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The Climate Ready Mine Project

Climate Change Factsheet

Implications for Long-Term Site Stewardship and Perpetual Care Planning

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Linking science and decision-making

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The purpose of this document is to provide information on climate projections for The Climate Ready Mine Project led by University of Guelph and RFS Energy and Research Consulting Inc. The material and information in the document reflect Climalogik's opinion and best judgment based on the scientific information available at the time of preparation. Any use of this document or reliance on its content by third parties is the responsibility of the third party. Climalogik accepts no responsibility for any damage suffered because of third-party use of this document.

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Executive Summary

This factsheet assesses local and regional climate shifts critical to the perpetual care of the Giant Mine Remediation Project. By combining historical observations (1950–2025) with bias-corrected Coupled Model Intercomparison Project Phase 6 (CMIP6) projections through 2150, it translates 200 years of climate data into actionable operational metrics. The following findings detail how evolving thermal, hydrological, and compound environmental stresses will impact ground stability and containment systems well beyond conventional infrastructure design timelines.

Long-term climate risk management is central to the success of the Giant Mine Remediation Project. Unlike conventional infrastructure designed for service lives of a few decades, containment and environmental protection systems at Giant Mine must remain effective for many generations under a perpetual care framework. Understanding how climate conditions have already changed, and how they are projected to evolve through the rest of the 21st century and into the early 22nd century, is therefore essential for climate-informed planning, adaptive stewardship, and risk-based decision-making.

Observed climate records show that the site is already operating under a warmer and more energy-intensive climate regime. Since 1950, mean annual air temperature has increased by approximately 2.5 °C, thawing energy has increased by more than 20%, and freezing energy has declined by more than 16%. Precipitation has increased modestly, while atmospheric evaporative demand has increased more rapidly. In combination, these changes indicate that the environmental loads acting on ground conditions, surface stability, and water management systems have already shifted away from historical norms.

Future projections indicate that warming and hydrological change will continue, with substantially larger impacts under high emissions. Under the low-emissions pathway (SSP1-2.6), climate change is projected to remain significant but stabilize toward the end of the century. Under the high-emissions pathway (SSP5-8.5), warming is projected to intensify through the 2080s, 2110s, and 2130s, leading to large declines in freezing energy, longer thaw seasons, stronger precipitation increases, and higher evaporative demand. These changes are projected to alter the thermal regime of the landscape and influence runoff generation, seasonal moisture balance, and surface process dynamics.

Future hydroclimate change at Giant Mine is projected to be characterized by stronger seasonal variability rather than a simple shift toward wetter or drier conditions. Cold-season precipitation is projected to increase substantially, particularly under SSP5-8.5, raising the potential for greater snow accumulation and spring runoff entering site drainage systems. At the same time, rising evaporative demand during the open-water season is projected to produce a more negative summer water balance and larger moisture deficits. The site may therefore experience both higher hydraulic loading and stronger drying pressures at different times of the year.

Compound climate stresses are projected to become increasingly important. Climate risks are unlikely to arise from single variables acting in isolation. Instead, interacting drivers, including warming, precipitation change, evaporation, and wind exposure, are projected to combine to intensify erosion, runoff variability, and surface instability. Warm-and-wet conditions are projected to become more frequent under high emissions, increasing the likelihood of periods when multiple environmental stresses occur simultaneously.

Regional climate change across the Great Slave Lake watershed reinforces the importance of a broader planning perspective. Projected increases in growing season length, shifts in long-term moisture balance, and greater seasonal variability in water inputs and losses indicate that the surrounding hydrological system is likely to become more dynamic over time. Climate risks affecting the mine site are therefore expected to be linked to regional-scale environmental change rather than isolated local trends.

The overall implication is that long-term stewardship should be adaptive and monitoring-based. Engineering design, operational planning, and environmental risk management should be guided by evolving climate conditions rather than fixed historical assumptions. The climate indicators and projections presented in this factsheet provide a defensible evidence base to support climate-informed decision-making and periodic reassessment of risk throughout the perpetual care horizon.

1 Why Climate Matters for Giant Mine

The Giant Mine Remediation Project represents one of the most complex environmental containment efforts undertaken in Canada. The long-term safety of the site depends not only on engineered systems but also on the surrounding physical environment. Surface drainage networks, water capture infrastructure, and containment systems operate within a landscape that is continuously influenced by temperature, precipitation, evaporation, and wind. These climate-driven processes determine how water moves across the site, how soils and surface materials respond to seasonal changes, and how environmental loads interact with engineered structures. As a result, climate is not simply a background environmental condition. It is a critical driver shaping the long-term performance of the site's containment and environmental protection systems (Crown-Indigenous Relations and Northern Affairs Canada [CIRNAC], 2023).

Historically, infrastructure design relied on the assumption that climate conditions fluctuate within a relatively stable range defined by past observations. This concept, often referred to as stationarity, allowed engineers to rely on historical weather records to guide design standards and operational planning. In northern regions such as Yellowknife, this assumption was reinforced by the historically consistent seasonal cycle characterized by long, cold winters, relatively short summers, and predictable transitions between freezing and thawing conditions.

Today, this assumption is increasingly unreliable (Milly et al., 2008). Northern Canada is warming at roughly three times the global average, significantly outpacing the rest of the country, which is already warming at twice the global rate (Bush et al., 2019). Across northern Canada, climate change is altering temperature regimes, precipitation patterns, and atmospheric moisture demand. Warmer air temperatures increase the amount of seasonal thaw energy applied to the landscape while reducing the cumulative freezing energy historically associated with northern winters. At the same time, changes in precipitation influence the timing and magnitude of runoff entering surface drainage systems, while rising evaporative demand intensifies drying pressures during the warmer months. Wind conditions can further amplify these processes by increasing evaporation rates and contributing to erosion across exposed surfaces. Together, these changes alter the environmental loads acting on the site, affecting freeze-thaw processes, water balance, surface stability, and the performance of drainage and containment systems. When these climate drivers shift simultaneously, they can create compound stresses that challenge infrastructure designed under past climate conditions.

Understanding how these climate drivers evolve is therefore central to climate risk management and adaptation planning for the site. Climate analysis translates large-scale atmospheric changes into operational indicators describing thermal conditions, water balance, seasonal timing, and exposure to extreme events. These indicators allow engineers and decision-makers to evaluate how environmental pressures may evolve over time and to design containment systems capable of performing reliably under changing conditions. A further challenge is that the stewardship horizon for Giant Mine extends well beyond conventional infrastructure planning cycles. Many climate adaptation strategies and engineering assessments rely on projections ending in 2100, reflecting common international reporting timelines. However, the environmental containment responsibilities associated with Giant Mine extend far beyond that timeframe. Infrastructure and environmental protection systems must remain effective for many decades, and potentially centuries, under a perpetual care framework. Limiting analysis to 2100 therefore risks underestimating the longer-term trajectory of climate change and the cumulative stresses that infrastructure may experience.

For this reason, climate projections in this assessment extend beyond the end of the 21st century until 2150. Examining longer-term climate trajectories allows the Giant Mine Oversight Board and other stakeholders to evaluate how thermal regimes, precipitation patterns, and hydrological conditions may continue to evolve over time. By integrating observed climate change with extended projections, this analysis supports forward-looking adaptation planning, ensuring that containment systems and water management strategies remain resilient under the full range of plausible future climate conditions.

2 Data Sources and Methods

2.1 Climate Data

This assessment combines observational climate records and bias-corrected global climate model projections to evaluate both historical climate conditions and potential future changes affecting the Giant Mine site.

Observed climate conditions were derived from the ERA5-Land reanalysis dataset (Sabater, 2021), which provides globally consistent, observation-constrained estimates of near-surface climate variables. Monthly ERA5-Land data spanning 1950–2025 were used to evaluate historical trends and characterize recent climate conditions. The analysis focuses on key climate variables relevant to site operations and environmental containment, including precipitation (*pr*), mean air temperature (*tas*), minimum temperature (*tasmin*), maximum temperature (*tasmax*), and surface wind speed (*sfcWind*).

Future climate projections were obtained from the Coupled Model Intercomparison Project Phase 6 (CMIP6) archive (https://metagrid.esgf-west.org/search). Monthly outputs from models participating in the Scenario Model Intercomparison Project (ScenarioMIP) and the Extended Scenario Model Intercomparison Project (ScenarioMIP-Ext) were used to ensure that both near-term and longer-term climate risks could be evaluated. Based on data availability beyond 2100, the analysis considers two emissions pathways (Figure 1) representing a range of potential global futures: SSP1-2.6 (low emissions) and SSP5-8.5 (high emissions). Extended projections beyond 2100 are available for a smaller subset of CMIP6 climate models. While the full CMIP6 archive contains more than 60 global climate models, only nine models provide simulations extending beyond the year 2100 under the ScenarioMIP framework used in this assessment. As a result, projections for the period 2101–2150 are derived from this reduced ensemble. Among the scenarios considered, SSP5-8.5 provides the most consistent model availability through the extended period, with simulations available to approximately 2140–2150. In contrast, SSP1-2.6 and SSP2-4.5 simulations become increasingly limited after 2100, resulting in a smaller model range for these scenarios in the far-future time windows.

All climate projections were bias-corrected against ERA5-Land observations using the 1991–2020 baseline period, ensuring consistency between modeled and observed climate conditions. The resulting bias-corrected dataset spans 1960–2150, providing a continuous climate record suitable for evaluating near-term adaptation planning as well as longer-term climate risks relevant to the site's perpetual care framework. In addition to site-specific analysis at Giant Mine, climate data were also analyzed across the entire Canadian domain to provide regional context for projected climate change. This broader spatial analysis allows regional climate shifts to be visualized alongside site-level results, demonstrating that projected changes at the mine site reflect large-scale climate trends across northern and southern Canada rather than localized anomalies.

Monthly climate data were used throughout the analysis. Monthly timescales provide a robust basis for evaluating long-term climate trends and hydroclimatic indicators while avoiding the uncertainties associated with bias correction of daily climate projections over very long future horizons.

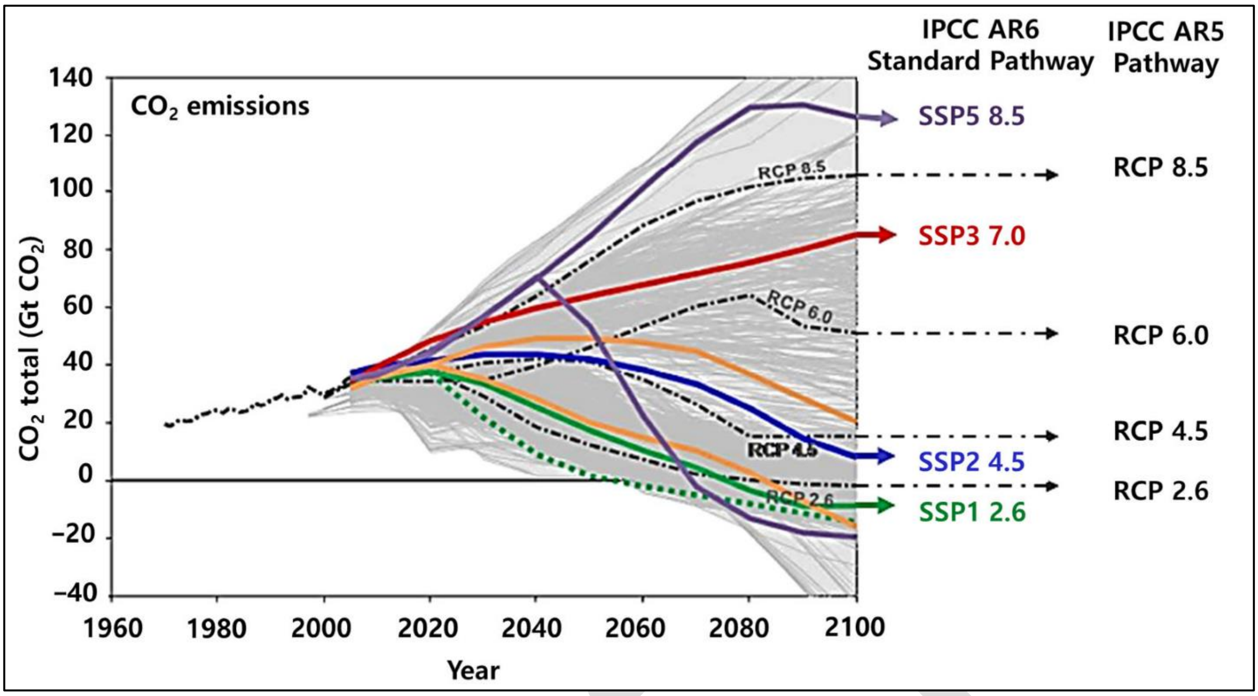

Figure 1: Shared Socioeconomic Pathways (O'Neill et al., 2016).

2.2 Bias Correction of Climate Projections Data

Raw global climate model output is known to exhibit systematic regional biases in temperature, precipitation, wind speed, and other climate variables. To address these limitations, projections were corrected using the *N-dimensional Multivariate Bias Correction (MBCn) algorithm* (Cannon, 2018). Unlike univariate approaches that adjust variables independently, MBCn corrects the full multivariate climate state simultaneously. This preserves key inter-variable dependence structures such as the co-occurrence of warm, dry, and windy conditions which are critical for representing compound hazards and climate-driven environmental stresses.

Bias correction was calibrated against ERA5-Land reanalysis data using the 1991–2020 baseline period, selected for its high-quality observational constraint and relevance to recent climate conditions. To ensure that projected climate change signals were not artificially distorted, the correction procedure employed a 31-year moving-window framework consistent with Quantile Delta Mapping (QDM) principles. The use of a 31-year window (15 years before and after each target year) preserves temporal symmetry and avoids introducing trend discontinuities. This approach allows long-term warming and hydroclimatic intensification signals to remain intact while removing systematic model bias.

Bias correction was applied independently for each calendar month, rather than across smoothed seasonal aggregates. This preserves the physical integrity of northern seasonal transitions, including the timing of spring thaw onset and autumn freeze-up, which are critical processes for hydrology, ground stability, and environmental management at northern mine sites.

2.3 Development of Operational Climate Indicators

The resulting bias-corrected dataset provides a physically consistent monthly climate record spanning 1960–2150. These projections form the foundation for deriving operational climate indicators relevant to infrastructure stability, water management, containment performance, and long-term stewardship planning at the Giant Mine site. The goal of these indicators is to translate raw climate projections into metrics that directly reflect environmental pressures acting on engineered systems across the site.

Because the bias-corrected CMIP6 projections are available at a monthly resolution, several temperature-based indicators that are traditionally calculated using daily data were estimated using well-established empirical approximations. In particular, Thawing Degree Days (TDD) and Freezing Degree Days (FDD) were calculated using the single-triangle approximation method (Zalom et al., 1983; Snyder, 1985), which uses monthly minimum and maximum temperatures to estimate the fraction of time temperatures occur above or below the 0 °C freezing threshold. This approach provides a robust representation of seasonal heat accumulation and freezing energy, particularly during transitional shoulder seasons when temperatures fluctuate around the freezing point.

Hydrological and water-balance indicators were derived from precipitation and potential evapotranspiration (PET). PET was calculated using the Hargreaves–Samani method (Hargreaves and Samani, 1985), which estimates evaporative demand from mean temperature, temperature range, and latitude-based solar radiation. This formulation provides a stable and widely applied estimate of evaporative demand suitable for long-term climate projection analyses. Using precipitation and PET, additional metrics were derived to describe directional shifts in hydroclimatic conditions, including net water balance (P − PET) and aridity ratios. The Standardized Precipitation–Evapotranspiration Index (SPEI) was calculated at 12- and 24-month accumulation scales relative to the 1991–2020 baseline to characterize persistent drought and wet conditions. For visualization and communication purposes, SPEI values were limited to the range −3 to +3, which corresponds to the commonly used bounds for extreme hydroclimatic conditions.

Indicators representing extreme and compound climate stresses were also derived from monthly statistics. These include metrics such as maximum monthly precipitation, multi-month wet totals, and high-wind frequency relative to historical percentiles. Together, these indicators capture upper-bound climate stresses relevant to surface drainage systems, erosion potential, dust mobilization, and structural loading across the mine site. Finally, long-horizon diagnostics were calculated to evaluate how the overall climate regime is evolving over time. These include century-scale trend estimates and changes in seasonal temperature amplitude, which help frame climate change as a persistent structural shift rather than short-term variability. All indicators were evaluated over the 1960–2150 period, with the 1991–2020 baseline used for bias correction and anomaly reference. This timeframe captures historical conditions, current planning horizons, and extended future projections within a single consistent framework. The resulting climate dataset and derived indicators (Appendix A; Table A1) provide a scientifically grounded evidence base for assessing evolving thermal, hydrological, and compound climate stresses relevant to the long-term management of the Giant Mine site.

3 Observed Climate Change at the Giant Mine Site (1950–2025)

3.1 A Warmer Climate and Less Winter Freezing

The observed climate record indicates that the thermal environment at the mine site has changed substantially over the past seven decades. Mean Annual Air Temperature (MAAT) has increased by 2.5 °C (Figure 2) since 1950, rising from an average of −5.3 °C during the early record (1950–1979) to −3.7 °C in the recent period (1996–2025). This warming corresponds to an average increase of approximately 0.3 °C per decade. The warming trend is also reflected in the balance between thawing and freezing energy at the site. Thawing Degree Days (TDD)—a measure of cumulative seasonal thaw energy—have increased from 1,599 °C·days during the early record to 1,785 °C·days in the recent record, representing a 21.4% increase since 1950. This increase indicates that the landscape now receives substantially more seasonal heat energy than it did during the historical operational period.

At the same time, Freezing Degree Days (FDD)—which represent the cumulative freezing energy available during winter—have declined from 3,491 °C·days to 3,075 °C·days, a reduction of 585 °C·days, or approximately 16.3% since 1950. This decline indicates that winters now deliver less cumulative cooling energy to the ground surface. The combined increase in thawing energy and decline in freezing energy indicates a clear shift in the site's thermal balance. While the average length of the freezing season has remained relatively stable at approximately 6.4 months, the overall thermal regime has become warmer and more energy-intensive.

For the Giant Mine remediation system, these changes are significant. Higher thaw energy increases the thermal load acting on soils, surface covers, and subsurface systems, while declining freezing energy reduces the natural cooling margin that historically characterized the northern environment. The observational record therefore confirms that the site is already operating under a different thermal regime than the one that existed during the early decades of mine operation.

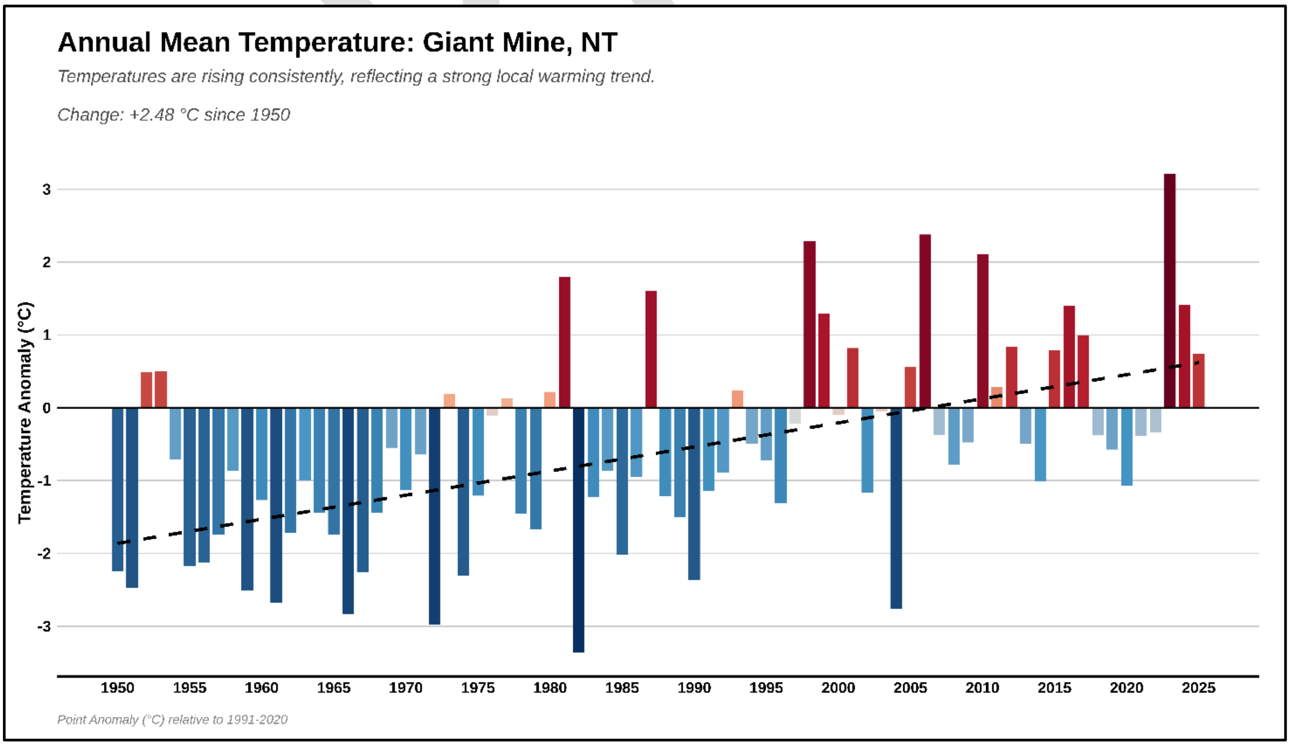

Figure 2: Observed Warming at Giant Mine (1950–2025).

3.2 Changing Rainfall and Increasing Evaporation

Observed hydroclimatic conditions at the mine site show both increasing precipitation and rising atmospheric demand for moisture. Total annual precipitation (annual water yield) has increased from 283 mm during the early record (1950–1979) to 313 mm in the recent period (1996–2025). This represents an increase of approximately 8% since 1950 (Figure 3), equivalent to about 3.5 mm per decade. Seasonal precipitation patterns show increases in both the cold season (October – April) and the open-water season (May – September). Cold-season precipitation has increased from 118 mm to 130 mm, an increase of roughly 14%, while open-water season precipitation has risen from 164 mm to 183 mm, representing an increase of approximately 6%.

However, temperature-driven changes in atmospheric demand are occurring at an even faster rate. Open-water potential evapotranspiration (PET)—a measure of the atmosphere's capacity to remove moisture from land and water surfaces—has increased from 350 mm in the early record to 372 mm in the recent record, representing an increase of 13% since 1950 (Figure 4), or approximately 6 mm per decade. Because evaporative demand has increased faster than precipitation, the summer climatic moisture deficit (SCMD) has also increased. SCMD rose from 201 mm in the early period to 208 mm in the recent record, representing a 15.6% increase since 1950. This indicates that while the site receives slightly more precipitation overall, the warmer atmosphere is drawing more moisture from the landscape during the open-water season. The resulting hydroclimatic environment is therefore more energy-intensive and more dynamic.

For site management, this pattern means that both water availability and drying stress must be considered simultaneously. Higher precipitation increases water management requirements, while rising evaporative demand increases drying pressure on exposed surfaces and engineered covers during the summer months.

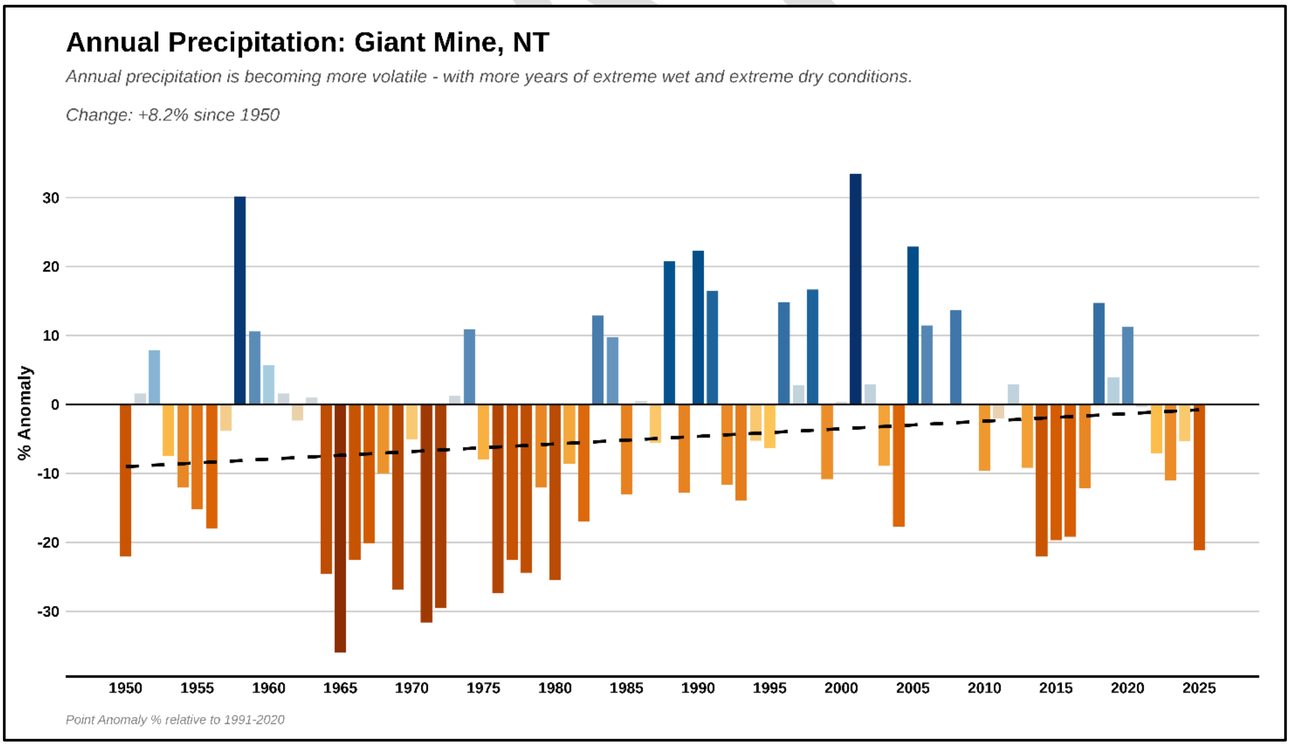

Figure 3: Observed Changes in Annual Precipitation at Giant Mine (1950–2025)

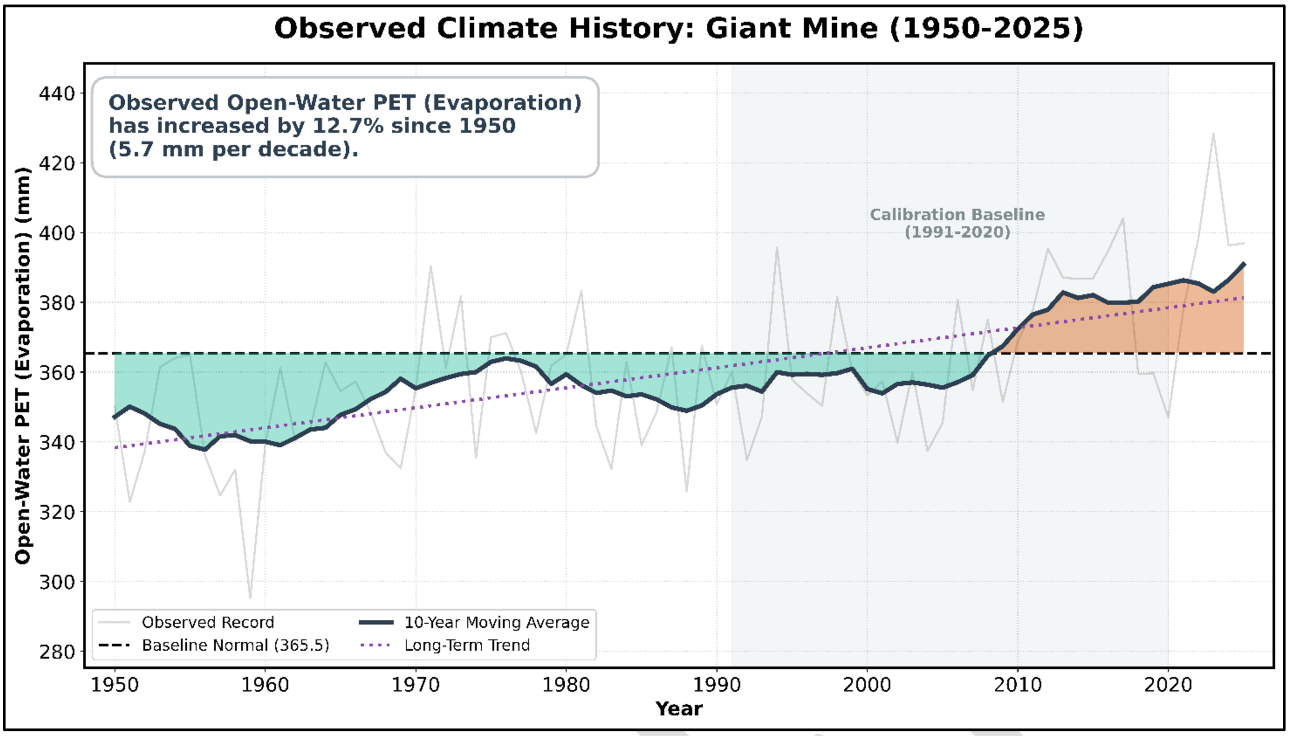

Figure 4: Increasing Evaporative Demand at the Mine Site (1950–2025)

3.3 Heavy Rainfall and Wind Exposure

In addition to long-term changes in temperature and water balance, the observed record provides insight into environmental stresses associated with precipitation extremes and wind exposure. Indicators of peak precipitation suggest that the magnitude of intense wet periods has increased modestly over time. The maximum monthly precipitation (peak hydraulic load) increased from 61.8 mm in the early record to 67.0 mm in the recent period (an 8.5% change), although long-term trend significance remains limited. Similarly, the wettest three-month precipitation total increased from 132 mm to 146 mm (an 11% change), indicating that prolonged wet periods can now deliver higher cumulative water inputs than during earlier decades. These indicators are particularly relevant for drainage and water management infrastructure at the site. Even moderate increases in peak precipitation and multi-month wet periods can influence runoff generation, drainage capacity requirements, and water treatment system loading.

Wind exposure remains another persistent environmental factor affecting surface conditions at the site. Observed summer wind intensity has remained relatively stable over the observational record, averaging approximately 3.3 m/s in both the early and recent periods. Although no significant long-term trend is evident, wind continues to interact with other climate variables. In practice, wind acts as a compounding stressor rather than an isolated hazard. When combined with higher evaporative demand and occasional dry conditions, wind can contribute to surface drying and increased erosion potential. Conversely, during wet periods, wind can enhance surface water movement and redistribution.

Overall, the observed record demonstrates that climate change is not a distant possibility for the Giant Mine site—it is already underway. The site is now operating in a warmer and more energy-intensive climate than during the early decades of mine operation. To support long-term stewardship and climate-informed adaptation planning, the next section examines how temperature, precipitation, and related climate stresses are projected to evolve over the coming century.

4 Future Climate Projections for the Mine Site and Regional Context (1960–2150)

Observed climate trends confirm that conditions at Giant Mine are already changing. Future projections extend this analysis by showing how temperature, precipitation, evaporation, and related climate stresses may evolve through the remainder of the 21st century and into the early 22nd century. This extended planning horizon is essential because stewardship obligations at the site continue well beyond the conventional infrastructure timeframe ending in 2100. To support long-term decision-making, projections are summarized for key planning windows: the baseline period (1991–2020), late century (2071–2100; 2080s), early 22nd century (2101–2130; 2110s), and deep-future conditions (2121–2150; 2130s). Temporal plots and summary tables focus on how climate indicators change at the mine site across these periods. Spatial maps are also included to place site-level changes within the broader regional context of climate change across Canada. Overall, these projections provide a forward-looking evidence base for evaluating how continued warming, shifting water balance conditions, and evolving environmental stresses may influence ground stability, water management systems, and long-term containment performance at Giant Mine. Baseline climate conditions used for interpreting projected changes are found in Appendix B.

4.1 Warming Temperatures and Loss of Freezing Energy

Continued warming is projected to be the most robust and consistent climate signal at Giant Mine (Table 1; Figures 5–10). Under the low-emissions pathway (SSP1-2.6), warming is projected to be substantial but is expected to stabilize toward the end of the analysis period. Mean annual air temperature is projected to increase from −3.9 °C during the baseline period (1991–2020) to approximately −0.8 °C by the 2080s and is expected to remain near −1.2 °C by the 2130s. Model projections for the deep-future period are expected to range from about −2.2 °C to near 0 °C, indicating that the site will likely retain a cold northern climate regime, although with reduced thermal buffering.

Under the high-emissions pathway (SSP5-8.5), warming is projected to be far more pronounced and is expected to continue throughout the projection horizon. Mean annual air temperature is projected to increase from approximately −4.0 °C in the baseline period to 4.2 °C by the 2080s, 8.6 °C by the 2110s, and 10.7 °C by the 2130s. The projected model range of 8.0 to 12.9 °C in the deep future indicates a fundamental shift toward a much warmer climate state at the site. These temperature changes are expected to be reflected in the seasonal energy balance. Under SSP1-2.6, Thawing Degree Days are projected to increase from about 1,714 °C·days during the baseline to roughly 2,099 °C·days by the 2080s, representing an increase of approximately 22%. At the same time, Freezing Degree Days are projected to decline from about 3,090 °C·days to approximately 2,345 °C·days, a reduction of roughly 24%. The length of the freezing season is projected to shorten modestly from approximately 6.6 months to about 6.0 months.

Under SSP5-8.5, changes are projected to be much larger. Thawing Degree Days are projected to increase to approximately 3,018 °C·days by the 2080s, 3,940 °C·days by the 2110s, and 4,463 °C·days by the 2130s. In contrast, Freezing Degree Days are projected to decline sharply to about 1,245 °C·days, then 544 °C·days, and finally 293 °C·days by the deep-future period. The freezing season is projected to contract substantially from about 6.5 months during the baseline period to 5.1 months in the 2080s, 3.9 months in the 2110s, and approximately 3.1 months by the 2130s. Seasonal temperature projections (Figure 10) suggest that the largest absolute warming will occur during the cold season. Winter temperatures are projected to increase more rapidly than summer temperatures, reducing the duration and intensity of sustained freezing conditions. As the climate continues to warm, the projected number of freeze-thaw threshold crossings is expected to decline because fewer months are likely to remain near 0 °C. Instead, temperatures are projected to remain increasingly either consistently above or below the freezing threshold.

For long-term stewardship, the key implication will be not simply higher temperatures but a progressive loss of natural winter freezing energy and a shorter period of reliably frozen ground conditions. Under SSP1-2.6, these changes are expected to suggest a continued northern thermal regime with reduced safety margins. Under SSP5-8.5, the projected loss of freezing energy will represent a more fundamental shift in the site's ground-thermal environment, with important implications for the long-term performance of remediation and containment systems that benefit from sustained cold conditions.

Table 1: Projected Changes in Temperature and Freezing Energy at Giant Mine (1960–2150). *Mean values and model ranges (10th –90th percentile) for key thermal indicators relative to the 1991–2020 baseline, shown for selected future planning windows. Arrows indicate the direction of projected change under low-emissions (SSP1-2.6) and high-emissions (SSP5-8.5) scenarios.*

Indicator	Baseline (1991–2020)	SSP1-2.6 2080s	SSP1-2.6 2130s	SSP5-8.5 2080s	SSP5-8.5 2110s	SSP5-8.5 2130s
MAAT (°C) *(Mean Annual Air Temperature)*	**-3.9** [-5.23 to -2.79]	↑ **-0.8** [-2.09 to 0.56]	↑ **-1.2** [-2.2 to ~0.0]	↑ **4.2** [1.65 to 7.41]	↑ **8.6** [5.97 to 11.05]	↑ **10.7** [7.97 to 12.93]
TDD (°C·days) *(Thawing Degree Days)*	**1714** [1509 to 1913]	↑ **2099** [1886 to 2319]	↑ **2060** [1870 to 2255]	↑ **3018** [2568 to 3495]	↑ **3940** [3461 to 4346]	↑ **4463** [4091 to 4865]
FDD (°C·days) *(Freezing Degree Days)*	**3090** [2717 to 3416]	↓ **2345** [1911 to 2716]	↓ **2449** [2061 to 2825]	↓ **1245** [687 to 1838]	↓ **544** [192 to 963]	↓ **293** [41 to 692]
Length of Freezing season (months)	**6.6** [6 to 7]	↓ **6.0** [6 to 6.1]	↓ **6.1** [6 to 7]	↓ **5.1** [4 to 6]	↓ **3.9** [3 to 5]	↓ **3.1** [1 to 5]

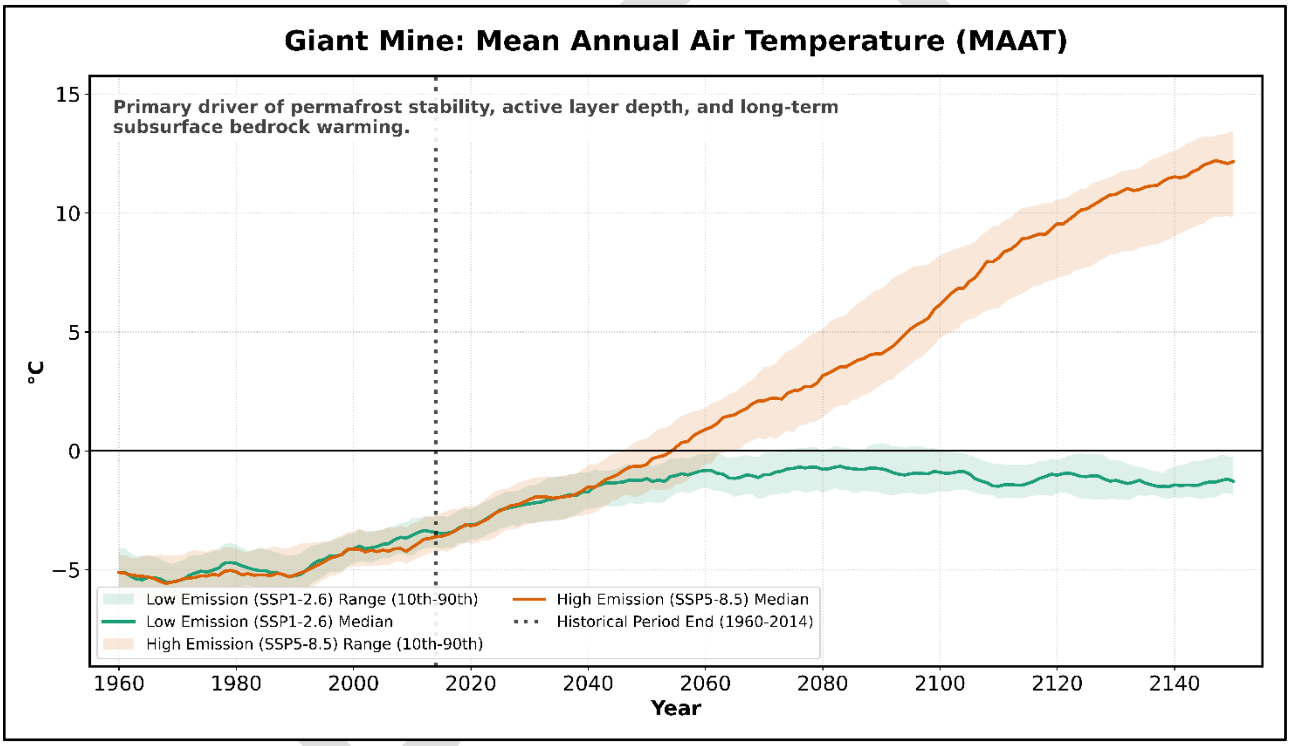

Figure 5: Mean Annual Air Temperature Projections for Giant Mine (1960–2150). *Projected changes in mean annual air temperature relative to the 1991–2020 baseline under SSP1-2.6 and SSP5-8.5. Shaded bands show the model range and solid lines represent the ensemble median.*

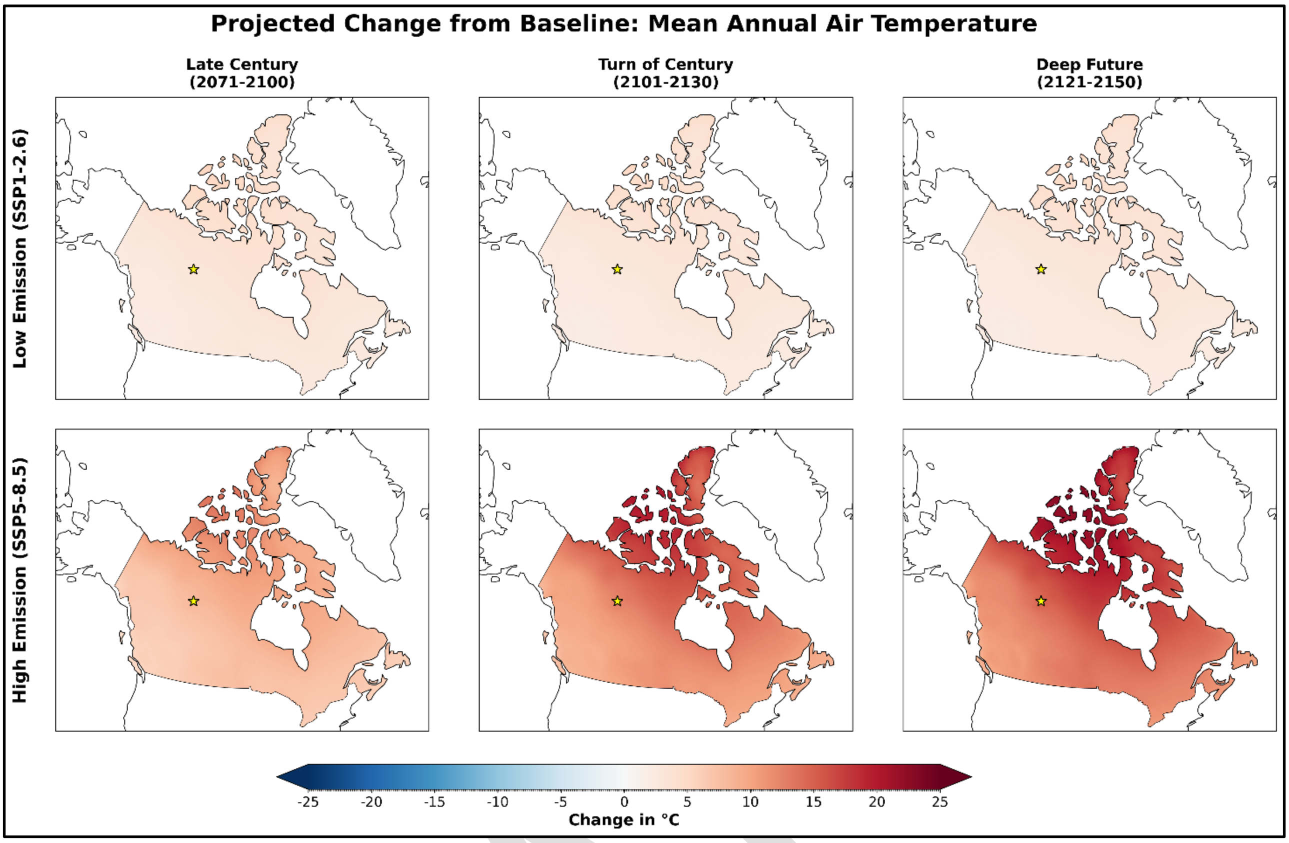

Figure 6: Projected Change in Mean Annual Air Temperature Across Canada. *Spatial distribution of projected temperature changes relative to the 1991–2020 baseline. The star marks the location of Giant Mine. Northern Canada shows the strongest warming, reflecting broader Arctic amplification.*

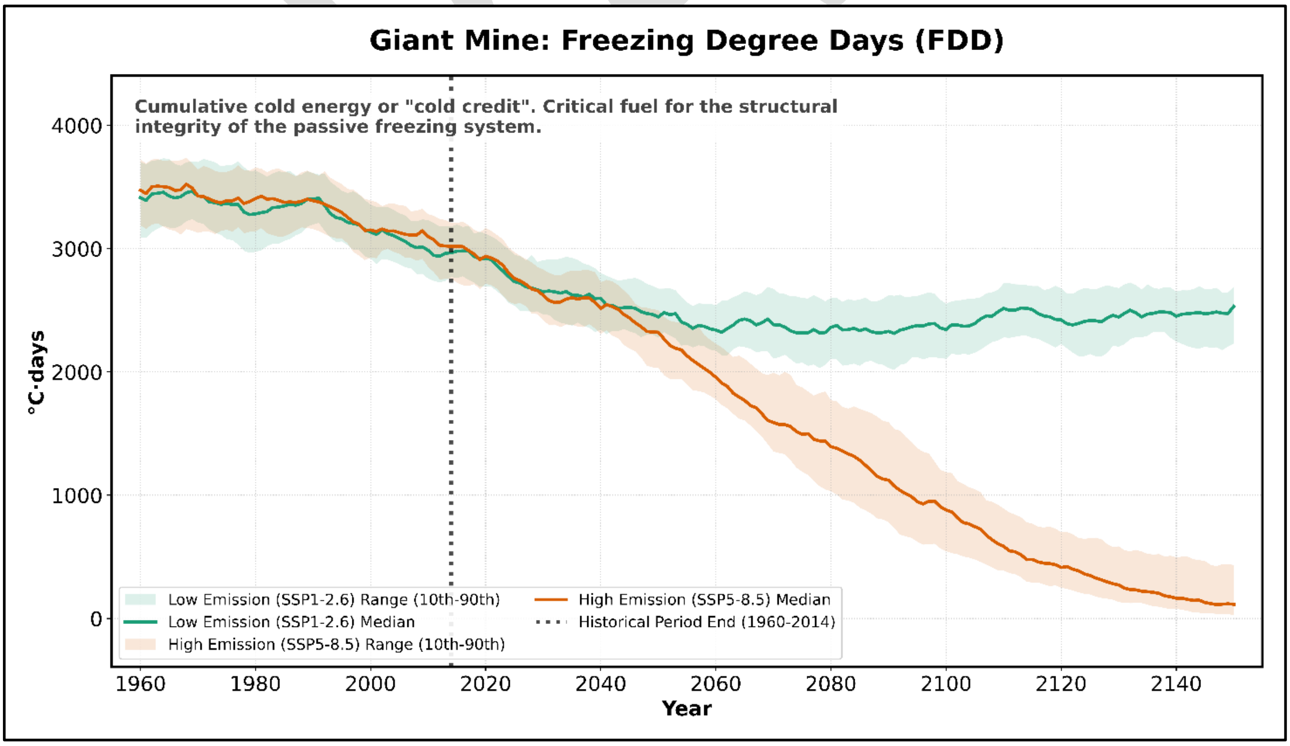

Figure 7: Projected Decline in Freezing Degree Days at Giant Mine (1960–2150). *Projected changes in cumulative annual freezing energy, measured as Freezing Degree Days (FDD). Declining FDD indicates reduced winter freezing potential and shorter periods of sustained ground cooling.*

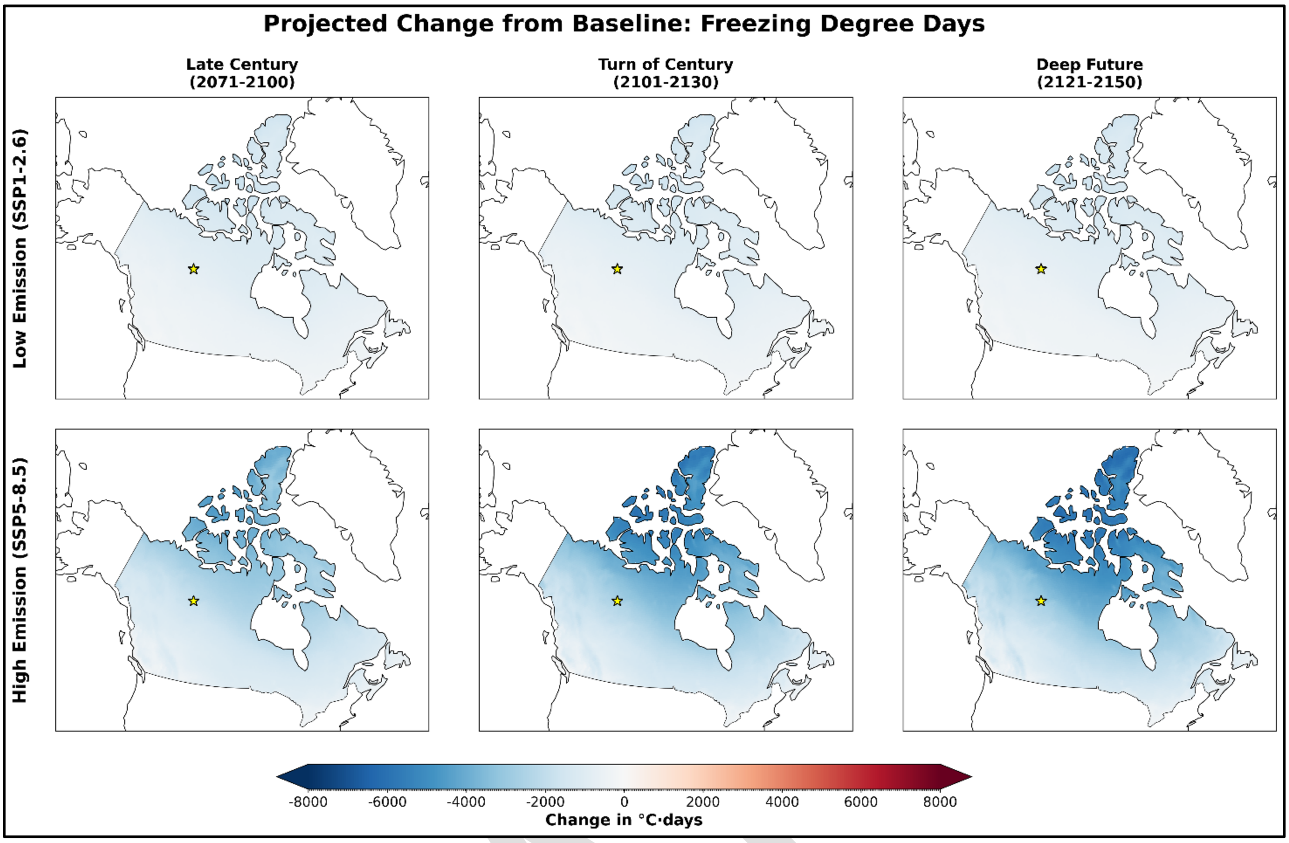

Figure 8: Projected Change in Freezing Degree Days Across Canada. *Projected reduction in annual freezing energy relative to the 1991–2020 baseline. Declines in Freezing Degree Days across northern regions indicate a weakening cold-season thermal regime.*

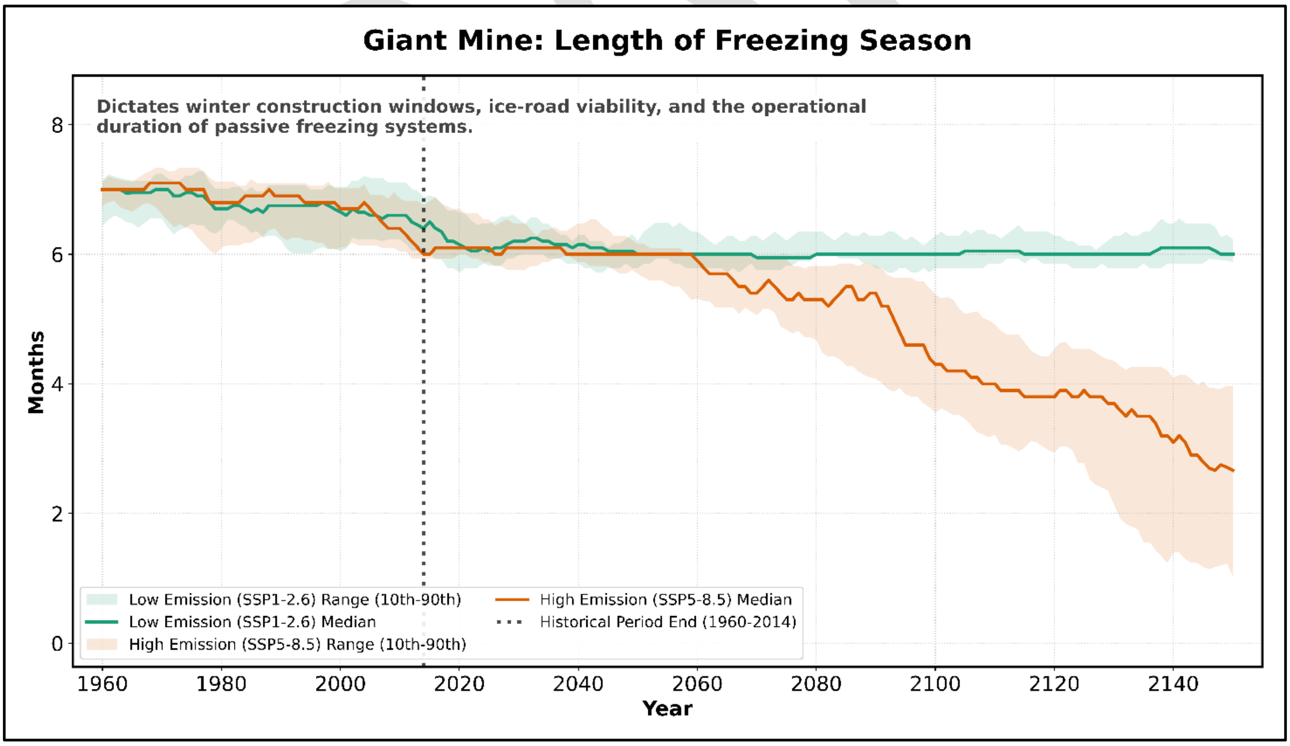

Figure 9: Projected Changes in the Length of the Freezing Season at Giant Mine (1960–2150). *Projected duration of the freezing season (months with mean temperature below 0 °C) under SSP1-2.6 and SSP5-8.5 scenarios.*

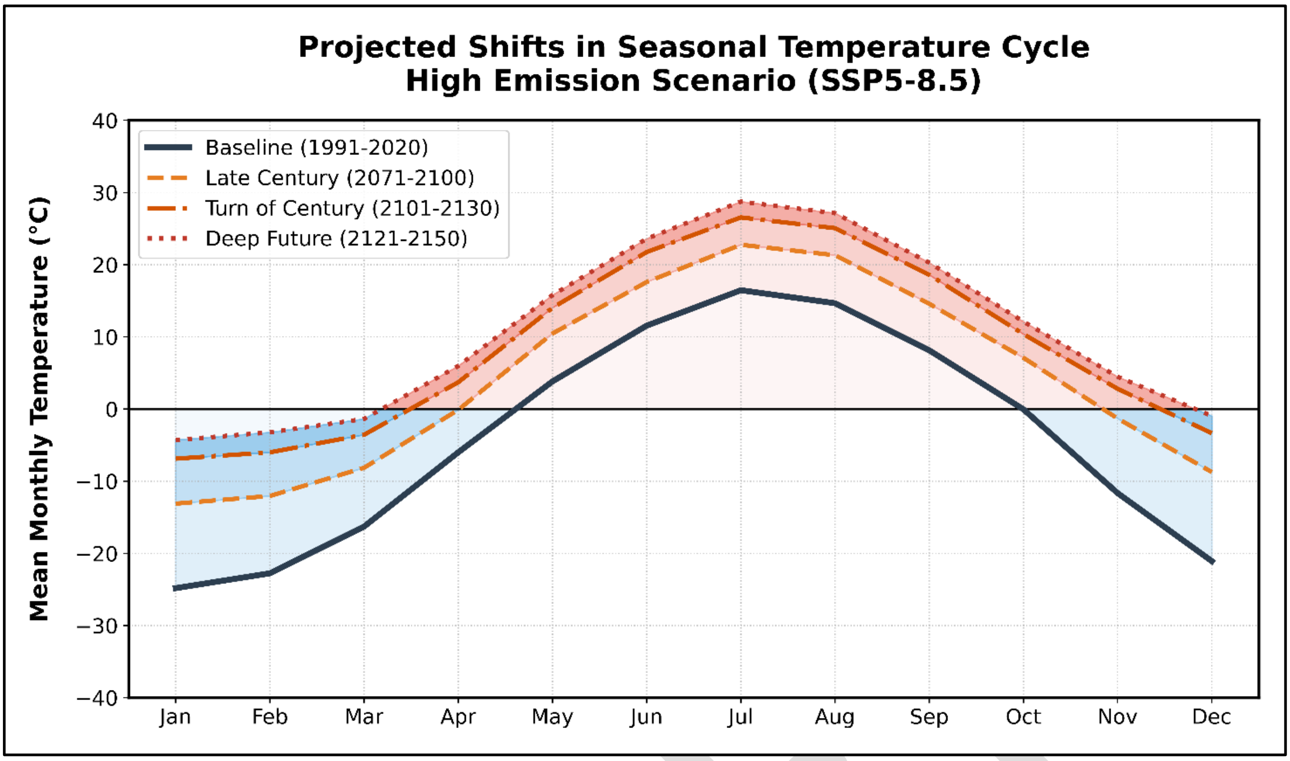

Figure 10: Projected Changes in the Seasonal Temperature Cycle at Giant Mine*. Monthly mean temperature projections showing how warming affects different seasons. Winter temperatures increase most strongly, shortening the duration of the cold season and shifting seasonal transitions.*

4.2 Changing Precipitation, Evaporation, and Water Balance

Future hydroclimate change at Giant Mine is projected to reflect simultaneous increases in precipitation and atmospheric evaporative demand, resulting in more dynamic seasonal water conditions. These shifts will influence runoff generation, drainage system loading, and surface moisture balance. Projected changes are summarized in Table 2, while Figures 11–17 illustrate the temporal evolution of key indicators and their broader regional context. Annual precipitation is projected to increase under both emissions pathways. Under SSP1-2.6, total precipitation is projected to rise from 315.8 mm/year during the baseline period (1991–2020) to approximately 364 mm/year by the 2080s, remaining near 362 mm/year by the 2130s, representing an increase of about 15% relative to baseline (Table 2). Under SSP5-8.5, increases are projected to be larger and will continue through the projection period, reaching 404.4 mm/year in the 2080s (+27%), 455.9 mm/year in the 2110s (+44%), and 490.2 mm/year by the 2130s (+54%). Regional projections are projected to show similar precipitation increases across northern Canada (Figure 13), indicating that projected changes at Giant Mine will reflect broader regional climate trends.

Seasonal precipitation patterns are also projected to evolve. Cold-season precipitation (October–April) is projected to increase substantially, rising from 129 mm during the baseline period to 152–156 mm under SSP1-2.6 by the 2080s–2130s (+18–21%). Under SSP5-8.5, cold-season precipitation is projected to increase more strongly to 186 mm in the 2080s (+43%), 224 mm in the 2110s (+72%), and 254 mm in the 2130s (+95%) (Figure 11; Table 2). These increases are expected to suggest greater snow accumulation and higher spring runoff entering site drainage systems. Open-water precipitation (May–September) is also projected to increase (Figure 12), with Figure 17 indicating intensification across multiple months rather than a shift concentrated in a single season. At the same time, evaporative demand is projected to increase as temperatures rise. Open-water potential evapotranspiration (PET) is projected to increase from 364.9 mm during the baseline period to approximately 394 mm by the 2080s under SSP1-2.6 (+8%), remaining near that level through the 2130s (Table 2). Under SSP5-8.5, PET is projected to increase more strongly to 444.7 mm in the 2080s (+23%), 494.9 mm in the 2110s (+36%), and 515.8 mm by the 2130s (+42%) (Figure 14).

Because both precipitation and evaporation are projected to increase, the net open-water water balance (P − PET) is projected to remain negative and to become more deficit-driven under high emissions. As shown in Figure 16, the balance is projected to decline from −178.6 mm during the baseline period to −221 mm in the 2080s, −257 mm in the 2110s, and −271 mm in the 2130s under SSP5-8.5 (Table 2). Regional patterns (Figure 15) are projected to show similar trends across much of Canada. This shift is projected to be reflected in the summer climatic moisture deficit, which is projected to increase from 199 mm during the baseline period to approximately 246 mm in the 2080s (+25%), 282 mm in the 2110s (+42%), and 298 mm by the 2130s (+50%) under SSP5-8.5 (Table 2). Overall, projections indicate a more seasonally variable water balance, expected to be characterized by greater winter precipitation and runoff potential combined with stronger evaporative drying during the warm season.

Table 2: Projected Changes in precipitation and evaporative demand at Giant Mine (1960–2150). *Mean values and model ranges (10th –90th percentile) for key thermal indicators relative to the 1991–2020 baseline, shown for selected future planning windows. Arrows indicate the direction of projected change under low-emissions (SSP1-2.6) and high-emissions (SSP5-8.5) scenarios.*

Indicator	Baseline	SSP1-2.6 2080s	SSP1-2.6 2130s	SSP5-8.5 2080s	SSP5-8.5 2110s	SSP5-8.5 2130s
Annual precipitation (mm/yr)	**315.8** [255 to 385]	↑ **364.2 [+15%]** [299 to 435]	↑ **362.1 [+15%]** [283 to 438]	↑ **404.4 [+27%]** [318 to 497]	↑ **455.9 [+44%]** [332 to 605]	↑ **490.2 [+54%]** [353 to 623]
Cold-season precipitation (mm)	**129.0** [105 to 154]	↑ **152.3 [+18%]** [118 to 185]	↑ **156.3 [+21%]** [119 to 192]	↑ **186.4 [+43%]** [138 to 229]	↑ **224.0 [+72%]** [152 to 293]	↑ **253.9 [+95%]** [171 to 341]
Open-water PET (mm)	**364.9** [343 to 386]	↑ **393.6 [+8%]** [366 to 422]	↑ **394.4 [+8%]** [369 to 421]	↑ **444.7 [+23%]** [394 to 490]	↑ **494.9 [+36%]** [413 to 566]	↑ **515.8 [+42%]** [423 to 590]
Net open-water balance (mm)	**-178.6** [-236 to -98]	↓ **-181.9** [-250 to -108]	↓ **-188.2** [-264 to -114]	↓ **-221.3** [-311 to -126]	↓ **-257.0** [-394 to -146]	↓ **-270.6** [-410 to -109]
Summer moisture deficit (mm)	**199.2** [135 to 252]	↑ **207.2** [153 to 268]	↑ **211.1** [149 to 269]	↑ **245.8** [171 to 322]	↑ **282.2** [178 to 398]	↑ **297.7** [174 to 425]

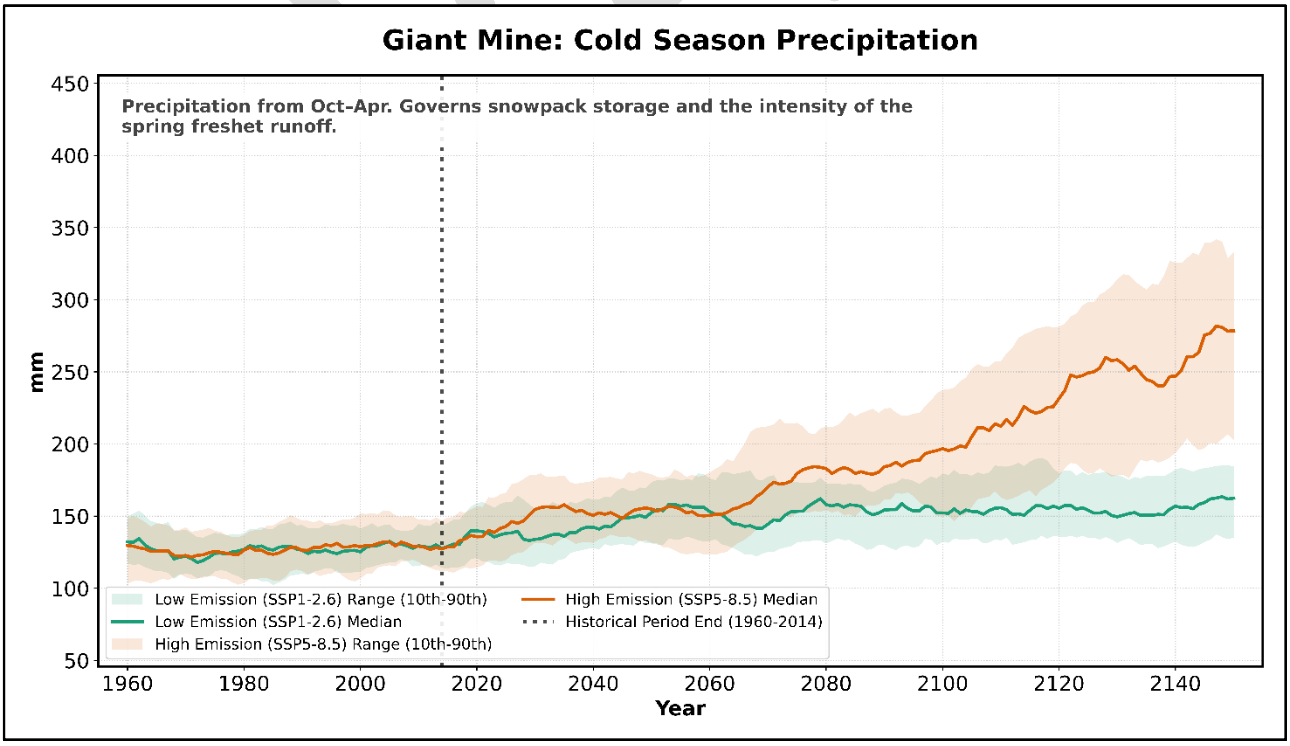

Figure 11: Cold-Season Precipitation Projections for Giant Mine (1960–2150). *Projected changes in precipitation occurring during the cold season (October–April) under SSP1-2.6 and SSP5-8.5. Increases in cold-season precipitation influence snow accumulation and spring runoff entering the site's water management system.*

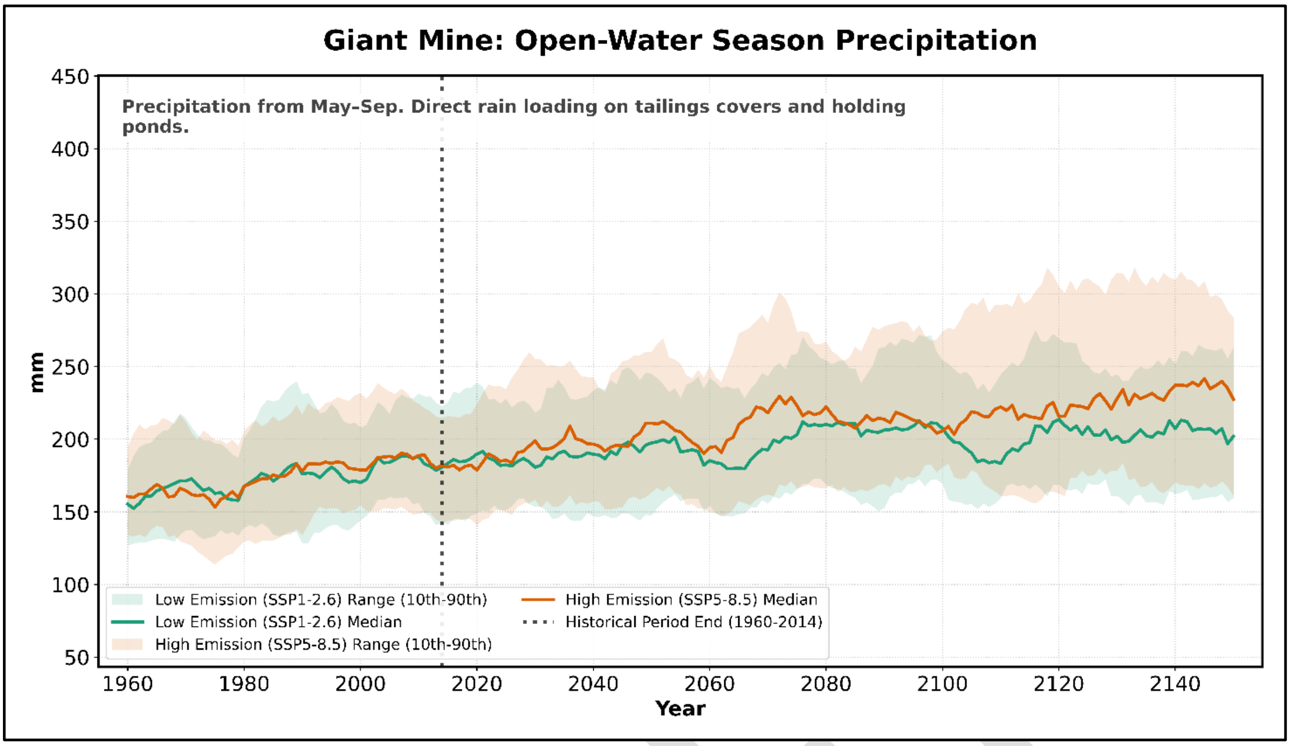

Figure 12: Open-Water Season Precipitation Projections for Giant Mine (1960–2150). *Projected changes in precipitation during the open-water season (May–September). This indicator reflects rainfall loading on surface drainage systems, containment structures, and the site's water treatment infrastructure.*

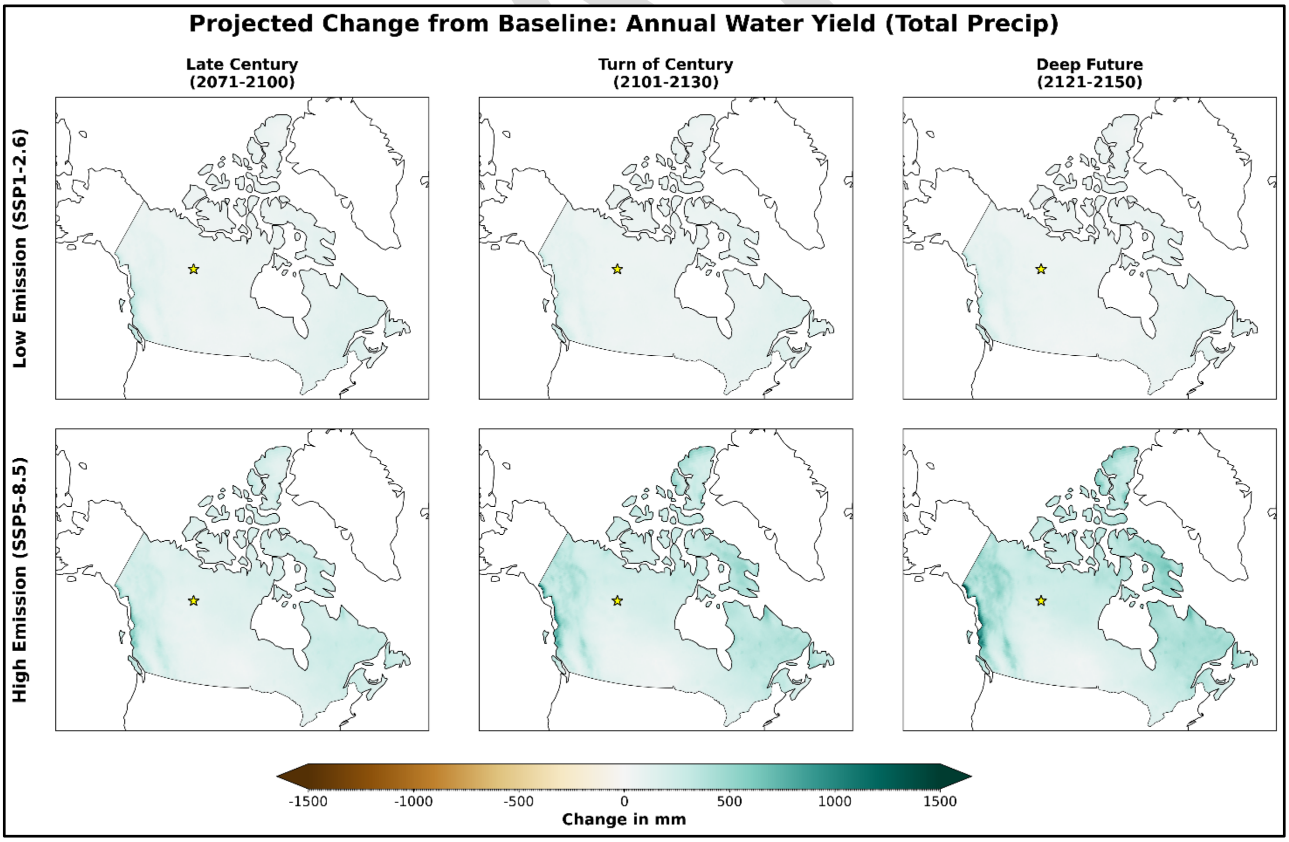

Figure 13: Projected Change in Annual Water Yield Across Canada. *Spatial distribution of projected changes in total annual precipitation relative to the* ***1991–2020 baseline****. The star marks the location of Giant Mine. Increases across northern Canada indicate greater overall water input to regional watersheds.*

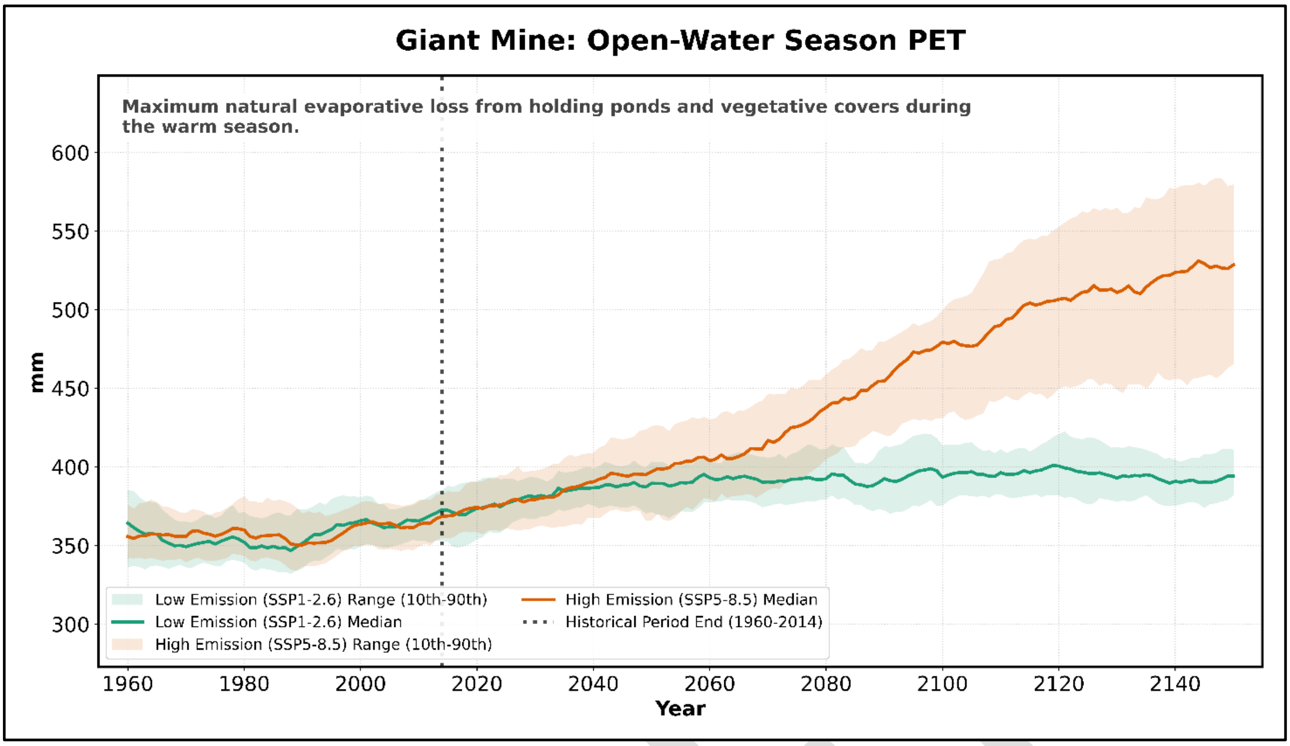

Figure 14: Projected Changes in Open-Water Evaporative Demand at Giant Mine (1960–2150). *Projected changes in potential evapotranspiration (PET) during the open-water season. Increasing PET indicates stronger atmospheric demand for moisture, which can increase drying pressure on exposed surfaces and engineered covers.*

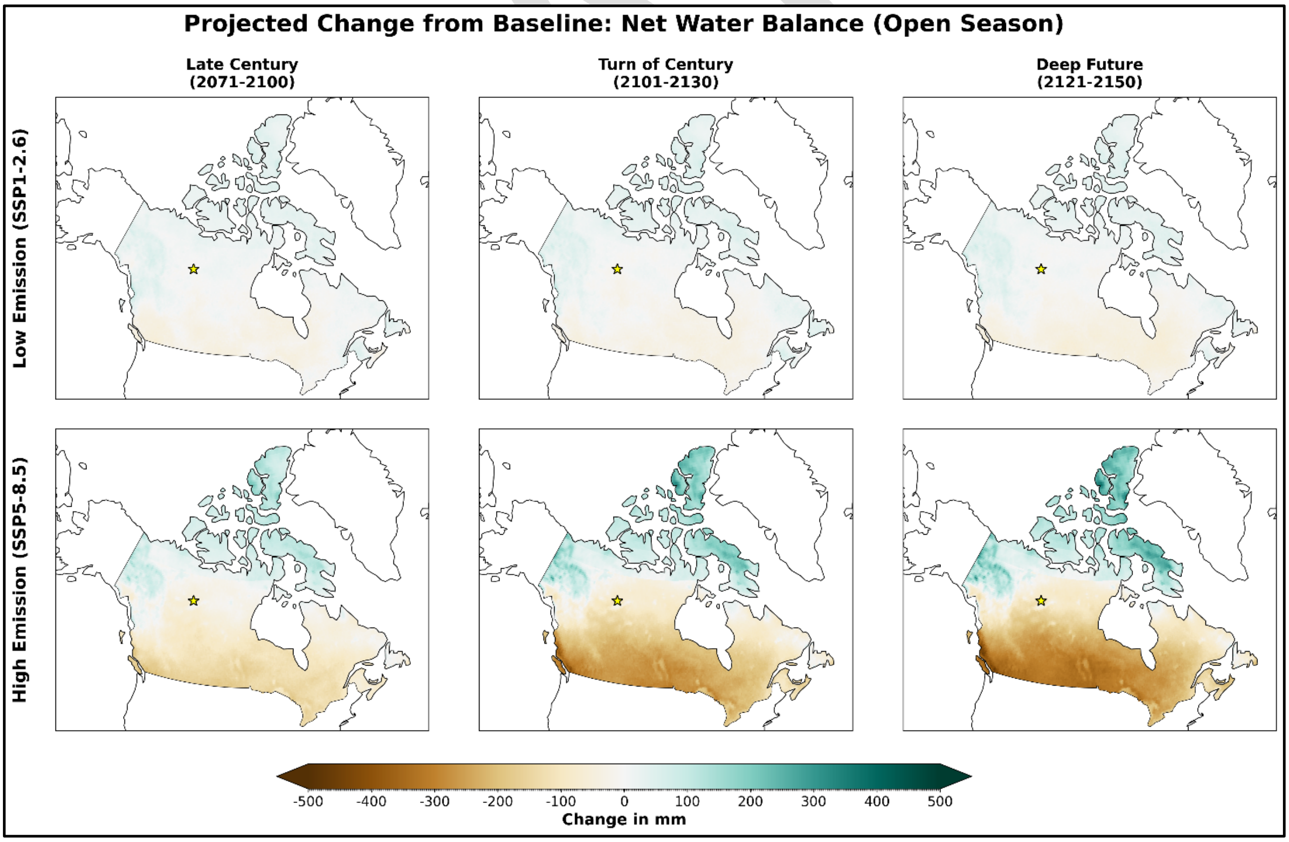

Figure 15: Projected Change in Net Water Balance Across Canada. *Projected changes in net water balance (precipitation minus evapotranspiration). This indicator highlights regions where increasing evaporative demand may offset precipitation gains, influencing long-term surface moisture conditions.*

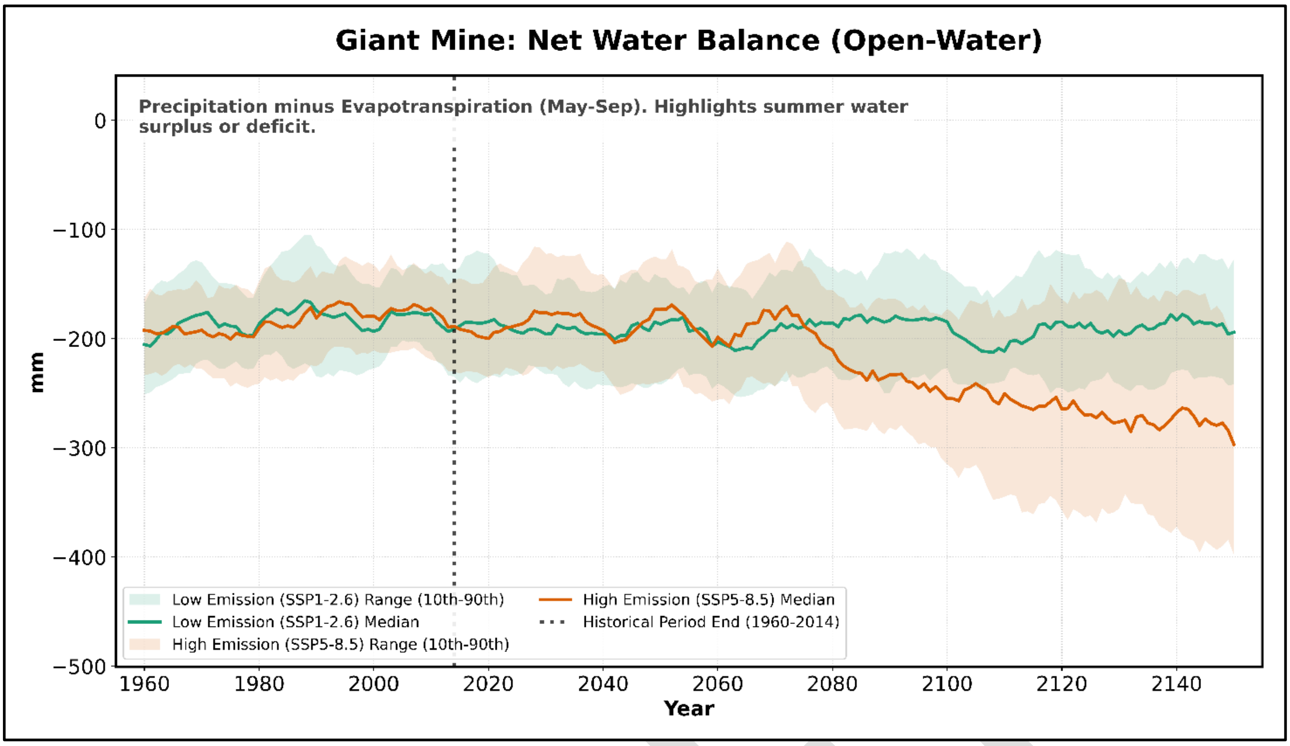

Figure 16: Projected Changes in Net Open-Water Water Balance at Giant Mine (1960–2150). *Projected changes in the difference between open-water precipitation and potential evapotranspiration (P – PET). Negative values indicate periods when atmospheric evaporative demand exceeds rainfall, increasing the likelihood of summer drying.*

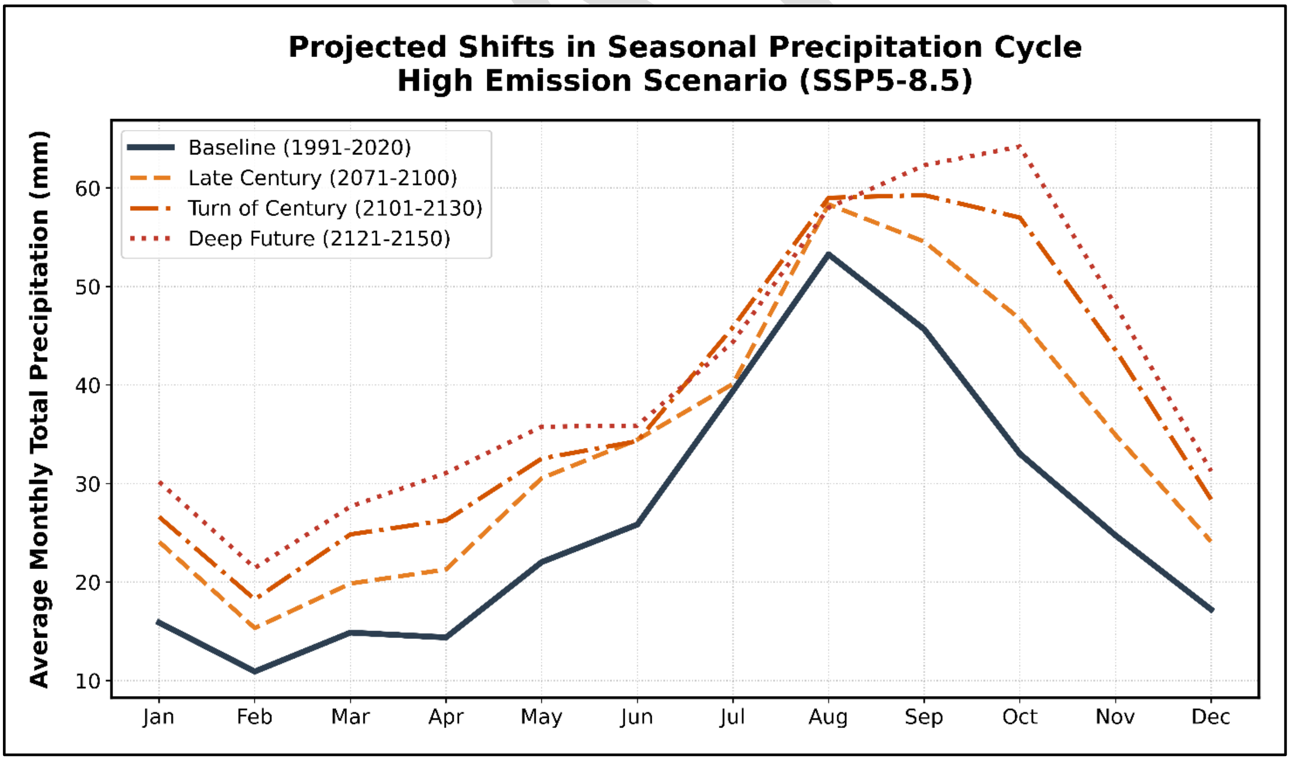

Figure 17: Projected Changes in the Seasonal Precipitation Cycle at Giant Mine. *Monthly precipitation projections showing how rainfall and snowfall patterns may shift throughout the year under SSP5 8.5. Changes in seasonal precipitation influence snow storage, runoff timing, and surface water loading.*

4.3 Wind Exposure and Compound Climate Stress

Projected wind changes at Giant Mine will be more nuanced than the temperature and precipitation signals. Mean summer wind intensity is projected to show a modest decline under both emissions pathways, indicating that wind will likely act primarily as a compounding climate stressor rather than a dominant driver of change. The projected changes in wind exposure and compound indicators are summarized in Table 3, while Figure 18 will illustrate the temporal evolution of high-wind frequency and Figure 19 will provide regional spatial context.

Under SSP1-2.6, average summer wind speeds are projected to decrease slightly from 3.32 m/s during the baseline period (1991–2020) to 3.25 m/s by the 2080s and 3.22 m/s by the 2130s, representing a reduction of roughly 2–3% (Table 3). Under SSP5-8.5, the decline is projected to be larger, with summer wind speeds projected to decrease from 3.34 m/s during the baseline period to 3.02 m/s by the 2080s, 2.94 m/s by the 2110s, and 2.85 m/s by the 2130s, corresponding to an overall reduction of approximately 15% by the deep future period. Spatial projections suggest that wind changes across northern Canada (Figure 19) will remain relatively modest compared with the strong warming and precipitation signals described earlier. Although mean wind speeds are projected to decline, the frequency of high-wind months will remain a more decision-relevant indicator because it will reflect periods when wind-driven surface processes are most likely to occur. As shown in Figure 18, the number of months exceeding the historical high-wind threshold is projected to decrease under SSP1-2.6, declining from 1.2 months per year during the baseline period to 0.73 months by the 2080s and 0.67 months by the 2130s (Table 3). Under SSP5-8.5, the decline is projected to be smaller and less consistent. High-wind frequency is projected to decrease slightly to 0.97 months by the 2080s and 0.99 months by the 2110s but is projected to increase again to 1.25 months per year by the 2130s, with model ranges widening to 0–3 months per year.

Compound climate indicators are projected to provide additional insight into how multiple stressors may interact. The Warm and Wet Season Index is projected to increase under both scenarios, but much more strongly under SSP5-8.5. Values are projected to increase from 0.39 events during the baseline period to 0.84–0.89 events by the 2080s–2130s under SSP1-2.6, and to 1.30 events by the 2080s, 1.77 by the 2110s, and 2.03 by the 2130s under SSP5-8.5 (Table 3). By the late projection period, the model range is projected to expand to 1–4 events, indicating that warm and wet months will become substantially more frequent. In contrast, the Warm and Dry Season Index is projected to remain low under SSP1-2.6 and is projected to increase only modestly under SSP5-8.5, reaching 0.24 events by the 2130s.

These results suggest that future compound climate risk at Giant Mine will be more likely to be driven by warm-and-wet conditions rather than warm-and-dry extremes. Periods combining elevated temperatures, increased precipitation, and occasional high winds may intensify erosion, runoff, and surface instability even if average wind speeds are projected to decline.

Table 3: Projected Changes in Wind Exposure and Compound Climate Stress Indicators at Giant Mine (1960–2150).
Mean values and model ranges (10th–90th percentile) relative to the 1991–2020 baseline, shown for selected future planning windows. Arrows indicate the direction of projected change under low-emissions (SSP1-2.6) and high-emissions (SSP5-8.5) scenarios.

Indicator	Baseline	SSP1-2.6 2080s	SSP1-2.6 2130s	SSP5-8.5 2080s	SSP5-8.5 2110s	SSP5-8.5 2130s
Summer wind (m/s)	**3.32** [3.12 to 3.53]	↓ **3.25** [3.07 to 3.46]	↓ **3.22** [3.06 to 3.37]	↓ **3.02** [2.80 to 3.23]	↓ **2.94** [2.62 to 3.25]	↓ **2.85** [2.55 to 3.21]
High-wind months (count/yr)	**1.20** [0 to 2]	↓ **0.73** [0 to 2]	↓ **0.67** [0 to 2]	↓ **0.97** [0 to 2]	↓ **0.99** [0 to 2]	↑ **1.25** [0 to 3]
Warm and wet index (count)	**0.39** [0 to 1]	↑ **0.84** [0 to 2]	↑ **0.89** [0 to 2]	↑ **1.30** [0 to 2.1]	↑ **1.77** [0 to 3]	↑ **2.03** [1 to 4]
Warm and dry index (count)	**0.01** [0 to 0]	↑ **0.04** [0 to 0]	↑ **0.02** [0 to 0]	↑ **0.11** [0 to 1]	↑ **0.19** [0 to 1]	↑ **0.24** [0 to 1]

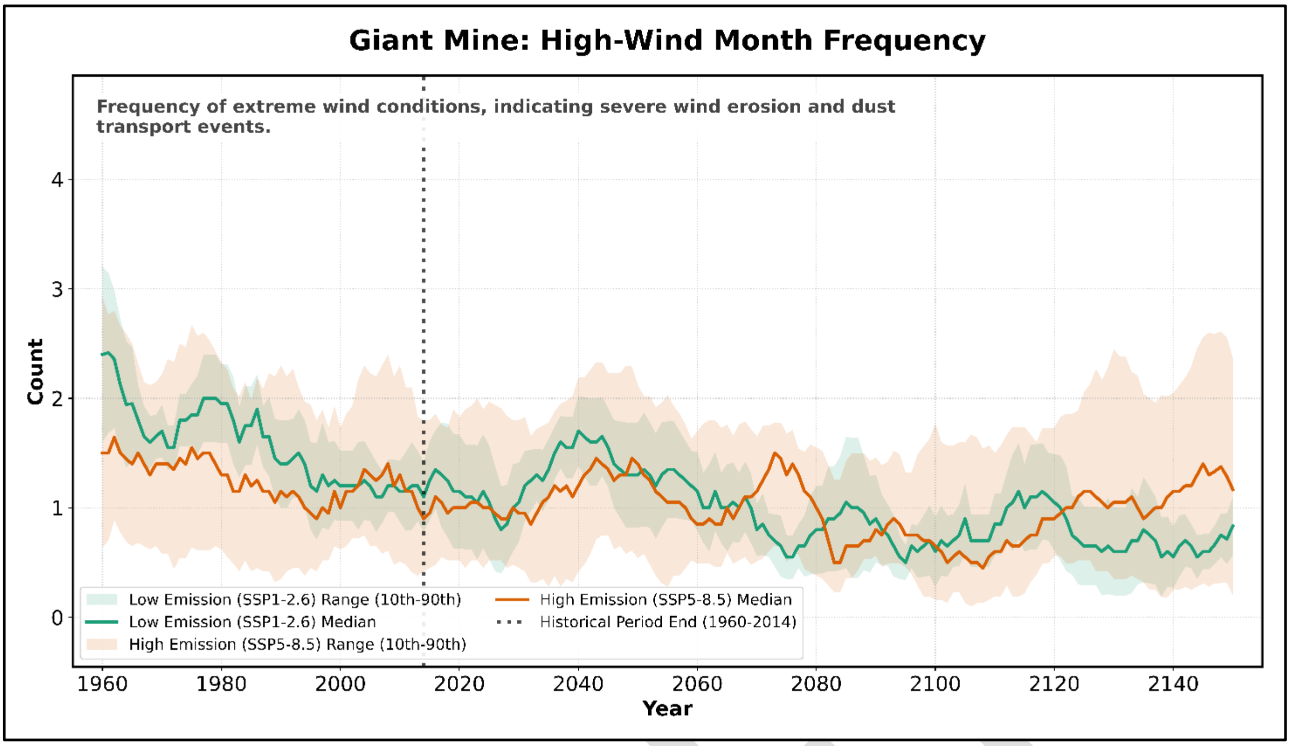

Figure 18: High-Wind Month Frequency Projections for Giant Mine (1960–2150). *Projected changes in the number of months per year exceeding the historical high-wind threshold under SSP1-2.6 and SSP5-8.5 scenarios. Changes in high-wind frequency influence wind-driven surface processes such as erosion, snow redistribution, and the transport of airborne materials.*

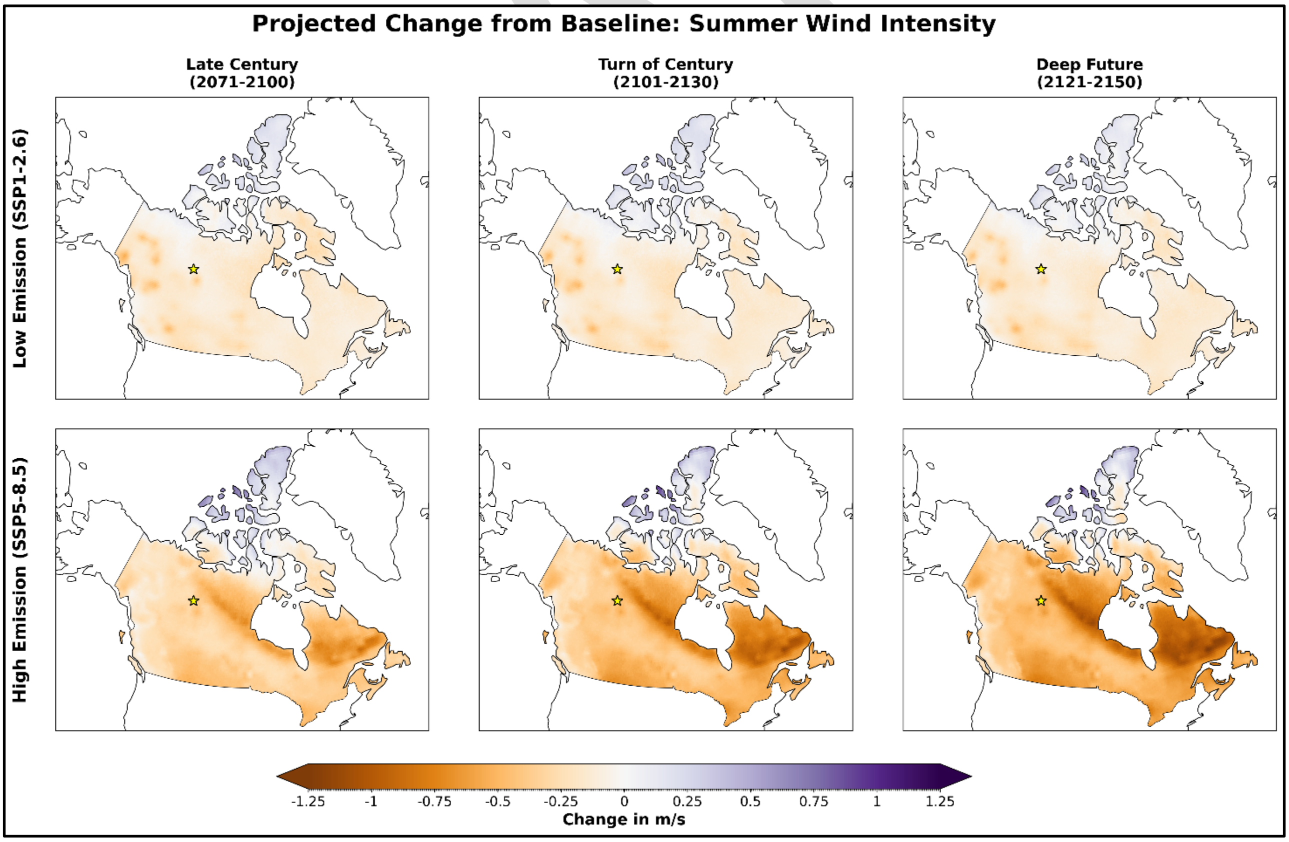

Figure 19: Projected Change in Summer Wind Intensity Across Canada. *Spatial distribution of projected changes in mean summer wind speeds relative to the 1991–2020 baseline. The star marks the location of Giant Mine.*

4.4 Great Slave Lake Water-Level Context

The Great Slave Lake context is intended to show how climate change at Giant Mine will fit within a broader northern water-balance system. It will not be a direct lake-level forecast or projection. Instead, it will use climate indicators that influence lake and watershed conditions, including precipitation, evaporation, persistent wet and dry cycles, and the length of the warm growing period. These indicators will help reveal whether the regional hydrologic system will become more evaporation-dominated, more storage-sensitive, or more seasonally dynamic over time (Table 4; Figures 20–22).

The clearest regional signal will be the growing season length (Table 4; Figure 20). Under SSP1-2.6, the growing season will increase modestly from 4.22 months during the baseline (1991–2020) to 4.71 months in the 2080s and 4.72 months in the 2130s. Under SSP5-8.5, the expansion will be much larger, increasing to 5.79 months in the 2080s, 6.50 months in the 2110s, and 7.11 months in the 2130s. This will reflect earlier spring warming and later autumn freeze-up, extending the period when open-water and evaporation processes will operate across the watershed. Northern regions (Figure 22) will be projected to experience some of the largest increases in growing season duration, reflecting earlier spring transitions and delayed autumn cooling.

The 24-month SPEI (SPEI-24) will provide additional context by tracking persistent wet and dry periods over multi-year timescales (Table 4; Figure 21). Under SSP1-2.6, SPEI-24 will shift slightly positive by the late century, reaching 0.29 in the 2080s and 0.28 in the 2130s, suggesting somewhat wetter multi-year conditions. Under SSP5-8.5, the index will become slightly negative (−0.13 in the 2080s and −0.26 in the 2110s) before moving closer to neutral by the 2130s (−0.05). More important than the mean value will be the widening range of outcomes, which will expand to approximately −3 to +3, indicating increasing variability in long-term moisture balance.

When interpreted alongside projected increases in cold-season precipitation (Figure 11) and a more negative open-water water balance (Table 4), the broader message will be that the watershed may experience greater seasonal variability in water inputs and losses, rather than a simple long-term shift toward wetter or drier conditions. For Giant Mine, this regional perspective will reinforce the importance of evaluating site-level risks within the context of broader watershed-scale climate change.

Table 4: Projected Changes in Seasonal Timing and Long-Term Moisture Balance Indicators at Giant Mine (1960–2150). *Mean values and model ranges (10th–90th percentile) relative to the 1991–2020 baseline, shown for selected future planning windows. Arrows indicate the direction of projected change under low-emissions (SSP1-2.6) and high-emissions (SSP5-8.5) scenarios.*

Indicator	Baseline	SSP1-2.6 2080s	SSP1-2.6 2130s	SSP5-8.5 2080s	SSP5-8.5 2110s	SSP5-8.5 2130s
Growing season length (months)	**4.22** [4 to 5]	↑ **4.71** [4 to 5]	↑ **4.72** [4 to 5]	↑ **5.79** [5 to 6]	↑ **6.50** [6 to 7]	↑ **7.11** [6 to 8]
SPEI-24 (unitless)	**0.00** [-1.29 to 1.29]	↑ **0.29** [-1.23 to 1.76]	↑ **0.28** [-1.24 to 1.96]	↓ **-0.13** [-2.49 to 1.98]	↓ **-0.26** [-3.00 to 2.47]	↓ **-0.05** [-3.00 to 2.98]
Cold-season precipitation (mm)	**129.0** [105 to 154]	↑ **152.3** [118 to 185]	↑ **156.3** [119 to 192]	↑ **186.4** [138 to 229]	↑ **224.0** [152 to 293]	↑ **253.9** [171 to 341]
Net open-water balance (mm)	**-178.6** [-236 to -98]	↓ **-181.9** [-250 to -108]	↓ **-188.2** [-264 to -114]	↓ **-221.3** [-311 to -126]	↓ **-257.0** [-394 to -146]	↓ **-270.6** [-410 to -109]

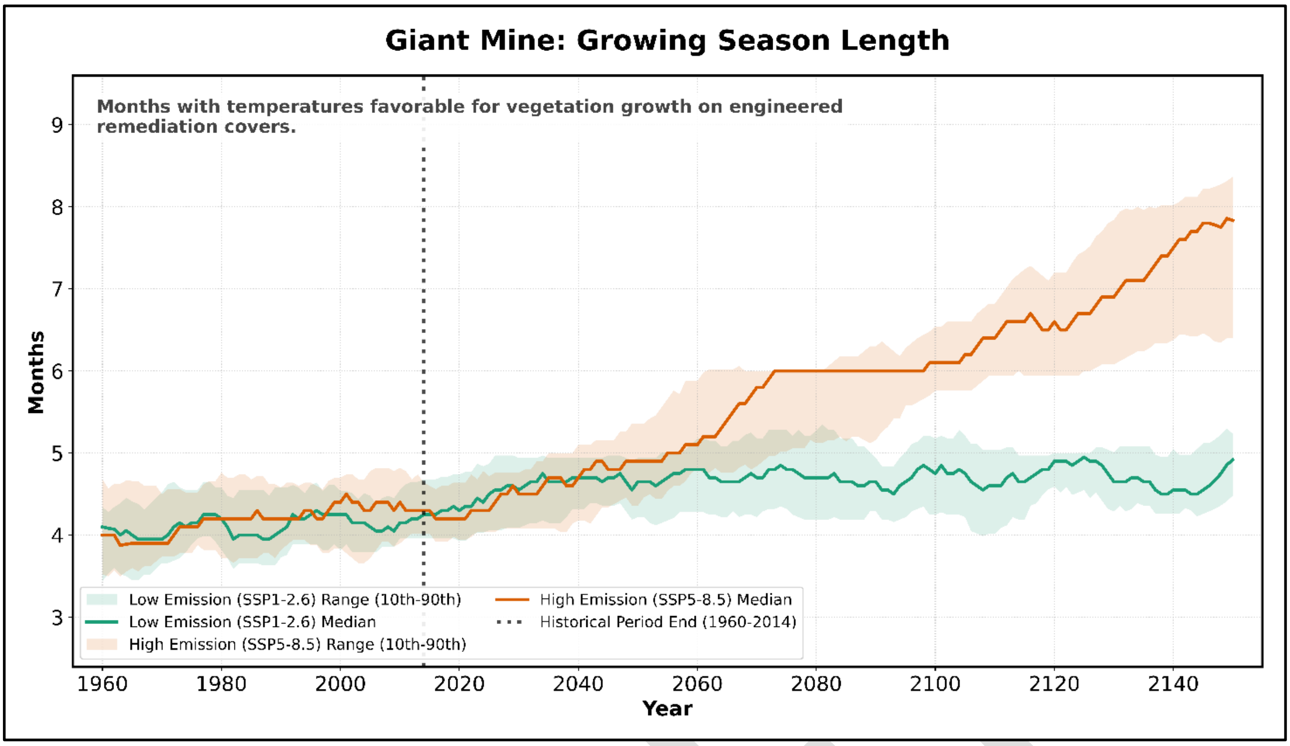

Figure 20: Growing Season Length Projections for Giant Mine (1960–2150). Projected changes in the length of the growing season (months with mean temperatures above biological growth thresholds) under SSP1-2.6 and SSP5-8.5 scenarios. Increasing growing season length reflects earlier spring onset and later autumn freeze, extending the period when biological and hydrological processes are active.

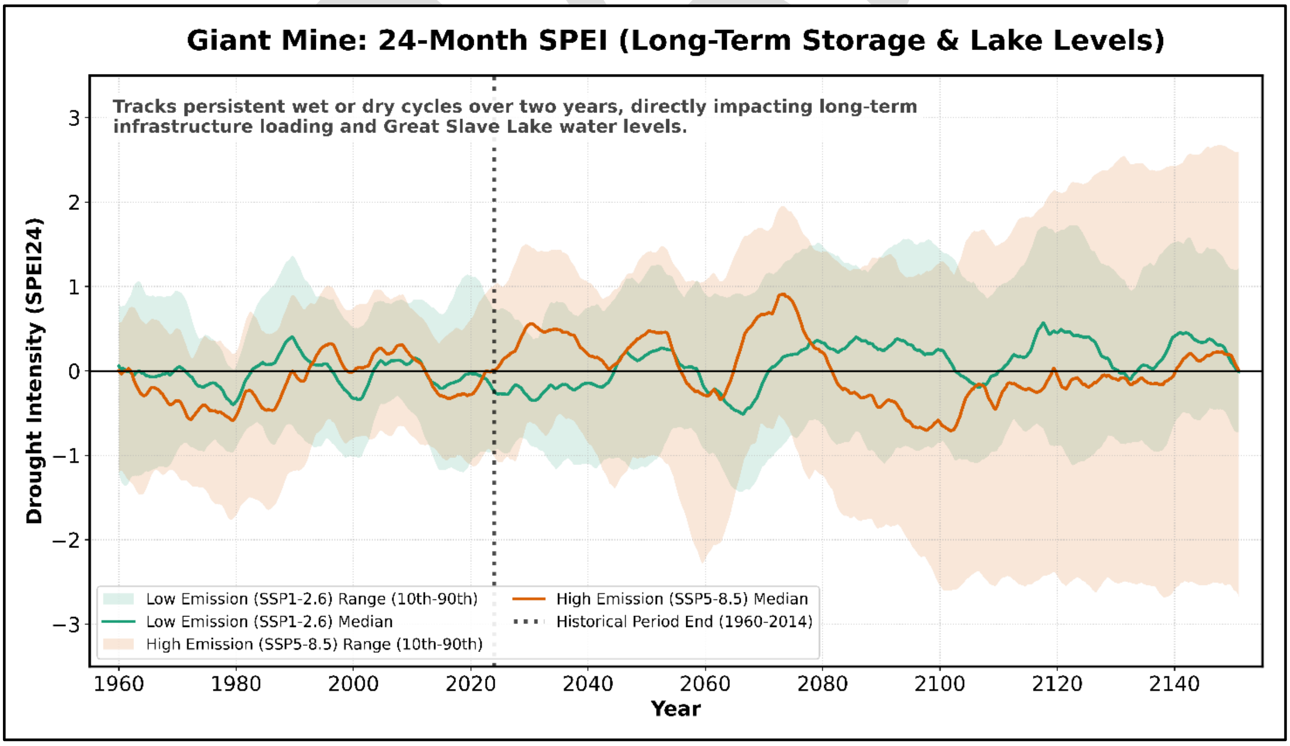

Figure 21: Multi-Year Moisture Balance Projections for Giant Mine (1960–2150). Projected changes in the 24-month Standardized Precipitation–Evapotranspiration Index (SPEI-24), which measures long-term moisture balance by accounting for both precipitation and atmospheric evaporative demand. Positive values indicate wetter-than-normal conditions, while negative values indicate multi-year moisture deficits.

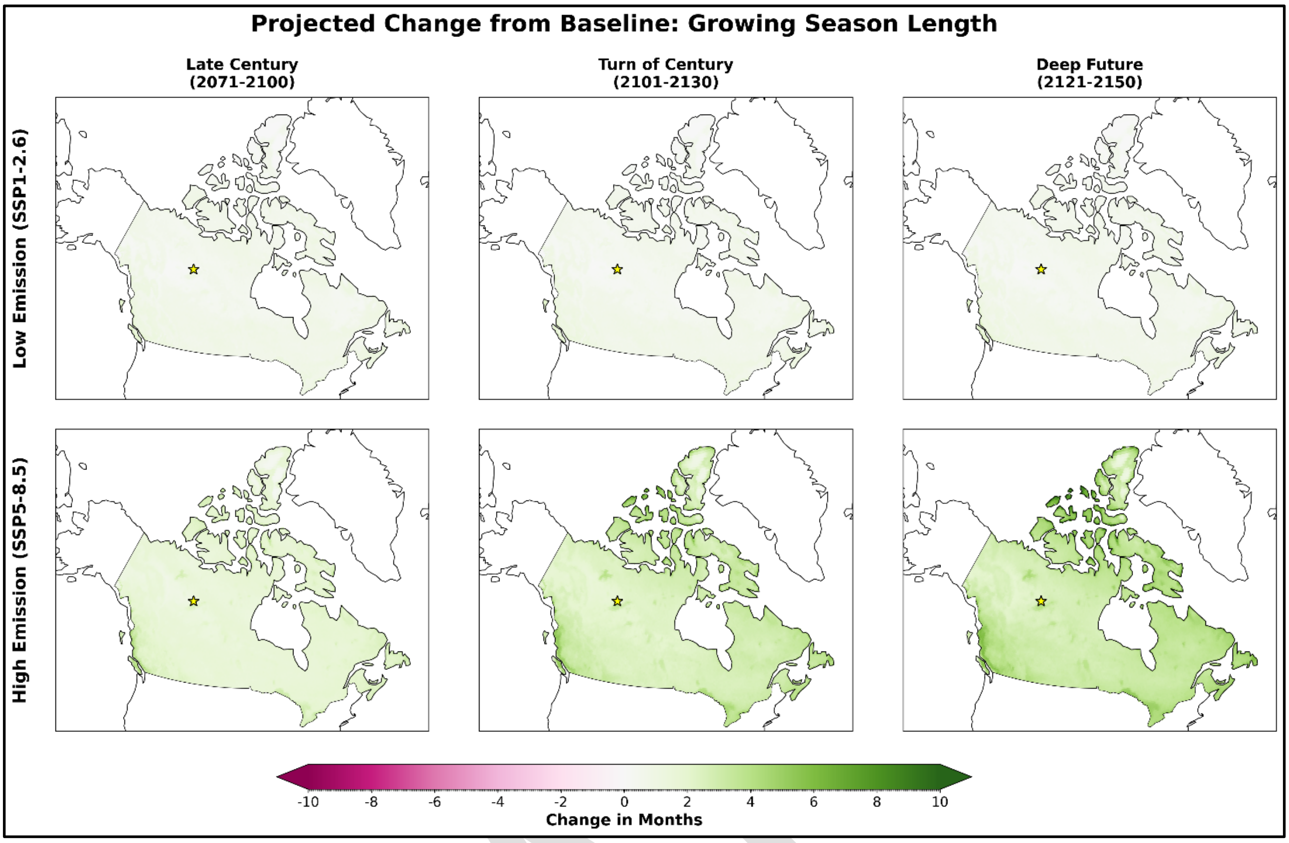

Figure 22: Projected Change in Growing Season Length Across Canada. *Spatial distribution of projected changes in growing season length relative to the 1991–2020 baseline. The star marks the location of Giant Mine. Northern regions are projected to experience some of the largest increases in growing season duration, reflecting earlier spring transitions and delayed autumn cooling.*

5 Climate Implications for Long-Term Stewardship

5.1 Ground Temperature and Permafrost Stability

Projected warming will represent the most fundamental long-term climate stress affecting the Giant Mine site. As shown in the thermal indicators presented in Section 4, mean annual air temperatures are projected to increase substantially across all scenarios, with the strongest warming expected to occur under the high-emissions pathway. This warming will drive a corresponding increase in thawing degree days and a decline in freezing degree days, indicating that the landscape will receive progressively more thawing energy while losing part of the natural freezing capacity that historically maintained cold ground conditions. For a site where subsurface containment strategies rely on maintaining stable thermal conditions, these changes will be highly relevant. The reduction in freezing energy will not imply that freezing processes will disappear, but it will indicate that the natural climatic margin supporting frozen ground conditions will gradually narrow over time. At the same time, increasing thawing energy will contribute to deeper seasonal thaw and longer periods when soils, rock fractures, and engineered surfaces are exposed to thaw conditions.

Changes in seasonal timing will reinforce this shift. The projected expansion of the growing season will indicate earlier spring warming and later autumn freeze-up, extending the period when ground temperatures remain above freezing. Over the long stewardship horizon considered in this assessment, this will mean that the ground thermal regime is likely to become more dynamic, with longer thaw periods and shorter periods of sustained freezing. For long-term stewardship planning, the key implication will be that thermal conditions influencing subsurface stability will continue to evolve. Monitoring systems, engineering designs, and adaptive management strategies should therefore account for gradual warming and the associated reduction in the natural climatic buffer that historically supported stable frozen ground conditions.

5.2 Water Management and Drainage Systems

Climate projections indicate that the Giant Mine site will experience increasing precipitation alongside rising atmospheric evaporative demand. While these changes may appear to offset each other at first glance, the combined effect will be a more dynamic hydrological system with stronger seasonal water movement. Annual precipitation is projected to increase under both emissions scenarios, with the largest increases expected under the high-emissions pathway. Cold-season precipitation is projected to increase particularly strongly, suggesting greater snowfall accumulation and potentially larger spring runoff volumes entering the site's drainage system. These changes suggest that future hydrologic conditions will involve greater seasonal throughput of water rather than a simple shift toward wetter or drier conditions.

At the same time, potential evapotranspiration is projected to increase substantially as temperatures rise. During the open-water season, evaporative demand is projected to increase faster than precipitation in many projections, resulting in a more negative net water balance. This means that summers may experience stronger drying pressure even as total annual precipitation increases. For water management systems, the implication will be that both ends of the hydrological spectrum will become more important. Higher precipitation and increased cold-season snow accumulation will be able to increase runoff and hydraulic loading on drainage infrastructure. At the same time, stronger summer evaporation may influence surface moisture conditions, pond water balances, and the behaviour of exposed soils and engineered covers.

In summary, these changes suggest that drainage systems and water treatment infrastructure should be designed and managed for greater seasonal variability. Planning assumptions based solely on historical precipitation conditions may underestimate the magnitude and timing of future water flows entering the site.

5.3 Surface Stability, Erosion, and Dust Risk

Climate change can influence surface stability at the Giant Mine site through several interacting mechanisms, including temperature change, precipitation intensity, wind exposure, and seasonal drying. The projections presented in Section 4 indicate that these drivers will evolve simultaneously over the coming decades. Warmer conditions and a longer growing season extend the period each year when soils and surface materials are exposed to thaw conditions. This longer thaw period increases the time window during which erosion, surface runoff, and soil movement can occur. When combined with projected increases in precipitation, particularly during colder months that influence snow storage and spring melt, these conditions may contribute to stronger seasonal runoff events.

At the same time, higher evaporative demand during the open-water season increases the likelihood of surface drying. Even though total precipitation increases, the rising atmospheric demand for moisture means that exposed soils may experience stronger drying pressure during summer months. Drying soils can be more susceptible to cracking and surface disturbance. Wind exposure adds another layer of influence. Although mean summer wind speeds show slight decreases in some projections, wind remains an important environmental driver because it interacts with both wet and dry conditions. Wind can influence snow redistribution during winter and can also transport fine particles when surfaces become dry.

From a stewardship perspective, this combination of processes highlights the importance of managing both moisture and surface integrity. Erosion control, surface stabilization, and vegetation performance will remain important elements of long-term site management.

5.4 Compound Climate Stress and System Interactions

Climate change will influence surface stability at the Giant Mine site through several interacting mechanisms, including temperature change, precipitation intensity, wind exposure, and seasonal drying. The projections presented in Section 4 indicate that these drivers will evolve simultaneously over the coming decades. Warmer conditions and a longer growing season will extend the period each year when soils and surface materials are exposed to thaw conditions. This longer thaw period will increase the time window during which erosion, surface runoff, and soil movement can occur. When combined with projected increases in precipitation, particularly during colder months that influence snow storage and spring melt, these conditions may contribute to stronger seasonal runoff events.

At the same time, higher evaporative demand during the open-water season will increase the likelihood of surface drying. Even though total precipitation will increase, the rising atmospheric demand for moisture will mean that exposed soils may experience stronger drying pressure during summer months. Drying soils may become more susceptible to cracking and surface disturbance. Wind exposure will add another layer of influence. Although mean summer wind speeds are projected to show slight decreases in some projections, wind will remain an important environmental driver because it will interact with both wet and dry conditions. Wind may influence snow redistribution during winter and may also transport fine particles when surfaces become dry.

From a stewardship perspective, this combination of processes will highlight the importance of managing both moisture and surface integrity. Erosion control, surface stabilization, and vegetation performance will remain important elements of long-term site management.

6 Conclusion and Path Forward

Observed and projected climate trends indicate that Giant Mine is expected to experience sustained warming, longer thaw seasons, higher precipitation, and stronger evaporative demand over the coming decades. These changes are expected to influence permafrost stability, water management capacity, surface integrity, and compound environmental risks. Long-term stewardship planning should therefore remain adaptive, monitoring-based, and designed for evolving climate conditions rather than fixed historical assumptions. The climate indicators and projections presented in this factsheet provide a practical evidence base to support risk-informed engineering design, operational planning, and periodic reassessment of mitigation strategies throughout the perpetual care horizon.

7 Notes on Interpretation and Limitations

The climate projections and indicators presented in this factsheet provide a scientifically robust basis for understanding potential long-term environmental change at the Giant Mine site. However, several important considerations should be considered when interpreting these results.

To begin with, climate projections represent plausible future conditions rather than precise forecasts. They are based on global climate model simulations driven by different assumptions about future greenhouse gas emissions and socio-economic development pathways. The two emissions scenarios used in this assessment (SSP1-2.6 and SSP5-8.5) are intended to represent a range of potential climate futures rather than specific predicted outcomes. Actual future climate conditions will depend on global mitigation actions, natural variability, and regional climate processes.

Next, extended projections beyond the year 2100 are based on a smaller subset of climate models. While the full CMIP6 archive contains more than sixty models, only nine provide simulations extending to approximately 2140–2150 under the ScenarioMIP framework used in this assessment. As a result, uncertainty ranges increase in the far-future time windows. These extended projections should therefore be interpreted as indicative of long-term trends and directional change rather than precise quantitative estimates.

Additionally, climate indicators were derived from monthly data rather than daily observations. Monthly timescales provide a stable basis for evaluating long-term climate change and hydroclimatic trends over extended horizons. However, some short-duration extreme events such as intense rainfall bursts or brief freeze-thaw episodes may not be fully captured. Where relevant, engineering design and risk assessments should complement these results with event-based analyses.

Furthermore, bias-correction methods were applied to align climate model projections with observed conditions. While these methods improve the reliability of projected climate statistics, they cannot eliminate all uncertainty associated with future climate change.

Finally, climate indicators describe environmental pressures rather than direct infrastructure performance. Crucially, detailed hydrological modelling of the Great Slave Lake basin was not performed for this assessment; instead, diagnostic climate indicators (such as Net Water Balance and SPEI) were used to evaluate regional moisture trends and infer potential directional shifts in lake levels. The results presented here should therefore be interpreted in conjunction with site-specific engineering assessments, geotechnical monitoring, dedicated hydrological modelling, and ongoing operational experience.

Overall, the findings of this assessment are most valuable when used as part of an adaptive management framework. Periodic updates incorporating new observations, improved climate projections, and evolving site knowledge will help ensure that long-term stewardship strategies remain robust under changing environmental conditions.

8 Appendix

8.1 Appendix A: Climate Indicators and Definitions

Table A1: Table of Climate Indicators and Definitions

Category	Indicator Name	Unit	Description / Definition	Relevance to Giant Mine
Thermal Regime and Ground Stability	**Mean Annual Air Temperature (MAAT)**	°C	Average air temperature over the year.	Primary driver of permafrost stability and long-term subsurface warming of the bedrock and frozen blocks.
	Thawing Degree Days (TDD)	°C days	Sum of daily temperatures > 0°C.	Runoff and Cover Stability: Drives rapid snowmelt (spring freshet) and deepens the active layer on tailings covers, potentially mobilizing contaminants.
	Freezing Degree Days (FDD)	°C days	Sum of daily temperatures < 0°C.	Ground Stability: The "fuel" for the passive freezing system. Low FDD years threaten the integrity of the frozen blocks and crown pillars.
	Length of Freezing Season	Months	Number of months with a mean temperature < 0°C.	Dictates winter construction windows, ice-road viability, and operational assumptions for passive cooling systems.
	Freeze-Thaw Cycle Count	Count/year	Number of times temperatures cross 0°C (monthly proxy).	Drives physical weathering, road degradation, concrete fatigue, and accelerated erosion of engineered caps.
Hydrology and Water Balance	**Annual Water Yield**	mm/year	Total precipitation received over a full year.	Water Treatment Capacity: Represents the total baseline volume of contaminated water that must be collected, treated, and discharged.
	Seasonal Precipitation Totals (P)	mm/season	Precipitation split into Cold (Oct–Apr) and Open-water (May–Sep) seasons.	Dictates the balance between winter snow storage (spring runoff volume) versus summer rain loading.
	Potential Evapotranspiration (PET)	mm/season	The atmospheric "thirst" or maximum evaporative demand based on temperature and radiation.	Determines the natural evaporative loss from holding ponds, surface water, and vegetative tailings covers.
	Net Water Balance (P – PET)	mm	The difference between precipitation supply and evaporative demand.	Directional lake-level and surface drainage signal; indicates if the overall site is trending wetter or drying out.
	Summer Moisture Deficit (SCMD)	mm	Cumulative deficit (PET – P) during the summer months when evaporation exceeds rain.	Dust Generation: High deficits severely dry out tailings covers, increasing the risk of surface cracking and arsenic dust dispersion.
	SPEI (12- and 24-month)	Z-score	Standardized index measuring	Tracks multi-year compounding drought or wet

			drought/wetness severity relative to historical normal (1991–2020).	persistence affecting long-term storage systems, lake levels, and groundwater tables.
Extreme Precipitation and Drainage	**Peak Hydraulic Load (Max Monthly Precipitation)**	mm/month	Maximum precipitation received in a single month.	Infrastructure Safety: Critical for sizing ditches, spillways, and holding ponds to prevent catastrophic overflows of contaminated water.
	Wettest 3-Month Running Total	mm/3-months	Cumulative precipitation over the wettest 3 consecutive months.	Hydrologically relevant loading indicator representing prolonged stress and saturation of water management infrastructure.
	95th Percentile Precipitation	mm	The precipitation threshold exceeded only by the top 5% of wettest months.	Extremes proxy framing the upper bounds of climate stress on the site's drainage network.
Wind and Surface Exposure	**Summer Wind Intensity**	m/s	Mean Wind Speed during the dry open-water season (May–Sep).	Dust Transport: Stronger summer winds increase the distance and volume of dust transport if protective covers degrade.
	High-Wind Month Frequency	Count	Number of months exceeding the historical 90th percentile for wind speed.	Tracks the increasing frequency of extreme wind events that threaten surface erosion and wave action on containment ponds.
Seasonality and Transitions	**Transition Month Shift**	Month	Shift in the timing of the first month > 0°C (Spring) and last month < 0°C (Fall).	Determines the shifting timing of the spring freshet and the expanding duration of the active drainage and evaporation season.
	Growing Season Length	Months	Number of consecutive months with temperatures > 5°C.	Dictates the viability and performance of vegetation used on engineered surfaces and tailings caps.
Compound Stress	**Warm and Wet Season Index**	Count	Occurrence of concurrent high temperature and high precipitation.	Identifies compounding extremes leading to enhanced thermodynamic erosion and rapid contaminant mobilization.
	Warm and Dry Season Index	Count	Occurrence of concurrent high temperature and low precipitation.	Highlights periods of extreme desiccation stress, leading to tailings cover cracking and vegetation failure.

8.2 Appendix B: Baseline Climate Conditions Used for Interpreting Projected Changes

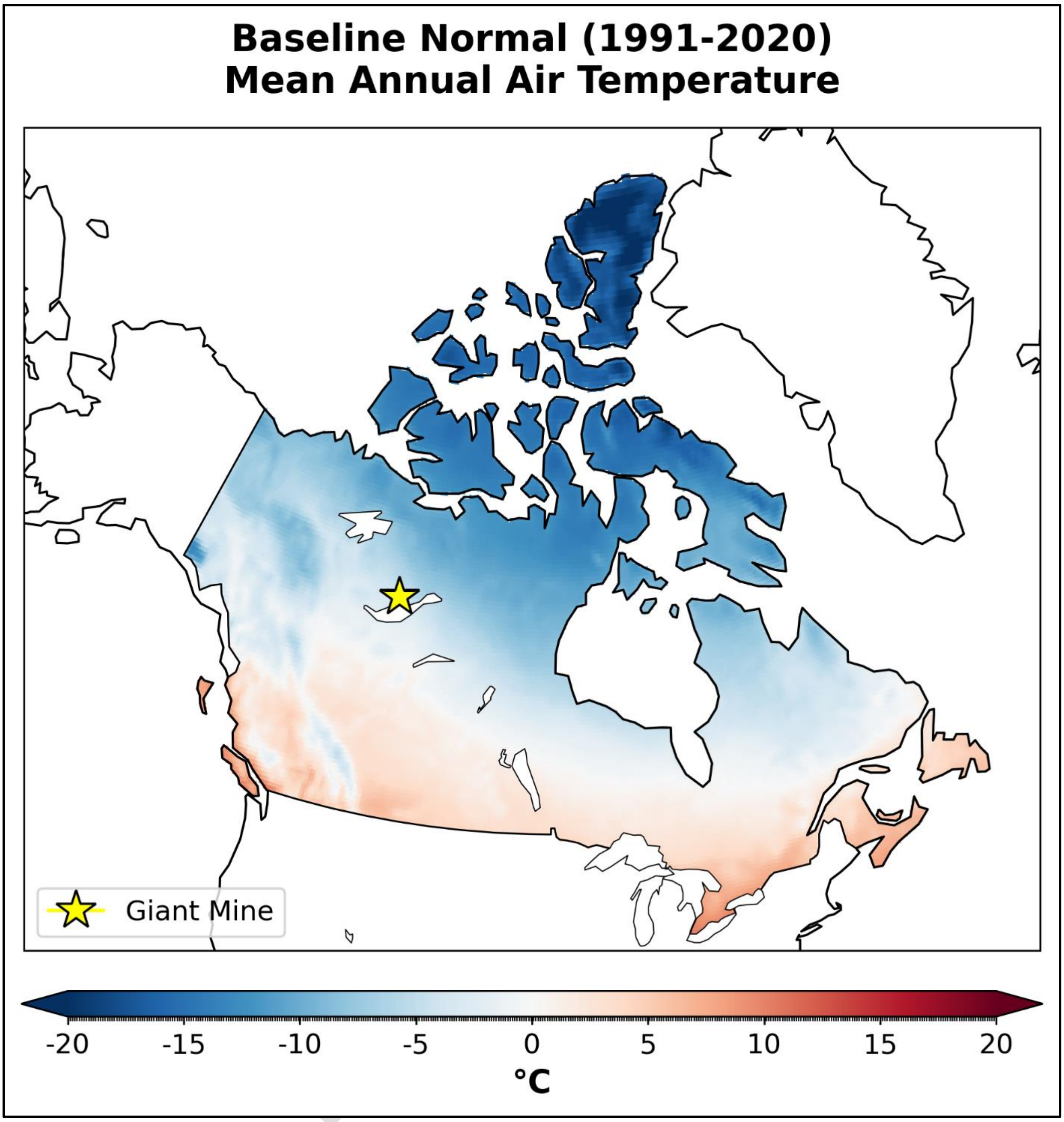

Figure B1: Baseline Climate Normal (1991–2020) Mean Annual Air Temperature from Bias-Corrected CMIP6 Ensemble. *Spatial distribution of ensemble-mean annual air temperature derived from bias-corrected CMIP6 climate model simulations for the reference period 1991–2020. The map represents the modeled baseline climate used for future change assessment rather than observed conditions. The star indicates the location of the Giant Mine site.*

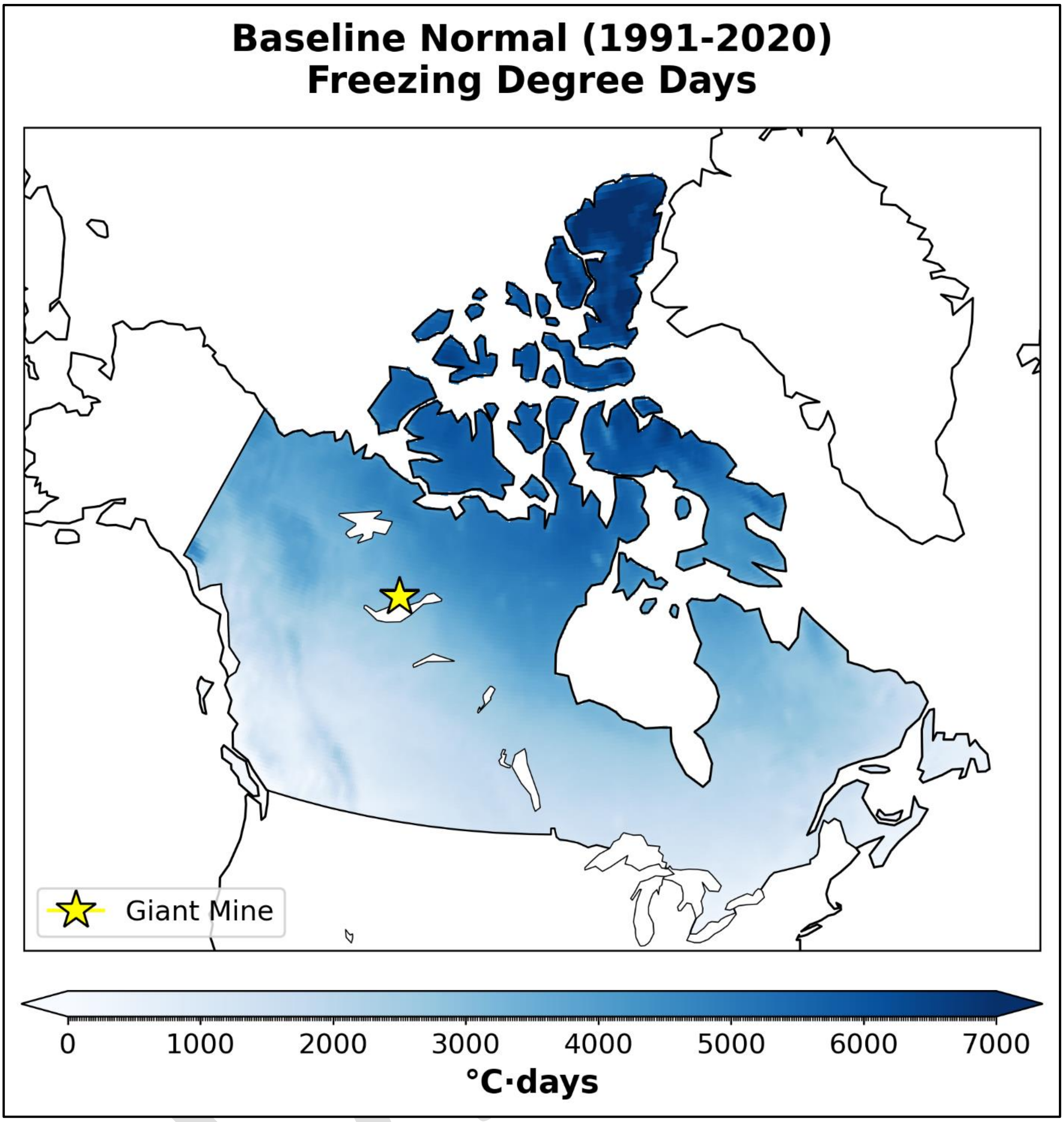

Figure B2: Baseline Freezing Degree Days (FDD) Across Canada (1991–2020 Climate Model Normals).
Spatial distribution of cumulative annual freezing energy derived from bias-corrected CMIP6 climate model simulations for the 1991–2020 baseline period. Higher values indicate regions with stronger and more persistent winter cooling. Northern Canada exhibits the largest accumulation of freezing energy, reflecting long cold seasons and sustained sub-zero temperatures. The star marks the location of Giant Mine near Yellowknife. These baseline conditions provide the reference thermal regime against which future projected declines in freezing energy are evaluated.

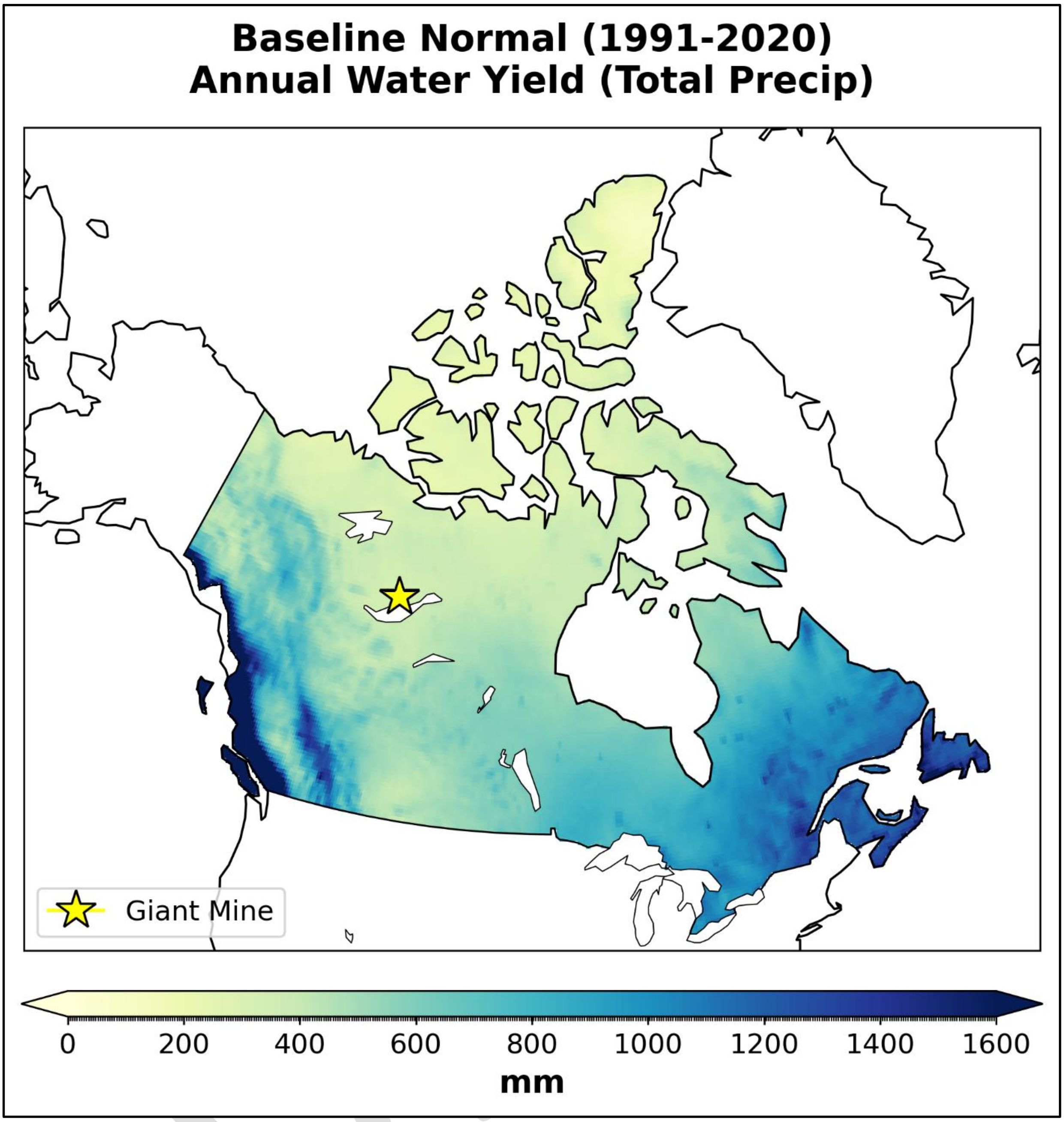

Figure B3: Baseline Annual Water Yield (1991–2020 CMIP6 Ensemble Normal).
Spatial distribution of annual total precipitation simulated by bias-corrected CMIP6 climate models for the 1991–2020 baseline period. The star indicates the location of Giant Mine. This baseline represents the reference hydroclimatic conditions used to evaluate projected changes in water inputs, runoff potential, and drainage system loading across the broader northern watershed.

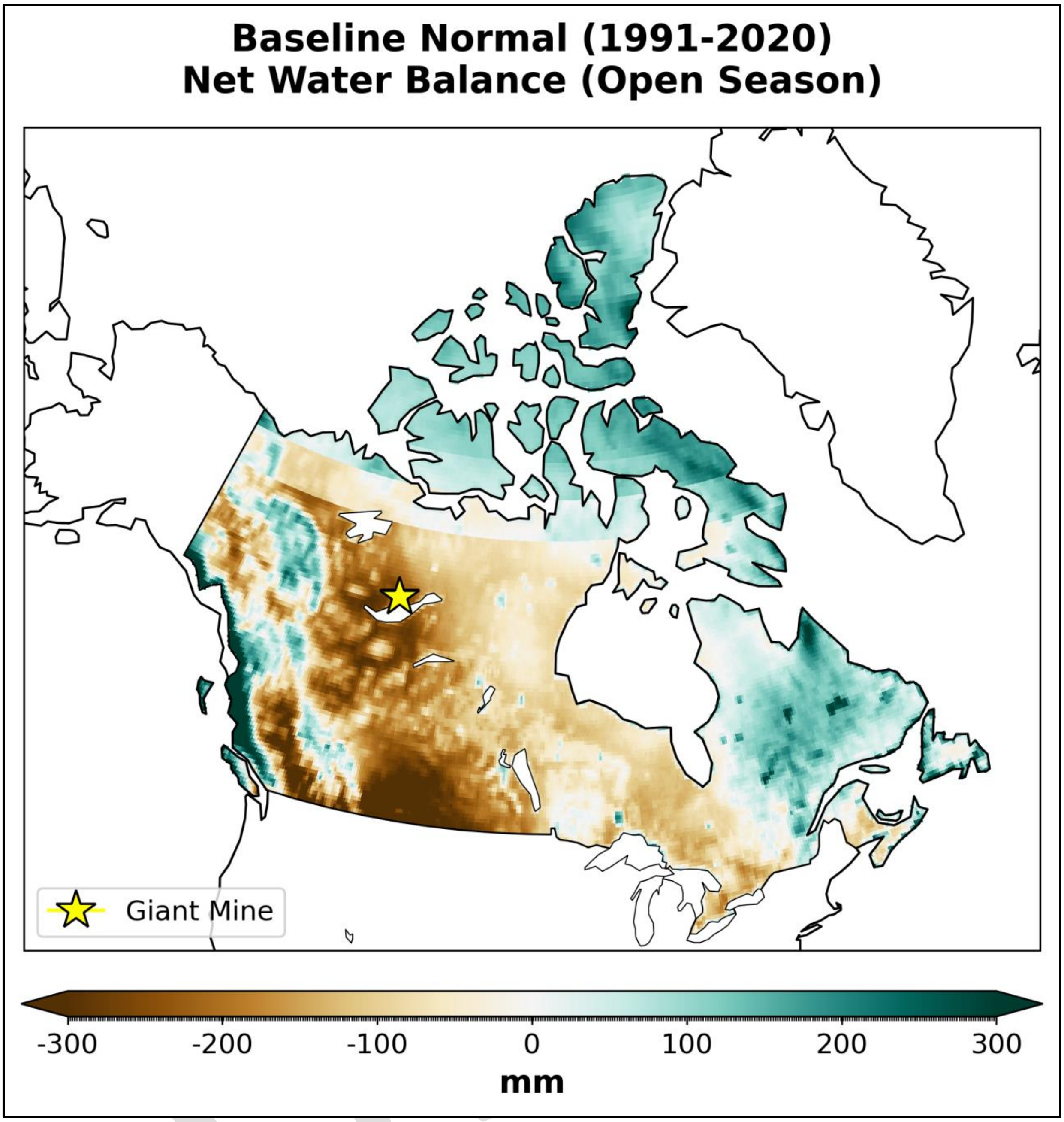

Figure B4: Baseline Net Water Balance (1991–2020).

Spatial distribution of mean net water balance (precipitation minus potential evapotranspiration) simulated by the CMIP6 climate model ensemble for the baseline period (1991–2020). Negative values indicate regions where atmospheric evaporative demand exceeds precipitation inputs on average, while less negative or positive values indicate relatively wetter hydroclimatic conditions. The star marks the location of the Giant Mine site. This baseline map provides regional context for interpreting projected future changes in seasonal moisture conditions and surface water availability.

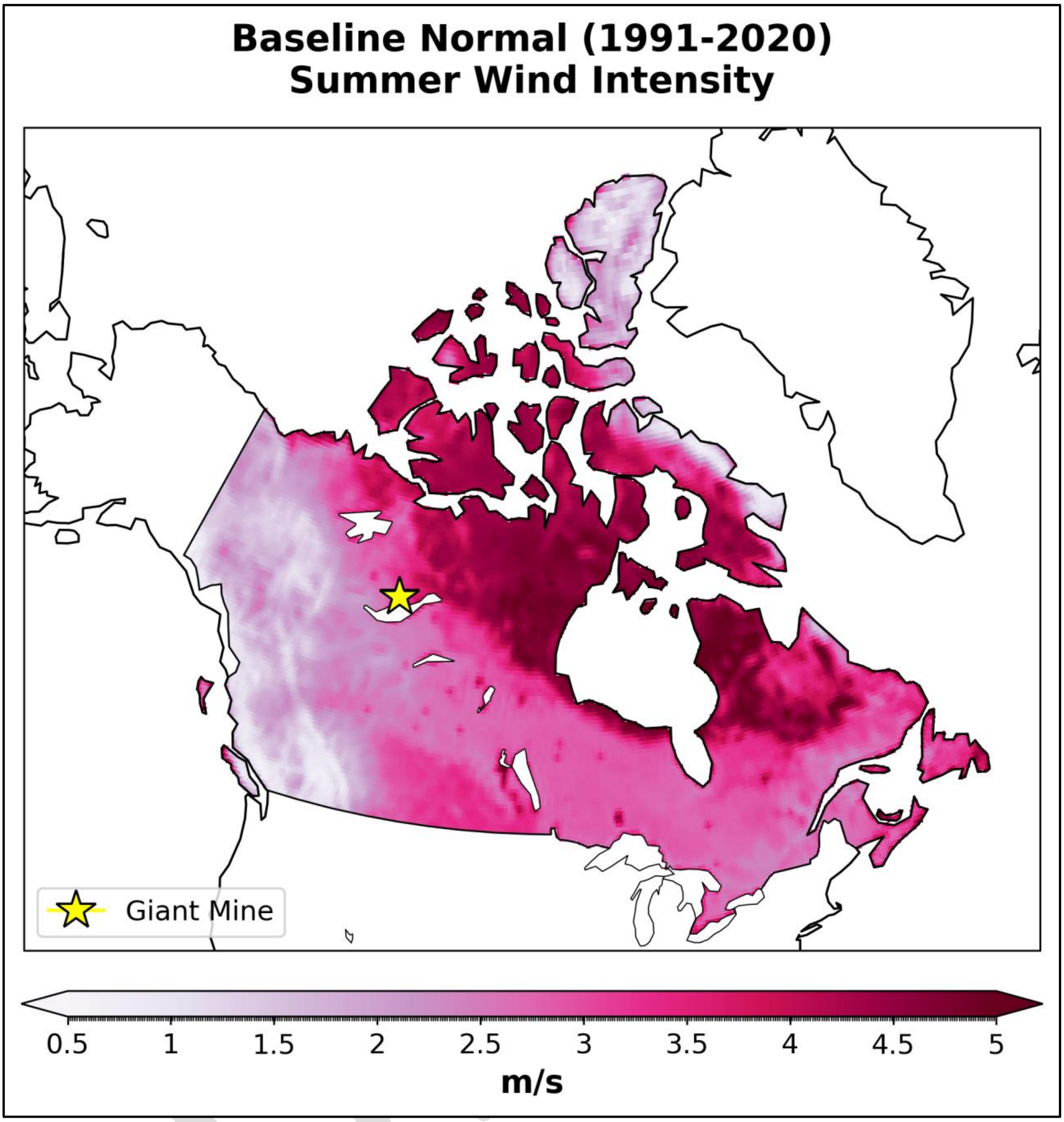

Figure B5: Baseline Summer Wind Intensity (1991–2020 CMIP6 Ensemble Normal).
Spatial distribution of mean summer wind speed across Canada derived from the bias-corrected CMIP6 climate model ensemble for the 1991–2020 baseline period. Values represent modeled climate normals used as the reference for future wind projections. The star indicates the location of Giant Mine. This baseline provides regional context for interpreting projected changes in wind-driven surface processes, including erosion, snow redistribution, and transport of airborne materials.

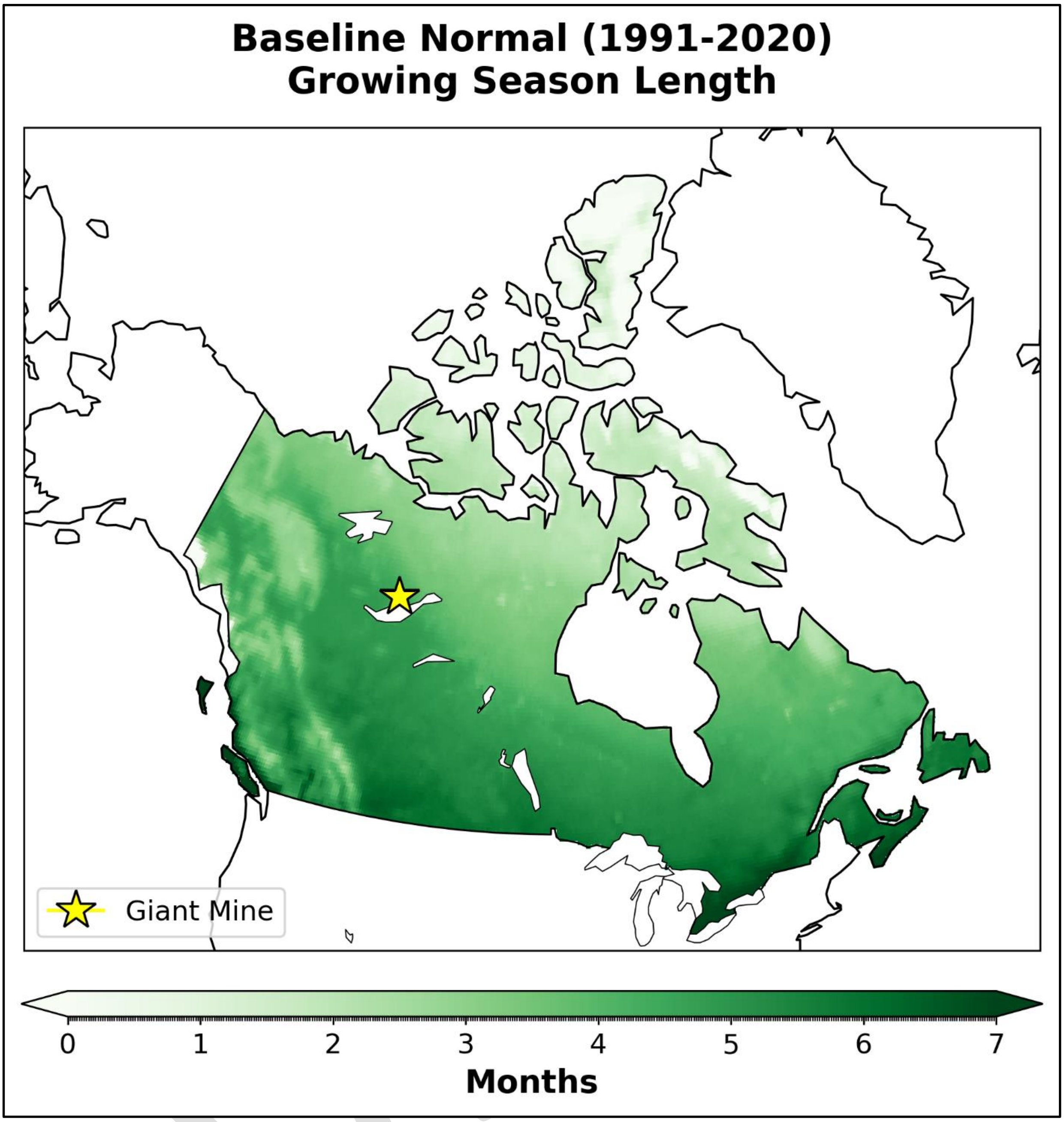

Figure B6: Baseline Climate Conditions Relevant to Great Slave Lake (1991–2020).
Spatial distribution of baseline climate conditions influencing regional water balance across the Great Slave Lake watershed, based on bias-corrected CMIP6 model normals for 1991–2020. These conditions provide a reference for interpreting projected changes in seasonal moisture balance, growing season duration, and broader hydroclimatic dynamics affecting the lake and surrounding landscapes.

9 References

Bush, E. and Lemmen, D.S., editors (2019): Canada's Changing Climate Report; Government of Canada, Ottawa, ON. 444 p https://changingclimate.ca/CCCR2019

Cannon, A. J.: Multivariate quantile mapping bias correction: an N-dimensional probability density function transform for climate model simulations of multiple variables, Clim. Dynam., 50, 31–49, 2018.

Crown-Indigenous Relations and Northern Affairs Canada. (2023). *Giant Mine Remediation Project annual report 2022-2023*. https://www.rcaanc-cirnac.gc.ca/eng/1748871512633/1748871540291

Hargreaves, G.H., & Samani, Z.A. (1985). Reference Crop Evapotranspiration from Temperature. *Applied Engineering in Agriculture*, 1(2), 96-99.

Milly, P. C., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, *319*(5863), 573-574.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., ... & Thépaut, J. N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349-4383.

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geosci. Model Dev., 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016, 2016.

Snyder, R. L. (1985). Estimating degree-days from daily maximum and minimum temperatures. *Agricultural and Forest Meteorology*, 35(1-4), 350-358. https://doi.org/10.1016/0168-1923(85)90092-8

Zalom, F. G., Goodell, P. B., Wilson, L. T., Barnett, W. W., & Bentley, W. J. (1983). *Degree-days: The calculation and use of heat units in pest management.* UC Division of Agriculture and Natural Resources, Leaflet 21373.