METHOD FOR ESTIMATING LONG-TERM HYDROCLIMATIC CONDITIONS FOR TAILING DAM WATER MANAGEMENT AND DAM SAFETY PLANNING

MÉTHODE POUR ESTIMER LES CONDITIONS HYDROCLIMATIQUES À LONG TERME POUR LA GESTION DE L'EAU DES BARRAGES-RÉSERVOIRS

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ABSTRACT

Water management planning that considers a wide range of climatic conditions is crucial for dam safety. Quantifying the climatic range, however, poses a challenge since site climate records are generally much shorter than what is needed to account for possible climate variability. To reduce the uncertainty of long-term climate estimates for mine sites, regional climate records are typically used to represent mine conditions, often with adjustments according to correlations with short-term site data. Long-term regional datasets, however, may not be available, or they may not exhibit similar hydroclimatic conditions to those of a mine site because differences may result from various topographic factors such as aspect, elevation, and distance to site. Furthermore, regional records may have data gaps, may be of unknown quality, or may not be concurrent with the site data.

State-of-the-art global reanalysis products such as ECMWF ReAnalysis 5 (ERA5) can help reduce the gap between what practicing professionals need (long-term climate estimates) and what they typically have (short-term site measurements). Reanalysis products result from combining past observations (collected from various sources such ground stations and earth observation satellites) with model results (weather model hindcasting) to generate consistent time series of multiple climate variables for the period of 1979 to present. Reanalysis products provide complete and consistent data, which can take the place of or supplement regional data. These products come in the form of gridded data that represent average conditions for areas with 8 to 32 km spacing, so similar to conventional regional data, they must be bias-corrected to site observed data to generate reliable long-term estimates of hydroclimatic conditions for a particular site.

Probability-based bias-correction (BC) techniques such as the quantile mapping (QM) method are widely used to bridge the gap between global climate models (GCMs) and local observations in climate change related research, and similarly can be used to bias-correct reanalysis products, though this is not common in the mining industry.

This paper presents a case study of the use of a reanalysis product (ERA5) and a probability-based BC method to develop long-term climate values for a mine site with short-term climate records. The results demonstrate that this state-of-the-art approach can produce reasonable long-term estimates of hydroclimatic conditions for a region where regional observations are scarce. Use of such a state-of-the-art approach can facilitate mine water management planning and increase dam safety by improving estimates of historical hydroclimatic variability.

RÉSUMÉ

Une gestion de l'eau qui prend en compte un éventail de conditions hydroclimatiques est essentielle à la sécurité des barrages. La quantification de cette gamme climatique pose un défi car les données climatiques d'un site sont généralement plus courtes que nécessaire. Pour réduire l'incertitude des estimations climatiques à long terme du site,

les données climatiques régionales sont généralement utilisées pour déterminer les conditions locales, ajustées en fonction des corrélations avec les données de court terme du site. Les données régionales ne représentent pas toujours les mêmes conditions hydroclimatiques que le site et souvent les données régionales ne sont pas concomitantes avec les données du site, manquent de données et la qualité des données est difficile à évaluer.

Les produits de réanalyse globale tels que ECMWF ReAnalysis 5 (ERA5) présentent des avantages dans la réduction de l'écart entre les estimations climatiques à long terme et les mesures de site à court terme. Les produits de réanalyse combinent des observations passées (collectées des stations et des satellites d'observation terrestre) avec des modèles météorologiques rétrospectifs pour générer des séries chronologiques cohérentes de multiples variables climatiques pour la période de 1979 à aujourd'hui. Bien que les produits de réanalyse fournissent des données complets et cohérents, les données maillées représentent les conditions moyennes pour des zones espacées de 8 à 32 km, et il est donc nécessaire de corriger les biais des valeurs de réanalyse en fonction des données de site pour générer des estimations hydroclimatiques à long terme.

Les techniques de correction de biais (CB) basées sur les probabilités telles que la méthode de cartographie quantile sont utilisées pour combler l'écart entre les modèles climatiques et les observations locales dans la recherche liée au changement climatique. L'utilisation des méthodes de CB sur des données de réanalyse pour développer des estimations de valeurs climatiques spécifiques à un site à long terme est encore une nouveauté dans l'industrie minière.

Cet article présente une étude de cas sur l'utilisation de ERA5 et d'une méthode de CB basée sur les probabilités pour développer des valeurs climatiques à long terme pour un site minier avec des données à court terme. Cette approche peut produire des estimations raisonnables des conditions hydroclimatiques à long terme dans une région où les observations régionales sont rares. L'utilisation d'une telle approche peut faciliter la planification de la gestion de l'eau de la mine en améliorant les estimations de la variabilité hydroclimatique historique.

1 INTRODUCTION

1.1 Climate Variability

Natural climate variability produced by decadal and multiple decadal climate cycles have important consequences in water management planning for dam safety. There are many indices to identify phases of long-term climate cycles; the best known is the El Niño–Southern Oscillation (ENSO) index, while the Pacific Decadal Oscillation (PDO) index is a particularly strong indicator of climate conditions in Western Canada. Both the ENSO and PDO indices have positive and negative phases, and the magnitudes of these indices indicate the strengths of deviations from "normal" (PDO history shown on Figure1). For ENSO, the two phases are best known by the terms of El Niño (positive) and La Niña (negative). In the authors' home region of southern coastal British Columbia (BC), periods of El Niño and positive PDO are associated with warmer and drier than usual weather conditions, while periods of La Niña and negative PDO are associated with colder and wetter than usual weather conditions (Whitfield, 2010).

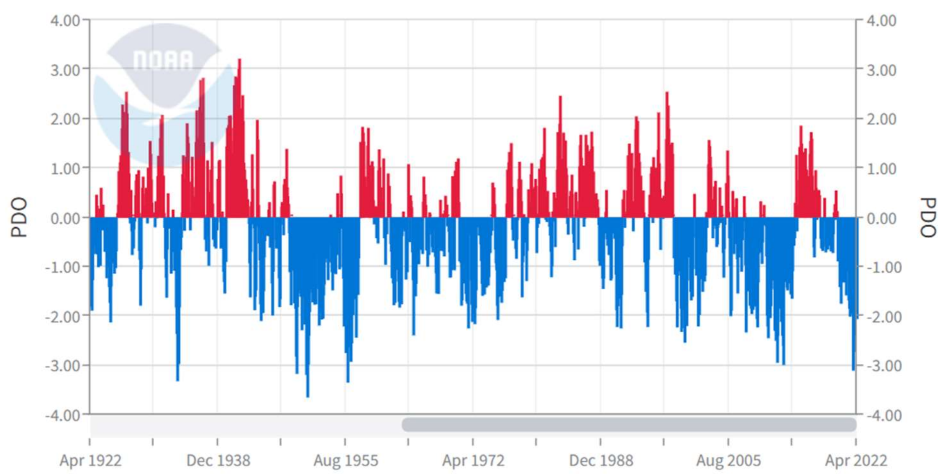

Figure 1: Pacific Decadal Oscillation Index of the past 100 years (US N National Oceanic and Atmospheric Administration)

These strong weather variations can result in droughts or floods, which may test a dam's capacity. Gurrapu et. al. (2016) have shown that flood magnitudes can be 23 to 53% higher in negative PDO years than in positive PDO conditions, and annual runoff volumes can be three or four times greater in wet years than dry years. In addition, it is important to note that this variability may increase over time as a results of climate change (Pendergrass et. al., 2017).

1.2 Problem 1: observation data availability

It is often challenging to obtain suitable long-term data for assessing climate variability and its ramifications for the design of mining dams. Although all mine developments require baseline climate monitoring, by the time a project enters permitting and preliminary designs are completed, only a few years of site weather data have typically been collected, and the datasets are too short to capture long-term climatic variability. Regional climate station data are often correlated with site data to provide long-term estimates of site climate conditions, but regional data may be inadequate for this, as the available regional data may be short term, incomplete, may not be reasonably representative of site conditions, or may not be concurrent with the site data. Even in regions where data collection networks are well established, gauge density is often very sparse in areas where mine developments typically take place. These issues are common to any analyses requiring long-term datasets, which has driven the advancement in reanalysis weather data in recent years. Reanalysis products result from combining past observations (collected from various sources such ground stations and earth observation satellites) with model results (weather model hindcasting) to generate consistent time series of multiple climate variables. ECMWF Reanalysis v5 (ERA5) is the fifth-generation atmospheric reanalysis of the global climate covering the period from January 1979 to present. ERA5 provides consistent time series of multiple climate variables on an hourly time step at a gridded resolution of 32 km. There are other reanalysis products which may offer different spatial coverage and temporal resolution that might be more suitable for certain circumstances. ERA5 is currently the most state-of-the-art global reanalysis product available.

1.3 Problem 2: how to properly bias-correct

The use of reanalysis data should be guided by observed at-site data, where available, since reanalysis products provide areal average conditions of a fairly large grid cell. As such, the grid average may not be representative of a particular point or area within the grid cell without bias correcting the data to the point or area of interest. Because point and areal average conditions often have very different probability distributions, the bias cannot be properly corrected by conventional statistical methods such as simple or multiple linear regression because those methods cannot adjust the variance of observations. Probability-based bias-correction methods such as the Quantile Mapping (QM) method are commonly used to address systematic biases in climate model outputs, as they correct the modeled data by matching equal-quantile values between the observed and the modeled data, as shown in the conceptual diagram presented on Figure 2. In general, when two datasets (shorter site data and longer reanalysis data) have different distributions, probability-based bias correction methods are preferable to conventional statistical methods. This finding is not just applicable to climate data. Knight Piésold has found success in using a similar probability-based method to estimate long-term streamflow conditions for mining projects by correlating short-term site streamflow records with longer-term regional streamflow records (Butt, 2013).

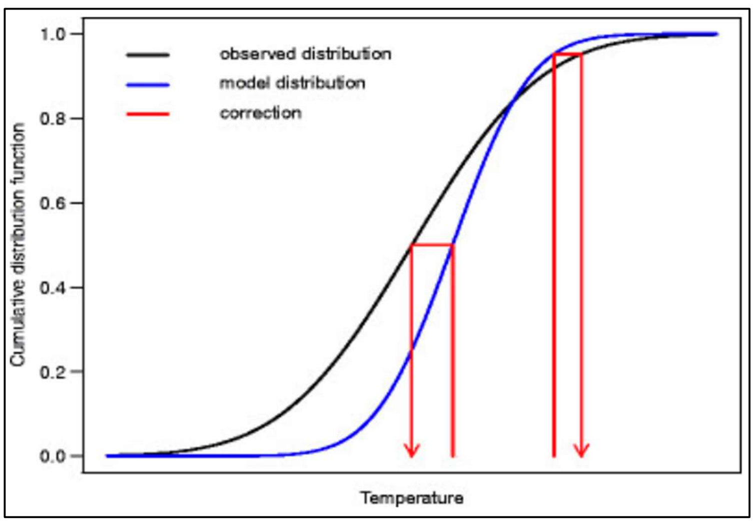

Figure 2: Conception Diagram of Quantile Mapping Bias-Correction (Maraun, 2016)

This manuscript is a proof of concept for combining the use of a reanalysis product (ERA5) and a probability-based bias-correction method (QM) to create long-term climate estimates that realistically quantify the climatic variability that must be considered in water management planning and dam design.

2 METHODS

2.1 Study Site and Data

The study area is near the town of Likely, which is 388 km northeast of Vancouver in British Columbia, Canada. This area is situated at the foothill of the Rocky Mountains. Mean Annual Precipitation (MAP) in the area increases rapidly between about 500 mm in the interior plateau (west of Likely) and 2000 mm in the Rocky Mountains (east of Likely) (Figure 3).

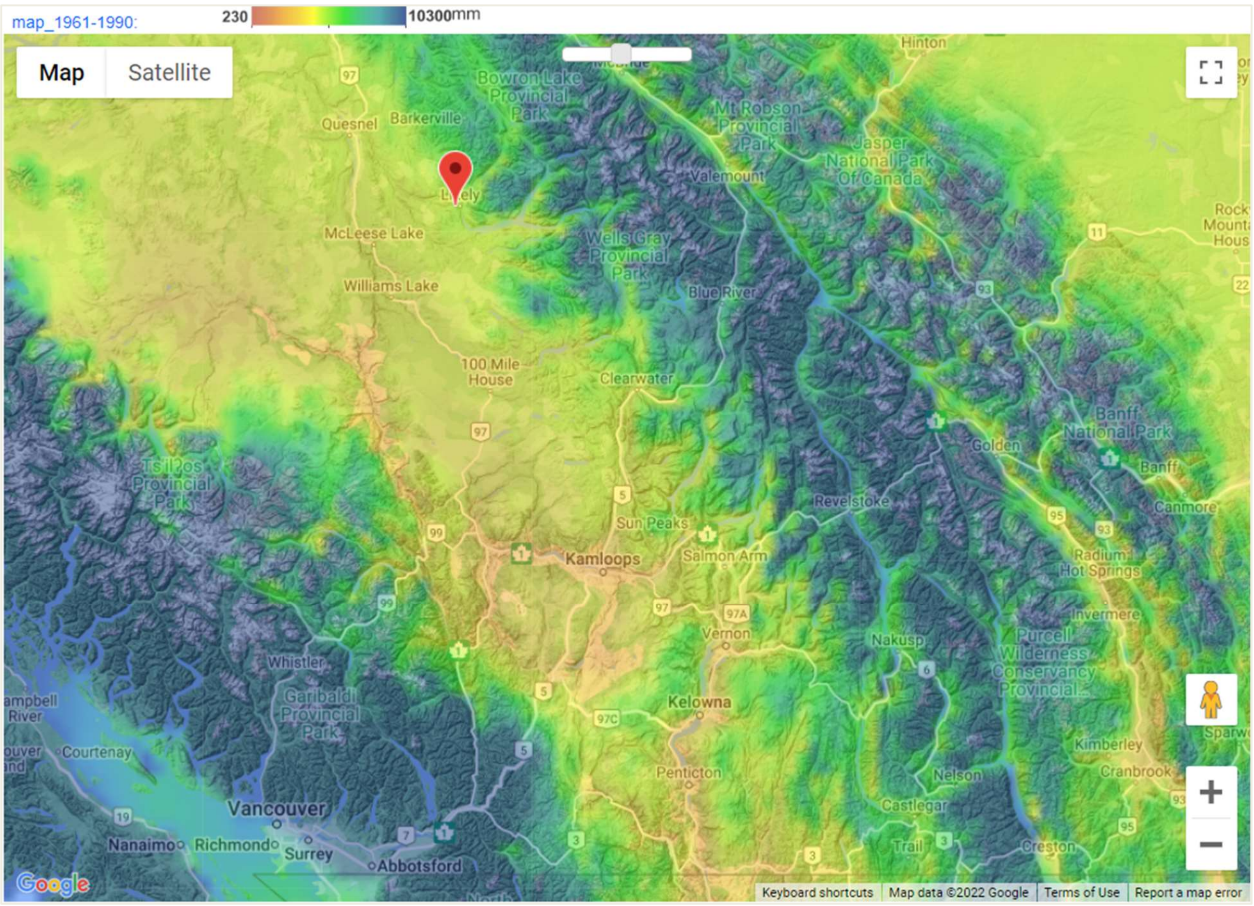

Figure 3: UNBC-QRRC Weather Station Location at the Red Tag (Google Map) and ClimateBC Modelled MAP Overlayed (UBC Forestry, Wang et. al., 2016)

Environment and Climate Change Canada (ECCC) operated a weather station in the town of Likely between 1974 and 1993 (19 years). At elevation 724 m, the station recorded a Mean Annual Temperature (MAT) of 4.6 °C and an MAP of 692 mm/year (Figure 4).

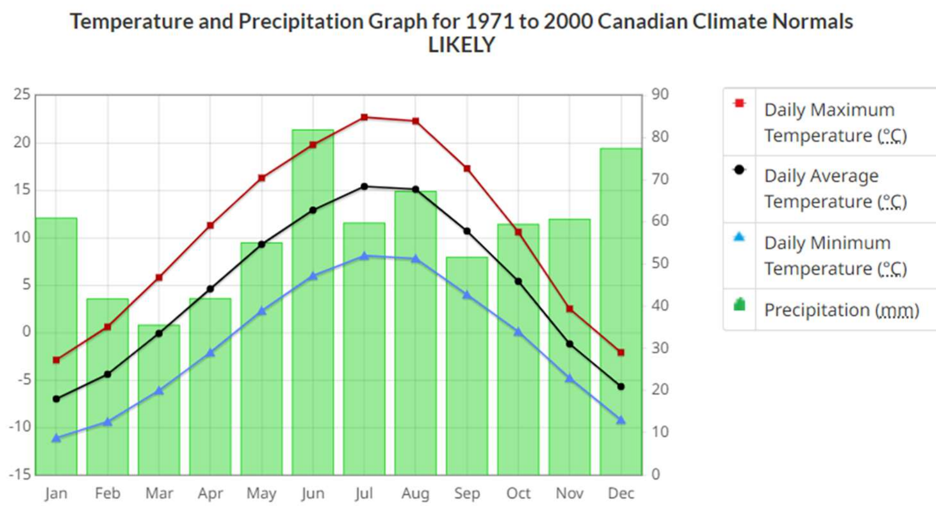

Figure 4: Estimated Climate Normals of Town of Likely, BC (ECCC Station 1974-1993)

A weather station is also operated in Likely at the University of Northern British Columbia's Quesnel River Research Centre (UNBC-QRRC). This station has an elevation of 743 m and the data are publicly provided through the data portal of the Pacific Climate Impacts Consortium (PCIC). This station recorded hourly weather conditions (average temperature, total precipitation, and others) from September 2006 to December 2017. The data have been reviewed for quality assurance and quality control for this study. This dataset was chosen for this study over the ECCC dataset because the ECCC station network is part of most Reanalysis data products, and therefore a performance evaluation using the ECCC data may inflate the performance metric.

2.2 Bias-correction method

For most mine related applications, the use of climate data on a daily interval is sufficient, and therefore the ERA5 and UNBC-QRRC data were summarized on a daily basis before bias-correction. The distributions of most climate variables vary seasonably, and therefore the bias-correction using the Quantile Mapping (QM) method was conducted monthly to ensure that the seasonable variation did not bias the inter-year variation. For example, the QM bias correction was first conducted with all January values, then all February values, and so on. The equal-quantile difference is calculated based on concurrent data between the UNBC-QRRC station data (shorter) and the ERA5 data (longer), and such difference were applied to non-concurrent period of the ERA5 data to calculate the bias-corrected estimates. Bias-correcting the ERA5 datasets was completed using the R package for QM, which is maintained by research scientists at ECCC (Cannon, 2016). Note that some values in the long-term ERA5 record may exceed the extreme values found in the shorter observed record of UNBC-QRRC. In this case, a simple extrapolation was used (Boé et. al., 2007). For example, if the first (or last) quantile of temperature in the long-term ERA5 record was corrected by +0.5 °C, all the values beyond the first (or last) quantile were corrected by the same +0.5 °C.

2.3 Scenarios

Three split-sample scenarios were set up to test how the bias-correction performed under different PDO phases (Table 1).

Table 1: Split-sample Set-up for Bias-correcting ERA5 with UNBC-QRRC Observations

Scenario	Bias-correction		Validation	
	Year	PDO Phase	Year	PDO Phase
#1	2015-2017	Positive	2007-2009	Negative
#2	2007-2009	Negative	2015-2017	Positive
#3	2007-2009	Negative	2011-2013	Negative
#4	2014-2015	Positive	2016-2017	Positive

3 RESULTS

3.1 Air Temperature

Comparisons of the Cumulative Distribution Functions (CDFs) of the bias-corrected ERA5 daily temperature data and the UNBC-QRRC observed daily temperature indicate very strong agreement, regardless of the PDO phase of the bias-correction or validation periods (Figure 5). Because of the probabilistic nature of the bias correction method, the time series of bias-corrected daily temperature were not expected to perfectly match the observed time series. Even so, the bias-corrected ERA5 daily time series were strongly consistent with the observed data at the UNBC-QRRC station (Scenario 1 shown in Figure 6). For all four scenarios, the Nash–Sutcliffe Efficiencies (NSE) are 0.97 to 0.98, where a NSE of 1.0 indicates a perfect match. Percentage biases are -4.4% to 3.0% for the four scenarios.

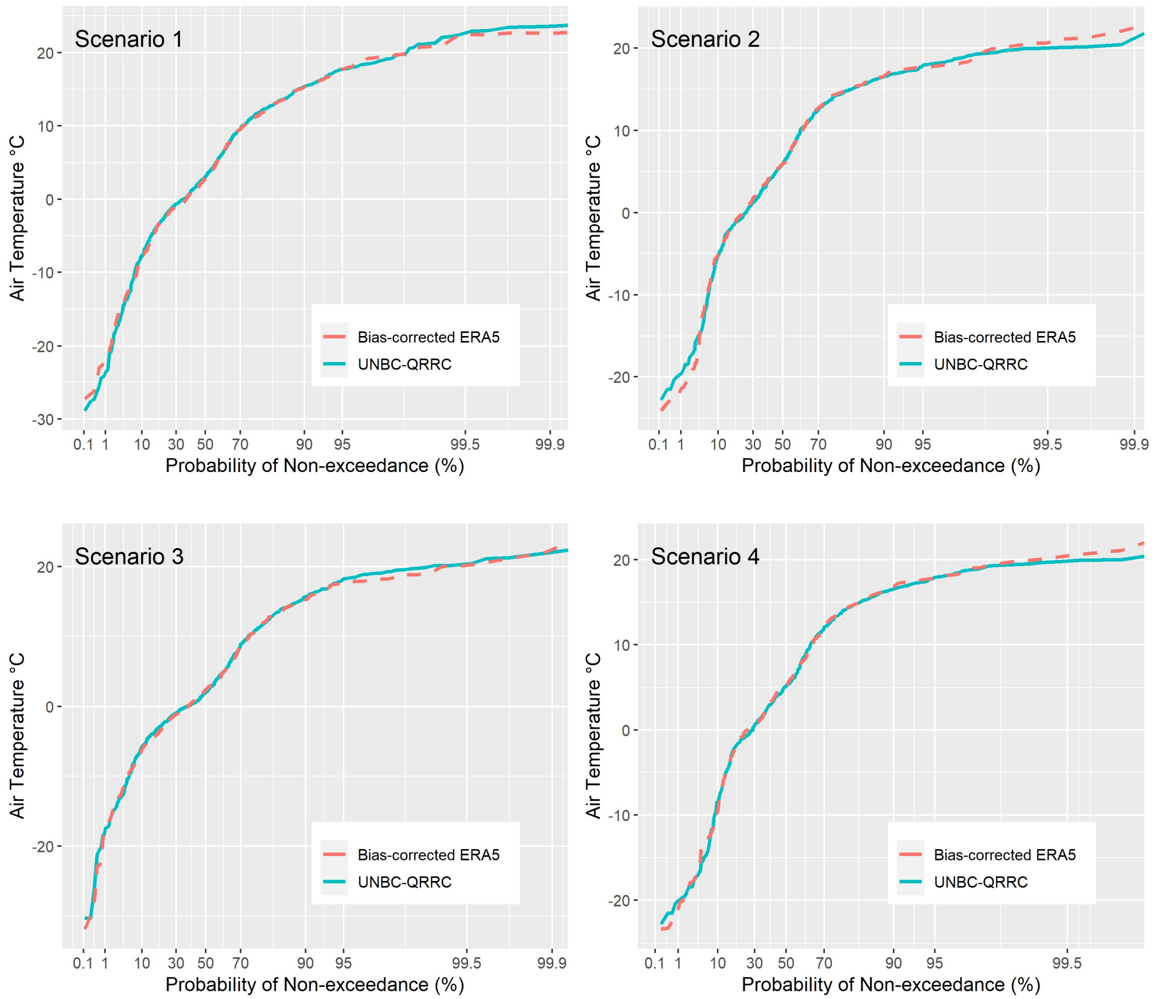

Figure 5: CDFs Comparison Between Bias-corrected ERA5 and UNBC-QRRC Observed Daily Temperature

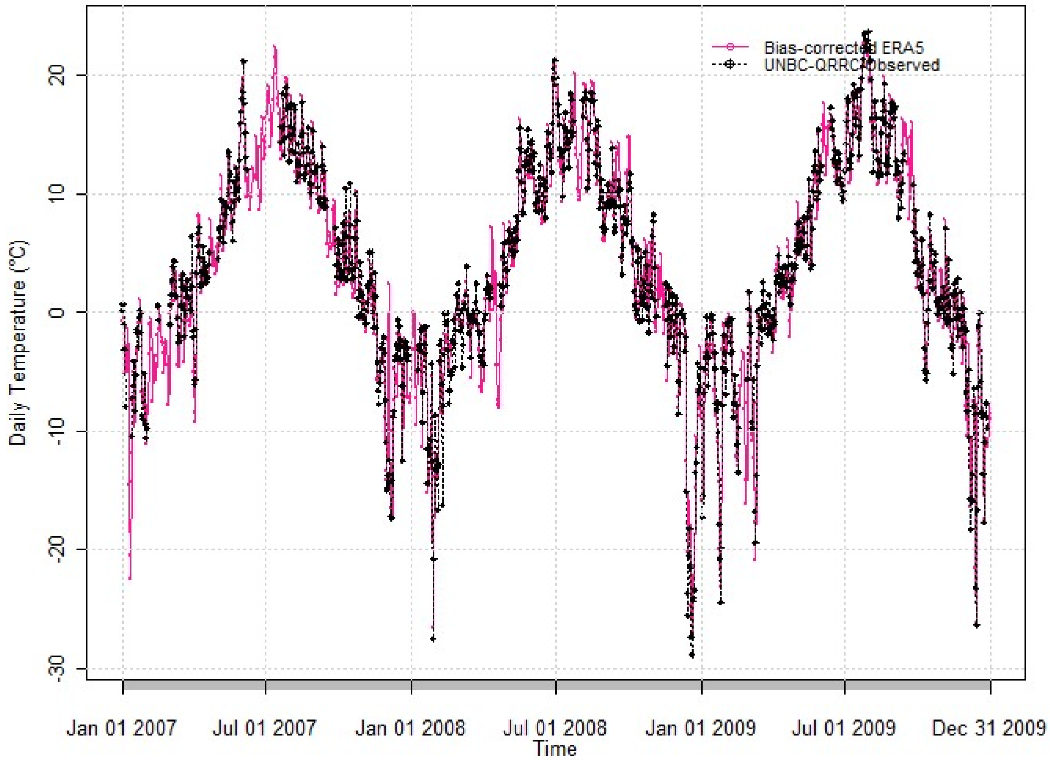

Figure 6: Scenario 1 Time Series Comparison Between Bias-corrected ERA5 and UNBC-QRRC Observed Daily Temperature

3.2 Wind Speed

Comparisons of Cumulative Distribution Functions (CDFs) of the bias-corrected ERA5 wind speed and the UNBC-QRRC observed wind speed show some differences, particularly in the top 5% range (Figure 7). Among the four scenarios, the bias-corrected ERA5 values often over-estimate the top 5% wind speeds during the positive PDO phase, regardless of the bias-correction period PDO phases (Scenario 2 vs Scenario 4). Because of the probabilistic nature of the bias correction method, as well as the fact that wind is highly localized, the time series of bias-corrected ERA5 wind speed were not expected to perfectly match the observed wind speeds. Nonetheless, the comparison indicates an error estimate of only approximately 10~20% for the ERA5 bias-corrected values.

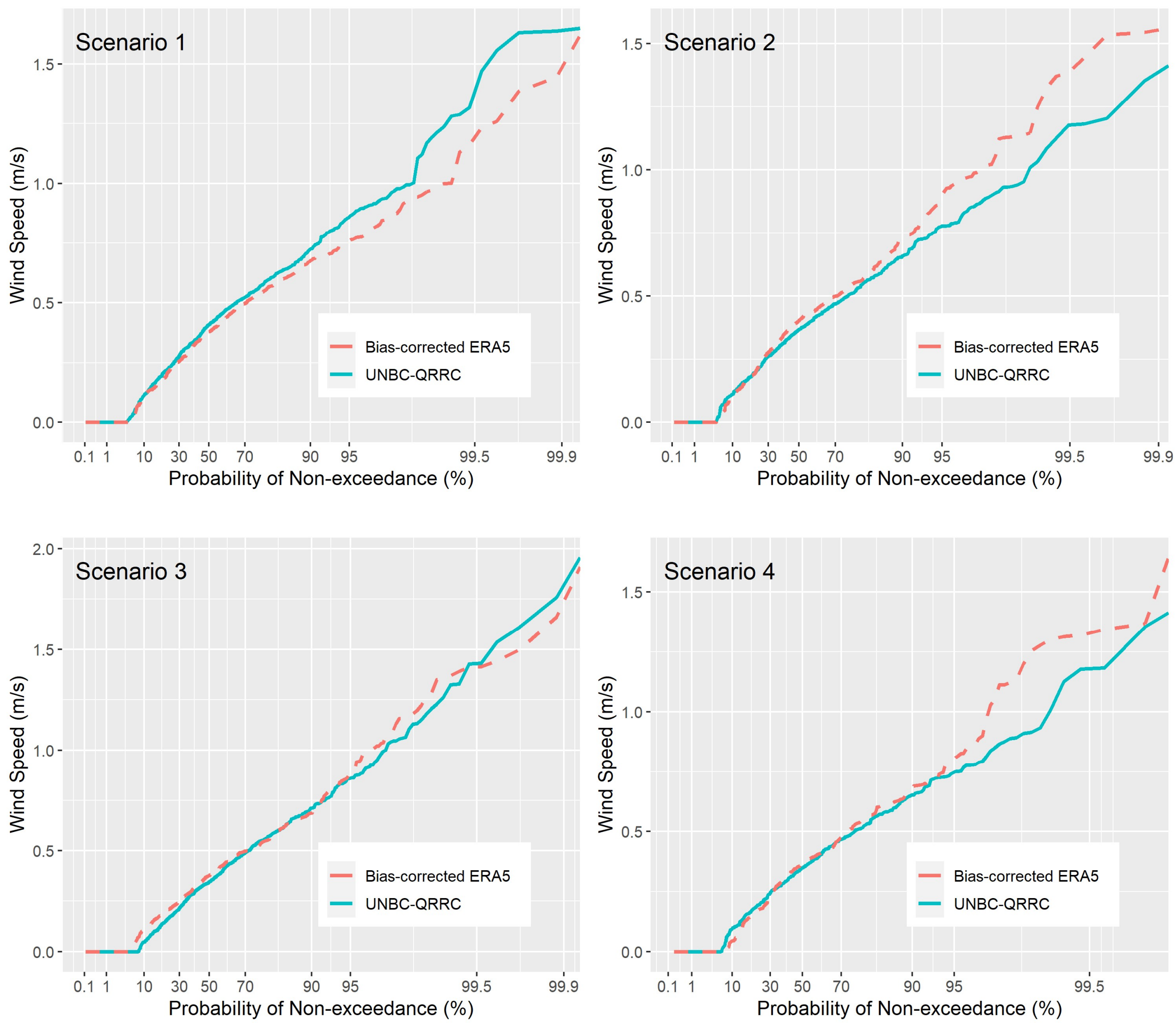

Figure 7: CDFs Comparison Between Bias-corrected ERA5 and UNBC-QRRC Observed Daily Wind Speed

3.3 *Precipitation*

Comparisons of the Cumulative Distribution Functions (CDFs) of the bias-corrected ERA5 daily precipitation data and the UNBC-QRRC observed daily precipitation indicates a generally good match between the values, with the difference depending on the PDO phases of the bias-correction and validation periods (Figure 8). If the bias-correction period is in a warm PDO phase, then daily precipitation might be underestimated under negative PDO condition (Scenario 1) but not so much if the validation period is also in a positive PDO phase (Scenario 4), and vice versa with Scenario 2 versus Scenario 3. Comparison of concurrent monthly precipitation values for the four scenarios are shown in Figure 9. Values are only presented for months with no more than two missing days in the UNBC-QRRC data. Overall, there is no noticeable wet or dry biases on the monthly scale, as most observations follow the 1:1 line. The monthly precipitation regression plots have R^2 values ranging from 0.78 to 0.82 for the four scenarios, indicating reasonably strong correlations. Mean percent bias values range from 1.5% to 12.1 %. There is also no noticeable correlation between the seasonality (month of the year in color) and the amount of prediction uncertainty.

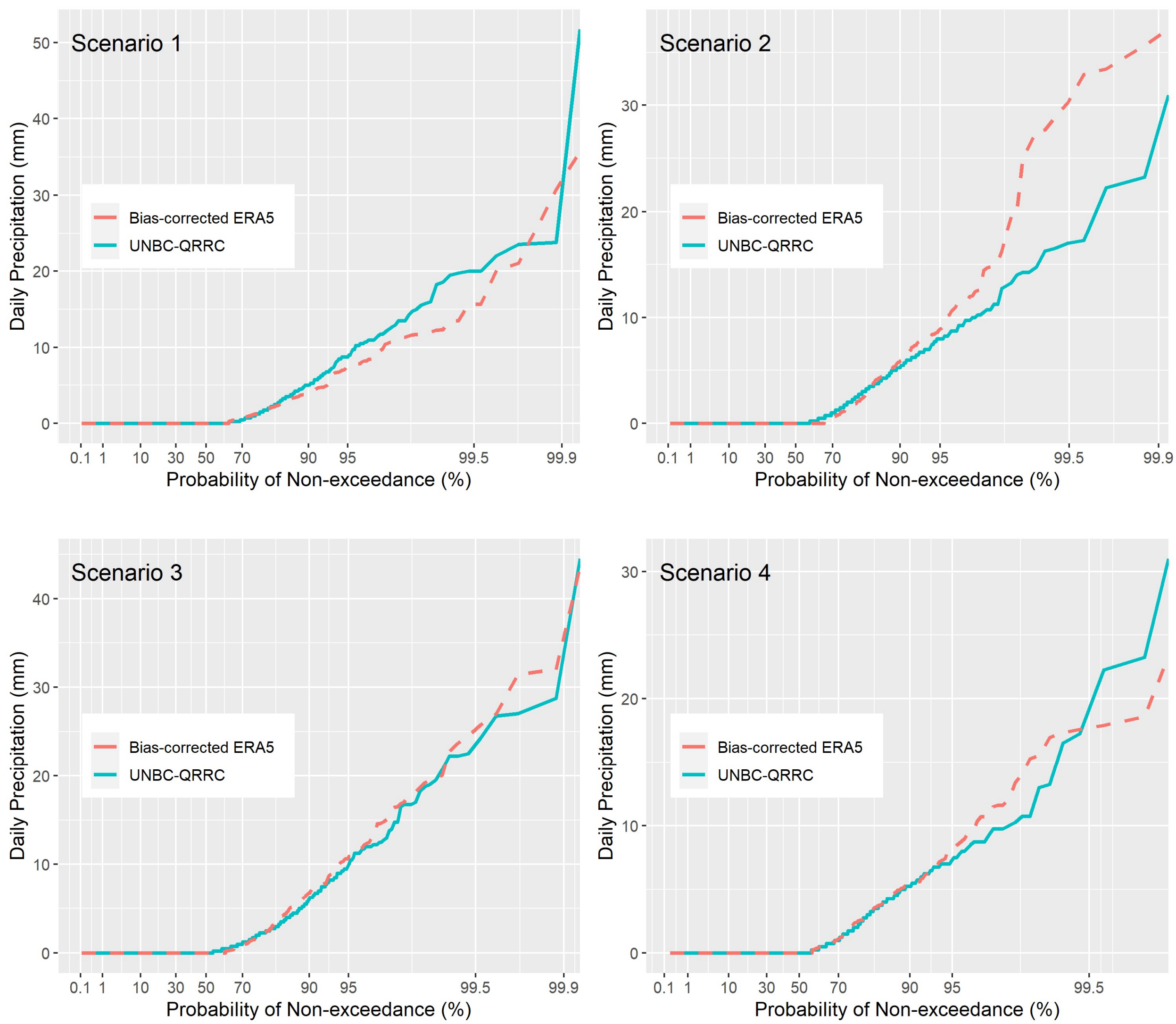

Figure 8: CDFs Comparison Between Bias-corrected ERA5 and UNBC-QRRC Observed Daily Precipitation

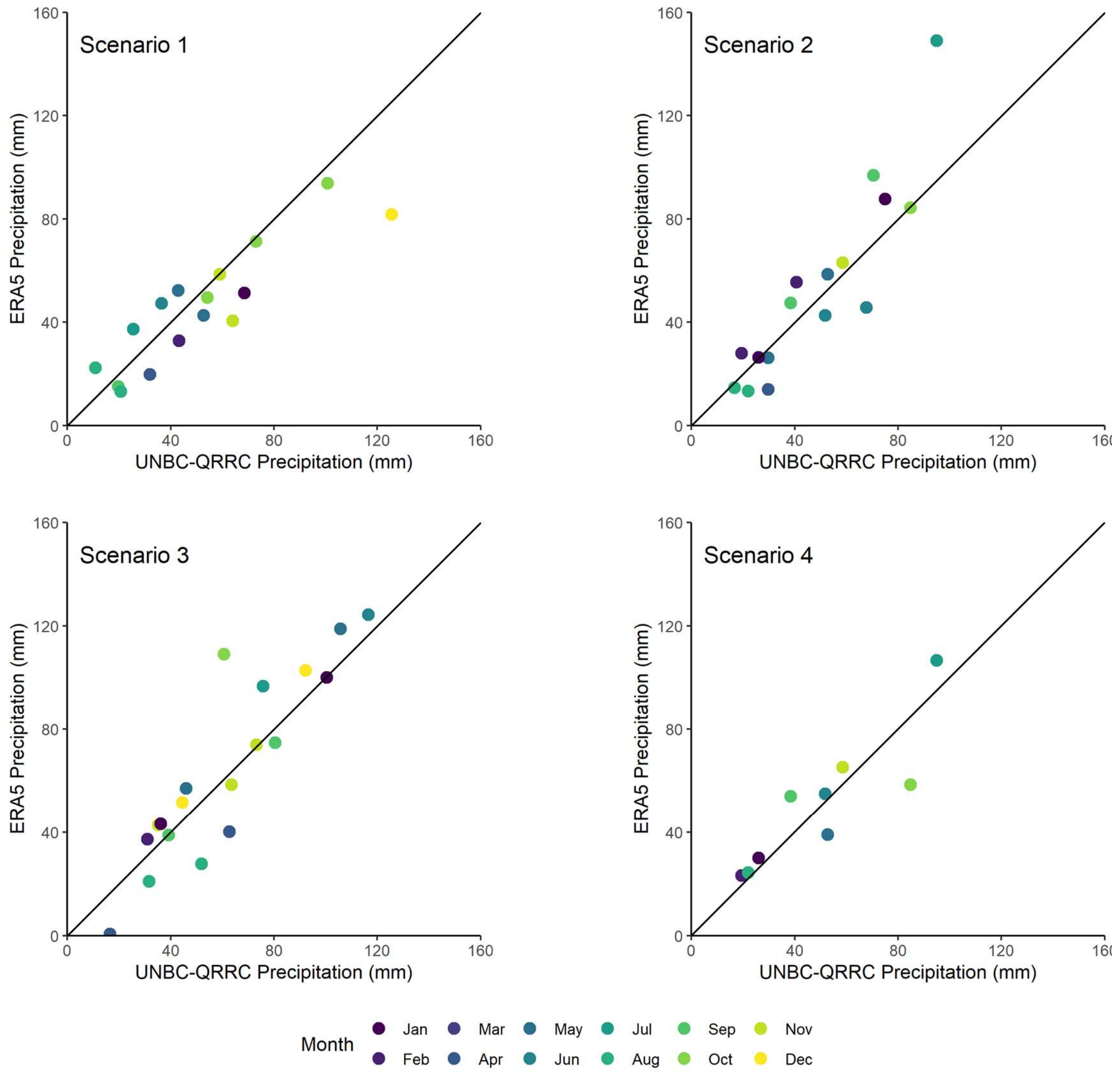

Figure 9: CDFs Comparison Between Bias-corrected ERA5 and UNBC-QRRC Observed Daily Precipitation

4 DISCUSSIONS

4.1 Bias and Uncertainty

The Quantile Mapping (QM) method was able to satisfactorily bias-correct ERA5 reanalysis product climate values, which represent area average conditions, to generate long-term estimates of climate values at a point of interest (a weather station). However, bias (error) can remain after bias-correction if the bias-correction is unduly influenced by a single phase of the climate cycle (positive or negative PDO). Increasing sample size for bias-correction and covering different ENSO/PDO conditions is expected to reduce such bias. In similar probability pairing exercises for generating long-term streamflow estimates, Butt (2013) demonstrated that substantial improvements are obtained as record length increases up to approximately three to five years, after which the improvements start to diminish.

As mentioned in the method section, extreme values that are outside of the observation range are simply extrapolated by a constant value based on the last quantile of the quantile mapping. This however may not always be the best approach. In our experience of generating long-term synthetic streamflow records using probabilistic pairing, it was found that manual adjustment of the extrapolation by expert opinion yields better results.

In this study, each climate variable (temperature, wind speed, and precipitation) was bias-corrected individually without any interaction. This approach of univariate bias-correction is simple to use and its benefits are easy to demonstrate. A multivariate version of Quantile Mapping is also available in R but its application is often complicated. Theoretically, bias-correcting multiple inter-correlated variables simultaneously could improve the results, so such an approach could be considered if the univariate approach does not yield adequate results. For example, if solar radiation and barometric pressure observations are available, a multivariate bias-correction of precipitation may produce better results since high precipitation is less probable with sunny skies and high barometric pressures conditions.

4.2 Other Reanalysis Products

There are many Reanalysis products available. Although ERA5 is the overall best global product available, others might be more suitable in different situations. For example, the North American Regional Reanalysis (NARR) is a good alternative for locations within North America, as it utilized the dense gauge network in Canada, United States, and Mexico. Hydrological Global Forcing Data version 3 (HydroGFD 3.0) is a further processed reanalysis product that is based on ERA5, but it only provides daily air temperature and precipitation values, but it has been found to be suitable as input for hydrological model simulations (Lilhare et. al., 2019).

One of the biggest drawbacks of reanalysis products such as ERA5, NARR, and HydroGFD is their large grid size, which ranges from 25 km to 32 km. They may not be the best synthetic dataset for estimating climate conditions in mountains regions where the localized variation of climate conditions may be very high. In this case, other synthetic datasets more be more appropriate, such as the ClimateBC/NA data, which are statistically downscaled products of the PRISM Climate Data that offers a grid size of 800 m. However, ClimateBC/NA only offers climate variables in monthly or larger time steps, so consideration must be given to the relative importance of temporal and spatial scales.

5 SUMMARY

The lack of long-term climate observations is a major challenge to the understanding of variability in climatic conditions. The presented study demonstrates the potential use of reanalysis products in developing long-term climate values for mine water management planning and dam safety. The presence of long-term reanalysis data products does not reduce the need for baseline monitoring of site weather conditions. Rather, as for situations where applicable long-term regional data are available, the use of reanalysis products must be accompanied by at least a few years of good climate observations at the site of interest.

Most reanalysis products are in the public domain and free to use. Most of the tools needed for bias-correction (such as the R package for QM) are also open-sourced and freely available. This framework of reanalysis products combined with probabilistic bias-correction is common in academia (particularly climate change research), but adoption of its use by the private sector has been slow. These tools are rapidly developing and provide promise for substantial improvements in climate variability modelling for mine water management planning and other applications.

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