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Identification of Climate Change Impacts and Tradeoffs Established Under Shared Socioeconomic Pathways of IPCC AR6 using A Moderate Resolution GCM viz. MRI-ESM2-0 of CMIP6 over Pakistan

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Abstract
Pakistan will be 100 years by the end of mid-21st century. Within its continued lifespan, it has borne witness to various climate change hazards exclusively conveyed under the umbrella of the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (ARs). Recently published IPCC's AR6 establishes its distinctiveness by addressing co-benefits, risks, interactions, trade-offs and economic development factors associated with magnitude of climate change factors, both regionally and globally. With heavy exposure to climate change indications in recent times, implications of such factors to shared socioeconomic narratives needed attention, especially over Pakistan region. To address this, a moderate resolution General Circulation Model (GCM) viz. MRI-ESM2-0 of Coupled Model Intercomparison Project phase 6 (CMIP6) was engaged to detect magnitude of potential risks associated with five Shared Socio-economic Pathways (SSPs) in the future. Change in mean state of global climate extracted over local realm was integrated with Gantt-like charts to depict severity and abruptness of the studied pathways to potential threats and balances over provinces and regions of Pakistan. Results revealed realms of risk that potentially placed the provinces and the regions at par with globally provoked hazards, yet simultaneously co-befitted them with tradeoff of boosts in economic development based on fossil fuel investments. Nevertheless predictions of such nature are constrained with global and local policy interventions, and hence are conveyed as spectrum of potential implications of the global climate change on national realms in the future.
Keywords: IPCC AR6, Climate Change, SSP, MRI-ESM-2.0, CMIP6, Pakistan.

Introduction

Climate change creates multidimensional and hard-to-assess risks to socioeconomic systems. Climate-related risks are pervasive; vary across sectors, regions and communities; and arise through the dynamic interaction among climate-related hazards as well as through the exposure and vulnerability of the affected systems (Lempert, 2021). Over the course of recent historical period, global emissions generally followed a medium-high pathway, captured by "middle-of-the-road" scenario narratives in preceding scenarios series, and by combinations of "global-sustainability" and "middle-of-the-road" narratives in the most recent scenarios series of Shared Socioeconomic Pathways (SSP) baselines (Pedersen et al., 2021). The Intergovernmental Panel on Climate Change (IPCC's) Sixth Assessment Report (AR6) being the most up-to-date physical understanding of the climate system and climate change, brings together the latest advances in climate science, and combines multiple lines of evidence from paleoclimate, observations, process understanding, and global and regional climate simulations (Eyring et al., 2021).

In order to determine robust areas of consideration under climate change diagnostics, the AR6 establishes its distinctiveness by addressing co-benefits, risks and co-costs of mitigation and adaptation, interactions and trade-offs, technological and financial challenges and options, equity, sustainable development, poverty eradication, livelihoods and food security (Zhongming et al., 2021).

Pakistan is known to be vulnerable to climate change. The geographical variation is such that glacial areas of the north, including the Himalayas, the Karakorum, and the Hindu Kush mountains (6000+ m height) bear average temperature less than zero°C (Burhan et al., 2015; Burhan et al, 2020), while the other low latitude regions have an average temperature above than 25°C (Riaz et al., 2020; Burhan et al., 2021). Extreme temperature conditions pose a threat to population - climate change adds to these threats (Fand et al., 2012; Hanna et al., 2011). With one of the most densely populated regions of the world, Pakistan ranked fifth in the world with a population of 220.1 million (Minallah et al., 2016), crossing population density of Brazil in the year 2020 (Iqbal, 2021). However, the population is not equally distributed - some of the regions in Pakistan are denser than the others (Karachi with 15 million people living over 3,780 km^2 area) (Ahmed et al., 2008; Peerzado et al., 2019). The people of these regions are highly vulnerable to impacts of climate change which influences quality of their life in sectors such as agricultural, labour production, health, migration, and other factors that affect economic development and poverty reduction. A warmer climate in a densely populated area has higher potential to transmit vector borne and other infectious diseases, which may result in a loss of productivity and revenue (Githeko et al., 2000; Rocklöv & Dubrow, 2020). Furthermore, variability in rainfall duration – due to urbanization impacts – can inversely impact worker productivity since out of phase wet and dry spell patterns can force people to stick into their homes, resulting in individuals not earning as much income on particular days (Sudarshan & Tewari, 2014).

A significant number of literature emphasizes on the impacts of changing climate on infrastructure, particularly on roads. A frequent observation in the literature is that climate change threatens current and future infrastructure, including high adaptation costs, maintenance, as well as road accidents. Road traffic incident is a major concern since cost of that is about 2% of the gross domestic product in Pakistan (Hammad et al., 2019). According to the United States Department of Transport (USDOT), nearly 23% of road accidents are attributed to extreme weather situations as a result of unpleasant weather conditions, such as fog, snow, and rain (Thordarson & Olafsson, 2008; Becker et al., 2020). Increased temperatures are causing numerous issues, such as tyre burst, overheating of motor cars engine, thermal contraction, and expansions of flyovers (Ali et al., 2020). Besides, these erratic variations in temperature lead to deterioration of road networks and thus shortens road life. Heavy or prolonged precipitation is also another significant factor behind the damage of road networks since it reduces friction between tires and cuts visibility (Drosu et al., 2020). In fact, climate change has been recognised as the main driver behind the increasing magnitude, augmenting severity, and enhanced frequency of rainfall in recent periods.

Climate change is also the main problem for water reservoirs in Pakistan, where diverse climate patterns have prevailed (Ali et al., 2009; Burhan et al., 2020). The higher altitude of Hindukush and Himalayan mountains supplies half of the freshwater reservoirs through snow and melting ice. For example, during boreal winter 70% of the rivers flow due to melting ice water (Burhan et al., 2020). However, global warming has enhanced snow and ice melting, prompted significant variations in precipitation that resulted in severe events such as flooding and droughts, increased sea levels, and triggered loss of habitat (Hashmi et al., 2020). Therefore, low latitude regions, especially the Sindh province remain highly vulnerable to such events, due to an enhanced flow rate in wet season and a shrunk flow rate in dry season (Nasir & Akbar, 2012). Thus, assessment of vulnerability to climate change on water reservoirs must be essential as a decision-support to policymaking agencies of Pakistan.

The General Circulation Models (GCMs) are used for prediction of climate change variables in the future. The Coupled Model Intercomparison

Project phase 6 (CMIP6) is the advanced updated version of the coupled global models, with the new SSP scenarios. The dataset of CMIP6 varies from the datasets of CMIP5 and CMIP3 in terms of increases in model resolution and an overall complexity of the CMIP6, where an increased number of variables are required to resolve climatic features (Petrie et al., 2021). It is already evident that the CMIP6 notes higher climate sensitivity to carbon dioxide emissions than in CMIP5 and thus contributes to projections of greater warming in the 21st century (Zelinka et al., 2020).

One of the main sets of simulations run by CMIP6 are future climate scenarios, where models are given narratives of socioeconomic development, energy systems, land use, greenhouse gas (GHG) emissions and air pollution (Gidden et al., 2019). The CMIP6 has added a new scenario – SSP3-7.0 – which lies right in the middle of the range of baseline outcomes produced by energy system models. Now researchers can examine worst case (SSP5-8.5), middle of the road (SSP3-7.0) and more optimistic (SSP4-6.0) outcomes when analysing how regions might warm in a world that fails to enact any climate policies. SSP4-3.4 is another new scenario that tries to explore the space between scenarios that generally limit warming to below 2°C (RCP2.6 / SSP1-2.6) and around 3°C (RCP4.5 / SSP2-4.5) by 2100. These new CMIP6 scenarios, thus have the ability to explore climate changes and their associated impacts with more robustness over a wider range of possibilities in future settings (Table I).

Table 1: The SSP quantifications in public database (Riahi et al., 2017)

Scenarios	Description	CO2 Emissions by 2050 (Global)	Estimated Warming by 2050 (Global)	Estimated Population by 2050 (Global)	Estimated GDP by 2050 (Global)	Challenges
SSP 1 26	Sustainability	41.8 GtCO2	1.7°C	8.53 billion	293.1 trillion	There might be few obstacles to mitigation and adaptation in the future. The world's population might peak in the mid-21st century. Focus might remain on human well-being. Renewable energy and environmentally friendly technology might prevail. On a global, regional, and national level, strong and flexible institutions are projected.
SSP 2 45	Middle of the road	55.9 GtCO2	2.0°C	9.17 billion	231.3 trillion	Mitigation and adaptation both might face moderate risks in the future. By the end of the century, population growth might stabilize. Social, economic, and technical changes might persist. Institutions at the international and national levels might make slow progress in achieving sustainable development goals.

SSP 3 70	Regional rivalry	64.8 GtCO2	2.1°C	9.96 billion	173.7 trillion	This future might present significant mitigation and adaptation issues. In developing countries, population growth might continue to remain dynamic. Due to regional tensions and nationalism, there might be a strong focus on national issues. Economic growth might remain slow and reliant on fossil fuels. There might be few international trade agreements and weak global institutions.
SSP 4 60	Inequity	55.7 GtCO2	2.1°C	9.15 billion	219.1 trillion	Mitigation could become easy in the future, but adaptation could be difficult. By the end of the century, population growth might stabilize. The gap between a globalised, well-educated civilization and fragmented lower-income societies could be widened. Unrest and conflict could become increasingly prevalent. Institutions at the global, regional, and national levels become ineffective.
SSP 5 85	Fossil-fueled development	84.4 GtCO2	2.4°C	8.58 billion	364.7 trillion	This future might present significant challenges to mitigation while posing few challenges to adaptation. The world's population could reach a peak in the mid-twentieth century. The emphasis could be on economic growth and technological advancement. Adoption of resource- and energy-intensive lifestyles on a global scale could become a norm. A lack of environmental consciousness might be there.

Of all the cited literature, it is well seen that socio-economic factors have serious implications on climate change and variability over the country. However, there has been no specific study related to identification of potential implications and tradeoffs for assessment of vulnerability factors, when studied under the new SSP scenarios over Pakistan. Our goal is hence, to minimize this gap by elaborating potential indications of accelerated changes in climatic factors via socio-economic attributes with associated impacts in the future over provinces and regions of Pakistan.

Study Area and Major National Assets

Geographic Location and Land Coverage

Pakistan lies in the west of south Asia between 23°39/N-37°01/N latitude and 60°49/E77°40/E longitude comprising of Indus agricultural plains to western high lands. The total geographical area of Pakistan is 79.6 million hectares (Mha). Due to complex topography and latitudinal variation, Pakistan experiences tropical to subtropical types of climate (Haider and Adnan, 2014). The study area in this research includes all 4 provinces – Punjab, Sindh, Khyber Pakhtunkhwa and Baluchistan – and nationally bounded high altitude regions of Gilgit-Baltistan and Azad Jammu Kashmir of Pakistan (AJK-GB). Population expanses, road networks, frozen reservoirs, and topographically sloping rivers are major national assets of Pakistan (Figure 1).

Population Density

Bearing a productive manpower, Pakistan is the world's sixth most populous nation with nearly 220 million individuals living in a 796,095 km² of area. Urban regions are home to 39.5 percent of the country's population. In terms of population, Karachi in Sindh province is Pakistan's most populated city, with a population of more than 16 million people. Karachi is the only major port city on the Arabian Sea with approximately 30% of the nation's industrial sector which contributes more than 20% to the national GDP of Pakistan (Fazal and Hotez, 2020). However there are several other dense cities in Pakistan like Lahore and Faisalabad – that belong to Punjab which is a densely populated province and contributes 110 million people to the total population of Pakistan (Saddique et al., 2021).

Road Network

Being custodian of national highways, motorways, expressways and strategic routes, Pakistan's total national roads network is about 263,775 kilometres. With over 200 million people, Pakistan annually generates a total domestic transport load of around 239 billion passenger kilometres and 153 billion ton kilometres (Shafique et al., 2017). Present freight density on Pakistan's roads is about 170 billion tonnes per kilometre which is expected to increase to 600 billion tonnes per kilometre by 2025. This demand of additional load on the roads is expected to be fulfilled by construction of various road networks under the China Pakistan Economic Corridor (CPEC) project in Pakistan. Nevertheless recent studies noted major environmental concerns after completion of road networks under the CPEC since the Karakorum highway (a major highway in the north of Pakistan) is expected to carry up to 7000 trucks per day that could release up to 36.5 million tons of CO_2 on the way to Gwadar towards the south of Pakistan (see e.g., Kouser and Subhan, 2020).

Frozen Reservoirs

The frozen reservoirs of Pakistan go across Hindu Kush, Karakoram, and western Himalayan confluence, which is the world's most glaciered region in middle and low latitudes. These glaciers, totalling to 16546 in number, spans an area of about 24942 kilometres square (Zheng et al., 2021). The debris-cover impact on glaciers significantly alters rate and spatial pattern of ice melt, affecting glacier response to climate change and hydrological responses. Almost all debris-free glacier termini in the Himalayas are retreating, whereas debris-covered glacier termini exhibit no consistent response to climate change other than a substantial trend toward negative mass balance and surface thinning (Zheng et al., 2021). Changing climatic scenarios has have a significant impact on ice and snow masses over these regions eversince Glacial Lake Outburst Floods (GLOF) and surge occurrences caused by climatic variation have impacted downstream environments (Ali et al., 2021). As a result, it is critical to assess vulnerability of these glaciers and ice masses for possible depreciative triggers due to climate change effects.

Major Rivers

Pakistan's river system is fed by the snow-capped Himalayan and Karakoram mountain ranges. The system is made up of five rivers that largely flow through Punjab province. Jhelum, Chenab, Ravi, Sultej, and Indus are the Pakistan's five main rivers (Arshad and Oad, 2017). Jhelum – also home to a number of dams and barrages – is about 725 km long with highest flood discharges exceeding 28300 cubic meters per second. Chenab – at 960 kilometres of length and an average discharge rate of 30.37 billion cubic meters per annum – flows through Jammu and Kashmir, and later joins the Jhelum River at a flood control mechanism near Jhang. River Ravi - whose water depends on spring snowmelt and monsoon that causes heavy rains from June to September – originates in the Himalayas and extends to stretch of nearly 720 kilometres. Sutlej – at 1400 km of length – is extensively used for irrigation, and is controlled by springs and summer snowmelt in the Himalayas and the rains of monsoon. River Indus being the longest river of Pakistan with a total length of 3180 km, has a total drainage area of about 1,165,000 square kilometres with annual flow estimated at 207 cubic kilometres , and stands as twenty-first largest river in the world in terms of annual flow. Water from these rivers - currently used in agriculture (92%), industries (3%), and domestic purposes and infrastructure (5%) – is susceptible to see increase in its demand due to socioeconomic development and the population increase in the future (Chaudhry, 2017).

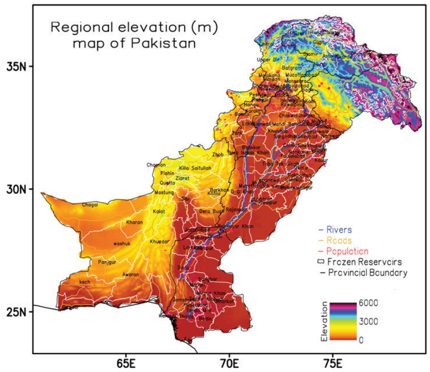

Figure 1: Regional elevation (m) map (Data source: https://pubs.usgs.gov/of/2011/1127/ss.html) overlaid with population expanses, road networks, frozen reservoirs, and topographically sloping rivers as major national assets of Pakistan (Overlaid data source: https://www.naturalearthdata.com)

Data and Methodology

Data

Model Data

The Working Group on Coupled Modelling (WGCM) is in charge of the CMIP6 project, which is part of the World Climate Research Programme (WCRP). The Earth System Grid Federation (ESGF) and the Centre for Environmental Data Analysis (CEDA), as well as several related initiatives, are used to undertake Phase 6, which builds on earlier stages led by the Program for Climate Model Diagnosis and Intercomparison (PCMDI). The original data is hosted and partially duplicated at a federated collection of data nodes, and most of the data used by the IPCC is kept for long-term preservation at the German Climate Commission's IPCC Data Distribution Centre (IPCC DDC).

The model used in this research is Meteorological Research Institute Earth System Model Version 2.0 (MRI-ESM2.0) whose data had been generated as part of the internationally-coordinated CMIP6 (Yukimoto et al., 2019). The simulation data provides a basis for climate research designed to answer fundamental science questions related to reproduction and projection of both mean climate and interannual variability components. The model was run by the Meteorological Research Institute, Tsukuba, Ibaraki 305-0052, Japan (MRI) in native nominal resolutions of 100 km for atmosphere and ocean components for the CMIP6.

Observed Data

This work also uses quality controlled and strategically adopted 31 stations daily temperature and daily precipitation data designed under an algorithm of Cressman Interpolated High-resolution Gauge-based Gridded Observations (CIHGGO) at 0.45° (49.95 km approximately) over a temporal scale of 35 years (1980-2014) for Pakistan region (Burhan et al., 2019). The CIHGGO was retrieved in NetCDF compression format for assistance in decision support of model application to this study. Used attributes of the observed and the model outputs are provided in Table II.

Methodology

GCM Validation

As a first step in deploying GCM based projections for the vulnerability assessment study, the observed and simulated air temperature and precipitation, averaged within similar time bands, were analyzed and compared. The object used for the analysis was the univariate spatial pattern characteristic. The comparison was made to show featured similarities and marked differences in the magnitude and spatial expanse of echelons over the studied domain (see e.g., Chen and Gao, 2019). The comparison was intended to reveal distribution of maxima and minima of the climatic variable which could either be identical or be different in both types of the data.

Table 2: Used attributes of the data output deployed in this study

Name	Project	Institute	Year	Variables	Time Period	Variant label	Frequency
MRI-ESM2-0	CMIP6	Institute (MRI) of the Japan Meteorological Agency (JMA).	2017	Precipitation (mm), Maximum Temperature (°C), Minimum Temperature (°C)	Historical (1950-2014), Projected (2015-2050)	r1i1p1f1	Daily
Observed	CIHGGO	Pakistan Meteorological Department	2019	Precipitation (mm), Maximum Temperature (°C), Minimum Temperature (°C)	Historical (1980-2014)	V1	Daily

On inspection of the GCM mean climate with respect to the CIHGGO based normal, the MRI-ESM2.0 is seen consistent with the observational patterns (Figure 2). The MRI-ESM2-0 is seen to replicate well, the observed temperature and precipitation over central-east, southeast, southwest, and western sides of the analysed domain, however some regions of the north are over/under estimated in precipitation/temperature along mean of the historical period. The MRI-ESM2-0 complements both the observed maximum (minimum) temperature distribution between 30 °C and 40 °C (5 °C and 20 °C), and the precipitation distribution of up to 3 mm/day towards the central and the southern regimes of the analysed domain. However, the northern domain is somewhat compromised in the MRI-ESM2-0 simulated climate which differs with the observed temperature (maximum and minimum) distribution by 7 °C to 10 °C by exhibiting underestimation, and further differs with the observed precipitation distribution at most by 2 mm/day while exhibiting overestimation. Such pattern of biases and dissimilarities were also illustrated by Mishra et al., (2020) who claimed a mean positive bias to persist in mean annual precipitation in regions located in Pakistan, as well as a high cold bias in both mean annual maximum and minimum temperatures to subsist over the Himalayan region, yet owing to salient agreement of the MRI-ESM2-0 to major regions of the country, the model was found to perform better overall in simulating observations and hence was advocated for utilization in future projection and impact studies over Pakistan (Karim et al., 2020).

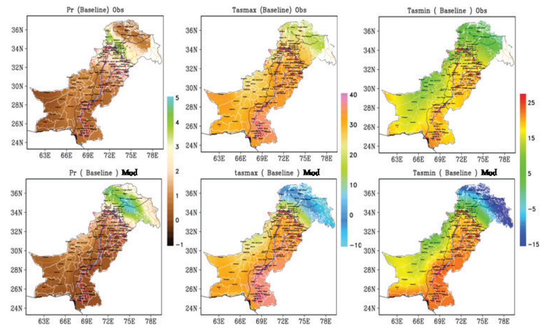

Figure 2: Representation of composite climate maps of the observation (top row) and the model replication (bottom row) for validation purposes.

Criteria for being Vulnerable

Those with significant magnitudes are more likely to be classified as 'key' than impacts with smaller effects. The scale (e.g., the area or number of people impacted) and intensity (e.g., the degree of damage inflicted) of an effect determine its magnitude. As a result, we can link significant vulnerabilities or harmful anthropogenic interference to large-scale geophysical changes in the climate system. Also, a negative impact is more likely to be labelled 'critical' if it is projected to occur soon rather than later (Xu et al., 2018). The rate at which affects occur is an essential feature of timing. In general, harmful impacts that emerge abruptly (and rapidly) are viewed as more important than those that occur gradually, since opportunity for adaptation for both human and natural systems is far more restricted in the former instance.

Magnitude of Composite Change

To identify vulnerability via magnitude, composite changes that highlighted differences in means were computed (see e.g. Fan et al., 2021). The focus was on finding differences in historical and SSP forced climate projections along the middle of 21st century. The years used for the composite anomaly analysis are already presented in Table II. Departure method was applied to compare the magnitude of differences obtained by the SSP forced projected composites with the historical composites. The results gave an estimate for locations of shifts, augmentation or detraction of high and low magnitude spots in the projected composite maps as compared to the size of those found in the historical composites (Figure 3).

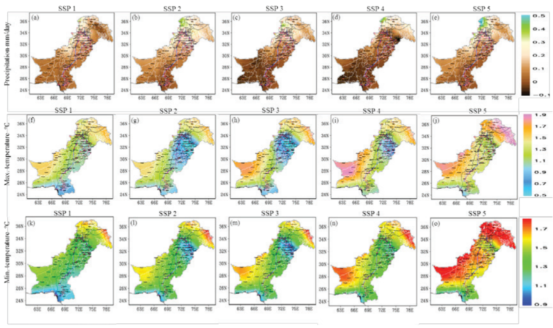

Figure 3: Composite changes for estimation of locations of shifts, augmentation or detraction of high and low magnitude spots in the projections

Table 3: Potential key vulnerabilities as per Schneider et al., (2007). Information on how consequences could vary when global mean temperature rises more dramatically is presented

Assets at risk	Relationship between temperature and risk			
	0°C	1°C	2°C	>2°C
Health (population density)	Present impacts are minor yet noticeable		Although certain hazards will be minimised, overall health consequences would worsen, owing to starvation, diarrhoeal illnesses, infectious diseases, floods and droughts, excessive heat, and other risk factors	
Infrastructure (road network)	Damages are projected to grow exponentially in response to climate change, as well as changes in catastrophic occurrences and adaptive capacity			
Freshwater ecosystem (frozen reservoir)	Some lakes are already seeing diminished fisheries productivity, as well as pole-ward movement of aquatic organisms		Hydrological cycles might be accelerated. Droughts and floods will be more severe	
Water resources (major rivers)	Reduced water availability and augmented drought		The severity of floods, droughts, erosion, and water-quality deterioration will worsen as climate change progresses. Sea-level rise will expand regions of groundwater salinization, reducing freshwater supply in coastal areas. Water supply would be cut for hundreds of millions of people	

Declaration of Vulnerability via Composite Changes

For the purpose to address our goal in determining vulnerability via acceleration of associated risk among the analysed SSPs, we colour coded "progress Gantt" like charts that depicted graduated risks and advantages attributed to their respective pace of reaching highest echelons in composite change maps by 2050. In a progress Gantt chart, tasks are shaded in proportion to the degree of their completion (Klein, 1999). In this way darkest of the shades in our charts represented high vulnerability and vice versa. Moreover, declaration of risk was affirmed with long term exposure of an asset to a specific hazard related to respective a province or the region (Table III).

Results and Discussion

Climate Vulnerability of the AJK-GB Region

The AJK-GB area of Pakistan is well known due to the presence of massive glacier reservoirs and icecaps. The community of this region exists in a very isolated environment. Their livelihoods depend on natural resources such as water, soil, reared and wild animals, and plants. However, in the future, the sustainability of these communities is potentially at risk due to increasing temperature and precipitation as mentioned in Table IV. The Table IV shows that the SSP4 pathway is extremely vulnerable for the AJK-GB area in terms of heavy precipitation. High adaptation problems will be observed in SSP4, implying that high unequal development with carbon-intensive fuels will be used in the future. This will result in rising temperatures and precipitation, threatening the AJK-GB community's survival by triggering GLOFs, damage to human settlements, road rutting, flash floods, and avalanches. Although increased precipitation in SSP4 is threatening the community's sustainability, at the same time, it is also highly beneficial for glacier preservation and increased runoff for lower catchment reservoirs.

According to Table III, the highest increase in maximum temperature (day) and minimum temperature (night) in the future can be spotted over the SSP5 pathway, which states that high challenges to mitigation will be experienced in the future with low challenges to adaptation. In complete contrast to the SSP4 pathway, which means using innovation and participatory societies to produce rapid technological progress and human capital development as the path to long-term development. There will also be significant investments in health, education, and institutions in order to improve human and social capital. Simultaneously, the push for economic and social development is accompanied by the extraction of abundant fossil fuel reserves. The AJK-GB community's lifestyle will boost (enhancement agricultural productivity, labor force, livestock insurance, and road assess).

Although, the SSP5 is demonstrating an intensive fossil fuel development in the AJK-GB region, yet, accelerating the demographic transition and production of electricity using coal and petroleum, and other uses of fossil fuels in transportation and industry affects the environment in many ways – most significantly, a higher threat is posed to the preservation of glaciers and icecaps of this region. In addition, mostly melting occurs over the daytime, since the night temperature also increases over the SSP5 pathway, human intervention and development can cause massive glacial retreat in the future over the AJK-GB region within a matter of decades.

Table IV: Risk and advantage associated with magnitude of composite changes in climate of the AJK-GB region

Vulnerable region	Vulnerable parameter	Valuable attribute	Vulnerable asset	Risk	SSP1	SSP2	SSP3	SSP4	SSP5	Beneficial side	SSP1	SSP2	SSP3	SSP4	SSP5
AJK-GB	Precipitation	Glacier Cover / Ice cap	Population sustainability	GLOFS, damage to human settlements						fresh water availability					
			Roads Networks	pavement distresses, rutting						not significant					
			Rivers	flash floods						runoff					
			Frozen reserve	avalanches						glacier preservation, glacier stress relief					
	Tasmax	Glacier Cover / Ice cap	Population sustainability	threats to Sub-alpine forests, warm spell						labour force, livestock insurance					
			Roads Networks	melting in summer leads to rutting						feeder road access					
			Rivers	no significant						water availability					
			Frozen reserve	glaciers melting, frost shattering						not significant					
	Tasmin	Glacier Cover / Ice cap	Population sustainability	fuel consumption, livestock damage						human and food security, relief from severe cold					
			Roads Networks	icing chemicals (Salt), ice crusher machines						not significant					
			Rivers	not significant						runoff					

Climate Vulnerability of the Punjab Province

Punjab is Pakistan's most populous province, and it contributes significantly to national agricultural production. It holds a significant portion of Pakistan's GDP and employs 47 percent of the labor force. Unfortunately, as shown in Table V, sustainability of these populations can be jeopardized due to rising temperatures and precipitation. The table shows that the SSP4 pathway is extremely vulnerable for the Punjab area in terms of heavy precipitation. SSP4 stated the inequality in which low challenges to mitigation and high challenge to adaptation will be witnessed in the future, implying that high unequal development with carbon-intensive fuels will be used in the future. As a result of disappearing Himalayan glaciers at a fast pace and of precipitation increase, the probability of extreme water flows renders it uncontrolled to bring heavy floods, loss of life, livestock, crops and infrastructural facilities in Punjab districts. The high challenges to the adaptation and inequality will affect all sectors of the economy not alone agricultural sector the most as well as human health, forests cover, energy, transport, ecology, and biodiversity.

According to Table V, the highest rise in maximum and minimum temperature over Punjab province in the future can be seen over the SSP5 pathway. As previously mentioned, with fossil-fueled development, more carbon footprints will be produced, which are strongly associated with future mitigation challenges. Similarly, methane is the second most significant contributor to global warming (after CO2). Currently, Punjab methane emissions are dominated by non-energy sources like manure management from livestock, rice cultivation, and enteric fermentation. Energy-related factors, such as the manufacture and transportation of coal, natural gas, and oil, add to pollution to a lesser degree (Riahi et al., 2017). Population development and food demand are major contributors to potential methane emissions around the SSP5 pathway, which is primarily due to the massive expansion of the fossil fuel infrastructure, particularly for the extraction and distribution of natural gas.

The SSP5 pathway bears greater reliance on CO2 and Methane emission which raises the maximum and minimum temperatures resulting in greater mitigation problems such as postharvest storage (highly influenced by temperature and humidity), crop loss through transportation (tyre burst, thermal contraction, and expansions of flyovers accidents), damage to Rabi (winter) and Kharif (summer) crop in terms of size, access, and utilization. The higher challenges to mitigation and fossil-fueled development will not alone affect agricultural sector, at the same time, it will push economic and social development with strong investments in health, education, and institutions to enhance human and social capital.

Table 5: Risk and advantage associated with magnitude of composite changes in climate of the Punjab province.

Vulnerable region	Vulnerable parameter	Valuable attribute	Vulnerable asset	Risk	SSP1	SSP2	SSP3	SSP4	SSP5	Beneficial side	SSP1	SSP2	SSP3	SSP4	SSP5
Punjab	Precipitation	Food basket	Population sustainability	flood, decline in labour force, Ponding						ground water recharge					
			Roads Networks	flash floods						not significant					
			Rivers	inundation, slow-rising riverine floods						water catchment increases					
			Frozen reserve	not significant						not significant					
	Tasmax	Food basket	Population sustainability	threat to flora and fauna						not significant					
			Roads Networks	tire burst, thermal contraction, and expansions of flyovers						not significant					
			Rivers	shifting precipitation patterns						not significant					
			Frozen reserve	no significant						not significant					
	Tasmin	Food basket	Population sustainability	horticultural crops loss, fuel consumption						not significant					
			Roads Networks	low visibility						not significant					
			Rivers	evapotranspiration						not significant					
			Frozen reserve	not significant						not significant					

Climate vulnerability of the KPK Province

In Pakistan, Khyber Pakhtunkhwa Province (KPK) has the highest forest cover (40 percent), especially in the districts of Shangla, Chitral, Dir, Swat, and Hazara. However, despite its high forest cover area, this province has been listed as one of Pakistan's highest hotspots for forest cover depletion, with a 30 percent decline from 1970 to 2010.

According to Table VI, the natural disasters (torrential rains), fluctuating monsoon rains, and rising temperatures all had and will have impact on the forest cover - especially in proximity to the community of rural areas of the KPK province. The table reveals that the SSP4 pathway is extremely susceptible to heavy precipitation in KPK districts. As mentioned in the SSP4 pathway, inequity with high adaptation challenges will be seen in the future, implying that high unequal growth of carbon-intensive fuels will be used in the future, and therefore due to inequalities of development, the rural areas of the KPK community are highly vulnerable to the SSP4 pathway in terms of heavy precipitation causing flooding and deluge in rivers.

From Table VI, the highest rise in maximum and minimum temperature over the KPK province in the future can be observed over the SSP5 pathway, which narrates the highest GDP expansion, with rapid equitable development and rural district catch-up. Moreover, coal will continue using as the primary energy source by the end of the century, resulting in high CO2 consternation in the atmosphere and raising temperatures. The rise in maximum and minimum temperatures over the KPK will trigger emergence of hotspots over the forest cover and will result in its degradation since it holds potential to alter frequency and intensity of attributed threats such as insect outbreaks, invasive species, wildfires, and storms. Moreover, the impact on the growth and function of forest tree plants will appear as differences in annual growth ring widths and other plant characteristics, in a climate effected region. These differences have an effect on forest products as well as the nature of timber and other products harvested from such forests (Shah et al., 2019). The fossil fuel-based economy will not only affect the forest cover, it will also act to trigger its effects on human health, land sliding, transport, ecology, and biodiversity.

Climate vulnerability of the Sindh Province

Drought condition in Sindh is quickly emerging as one of Pakistan's worst disasters. The southern uplands of Sindh have been hit worst by extreme drought in recent decades. Sindh's impacted areas have been vulnerable to water shortages, as rainfall measured over the last few years has reached a record low, with little or no rainfall. According to the Pakistan Meteorological Department, "severe to serious drought-like conditions" have arisen over much of Pakistan's southern parts due to a lack of summer rain.

According to Table VII, the SSP4 pathway is highly vulnerable to Sindh province in terms of low precipitation expected in the near future, making this community more susceptible to water scarcity. Furthermore, the SSP4 is more pessimistic about their potential economic and social growth, with minimal spending on schooling or health in deprived districts, with rapidly rising population, and growing inequality. As a result of the unequal investment, the majority of valleys and low-lying rural areas are expecting to lose all surface drinking water supplies and perhaps even the water table. Furthermore, the high challenges to climate adaptation posed by chronic inequality and poverty in many rural districts of Sindh may contribute to prolonged drought conditions in those districts, as well as a negative impact on food production systems and the health of community members, including women and children. As a result, a massive migration could take place from rural to barrage land in search of food, water, and jobs.

The highest increase of maximum temperature in Sindh can also be observed over the SSP4 pathway, which leads to the conclusion that with low precipitation and an increase in temperature, the rural areas of Sindh may push into drought-prone regions, and by the mid-century, survival in these districts could be impossible due to the augmented warmer climate and a lack of water supply. Moreover, due to high adaptation challenges, as well as uneven development within districts, the SSP4 could result in high societal impacts such as distress or depression over economic losses, disputes where there is insufficient water, decreased wages, fewer leisure opportunities, increased cases of heatstroke, and even loss of human life.

According to Table VII, the maximum rise in minimum temperature across Sindh province in the future can be observed over the SSP5 pathway. While the SSP5 pathway states rapid and unconstrained growth in economic output and energy use, it is also very vulnerable to the community of low-lying rural areas of Sindh in terms of environmental factors such as increases in the night temperature (which could eventually result in more energy demand for air-conditioning) and increases evapotranspiration (which could eventually result in soil moisture deficit). Aside from that, the use of abundant fossil fuel energy may raise the carbon footprint in the atmosphere, which can be a contributing factor to the enhancement of a warming climate and water shortages.

Table 6: Risk and advantage associated with magnitude of composite changes in climate of the KPK province

Vulnerable region	Vulnerable parameter	Valuable attribute	Vulnerable asset	Risk	SSP1	SSP2	SSP3	SSP4	SSP5	Beneficial side	SSP1	SSP2	SSP3	SSP4	SSP5
KPK	**Precipitation**	**Forest Cover / Ice Cap**	Population sustainability	urban and flash floods						afforestation, reforestation					
			Roads Networks	pavement distresses						not significant					
			Rivers	deluge						increase flow, ground water recharge					
			Frozen reserve	land sliding						glacier preservation					
	Tasmax	**Forest Cover / Ice Cap**	Population sustainability	growth ring-widths, Alpine Pastures						not significant					
			Roads Networks	overheating of motor cars engine						not significant					
			Rivers	arroyo (dry riverbed)						not significant					
			Frozen reserve	ice melting						not significant					
	Tasmin	**Forest Cover / Ice Cap**	Population sustainability	plant foliage, yield loss						not significant					
			Roads Networks	work related accidents						not significant					
			Rivers	evapotranspiration						not significant					
			Frozen reserve	de icing						not significant					

Table 7: Risk and advantage associated with magnitude of composite changes in climate of the Sindh province

Vulnerable region	Vulnerable parameter	Valuable attribute	Vulnerable asset	Risk	SSP1	SSP2	SSP3	SSP4	SSP5	Beneficial side	SSP1	SSP2	SSP3	SSP4	SSP5
Sindh	Precipitation	Water scarcity / Drought prone	Population sustainability	drought , water shortage,						Fresh water availability,					
			Roads Networks	wreaking havoc						not significant					
			Rivers	costal inundation, sea water intrusion, tropical storm						availability of water for rural areas of Sindh					
			Frozen reserve	no significant						not significant					
	Tasmax	Water scarcity / Drought prone	Population sustainability	heat strokes, health deterioration						not significant					
			Roads Networks	tire burst,						not significant					
			Rivers	high stress						not significant					
			Frozen reserve	no significant						not significant					
	Tasmin	Water scarcity / Drought prone	Population sustainability	dehydration, sleep loss,						not significant					
			Roads Networks	driver fatigue						not significant					
			Rivers	municipal water demand,						not significant					
			Frozen reserve	not significant						not significant					

Climate vulnerability of the Baluchistan Province

Water is one of the most indispensable of all-natural resources, however, Baluchistan is facing unprecedented water shortage, owing to climate change that has resulted in depletion of water at a rate faster than it is replenished, directly contributing to the growing water scarcity crises. In Baluchistan, currently, the groundwater is the only source to fulfil the requirement for domestic, industrial and agriculture purpose.

From Table VIII, the SSP4 pathway is highly sensitive to risk over the Baluchistan province due to an expected lower precipitation projection, making the districts of this province more susceptible, especially over the rural areas of the province. However, since high inequality and minimal development in rural areas are expected along this pathway, rural areas would be more vulnerable to water scarcity, inevitably leading to widespread migration of people. This would result in a substantial number of settled farmers becoming refugees. Furthermore, during severe drought conditions, there is a scarcity of nutritious food and potable water, which leads to the spread of disease, putting the community, particularly women and children, at risk.

Highest of the rises in maximum temperature over Baluchistan can be noted in the SSP4 pathway, leading to the hypothesis that the rural areas of Baluchistan may shift toward complete drought-prone regions with low precipitation and an augmented temperature anomaly. Sustainability over those districts could not be possible due to lack of freshwater for drinking, irrigation, and other need of life, under the SSP4 scenario.

According to Table VIII, highest of the rises in minimum temperature across Baluchistan province in the future can be observed under the SSP5 pathway. The SSP5 narrates rapid and unconstrained growth in economy with equal development over the districts which although, is in high contrast to the SSP4 pathway, yet is inclined more towards investment in all sectors such as health, education, and institutions to enhance human and social capital. At the same time, this pathway poses high vulnerability in terms of highest surges in minimum temperature regime which could lead to the excessive use of energy derived from fossil fuel resources for air-conditioning purposes even during nighttime over the Baluchistan province.

Table 8: Risk and advantage associated with magnitude of composite changes in climate of the Baluchistan province

Vulnerable region	Vulnerable parameter	Valuable attribute	Vulnerable asset	Risk	SSP1	SSP2	SSP3	SSP4	SSP5	Beneficial side	SSP1	SSP2	SSP3	SSP4	SSP5
Baluchistan	**Precipitation**	**water scarcity**	Population sustainability	lowering water table, droughts						fresh water availability					
			Roads Networks	wreak havoc						not significant					
			Rivers	coastal erosion, Saline Water Intrusion						ground water recharge					
			Frozen reserve	not significant						not significant					
	Tasmax	**water scarcity**	Population sustainability	climate migration, loss of biodiversity						not significant					
			Roads Networks	road accidents						not significant					
			Rivers	desiccation						not significant					
			Frozen reserve	not significant						not significant					
	Tasmin	**water scarcity**	Population sustainability	Food security, dehydration						relief from severe cold					
			Roads Networks	not significant						not significant					
			Rivers	evaporation						not significant					
			Frozen reserv	no significant						no significant					

Discussion

With our premeditated temperature deviation of delta 1.7 degrees threshold in view, the SSP1 being the sustainability scenario refuses to reach the global extent of warming by 2050s over any of the regions in the analysed domain. Highest of the maximum temperature departures is seen over the north eastern and the south western regimes of the analysed domain, with merely 1.5 degrees of deviation from the historical mean. Therefore, under this optimistic scenario the country, even with a noteworthy departure in the mean maximum temperature, may overcome any obstacles to mitigation and adaptation in the future. Although the regional population may peak in the mid-21st century, yet persistent global focus on human well-being that can reflect on regional scale, may pacify any population growth based dilemmas in the country. Shifting to renewable energy and environmentally friendly technology may also contribute to dampen the effect of global scale warming over regional scale of the country (Figure 4). Such interventions may act to reduce the globally prevailing 43 billion tonnes of CO2 to merely 41.8 billion tonnes of the same by the mid- 21st century. Owing to sustainable operations globally, regional and national institutions may get resilient and flexible under such scenario, and hence the country can act to elevate currently modest global GDP of US$80.9 trillion to the sophisticated US$293.1 trillion – projected under the SSP1 scenario. The global threshold of the SSP2 scenario is delta 2.0 degrees, which indicates prevalence of moderate risks to adaptation and mitigation at global scale by the 2050s. However, fortunate enough, none of the regions of the analysed domain converges to such higher thresholds of the globe and hence, impacts borne globally may not reflect over Pakistan in the sustainable and the middle of the road scenarios by the mid- 21st century.

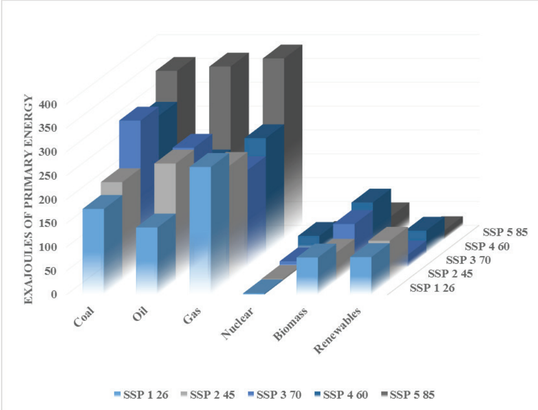

Figure 4: Global primary energy use by fuel type by 2050 in exajoules (EJ) for each SSP scenario

Conclusion

With the advent of the AR6 emissions scenarios and their associated SSPs in recent report of the IPCC, global climate change will have regional implications. In this study, we have attempted to deliver such indications of regional impacts over Pakistan using projections of a moderate resolution GCM whose replication of local climate follows well with the observed state of climate over Pakistan. Results have revealed that all provinces and regions of Pakistan are susceptible to experience impacts of climate change – that will be more pronounced under the SSP4 and the SSP5 scenarios. Major indications of the projected change is seen to put population expanses, road networks, frozen reservoirs, and major rivers of Pakistan at risk of exposure to associated hazards under these high end emission scenarios. The climate change impacts are seen milder under the SSP4 scenario than those under the SSP5 scenario, nevertheless such state of temperance will come only when cost of regional inequality is borne and significant loss in growth of economic development in provinces and regions of Pakistan is seen by 2050.

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