normals uses physical weather stations to help inform the creation and subsequent publication of these climate normals. For this research, the Climate Normals of 1981-2010 were used because the Climate Normals for 1991-2020 were not published at the time of this research.

3.2.9 Excel & XLSTAT

Statistical analysis for the research was done using the utility of *Excel*. *Excel* is a Microsoft-developed program part of the larger Microsoft Office product group. *Excel* is a spreadsheet program that allows users to organize data, perform a series of analyses, and produce charts of various kinds. For this research, *Excel* was used to create charts and perform statistical analyses. In addition to *Excel*, an additional Excel add-on, called *XLSTAT*, was used to perform trend series analysis instead of *Excel* as the program lacks a function. Massachusetts-based QSR International developed *XLSTAT*, and it is usually only accessed through paid subscriptions. For the research undertaken in this paper, a 14-day trial version was utilized for data analysis.

3.2.10 Goodness of Fit Formulas

1. Regression (R^2)

R^2 is a statistical goodness of its method for determining how well the independent variable can explain the variance seen in the dependent variable (Belsley et al., 1980). R^2 is used to determine how well data predicted by *ERA5*, *CHIRPS*, *TerraClimate*, and *CMIP6* is compared to the Climate Normal reference data. Regression values range between 0 and 1, with values close to 0 indicating a poor relationship between the dependent and independent variable and values closer to 1 indicating a more significant data fit from the dependent variable to the independent variable (Belsley et al., 1980).

$$R^2 = 1 - \frac{RSS}{TSS}$$

Source: (Belsley et al., 1980)

R^2 = Coefficient of Determination
RSS = Sum of Squares of Residuals
TSS = Total Sum of Squares

2. Pearson Correlation Coefficient

The Pearson Correlation Coefficient is a commonly used method to measure the covariance between two variables, all divided by the multiplication of their standard deviations (Freedman et al., 2007). Values range between -1 and 1, with -1 indicating no fit and 1 being perfect (Freedman et al., 2007).

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}}$$

Source: (Freedman et al. 2007)

R = Pearson Correlation Coefficient
x_i = Value of x variable in sample
$\bar{x}$ = Mean of x variables
y_i = Value of y variable in sample
$\bar{y}$ = Mean of y variables

3. Root Mean Square Error (RMSE)

The Root Mean Square Error is the residual difference between what is predicted and what has been observed ("Mastering", 2023). RMSE can help indicate how well a model fits actual value (“Mastering”, 2023). RMSE will help indicate how well *ERA5, CHIRPS, TerraClimate*, and *CMIP6* fit actual climate data provided by weather stations. Smaller RMSE values indicate a better fit of the predicted data with what is observed (“Mastering”, 2023).

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}}$$

Source: (“Mastering”, 2023)

RMSE = Root Mean Square Error

i = Variable of interest

$\hat{y}$ = Estimated Values

y_i = Actual Values

3.2.11 Statistical Trend Formula

Mann-Kendall Test

The Mann-Kendall test is non-parametric. Non-parametric tests are statistical tests that can be utilized for data that may not be able to meet the requirements of parametric tests, such as normally distributed data (Meals et al., 2011).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k)$$

$$\tau = \frac{\mathbf{S}}{\mathbf{n(n-1)/2}}$$

Source: (Meals et al., 2011)

S = Sum of Integers

X_j = Later Measured Values

X_k = Earlier Measured Values

Tau = Monotony of Slope

N = Number of Sample Pairs

This test assigns the integer of -1, 0, and 1 indicating a negative, no, or positive difference (Meals et al., 2011). When the sum of integers is large, it indicates that values later in a series are larger than earlier; thus, a positive upward trend is considered (Meals et al., 2011). The opposite can be said, a small S value indicates that later values may not be as high, and a change in trend may not be detected (Meals et al., 2011). Kendal tau is a slope analysis metric, assigning values of 1, 0, or -1 depending on if the trend slope is increasing, neutral, or decreasing (Meals et al., 2011). A confidence level of .05 is set with any P-values <.05 classified as significant and the null hypothesis is rejected while P-values >.05 are insignificant and the null hypothesis is accepted (Meals et al., 2011).

Chapter 4: Methodology

4.1 Methodology

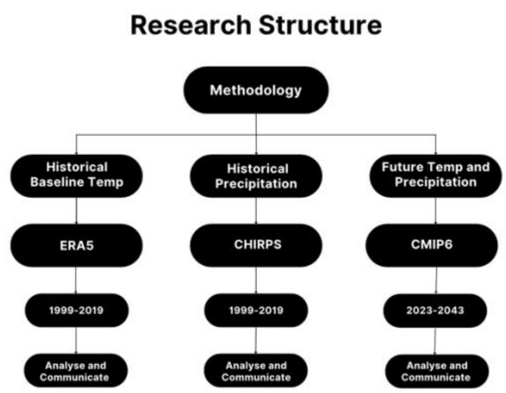


Figure 11: Conceptual Research Framework

Our data, including our baseline reference period, is being collected from the GEE data catalogue. To ensure that our *ERA5* near-surface temperature, *CHIRPS/TerraClimate* precipitation, and long-term downscaled *CMIP6*, there must be a comparison to physical weather station data. Weather stations were in each province of interest, with one station chosen for each intra-provincial wine-growing appellation. For example, Ontario has three smaller wine-growing regions: Niagara Peninsula, Prince Edward County, and Lake Erie North Shore. In each of these smaller regions, one station was selected. Canadian temperature and precipitation Climate Normals data from 1981 to 2010 was collected from one station in each of the smaller growing regions in Ontario. Near-surface temperature and precipitation outputs were averaged across the three Ontario wine-growing regions to give a generalized climate of the wine-growing regions. This approach was taken in the remaining provinces, Quebec, British Columbia, and Nova

Scotia. Validating the *ERA5, CHIRPS/TerraClimate*, and *CMIP6* outputs to physical weather station data helps to determine whether data acquired through *Google Earth Engine* is accurate.

For the purposes of validation, *ERA5, CHIRPS/TerraClimate* and *CMIP6* from 1999-2019 are compared to the 1981-2010 *Canadian Climate Normals*. Average monthly temperatures and precipitation are compared using regression, root mean square error, and Pearson's Correlation. A high correlation between *ERA5, CHIRPS/TerraClimate*, and *CMIP6* data to *Canadian Climate Normals* would indicate that the remotely acquired near-surface temperature and precipitation can produce accurate results.

Following *ERA5, CHIRPS*, and *CMIP6* validation against Climate Normals, the long-term climate downscale projection will be run from 2023 to 2100. Long-term climate projections could help understand the potential change in near-surface temperature and precipitation in our areas of interest.

This research attempt to determine if there are any increasing, decreasing, or neutral trends between the fall, winter, spring, and summer seasons (**Table 6**). Individual seasons will provide a lens to determine if there are any significant trends in one season over another.

Seasons	**Months**
Fall	September, October, November
Winter	December, January, February
Spring	March, April, May
Summer	June, July, August

Table 6: Classification of Seasons and Months.

Moreover, as assessment will be done contrasting the near-surface temperature and precipitation trends, if there are any, between the dormancy period and the growing season (**Table 7**).

Dormancy Period vs. Growing Season	**Months**
Growing Season	April – October
Dormancy Period	November - March

Table 7: Classification of Dormancy Period and Growing Season.

4.2 Research Objectives

Wine production is becoming an international business, with regions becoming prevalent around non-traditional wine areas such as Canada, the United States, and elsewhere like Ethiopia. The ability of non-traditional wine-producing nations to produce vintages rivalling some of the best French and Italian years reflects changing climates allowing for the commercialization of wine.

This research attempts to achieve a broader understanding of how climate enables wine production in Canada and whether this industry has the opportunity for expansion. Specifically, this research tries to understand present climate trends to project long-term near-surface temperature and precipitation patterns across the four primary Canadian wine-growing provinces. A baseline reference period 1999-2019 is used to see any noticeable trends. Long-term assessment of near-surface temperature and precipitation will be done using *NEX-GDDP-CMIP6* downscaled climate projections from 2023 to 2100.

4.3 Research Questions

1. Has there been an increase, decrease, or neutral trend in near-surface temperature and precipitation in our baseline reference period of 1999-2019?
2. Do long-term future trends indicate an increase, decrease, or neutral trend in near-surface temperature and precipitation?
3. Do the trends observed bode well for the future production of wine in Canada, and what conditions may producers face?
4. Can data acquired remotely through *Google Earth Engine* have a high correlation to validation data from metrological stations?

4.4 Mapping of Primary Wine Regions of Canada

The growing regions under analysis were chosen because of general recognition by several viticultural organizations for their viticultural abilities. Emerging regions exist outside the areas of interest in this study but do not have the same production levels to justify their inclusion as a predominant wine-growing region within their respective provinces. The takeaways from this research will likely be applicable.

4.5 Near-Surface Temperature and Precipitation Mapping Using Earth Engine

To undertake this research using Earth Engine, skills in JavaScript were needed. Several tutorials online were the aids needed to help understand the nuances of JavaScript code and what errors could exist in code that would prevent a command from running. Much of these tutorials and examples of code could be found through Google, provided by the Earth Engine Code Editor. Some learning curves still exist, but the tutorials remain easily accessible if needed. The workflow used to help guide data acquisition and processing can be found in **figure 11** above.

Following this learning period, a time frame of 20 years was decided upon for near-surface temperature and precipitation trend mapping, and the years of data availability of the raster datasets found in the GEE data catalogue determined timespans of interest. Near-surface temperature provided by *ERA5* had data availability only up to 2020, *CHIRPS* was available until 2023, and *CMIP6* up to 2100.

4.6 Data Validation

All data was accessed through *Google Earth Engine*. Weather stations acted as a validation measure to ensure accurate outputs from *ERA5, CHIRPS/TerraClimate, TerraClimate*, and *CMIP6*. The weather station derived 1981-2010 *Canadian Climate Normals*, available through the website of Environment Canada, were selected for our validation test. A more recent climate normal from 1990-2020 is advertised but has yet to be published.

Climate Normal data is derived from a series of weather stations around Canada. Data like temperature and precipitation collected by these stations help create the 30-year average climate normals. The Climate Normals data categories of focus on daily average temperature and precipitation. Temperature and precipitation data can vary from station to station, given that local weather patterns and trends influence the data collected by individual weather stations. For this research, a series of weather stations were selected from each subregion/appellation within each growing province to form the baseline conditions in which *ERA5, CHIRPS/TerraClimate*, and *CMIP6* data from 1999-2019 are validated. The weather stations (**Tables 8-11**) are in the wine-growing areas within each province. Weather stations were located using the weather station search tool provided by Environment Canada.

4.6.1 Ontario Weather Stations

Station Name	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
Niagara Falls NPCSH	43.13N	79.05W
Mountain View	49.13N	113.63W
Amherstburg	42.1N	83.09W

Table 8: Coordinate Data for Ontario Weather Stations of Interest (Environment Canada, 2023)

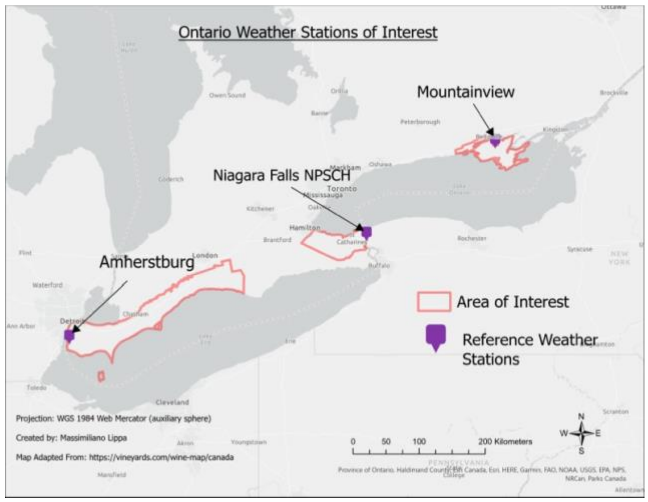


Figure 12: Ontario Weather Stations of Interest

4.6.2 British Columbia Weather Stations

Station Name	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
Kelowna A	49.96N	119.38W
Cape Mudge	50N	125.2W
Victoria Highland	48.51N	123.51W
Princeton A	49.47N	120.51W
Westminster Abbey	49.15N	122.27W

Table 9: Coordinate data for British Columbia Weather Stations of Interest (Environment Canada, 2023)

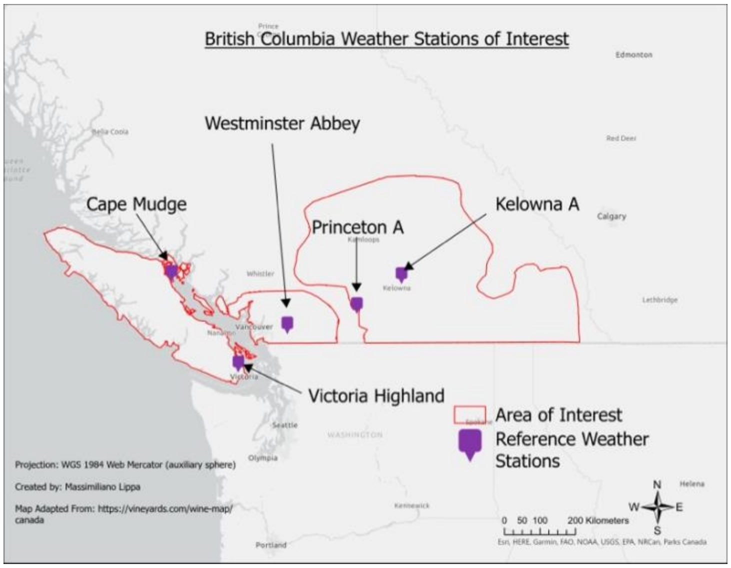


Figure 13: British Columbia Weather Stations of Interest.

4.6.3 Quebec Weather Stations

Station Name	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
Belleterre	47.38N	78.7W
Wright	46.07N	76.05W
Montreal/St. Hubert	45.52N	73.42W
Bromptonville	45.48N	71.95W
Lac-Mégantic	45.6N	70.87W
St. Prosper	46.22N	70.5W
Drummondville	45.88N	72.48W
Quebec/Jean Lesage Int.	46.8N	71.38W
Joliette Vie	46.02N	73.43W

Table 10: Coordinate Data for Quebec Weather Stations of Interest (Environment Canada, 2023)

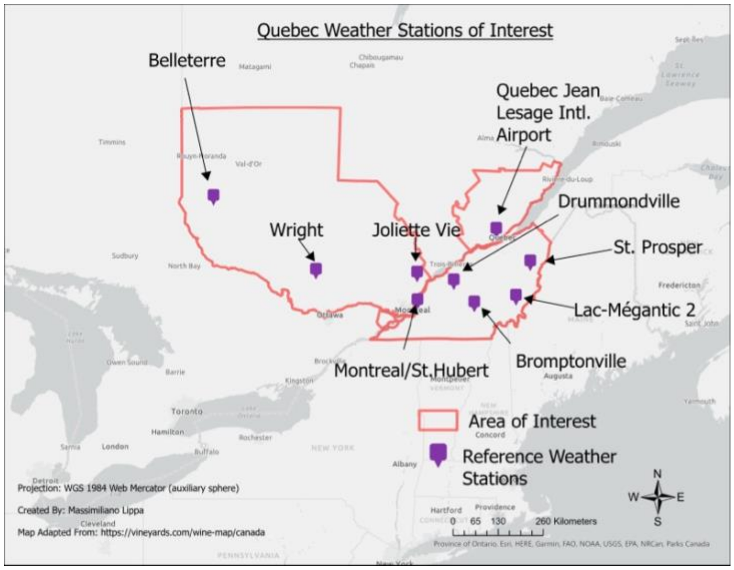


Figure 14: Quebec Weather Stations of Interest

4.6.4 Nova Scotia Weather Stations

Weather Station	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
Sydney A	46.17N	60.05W
Bridgewater	44.4N	64.55W
Greenwood A	44.98N	64.92W
Lyons Brook	45.66N	62.8W

Table 11: Coordinate Data for Nova Scotia Weather Stations of Interest (Environment Canada, 2023)

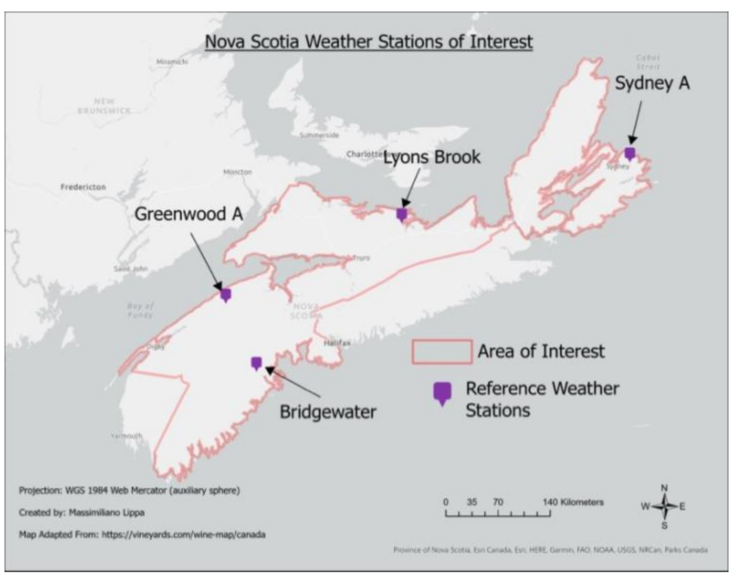


Figure 15: Nova Scotia Weather Stations of Interest.

4.6.5 Ontario Near-Surface Temperature and Precipitation Validation

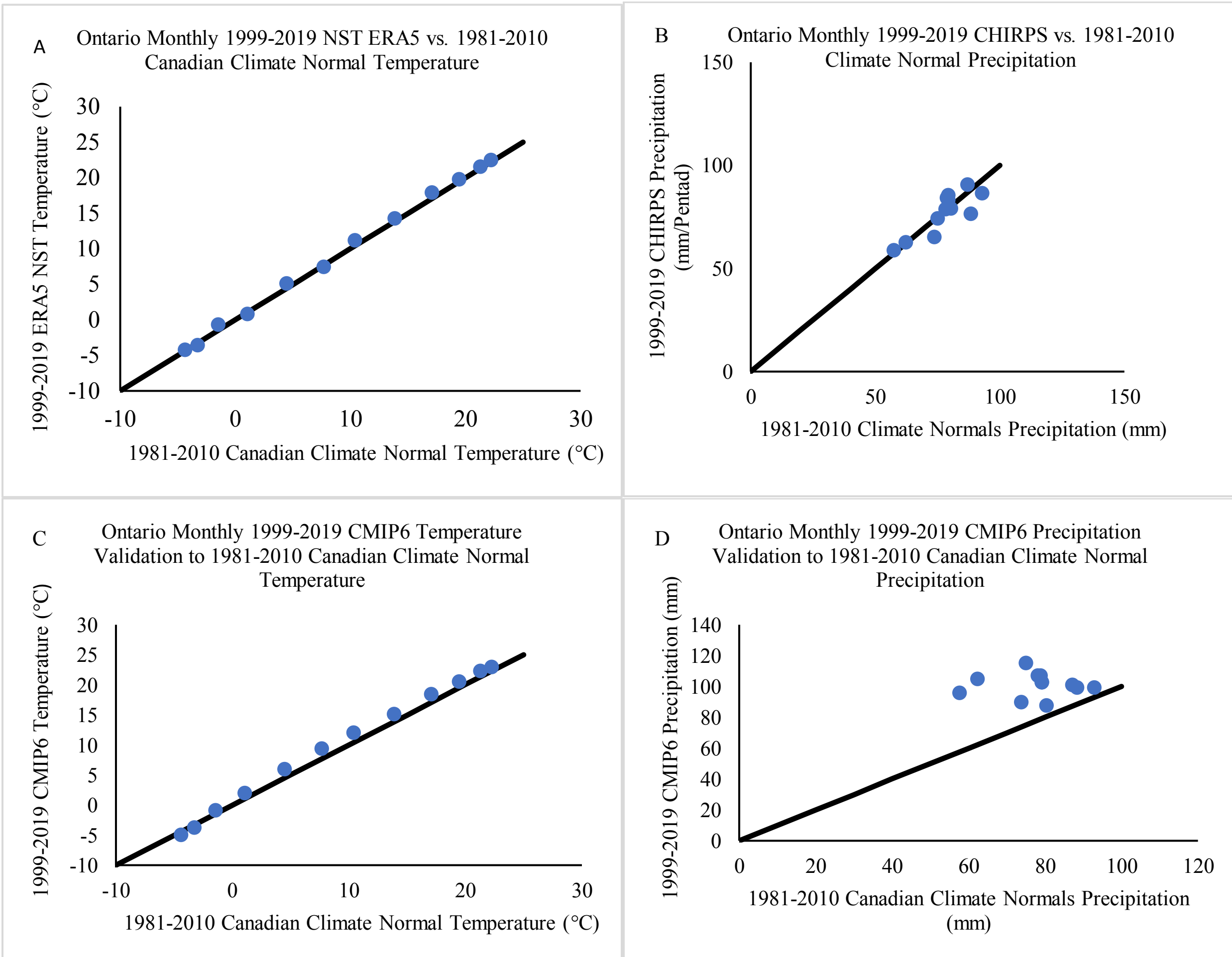


Figure 16: A) Ontario Monthly 1999-2019 *ERA5* Near-Surface Temperature Comparison to *Canadian Climate Normals* from 1981-2010. B) Ontario Monthly 1999-2019 *CHIRPS* Precipitation Comparison to *Canadian Climate Normals* of 1981-2010. C) Ontario Monthly 1999-2019 *CMIP6* Temperature Comparison to *Canadian Climate Normals* of 1981-2010. D)Ontario Monthly 1999-2019 *CMIP6* Precipitation Comparison to *Canadian Climate Normals* of 1981-2010.

Goodness-of-Fit Tool	**Value**
Regression (R^2)	0.99842298
Root Mean Square Error (RMSE)	0.47526675
Pearson Correlation Coefficient (R)	0.99921118

Table 12 Goodness-of-Fit analysis comparing Ontario *ERA5* Near-Surface Temperature and Weather Station *Canadian Climate Normals* Data for Ontario.

Goodness-of-Fit Tool	**Value**
Regression (R^2)	0.706144744
Root Mean Square Error (RMSE)	5.5173553

Pearson Correlation Coefficient (R)	0.84032419

Table 13: Goodness-of-Fit Analysis Comparing Ontario 1999-2019 *CHIRPS* Precipitation to 1981-2010 *Canadian Climate Normals.*

Goodness-of-Fit Tool	Value
Regression (R^2)	0.996240084
Root Mean Square Error (RMSE)	1.14269459
Pearson Correlation Coefficient (R)	0.998118272

Table 14: Goodness-of-fit Analysis Comparing Ontario 1999-2019 *CMIP6* Temperature to 1981-2010 *Canadian Climate Normals.*

Goodness-of-Fit Tool	Value
Regression (R^2)	0.000575136
Root Mean Square Error (RMSE)	26.18620256
Pearson Correlation Coefficient (R)	-0.023981997

Table 15: Goodness-of-Fit Analysis Comparing Ontario 1999-2019 *CMIP6* Precipitation to 1981-2010 *Canadian Climate Normals.*

For Ontario (**Figure 16A**), *ERA5* near-surface temperature appears to have high goodness of fit to the Climate Normal outputs provided by weather stations within the province. A regression value very close to 1, an extremely low RMSE, and a Pearson value also very close to 1 indicate that *ERA5* outputs for 1999-2019 can accurately model temperature and precipitation compared to weather station data. The same can be said for the long-term *CMIP6* data (**Figure 16CD**) when running the future temperature through the *CanESM5* model. A regression between *CMIP6* values and that of the Climate Normals indicate a high level of accuracy. In other words, what is being predicted by the Climate Normals is closely matched by the *CMIP6* temperature value. While long-term climate models are never perfect, high R^2 and Pearson Correlation values indicate that future long-term temperature predictions may have some accuracy.

Precipitation does not follow the same trends as seen in temperature. The *CHIRPS* dataset (**Figure 16B**) seems able to model baseline precipitation to climate normals, but long-term *CMIP6* data does not. What is being modelled by *CMIP6* overestimates that of the Climate Normals. When analyzing R^2 and Pearson Correlation values of *CMIP6* precipitation, it’s extremely low, thus indicating a poor fit. Future precipitation predictions may indicate trends, such as increasing or decreasing precipitation. However, precipitation values are overestimated and not truly reflect how much precipitation will fall in the region of interest.

4.6.6 British Columbia Near-Surface Temperature and Precipitation Validation

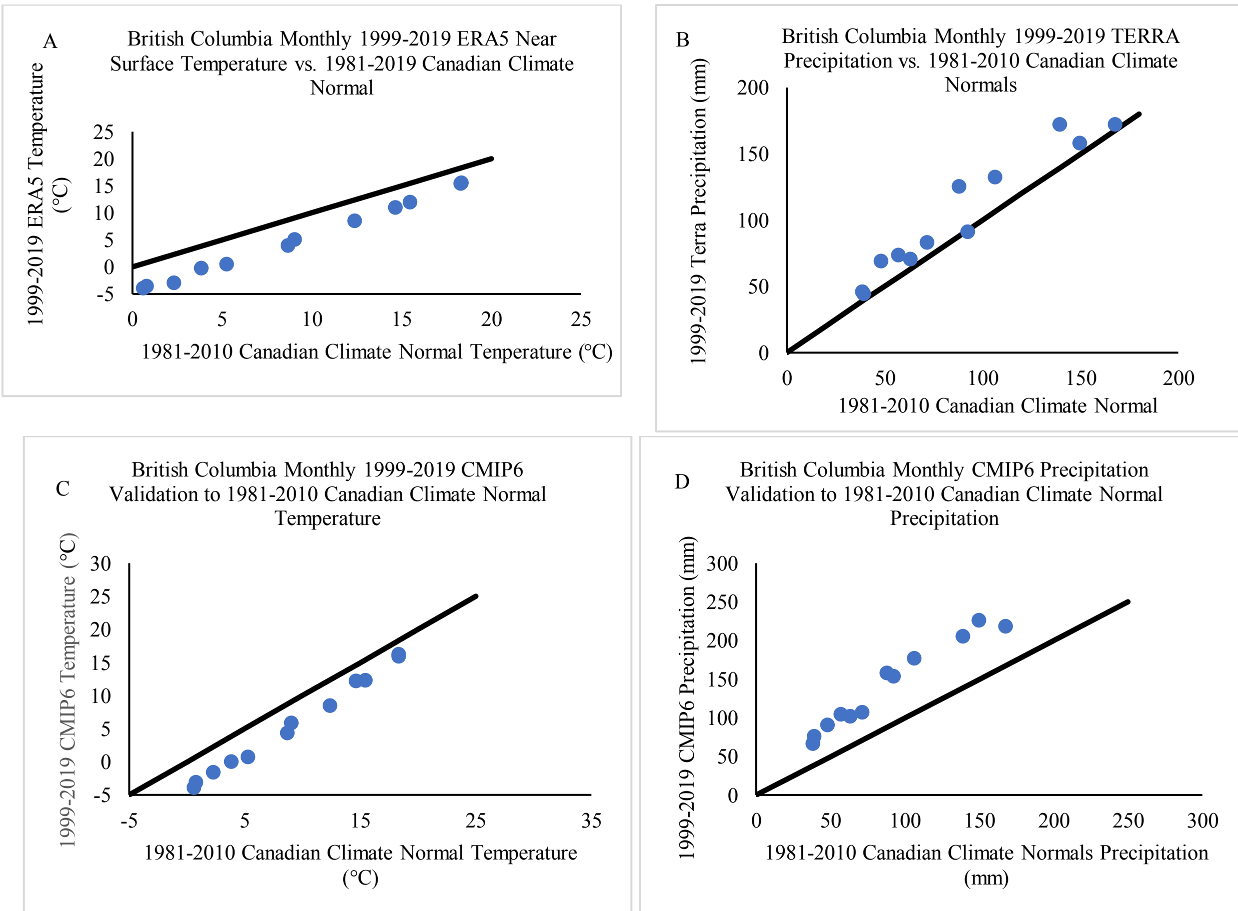


Figure 17: A) British Columbia Monthly 1999-2019 *ERA5* Near-Surface Temperature Comparison to *Canadian Climate Normals* from 1981-2010. B) British Columbia Monthly 1999-2019 *TerraClimate* Precipitation Comparison to *Canadian Climate Normals* of 1981-2010. C) British Columbia Monthly 1999-2019 *CMIP6* Temperature Comparison to *Canadian Climate Normals* of 1981-2010. D) British Columbia Monthly 1999-2019 *CMIP6* Precipitation Comparison to *Canadian Climate Normals* of 1981-2010.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.93276665
Root Mean Square Error (RMSE)	18.4432131
Pearson Correlation Coefficient (R)	0.96579845

Table 16: Goodness-of-Fit Analysis Comparing British Columbia 1999-2019 *TerraClimate* Precipitation to 1981-2010 *Canadian Climate Normals*.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.997085141
Root Mean Square Error (RMSE)	4.121861498
Pearson Correlation Coefficient (R)	0.998541507

Table 17: Goodness-of-Fit analysis comparing British Columbia 1999-2019 *ERA5* Near-Surface Temperature and *Canadian Climate Normals*.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.95800163
Root Mean Square Error (RMSE)	54.17637441
Pearson Correlation Coefficient (R)	0.978775577

Table 18: Goodness-of-Fit Analysis Comparing British Columbia 1999-2019 *CMIP6* Precipitation to 1981-2010 *Canadian Climate Normals*.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.99552383
Root Mean Square Error (RMSE)	3.610463932
Pearson Correlation Coefficient (R)	0.997759405

Table 19: Goodness-of-Fit Analysis Comparing British Columbia 1999-2019 *CMIP6* Temperature to 1981-2010 *Canadian Climate Normals*.

The *ERA5* dataset slightly underestimates near-surface temperature from 1999-2019 in British Columbia, whereas *TerraClimate* precipitation for the same period is slightly overestimated. However, these overestimations and underestimates do not stray far from the mean as the R^2 values for both near-surface temperature and precipitation for 1999-2019 are high and close to 1, indicating close matches to what is being observed. When validating the NASA downscaled model to the 1999-2019 reference period for NST, the R^2 and Pearson values between what was observed from weather stations and what was being predicted were high, and the RMSE was relatively low.

When comparing *TerraClimate* precipitation data from 1999-2019 to data outputs from Climate normals, *TerraClimate* data looks to fit data outputs from weather stations. The regression value is lower than near-surface temperature, the RMSE error is high, and the Pearson R value indicates a correlation that is not as strong by comparison. A similar outcome was observed when comparing *CMIP6* precipitation to the Climate Normals. There was an overestimation of precipitation compared to the observable data.

One aspect that should be considered, especially for British Columbia, is the high variability in topography. Unlike the other provinces, British Columbia has wine-growing areas in low-lying coastal regions with lots of annual precipitation and growing areas within the Rockies with limited precipitation. Such variability does make it difficult to gain an average for the area given such a difference. Moreover, in the case of British Columbia, *TerraClimate* had to be used because *CHIRPS* precipitation data did not cover the entirety of the wine-growing areas within the province.

4.6.7 Nova Scotia Near-Surface Temperature and Precipitation Validation

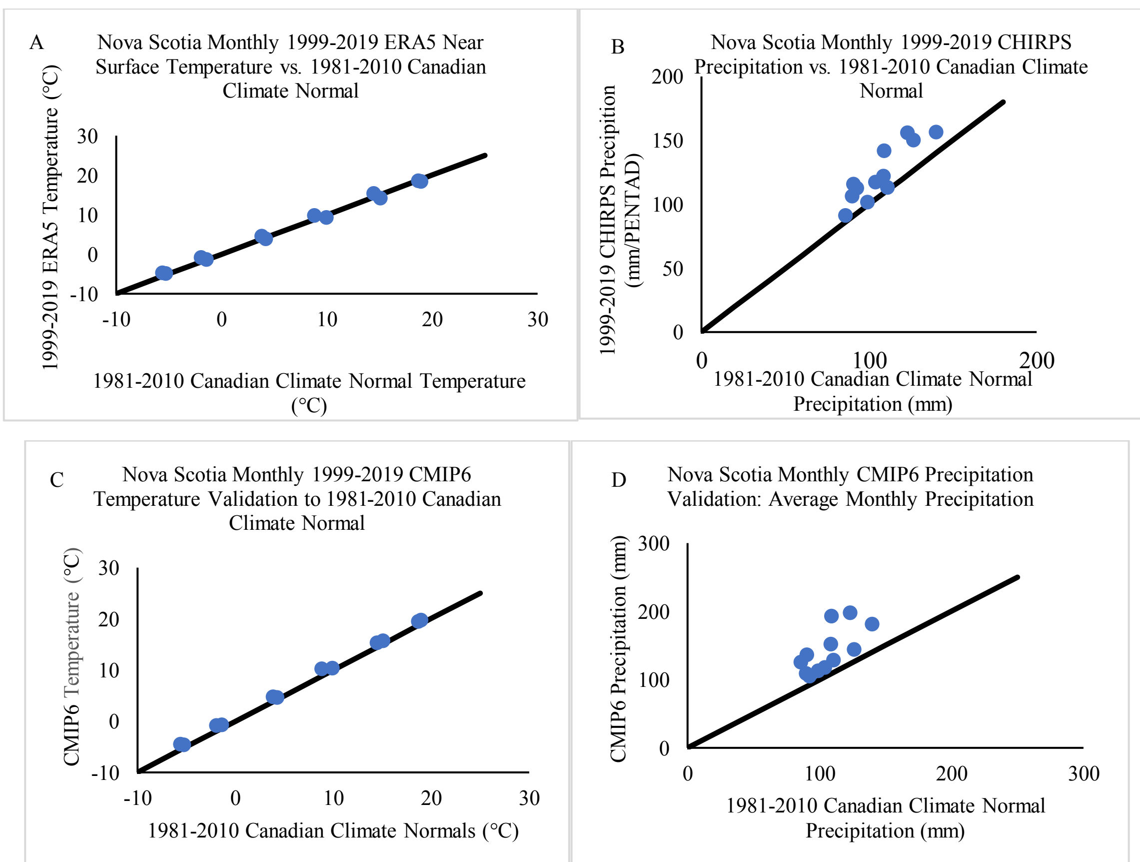


Figure 18: A) Nova Scotia Monthly 1999-2019 *ERA5* Near-Surface Temperature Comparison to *Canadian Climate* Normals from 1981-2010. B) Nova Scotia Monthly 1999-2019 *CHIRPS* Precipitation Comparison to *Canadian Climate Normals* of 1981-2010. C) Nova Scotia Monthly 1999-2019 *CMIP6* Temperature Comparison to *Canadian Climate Normals* of 1981-2010. D) Nova Scotia Monthly 1999-2019 *CMIP6* Precipitation Comparison to *Canadian Climate Normals* of 1981-2010.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.914444368
Root Mean Square Error (RMSE)	0.671100240
Pearson Correlation Coefficient (R)	0.997575674

Table 20: Goodness-of-Fit Analysis comparing Nova Scotia 1999-2019 *ERA5* Near-Surface Temperature to 1981-2010 *Canadian Climate Normals*.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.81521
Root Mean Square Error (RMSE)	19.434231
Pearson Correlation Coefficient (R)	0.88931999

Table 21: Goodness-of-Fit Analysis Comparing Nova Scotia 1999-2019 *CHIRPS* Precipitation and 1981-2010 *Canadian Climate Normal*s Precipitation.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.998977414
Root Mean Square Error (RMSE)	0.83264829
Pearson Correlation Coefficient (R)	0.999488576

Table 22: Goodness-of-Fit Analysis Comparing Nova Scotia 1999-2019 *CMIP6* Near-Surface Temperature to 1981-2010 *Canadian Climate Normals*.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.479193316
Root Mean Square Error (RMSE)	42.05814485
Pearson Correlation Coefficient (R)	0.692237904

Table 23: Goodness-of-Fit Analysis Comparing Nova Scotia 1999-2019 *CMIP6* Precipitation to 1981-2010 *Canadian Climate Normals.*

Like the regions of Ontario and British Columbia, the ability of *ERA5* and *CHIRPS* to accurately model Nova Scotia near-surface temperature and precipitation compared to outputs from weather stations is relatively high and demonstrated through higher R^2 and Pearson values. Like Ontario and British Columbia, the precipitation values are slightly overestimated even for the reference period. The RMSE for near-surface temperature indicates that predicted values are very close to what is modelled, with the RMSE value being under 1.

Using data acquired from *CMIP6* bands for temperature and precipitation, observed was the ability of *CMIP6* temperature to model with a high degree of accuracy what was predicted by the *Canadian Climate Normals*, but once again, the long-term precipitation data was not able to produce valid results when running *CMIP6* between the years of 1999-2019. The results suggest that within Nova Scotia, satellite-derived data can project future temperature with some accuracy, while precipitation may be overestimated.

4.6.8 Quebec Near-Surface Temperature and Precipitation Validation

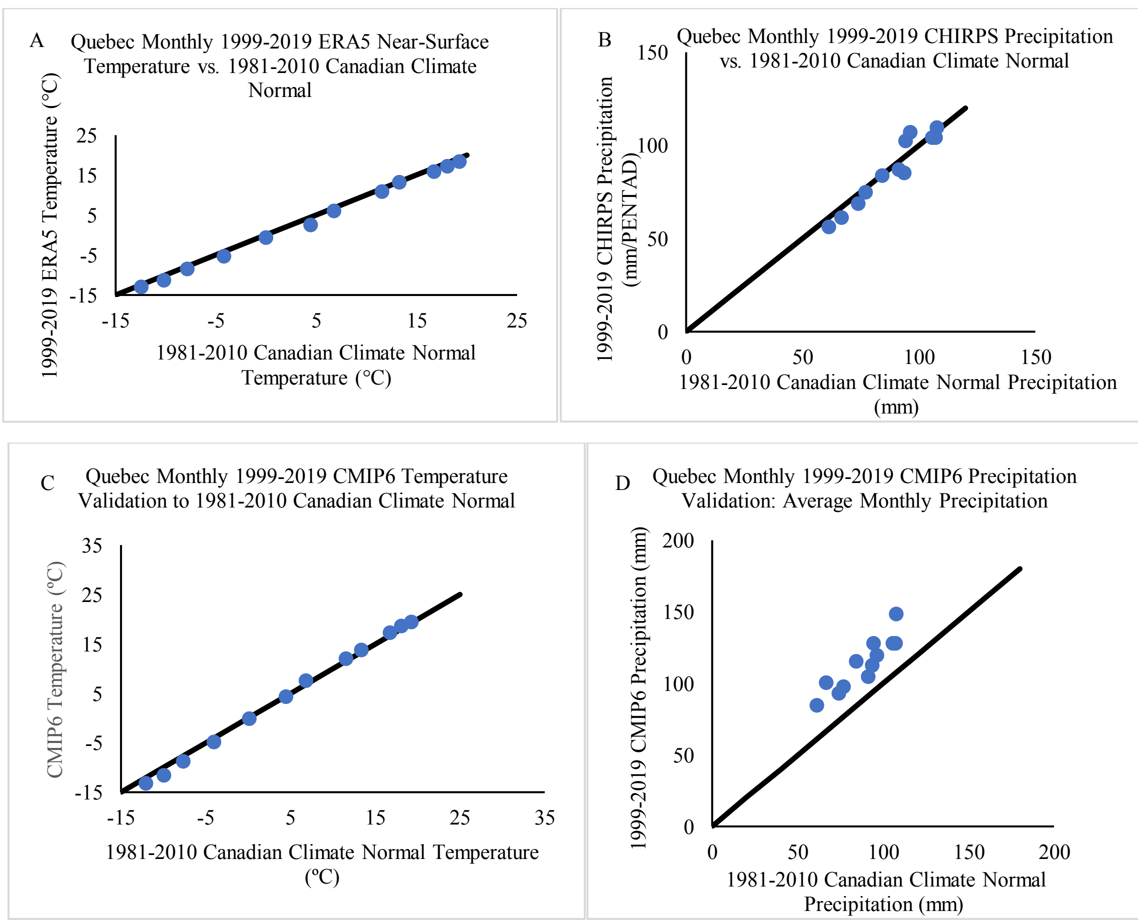


Figure 19: A) Quebec Monthly 1999-2019 *ERA5* Near-Surface Temperature Comparison to *Canadian Climate Normals* from 1981-2010. B) Quebec Monthly 1999-2019 *CHIRPS* Precipitation Comparison to *Canadian Climate Normals* of 1981-2010. C) Quebec Monthly 1999-2019 *CMIP6* Temperature Comparison to *Canadian Climate Normals* of 1981-2010. D) Quebec Monthly 1999-2019 *CMIP6* Precipitation Comparison to *Canadian Climate Normals* of 1981-2010.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.92
Root Mean Square Error (RMSE)	1.01
Pearson Correlation Coefficient (R)	0.999

Table 24: Goodness-of-Fit Analysis Comparing Quebec 1999-2019 *ERA5* Near-Surface Temperature to 1981-2010 *Canadian Climate Normals*.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.88058335
Root Mean Square Error (RMSE)	5.59905193
Pearson Correlation Coefficient (R)	0.96063638

Table 25: Goodness-of-Fit Analysis Comparing Quebec 1999-2019 *CHIRPS* Precipitation and 1981-2010 *Canadian Climate Normal* Precipitation.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.999090757
Root Mean Square Error (RMSE)	0.821565285
Pearson Correlation Coefficient (R)	0.999545275

Table 26: Goodness-of-Fit Analysis Comparing Quebec 1999-2019 *CMIP6* Near-Surface Temperature to 1981-2010 *Canadian Climate Normals*.

Goodness-of-Fit Tool	Value
Regression (R^2)	0.8125653
Root Mean Square Error (RMSE)	25.677982
Pearson Correlation Coefficient (R)	0.9014241

Table 27: Goodness-of-Fit Analysis Comparing Quebec 1999-2019 *CMIP6* Precipitation to 1981-2010 *Canadian Climate Normals.*

The last province in our analysis, Quebec, fell in line with the rest. Near-surface temperature between 1999-2019 was accurate, with R^2 and Pearson values close to one and an RMSE relatively small. Together these metrics demonstrate that satellite derived *ERA5* data can predict with some degree of accuracy what is being observed on the ground using weather stations. Precipitation data for 1999-2019 remains relatively high, as indicated by a higher R^2 and Pearson value.

The *CMIP6* data for temperature was highly accurate, with a low RMSE and high R^2 and Pearson values. Once again, for *CMIP6* precipitation, there wasn't as much accuracy. The fit was not as high, and there was a high RMSE which made any future prediction need contextualization and possible scaling for bias. Future predictions for this region regarding temperature may hold some weight, given the accuracy of *CMIP6* temperature between 1999-2019. In contrast, for precipitation, estimates of a wetter future are questionable.

Chapter 5: Results & Analysis

5.1 Results & Analysis

The analysis section will look to answer the first three questions set out in the research questions section. As a reminder, these are the questions the results section will try to answer.

1. Has there been an increase, decrease, or neutral trend in near-surface temperature and precipitation in our baseline reference period of 1999-2019?
2. Do long-term future trends, from 2023-2100, indicate an increase, decrease, or neutral trend in near-surface temperature and precipitation?
3. Do the trends observed bode well for the future production of wine in Canada, and what conditions may producers face?

The analysis will be broken down provincially and first assess the near-surface temperature and precipitation trends of the 1999-2019 reference periods. Following this, long-term trends, 2023-2100, will be discussed.

5.2 Ontario Near-Surface Temperature

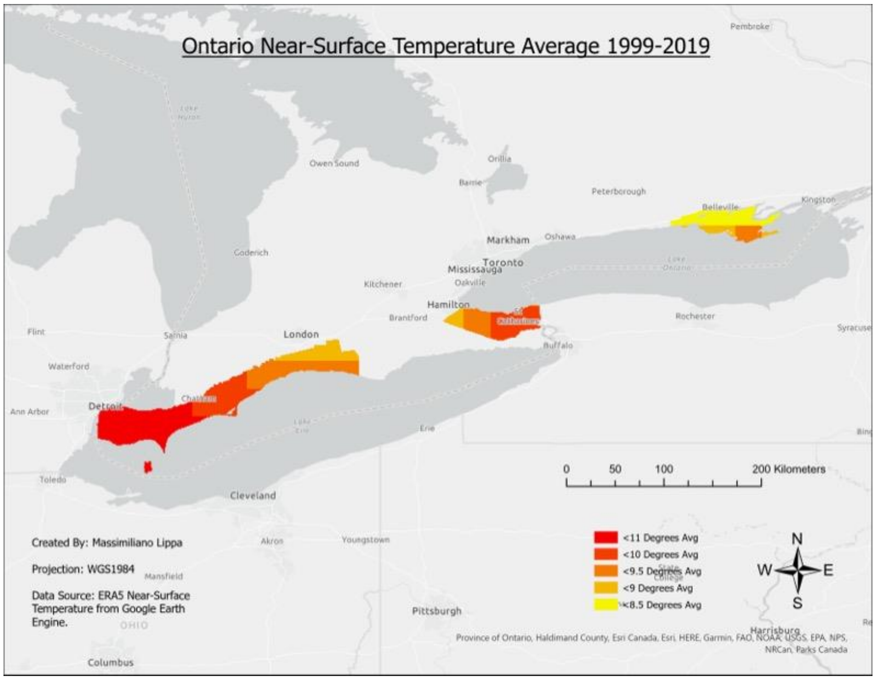


Figure 20: Ontario *ERA5* Near-Surface Temperature Average 1999-2019

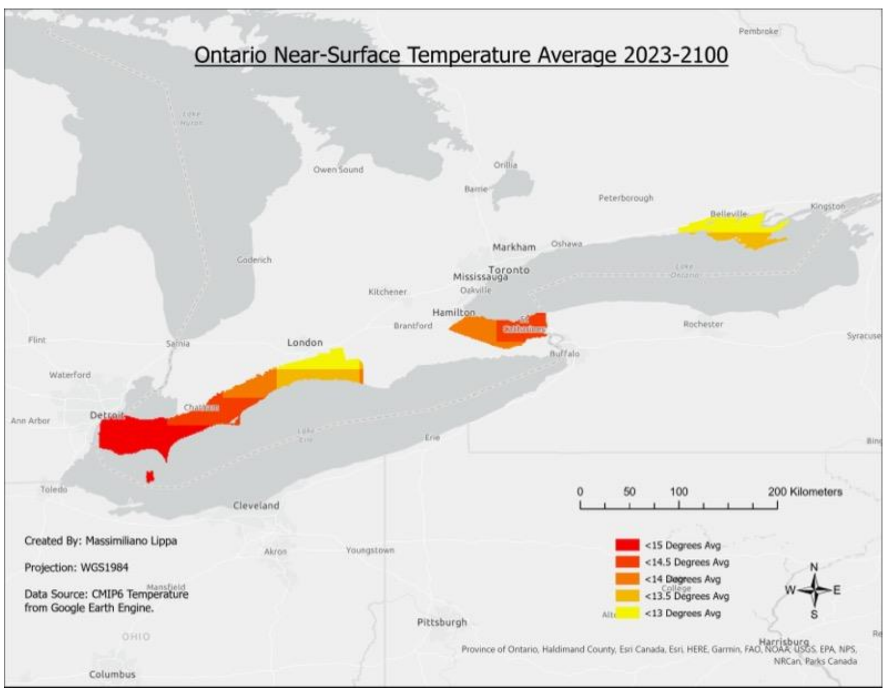


Figure 21: Ontario Projected *CMIP6* Temperature 2023-2100.

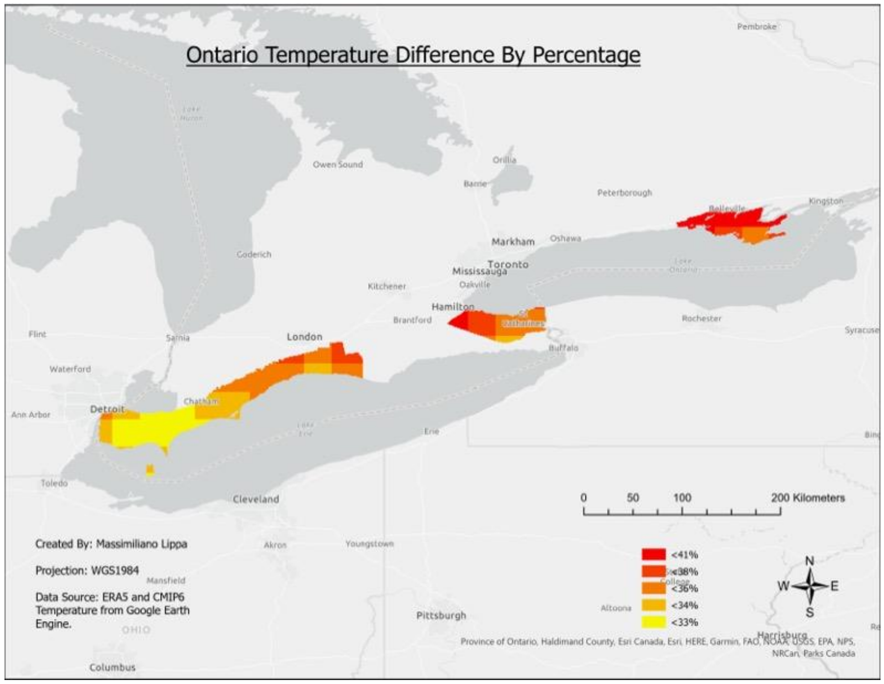


Figure 22: Ontario Temperature Difference By Percentage

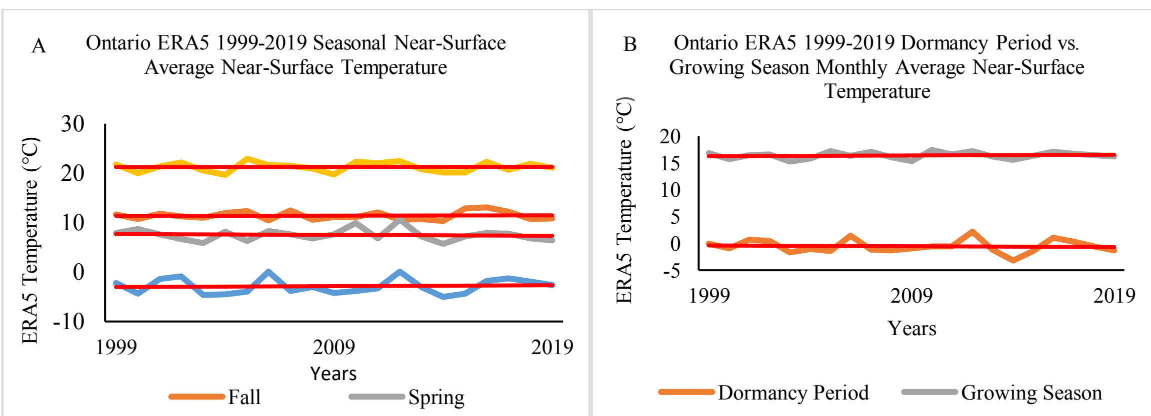


Figure 23: A) Ontario season *ERA5* Near-Surface Temperature 1999-2019. B) Ontario Dormancy vs. Growing Season *ERA5* Near-Surface Temperature 1999-2019.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	21	0	21	10.324	13.070	11.405	0.828
Spring	21	0	21	5.699	10.628	7.505	1.223
Summer	21	0	21	19.658	22.899	21.248	0.961
Winter	21	0	21	-5.031	0.065	-2.851	1.562

Table 28: Minimum, Maximum, Mean, and Standard Deviation values from Ontario seasonal *ERA5* Near-Surface Temperature data from 1999-2019.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	0.010	P < .05	0.952
Spring	-0.105	P < .05	0.506
Summer	0.029	P < .05	0.856
Winter	0.124	P < .05	0.432

Table 29: Kendall Tau, P-Value Expected, and P-Value Calculated from Ontario seasonal *ERA5* Near-Surface Temperature data from 1999-2019.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	21	0	21	-3.187	2.189	-0.533	1.220
Growing	21	0	21	15.237	17.400	16.369	0.595

Table 30: Minimum, Maximum, Mean, and Standard Deviations from Ontario *ERA5* Dormancy Period vs. Growing Season data from 1999-2019.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	-.048	P < .05	0.763
Growing Season	0.076	P < .05	0.629

Table 31: Kendall Tau, P-Value Expected, and P-Value Calculated from Ontario *ERA5* Near-Surface Temperature Dormancy Period vs. Growing Season data from 1999-2019.

Across seasonally separated spatial data of our baseline 1999-2019 period, no trends of any significance can be observed in Ontario. Ontario's near-surface temperature has remained relatively stable from 1999-2019. Across three seasons, we see a slight trend increase, while the spring season had a slightly decreasing trend. The only season that did not have an increasing slope was spring. Within the 20-year reference period, there was no significant near-surface temperature trend. It has remained relatively stable. These results are confirmed through insignificant P-values, exceeding our confidence level of .05.

The same trend is witnessed in comparing the 1999-2019 growing and dormancy seasons. There is a relatively neutral trend of near-surface temperature. The P-values of both the growing season and dormancy season have values that exceed the .05 confidence value, indicating that these slight trends are of no significance.

From the visualization provided in **figure 20**, between 1999-2019, it appears the growing region with some lower values of near-surface temperature was found in Prince Edward County, while the Lake Erie North Shore region exhibited higher temperature levels when comparing the three Ontario growing regions.

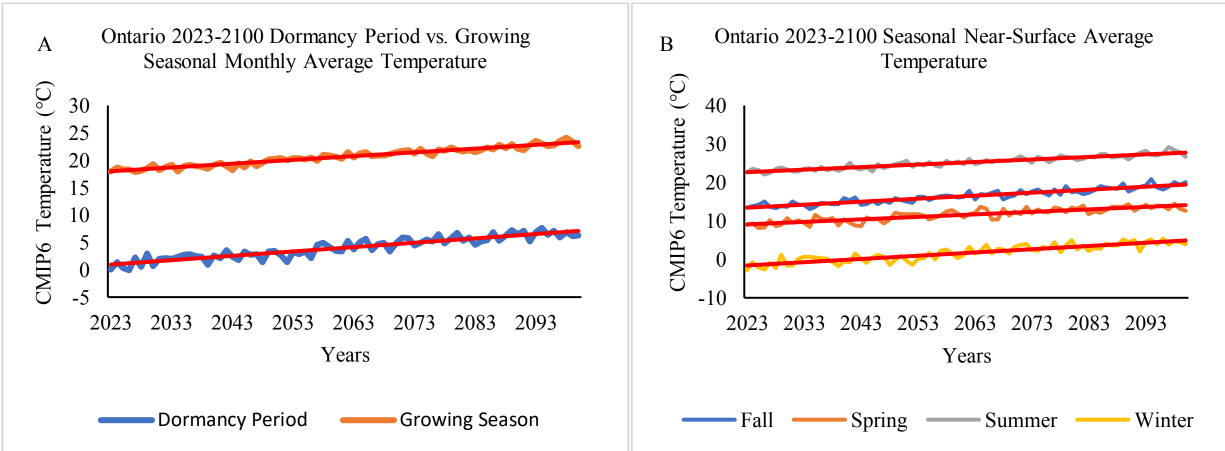


Figure 24: A) Ontario Dormancy vs. Drowing season *CMIP6* Temperature Domparison for 2023-2100. B) Ontario Seasonal *CMIP6* Temperature comparison for 2023-2100.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	78	0	78	13.058	20.838	16.430	1.896
Spring	78	0	78	8.129	14.462	11.588	1.704
Summer	78	0	78	22.040	29.191	25.202	1.607
Winter	78	0	78	-2.824	5.377	1.652	2.161

Table 32: Minimum, Maximum, Mean, and Standard Deviations for Ontario *CMIP6* Seasonal Temperature Average 2023-2100.

Long-term, there are significant near-surface trends up to 2100 seasonally. The increasing near-surface temperature trends are all highly significant, indicating that results are not simply due to chance.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	0.789	P < .05	<0.0001
Spring	0.672	P < .05	<0.0001
Summer	0.785	P < .05	<0.0001
Winter	0.692	P < .05	<0.0001

Table 33: Minimum, Maximum, Mean, and Standard Deviations for Ontario *CMIP6* 2023-2100 Dormancy Period vs. Growing Season Temperature Comparison.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	78	0	78	-0.089	7.650	4.020	1.973
Growing	78	0	78	17.854	24.102	20.645	1.623

Table 34: Minimum, Maximum, Mean, and Standard Deviations for Ontario *CMIP6* Temperature Dormancy Period vs. Growing Season Comparison 2023-2100.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	0.738	P < .05	<0.0001
Growing Season	0.830	P < .05	<0.0001

Table 35: Kendall Tau, P-Value Expected, and P-Value Calculated from Ontario *CMIP6* Dormancy Period vs. Growing Season Temperature data from 2023-2100.

There is an increasing trend of near-surface temperature favouring higher temperatures moving towards the end of the century for both the growing and dormancy periods. All upwards trends were significant according to the Mann-Kendall test, which yielded highly significant P-values of <.0001. The standard deviations across seasonal and dormancy/growing seasons are relatively small, suggesting that the near-surface temperature values tightly follow the mean of the data series. The statistical analysis results for near surface temperature within Ontario wine-growing areas suggest that the future may be warmer.

Of the three Ontario wine-growing areas, notable increases are occurring in all. Notably, the higher proportionally increases are occurring in the eastern portion of Lake Erie North Shore, Niagara Peninsula, and Prince Edward County.

5.2.1 Ontario Precipitation

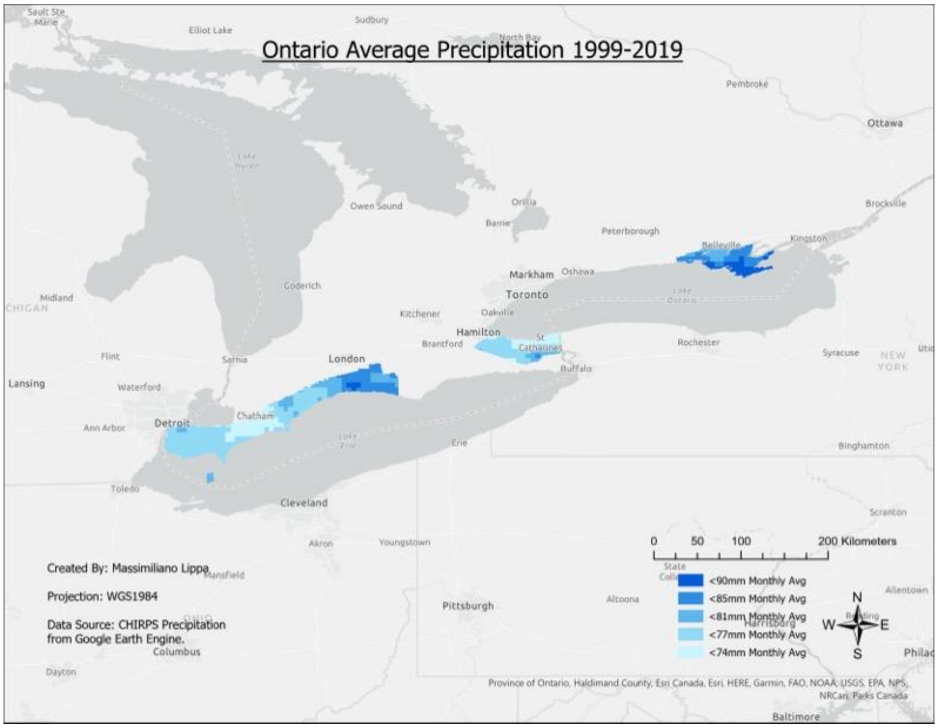


Figure 25: Ontario *CHIRPS* Precipitation Average 1999-2019

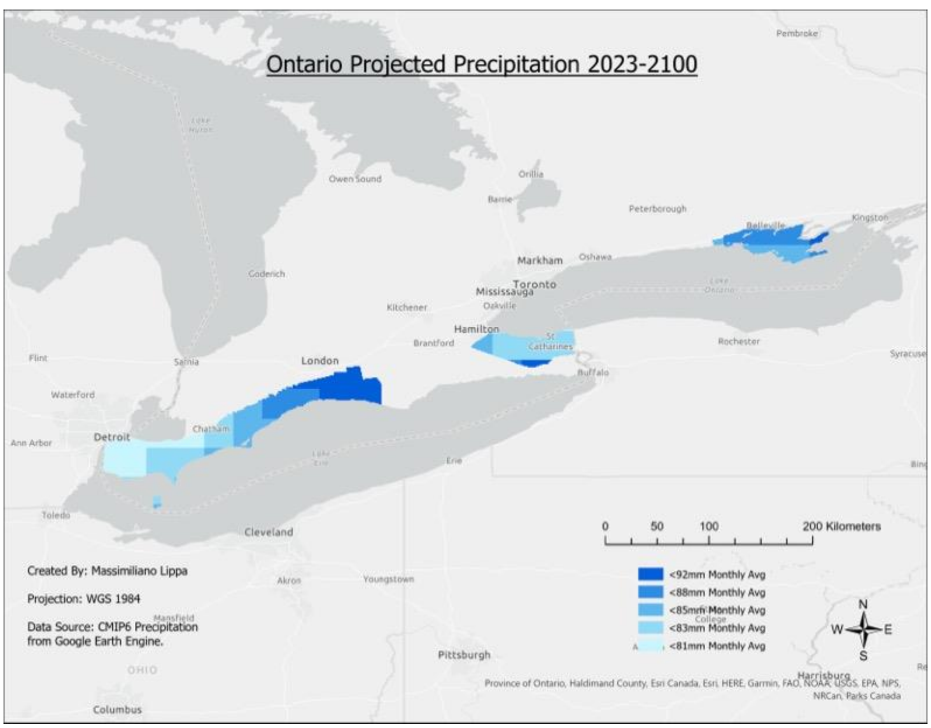


Figure 26: Ontario Projected *CMIP6* Precipitation Average 2023-2100

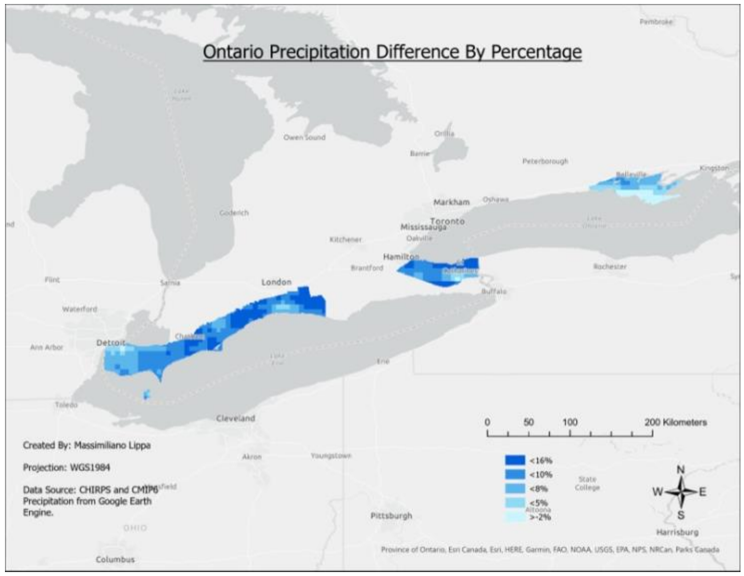


Figure 27: Ontario Precipitation Difference by Percentage

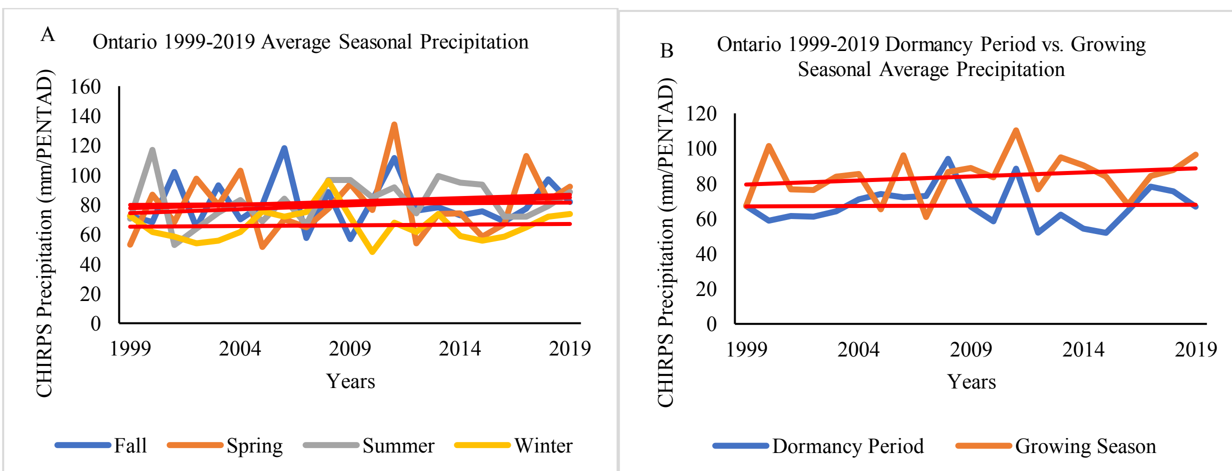


Figure 28: A) Ontario Seasonal *CHIRPS* Precipitation Comparison for 1999-2019 B) Ontario Dormancy Period vs Growing Season *CHIRPS* Precipitation Comparison for 1999-2019

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	21	0	21	56.777	118.153	80.623	16.206
Spring	21	0	21	51.454	134.109	79.570	20.782
Summer	21	0	21	52.789	116.967	82.153	14.897
Winter	21	0	21	48.060	96.049	66.061	10.596

Table 36: Minimum, Maximum, Mean, and Standard Deviations from Ontario 1999-2019 *CHIRPS* Precipitation Comparison.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	0.057	P < .05	0.717
Spring	0.095	P < .05	0.546
Summer	0.200	P < .05	0.205
Winter	0.019	P < .05	0.904

Table 37: Kendall Tau, P-Value Expected, and P-Value Calculated from Ontario seasonal *CHIRPS* Precipitation from 1999-2019.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	21	0	21	51.886	94.066	67.422	10.887
Growing	21	0	21	60.891	110.305	84.016	12.410

Table 38: Minimum, Maximum, Mean, and Standard Deviations from Ontario 1999-2019 *CHIRPS* Precipitation Dormancy Period vs. Growing Season Comparison.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	0.048	P < .05	0.763
Growing Season	0.210	P < .05	0.184

Table 39: Kendall Tau, Sens Slope, P-Value Expected, and P-Value Calculated from Ontario Dormancy Period vs. Growing Seasons *CHIRPS* Precipitation data from 1999-2019.

Precipitation from 1999-2019 has not demonstrated any significant trends. All P-values exceed our .05 confidence level. The precipitation was measured using the monthly average for the 20-year reference period. Singular severe precipitation events that resulted in precipitation at higher-than-normal rates may have occurred but, when averaged over the 20-year reference period, did not lead to significant increases, or decreases.

Figures 25-26 show high precipitation rates in the eastern portions of the Lake Erie North Shore Region and the northern part of Prince Edward County. The lowest precipitation rates are around the middle regions of Lake Erie North Shore in the areas around Chatham-Kent and Essex County. The high precipitation in this region coincides with high-near surface temperatures and is certainly something to consider.

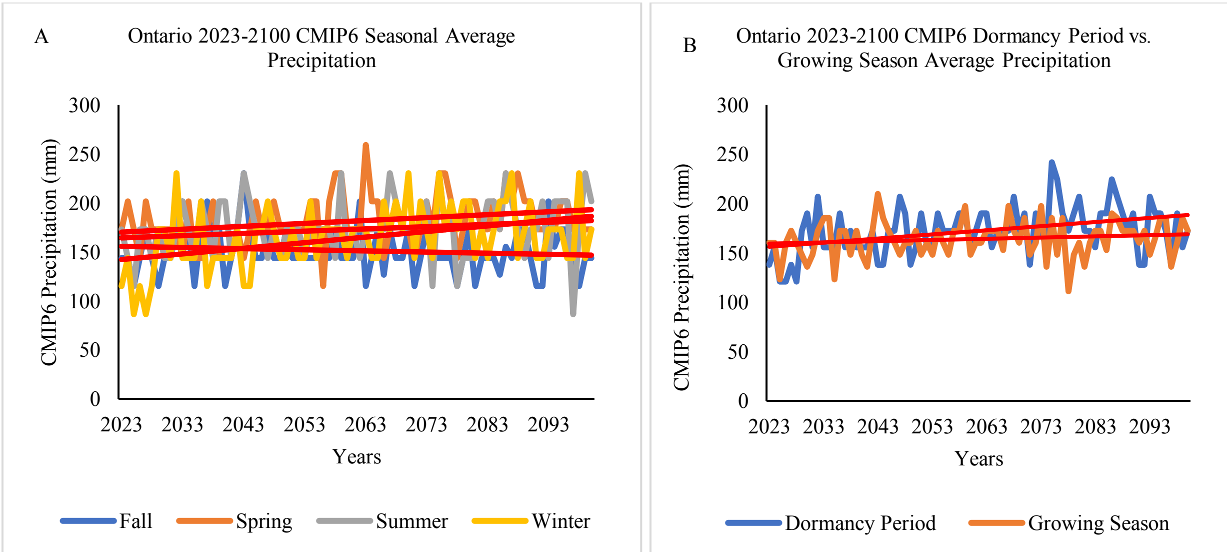


Figure 29: A) Ontario Seasonal *CMIP6* Precipitation Comparison for 2023-2100 B) Ontario Dormancy Period vs Growing Season *CMIP6* Precipitation Comparison for 2023-2100

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	78	0	78	115.200	230.400	151.237	23.693
Spring	78	0	78	115.200	259.200	181.662	25.971
Summer	78	0	78	86.400	230.400	173.169	29.169
Winter	78	0	78	86.400	230.400	164.308	31.858

Table 40: Minimum, Maximum, Mean, and Standard Deviations from Ontario 2023-2100 Seasonal *CMIP6* Precipitation Comparison.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	-0.070	P < .05	0.421
Spring	0.195	P < .05	0.025
Summer	0.173	P < .05	0.045
Winter	0.302	P < .05	<0.0001

Table 41: Kendall Tau, P-Value Expected, and P-Value Calculated from Ontario Seasonal *CMIP6* Precipitation from 2023-2100.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	78	0	78	120.960	241.920	172.357	24.749
Growing	78	0	78	111.086	209.829	164.192	18.421

Table 42: Minimum, Maximum, Mean, and Standard Deviations from Ontario 2023-2100 Dormancy Period vs. Growing Season *CMIP6* Precipitation Comparison.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	0.292	P < .05	<0.0001
Growing Season	0.124	P < .05	0.134

Table 43: Kendall Tau, Sens Slope, P-Value Expected, and P-Value Calculated from Ontario *CMIP6* Dormancy Period vs. Growing Season Precipitation from 2023-2100.

In the future scenario, up to 2100, a significant increase in precipitation is observed in the spring and summer, with a high significance increase in the winter period. As mentioned, many of Ontario's wine-growing regions are located beside either Lake Ontario or Lake Erie. These lakes do not freeze over entirely due to their size and depth. Failure to freeze over with higher temperatures could increase evaporation rates and humidity, possibly leading to higher precipitation rates. A significant precipitation trend can also be observed within the dormancy period alone.

Interestingly, the P-value exceeds the .05 confidence level in the growing season. Comparing precipitation seasonally, there are significant trends for both spring and summer. This phenomenon might be attributed to a non-significant fall trend, considering grape harvests typically run into the fall season. Thus, the inclusion of fall precipitation rates in the growing season average may have led to an insignificant trend. However, this would need further investigation. To sum up, precipitation in Ontario wine-producing areas is expected to increase but may increase in times of the year that do not interfere with grape growth.

Figure 27 shows high variability in proportional precipitation increases across the three wine-growing areas. Prince Edward County may experience the highest proportion of precipitation increase long-term, but this is simply a general assessment given what is seen from the Earth Engine visualization. It should be noted that some areas saw slight decreases in precipitation. However, most areas saw an increase in precipitation.

5.3. British Columbia Near-Surface Temperature

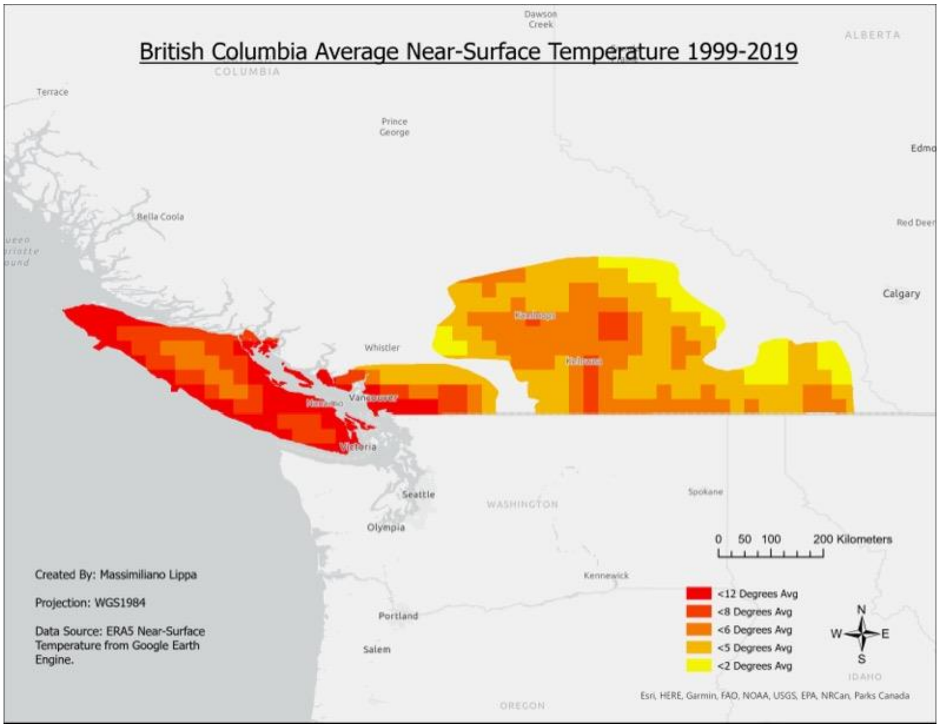


Figure 30: British Columbia *ERA5* Near-Surface Temperature Average 1999-2019

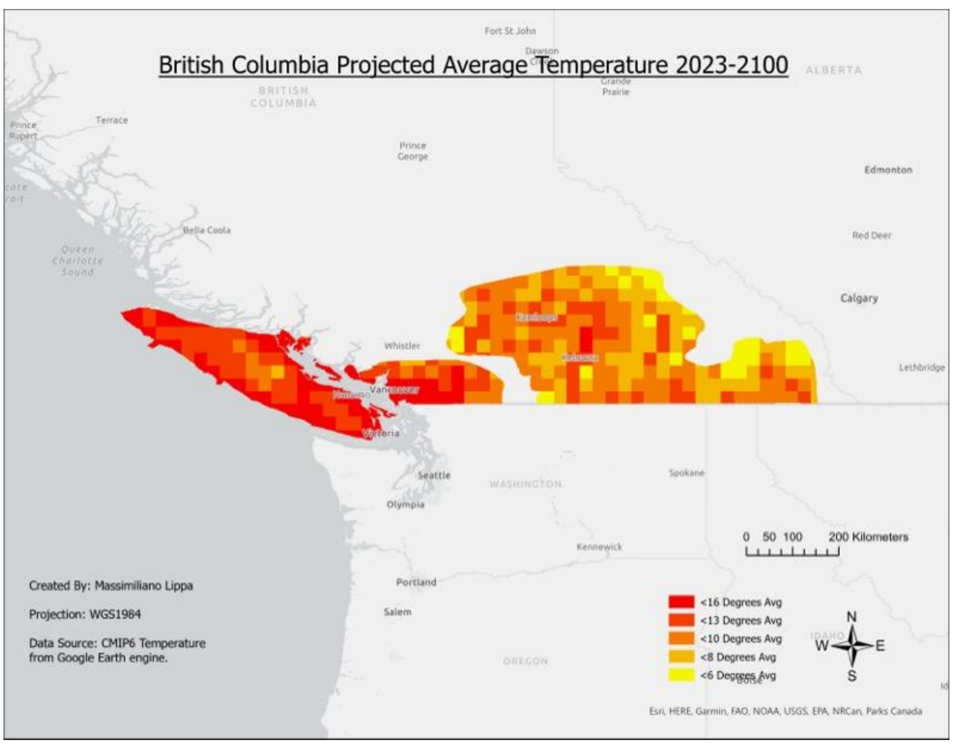


Figure 31: British Columbia Projected *CMIP6* Temperature Average 2023-2100

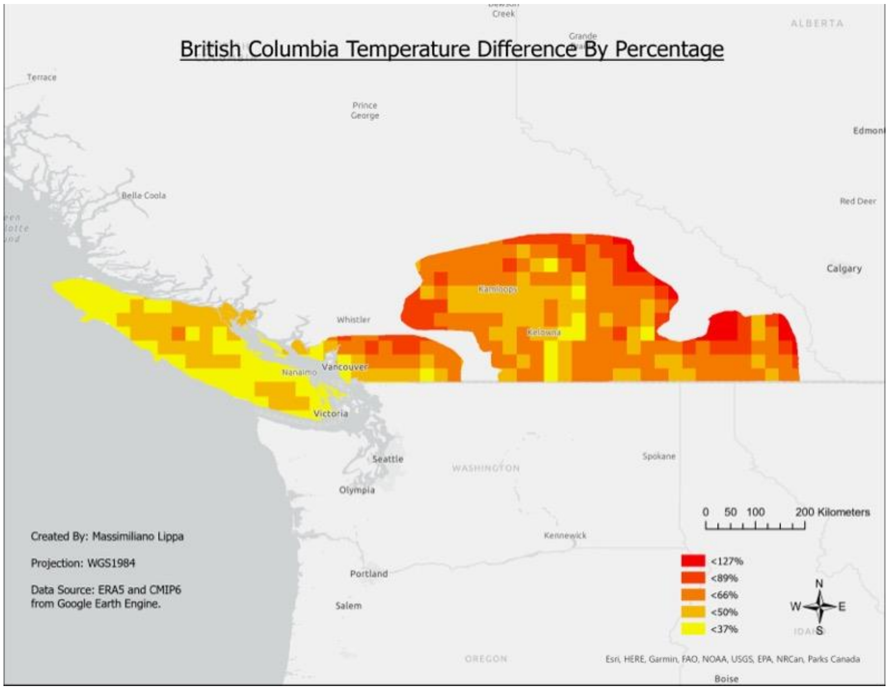


Figure 32: British Columbia Temperature Difference by Percentage

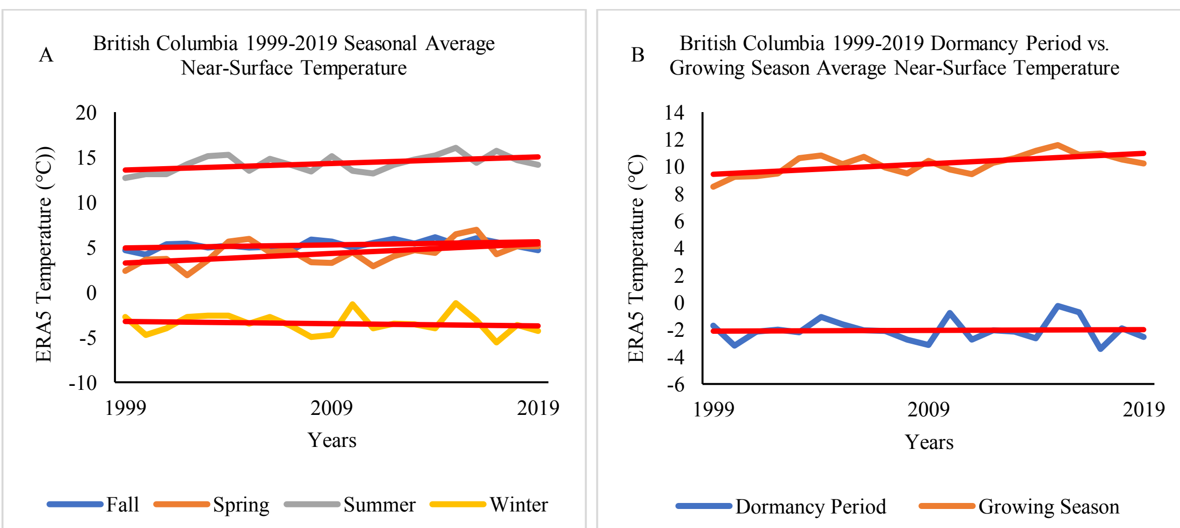


Figure 33: A) British Columbia Seasonal *ERA5* Near-Surface Temperature for 1999-2019 B) British Columbia Dormancy Period vs Growing Season *ERA5* Near-Surface Temperature for 1999-2019

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	21	0	21	4.168	6.105	5.254	0.497
Spring	21	0	21	1.882	6.931	4.304	1.278
Summer	21	0	21	12.685	16.033	14.295	0.930
Winter	21	0	21	-5.577	-1.213	-3.496	1.107

Table 44: Minimum, Maximum, Mean, and Standard Deviations from British Columbia 1999-2019 Seasonal *ERA* 5 Near-Surface Temperature Comparison.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	0.267	P < .05	0.091
Spring	0.352	P < .05	0.025
Summer	0.314	P < .05	0.046
Winter	-0.133	P < .05	0.398

Table 45: Kendall Tau, P-Value Expected, and P-Value Calculated from British Columbia Seasonal ERA5 Near-Surface Temperature data from 1999-2019.

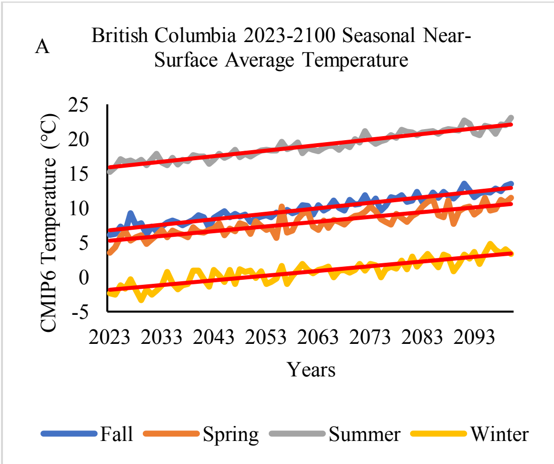
Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	21	0	21	-3.426	-0.258	-2.056	0.825
Growing	21	0	21	8.510	11.575	10.194	0.754

Table 46: Minimum, Maximum, Mean, and Standard Deviations from British Columbia 1999-2019 *ERA5* Near-Surface Temperature Dormancy Period vs. Growing Season Comparison.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	-0.029	P < .05	0.856
Growing Season	0.438	P < .05	0.005

Table 47: Kendall Tau, P-Value Expected, and P-Value Calculated from British Columbia *ERA5* Dormancy Period vs. Growing Season Near-Surface Temperature from 1999-2019.

In British Columbia, seasonal temperatures between 1999-2019 have seen significant increases in the spring and summer seasons, while winter and fall see no significant trend changes. The increasing trend of near-surface temperature is also reflected in the growing season while not occurring in the dormancy period. P-values outside of the spring and summer seasons remain insignificant, with P-values exceeding >.05. Areas of high near-surface temperature are observed primarily in the coastal regions of Vancouver Island and the Gulf Islands, with some spots of higher temperatures in the mountainous regions.



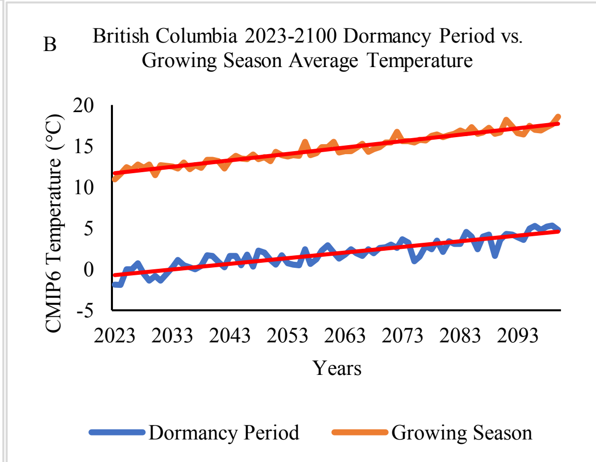


Figure 34: A) British Columbia Seasonal *CMIP6* Temperature Comparison for 2023-2100 B) British Columbia Dormancy Period vs Growing Season *CMIP6* Temperature Comparison for 2023-2100

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	78	0	78	6.110	13.520	9.840	1.905
Spring	78	0	78	3.522	11.474	7.917	1.802
Summer	78	0	78	15.216	23.052	18.979	1.903
Winter	78	0	78	-3.337	4.803	0.788	1.773

Table 48: Minimum, Maximum, Mean, and Standard Deviations from British Columbia 2023-2100 Seasonal *CMIP6* Temperature Comparison.

Season	**Kendall Tau**	**P-Value Expected**	**P-Value Calculated**
Fall	0.811	P < .05	<0.0001
Spring	0.696	P < .05	<0.0001
Summer	0.820	P < .05	<0.0001
Winter	0.700	P < .05	<0.0001

Table 49: Kendall Tau, P-Value Expected, and P-Value Calculated from British Columbia Seasonal CMIP6 Temperature from 2023-2100.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	78	0	78	-1.907	5.320	1.931	1.739
Growing	78	0	78	10.946	18.571	14.703	1.835

Table 50: Minimum, Maximum, Mean, and Standard Deviations from British Columbia 2023-2100 *CMIP6* Dormancy Period vs. Growing Season Temperature Comparison.

Dormancy vs. Growing Season	**Kendall Tau**	**P-Value Expected**	**P-Value Calculated**
Dormancy Period	0.733	P < .05	<0.0001
Growing Season	0.850	P < .05	<0.0001

Table 51: Kendall Tau, P-Value Expected, and P-Value Calculated from British Columbia *CMIP6* Dormancy Period vs. Growing Season Temperature from 2023-2100.

Near-surface temperature up to 2100 in British Columbia results in highly significant trends with a P-value of <.0001. The high significance values of these results suggest an increasing near-surface temperature trend amongst the wine-growing areas of British Columbia, with Kendall tau correlation values closer to 1 suggesting higher correlation within ranked pairs.

In **figure 32**, mapping the percentage difference of near-surface temperature between the 1999-2019 reference period and the 2023-2100 future period, it can be observed that there is a high variability of near-surface temperature increases across the provinces wine growing regions. Vancouver Island and the Gulf Islands have relatively low percentages of temperature change, staying below the 50% temperature increase. In comparison, inland wine regions experience high temperature increases of up to 66% or more of their surface temperature in the reference period. These areas inland are traditionally colder in near-surface temperatures. Therefore, even smaller increases will result in higher percentages as the increased value makes up a more significant proportion of the reference near-surface temperature.

5.3.1. British Columbia Precipitation

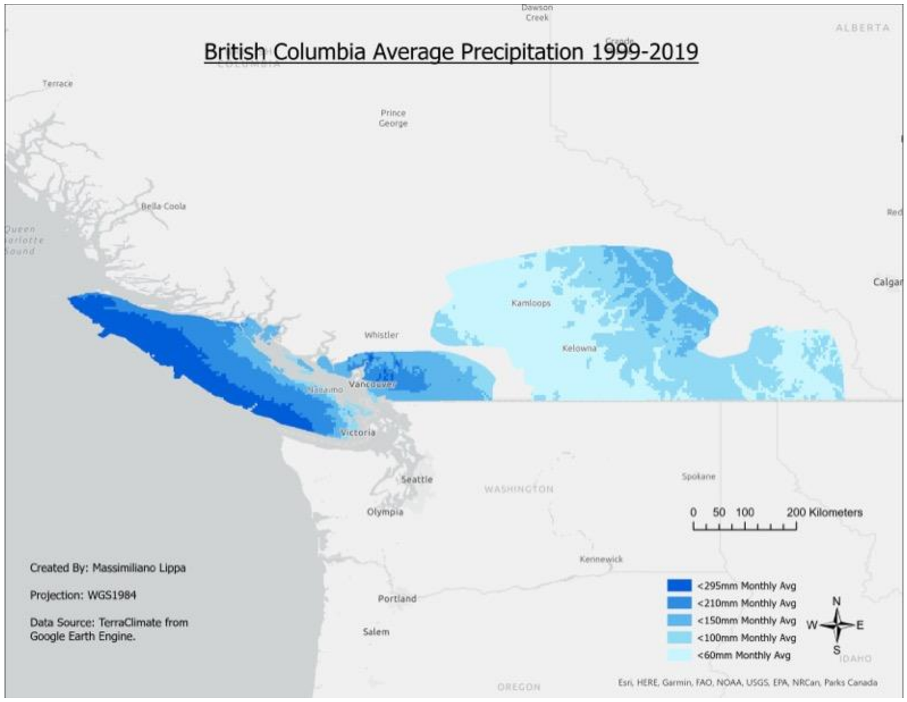


Figure 35: British Columbia *TerraClimate* Precipitation Average 1999-2019

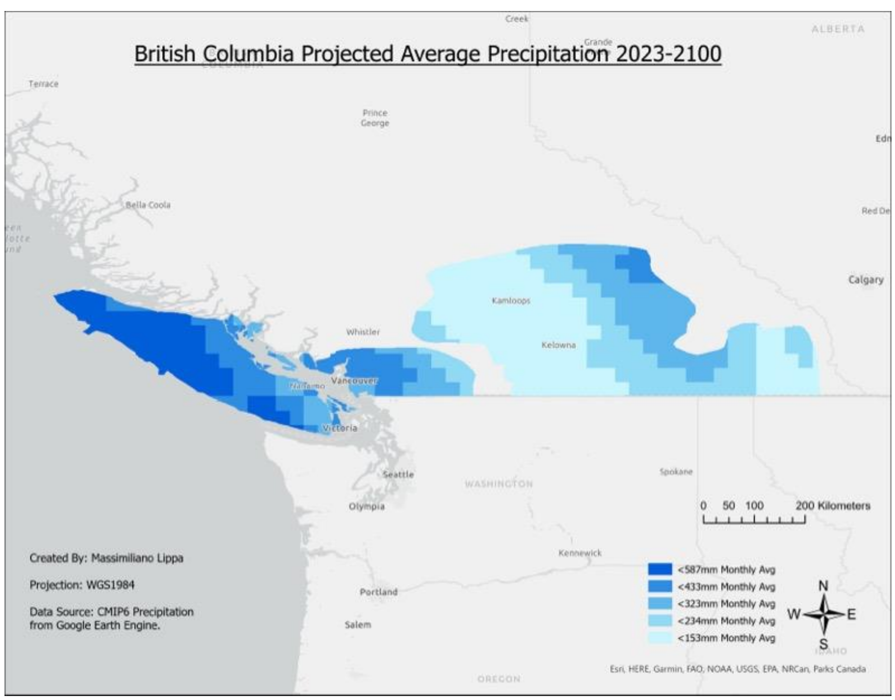


Figure 36: British Columbia *CMIP6* Precipitation Average 2023-2100

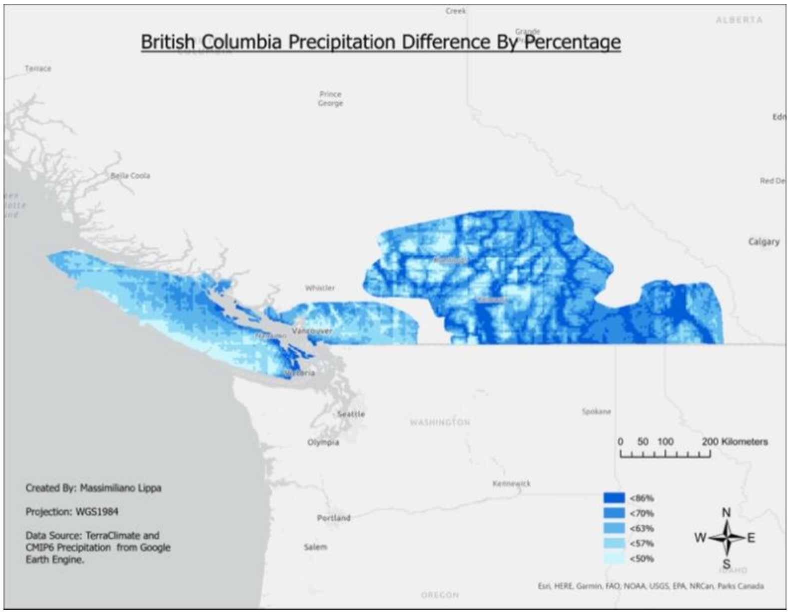


Figure 37: British Columbia Precipitation Difference by Percentage

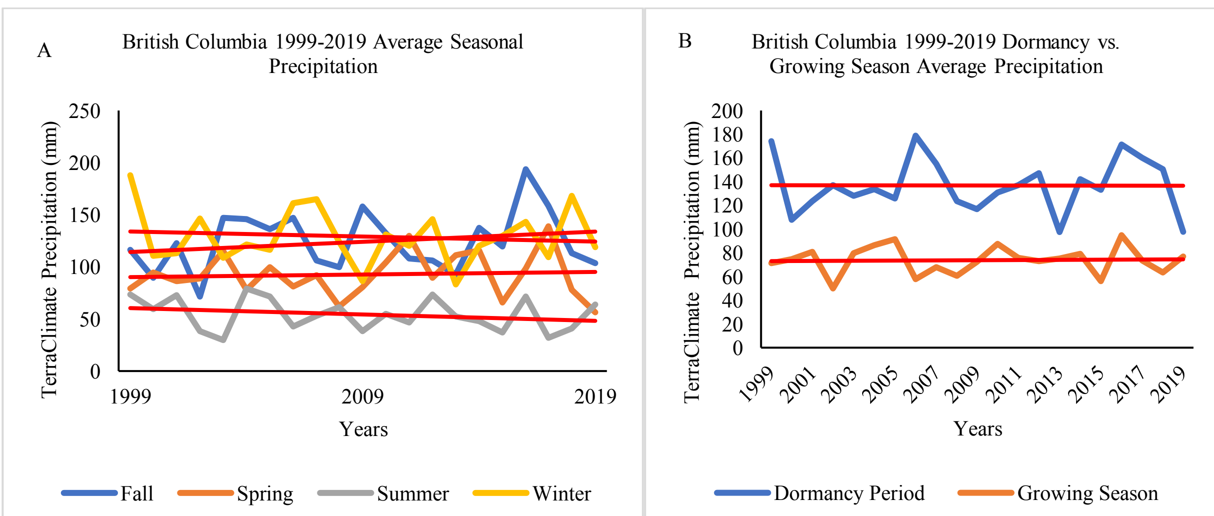


Figure 38: A) British Columbia Seasonal *TerraClimate* Precipitation Comparison for 1999-2019 B) British Columbia Dormancy Period vs Growing Season *TerraClimate* Precipitation Comparison for 1999-2019

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	21	0	21	107.416	241.347	154.450	35.082
Spring	21	0	21	60.941	159.792	107.083	25.058
Summer	21	0	21	29.973	69.439	49.770	10.325
Winter	21	0	21	112.547	238.950	162.178	38.679

Table 52: Minimum, Maximum, Mean, and Standard Deviations from British Columbia 1999-2019 *TerraClimate* Precipitation Seasonal Comparison.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	-0.057	P < .05	0.717
Spring	-0.010	P < .05	0.952
Summer	-0.105	P < .05	0.506
Winter	-0.276	P < .05	0.080

Table 53: Kendall Tau, P-Value Expected, and P-Value Calculated from British Columbia Seasonal TerraClimate Precipitation from 1999-2019.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	21	0	21	96.084	255.834	171.083	35.589
Growing	21	0	21	54.422	103.949	80.718	12.125

Table 54: Minimum, Maximum, Mean, and Standard Deviations from British Columbia 1999-2019 *TerraClimate* Precipitation Dormancy Period vs. Growing Season Comparison.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	-0.171	P < .05	0.296
Growing Season	0.095	P < .05	0.572

Table 55: Kendall Tau, P-Value Expected, and P-Value Calculated from British Columbia *TerraClimate* Precipitation Dormancy Period vs. Growing Season from 1999-2019.

To no surprise, the areas with the highest precipitation rates between 1999-2019 are in the coastal regions. Some higher precipitation rates are seen in cities like Vancouver. However, the Rocky Mountains lift the warm moist air masses coming off the Pacific Ocean, and much of the potential precipitation remains west of the mountain range.

Short-term precipitation data for British Columbia indicates a climate with no significant increasing or decreasing trends. There may be a slightly increasing trend for winter precipitation averages, but an insignificant P-value implies that the null hypothesis that no trend is occurring should be accepted. When comparing season and dormancy periods versus the growing season, no trends have indicated that the climate has experienced ongoing change over the 20 years of interest in precipitation.

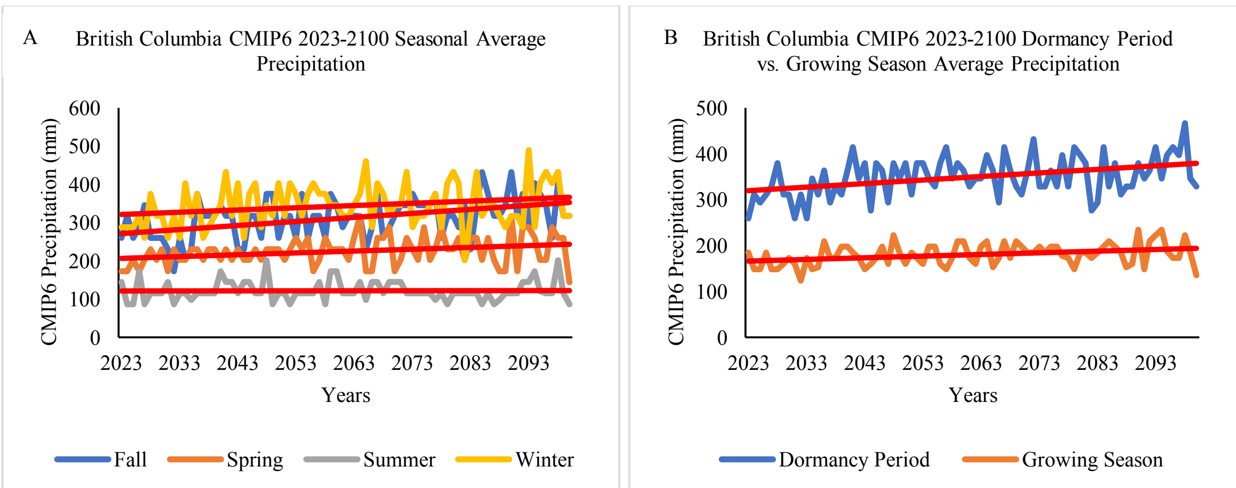


Figure 39: A) British Columbia Seasonal *CMIP6* Precipitation Comparison for 2023-2100 B) British Columbia Dormancy Period vs Growing Season *CMIP6* Precipitation Comparison for 2023-2100

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	78	0	78	172.800	432.000	312.000	53.006
Spring	78	0	78	144.000	316.800	224.862	37.149
Summer	78	0	78	86.400	201.600	121.773	25.721
Winter	78	0	78	201.600	489.600	343.754	55.376

Table 56: Minimum, Maximum, Mean, and Standard Deviations from British Columbia 2023-2100 *CMIP6* Seasonal Precipitation Comparison.

Season	**Kendall Tau**	**P-Value Expected**	**P-Value Calculated**
Fall	0.316	P < .05	<.00001
Spring	0.232	P < .05	0.006

Summer	0.008	P < .05	0.926
Winter	0.163	P < .05	0.048

Table 57: Kendall Tau, P-Value Expected, and P-Value Calculated from British Columbia Seasonal *CMIP6* Precipitation from 2023-2100.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	78	0	78	259.200	466.600	349.365	43.563
Growing	78	0	78	123.400	234.500	180.045	23.672

Table 58: Minimum, Maximum, Mean, and Standard Deviations from British Columbia 2023-2100 *CMIP6* Dormancy Period vs. Growing Season Precipitation Comparison.

Dormancy vs. Growing Season	**Kendall Tau**	**P-Value Expected**	**P-Value Calculated**
Dormancy Period	0.275	P < .05	0.001
Growing Season	0.247	P < .05	0.002

Table 59: Kendall Tau, P-Value Expected, and P-Value Calculated from British Columbia *CMIP6* Dormancy Period vs. Growing Season Precipitation from 2023-2100.

Future precipitation projections do show significant upward trends moving into the future. The trends observed are average across the main growing regions of British Columbia and do not delineate trend variation region by region. The increasing trend until 2100 implies that the future in the wine-growing regions will be wetter alongside the increased near-surface temperature described above.

Referring to the mapped differences (**Figure 37**), most of the precipitation appears to occur in the inland regions of British Columbia in the wine regions of the Fraser Valley and the Similkameen Valley. The wine-growing areas of Vancouver Island and the Gulf Islands are seeing the lowest increase in precipitation compared to the inland regions.

5.4 Quebec Near-Surface Temperature

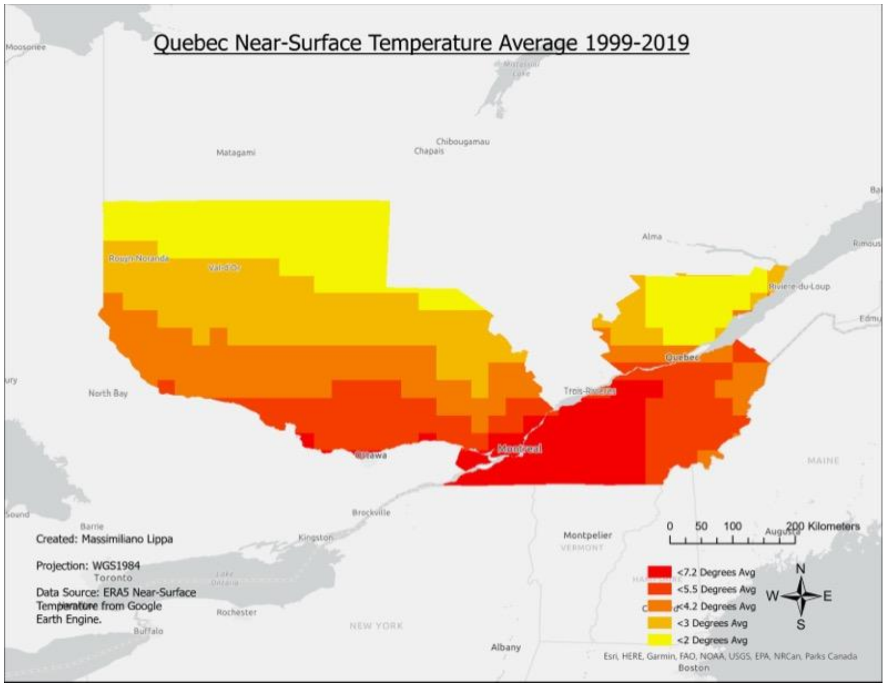


Figure 40: Quebec *ERA5* Near-Surface Temperature Average 1999-2019

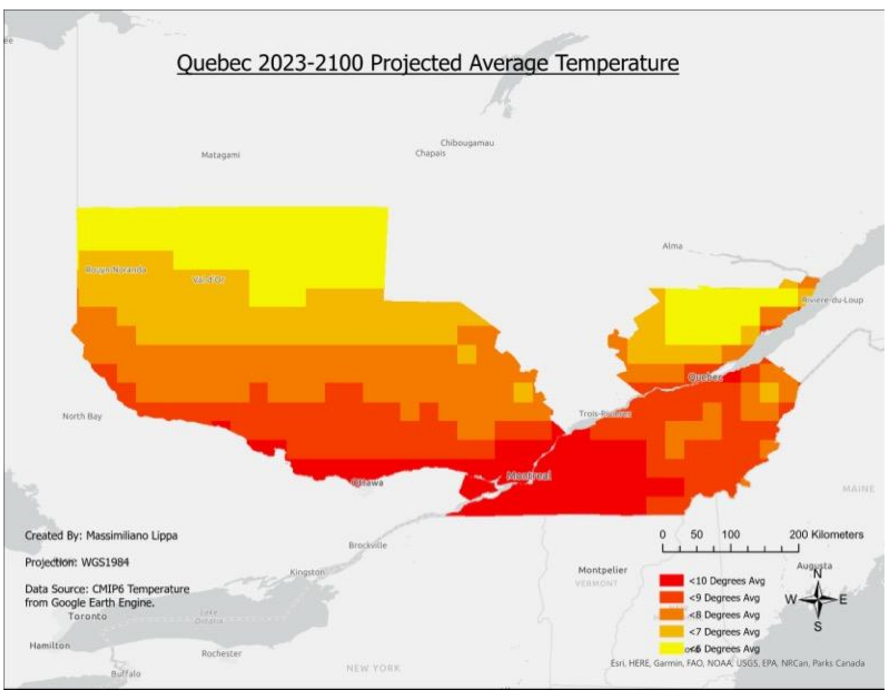


Figure 41: Quebec *CMIP6* Projected Temperature Average 2023-2100

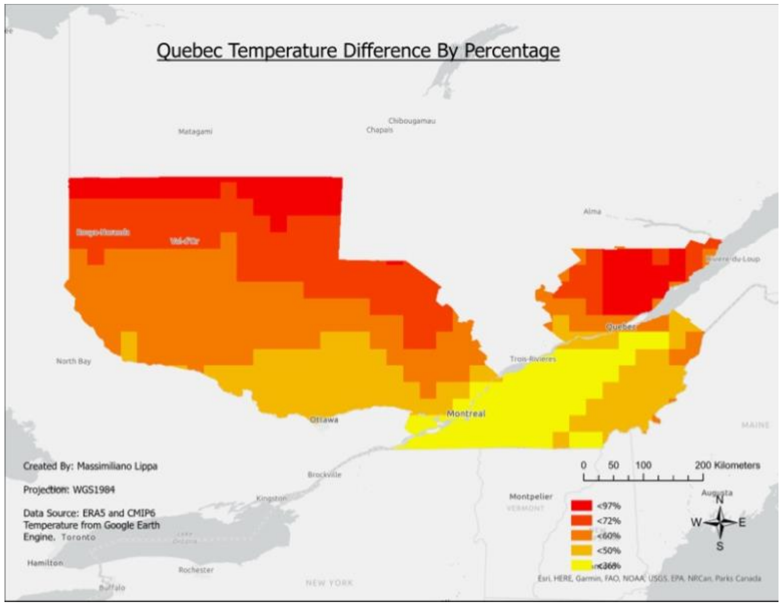


Figure 42: Quebec Temperature Difference by Percentage

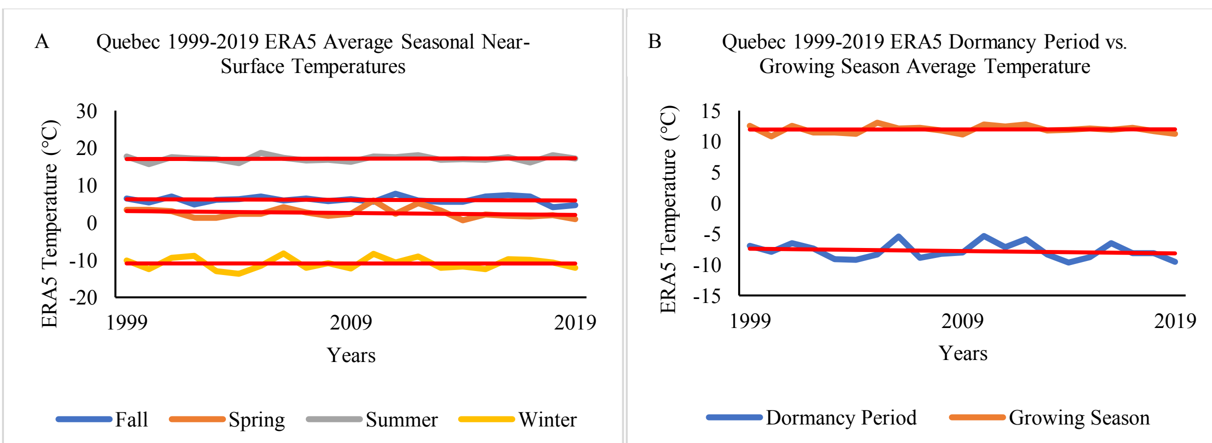


Figure 43: A) Quebec Seasonal *ERA5* Near-Surface Temperature for 1999-2019 B) Quebec Dormancy Period vs Growing Season *ERA5* Near-Surface Temperature Comparison for 1999-2019

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	21	0	21	4.129	7.746	6.101	0.922
Spring	21	0	21	0.623	5.924	2.582	1.327
Summer	21	0	21	15.664	18.693	17.133	0.740
Winter	21	0	21	-13.700	-8.243	-10.931	1.577

Table 60: Minimum, Maximum, Mean, and Standard Deviations from Quebec 1999-2019 *ERA5* Seasonal Near-Surface Temperature Comparison.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	-0.067	P < .05	0.699
Spring	-0.295	P < .05	0.066
Summer	0.029	P < .05	0.882
Winter	0.019	P < .05	0.929

Table 61: Kendall Tau, P-Value Expected, and P-Value Calculated from Quebec Seasonal *ERA5* Near-Surface Temperature from 1999-2019.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	21	0	21	-9.659	-5.347	-7.793	1.288
Growing	21	0	21	10.819	13.037	11.946	0.606

Table 62: Minimum, Maximum, Mean, and Standard Deviations from Quebec 1999-2019 *ERA5* Near-Surface Temperature Dormancy Period vs. Growing Comparison.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	-0.124	P < .05	0.456
Growing Season	0.000	P < .05	0.976

Table 63: Kendall Tau, P-Value Expected, and P-Value Calculated from Quebec *ERA5* Dormancy Period vs. Growing Season Near-Surface Temperature from 1999-2019

In evaluating near-surface temperature for the 1999-2019 reference period in Quebec, no trends of significance were observed for our seasonally graphed data, or our data separated by dormancy and growing seasons. The P-value for the trends in interest all went above the confidence level of .05.

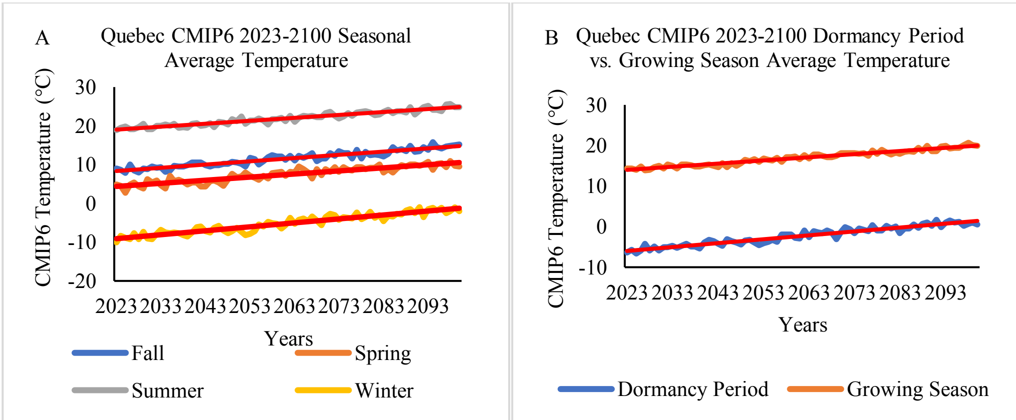


Figure 44: A) Quebec Seasonal *CMIP6* Temperature for 2023-2100 B) Quebec Dormancy Period vs Growing Season *CMIP6* Temperature Comparison for 2023-2100

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	78	0	78	7.861	15.790	11.559	1.994
Spring	78	0	78	2.730	10.919	7.453	1.979
Summer	78	0	78	18.877	25.632	21.940	1.792
Winter	78	0	78	-10.055	-1.024	-5.176	2.437

Table 64: Minimum, Maximum, Mean, and Standard Deviations from Quebec 2023-2100 *CMIP6* Temperature Seasonal Comparison.

Season	**Kendall Tau**	**P-Value Expected**	**P-Value Calculated**
Fall	0.776	P < .05	<0.0001
Spring	0.717	P < .05	<0.0001
Summer	0.798	P < .05	<0.0001
Winter	0.756	P < .05	<0.0001

Table 65: Kendall Tau, P-Value Expected, and P-Value Calculated from Quebec Seasonal *CMIP6* Temperature from 2023-2100.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	78	0	78	-6.630	1.681	-2.292	2.277
Growing	78	0	78	13.875	20.658	16.970	1.814

Table 66: Minimum, Maximum, Mean, and Standard Deviations from Quebec 2023-2100 *CMIP6* Temperature Dormancy Period vs. Growing Season Comparison.

Dormancy vs. Growing Season	**Kendall Tau**	**P-Value Expected**	**P-Value Calculated**
Dormancy Period	0.814	P < .05	<0.0001
Growing Season	0.843	P < .05	<0.0001

Table 67: Kendall Tau, P-Value Expected, and P-Value Calculated from Quebec 2023-2100 *CMIP6* Temperature Dormancy Period vs. Growing Season Comparison.

Future precipitation projections in Quebec result in highly significant trends for the dormancy and growing seasons. The same result can be seen seasonally, with significant near-surface temperature growth in the fall, spring, summer, and winter seasons.

In **figure 42**, Quebec's near-surface temperature difference appears to take a ladder-like effect, with the lowest increases of near-surface temperature occurring in the southern parts of the province and the highest in the furthest north. This stratified pattern was present when evaluating the 1999-2019 reference period and the 2023-2100 future period. There was an increase in near-surface temperature across all growing areas of Quebec, indicating a potential for a province-wide near-surface temperature alteration.

5.4.1 Quebec Precipitation

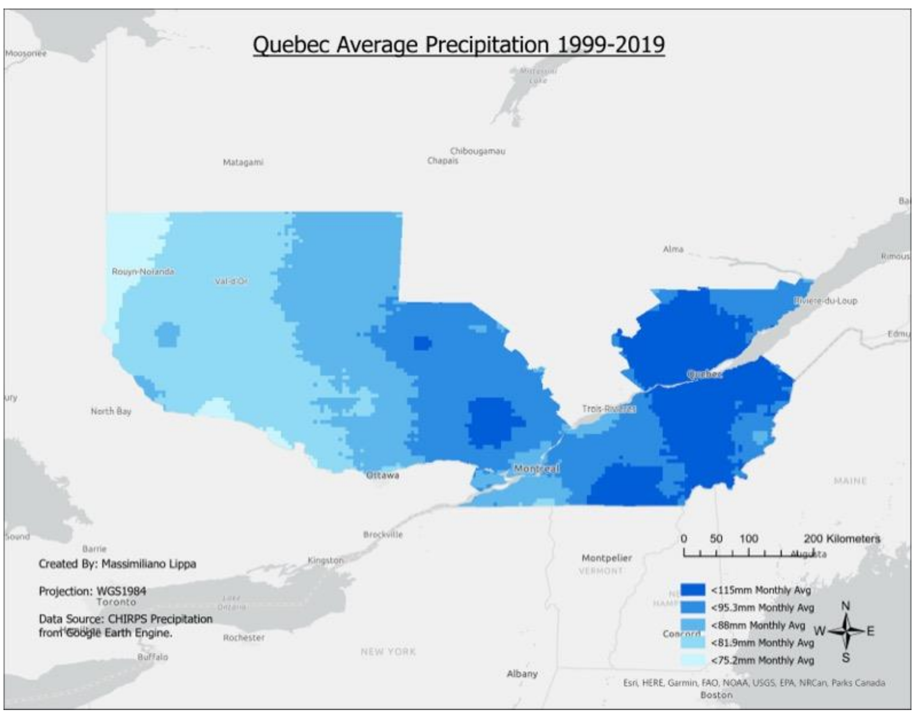


Figure 45: Quebec *CHIRPS* Precipitation Average 1999-2019

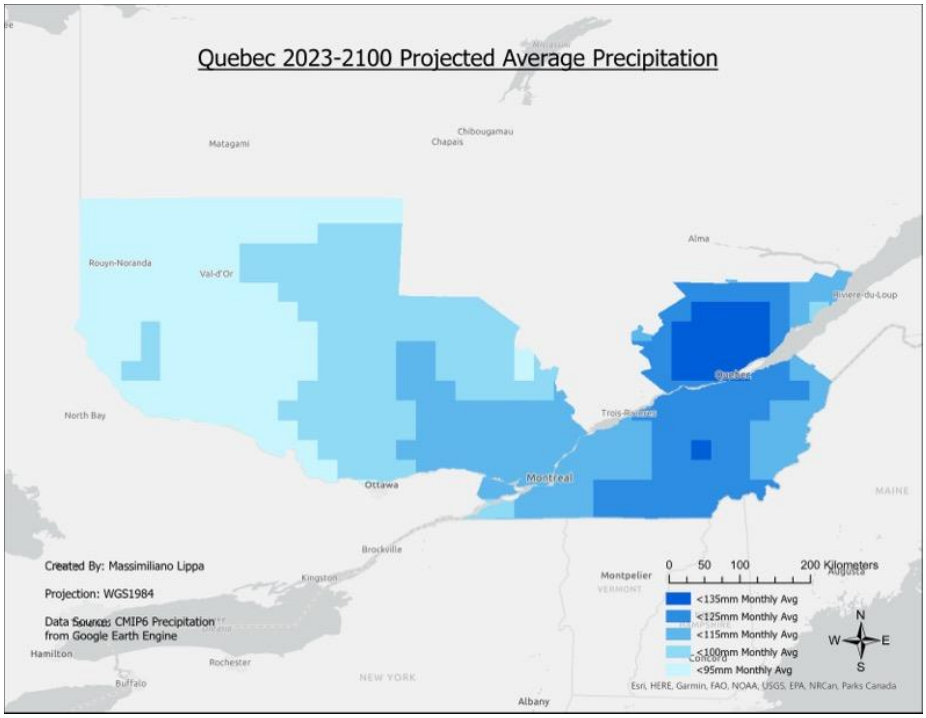


Figure 46: Quebec *CMIP6* Projected Precipitation Average 2023-2100

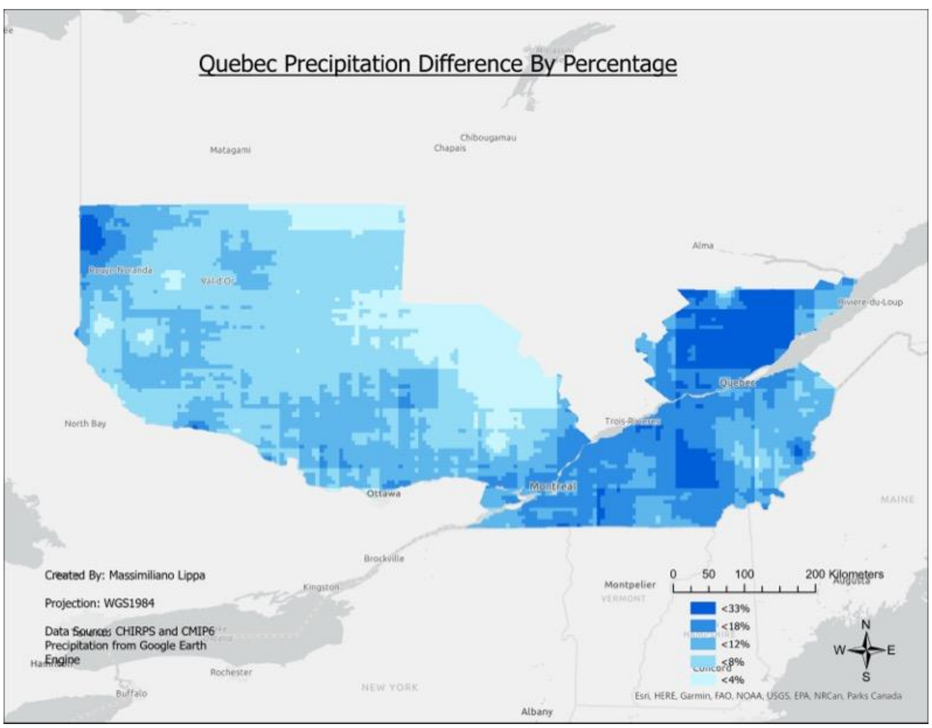
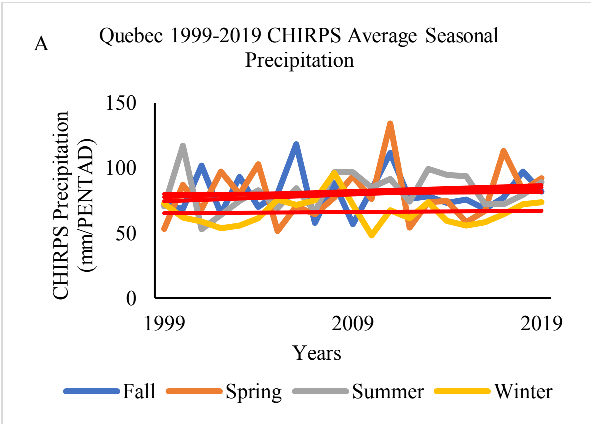


Figure 47: Quebec Precipitation Difference by Percentage



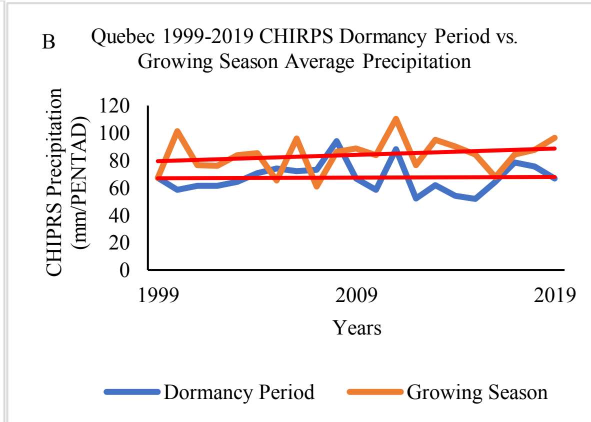


Figure 48: A) Quebec Seasonal *CHIRPS* Precipitation for 1999-2019 B) Quebec Dormancy Period vs Growing Season *CHIRPS* Precipitation Comparison for 1999-2019

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	21	0	21	56.777	118.153	80.623	16.206
Spring	21	0	21	51.454	134.109	79.570	20.782
Summer	21	0	21	52.789	116.967	82.153	14.897
Winter	21	0	21	48.060	96.049	66.061	10.596

Table 68: Minimum, Maximum, Mean, and Standard Deviations from Quebec 1999-2019 *CHIRPS* Precipitation Seasonal Comparison.

Season	**Kendall Tau**	**P-Value Expected**	**P-Value Calculated**
Fall	0.057	P < .05	0.744
Spring	0.095	P < .05	0.572
Summer	0.200	P < .05	0.220
Winter	0.019	P < .05	0.929

Table 69: Kendall Tau, P-Value Expected, and P-Value Calculated from Quebec 1999-2019 *CHIRPS* Precipitation Seasonal Comparison.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy Period	21	0	21	51.886	94.066	67.422	10.887
Growing Season	21	0	21	60.891	110.305	84.016	12.410

Table 70: Minimum, Maximum, Mean, and Standard Deviations from Quebec 1999-2019 *CHIRPS* Precipitation Dormancy Season vs. Growing Season Comparison.

Dormancy vs. Growing Season	**Kendall Tau**	**P-Value Expected**	**P-Value Calculated**
Dormancy Period	0.048	P < .05	0.789
Growing Season	0.210	P < .05	0.198

Table 71: Kendall Tau, P-Value Expected, and P-Value Calculated from Quebec 1999-2019 *CHIRPS* Precipitation Dormancy Period vs. Growing Season Comparison.

Short-term climate trends regarding precipitation in the province of Quebec follow similar trends seen in other provinces. Trends with slight increases or decreases are occurring; however, none with any significance; the null hypothesis that no significant trends are occurring is accepted. Most precipitation between the 1999-2019 period appears to occur in the eastern portions of Quebec, around the regions near Quebec City on both sides of the St. Lawrence River. In interesting patterns of east-west precipitation, stratification can be observed where lower precipitation rates are observed in the western parts of the province and increase moving eastward.

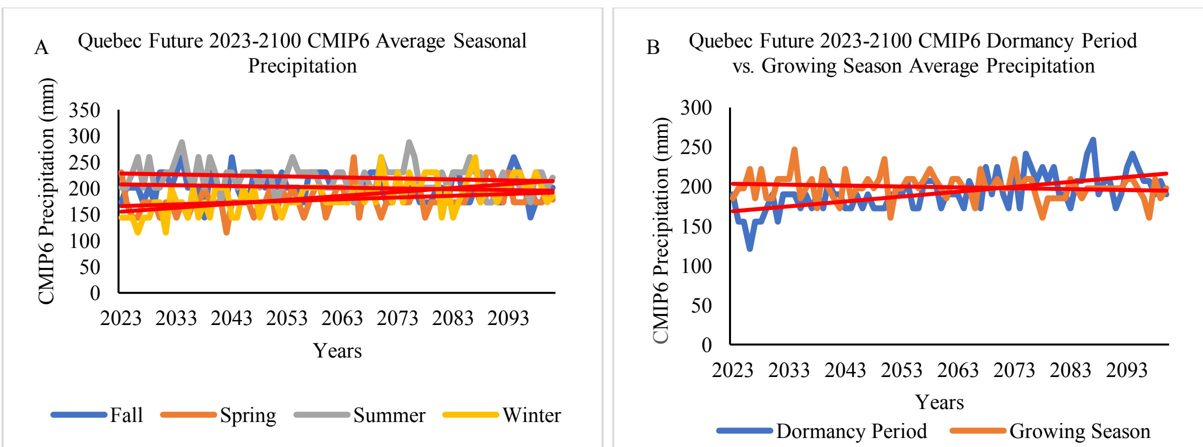


Figure 49: A) Quebec Seasonal *CMIP6* Precipitation for 2023-2100 B) Quebec Dormancy Period vs Growing Season *CMIP6* Precipitation Comparison for 2023-2100

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	78	0	78	144.000	259.200	201.231	25.631
Spring	78	0	78	115.200	259.200	178.708	25.150
Summer	78	0	78	172.800	288.000	220.800	25.281
Winter	78	0	78	115.200	259.200	184.615	30.941

Table 72: Minimum, Maximum, Mean, and Standard Deviations from Quebec 2023-2100 *CMIP6* Precipitation Seasonal Comparison.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	0.057	P < .05	0.744
Spring	0.095	P < .05	0.572
Summer	0.200	P < .05	0.220
Winter	0.019	P < .05	0.929

Table 73: Kendall Tau, P-Value Expected, and P-Value Calculated from Quebec 2023-2100 *CMIP6* Precipitation Seasonal Comparison.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	78	0	78	-6.630	1.681	-2.292	2.277
Growing	78	0	78	13.875	20.658	16.970	1.814

Table 74: Minimum, Maximum, Mean, and Standard Deviations from Quebec 2023-2100 *CMIP6* Precipitation Dormancy Period vs. Growing Season Comparison.

Dormancy vs. Growing Season	**Kendall Tau**	**P-Value Expected**	**P-Value Calculated**
Dormancy Period	0.814	P < .05	<0.0001
Growing Season	0.843	P < .05	<0.0001

Table 75: Kendall Tau, P-Value Expected, and P-Value Calculated from Quebec 2023-2100 *CMIP6* Precipitation Dormancy Period vs. Growing Season Comparison.

Trends up until 2100 for Quebec's near-surface temperature are highly significant for only the growing and dormancy seasons. Insignificant trends are observed throughout the individual seasons. Growing and dormancy seasons stretch over two seasons each. Therefore, insignificant seasons do not necessarily nullify the highly significant growing season and dormancy period results. Most of the precipitation change by assessing **figure 47** will occur within the eastern reaches of the provinces, with a small area of high proportional increase occurring in the northwest corner.

5.5 Nova Scotia Near-Surface Temperature

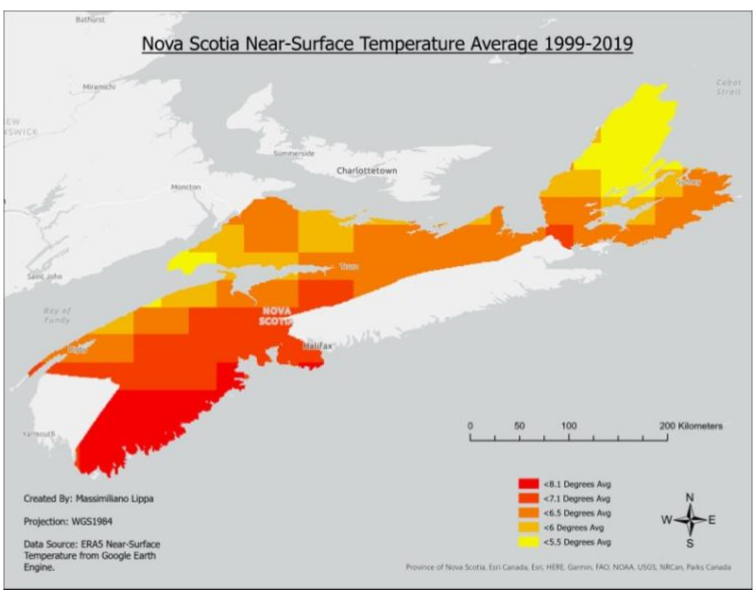


Figure 50: Nova Scotia *ERA5* Near-Surface Temperature Average 1999-2019

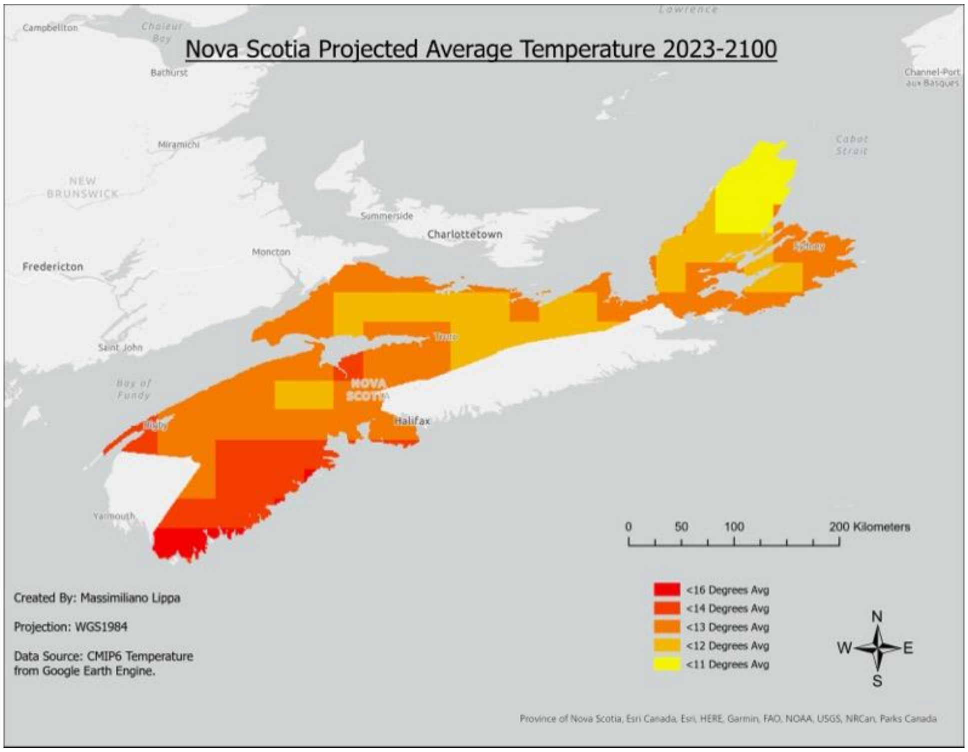


Figure 51: Nova Scotia *CMIP6* Temperature Average 2023-2100

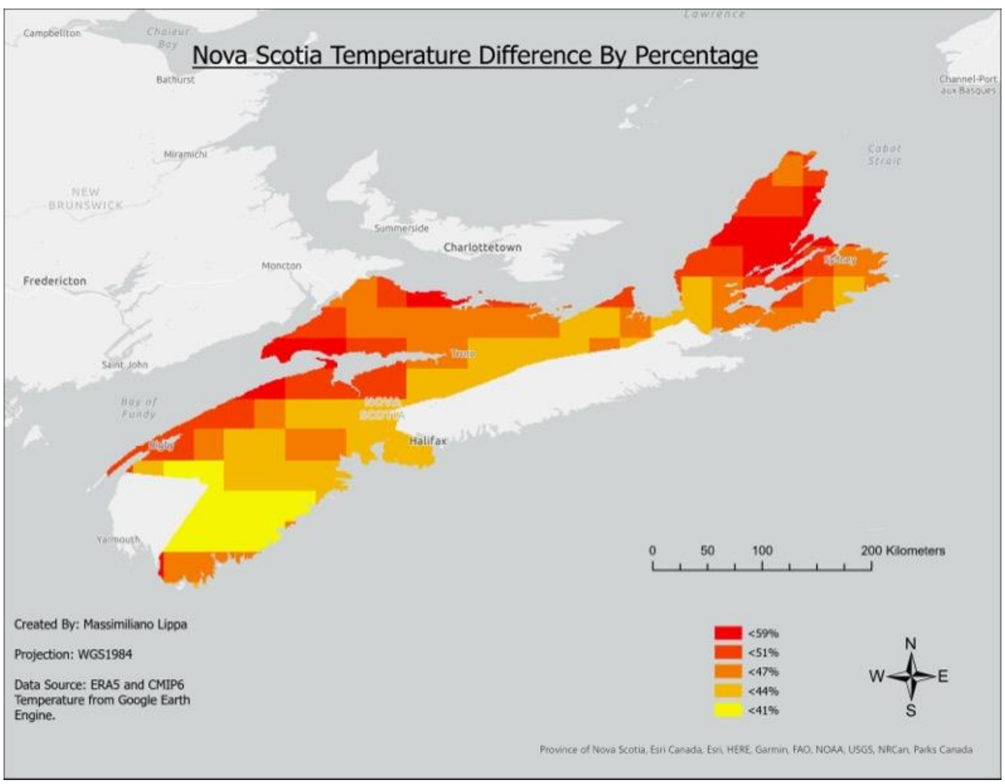


Figure 52: Nova Scotia Temperature Difference by Percentage

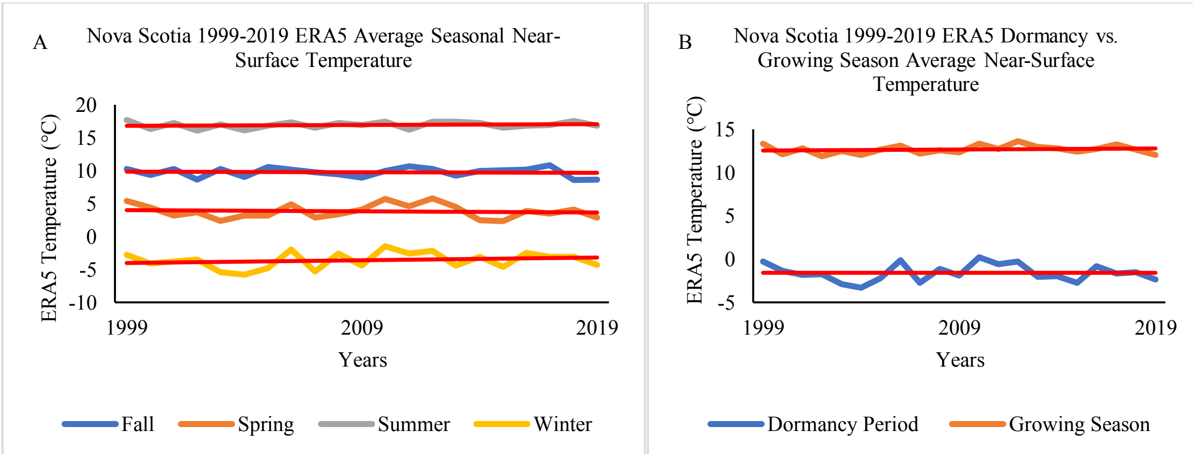


Figure 53: A) Nova Scotia Seasonal *ERA5* Near-Surface Temperature for 1999-2019 B) Nova Scotia Dormancy Period vs Growing Season *ERA5* Near-Surface Temperature for 2023-2100

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	21	0	21	8.579	10.821	9.756	0.699
Spring	21	0	21	2.337	5.784	3.821	1.044
Summer	21	0	21	16.077	17.687	16.932	0.481
Winter	21	0	21	-5.797	-1.488	-3.612	1.219

Table 76: Minimum, Maximum, Mean, and Standard Deviations from Nova Scotia 1999-2019 *ERA5* Near-Surface Temperature Comparison.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	-0.057	P < .05	0.744
Spring	-0.057	P < .05	0.744
Summer	0.124	P < .05	0.456
Winter	0.114	P < .05	0.493

Table 77: Kendall Tau, P-Value Expected, and P-Value Calculated from Nova Scotia 1999-2019 *ERA5* Seasonal Near-Surface Temperature Comparison.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	21	0	21	-3.311	0.208	-1.587	0.993
Growing	21	0	21	11.881	13.626	12.661	0.483

Table 78: Minimum, Maximum, Mean, and Standard Deviations from Nova Scotia 1999-2019 *ERA5* Near-Surface Temperature Dormancy Period vs. Growing Season Comparison.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	-0.019	P < .05	0.929
Growing Season	0.095	P < .05	0.572

Table 79: Kendall Tau, P-Value Expected, and P-Value Calculated from Nova Scotia 1999-2019 *ERA5* Near-Surface Temperature Dormancy Period vs. Growing Season Comparison.

Average near-surface temperature varies across the province of Nova Scotia. In the northeastern parts, up around Cape Breton Island, NST hovers around 5.5 °C, whereas the southwest parts are around 13.5 °C to 16 °C. The reference period of 1999-2019 for the province of Nova Scotia illustrates relatively stable growing conditions regarding near-surface temperature. With P-values for near surface trends being insignificant both seasonally and when comparing the growing season to the dormancy period, the climate within the 20-year reference timespan of interest does not seem to have changed drastically.

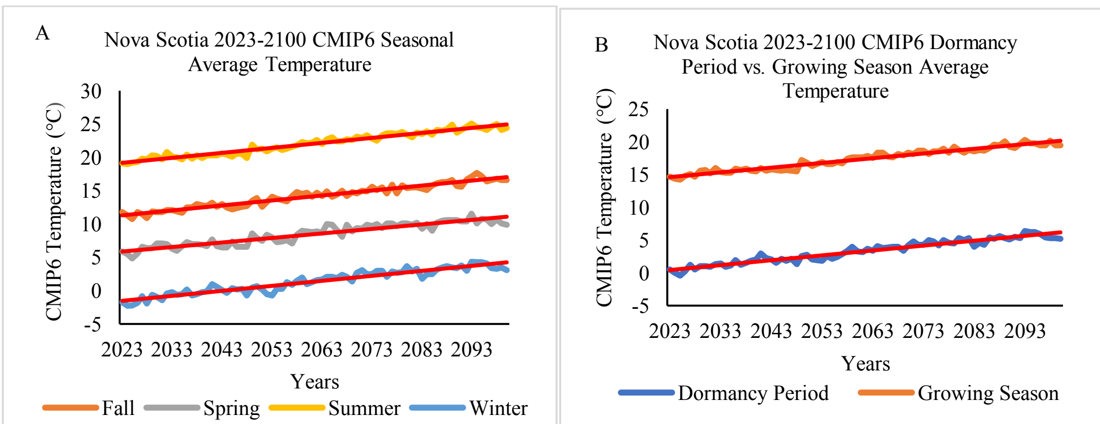


Figure 54: A) Nova Scotia Seasonal *CMIP6* Temperature for 2023-2100 B) Nova Scotia Dormancy Period vs Growing Season *CMIP6* Temperature for 2023-2100

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	78	0	78	10.740	17.666	14.166	1.745
Spring	78	0	78	4.831	11.543	8.481	1.646
Summer	78	0	78	18.986	25.071	22.061	1.741
Winter	78	0	78	-2.273	4.328	1.357	1.791

Table 80: Minimum, Maximum, Mean, and Standard Deviations from Nova Scotia 2023-2100 *CMIP6* Temperature Seasonal Comparison.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	0.841	P < .05	<0.0001
Spring	0.767	P < .05	<0.0001
Summer	0.867	P < .05	<0.0001
Winter	0.806	P < .05	<0.0001

Table 81: Kendall Tau, P-Value Expected, and P-Value Calculated from Nova Scotia 2023-2100 *CMIP6* Temperature Seasonal Comparison.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	78	0	78	-0.419	6.389	3.304	1.756
Growing	78	0	78	14.231	20.292	17.383	1.676

Table 82: Minimum, Maximum, Mean, and Standard Deviations from Nova Scotia 2023-2100 *CMIP6* Temperature Dormancy Period vs. Growing Season Comparison.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	0.835	P < .05	<0.0001
Growing Season	0.849	P < .05	<0.0001

Table 83: Kendall Tau, P-Value Expected, and P-Value Calculated from Nova Scotia 2023-2100 *CMIP6* Temperature Dormancy Period vs. Growing Season Comparison.

Future projections of near-surface temperatures for Nova Scotia result in highly significant trends both seasonally and when comparing dormancy and growing seasons. The highest increase rates are split between the coastal regions on the province's northern reaches and in Cape Breton Island, with the lowest increases occurring inland and in the South Shore wine-growing areas. The results suggest future warming trends across the peninsula that will impact all wine-growing areas.

5.5.1 Nova Scotia Precipitation

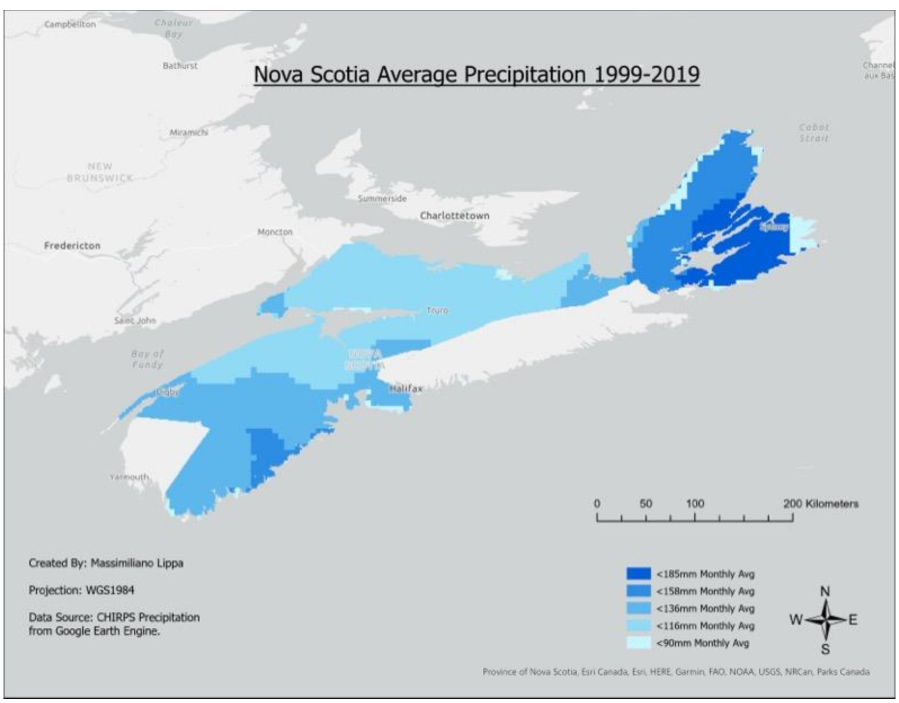


Figure 55: Nova Scotia *CHIRPS* Precipitation Average 1999-2019

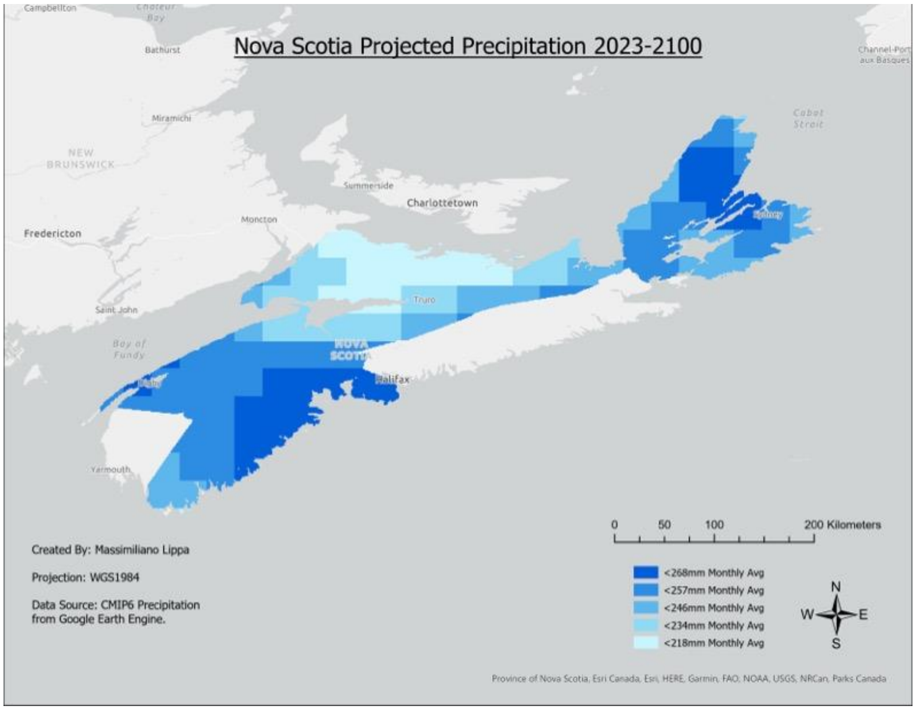


Figure 56: Nova Scotia *CMIP6* Projected Precipitation Average 2023-2100

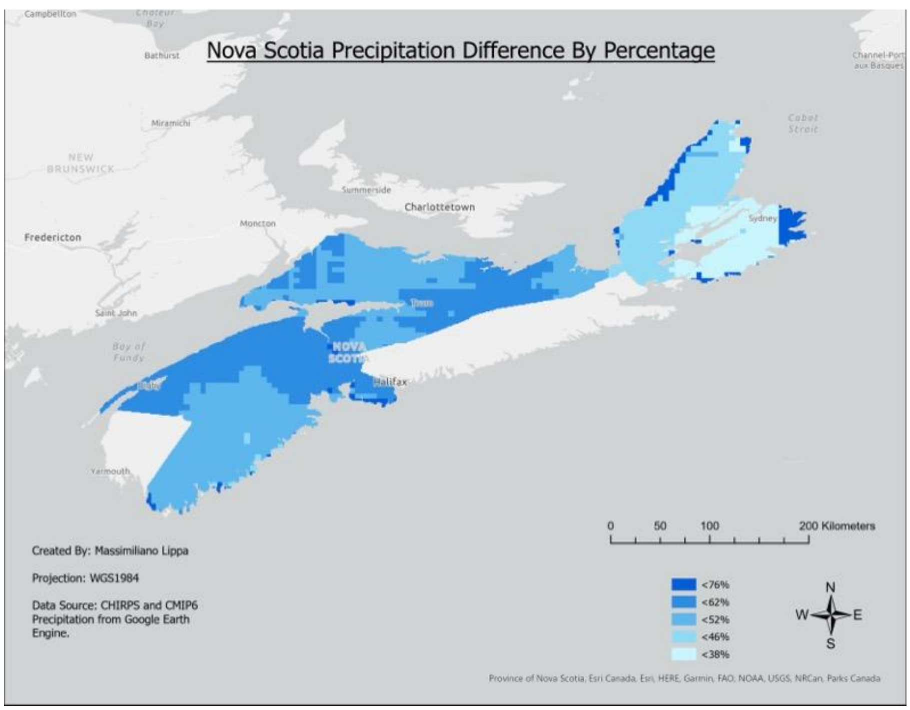


Figure 57: Nova Scotia Precipitation Difference by Percentage

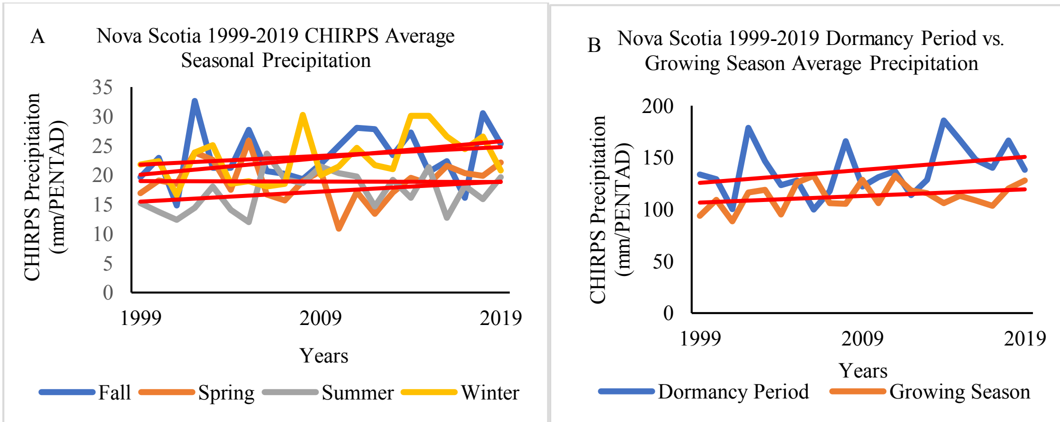


Figure 58: A) Nova Scotia Seasonal *CHIRPS* Precipitation for 1999-2019 B) Nova Scotia Dormancy Period vs Growing Season *CHIRPS* Precipitation for 1999-2019

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	21	0	21	14.832	32.637	23.281	4.544
Spring	21	0	21	10.873	25.870	18.904	3.425
Summer	21	0	21	11.990	23.682	17.191	3.358
Winter	21	0	21	16.586	30.257	22.919	4.085

Table 84: Minimum, Maximum, Mean, and Standard Deviations from Nova Scotia 1999-2019 *CHIRPS* Precipitation Seasonal Comparison.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	0.171	P < .05	0.296
Spring	0.086	P < .05	0.613
Summer	0.200	P < .05	0.220
Winter	0.267	P < .05	0.098

Table 85: Kendall Tau, P-Value Expected, and P-Value Calculated from Nova Scotia 1999-2019 *CHIRPS* Precipitation Seasonal Comparison.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy Period	21	0	21	99.833	185.778	138.115	23.708
Growing Season	21	0	21	88.502	132.567	112.963	12.500

Table 86: Minimum, Maximum, Mean, and Standard Deviations from Nova Scotia 1999-2019 *CHIRPS* Precipitation Dormancy Period vs. Growing Season Comparison.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	0.229	P < .05	0.159
Growing Season	0.200	P < .05	0.220

Table 87: Kendall Tau, P-Value Expected, and P-Value Calculated from Nova Scotia 1999-2019 *CHIRPS* Precipitation Dormancy Period vs. Growing Season Comparison.

Some of the highest average monthly precipitation amounts in Nova Scotia are found on Cape Breton Island and the southwest tip of the province. No precipitation trends of significance were observed in our 1999-2019 reference period for Nova Scotia. None of the observed trends are significant.

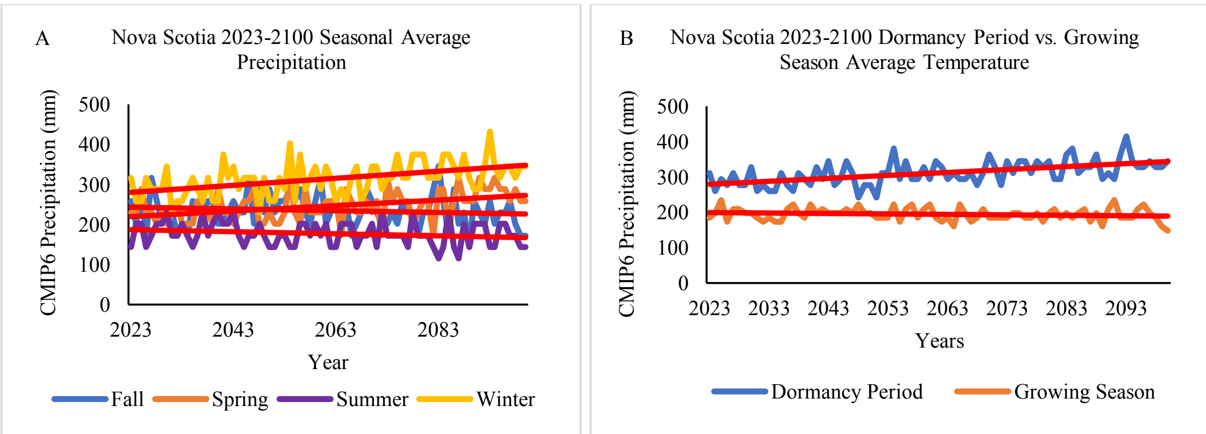


Figure 59: A) Nova Scotia Seasonal *CMIP6* Precipitation for 2023-2100 B) Nova Scotia Dormancy Period vs Growing Season *CMIP6* Precipitation for 2023-2100

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Fall	78	0	78	144.000	345.600	234.514	40.112
Spring	78	0	78	172.800	316.800	246.483	36.338
Summer	78	0	78	115.200	230.400	177.662	28.952
Winter	78	0	78	230.400	432.000	314.182	41.573

Table 88: Minimum, Maximum, Mean, and Standard Deviations from Nova Scotia 2023-2100 *CMIP6* Precipitation Seasonal Comparison.

Season	Kendall Tau	P-Value Expected	P-Value Calculated
Fall	-0.079	P < .05	0.348
Spring	0.345	P < .05	<0.0001
Summer	-0.177	P < .05	0.041
Winter	0.371	P < .05	<0.0001

Table 89: Kendall Tau, P-Value Expected, and P-Value Calculated from Nova Scotia 2023-2100 *CMIP6* Precipitation Seasonal Comparison.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Dormancy	78	0	78	-0.419	6.389	3.304	1.756
Growing	78	0	78	14.231	20.292	17.383	1.676

Table 90: Minimum, Maximum, Mean, and Standard Deviations from Nova Scotia 2023-2100 *CMIP6* Precipitation Dormancy Period vs. Growing Season Comparison.

Dormancy vs. Growing Season	Kendall Tau	P-Value Expected	P-Value Calculated
Dormancy Period	0.835	P < .05	<0.0001
Growing Season	0.849	P < .05	<0.0001

Table 91: Kendall Tau, P-Value Expected, and P-Value Calculated from Nova Scotia 2023-2100 *CMIP6* Precipitation Dormancy Period vs. Growing Season Comparison

All seasons but fall exhibited significant positive trends. This result indicates a positive trend for both the dormancy period and growing seasons, with the increases happening in spring, summer, and winter.

Results exhibited in Nova Scotia are fascinating because in other Canadian wine-producing regions, highly significant long-term trends were exhibited across all seasons and in both the dormancy period and growing seasons. Whereas in Nova Scotia, highly significant trends were only observed in spring and winter, with summer also significant, but not highly.

Long-term trends visualized across the province illustrate increases of some level across the entirety of the wine-growing area. Most of the increases occur in northern Cape Breton Island and the inland regions, with the lowest percentage increases in the southern regions of Cape Breton. Regardless, *CMIP6* precipitation suggests Nova Scotia will experience increased precipitation rates towards the end of the century.

Chapter 6: Discussion & Conclusion

6.1 Discussion

What does this all mean for Canadian wine production? This research has demonstrated that an expected increase in near-surface temperature and precipitation should be anticipated. The possibility for Canada to start producing wine, typically seen in old-world nations such as France and Italy, is genuine. The cool climate viticultural regions with growing seasons bookended by frigid temperatures might start to see that change.

The first question in our research questions attempted to understand climate trends within the four wine-growing provinces from 1999-2019. No significant trends were found for both near-surface temperature and precipitation, implying that the climate within these regions has remained relatively stable, and there have been no significant increases or decreases in near-surface temperature or precipitation. This can only be seen as beneficial, considering how sensitive grapes are to climate fluctuations (Jones et al., 2022).

While climate may have mostly stayed the same during the 20-year reference period of 1999-2019, future climate predictions under *CMIP6* produced results that projected future near-surface temperature and precipitation increases within all four Canadian Wine growing regions. Given the broad scale of analysis in this research, understanding the regional impacts of NST and precipitation increases across provinces needs to be accomplished with further research.

Research utilizing models, such as *CMIP6*, remains limited as many aspects of climate change and interactions still need to be known. It cannot be said with full certainty which intra-provincial regions or provinces will be impacted more or less than others. This point aside, it is essential to note that the modelling done in this research is to try and understand what the future may look like for Canadian wine-growing regions; it is by no means definitive and further research is needed.

Long-term, across all the analyzed provinces, there were similar patterns forecasting increasing temperature and precipitation up until 2100. When analyzed using the Mann-Kendall trend analysis, all these trends were significant, and this pattern responds to question two of our research questions. Currently classified as a cool climate region, the future of Canadian Wine appears to be outside of this climate classification. The increase in climate follows what is being predicted by the IPCC, which expects an increase in temperature by roughly 1.5 °C by the mid-century and up to 4 degrees by the end of the century, depending on the emission scenario (IPCC, 2023). Negative impacts associated with increased temperature and precipitation include increased drought frequency, high frequency of extreme climate events, or higher pest risk, potentially posing severe problems for wine production (Jobin-Poirier et al., 2019; Fraga et al., 2013). However, potential climate alteration, including higher temperatures, opens the possibilities for new varietals that typically require longer growing seasons to grow in Canada.

In the results, near-surface temperature appeared far more accurate than precipitation. A quick literature review highlighted the need for a bias correction measure or linear scaling. Methods such as bias correction and linear scaling help close the gap between what is predicted via satellite and observed from ground weather stations and produce a better overall fit (Soriano et al., 2018). Applying some scaling methods to aid in bias correction is an aspect that certainly needs to be considered. This research tried to understand what the future climate would look like for the Canadian wine industry. Bias correction for this research felt outside the bounds of interest. However, further research should isolate each wine-growing province and apply bias correction methods to understand future climate scenarios better as projected by future climate models.

Even though there were significant trends within the precipitation data, validations predicted *CMIP6* data to weather stations provided by the *Canadian Climate Normals* tended to overestimate precipitation rates. Further, the low R^2 and Pearson values demonstrate that when predicting long-term precipitation data, *CMIP6* precipitation was inaccurate. With precipitation, it is expected that there will be some change with increasing temperatures. However, the results demonstrated in this research show that an understanding of future scenarios takes time to ascertain, and more research is required.

To answer question number three, it is challenging to say what the future holds for Canadian producers. Growing seasons possibly are lengthening, which is considered a positive for the ability of Canadian wines to infiltrate the global wine market with new products. On the contrary, temperatures and precipitation are not the only climate-related phenomena of concern. Climate change is expected to increase storm frequency, drought events, heatwaves, and pest pressures (Jobin-Poirier et al., 2019; Fraga et al., 2013; Lavalle et al., 2009). New technology being developed makes wine grape growth in Canada possible, given the increasing frequency of such climate events. For example, technologies like CRISPR allow for the gene editing of varietals and focus on altering genetic sequences that favour cold hardiness (Mahdavi, 2023). Increasing temperature and precipitation can improve conditions for growth and benefit the Canadian wine industry. In an age of technological development, growing climates are no longer the difference between successful and unsuccessful harvests. Harnessing of power of new tech can help Canadian wine producers succeed even if conditions are not ideal.

This research had some obvious limitations, and they must be mentioned. The most obvious limitation was the coverage of specific datasets over our areas of interest, which was seen with the *CHIRPS* precipitation data over both Vancouver Island and mainland British Columbia. *CHIRPS* precipitation failed to cover these regions, so another dataset, *TerraClimate*, was needed to provide a reference precipitation baseline. Another limitation for consideration is the need for scaling data, given that most of the precipitation data was overestimated. Scaling must be done to ensure that what is predicted accurately depicts what is being observed (Soriano et al., 2018).

6.2 Conclusion

This thesis aims to provide a future climate assessment to understand near-surface temperature and precipitation across the four primary Canadian viticultural regions of Ontario, Quebec, Nova Scotia, and British Columbia. Analysis of NST and precipitation trends using a reference period of 1999-2019, a long-term projected comparison is made up to 2100. Gaining insight into future near-surface temperature and precipitation trends is advantageous as it can illustrate the future of the Canadian wine industry.

Data from *Google Earth Engine* is used to map variations spatially and temporally in NST and precipitation over a defined boundary of interest. *Google Earth Engine* is helpful in the ability to access many pre-loaded datasets through its data catalogue easily.

The datasets used for this research were *CHIRPS* and *TerraClimate* precipitation, *ERA5* near-surface temperature, and *CMIP6* temperature and precipitation. These datasets were validated using 1981-2010 *Canadian Climate Normals* to determine the accuracy of outputs within the reference period and in the future.

The purpose of this research was done with the understanding that the current global wine-growing areas of note are starting to see shifting capabilities for growing traditional varieties. Grapes for wine production are susceptible to changing climates (Jones et al., 2022). Regional temperatures and precipitation rates in old-world wine-growing nations like Italy, France, and Spain are moving toward the climate extremes for wine production (Sgubin et al., 2022). Nations like Canada could benefit as favourable wine-growing climate move northwards (Mozell & Thach, 2014). For some, the thought of wine production existing in Canada was almost a fantasy, given the extremely short growing seasons and the long, frigid winters. However, wine production in Canada has a long and rich history (Phillips, 2017).

Using near-surface temperature and precipitation, the two most important variables in wine production, this thesis will provide an understanding of the future of the Canadian wine industry (Hannah et al., 2013; Droulia & Charalampopoulos, 2022; Verdugo-Vasquez et al., 2015; Reis et al., 2021).

Our results were extremely interesting. For the past 20 years, between 1999-2019, trends have remained relatively stable, but projections to 2100 suggest overall increases in NST and precipitation. The increasing trends in NST and precipitation are all highly significant, suggesting an increasing trend that should be considered. Warmers climates open the possibility for wine varietals not typically associated with Canada to find a new home. In the future, varietals that need warmer climates, like Grenache and Cabernet Sauvignon, will be produced in one of the four growing provinces of Canada (Schultze & Sabbatini, 2019).

The results of this study should undoubtedly be an exciting prospect for wine producers, but one paper is not enough. More research is needed into the future of the Canadian Wine industry. Moreover, climate modelling is not always as accurate as researchers would like. As demonstrated in our precipitation results, climate variables measured over a similar temporal period can vary depending on whether the data comes from weather stations or via satellite. One real benefit of this research is to help fill the research gaps concerning Canadian viticulture.

Future research should focus on continuing to fill these gaps. Modelling future trends is crucial in allowing producers to modify harvest and vineyard management plans to maximize harvests. There are certain limitations to what is projected by models, which must be considered. Modelling is not the means to an end but an asset that researchers and wine producers can utilize.

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