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Article

Using CMIP6 Models to Assess Future Climate Change Effects on Mine Sites in Kazakhstan

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Abstract: Climate change is a threat to mining and other industries, especially those involving water supply and management by inducing or amplifying some climatic parameters such as changes in precipitation regimes and temperature extremes. Using the latest NASA NEX-GDDP-CMIP6 datasets, this study quantifies the level of climate change that may affect the development of two mine sites (Site1 and Site2) in northeast Kazakhstan. The study analyses the daily precipitation and maximum and minimum temperature a of a number of global circulation models (GCM) over three future time periods, 2040s, 2060s and 2080s, under two shared socioeconomic pathway (SSP) scenarios, SSP245 and SSP585, against the baseline period 1981- 2014. The analyses revealed that: (1) Both maximum and minimum temperature will increase under both SSP in those time periods, with the rate of change for minimum temperature being higher than maximum temperature. (2) The mean annual precipitation will increase by an average rate of 7% and 10.5% in 2040s for SSP245 and 17.5% and 7.5% for SSP585 in 2080s at Site1 and Site2, respectively. It is also observed that summer months will experience drier condition whilst all other months will increase in precipitation. (3) The values of 24-hour precipitation with 10-year return period will also increase under both SSP scenarios and future time periods for most of the studied GCM and at both mine sites. These predicted changes should be considered as design criteria adjustments for project water supply and water management structures.

Keywords: climate change; SSPs scenarios; water management; mining; Kazakhstan

1. Introduction

With growing threat of climate change in the past few decades exacerbated by worsening scenarios in the areas of energy, water and desertification, the pressures on natural resource management as a result of poverty has also been intensified [1]. It is believed that the risk associated to climate change is one of the most prominent threats to human societies [2], manifested by increasing intensity, frequency and impacts of extreme weather events such as hurricanes, floods, droughts and heatwaves. In response to these pressures, Global Industry Standard on Tailings Management (GISTM) suggests adjusting design standards are required as a result of evolving climate change impacts [3].

It is widely recognised that available mining deposits are increasingly deeper and of declining ore grade. This will lead to growing demands for water as well as greater mine waste [4], with climate change expected to increase pressure on the mining industry as more frequent droughts and floods are predicted, leading to an alteration in water supply and disruption of mining operations. Climate change studies should be adopted as a consistent approach to help mining companies identify the risks and opportunities related to the management of water resources to all stages of the mine development and closure of their mining projects [5].

It is essential for mining companies to consider climate change and its impact on sustainability and cost of water and energy supplies and use decision making tools that help them optimise available water resources. Climate change analysis coupled with stochastic project water balance models can provide good predictions of water surplus or deficit over mine life (and closure) enabling solutions/measures to be prepared and costed for at early stage of project development. To address climate change, Coupled Model Intercomparison Project (CMIP) models provide a feasible tool to predict future climate condition under the changing conditions [6]. CMIP6 is the latest version of the CMIP which are featured in the IPCC's sixth assessment report (AR6).

In very limited research conducted in the central Asia region using CMIP6 models, Dike et al. used the outputs of these models to project future conditions of extreme precipitation in the Central Asia region under four SSP scenarios. They found that summer precipitation will increase in south Central Asia and decrease at the North central Asia region [7].

Due to climate models' structural uncertainties, complexity in earth-atmosphere systems and coarse resolution of the global circulation models (GCM), the application of their outputs is limited to some extent [8]. NASA implemented the NASA Earth Exchange Global Daily Downscaled Projections 6 (NEX-GDDP-CMIP6) project to provide downscaled historical and future projections for the period 1950 to 2100 based on CMIP6 models [9].

Since its release, NEX-GDDP-CMIP6 has been used for studies around the world; for example, Wu et al. used 16 GCM in NEX-GDDP-CMIP6 to evaluate the performance of these models in capturing drought characteristics over China. They found the acceptable performance of the models in producing the spatial distribution pattern of drought in China [10]. In another study, Murali et al. [11] applied NEX-GDDP-CMIP6 to project future extreme thermal events at global scale. They found that, for example, under high emission scenario of SSP585 and intermediate SSP245 scenario, 41% and 15.1% of all land vertebrate will be exposed to extreme thermal events beyond their historic level.

While the outputs of global models provide an appropriate tool for understanding future climate conditions, very little research has been reported using the latest NASA NEX-GDDP-CMIP6 product in Central Asia countries. The purpose of this study is to evaluate the future climate condition at two mine sites located in two distinctive climate condition in Kazakhstan using the NEX-GDDP-CMIP6. The changes in projected average and extreme precipitation and temperature conditions in future were evaluated to provide more in-depth information on potential future climate conditions in the region.

2. Materials and Methods

Two case study sites were selected to assess the future climate condition based on different emission scenarios in Kazakhstan (Figure 1). According to Köppen-Geiger classification [12], Site1 is located in a region with cold semi-arid climate (BSk) while Site2 falls at the edge of two climate classes, BWk with cold desert climate and BSk with cold semi-arid climate, respectively.

Based on historical data, the air temperature variability in the region is high, ranging from -14.9°C and -8.1°C in winter (December-January-February) and +22.3°C and 27.7°C in the summer (June-July-August) for Site1 and Site2, respectively. The average annual air temperature is 4.1°C and 10°C with a mean annual precipitation of about 270 mm/year and 150 mm/year for Site1 and Site2, respectively.

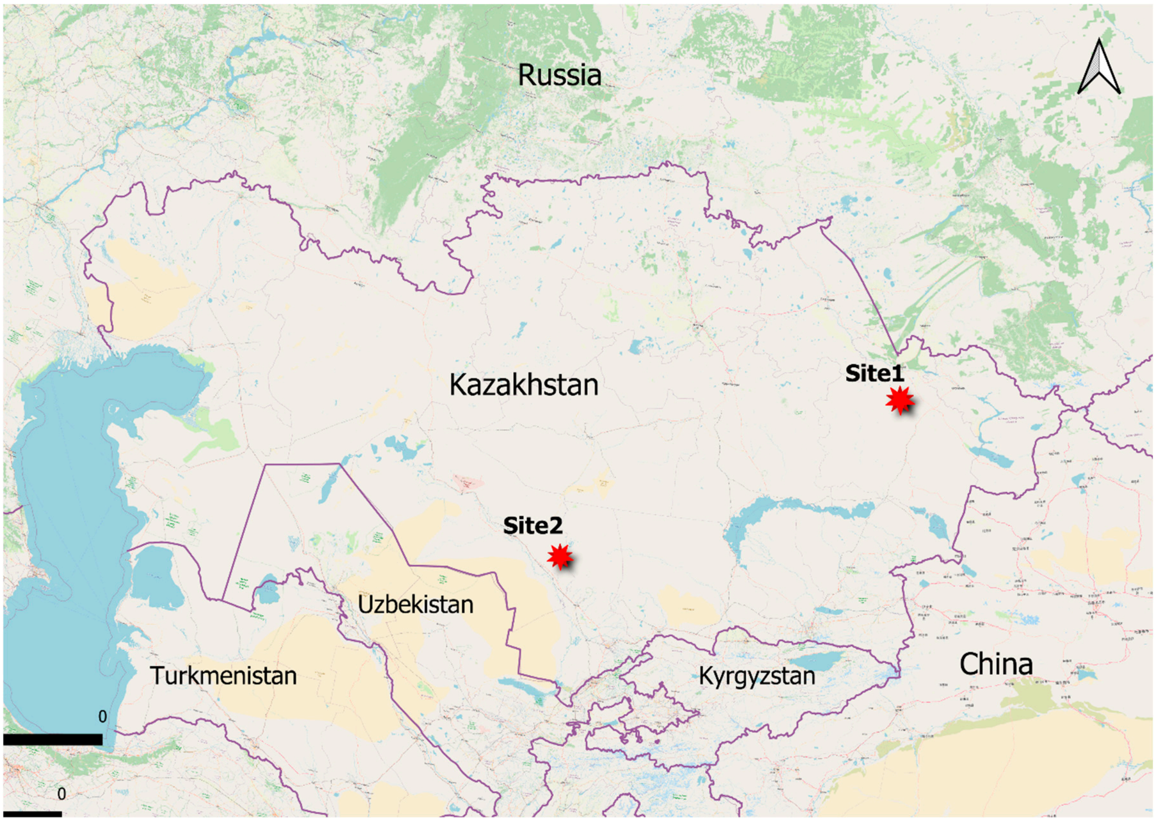

Figure 1. Location of selected mine sites in Kazakhstan.

In this study, climate change for each site is assessed based on GCM from NASA's NEX-GDDP dataset, which is compatible with Phase 6 of the Coupled Model Intercomparison Project (CMIP6). The statistical downscaling algorithm used is a daily Bias-Correction–Spatial Disaggregation (BCSD) method [9]. The NEX-GDDP-CMIP6 dataset spans the entire globe with a 0.25° (≈25 km) spatial resolution for the periods from 1950 through 2014 (historical) and from 2015 to 2100 (climate projections). Under the latest IPCC Assessment Report, AR6, two scenarios following the Shared Socioeconomic Pathway (SSP) framework were defined, SSP2-4.5 and SSP5-8.5, and are included in the analysis. Scenarios SSP245 and SSP585 show additional radiative forcing of 4.5 and 8.5 W/m2 representing the intermediate and high limits of the climate change projections, respectively. To reduce uncertainty in climate projections, an ensemble of GCM outputs is used to obtain a spectrum of possible future outcomes. Table 1 shows the 18 GCM used in this study.

The climate change studies usually take the following steps: (1): Historical data review to obtain a more transparent picture of the climate condition at the study site. (2) Downloading downscaled outputs of available GCM at the site location from NEX-GDDP-CMIP6 datasets and comparing the outputs of GCM with observed values for the baseline period. If required, bias-correction of the GCM outputs should be carried out. (3) Analysing time series of variables for time horizons of interest in future under different climate change scenarios and assessing the rate of change compared to the baseline period. Figure 2 shows the different stages which should be implemented for climate change studies. In this study, besides the baseline period (1981-2014), three future horizons, 2040s, 2060s and 2080s covering the period 2030 to 2100, were considered.

To have a better projection of future climate conditions, the observed data at the mine site the quantile delta mapping (QDM) method was used to bias-correct the outputs of GCM. Finally, the effect of climate change on (1) Mean annual precipitation (MAP) as well as monthly precipitation, (2) maximum and minimum temperature at monthly time scale, and (3) 24-hour precipitation with 10-year return period have been evaluated.

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Table 1. Global Climate Models (GCM) considered within Coupled Model Intercomparison Project Phase 6 (CMIP6) and downscaled by NASA as a part of the NEX-GDDP project.

Climate Institute/Centre	Country	GCM Model Name
Beijing Climate Centre	China	BCC-CSM2-MR
Canadian Centre for Climate Modelling and Analysis	Canada	CanESM2
Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	France	CNRM-CM6
Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology	Australia	ACCESS-ESM1 ACCESS-CM2
Russian Academy of Sciences, Institute of Numerical Mathematics	Russia	INMCM5.0
Institute Pierre Simon Laplace	France	IPSL-CM6A-LR IPSL-CM6A-LR
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan	MIROC6
Max Planck Institute for Meteorology	Germany	MPI-ESM-LR MPI-ESM-MR
Meteorological Research Institute	Japan	MRI-ESM2
Bjerknes Centre for Climate Research, Norwegian Meteorological Institute	Norway	NorESM2
Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM4
Euro-Mediterranean Centre on Climate Change	Italy	CMCC-ESM2
European consortium of national meteorological services and research institutes	European community	EC-Earth3
Chinese Academy of Sciences	China	FGOALS-g3
Nanjing University of Information Science and Technology	China	NESM3

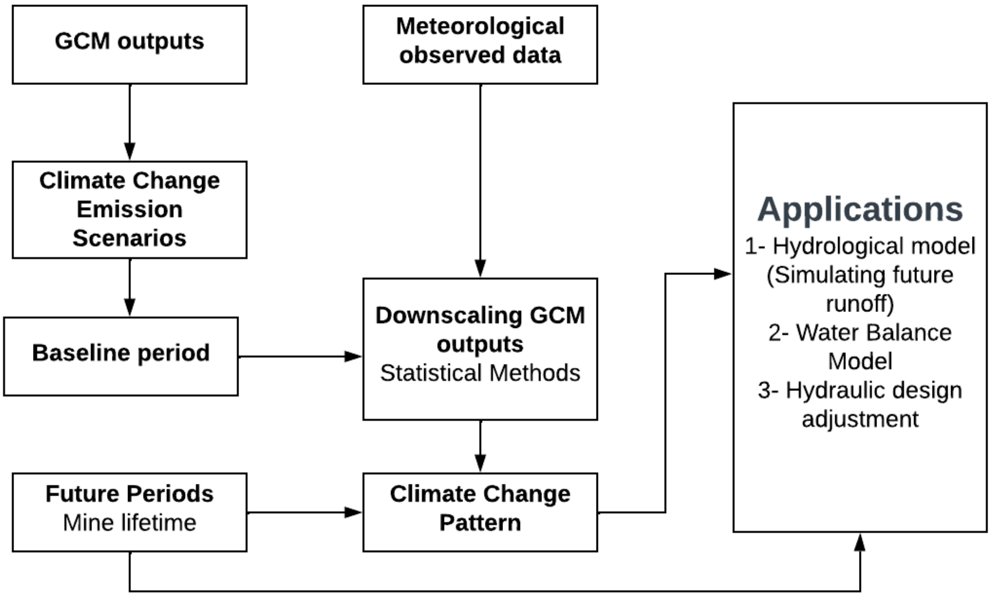

Figure 2. Flowchart of different phases for climate change studies.

3. Results and Discussion

The effects of climate change on precipitation as well as minimum and maximum temperature at monthly and annual time scale will be assessed to determine the rate of change compared to the baseline period. To have a better projection of future climate conditions, the observed data at the mine sites were compared to outputs of GCM over the baseline period to evaluate if any further bias-correction is required. Figure 3 shows the mean annual precipitation derived based on different GCM for the period 1981-2014 as well as observed value estimated at Site1 location as an example. It can be seen in Figure 3a that all climate models tend to overestimate precipitation at the mine site (Figure 3b). Consequently, for both precipitation and temperature data (minimum and maximum temperature) at both Site1 and Site2, the QDM method was applied to the outputs of the GCMs to have a more realistic projection of the future climate condition at the site locations.

Figure 4 shows the time series of average annual temperature at both sites for the historical (1981-2014) and future periods based on the outputs of all GCM used in this study. In this figure, 50%, 80% and 95% uncertainty bands are shown. It can be seen that over the historical period, most of the observed average annual temperature are bracketed inside the 95% uncertainty interval with a few exceptions, such as year 2010 at Site1 where all GCM overestimate the mean annual temperature. Only MPI-ESM1-2-HR has a smaller temperature than observed value at this year. It can also be seen from Figure 4 that the uncertainty (the confidence interval around the median values) increases with time; more uncertainty in far future (2080s) and then in mid future (2060s, i.e. 2051-2080) compared to the near future (2040s, i.e. 2031 to 2060) and the baseline period (i.e. 1981-2014). Also, the uncertainty associated with SSP585 is higher than of SSP245.

The change in minimum and maximum temperature at monthly scale has been calculated based on median temperature from all 18 models used in this study and the results are presented in Figure 5.

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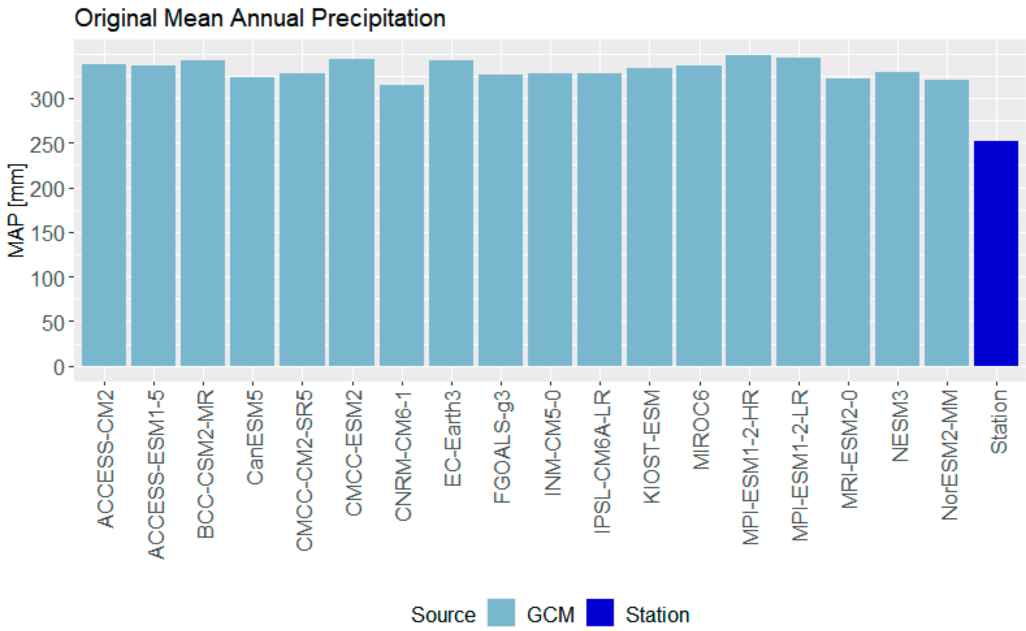
(a)



(b)

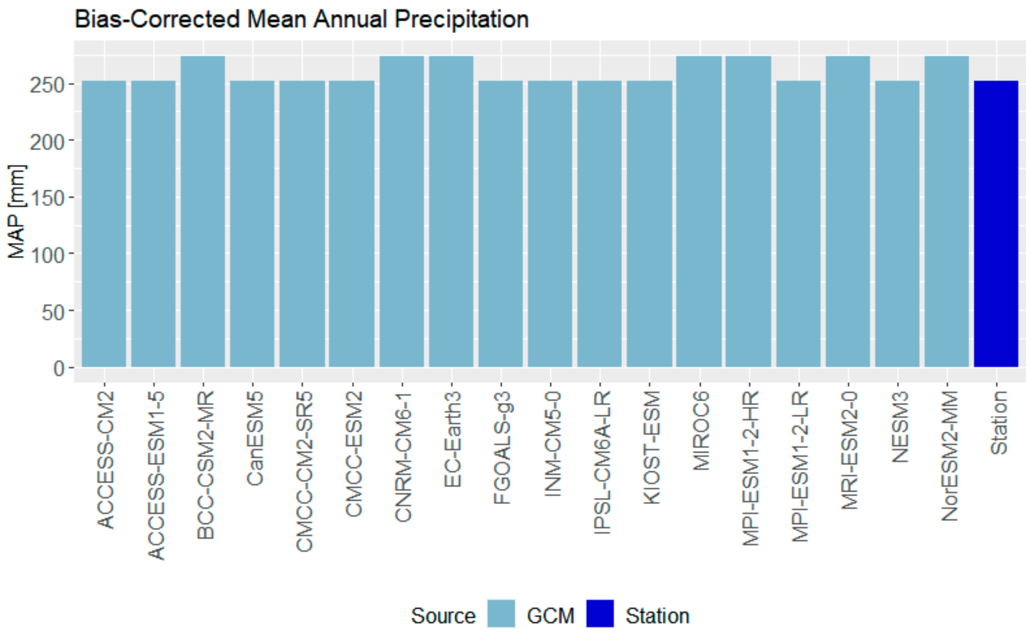


Figure 3: Average annual precipitation before bias-correction (**a**) and after bias-corrections (**b**) at Site1

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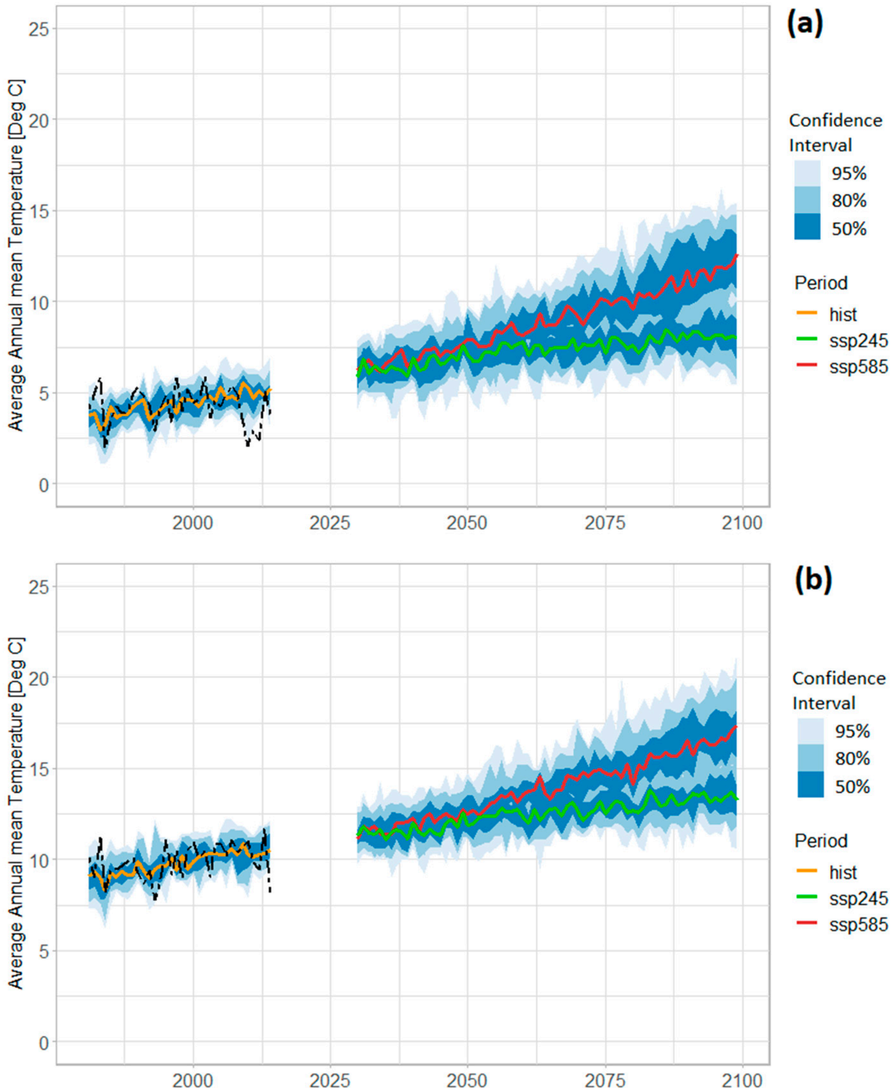

Figure 4. Time series of average annual temperature at (**a**) Site1 and (**b**) Site2. Coloured Solid lines show the median of GCMs outputs. Black dashed line shows the observed values at each site.

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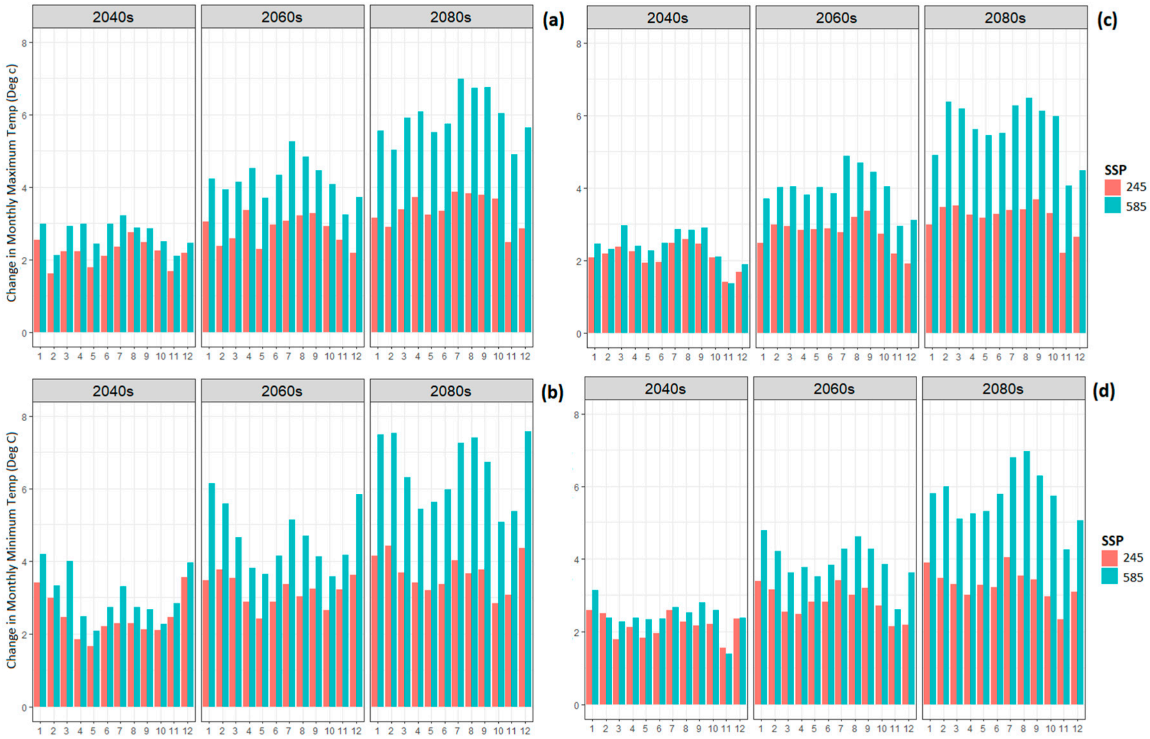

Figure 5. Change in monthly maximum (**a**,**c**) and minimum (**b**,**d**) temperature (in °C) over future periods for Site1 (**a**,**b**) and Site2 (**c**,**d**).

The results suggest that whilst both maximum and minimum temperatures will increase over the future periods, the rate of increase is higher based on the pessimistic SSP585 scenario compared to the moderate scenario of SSP245. Also, the increase in temperature is higher in the far future period, i.e. 2080s, compared to middle (2060s) and near (2040s) periods. It is also interesting to see that Site1 is likely to experience a slightly higher increase in temperature compared to Site2. For example, under SSP585 and over 2040s period, Site1 and Site2 would have 2.7°C and 2.5°C increase in their annual maximum temperature, respectively.

The number of freezing days (days with average temperature bellow zero) will also decrease especially in March and then April and November in Site1 and February, March, November and December at Site2, with Site2 experiencing a slightly greater decrease in freezing days condition compared to Site1. Overall, it means fewer freezing conditions are expected to happen during these months at the Site2 (results not shown). A significant change in freezing periods and air temperature can have defining consequences on the development of projects that would rely on water sources such as glaciers or groundwater baseflows that feed streams/rivers/lakes.

While air temperature alone is not an accurate indicator showing a bearable/comfortable workplace temperature, in this study 35°C is considered as a threshold for heat stress. Analysis of hot days (number of days with temperature above 35°C as a threshold) also shows that both sites would experience more frequent hot days, especially in summer months. Site2 will have more harsh summer months with maximum daily temperature above 35°C compared to Site1. For example, in July and over 2040s, Site2 will have 7 and 8 more days with temperature above 35°C, while Site1 will have 4 and 6 more days with hot temperature based on SSP245 and SSP585, respectively (Figure 6). This can lead to more heat stress among the workforce especially in hot months which can reduce their efficiency [13]. This might even lead to temporary interruption on mine activities during hot months. This analysis is essential to evaluate the potential impacts of climate change on human health.

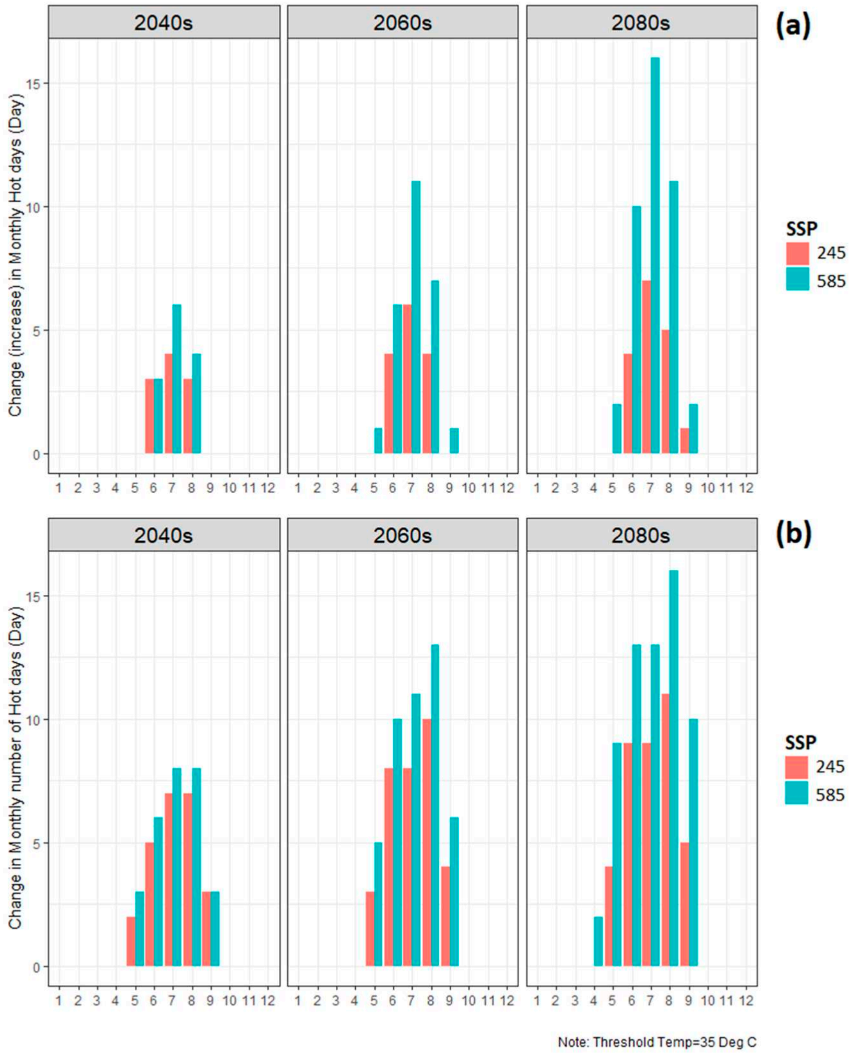

Figure 6. Change in number of hot days (days with temperature above 35°C) over future periods for Site1 (**a**) and Site2 (**b**).

For precipitation, almost all climate models for both SSP scenarios and all future time periods predict an increase in annual precipitation at Site1. The only exceptions are MPI-ESM1-2-HR (all cases) and ACCESS-ESM1 over 2040s for SSP245 and 2040s, and 2060s for SSP585 scenarios, which show less precipitation in future compared to the baseline period (Figure 7a). On the other hand, at Site2, while the majority of GCM reveal increases in annual precipitation, more models show no change or even show a decrease in mean annual precipitation compared to Site1 (Figure 7b). Based on RCP245 and RCP585, the increase in MAP in 2040s will be approximately 5.9% and 7.9% at Site1, and 7.9% and 3.8% at Site2, respectively. Conversely, based on SSP245 and SSP585, over the 2080s, the precipitation will increase by 14% and 18% at Site1 and 11% and 13% at Site2 respectively. This means over the near future, Site2 would experience more increase in precipitation compared to Site2, while both sites would experience a decrease over middle and far future periods. These results are in agreement with previous studies showing an increase in annual mean precipitation of 10.5% and 14.4% under SSP245 and SSP585, respectively, by the end of 21st century at Central Asia region [14].

At monthly time scales, the results suggest that while in almost all months and under both SSP245 and SSP585, precipitation would increase over all future periods at Site1, at Site2 and in summer months, July, August and September, precipitation would decrease in almost all time periods and SSP. All other months at both sites will experience increase in precipitation with the SSP585 causing more increase compared to SSP245 in those months (Figure 8).

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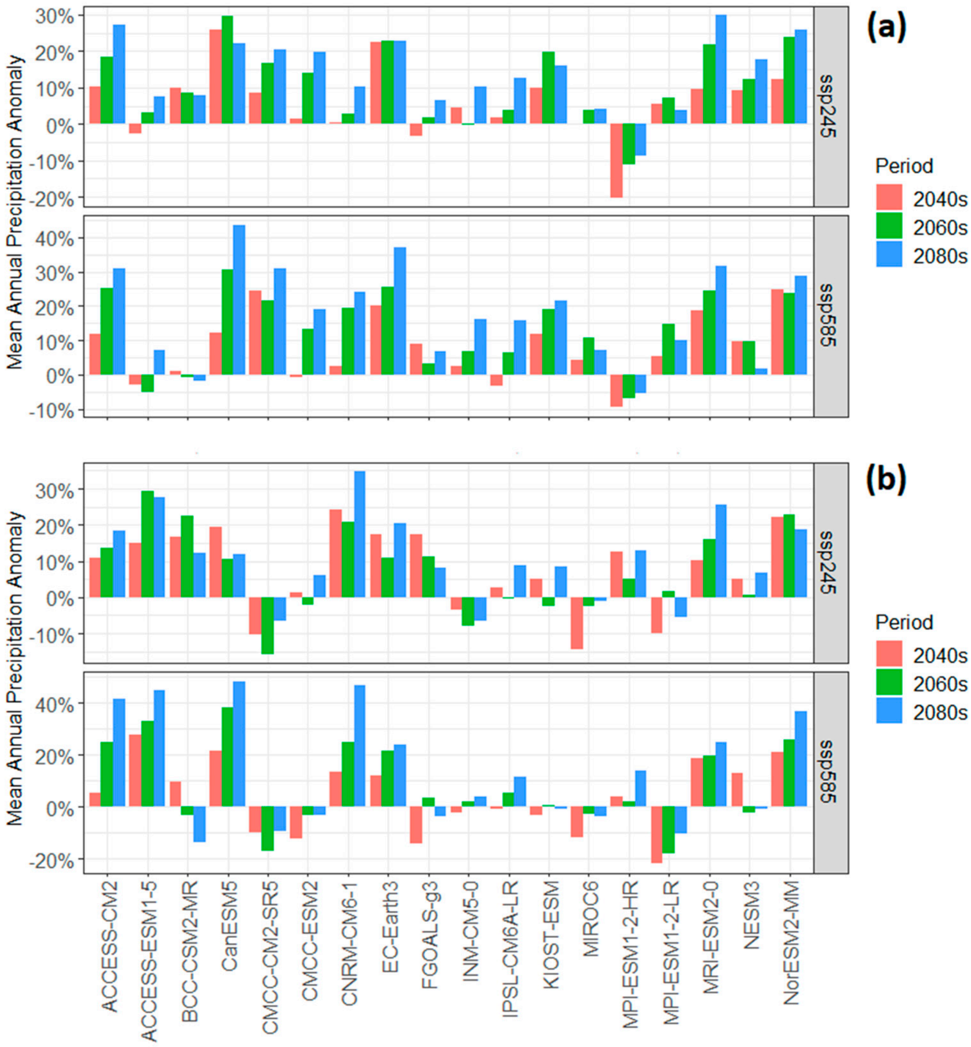

Figure 7. Rate of change (%) in MAP over future time periods and two climate change scenarios at (**a**) Site1 and (**b**) Site2.

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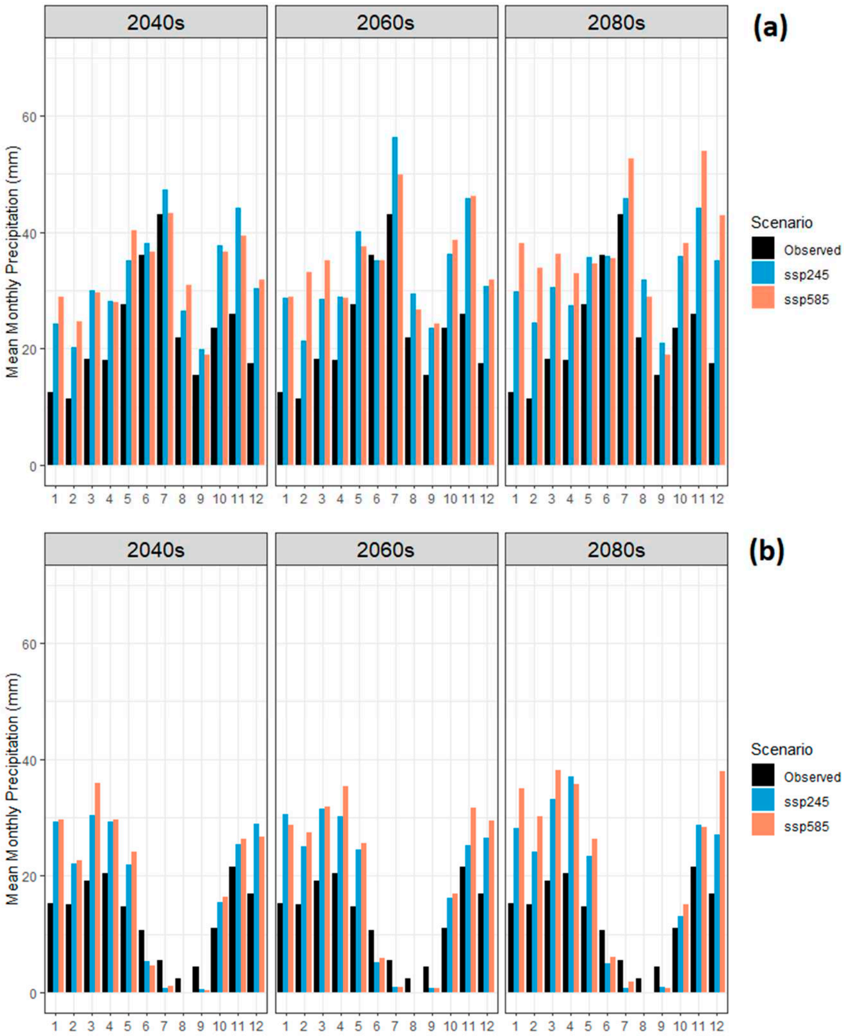

Figure 8. Monthly precipitation over future time periods and different SSPs based on median of 18 GCM used in this study at (**a**) Site1 and (**b**) Site2. Black bars show the historical observed precipitation.

Finally, the change in 24-hour precipitations with 10% annual exceedance probability (10-year return period) was also assessed, as illustrated in Table 2. Again, it can be seen that except for a few GCM, SSP and time horizons (e.g. CMCC-CM2-SR5 in most combination of SSP and time horizons at Site2 and FGOALS-g3 for both SSP245 and SSP585 in 2080s at Site1), in most of the cases the 24-hour precipitation with 10-year return period is predicted to increase at each site. Over the near future, i.e. 2040, Site1 would experience an average of 6.9% and 4.8% increase in 10-year precipitation events with 24-hour duration, while Site2 will expect an increase of 2.8% and 5.9% under SSP245 and SSP585, respectively.

Table 2. Percent change in 24-hour precipitation with 10-year return period based on different GCM.

Mine Location	**Site1**						**Site2**					
period	**2040s**	**2040s**	**2060s**	**2060s**	**2080s**	**2080s**	**2040s**	**2040s**	**2060s**	**2060s**	**2080s**	**2080s**
RCP	**SSP245**	**SSP585**	**SSP245**	**SSP585**	**SSP245**	**SSP585**	**SSP245**	**SSP585**	**SSP245**	**SSP585**	**SSP245**	**SSP585**
ACCESS-CM2	17.3	13.2	17.9	16.5	13.7	20.6	8	1.9	19.3	28.1	19.6	25.4
ACCESS-ESM1-5	13.5	10.8	23.2	10.7	20.9	19.2	7.4	12.8	15.4	13.1	14.2	13
BCC-CSM2-MR	19.2	11.6	17.9	9.6	13.7	4.5	1.6	2.7	6.9	1.9	2	0.4

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CanESM5	4.8	3.9	7.5	13.2	8.5	19.8	3.7	13.9	12.7	15.7	17.5	26.1
CMCC-CM2-SR5	1.7	1.4	1.6	-2.6	6.9	15	-4.1	-6.2	5	1.3	-1	-0.7
CMCC-ESM2	-3.6	-9.1	-4.2	-5.6	-2.4	4.1	1.2	6.7	12.1	6.1	8.5	13.4
CNRM-CM6-1	-3.3	-3.9	8.4	6.3	17.7	5.7	5.1	19.2	-1.4	15.8	21.6	34.5
EC-Earth3	17.9	20.3	18.2	17.3	24.7	13.2	26.3	18.9	19.8	17.7	9.9	12.8
FGOALS-g3	7.4	-4.9	6.4	-8.7	-8.7	-8.3	9.3	0	11	10.4	1.8	13.7
INM-CM5-0	-1.1	1.9	0	7.1	9.6	9.5	0.1	13.8	6.2	7.2	-5.6	8.5
IPSL-CM6A-LR	9.8	-0.3	0.7	5.8	13.9	22.7	-4.4	15	-4.6	17.5	6.8	6.4
KIOST-ESM	15.9	4.6	21.3	5.7	8.7	10.7	7.7	0.7	-0.3	11.3	0.1	15.8
MIROC6	-3.2	-1.6	-6.4	1.8	2.1	-0.8	-10.5	-10.4	-0.8	-5.7	2.3	-4.4
MPI-ESM1-2-HR	8.5	9.1	14.8	11.1	6.2	9.9	-2.8	8.7	-9.9	2	6.8	7
MPI-ESM1-2-LR	6.5	6.8	3.1	6	6.5	10.6	-2.4	-1.5	3.2	-2.1	9.7	8.6
MRI-ESM2-0	11.4	7.3	8.9	14.5	12.8	24.8	-1.2	2.7	-1.1	12.5	-1.8	18.1
NESM3	-1.5	1.9	-0.4	2.6	-0.5	-5.2	-5.4	-2.9	-6.2	-10.3	3.4	0.7
NorESM2-MM	2.6	14.5	5.2	3.4	5.6	8.8	10.6	9.8	15.9	7.5	12.6	13.9

5. Conclusions

Kazakhstan is ranked sixth in the world in terms of estimated mineral resources, and mining and metallurgy are key industries that make considerable contribution to Kazakhstan GDP. On the other hand, most of Kazakhstan is in arid and semi-arid climate with limited water resources, and the origin of the rivers used for water supply being in neighboring countries. Despite the risk of water supply shortage in near future, from SRK's experience only a few mining projects have conducted studies to evaluate the future climate condition as a result of global warming and climate change.

In this research, the climate change effects on precipitation and temperature at two mine site in the northeast part of Kazakhstan were evaluated using the latest IPCC Assessment Report, AR6 Socioeconomic Pathway-Representative Concentration scenarios, namely SSP245 and SSP585.

The downscaled outputs of 18 GCM were bias corrected using observed historical values, then used to evaluate how maximum and minimum temperature as well as precipitation would likely change in three future periods, namely 2040s, 2060s, and 2080s.

The results showed that the maximum and minimum temperature is very likely to increase in future periods based on all climate models and both SSP245 and SSP585 scenarios. Greater increase in temperature is expected based on SSP585 in all future time periods and even greater increase in the far future period, i.e. 2080s compared to other two periods under both SSP scenarios. For minimum temperature, the increase will be more in winter months, i.e. in January, February and December, which means fewer freezing hours/days are expected in the light of climate change. Such predicted change is significant considering the fact that aquifer recharge and highest river flows in Kazakhstan is mainly due to snowmelt. Further more, this warmer climate means freeze-thaw cycles will increase leading to more freeze-thaw induced landslides which are one of the major geohazards especially on grasslands [15].

For precipitation, the average annual increase will be around 7% under both SSP245 and SSP585 at Site1, and 10.5% and 4.5% under SSP245 and SSP585 at site2 in 2040s. In 2080s, an increase of up to 14% and 17% at Site1 and 10% and 7% at Site2 is expected under SSP245 and SSP585, respectively. At a seasonal time scale, winter, spring and autumn months show increase in precipitation under most SSP and future time period combinations, whereas it is expected there will be drier summer months, i.e. July and August at Site1 and July, August and September at Site2. This could have significant consequences as under current conditions summer is the wettest season in this region with high temperatures. Therefore, the analysis results suggest that climate change will alter the precipitation regime in the area, and this should be considered in the mine design and cost implications, especially in relation to water supply and management.

Finally, the results of the analysis of 24-hour precipitation with 10-year return period suggest an average increase in precipitation ranging from 4% to 10% for SSP585/2040s and SSP585/2080s at Site1 and 1.4% to 13% for SSP245/2040s and SSP585/2080s scenario/future period combination at Site2. This predicted increase in precipitation and resulting runoff should be considered in the design of infrastructures such as tailing facilities and diversion channels.

These climate change assessments can provide an opportunity for mine owners and managers to incorporate these assessments for improved management of climate change-related liability and risks and also to demonstrate to investors and insurance companies how climate-related risks will be coped with in the future. By undertaking climate risk assessments, managers are able to identifying potential adaption measures to address relevant risks/opportunities.

Data Availability Statement: Downscaled climate projection for all GCMs used in this study can be downloaded from NASA website at www.nasa.gov/nex/gddp.

Conflicts of Interest: The authors declare no conflict of interest.

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