Ministry of Climate Change and Environmental Coordination

CURRENT STATUS OF CLIMATE CHANGE PROJECTS IN PAKISTAN

National Adaptation Plan for Pakistan

"Adapting Today for Sustainable Tomorrow"

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This report was commissioned by the GCF PAK-RS-003 Project "Building capacity to advance National Adaptation Plan Process in Pakistan" which aims to support the Federal Ministry of Climate Change and Environmental Coordination (MOCC&EC) and its partners at Federal and Province levels to implement the National Adaptation Plan (2023). The Delivery Partner is the United Nations Environment Programme (UNEP).

Executive Summary

The report presents the findings of an assessment that was undertaken to review the current status of climate change projections for Pakistan. The assessment considered many sources including documents from the Government of Pakistan, Provincial Governments, international organisations and other research within Pakistan and elsewhere. The documents were examined under the following themes: projections used at the global scale, projections used at the regional scale, emission scenarios and uncertainties.

Under all themes, it was established that there was limited information provided as to the choices of climate models, scenarios and climate parameters addressed, as well as the methodologies used for downscaling. In addition, the documents were without or with limited interpretation and/or guidance for decision making.

The Global Climate Models (GCMs) used across the studies varied from the use of CMIP3 and CMIP5, whereby Special Report on Emission Scenarios (SRES) and Representative Concentration Pathways (RCPs) have been derived, respectively. Two sources made use of the most up to date version CMIP6 making use of Shared Socio-economic Pathways (SSPs). Except where individual models were used, no specific scenarios were created in the documents other than as ensemble means or individual projections. Limited guidance was provided as to how an interpretation for decision making might be made, particularly for cases where alternative data sets were produced.

There are two basic approaches to downscaling – empirical and numerical. Both empirical and numerical downscaling have been used for Pakistan. Empirical approaches use a variety of statistical techniques, often borrowed from those originally designed to help interpret numerical weather forecasts. Numerical approaches use a variety of models, the most common of which is the Regional Climate Model (RCM). RCMs are mixtures of numerical weather and climate models designed to run over selected domains of the globe. As RCMs do not cover the full globe, they can run with smaller spatial and temporal scales and as a result can simulate directly more climate processes than can be achieved within GCMs. Therefore, RCMs provide decision makers with greater detail on processes. The justification for the methods, model selection and scenarios within the documents were found to be limited. In addition, the parameters assessed were limited to temperature and rainfall.

Emissions scenarios are required in any climate change projection work. These scenarios provide a narrative for the changes in the climate over the coming decade. As greenhouse gas concentrations in the atmosphere are one of the main drivers of these changes, the scenarios used represent the unknown future greenhouse gas concentrations. Throughout the documents, relatively high emission scenarios were analysed (specifically A2, A1B of CMIP3 and RCP8.5 of CMIP5), with less use of lower emission scenarios including RCP4.5 and RCP2.6 (of CMIP5). For the majority of documents, there was no indication of the justification for the use of particular scenarios. For the choices of GCMs and RCMs, all results from different scenarios were presented without or with limited interpretation and/or guidance to inform decision making.

Uncertainties arise from two main sources:

a. Various limitations in the abilities of the various models to simulate the climate system in all its forms, including feedbacks; and
b. Unknown details of anthropogenic impacts on the atmosphere, most significantly through emissions of greenhouse gases.

Ensemble mean projections were analysed for different emission scenarios however there was no discussion provided within the documentation on the consequence of these scenarios. In addition, very few of the documents provided a likelihood for the scenarios. In instances where envelop approaches were used, the attention was not on past performance but on covering all aspects of climate sensitivities within the full ensemble. The selections to the specific performances reduced the range of ensembles, thereby suggesting lesser uncertainties and increased confidence. This increased the uncertainty as there is no approach to verify the realism of the smaller ensembles against the originals.

The assessment also identified key recommendations for future downscaling and use of climate scenarios for decision making in Pakistan. The findings from this review are detailed as follows:

- Use artificial intelligence (AI) to identify climate change pathways supported by the majority of projections (for each CMIP ensemble under the emission scenarios for RCP2.6, RCP4.5 and RCP8.5). This approach provides full ensembles, with equal weighting for the different emission scenarios.
- Determine a likelihood pathway using predictable theory. This approach provides information on uncertainty, and assumes that the ensemble includes all possibilities in their correct likelihood.
- Produce of two “extreme” pathways i.e., the most outlying pathways where no likelihood can be attached. This approach does not capture the possible solutions external to the ensembles.
- Use the closest RCM to each pathway from the CORDEX data. Although CORDEX data provides more flexibility and is easier to use, the CORDEX ensembles tend to not consider the full width of CMIP ensembles and limitation in timing, therefore the nearest RCM is required.
- Use the downscaled RCM information to provide detail on each pathway. Using the parameters available allows for the development of climate indicators, for example, heat and drought indices.
- Make use of storylines that consider all the downscaled information and consolidating it into relatively simplified presentations suitable for provision to decision makers.

Assumptions and Limitations

This report is based on accessed projections up to and including those in the Second National Contribution (2NC) to the UNFCCC of 2018, plus some more recent peer-reviewed studies, including some using CMIP6. No studies used directly in preparation for the Third National Communication (3NC), scheduled for 2024, have been accessed, and as far as is known none have been published as such by the GoP. The views expressed in the report are based on the perspective available from all information to hand.

Contents

1 Introduction and structure of the document

This document presents an overview of the current status of climate change projections for Pakistan. The report makes recommendations on strengthening the Climate Change Scenarios for Pakistan (2021) and downscaling methods used and means to address identified gaps. It also provides a high-level description of the methodology for downscaling of climate models at provincial level.

The main report covers the approach used for the assessment, and also the recommendations made based on this approach. Individual documents used to produce the assessment are provided in Annexes 1 to 4 as:

1. Government of Pakistan documents (in **Annex I** numbered N1, N2,…, and including peer-reviewed documents authored in part by GCISC experts)
2. Provincial Government documents (in **Annex 2** numbered P1, P2,…)
3. Documents from international organisations (in **Annex 3** numbered I1, I2,…)
4. Other research, including from universities within Pakistan and elsewhere (in **Annex 4** numbered U1, U2,…)

A critique of approaches taken to reducing ensemble sizes through selection is given in **Annex 5**, with more in Section 3, Part 5.

Following stakeholder engagement, further texts were reviewed and summarised in **Annex 6.**

In addition, topic papers for glaciers on downscaling and projections (**Annex 7**) and an overview of climate change and glaciers in the Karakoram Himalayas (**Annex 8**).

In the following report, a list of issues against which the review has been made is provided, followed by individual sections that cover the justifications for each of these issues together with a draft assessment based on documents reviewed to date.

2 Approach to assessing and critiquing extant climate change projections and downscaling for Pakistan

Climate change projections, some including downscaling, have been prepared both by agencies of Government of Pakistan, as well as by independent institutes within country and elsewhere have been published. These reports were selected based on availability and consultation with MoCC, GCISC and UNEP and include:

- **N1**. The First National Communication to the UNFCCC of 2003, MoE, GoP
- **N2**. The Technical Needs Assessment for Climate Change Adaptation of 2016, MoCC, GoP
- **N3**. The Second National Communication to the UNFCCC of 2018, MoCC, GoP
- **N4**. The updated Nationally Determined Contributions to the UNFCCC of 2021, GoP
- **N5**. The First Biennial Update Report to the UNFCCC of 2022, GoP
- **N6**. The Pakistan Meteorological Department web site, creation date not known, PMD, GoP
- **N7**. GCISC-RR-08 Climate Change Projections over South Asia under SRES A2 Scenario using Regional Climate Model RegCM3 of 2009, GCISC
- **N8.** GCISC-RR-09 Development of Climate Change Scenarios for Specific Sites Corresponding to Selected GCM Outputs, using Statistical Downscaling Techniques of 2009, GCISC
- **N9.** Assessment of climate extremes in future projections downscaled by multiple statistical downscaling methods over Pakistan, 2019, Atmospheric Research, 222, 114-133
- **N10.** Future Extremes and Variability of Rainfall over Monsoon Region of Pakistan, copy not dated but has references to 2019, Pakistan Journal of Meteorology, 14, 61-78
- **N11.** Assessment of Future climatic changes, extreme events, related uncertainties, and policy recommendations in the Hindu Kush sub-regions of Pakistan, 2021, Theoretical and Applied Climatology, 143, 193-209
- **P1**. The Khyber Pakhtunkhwa Climate Change Action Plan of 2022
- **P2**. The Sindh Climate Change Policy of 2017
- **P3**. The Balochistan Climate Risk and Vulnerability Report of 2017
- **I1**. The Climate Change Profile of Pakistan published in 2017 by the ADB
- **U1**. Evaluation and projection of precipitation in Pakistan using the Coupled Model Intercomparison Project Phase 6 model simulations 2022, International Journal of Climatology, 1–20. https://doi.org/10.1002/joc.7602
- **U2**. Projected changes in temperature, precipitation and potential evapotranspiration across Indus River Basin at 1.5–3.0 °C warming levels

using CMIP6-GCMs, 2021, Science of the Total Environment, https://doi.org/10.1016/j.scitotenv.2021.147867

- **U3.** Evaluation of global climate models for precipitation projection in sub-Himalaya region of Pakistan, 2020, Atmospheric Research, 245, 105061
- **U4.** Performance Assessment of General Circulation Model in Simulating Daily Precipitation and Temperature Using Multiple Gridded Datasets, 2018, Water, 10, 1793, doi:10.3390/w10121793

To provide a critique and assess the current extant of climate change projections and downscaling for Pakista, the various documents have been examined in terms of the following structure:

- Projections used at the global scale
    - Source
    - Model(s) used
    - Justification(s) for the selection of model(s) used
    - Parameter(s) considered
    - How was/were the final selection of (a) scenario(s) used made?
    - Have likelihoods of any scenarios been calculated?
    - If so, how?
    - Have and ‘extreme’ scenarios been considered?
    - If so, how were these selected?
    - What ‘extreme’ parameters were included?
    - Have any weather ‘extremes’ been addressed
    - If so, how?
    - What ‘extreme’ weather parameters were included?
    - Has inter-annual variability been addressed?
    - If so, how?
    - What inter-annual variability parameters were included?

- Projections used at the regional scale for and around Pakistan
    - Was any downscaling used?
    - What technical approach was used?
    - How did the approach used relate to scenarios at the global scale?
    - What regions were included?
    - What parameters were included?
    - Were any ‘extremes’ considered?
    - If so, how?
    - What ‘extremes’ were included?
    - Was inter-annual variability considered?
    - If so, how?
    - What inter-annual variability parameters were included?

- Emissions scenarios
    - What emissions scenarios were included?
    - What is/are the justification(s) for the scenario(s) used?

    - Are dependencies of any climate change scenarios on emissions scenarios covered?
- Handling of uncertainties
    - Are uncertainties discussed?
    - How are uncertainties handled?
    - Have uncertainties formed any consideration in the production of the climate change scenario(s) to be used?
    - What interpretation to assist decision makers of the uncertainties has been provided?

The discussion also covers some of the issues regarding the use of the CMIP ensembles[1] including:

- Model independence, **i.e.,** the use of different versions of the same model, plus the sharing of modules between models from different modelling centres
- Model performance in simulating both the regional historical climate and the large-scale atmospheric circulation within which the regional climate resides

[1] As covered in Chapter 1 of the WGI IPCC AR6 report (starting on page 568)

3 Assessment and review of the extant of climate change projections and downscaling for Pakistan

The sequence below follows the approach and the list described in Section 2. In addition, the following has been used in the review:

Projections at the Global Scale

Global Climate Models, GCMs, come in a variety of types that have been developed continuously over recent decades, and which provide the bedrock information on which climate change scenarios can be developed. In the early days of climate research access to information from these models typically required communication with individual modelling houses, but rapid improvements in facilities have made most data readily available from central storage bases organised around the Earth System Grid Federation, ESGF. Through the work of a group under the World Climate Research Programme (WCRP) various generations of GCMs are stored on ESGF, each using standardised running conditions to enable coordination into large data sets of projections, these ensembles being referred to as Climate Model Intercomparison Project, CMIP, sets. The latest, CMIP6, has been used in two of the documents reviewed in this draft, and it *might* be included in the Third National Communication (3NC). The most frequently used CMIPs in this critique are from CMIP3 and CMIP5, completed roughly in 2006 and 2012 respectively ("roughly" as data submissions continued past these dates at lesser rates).

There are solid theoretical and practical reasons for using a large number of projections, such as a CMIP ensemble, most specifically in order to test uncertainties involved (see the section below on uncertainties). Prior to the regular use of downscaling to smaller spatial scales than provided by the GCMs (see the section below on downscaling) either the full CMIP ensemble or a selection of one or more models typically provided the detail for climate change scenarios. The questions posed in this section ask about the selection of the GCM(s) and justifications thereof, the approach to creating any scenario(s), and finally whether or not 'extreme' possibilities in terms of weather and of inter-annual variability have been considered.

Except for two papers [P1 and P2, that used CMIP6], all GCMs used were from the CMIP3 or CMIP5 sets, either the full ensembles or one or more models selected from these sets. No specific justifications for the use of specific models have been offered in several cases. In some earlier cases single GCMs were supplied in collaboration with individual modelling houses, often in support of downscaling using in-house RCMs. In [P1] the full CMIP6 set is reduced to the 13 GCMs that most closely simulate historic annual rainfall averaged over the country. While in [P2] seven GCMs are used with seven of the eight SSPs available in CMIP6 (see the section below on emissions scenarios) as the only GCMs with, at the time of that analysis, projections for all seven SSPs.

Temperature and rainfall were the main parameters studied, typically from the selected models or as averages for the full ensembles. On occasion there are extensions to additional parameters or indices, including:

- Drought and standard precipitation indices [P1]
- Potential evapotranspiration and water surplus [P2]
- Climate 'extremes' indices created by a working group of WCRP, ETCCDI.

Rather than undertaking detailed assessments, some of the publications reviewed revert to generic quotations from the IPCC Assessment Reports [e.g. N3], perhaps the most frequently mentioned being the anticipated increased frequencies of events such as droughts and floods as mentioned in the Third IPCC Assessment of 2007.

Summary of the assessments. Except where individual models were used, no specific scenarios have been created in the assessed documents other than as ensemble means or individual projections. Certain details provided might be viewed as scenarios, but one common aspect is that in no cases is any conditioning commentary provided. For example, there are cases where different data sets produced varying, say, temperature projections (often under alternate emissions scenarios as discussed below), presented in the text and/or as diagrams, but with little accompanying guidance as to how an interpretation for decision making might be made.

Projections at the regional scale

Downscaling of projections to smaller spatial and temporal scales is popular amongst decisions makers who wish to gain more spatial detail in information than supplied by the GCMs (normally about 200km spacing for CMIP3 and CMIP5 and 100km spacing for CMIP6). There are two basic approaches to downscaling – empirical and numerical (although [P2] uses the term in respect to common gridding through interpolation of the projected data to a scale below that of most individual models). Empirical approaches use a variety of statistical techniques, often borrowed from those originally designed to help interpret numerical weather forecasts. Numerical approaches use a variety of models, the most common of which is the Regional Climate Model (RCM); RCMs are effectively mixtures of numerical weather and climate models designed to run over selected domains of the globe. Because RCMs do not cover the full globe they can run with smaller spatial scales and as a result can simulate directly more climate processes than can be achieved within GCMs. Typically, though, because of the increased resolutions, RCMs take about as much computer resource as GCMs.

As occurred with the GCMs, some modelling houses transferred their RCMs to individual countries, including Pakistan, in early capacity building activities. As RCMs only cover a portion of the globe they have to be run using a constant supply of meteorological information at their boundaries, information provided by a GCM, meaning that downscaling by this approach often has been limited in these early studies to the use of a single RCM with just or two host GCMs, again often those of the individual modelling house. One obvious consequence of this technique is that any climate details supplied by the GCM are enhanced, but cannot be corrected, by the RCM.

Happily, as facilities have developed, it is now straightforward to access an ensemble of downscaled projections produced with a range of RCMs using a number of different host GCMs. This data set, CORDEX, is run as a continuous project rather than the stepwise approach used in the CMIP series. All downscaled projections readily available at the time of writing this report use CMIP5 hosts, with those using CMIP6 hosts in preparation. Initial downscaling on CORDEX was nominally at a spacing of about 50km, but more recently this has been brought down to 20km or even 10km (although few such are on ESGF at present).

Both empirical and numerical downscaling has been used for Pakistan, and in this critique a similar set of questions to those for the GCM projections has been assessed. In addition, the PMD [N6] has provided downloadable data sets of downscaled data at 50km and 25km resolution using two RCMs with a single host GCM under a just one emissions scenario (see below).

Summary of the assessments. Otherwise, the assessment for numerical downscaling is similar to that for the global scale work, with limited justifications given in the assessed documents for any model selection, no discussion of differences between any two sets of projections, no specific scenarios produced, and limited detail of parameters other than temperature and rainfall.

Emissions scenarios

The next topic examined is the use of emissions scenarios. Emissions scenarios are required in any climate change projection work to stand in for the unknown future greenhouse gas concentrations in the atmosphere that are the main drivers of these changes. Numerous bodies have approached the task of developing emissions scenarios from a variety of perspectives, but the only ones of issue here are those developed on behalf of the IPCC and used in support of the CMIP projections. These emissions scenarios have become increasingly sophisticated in time, from the very earliest SA90, SB90, SC90 and SD90 (SA90 – Scenario A of 1990 – which was effectively business-as-usual) and then IS92a,…IS92f (IPCC Scenarios 1992a, etc., in which IS92a was the business-as-usual scenario), to the most recent SSPs (see below).

A major breakthrough came with the IPCC Special Report on Emissions Scenarios (SRES) of 2000, which built scenarios out of socio-economic storylines quantified through a number of integrated assessment models. At the higher end of emissions, closer to business-as-usual, were the SRES scenarios A1B, A2 and A1F1, while lower emissions were covered by B1 and B2. The SRES scenarios were used for CMIP3.

A new, interim, direction was taken in the development of CMIP5 with the introduction of Relative Concentration Pathways, RCPs, which do not consider any socio-economic issues but simply reflect the degree of forcing of climate change by greenhouses gases at around the year 2100; the higher the number the higher the forcing (and thus the higher the global temperature increase), with the highest, RCP8.5, again representing business-as-usual and roughly equivalent to SRES A1F1. Others used in CMIP5 were a middle-of-the road RCP6.0, a lower-end RCP4.5 (roughly equivalent to SRES B1) and a somewhat lower emissions scenario than used previously, RCP2.6. It is worth noting that IPCC calculations suggest that the pathway indicated by RCP2.6 is the only one of this set that offers a realistic prospect of meeting the Paris Agreement.

The full circle has now been completed with the re-introduction of socio-economic considerations in the Shared Socioeconomic Pathways, the SSPs. There are no greenhouse-gas emissions as such in the SSPs, but, in principle, any SSP can be attached to any RCP to provide a full socio-economic-emissions scenario. However some such combinations are pragmatically meaningless, so a number of reasonable combinations have been identified as top (Tier 1) or secondary (Tier 2) priority for creating projections for CMIP6, as indicated in the following table:

SSP Scenario	Basis of storyline	Tier 1	Tier 2
SSP 1	Sustainability (Taking the Green Road): Low challenges for mitigation (resource efficiency) and for adaptation (rapid development)	SSP1-2.6	SSP1-1.9
SSP 2	Middle of the Road: with intermediate changes for both mitigation and adaptation	SSP2-4.5	-
SSP 3	Regional Rivalry (A Rocky Road): High challenges for mitigation (regionalised energy/land policies) and for adaptation (slow development)	SSP3-7.0	-
SSP 4	Inequality (A Road Divided): Low challenges for mitigation (global high tech economy) but high challenges for adaptation (regional low tech economies)	-	SSP4-3.4; SSP4-6.0
SSP 5	Fossil-Fuelled Development (Taking the Highway): High challenges for mitigation (resource/fossil fuel intensive) but low challenges for adaptation (rapid development)	SSP5-8.5	SSP5-3.4

Most, other than from two papers, of the work examined in this critique is too early to use the SSPs and CMIP6, but projections have been developed that use both SRES and the RCPs. As with the discussions above, results are presented typically for the various emissions scenarios without comment. It is noticeable that most of the earlier work has covered only the relatively high emissions scenarios such as A2 and

A1B or RCP8.5 [e.g. N3]; there are fewer examinations of lower emissions such as RCP4.5 [N3] and only a few use RCP2.6. The PMD web site [N6] uses the high-emissions SRES A1B only.

Summary of the assessments. No justifications for the used scenarios have been provided in most of the documents, while, as for the choices of GCMs and RCMs, all results from different scenarios are presented without or with limited interpretation or guidance to decision making.

Handling of uncertainties

Uncertainties arise from two main sources: a) various limitations in the abilities of the various models to simulate the climate system in all its forms, including feedbacks; b) unknown details of anthropogenic impacts on the atmosphere, most significantly through emissions of greenhouse gases.

The latter uncertainties are handle to a large degree by the use of emissions scenarios, but in addition there are political/commercial decisions to consider, such as the extent of removal of tropical forests. Models can be used to simulate the impacts of, say, varying degrees of forest removal, but none of the SRES or SSP storylines incorporates such human-determined removals directly. The SRES, RCP and SSP scenarios have been designed to provide a reasonable range of possible future missions in combination with the ability to permit scientific exploration of options. It is not possible to select a "best" or a "more likely" emissions scenario, just as it is not possible to select a "best" or a "more likely" projection, although current thinking is that the top end, business-as-usual, scenarios, such as represented by RCP8.5, might in reality be too high. At the other end of the spectrum the addition of RCP2.6 below the lowest SRES scenarios has proved insightful given that it offers a guide to achievement of the Paris Agreement. With the SSPs an even lower emissions scenario of RCP1.9 has been added.

A full discourse on the uncertainties associated with modelling is beyond this discussion; the IPCC AR6 WGI Chapter 6 outlines four main areas of uncertainties:

- Radiative forcing uncertainty – an alternate way of expressing uncertainties handled through emissions scenarios as discussed above
- Climate response uncertainty – the actual response of the atmosphere to various, including anthropogenic, forcings, and the ability of the models to simulate these
- Natural and internal climate variations – including external factors such as volcanic eruptions and long-term (including multi-decadal) internal variability of the atmosphere
- Interactions between variability and radiative forcings – including complex feedback mechanisms.

CMIP6 consists of 23 individual MIPs (Model Intercomparison Projects), many of which are designed to gain insight into the uncertainties listed above. For climate change projections through this century the critical MIP is the ScenarioMIP, an intercomparison between voluntarily submitted models run under common conditions, including using the SSPs. The design of earlier CMIPs was less complex but each included an equivalent to ScenarioMIP run under common conditions.

No two models, or even different versions of the same model, produce the same projections, but each is fully scientifically valid such that it is not possible to define a "best" model or projection. All projections within the ensemble created under ScenarioMIP (or the earlier versions in CMIP3 and CMIP5) should be considered realistic possibilities, and thus it is not appropriate to debate the future in deterministic terms, but only in probabilistic terms.

Summary of the assessmernts. Few of the papers discussed here formulate their outputs in probabilistic terms, mainly limited to a few pdfs, but all use deterministic terms. In deterministic terms the ensemble mean, used in most often in the papers, is the best option, but strictly only if certain conditions are met. One condition is that the distribution of values is Gaussian, often the case for temperature but not always for rainfall or for distributions of other spatially and/or temporally heterogeneous parameters. A second important condition is whether an ensemble is 'proper', meaning that it covers all of the range of possibilities with each in its correct likelihood. This cannot be examined for the CMIP ensembles, but experience with predictions for shorter time periods, where properness can be verified, suggests that the CMIP ensembles are likely to fail the test. The observed speed of Arctic sea ice melt compared to all model projections is one example of the CMIP ensembles perhaps not covering all possibilities.

None of the papers studied touches on any of these issues. Even where ensemble mean projections for different emissions scenarios are presented there is no discussion of the consequences.

The IPCC issues of independence and model performance

Beginning on p586 of the WGI Report to the IPCC AR6, the authors consider the thorny issue of selecting those models likely to provide the more 'reliable' projections. The list of considerations is lengthy and only two are considered here, independence and past performance.

Independence. An ensemble can explore the future uncertainty space correctly in correct proportions only if the individual projections are independent. Independence comes in a variety of forms but in this case it means calculation independencies, i.e. not using different versions of the same model, with substantial common code, or using sharing code between different models. All CMIP sets include dependencies of both types, while CORDEX is built from reduced sets of both GCMs and RCMs, and is perhaps on the whole less independent than CMIP. There is thus no full independence in any of the ESGF data sets, nor is there any straightforward solution to this issue. None of the papers reviewed mention independence and there are examples of use of different versions of selected models.

Past performance. Past performance is an obvious way forward in selection, although, as has been noted by the IPCC, there is no current way to assess the required closeness of model simulations to historical observations that provides confidence, or in this case reliability, in the projections. Two areas of past performance need to be assessed according to the IPCC: past performance in simulating local climates, and past performance in simulating the global scale circulations responsible for local climate climates. None of the papers seen consider the large-scale circulation but several use closeness to simulating past local climates in selecting GCMs.

Currently there is no agreed approach to the methodology of selection via past performance in terms of either parameters or metrics. Work for Pakistan in all cases uses one or both of temperature and rainfall, but the metrics adopted differ somewhat between individual papers, although there is commonality in some cases. The following table, drawn from Annex 5, provides a list of GCMs selected in various papers based on past performance:

Paper	Area	Target parameter(s)	Original set	Models selected
Ahmed et al 2019a, Journal of Hydrology, 573, 281-298	Pakistan	Temperature and precipitation	20 CMIP5	3 different groups according to metric: Group 1 - *CESM1-CAM5, HadGEM2-AO, NorESM1-M* and HadGEM2-ES; Group 2 - *CESM1-CAM5, HadGEM2-AO, NorESM1-M* and GFDL-CM3; Group 3 - *CESM1-CAM5, HadGEM2-AO, NorESM1-M* and GFDL-CM3
[U4]	Pakistan	Temperature and precipitation	31 CMIP5	ACCESS1-3, CESM1-BGC, CMCC-CM, HadGEM2-CC, HadGEM2-ES and MIROC5
Ahmed et al 2019b, Hydrology and Earth System Sciences, 23, 4803-4824	Pakistan	Temperature and precipitation	36 CMIP5	NorESM1-M, MIROC5, BCC-CSM1-1, and ACCESS1-3
[U3]	Upper Indus Basin	Precipitation	22 CMIP5	MIROC5, EC-EARTH, CNRM-CM5, BCC-CSM1.1(m) and BCC-CSM1.1
Lutz et al 2016, International Journal of Climatology, DOI: 10.1002/joc.4608	Indus, Ganges and Brahmaputra basins	Temperature and Precipitation	94 for RCP4.5 and 69 for RCP8.5	BNU-ESM, CSIRO-Mk3-6-0, inmcm4, **CMCC-CMS**, **BCC-CSM-1**, CanESM2
[N11]	Hindu Kush sub-regions	Temperature, rainfall, ETCCDI indices	14 for RCP4.5 and RCP8.5	**EC-EARTH**, FGOALS-s2, GFDL-ESM2G, GFDL-ESM2M, inmcm4

The first four works are all common to a specific series of research; in the top paper three approaches to selection were used, and common GCMs are italicised. Otherwise GCMs common to all 4 papers are in red (there are none), to three papers in orange, and to two papers in blue. Two additional papers not part of the series are listed at the bottom of the table, with GCMs in bold if they are repeated in any of the top four papers (one model is common just to these two papers).

As can be seen, there are common GCMs selected between papers, but not throughout, and a number of models only occur in a single paper. On occasion non-independent models have been selected. Some of the selection variability might be explained by the different regions, metrics or methodologies used, but it is evident that selection itself using current approaches can lead to additional uncertainties.

There is a further issue regarding selection. Most of the papers above use past performance as their guide, but that by Lutz et al 2016 (see the table above for details) uses the alternate 'envelope' approach. In this case the attention is not on past performance but on covering all aspects of climate sensitivities within the full ensemble. It is achieved in this paper by selecting four GCMs, one representative of each of cold/wet, cold/dry, warm/wet and warm/dry projections.

None of the works mentioned in the above table provide likelihoods of scenarios.

In general the performance selections result in reduced ensemble ranges, in effect suggesting lesser uncertainties and increased confidence. The problem is that there is no way in which the realism of the smaller ensembles, against the originals, can be verified. The single envelope method produces scenarios covering extrema that might be useful in planning, but as used above gives no view on possibilities elsewhere in the ensemble, including towards the mean.

4 Summary and Recommendations, including an approach to downscaling of climate models at provincial level

The requirement in this project is: a) to make recommendations on strengthening the Climate Change Scenarios for Pakistan and in particular downscaling methods used and means to address gaps that are identified; b) to provide a methodology paper describing downscaling of climate models at provincial level. Both requirements are approached jointly in this Section, noting that statements of intent to develop new and more detailed climate change projections, including downscaling, have been made at least by some Provincial Governments [P1, P2, P3] and presumably, if created, will be used additionally in preparation of the 3NC.

Basic recommendations that might be made to help create improved climate change projections for Pakistan:

i. There is limited benefit in running GCMs and/or RCMs in-country unless there is a specific reason for doing so given ready access to data on ESGF; in CMIP6 data for all MIPs are available should they be of interest
ii. CMIP6 includes the most sophisticated models available at present, but in the IPCC AR6 it is noted that advances from CMIP5 are limited and thus there is no clear specific reason to choose one over the other:
    a. One advantage of CMIP6 is the larger range of emissions scenarios (SSPs) used, and the increased populations of projections for each SSP as compared to those for some RCPs in CMIP5
    b. A current disadvantage of CMIP6 is that there are no associated CORDEX data readily available, although this will change in due course
    c. It is also known that the ranges covered by the CMIP6 projections are somewhat wider than those of CMIP5, with at least some of the later

models showing relatively increased sensitivity to emissions; thus results might differ somewhat between CMIP5 and CMIP6[2]

iii. A full range of emissions scenarios might be considered, unless cogent reasons for excluding any can be seen (none are omitted by the IPCC)

iv. Plan any work not in terms of what projections/downscaling might be produced but in terms of the ultimate information requirements of decision makers

v. While decision makers prefer straightforward solutions the full scientific background should be considered when developing such advice; recommendations for doing so include:
   a. Full examination of the entire ensembles under all emissions scenarios
   b. Consideration of all options within a probabilistic framework, including advising on likelihoods
   c. Production of alternate pathways together with concrete advice on their interpretation.

Methodological options

To follow the advice above in full is complex, and requires the adoption of new approaches. The Consortium has been engaged to critique and advise, but not to develop climate change scenarios or to produce onward interpretation for decision makers. Nevertheless it might be help to summarise the approach taken by the Consortium to this problem; here this summary is limited to the creation of climate change scenarios.

To be clear, the approach currently taken by the Consortium does not consider either model independence or testing of closeness of local- and/or large-scale simulations to observations, although in principle the approach might be modified readily given suitable solutions to these issues. In its present form the Consortium's approach uses all ensemble members from CMIP5 under RCP2.6, RCP4.5 and RCP8.5; RCP6.0 is not considered as there are few, in general no, associated downscaled projections in CORDEX, while CMIP6 is not used in general for the same reason (although the technique could be applied immediately to the CMIP6 GCM ensembles).

The approach as used by the Consortium is formulated as follows:

- For each CMIP ensemble under each emissions scenario use a technique from AI (artificial Intelligence) to identify those climate change pathways

[2] Members of the consortium have examined consistency between CMIP5 and CMIP6 in a separate project for a different country. The results indicated disparities in CMIP6 projections, particularly in rainfall, as compared to CMIP5, to the extent that it is not viable to use current CORDEX downscaling with CMIP6

supported by the majority of projections; this tends to identify between 2 and 4 pathways per emissions scenario

  - This approach is consistent with predictability theory, and while it does not consider part performance it does cover the full ensembles unlike envelope approaches
  - We know of no approach to weighting results for the different emissions scenarios, so treat all equally

- Attach likelihoods to each pathway determined from predictability theory
  - By doing this information on uncertainties is covered; nevertheless this assumes that the ensemble includes all possibilities in their correct likelihoods, i.e. it is proper, something as pointed out earlier is unlikely to be the case, but the issue cannot be managed
- Identify additionally the most outlying pathways in terms of the entire ensemble to produce two “extreme” pathways but to which no likelihoods can be attached
  - This attaches limits to all possibilities as indicated by the ensembles, but it does not address the possibility of solutions outlying the ensembles; it is normally achieved giving attention to rainfall but could equally be done with attention to temperature
- From CORDEX find the closest RCM to each pathway, including the “extremes”, to provide representative downscaling
  - We do not use empirical downscaling because of the substantially increased flexibility available in dynamical downscaling and the ease with which CORDEX data are available
  - Various analyses have indicated, because of the limited number of GCM/RCM pairings within CORDEX plus non-independence, that CORDEX ensembles tend not to cover the full widths of CMIP ensembles and therefore ‘close’ pathways may not exist each time, in which case we are forced to accept the nearest RCM
- Use the downscaled RCM information to provide detailed information for each pathway, with the parameters selected from those available designed to facilitate interpretation of the objectives of the analysis
  - The list of standard CORDEX variables extends to perhaps 40 or more that might inform different aspects of a NAP, such that restriction to temperature and rainfall is unnecessary, and perhaps unreasonably uninformative
  - Similar parameters are available in CMIP, and in fact there is a more extensive set of parameters that might be used to inform a NAP in CMIP than there is in CORDEX
  - Further, using the parameters available, numerous pertinent climate indices, such as heat and drought indices, can be calculated including, but extending well beyond, those in the ETCCDI list
- The outputs are a series of detailed downscaled projections that can be used for interpretation towards the requirements of decision makers in the later stages of the process employed by the Consortium; typically this is done using storylines that consider all of the downscaled information but

consolidate it into a relatively simplified presentation suitable for provision to decision makers

  - As noted earlier, it is important to determine ahead of time that all expected results will satisfy the needs of decision makers as far as the science permits.

Recommendations for a methodology for Pakistan.

There is no ready translation of the above into a final methodology for downscaling for Pakistan and/or the Provinces. The following covers options in a list of recommendations:

1. The first is to undertake all projection work at national level rather than risk disparate results existing across boundaries if undertaken at individual Provincial level; subsequent interpretation might involve individual Provinces.
2. Plan and agree with national and provincial decision makers the downscaling output requirements considering all possible parameters and indices ahead of beginning the downscaling.
3. Accept uncertainties, with the aim to produce expertly-interpreted future scenarios with attached estimated likelihoods
4. Unless there are strong scientific arguments otherwise, use the full CMIP and CORDEX ensembles (there are 3 CORDEX domains that entirely cover Pakistan), as well as all available emissions scenarios.
5. Base all initial work on the CMIP ensembles, rather than using only the CORDEX ensembles with their relatively limited ranges
6. Use selection to reduce the complexity of the outputs, but use an approach that retains the full uncertainty information within the original CMIP ensembles [we recognise the difficulty of doing this using published approaches for the region – we can advise in a separate project if required; however, a relatively straightforward approach that uses the envelope principle but explores the full ensemble spaces is to identify regions more highly populated in the joint temperature/rainfall distributions – note, we have not trialled this approach]
7. When defining locations to be used in selection restrict the areas considered to single climatological rainfall regimes in order to reduce risks of identifying models with relatively limited dynamical simulation capabilities across all. Pakistan has at least two such regimes, that associated with the zonal westerlies and that associated with the monsoon, with more capable model simulations in general of the former compared to the latter. The large-scale atmospheric processes and linkages differ between the two. Thus the

recommendation is to use at least two parallel sets of projections, perhaps more.

8. Do not use empirical downscaling because of the restricted flexibility, but ensure that all numerical downscaling retains the uncertainty information provided by the full CMIP ensembles to the maximum extent possible
9. Following 2 above, use a wide range of parameters and indices calculated from the downscaling designed to inform all later aspects of the work as required by decision makers
10. The objective to provide guidelines to the future, and not high-precision information
11. The next stage might be to use the projection results in process models, such as for water or crops; if done then it is important to recognise that individual process models tend to offer markedly different outputs and therefore using several of each might be considered, with all contrasted with historical data to provide basic validation
12. Present all results in a transparent manner and provide a full interpretation in terms of uncertainties and possible impacts
13. Improve in-situ observation and data collection infrastructure
14. Mainstreaming and centralise downscaling efforts currently being carried out.
15. Encourage communication across national and provincial levels on climate data needs and projection research.

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Abbreviations

CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
ENSO	El Niño-Southern Oscillation
ESGF	Earth System Grid Federation
EWS	Early Warning System
GCF	Green Climate Fund
GCISC	Global Climate Change Impact Studies Centre
GCM	Global Climate Model
GLOF	Glacial Lake Outburst Flood
GoP	Government of Pakistan
IPCC	Intergovernmental Panel on Climate Change
MOCC	Ministry of Climate Change
NAP	National Adaptation Policy
NC	National Communication
NCCPIC	National Climate Change Policy Implementation Committee
NDMA	National Disaster Management Authority
NGO	Non-Governmental Organization
PMD	Pakistan Meteorological Department
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SSP	Shared Socio-Economic Pathway
SUPARCO	Space and Upper Atmosphere Research Commission
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WB	World Bank
WEF	World Economic Forum
WFP	World Food Programme
WMO	World Meteorological Organzation
WWA	World Weather Attribution

Annex 1. The National Government of Pakistan and Related Agencies Documents (including peer-reviewed documents with GCISC authorship)

Contents:

- **N1**. The First National Communication to the UNFCCC of 2003, MoE, GoP
- **N2**. The Technical Needs Assessment for Climate Change Adaptation of 2016, MoCC, GoP
- **N3**. The Second National Communication to the UNFCCC of 2018, MoCC, GoP
- **N4**. The updated Nationally Determined Contributions to the UNFCCC of 2021, GoP
- **N5**. The First Biennial Update Report to the UNFCCC of 2022, GoP
- **N6**. The Pakistan Meteorological Department web site, creation date not known, PMD, GoP
- **N7**. GCISC-RR-08 Climate Change Projections over South Asia under SRES A2 Scenario using Regional Climate Model RegCM3 of 2009, GCISC
- **N8.** GCISC-RR-09 Development of Climate Change Scenarios for Specific Sites Corresponding to Selected GCM Outputs, using Statistical Downscaling Techniques of 2009, GCISC
- **N9.** Assessment of climate extremes in future projections downscaled by multiple statistical downscaling methods over Pakistan, 2019, Atmospheric Research, 222, 114-133
- **N10.** Future Extremes and Variability of Rainfall over Monsoon Region of Pakistan, copy not dated but has references to 2019, Pakistan Journal of Meteorology, 14, 61-78
- **N11.** Assessment of Future climatic changes, extreme events, related uncertainties, and policy recommendations in the Hindu Kush sub-regions of Pakistan, 2021, Theoretical and Applied Climatology, 143, 193-209

The earliest GOP document reviewed is the **1st National Communication to the UNFCCC [N1]** of 2003. Access to global projections was difficult at that time, in general requiring individual requests to modelling houses. Downscaling through RCMs was beginning, often using models with embedding techniques developed from weather forecasting systems, with the Third Assessment Report of the IPCC illustrating some encouraging downscaled results for South Asia. Nevertheless empirical downscaling, again borrowing techniques from weather forecasting in many cases, tended to be the more common approach. Emissions scenarios had taken a major step forward with the publication in 2000 of the IPCC Special Report on Emissions Scenarios (SRES), but in the Third Assessment Report the majority of projections discussed were based "on the IS92a[3] and draft SRES A2 and B2 scenarios".

Against that background the GoP 1st NC used a synthetic approach to producing scenarios based on assumed temperature increases across the entire country of 0.1ºC per decade together with ±1% per decade change in rainfall to produce specific scenarios for the 2020s and 2050s of, respectively, +3ºC and +6ºC, with ±3% and ±6% change together with a further assumption of zero change. These scenarios were then passed through the MAGICC integrated assessment model, used widely at the time, to assess possible impacts.

Assessment of the 1st National Communication.
Not assessed in detail given its early provenance, but a document that compares favourably with similar around that time.

In the **Technical Needs Assessment for Climate Change Adaptation [N2]**, of 2016, projections from the Fifth IPCC Assessment Report, focussing on RCP4.5 and RCP8.5, are presented. Differences between these two emissions scenarios are illustrated, but without any further discussion of uncertainties.

By the time of presentation of the **2nd National Communication to the UNFCCC [N3]** in 2018 the Ministry of Environment had handed over the reins to the Ministry of Climate Change, awareness of extant impacts had increased, and the science had progressed substantially, as reviewed in the Fourth (2007) and Fifth (2013-14) IPCC Assessment Reports. Many of the basic positions in the 2nd NC were taken from unpublished references in addition to reliance on generic conclusions of the 5th Assessment Report. At the global scale GCMs from CMIP3 and CMIP5 projections were used. Both empirical and dynamical downscaling was employed, the latter with RCMs supplied and supported by UK and US centres. A variety of emissions scenarios were examined, including A2 and A1B (for CMIP3) and RCP4.5 and RCP8.5 (for CMIP5); in addition, for crop modelling A2 and B2 were used.

Assessment of the 2nd National Communication.

- Projections used at the global scale
    - A number of individual studies were summarised in the Communication; while this did cover many of the studies available there was limited endeavour to build these works into a comprehensive whole with model selection left to individual authors
    - The focus was on bulk temperature and rainfall changes with little consideration of other parameters
    - No specific climate change scenarios were produced
    - No analysis of any 'extreme' changes or of inter-annual variability was undertaken, but frequent recourse to generic statements from the

[3] IS92a was a business-as-usual scenario prepared for use in the IPCC Second Assessment Report. There is always a delay between new models or scenarios being developed and results from them being available for assessment by the IPCC.

IPCC of increasingly severe weather and climate impacts were forwarded as a planning basis

- Projections used at the regional scale
  - Two RCMs with three host GCMs (one RCM used one GCM, the other two different GCMs), selected because of ready support from the modelling centres, were used to downscale to 50km for temperature and rainfall
  - No specific climate change scenarios were produced
  - No 'extreme' parameters or inter-annual variability were considered
  - A separate downscaling exercise for crop yields in the high mountainous regions was run using A2 and B2 but the document does not make it clear whether the results were based on GCM or RCM projections
- Emissions scenarios
  - As noted above a range of emissions scenarios were used dependent on choices by individual authors
  - With the exception of RCP4.5 (and of B2 for the crop production analysis) all of the emissions scenarios used were towards the higher end of those available, close to business-as-usual approaches
- Handling of uncertainties
  - In several places results are presented of the differences in projections from various inputs, in particular using alternate emissions scenarios, but in no case does the presentation extend beyond straightforward statements of results, with no discussions offered of uncertainties or proposed interpretation

Two additional relevant government documents are the updated **Nationally Determined Contributions [N4]** of 2021 and the first **Biennial Update Report [N5]** of 2022. Neither incorporate climate change scenarios as such but appear to have taken lead from the 2NC in using generic IPCC positions regarding increased temperatures and glacier melt, as well as amplified climate variability and severity of systems.

The PMD web site [N6] - https://www.pmd.gov.pk/rnd/rndweb/rnd_new/climchange.php - is an open access site offering downscaled temperature and rainfall projections at both 25km and 50km resolution. Users are offered links to data sets to download, but otherwise there is limited guidance on the site. Only emissions scenario A1B is used. At 25km data are provided annually from 2010-2100 using the ECHAM5 GCM with two RCMs, PRECIS and RegCM4, this latter also giving decadal and monthly data. At the 50km resolution ECHAM5 is used again, with PRECIS to give 2010-2100 decadal and monthly mean values and also for 2071-2100 monthly mean values (the differences between these two sets is not clear), whereas only the latter 2071-2100 data are supplied using RegCM4.

Assessment of the PMD Web Site

- Projections used at the global scale
    - Just a single GCM used, ECHAM4, it appears in coordination to a certain extent with the work on the 2nd National Communication [N3]
    - No further details provided and all interpretation is left to the user (it is not clear whether additional advice is available on request)
- Projections used at the regional scale
    - Two RCMs, again with links to the 2nd National Communication background work
    - No further details as noted above
- Emissions scenarios
    - Only the single, effectively business-as-usual, scenario A1B was used
- Handling of uncertainties
    - No guidance given on the web site

In the first of two relatively early of studies from the GCISC, **Climate Change Projections over South Asia under SRES A2 Scenario using Regional Climate Model RegCM3 [N7]**, 2009, by Shahbaz Mehmood, M. Adnan Abid, Faisal S. Syed, M. Mubashar Ahmad, M. Munir Sheikh, Arshad M. Khan, downscaling was achieved using the RegCM3 RCM with two host GCMs, ECHAM5 and FVGCM, subsequent to straightforward statistical examination of performance of the RegCM3 over South Asia and over Pakistan against observation data. Annual and seasonal temperature and rainfall projections for 2040 to 2069 and 2071-2100 are provided for both South Asia and Pakistan, with the national projections further detailed for 8 climate zones and for 4 agro-climatic zones. Tabulated projections are presented to 2 decimal places for both temperature and proportional rainfall changes.

Assessment of Climate Change Projections over South Asia under SRES A2 Scenario using Regional Climate Model RegCM3

- Projections used at the global scale
    - Two models, both readily accessible at the time of writing, were used as hosts
    - No further details, such as projections from either GCM, are provided
- Projections used at the regional scale
    - The single RCM used is one frequently employed at the time in several regions of the globe
    - No further details as noted above
- Emissions scenarios
    - Only the single, high emissions, scenario A2 was used
- Handling of uncertainties
    - Other than straightforward presentation of differences between the results using the two host GCMs there is no interpretation in terms of uncertainties

The second early GCISC study, **Development of Climate Change Scenarios for Specific Sites Corresponding to Selected GCM Outputs, using Statistical Downscaling Techniques [N8]**, 2009, by Fahad Saeed, Muhammad Rehan Anis, Rizwan Aslam, Arshad M. Khan, uses statistical downscaling individually for temperature and rainfall at 50 stations across Pakistan: "Not unlike other regression approaches, the results indicate the strength of statistical downscaling for modeling temperature and less success for precipitation". For projections the HadCM3 model was used under scenario A2; multiple details of results are graphed and tabulated, to 2 decimal places in the latter.

Assessment of Development of Climate Change Scenarios for Specific Sites Corresponding to Selected GCM Outputs, using Statistical Downscaling Techniques

- Projections used at the global scale
    - A single model was used as a host but no further details, such as reasons for this selection or of any projections from the GCM, are provided
- Projections used at the regional scale
    - A straightforward regression approach is used for downscaling after calibration individually against 50 stations
- Emissions scenarios
    - Only the single, high emissions, scenario A2
- Handling of uncertainties
    - Other than straightforward presentation of the results there is no interpretation in terms of uncertainties

Assessment of climate extremes in future projections downscaled by multiple statistical downscaling methods over Pakistan [N9], 2019, by Shaukat Ali, Hyung-Il Eum, Jaepil Cho, Li Dan, Firdos Khan, K. Dairaku, Madan Lall Shrestha, Syewoon Hwang, Wajid Nasim, Imtiaz Ali Khan, Shah Fahad, [included in this section as two of the authors are affiliated to the GCISC] uses 14 CMIP5 GCMs selected in an earlier study, but unfortunately the link to this un-referenced study provided in the paper did not work and thus the study could not be reviewed. Six sub-regions of Pakistan are considered over which climate extremes as defined by the ETCCDI were assessed under RCP4.5 and RCP8.5. Three statistical approaches to downscaling for 34 stations were assessed, of which one was deemed superior. Box-and-whisker plots illustrate projections for both temperature and rainfall extremes over Pakistan and over six sub-regions. Other approaches to examining uncertainty are used, but no specific conclusions are drawn to assist decision making. The authors identify areas for further research.

Assessment of Assessment of climate extremes in future projections downscaled by multiple statistical downscaling methods over Pakistan

- Projections used at the global scale
  - Uses 14 CMIP5 GCMs but unfortunately the link that provides information as to the selection of these did not work
  - Does not assess the performance of the GCMs in this paper but uses all in the later downscaling work
  - No information on extremes supplied
- Projections used at the regional scale
  - Statistical downscaling used to produce projections for a variety of temperature and rainfall extremes as opposed to the usual basic changes in mean temperature and rainfall
  - Any downscaling, not least statistical, faces issues of calibration for the relatively rare events studied here, but the authors conclude "it is evident that statistical downscaling methods have significantly improved the performance for majority of indices over Pakistan, especially for high resolution models "
- Emissions scenarios
  - Uses, as is the case of many of the papers reviewed here, RCP4.5 and RCP8.5
- Handling of uncertainties
  - The use of box-and-whisker plots, in addition to further statistical assessment, is used to illustrate the uncertainties, discussed briefly towards the end of the paper
  - However there is no assistance to decision making provided

In **Future Extremes and Variability of Rainfall over Monsoon Region of Pakistan [N10]**, [copy received not dated but latest reference is from 2019] by Rehman, N., M. Adnan, S. Ali [all authors are affiliated to the GCSIC], only a small, sub-montane, part of the monsoon area of Pakistan on the eastern side of the country south of the Himalayas is considered using a single CMIP5 GCM, CMCC-CM, selected on the basis of having relatively high spatial resolution compared to other available models. Calculations are provided for a number of the ETCCDI rainfall extremes under RCP4.5 and RCP8.5. Results are presented in multiple graphs plus a table that includes some values to 2 decimal places.

Assessment of Future Extremes and Variability of Rainfall over Monsoon Region of Pakistan

- Projections used at the global scale
  - Uses just a single CMIP5 GCM selected because of its relatively high spatial resolution compared to others
  - Some of the ETCCDI extreme statistics used
- Projections used at the regional scale
  - No downscaling used
- Emissions scenarios
  - Uses, as is the case of many of the papers reviewed here, RCP4.5 and RCP8.5
- Handling of uncertainties
  - No mention of uncertainties is given, with the authors suggesting the work should be extended to the entire country and intimating clearly that the information is sufficiently reliable to be used as a basis for forwarding to decision makers for planning purposes

Future climatic changes, extreme events, related uncertainties, and policy recommendations in the Hindu Kush sub-regions of Pakistan [N11], 2021, by Shaukat Ali & Alia Saeed & Rida Sehar Kiani & Sher Muhammad & Firdos Khan & Romaisa Babar & Asif Khan & Muhammad Shahid Iqbal & Muhammad Arif Goheer & Wajid Naseem & Shah Fahad, includes GCISC and other Pakistan authors. The selection approach used first to identify 14 original CMIP5 GCMs and then to reduce them to 5 subsequently employed for empirical downscaling was based on "availability of data and previous literature", with no further details in this paper. A second set of 3 of the GCMs (no common GCMs with the 5) were employed with 3 RCMs for empirical downscaling. A number of the ETCCDI extremes indices are used. Projections for both temperature and rainfall changes are tabulated to 2 decimal places, while the ETCCDI indices are presented in time series by what appears to be an average across both sets of GCMs.

Assessment of Future climatic changes, extreme events, related uncertainties, and policy recommendations in the Hindu Kush sub-regions of Pakistan

- Projections used at the global scale
  - 14 original GCMs are reduced to a set of 5 and a separate set of 3 by unclear approaches based on earlier analyses
  - No extremes calculated for then GCMs themselves
- Projections used at the regional scale
  - Both empirical (the 5 GCMs) and dynamical downscaling (the 3 GCMs) is used with outcomes then mixed to produce the final results
  - Extremes assessed using some of the ETCCDI indices
- Emissions scenarios
  - Uses, as is the case of many of the papers reviewed here, RCP4.5 and RCP8.5
- Handling of uncertainties
  - Uncertainties are treated through presentation of box-and-whisker plots and of some temperature pdfs, but with minimal interpretation

Annex 2. The Provincial Government of Pakistan Documents

Contents:

- **P1**. The Khyber Pakhtunkhwa Climate Change Action Plan of 2022
- **P2**. The Sindh Climate Change Policy of 2017
- **P3**. The Balochistan Climate Risk and Vulnerability Report of 2017

In August 2022 the Provincial Government published the **Khyber Pakhtunkhwa Climate Change Action Plan [P1]** in which there are no new projections but a discussion based on prior publications, most specifically the IPCC AR5. The main body of the document provides an extensive list of strategies under a number of headings but omitting details of the approaches to achieving each strategy. Relevant quotations within the context of climate change projections include:

- Develop a climate model to predict the impact of climate change on agricultural activities at the local level
- Strengthen institutional capacity of relevant organizations to develop climate models in order to generate future climate projections
- Downscale the output of regional climate models to a scale appropriate for farmers and local planners
- Use these Climate Change scenarios for informed agricultural decision-making.

In addition there are a number of strategies related to atmospheric modelling at shorter time scales.

The **Sindh Climate Change Policy [P2]** is not dated but includes references, including national, up to 2017. There are no specific scenarios identified, with much of the discussion based around the economic impacts thesis of Rafiq, 2014, which in turn is based on earlier economic studies and on the IPCC Third (2001) and Fourth (2007) Assessment reports, as well as on the World Bank Report of Chaudhry (2017) [I1] that forms much of the basis for the Pakistan 2NC (see the appropriate section below). The following policy proposals relate to climate and/or meteorology:

- Establish climate change units or centers at agriculture research organizations in the province to; categorize areas according to their vulnerability to extreme climate change events, climate resilient crop varieties, modern farming techniques
- Develop climate models to allow for better analysis and understanding of the climatic processes in Sindh, particularly for major sectors of agriculture, water resources, energy and land-use planning (urban areas)
- Develop expertise of young professionals on climate services to provide research, technical assistance, policy and planning, and knowledge management related support to Government of Sindh

The Government of Balochistan published a **Climate Risk and Vulnerability Analysis Report [P3]** in 2017 with a focus on water resources (it is stated to be a "*Supplementary Linked Document 25*", but the context is not outlined). Following a review of recent downscaled projections for Pakistan, none immediately relevant to Balochistan, results are presented for a GCM projection. This used RCP6.0 because "it resembles to the condition of Pakistan the most", which appears to be a reference to the closest SRES storyline to RCP6.0, that of B2, that includes "heavy reliance on fossil fuels, intermediate energy intensity, increasing use of croplands and declining grasslands, and stable methane emissions". The model used is not identified, nor reasons for its selection given, nor are details of any downscaling used to produce separate results from the Mula and Zhob watersheds. Temperature and rainfall changes are estimated by decade to 2099 as well as detailing changes in the seasonal cycle by month between 1982-2004 and 2017-2099. In addition several indices have been calculated, both historically and for the projections, on an annual basis, with data provided in an appendix, and separated into different annual categories: these include a drought index (mean annual rainfall/mean annual potential evaporation), the standard precipitation index (the years used in the standard deviation calculations are not given), and years with rainfall and flood events exceeding the 100, 50, 30 and 20 return values (flood events only for 100 and 30 years). Given the severe flooding of 2022 across much of Pakistan it is worth noting that the year does not appear as such in any of the "extreme" projections, and in the appendix it is characterised, for both the Mula and Zhob watersheds, as "moderate drought" and "moderately dry", for the aridity and standard precipitation indices respectively.

Several relevant strategies are proposed:

- Developing models for assessment of climate change impacts on agricultural production systems in all agro-ecological zones.
- Developing quality datasets on crop, soil and climate-related parameters to facilitate research work on climate change impact assessment and productivity projection studies.
- Enhancing research capacity of relevant organizations to make reliable climate change projections to assess the corresponding likely impacts on various agriculture products and develop appropriate adaptation measures.

Annex 3. Documents from International Organisations

Contents:

- **I1**. The Climate Change Profile of Pakistan published in 2017 by the ADB

The **Climate Change Profile of Pakistan [I1]**, by Q.U.Z. Chaudhry and published by the ADB in 2017, appears to provide much of the basic information for the 2NC [N3]. Nonetheless it in turn is developed on a 2007 report from the GCISC which uses, it appears, just a single GCM under A2 and A1B, and on a further technical report from the PMD, again authored by Chaudhry, that uses A2, A1B and B1. Also mentioned are projections using 4 GCMs for the Indus Basin for RCP4.5 and RCP8.5 that are downscaled according to this report to 10km; this appears to refer to the PMD web site discussed above [P6], but there the values are available at 25km and 50km resolution. Differences between these various projections are presented without further interpretation; in one case the projections for northern Pakistan suggest temperature increases under RCP8.5 by the end of the century of 10-12ºC.

Assessment of the Climate Change Profile of Pakistan:

- Projections used at the global scale
    - Uses a variable set of projections from CMIP3 and CMIP5 to produce conclusions but without any indication of the coherence of these sets
    - No extremes are discussed
- Projections used at the regional scale
    - No details of the downscaling used are provided
- Emissions scenarios
    - Uses a range of scenarios, both SRES and RCP, that include some lower emissions but the results are presented without interpretation to assist decision makers
- Handling of uncertainties
    - Not covered

Annex 4. Peer-Reviewed Papers and Grey Literature Documents

Contents:

- **U1**. Evaluation and projection of precipitation in Pakistan using the Coupled Model Intercomparison Project Phase 6 model simulations 2022, International Journal of Climatology, 1–20. https://doi.org/10.1002/joc.7602
- **U2**. Projected changes in temperature, precipitation and potential evapotranspiration across Indus River Basin at 1.5–3.0 °C warming levels using CMIP6-GCMs, 2021, Science of the Total Environment, https://doi.org/10.1016/j.scitotenv.2021.147867
- **U3.** Evaluation of global climate models for precipitation projection in sub-Himalaya region of Pakistan, 2020, Atmospheric Research, 245, 105061
- **U4.** Performance Assessment of General Circulation Model in Simulating Daily Precipitation and Temperature Using Multiple Gridded Datasets, 2018, Water, 10, 1793, doi:10.3390/w10121793

Evaluation and projection of precipitation in Pakistan using the Coupled Model Intercomparison Project Phase 6 model simulations [U1], by Abbas et al., covers a Chinese-funded project with Chinese and US authors in addition to ones from two Pakistan universities and the PMD. It is one of the first to use CMIP6 for Pakistan and uses a novel approach to simplifying the full ensembles for each of the four Tier 1 SSPs (see table in main section). Through statistical means the models that most closely simulate average annual rainfall over the entire country from 1951 to 2014 are selected for further analysis. The result is a group of 13 GCMs from which ensemble means and distributions are used for each SSP.

Assessment of Evaluation and projection of precipitation in Pakistan using the Coupled Model Intercomparison Project Phase 6 model simulations:

- Projections used at the global scale
  - Simplifies the issue of interpreting an ensemble through selection of those models that best simulate historical rainfall. This approach addresses the issue of confirming reasonable simlation of local climate raised in the IPCC AR6 as discussed in the main section, but there is no further detail beyond rainfall from a reduced ensemble mean.
  - The question remains whether the projected ensemble mean from the reduced model set provides improved information for decision making beyond that from the full set.
  - No discussion of extremes.
- Projections used at the regional scale
  - No downscaling used; all details are for annual averages across the country

- Emissions scenarios
    - Uses the 4 Tier 1 SSPs, so covers a good range, but limited discussion on discrimination of the projections under each
- Handling of uncertainties
    - Provides some graphics of spread but without detailed discussion

Projected changes in temperature, precipitation and potential evapotranspiration across Indus River Basin at 1.5–3.0 °C warming levels using CMIP6-GCMs [U2], by Mondal et al., is a second Chinese-funded project, this time with purely Chinese authorship. CMIP6 GCMs are used commendably with 7 of the 8 SSPs to provide an extended coverage of emissions scenarios, with results just for ensemble means. Only 7 GCMs were used, selected as those available that had completed projections for all 7 SSPs. The authors then combine all of the information into projections for three SWLs (Specified Warming Levels) calculated cross the Indus Basin, 1.5ºC, 2.0ºC and 3.0ºC. A relatively wide selection of parameters was studied, including temperature, rainfall, potential evapotranspiration (PET), and water supply (rainfall less PET). Information from all GCMs was downscaled to a common grid of 0.5º by 0.5º. As noted in the title the work focuses on the Indus Basin and thus does not cover all of Pakistan; it includes parts of India.

Assessment of Projected changes in temperature, precipitation and potential evapotranspiration across Indus River Basin at 1.5–3.0 °C warming levels using CMIP6-GCMs:

- Projections used at the global scale
    - Novel in terms of using all but one SSPs, but the approach to selection inevitably might incorporate biases. This could be offset by combining projections under different degrees of warming using all 7 projections. A wider set of parameters is studied than in many documents covered in this critique, with regional maps of changes for , but no further interpretation.
    - Noi specific discussion of extremes, unless the water supply index is counted as such.
- Projections used at the regional scale
    - The only downscaling is from the GCMs, with interpretation as above.
- Emissions scenarios
    - Uses an excellent wide set of SSP scenarios, with consolidation into three specified warming levels, an approach used extensively in the IPCC AR6
- Handling of uncertainties
    - Not discussed

Evaluation of global climate models for precipitation projection in sub-Himalaya region of Pakistan [U3], by Zafar Iqbal, Shamsuddin Shahid, Kamal Ahmed, Tarmizi Ismail, Najeebullah Khan, Zeeshan Tahir Virk, Waqas Johar, is part of a sequence of papers focused on selection methods for reducing ensemble size based on historic precipitation over the Upper Indus Basin, but with limited attention to projections *per se*. In this paper an initially reduced set of 22 CMIP5 models based on data availability was empirically processed against APHRODITE records to produce a final selection of 5 models. Rainfall projections under RCP2.6, RCP4.5 and RCP8.5 as the ensemble means of the five models revealed some spatial heterogeneity, particularly later in the century, however, perhaps more critically, mainly rainfall increases under RCP2.6 and RCP8.5 but large areas with decreases under RCP4.5. "*A large variation in topography may be the major cause of large heterogeneity in precipitation changes in the region. The heterogeneous changes in precipitation can make water resources management in the region more challenging*".

Assessment of Evaluation of global climate models for precipitation projection in sub-Himalaya region of Pakistan:

- Projections used at the global scale
  - Used on CMIP5 GCMs with a sophisticated selection approach that nonetheless still provides results with substantial spatial and inter-RCP heterogeneity. No results for the 22 original GCMs are provided for comparison to assess the benefits of using selection.
  - No consideration of extremes
- Projections used at the regional scale
  - Not used.
- Emissions scenarios
  - Uses a wide range from the RCPs, omitting only RCP6.0 on the basis of require just a single middle-of-the-road scenario.
- Handling of uncertainties
  - Perhaps the focus issue of the paper, as an attempt to reduce uncertainties through selection. The authors point to large uncertainties in provided gridded rainfall data in APHRODITE as one issue, but it is evident that the selection itself has produced models that presumably lack overall inter-consistency in their projections, but unfortunately details of individual model performances are not provided.

Performance Assessment of General Circulation Model in Simulating Daily Precipitation and Temperature Using Multiple Gridded Datasets [U4] Najeebullah Khan, Shamsuddin Shahid, Kamal Ahmed, Tarmizi Ismail, Nadeem Nawaz and Minwoo Son is an earlier paper on selection than the above for Pakistan based on historic temperature and precipitation. From 31 CMIP5 models a final six are selected for "reliable" projections of maximum and minimum temperatures in addition to rainfall across the country. Simple ensemble mean plus range comparisons for the full and for the reduced ensembles for the late century under RCP4.5 and RCP8.5 are provided that indicate reduced ranges plus higher means in the selection (except for lower temperature maxima in the means). The selection has tended to omit most of the outlying models, producing relatively reduced changes in minimum temperatures and rainfall.

Assessment of Performance Assessment of General Circulation Model in Simulating Daily Precipitation and Temperature Using Multiple Gridded Datasets:

- Projections used at the global scale
  - Used with the majority of CMIP5 models, but no details of spatial performance provided (as in [U3]); just rank order supplied.
  - No consideration of extremes.
- Projections used at the regional scale
  - Not used.
- Emissions scenarios
  - Uses only RCP4.5 and RCP8.5, with minimal information on differences between the related projections, but this aspect is not the focus of the paper.
- Handling of uncertainties
  - The main focus of the paper, and summarised by the authors as follows: "The selected GCMs are found to be different from those found by [an analysis for India]. This is due to the selection of GCMs based on different set of gridded data. The results emphasize the use of different gridded data in selection of GCMs to avoid uncertainty of selection.

Annex 5. Discussion on selection approaches for Pakistan

Four papers based on Malaysian lead authors, mostly including co-authors from various Pakistan universities, that cover selection ensemble methods for Pakistan, are summarised in rows 1 to 5 of the table below in terms of the models chosen by the various approaches. These approaches have not been detailed here but all are based on metrics that measure closeness to observed records. Two of these papers have been reviewed in the Annex 4 (U3 and U4), but the other two have not be included as they provide no projections. In the top row, Ahmed, et al., the selected models common to the three metrics used in this particular paper are italicised, while those common to approaches in the other three papers are underlined. Only one model was not selected twice in this paper, and three were common to approaches in all papers, but with one additional model selected each time; the additional models were common in two of the other approaches.

Across the four documents in rows 2-5, models selected 4 times would have been highlighted in red, but there are none, those selected three times are in orange, and those selected twice in blue. In total 5 models were selected just once, 5 twice and just one three times. While there is some consistency amongst the selections of the top paper, there appears, subjectively, to be less between that and the three other papers; perhaps the latter are relatively consistent amongst themselves.

Two additional papers have been included in the table marked in rows 6 and 7 by dash-dotted lines. Common models with the prior four papers are highlighted in bold.

Lutz et al (2016) takes an alternative method, sometimes referred to as an ‘envelope approach’ as opposed to the ‘performance approaches’ discussed above, that attempts to maintain the full width of the CMIP5 distribution by seeking representative projections for all combinations of relative hot-cold/dry-wet. All models selected (some are repeated) are listed. This approach has selected 4 alternate models, with two common.

The second paper is reviewed as N11 in Annex 1, but the details of the selection approach are not known. A single model common with those in rows 2-5 has been selected.

Paper	Area	Target parameter(s)	Original set	Models selected
Ahmed et al 2019a, Journal of Hydrology, 573, 281-298	Pakistan	Temperature and precipitation	20 CMIP5	3 different groups according to metric: Group 1 - *CESM1-CAM5, HadGEM2-AO, NorESM1-M* and HadGEM2-ES; Group 2 - *CESM1-CAM5, HadGEM2-AO, NorESM1-M* and GFDL-CM3; Group 3 - *CESM1-CAM5, HadGEM2-AO, NorESM1-M* and GFDL-CM3
[U4]	Pakistan	Temperature and precipitation	31 CMIP5	ACCESS1-3, CESM1-BGC, CMCC-CM, HadGEM2-CC, HadGEM2-ES and MIROC5
Ahmed et al 2019b, Hydrology and Earth System Sciences, 23, 4803-4824	Pakistan	Temperature and precipitation	36 CMIP5	NorESM1-M, MIROC5, BCC-CSM1-1, and ACCESS1-3
[U3]	Upper Indus Basin	Precipitation	22 CMIP5	MIROC5, EC-EARTH, CNRM-CM5, BCC-CSM1.1(m) and BCC-CSM1.1
Lutz et al 2016, International Journal of Climatology, DOI: 10.1002/joc.4608	Indus, Ganges and Brahmaputra basins	Temperature and Precipitation	94 for RCP4.5 and 69 for RCP8.5	BNU-ESM, CSIRO-Mk3-6-0, inmcm4, **CMCC-CMS**, **BCC-CSM-1**, CanESM2
[N11]	Hindu Kush sub-regions	Temperature, rainfall, ETCCDI indices	14 for RCP4.5 and RCP8.5	**EC-EARTH**, FGOALS-s2, GFDL-ESM2G, GFDL-ESM2M, inmcm4

Summary. Each paper in the table makes a somewhat different selection of models dependent on the specific metrics, parameters and regions used. It is not clear what the overall conclusion might be from this exercise other than there appears to be uncertainties introduced by specific selection techniques. There are insufficient details provided across the papers to assess any consequences for use of the various selections in projections, as discussedin more detail in the main section.

Annex 6. Further report reviews

Contents:

- Brief comments on the 14 CMIP6-based research studies supplied since the 14 February 2023 meeting
- Comments on the use of the CMIP6 projections as against the CMIP3 and CMIP5 projections used in the 19 reviewed studies (note that the recently-provided 14 CMIP6 studies have not been reviewed in similar detail here)
- Comments on downscaling over complex terrain
- Comments on aspects of the project covering glaciers, their monitoring and their response to climate change
- Extended comments on a recommended methodology for downscaled projections for Pakistan.

Note that none of the following adjusts any of the recommendations made in the main body of the report. Nor does this annex cover the requested information on technical and costs gaps for Pakistan.

Comments on the 14 CMIP6-based studies

A brief overview of the 14 new studies received using the same basic review structure as in the main report:

- Some of the studies were produced while the CMIP6 set was being developed and so include only model data as available; others use selection in some form, typically but not uniquely based on performance in simulating historic climate; only one appears to have used the full CMIP6 set as in the AR6; model independence does not appear to have been considered in any study
- In some cases projections for "extremes" indices as used in the AR5 and AR6 were provided
- Emissions scenarios used vary between 1 and 5; in some cases SSPs were selected so that direct matches could be made with CMIP5 projections using one or more of RCP2.6, RCP4.5 and RCP8.5; when used, SSP3-7.0 was preferred over SSP4-6.0; the bias towards higher emissions scenarios noted in the main document was not as prominent in these 14 studies
- No downscaling using RCMs is covered in any paper (CORDEX RCMs under CMIP6 are not yet available)
- Discussions on uncertainties varied between effectively none, or perhaps tacit acknowledgement, to reasonably detailed, although at the latter end of the spectrum the discussion tended to be limited to presentation rather than to interpretation in terms of impacts, with exceptions; one paper argues that uncertainties can be reduced through selection
- Selected quotations from four different papers:
    - *"the wide range in model ability to capture the leading teleconnection suggests caution in interpreting climate regional projections."*
    - *"Despite an overall agreement that extreme precipitation follow a ≈7%/K rate of increase at the global scale, projected changes in*

extreme precipitation are influenced by multiple factors that can lead to large uncertainties at the regional scale."
  - *"Consequently, there is huge uncertainty regarding future glacier extent."*
  - *"The downscaled GCM ensembles for SSP126, SSP245, and SSP585 show that the future climate is highly uncertain in the UIB [Upper Indus Basin]"*

The use of CMIP6 as opposed to CMIP3 and CMIP5

Most of the 19 studies reviewed in the detailed report were based on the CMIP3 and CMIP5 data sets, with exceptions of early capacity building activities in which projections from single GCM/RCM combinations were analysed. The recently supplied 14 studies discussed above have provided the majority of studies that use CMIP6 projections (two studies used CMIP6 in the main document). An important consideration therefore covers the relative benefits of using the latest CMIP projections over earlier versions.

The pros of using CMIP6 include:

- These are the latest versions of the models, and include augmented simulation of climate processes and overall increased sophistication of the calculations
- The SSP emissions scenarios incorporate socio-economic storylines as opposed to the pure scientific structures of the RCPs
- There is comprehensive coverage of the four Tier 1 SSP scenarios, for each of which similar numbers of projections are available, in contrast to the main focus on RCP4.5 and RCP8.5 in CMIP5 and to the reduced spread of scenarios in CMIP3
- It might be possible to combine CMIP6 with CMIP5 to create an enlarged ensemble.

The cons of using CMIP6 include:

- For downscaling there are no readily accessible downscaled projections based on CMIP6 from CORDEX at this time, although this will change in due course
- As discussed further below there are structural changes in CMIP6 from CMIP5 that raise issues of consistency between the two sets
- It is not immediately clear whether there are any improvements in the projections produced under CMIP6 as compared go those from earlier sets; the following is quoted from the IPCC AR6 WGI Report on p216: "*Despite the documented progress of higher resolution, the model evaluation carried out in subsequent chapters shows that improvements between CMIP5 and CMIP6 remain modest at the global scale (Section 3.8.2; Bock et al., 2020). Lower resolution alone does not explain all model biases, for example, a low blocking frequency (Davini and D'Andrea, 2020) or a wrong shape of the Intertropical Convergence Zone (Tian and Dong,*

2020). Model performance depends on model formulation and parameterizations as much as on resolution (Chapters 3, 8 and 10).”

No projections are being produced in this project but for one area of Africa we have used an AI approach to interpreting the cloud of CMIP projections, as summarised in the detailed report, to examine differences in the structures of CMIP5 and CMIP6; until further analyses are made the representativeness of the outcomes cannot be assessed, including for Pakistan, but are likely to be indicative.

It is well known that the CMIP6 projections have a wider range than those from CMIP3 and CMIP5. There are a number of metrics that can be applied to ensembles to test the validity of the ranges produced, but their calculation requires a substantial number of independent test ensemble sets, something not available for climate change projections. The range covered by an ensemble is important as one contribution not only towards providing the full reasonable scope of future changes but also for allocating likelihoods to the distribution of those changes. All CMIP data sets have issues regarding reliable discernment of likelihoods as, given the voluntary contribution protocols of these sets, there is non-independence between some of the projections because of either or both of different variants of the same model or of code sharing between models.

Issues of lack of range in the ensemble sets up to CMIP5 are perhaps most apparent in observed polar warming proceeding more rapidly than any projection. Thus the increased range of CMIP6 might indicate a move towards a more realistic range. One caveat still needs to be indicated, however, in that in the early development of ensembles for shorter time ranges using state-of-the-art models and techniques, ensembles that quickly provided sufficiently large sets for assessment, it took several years of research to make technical adjustments to satisfy these metrics. The contributory nature of CMIP does not permit such an approach and therefore the possibility remains that even the CMIP6 projections are not satisfactorily structured.

In the case of the African study the CMIP6 range was wider than that for CMIP5, and the AI approach provided insight into the reasons for this. In summary, the majority of the CMIP6 projections occupied roughly the same space as the majority from CMIP5. However, there was a relatively small proportion of the CMIP6 projections that were responsible for extending the range in both directions, plus a few that amplified the temperature increases as compared to CMIP5. The differences were most pronounced in the rainfall projections.

The recommendation overall is to focus on CMIP5 projections at this stage in the interests of ready downscaling using available CORDEX models. Once a sufficient body of CORDEX models using CMIP6 are available then CMIP6 might be considered as preferable, or in addition, to CMIP5.

Downscaling over complex terrain

Downscaling is the preferred option of decision makers as increased spatial information assists in planning adaption in areas of complex terrain[4], such as accounting for climatic differences across relatively small areas of topography. In Pakistan the objective, it is understood, is to be able to downscale the climate projections to District level. According to a web search there are about 170 districts, of varying sizes. Roughly a model spatial resolution of 50 to 100km would be sufficient to place at least one model grid point within most districts.

Spatial resolution varies between RCMs, and continues to increase, but most currently available CORDEX models provide data at resolutions of 50km or less. New models under development have reached resolutions down to 2km for some parts of the world but as yet for Pakistan the CORDEX set is the most appropriate for consideration.

The pros of using CORDEX include:

- According to the latest CORDEX summary close to 100 projections are available that cover all or most of Pakistan
- CORDEX provides an ensemble that offers indications of likelihoods
- Most projections are freely and readily accessed and offer opportunities for detailed assessment across Pakistan
- There is a substantial number of surface variables included that cover most demands for information regarding adaptation in contrast to empirical downscaling that tends to offer only a few.

The cons of using CORDEX include:

- Most available projections are for RCP4.5 and RCP8.5 only; there are a few for RCP2.6 and only a handful for RCP6.0
- There are only a limited number of host CMIP models used together with a relatively small number of RCMs and thus the issue of independence mentioned above is more critical than for CMIP; also as a result the projection range is smaller for CORDEX than for CMIP and may therefore cover relatively fewer of the futures possible
- Downscaling cannot address inadequacies in the projections of a host GCM nor, at the current stage of development, feed information back to the host
- Downscaling quality can depend in part on distance of the region of interest from the CORDEX Domain boundaries; simulations for regions close to the boundaries are relatively constrained by information from the host GCMs while there is evidence that RCMs can simulate excess climate variability towards the centres of domains.

[4] Note that no additional temporal resolution is available directly from the CORDEX projections as compared to those from CMIP.

Dynamical downscaling has progressed substantially over the past few years, not least in terms of the CMIP5 statement that the main advantages of downscaling were seen only in areas of topography or along coastlines.

Note that, as with the use of global models, it is important to retain as much uncertainty knowledge as possible when using RCMs even where the final objective is to use model selections to focus information to decision makers.

As pointed out in the main report, Pakistan is subject at the simplest level to two main rainfall climatologies, the winter westerlies that mainly affect more northerly areas, and the summer monsoon, most prevalent in the south east. There is no certainty that individual GCMs and any related downscaling might provide equivalent quality projections for both seasons, and therefore the recommendation is, at least in the first stages, to treat the two seasons independently. One test of reliability of any projection as suggested by the IPCC AR6 WGI report, p569, is that any model should reasonably reproduce the historic climate of the area of interest, and that that reproduction should also include adequate simulation of the large scale processes that drive local climate. This recommendation from the IPCC, for which there is no currently agreed standard approach, has not been used as yet in our AI-based approach to identifying individual RCM projections on which to plan adaptation[5]. Assessment for both seasons individually would be required was this approach adopted.

The IPCC AR6 WGI report provides further insights into the current state-of-the art of downscaling with relevance to Pakistan [see the original IPCC report for details of references, sections, etc. provided in the following]:

- For Asia itself:
    - p1402: *There is medium confidence that representing irrigation is important for a realistic simulation of South Asian monsoon precipitation. There is limited evidence that including irrigation in climate models improves the simulation of maximum and minimum daily temperatures as well as precipitation for other regions.*
    - p1407: *... increasing resolution in global models has been shown to improve Asian monsoon rainfall anchored to orography and the monsoon circulation (Johnson et al., 2016), but fails to solve the major dry bias.*
- In general for downscaling over complex regions:
    - p1394*: There is high confidence that to assess whether a climate model realistically simulates required aspects of present-day regional climate, and to increase confidence of future projections of these aspects, evaluation needs to be based on diagnostics taking into account multiple variables and process understanding.*

[5] In the main report it was demonstrated that various approaches using historic climate to select downscaling models over Pakistan tended to produce mainly distinct sets of selected models.

- p1397: *There is high confidence that atmospheric circulation biases can deteriorate the model representation of regional land surface climate. Assessing the relative contributions of atmospheric circulation and other sources of bias remains a challenge due to the strong coupling between the atmosphere and other components of the climate system, including the land surface.*
- p1399: *There is high confidence that climate models with resolutions of around 10 km or finer are necessary for realistically simulating mountain wind systems such as slope and valley winds and the channelling of winds in valleys.*
- p1404*: There is high confidence that bias adjustment can improve the marginal distribution of simulated climate variables, if applied to a climate model that adequately represents the processes relevant for a given application.*
- p1407: *The assessment of RCM performance needs to focus not only on mean climatology (Atlas), but also trends (Section 10.3.3.8) and extremes (Chapter 11), and the RCM's ability at correctly reproducing relevant processes, forcings and feedbacks (including e.g., aerosols, plant responses to increasing* CO_2*, etc., Schwingshackl et al., 2019; Boé et al., 2020; Sections 11.2. and 10.3.3.3 to 10.3.3.8) to be fit for future projections (Section 10.3.3.9).*
- p1407: *Resolving regional processes may be required to correctly represent the sign of regional climate change (medium confidence). However, the performance of RCMs and their fitness for future projections depend on their representation of relevant processes, forcings and drivers in the specific context (Sections 10.3.3.4-10.3.3.8).*

The details listed above undoubtedly are intimidating and, at the present time, many cannot readily be satisfied. The degree of attention to be given to these details within Pakistan is not to be determined in this project but the recommendations given previously remain valid. These might be restated in terms of the preparation of a NAP as (see also the final section of this extension):

- use model selection in such a manner as to retain all uncertainty information given by the CMIP set
- interpret the downscaled information provided by each selected model in terms of impacts as appropriate to the NAP; it is likely that similar impacts may result from more than one model offering an opportunity to simplify the information at the impacts stage rather than at the climate stage
- note that rainfall data, and data for other heterogeneous parameters, can be noisy, especially if assessed on a daily basis.

The list of recommendations might be extended to include examination of the historic performance of selected models, with replacement when necessary, but while retaining the uncertainty information. The AI approach we use facilitates such replacement, as may other approaches.

Annex 7. Downscaling and projections for glaciers

A separate document has been provided discussing the issues of interpreting glacial changes in Pakistan; here the focus will be primarily on downscaled projections covering glaciers.

It was noted during preparatory work for Task 4 of this project that examination of WMO data sets provided no evidence of glacier monitoring in Pakistan, nor is the extent of observational data available in the mountain areas currently clear to the project. The issues raised in the previous section regarding downscaling over complex terrain apply naturally to the glacier regions, together with additional considerations.

The 2019 IPCC Special Report "The Ocean and Cryosphere in a Changing Climate" offered recent insight into impacts of climate change globally, but with limited direct reference to Pakistan. New details were provided in the AR6, that include on p1387 when referencing the global observations-based data sets (such as ERA5) that are valuable for use over data-scarce regions: *"Generally, the differences between RCMs are larger than those between observation datasets, but for individual regions and performance metrics, observational uncertainty can dominate. They also showed that the choice of reference dataset can have an influence on the RCM performance score. Over the high mountain Asia region and East Asia, differences among gridded precipitation datasets can generate significant uncertainties in deriving precipitation characteristics (J. Kim et al., 2015; Kim and Park, 2016; Guo et al., 2017)".*

Nevertheless, p1396: *"Thus, added value of downscaling global model simulations is most likely where regional- and local-scale processes play an important role in a region's climate, for example in complex or heterogeneous terrain such as mountains (Lee and Hong, 2014; Prein et al., 2016b), …"*

Cross-Chapter Box 10.4, on pp1456-1458, provides a more detailed assessment of the current state of glaciers and projections over Pakistan and nearby Himalayan areas, but without specific attention to projections for the Karakoram region where glacial mass is accumulating rather than declining. Overall, on p1458, "*CMIP6 projects an increase of winter precipitation over the western Himalayas, with a corresponding decrease in the east (Almazroui et al., 2020b). HKH [Hindu Kush Himalaya] projections are subject to large uncertainties in CMIP5 and CORDEX (Hasson et al., 2013, 2017; Mishra, 2015; Sanjay et al., 2017). CORDEX, in particular, has inherent limitations at reproducing the characteristics of summer monsoon rainfall variability (Singh et al., 2017). There is medium confidence that HKH precipitation will increase in the coming decades."*

Providing projections for the Pakistan glaciers, and for consequent impacts on water security and on GLOFs, is complex and it is recommended that it is undertaken with full consideration of all sources of uncertainties, not only covering direct climatic uncertainties but including also, but not limited to, glacial darkening and development of rock glaciers.

Extended recommendations for Pakistan

None of the recommendations offered in the main document require adjustment in terms of this extended report; all remain valid. The comments following expand on these original recommendations.

In preparing a NAP one critical step is to convert climate change projections into impacts that can subsequently be collated with other information to develop adaptation requirements and options. Projections carry numerous uncertainties, both scientific, as indicated by the spreads in all CMIP sets, and external, including unknown future anthropogenic modification to the climate system. It is a frequent characteristic of projection studies, globally but also for Pakistan, that projection science is infrequently carried over into detailed impact studies covering all uncertainties. Ultimately decision makers need clear information on which to base policies and strategies, but we argue that that information should not be simplified to the extent of neglecting critical uncertainties, of which the above discussion points to many.

Providing the range of future climates that cover and retaining all likelihoods as produced by the models is the first step we recommend (as covered in the main document), followed by full conversion of all of these possibilities into impacts, perhaps through process models. The outcome at this stage, cognisant of the limitations of all models, is a distribution of impacts with associated estimated likelihoods. Once that has been achieved the range of impacts can be reviewed and likely reduced in complexity given that impacts from different climate change scenarios might be reasonably similar. This simplified set of impacts, that retains coverage of all uncertainties, might then be taken forward into the next stages of the NAP process.

Annex 8 - Karakoram Himalayas: Review of climate change, glacier behaviour and natural hazards in the Karakoram Himalaya

This annex covers a brief overview of the problems of climate modelling in High Mountains in regards to natural hazards and climate change in the Karakoram Himalaya.

Context

The Karakoram Himalaya form part of the Himalayan region which, in turn, forms part of a broader mountain region called High Mountain Asia (HMA). Combined, these systems represent the Earth's most important and vulnerable water towers (Immerzeel et al 20210; Viviroli et al 2021). Climate change is warming the wider region at a rate more than double the global average, and this is strongly and negatively impacting mountain glaciers and permafrost stores. Retreating glaciers in HMA cause a decline in reliable water stores which has the potential to create social and political conflict in the region (Nie et al 2021). In response to this major HEP schemes and dams have been built to help achieve United Nations' Sustainable Development Goals (providing renewable energy SDG 7), (zero hunger SDG 2) and facilitating clean water access (SDG 6 UN 2015). The HEP potential of HMA is considerable, and largely undeveloped; that of HMA exceeds 500 GW (Vaidya et al 2021). Currently, there are around 100 major HEP schemes in HMA (median storage capacity of 250 million m^3; Lehner et al 2011; Zarfl et al 2015) with more 650 under construction or planned. However, many of these are being built in areas with rapidly melting glaciers and associated glacier and mountain hazards, and so are likely to be highly vulnerable to climate impacts.

Representative paper: Forsythe, N., Fowler, H.J., Li, X.F., Blenkinsop, S. and Pritchard, D., 2017. Karakoram temperature and glacial melt driven by regional atmospheric circulation variability. *Nature Climate Change*, *7*(9), pp.664-670.

Identifying mechanisms driving spatially heterogeneous glacial mass-balance patterns in the Himalaya, including the 'Karakoram anomaly', is crucial for understanding regional water resource trajectories. Streamflows dependent on glacial meltwater are strongly positively correlated with Karakoram summer air temperatures, which show recent anomalous cooling. We explain these temperature and streamflow anomalies through a circulation system—the Karakoram vortex—identified using a regional circulation metric that quantifies the relative position and intensity of the westerly jet. Winter temperature responses to this metric are homogeneous across South Asia, but the Karakoram summer response diverges from the rest of the Himalaya. We show that this is due to seasonal contraction of the Karakoram vortex through its interaction with the South Asian monsoon. We conclude that interannual variability in the Karakoram vortex, quantified by our circulation metric, explains the variability in energy-constrained ablation manifested in river flows across the Himalaya, with important implications for Himalayan glaciers' futures.

The Himalayas

The region contains glaciers covering an area of ~22,800 km² (Bolch et al., 2012; Immerzeel et al., 2013). These ice resources provide much of the water for around 210 million people in the Himalayas and contribute to the flow of many of the major river systems in Asia, providing water supplies downstream to a further 1.2 billion people.

Estimates of the volume of water stored across the Himalayas depend on accurate and precise assessment of glacier volume and range from 3600 to 6500 km^3 (Bolch et al., 2012). These estimates do not take account of water resources in non-glacial cryospheric reservoirs, and this is described later. Himalayan glaciers are generally losing mass, with estimated glacial mass change rates of -26±12 Gt yr^{-1} (2003-2009) across the wider High Mountain Asia region (Gardner et al., 2013) (see Parry et al 2020). Climate projections suggest substantial long-term reductions in glacier mass and consequent severely negative consequences for water supply, especially after peak non-renewable water (Bliss et al 2014; Lutz et al 2014; Sorg et al 2014; Kraaijenbrink et al 2017).

There is a strong seasonal cycle associated with the Indian Summer Monsoon (ISM) which produces distinct wet (June to September) and dry seasons. This seasonal cycle drives the observed variability in hydrological regimes, and in the mass balance behaviour of Himalayan glaciers (Parry et al 2020). Although the glacier and snow coverage and contribution to hydrological regimes vary significantly over space, it is during the pre-monsoon period of the annual cycle that the glacier and snowmelt components of the hydrological regimes are of particular importance in augmenting low river flows. This baseflow also helps smooth interannual variability in streamflow resulting from variations in the onset, strength and duration of the monsoon.

The effect of topography on regional climate is profound, and forms part of the reason for the spatial and temporal climate variability experienced across the region, and the problems of using sparse data sets to characterise the climatological regimes for the purpose of climate modelling and prediction (Parry et al 2020). The Himalaya and Tibetan Plateau form a physical topographic barrier to air masses from north to south and west to east throughout the year and during monsoon times. The barrier also affects the path of the sub-tropical jet stream in the upper atmosphere and creates orographic enhancement of precipitation. As a result, the highest precipitation in the Himalayas is found within a few kilometers of the southern side of the highest mountains, where the orographic rise in air masses is most rapid, producing the steep precipitation gradients found in the region.

Although there are considerable spatial variations in precipitation and temperature patterns, detailed analysis of these patterns is restricted by the absence of a well-developed instrumental data network. High altitude observations are especially sparse with few stations above 3000 m elevation (eg Kansakar et al., 2004). This restricts our understanding of contemporary temperature and precipitation trends and variability in high mountains and their impacts on glacier mass balance. As a result, satellite data have played a major role in understanding precipitation patterns in the region. These show that there are large variations in precipitation across even small spatial scales; for example between valley floors and surrounding ridges (eg. Bookhagen and Burbank 2010), invalidating broad generalisations about spatial and temporal climate trends.

The Karakoram

The Karakoram contain some of the highest mountains in the world, and some of the longest glaciers outside of the polar regions. While climate change has driven glacier recession in large parts of HMA, parts of the Karakoram have not followed this trend, and this has been termed the 'Karakoram Anomaly' (e.g Farinotti et al.; 2020; Dimri 2021). Over the past two decades, the region has shown balanced to slightly positive glacier budgets, an increase in glacier ice flow speeds, stable to partially advancing glacier termini and widespread glacier surge activity. Recent observations show that the anomalous glacier behaviour partially extends to the nearby Western Kun Lun and Pamir. Several explanations have now been presented for the Anomaly's deeper causes, but our understanding is far from complete. This is partly because data coverage is very poor. Whether the Anomaly will continue to exist in the coming decades remains unclear, but its long-term persistence seems unlikely in light of the considerable warming anticipated by current projections of future climate.

Modelling and downscaling

The spatial and temporal climate variability, and the topographic variability which partly accounts for variable glacier trends, also limits the applicability of low-resolution Global Climate Models (GCMs) for detailed climate projections in this region, unless suitable downscaling methods are applied. It also makes trends difficult to detect in the relatively short and spatially-sparse observed time series of meteorological, glacial and hydrological data which are available for the region. Despite these caveats, it is clear that recent climate change has driven glacier recession over much of the Himalayas (e.g. Kaab et al., 2012). This is combined with reduction in the strength of Indian summer monsoon rainfall (Kumar et al., 2006; 2011) which has reduced high altitude snow accumulation, although in the Karakoram this may have been offset by westerly precipitation.

Recent modelling has used high-sensitivity climate models to produce 'worst-case' scenarios of climate impacts. For instance work by the HELIX consortium used high-sensitivity runs from CMIP5 models and HadGem with JULES modelling to assess future glacier mass balance over the Himalayas. They drove the projections using high-end climate change scenarios of +1.5 ^{o}C, +2 ^{o}C and 4^{o}C global average warming, relative to the pre-industrial period. Glacier volume was modelled by developing an elevation dependant mass balance model within the Joint UK Land Environment Simulator (JULES). JULES was forced with a six-member ensemble of high resolution

HadGEM3 atmosphere only global climate model projections for the twentieth century. The Himalaya region was subdivided into South Asia west (covering the western Himalaya and Karaokoram regions of Pakistan) and South Asia east (covering the Indian, Nepalese and Bhutan Himalayas) as defined in the Randolph Glacier inventory version 6.0. Results from this project a reduction in glacier volume of 95±2 % for South Asia east (including Nepal and Bhutan) by 2100 under RCP8.5.

Other modelling projects have supported this view that future climate warming will result in widespread glacier recession and almost total ice loss in some parts of the Himalayas and wider HMA. This is further analysed by projections made by the Glacier Model Intercomparison Project (glacierMIP1) (Hock et al., 2019) . GlacierMIP1 was a coordinated intercomparison of global-scale glacier evolution models, which used standard initial glacier conditions and climate change scenarios. The participating glacier models varied in complexity; for example, some models used temperature index schemes to calculate melting while others used full energy balance models. Models also differed in the complexity with which glacier evolution was represented and each model had a bespoke approach to calibration. The consensus view, from glacierMIP1, however, is that HMA will experience significant reductions in ice volumes under the business-as-usual RCP8.5 climate change scenario (See Table 1 below). While this scenario is seen as increasingly unlikely to be reached, the possibility of high Equilibrium Climate Sensitivity (ECS) means that it is sensible to continue to model such high radiative forcing estimates.

Table 1 Projected relative mass losses by the end of the Century for HMA. * denotes the projections generated by glacierMIP1 using CMIP5 RCP8.5 climate forcing. ** are projections made with downscaled CMIP5 RCP8.5 model for high-end climate scenarios. The values refer to the multi-GCM means and their standard deviation.

	(Marzeion et al., 2012)*	(Giesen and Oerlemans, 2013)*	(Hirabayashi et al., 2013)*	(Radić et al., 2014)*	(Huss and Hock, 2015)*	(Shannon et al., 2019)**
Central Asia	63.7±6.8	67.2±8.7	61.0±6.6	73.6±11.0	88.3±7.8	-80±7
South Asia West	43.1±6.2	78.1±10.4	57.5±5.6	62.7±15.2	84.0±13.7	-98±1
South Asia East	62.9±8.2	93.7±4.3	42.3±8.5	76.4±9.9	86.0±24.2	-95±2

Problems with modelling

Climate and hydrological modelling in high mountains is difficult for a number of reasons. Uncertainty in hydrological and climate projections is caused by sparse meteorological station networks. These are often clustered at low altitudes, which means that driving variables such as precipitation changes with altitude and lapse rates are often uncertain. Observations of solid precipitation can be underestimated by 20%-50% due to windiness at high elevations (Rasmussen et al., 2012).

Catchment hydrological models often use semi-distributed and conceptual approaches, and these are computationally relatively efficient, allowing uncertainty estimates to be presented and large catchments to be studied. In contrast models of glacier change tend to use spatial grids and physically based approaches. These models require large amounts of input data and are computationally intensive (van Tiel et al 2020).

Glacier melt modelling in glacio-hydrological models varies from simple temperature index models (eg Zhang et al., 2013), temperature index models (Mayr et al., 2013), to full energy balance models (Ren et al., 2018). Obviously, the simple temperature index model that only temperature is used to calculate melting; more complicated energy balance models require more observational data on radiation, temperature, wind speed and humidity. As a result, these are often used for pragmatic reasons where data is sparse or data storage is an issue.

To assess glacier evolution several paths have been chosen. One is the glacier enhanced Soil and Water Assessment Tool model (SWAT) model which assesses glacier hypsometry using a volume-area scaling technique that relates glacier volume and area using an empirically derived scaling parameter (eg Fang et al., 2018).

Other models include those using parameterisations to assess glacier thickness variations with mass balance using an empirical relationship (Huss et al., 2010). More complex model assessments use shallow ice approximations and glacier dynamics models allied to a hydrology model (see discussion in Shannon et al 2023). Limitations of using increased complexity with given computer and data storage capacity include the reduced catchment size that can be modelled.

Finally, the processes driving glacier change include those associated with debris supply to glacier surfaces (driving the transition from clean ice glaciers to debris-covered glaciers). These occur at small scales, well below those used in GCM or RCM experiments, and have to be parameterized. Such approaches are made difficult by the lack of observational data with which to develop these parameterisation schemes (see Shannon et al 2019; 2023 for a discussion).

Climate impacts

There are four broad categories of concern for infrastructure planners and policymakers: (1) continued loss of glaciers and permafrost systems and the changes in slope stability that result; (2) glacial lake outburst floods (GLOFs) and catastrophic landslides; (3) increased paraglacial sediment loads to valley bottoms and fluvial systems as the cryosphere contracts; (4) changes in water supplies as glaciers melt and the impact of rock glacier development.

1. Changes in slope stability.

This issue is seen within the context of paraglaciation (geomorphological responses to deglaciation). Glacier melt and permafrost thaw causes landscape instability and enhances geomorphological processes. Such paraglacial processes result in progressive erosion of landscape features in high valleys left by earlier glaciations and have a direct impact on slope instability. Debuttressing of steep mountain slopes by glacier melt leads to slope failures, including landslides, rockfalls, avalanches, and debris flows.

Recent examples of such catastrophic events include the 2021Chamoli disaster, which was triggered by a rockslide that impacted older mass wasting deposits in previously glaciated terrain in the valley bottom. This lead to the deaths of over 200 people and the destruction of an HEP scheme in the valley bottom (Shugar et al 2021). The melting of permafrost also produces detachment slides and thaw slumps.

2. GLOFs

The future evolution of these damaging floods is currently unknown. Despite assertions that GLOFs will become more common and damaging with climate change, this is currently not yet seen. Studies at global scales show that GLOFs have become less frequent in recent decades, with no trends in magnitude (Harrison et al 2018); and this pattern is replicated at Himalayan-wide scales (Veh et al 2019). The latter show that the average rate of GLOFs in the greater Himalayan region has remained unchanged in the past 3 decades, and argue that the rapid growth of glacier lakes is a poor predictor for GLOFs. However, others (eg Zheng et al 2021) argue that Nepal and other regions of central and eastern Himalaya currently have about twice the GLOF risk of surrounding regions, and that the future GLOF risk will triple with lake enlargement. Veh et al (2020) suggest that glacial lakes will increase in number with projected global temperature rise of 1.5 °C. Modelling suggests that this could melt around half of the Himalayan glacier mass by 2100 and provide the space for about another 16,000 meltwater lakes with a maximum total volume of 120 km^3.

Representative papers

Harrison, S., Kargel, J.S., Huggel, C., Reynolds, J., Shugar, D.H., Betts, R.A., Emmer, A., Glasser, N., Haritashya, U.K., Klimeš, J. and Reinhardt, L., 2018. Climate change

and the global pattern of moraine-dammed glacial lake outburst floods. *The Cryosphere*, *12*(4), pp.1195-1209.

Despite recent research identifying a clear anthropogenic impact on glacier recession, the effect of recent climate change on glacier-related hazards is at present unclear. Here we present the first global spatio-temporal assessment of glacial lake outburst floods (GLOFs) focusing explicitly on lake drainage following moraine dam failure. These floods occur as mountain glaciers recede and downwaste. GLOFs can have an enormous impact on downstream communities and infrastructure. Our assessment of GLOFs associated with the rapid drainage of moraine-dammed lakes provides insights into the historical trends of GLOFs and their distributions under current and future global climate change. We observe a clear global increase in GLOF frequency and their regularity around 1930, which likely represents a lagged response to post-Little Ice Age warming. Notably, we also show that GLOF frequency and regularity – rather unexpectedly – have declined in recent decades even during a time of rapid glacier recession. Although previous studies have suggested that GLOFs will increase in response to climate warming and glacier recession, our global results demonstrate that this has not yet clearly happened. From an assessment of the timing of climate forcing, lag times in glacier recession, lake formation and moraine-dam failure, we predict increased GLOF frequencies during the next decades and into the 22nd century.

Veh, G., Lützow, N., Tamm, J., Luna, L.V., Hugonnet, R., Vogel, K., Geertsema, M., Clague, J.J. and Korup, O., 2023. Less extreme and earlier outbursts of ice-dammed lakes since 1900. Nature, pp.1-7.

Episodic failures of ice-dammed lakes have produced some of the largest floods in history, with disastrous consequences for communities in high mountains[1,2,3,4,5,6,7]. Yet, estimating changes in the activity of ice-dam failures through time remains controversial because of inconsistent regional flood databases. Here, by collating 1,569 ice-dam failures in six major mountain regions, we systematically assess trends in peak discharge, volume, annual timing and source elevation between 1900 and 2021. We show that extreme peak flows and volumes (10 per cent highest) have declined by about an order of magnitude over this period in five of the six regions, whereas median flood discharges have fallen less or have remained unchanged. Ice-dam floods worldwide today originate at higher elevations and happen about six weeks earlier in the year than in 1900. Individual ice-dammed lakes with repeated outbursts show similar negative trends in magnitude and earlier occurrence, although with only moderate correlation to glacier thinning[8]. We anticipate that ice dams will continue to fail in the near future, even as glaciers thin and recede. Yet widespread deglaciation, projected for nearly all regions by the end of the twenty-first century[9], may bring most outburst activity to a halt.

Taylor, C., Robinson, T.R., Dunning, S., Rachel Carr, J. and Westoby, M., 2023. Glacial lake outburst floods threaten millions globally. Nature Communications, 14(1), p.487.

Glacial lake outburst floods (GLOFs) represent a major hazard and can result in significant loss of life. Globally, since 1990, the number and size of glacial lakes has grown rapidly along with downstream population, while socio-economic vulnerability has decreased. Nevertheless, contemporary exposure and vulnerability to GLOFs at the global scale has never been quantified. Here we show that 15 million people globally are exposed to impacts from potential GLOFs. Populations in High Mountains Asia (HMA) are the most exposed and on average live closest to glacial lakes with ~1 million people living within 10 km of a glacial lake. More than half of the globally exposed population are found in just four countries: India, Pakistan, Peru, and China. While HMA has the highest potential for GLOF impacts, we highlight the Andes as a region of concern, with similar potential for GLOF impacts to HMA but comparatively few published research studies.

3. Paraglacial sediment loads to valley bottoms

As glaciers melt and thin, surrounding bedrock and debris-covered mountain slopes become unstable and shed debris to valley floors. This is known as the paraglacial period; a time of enhanced geomorphological instability and heightened natural hazards. While most modeling of the impact of climate change on mountain glaciers produces projections showing considerable reduction in glacier mass balance (e.g. Shannon et al. 2019), few climate modeling approaches have attempted to resolve the impact of paraglacial processes on glacier mass balance. For instance, one response of some mountain glaciers to climate change will be a transition from 'clean' glaciers to debris-covered glaciers (Herreid and Pellicciotti, 2020), and a potential further transition to rock glaciers in response to paraglacial processes increasing debris fluxes to glacier surfaces (see Jones et al. 2019). This means that the impact of climate change on these ice-debris systems will vary as the systems change. As a result, viewed from the landsystem perspective, a debris-covered glacier landsystem incorporates numerous processes that respond to climate in different ways over time.

Paraglacial debris supply rates to valley floors may also show a complex non-linear response to the same warming: initial debutressing of rockwalls by glacier recession can cause weakening of the valley walls and slopes, but the timescale and duration of this effect is difficult to constrain and contingent on many structural, lithological and geomorphological conditions (Knight and Harrison 2018, Mancini and Lane 2020).

Representative papers

Hewitt, K., 2009. Rock avalanches that travel onto glaciers and related developments, Karakoram Himalaya, Inner Asia. *Geomorphology*, *103*(1), pp.66-79.
Knowledge about the coverage and characteristics of glaciers in High Mountain Asia (HMA) is still incomplete and heterogeneous. However, several applications, such as modelling of past or future glacier development, run-off, or glacier volume, rely on the existence and accessibility of complete datasets. In particular, precise outlines of glacier extent are required to spatially constrain glacier-specific calculations such as length, area, and volume changes or flow velocities. As a contribution to the Randolph Glacier Inventory (RGI) and the Global Land Ice Measurements from Space (GLIMS) glacier database, we have produced a homogeneous inventory of the Pamir

and the Karakoram mountain ranges using 28 Landsat TM and ETM+ scenes acquired around the year 2000. We applied a standardized method of automated digital glacier mapping and manual correction using coherence images from the Advanced Land Observing Satellite 1 (ALOS-1) Phased Array type L-band Synthetic Aperture Radar 1 (PALSAR-1) as an additional source of information; we then (i) separated the glacier complexes into individual glaciers using drainage divides derived by watershed analysis from the ASTER global digital elevation model version 2 (GDEM2) and (ii) separately delineated all debris-covered areas. Assessment of uncertainties was performed for debris-covered and clean-ice glacier parts using the buffer method and independent multiple digitizing of three glaciers representing key challenges such as shadows and debris cover. Indeed, along with seasonal snow at high elevations, shadow and debris cover represent the largest uncertainties in our final dataset. In total, we mapped more than 27 800 glaciers >0.02 km^2 covering an area of 35 520±1948 km^2 and an elevation range from 2260 to 8600 m. Regional median glacier elevations vary from 4150 m (Pamir Alai) to almost 5400 m (Karakoram), which is largely due to differences in temperature and precipitation. Supraglacial debris covers an area of 3587±662 km^2, i.e. 10 % of the total glacierized area. Larger glaciers have a higher share in debris-covered area (up to >20 %), making it an important factor to be considered in subsequent applications (https://doi.org/10.1594/PANGAEA.894707).

Shugar, D.H., Jacquemart, M., Shean, D., Bhushan, S., Upadhyay, K., Sattar, A., Schwanghart, W., McBride, S., De Vries, M.V.W., Mergili, M. and Emmer, A., 2021. A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. Science, 373(6552), pp.300-306.
On 7 February 2021, a catastrophic mass flow descended the Ronti Gad, Rishiganga, and Dhauliganga valleys in Chamoli, Uttarakhand, India, causing widespread devastation and severely damaging two hydropower projects. More than 200 people were killed or are missing. Our analysis of satellite imagery, seismic records, numerical model results, and eyewitness videos reveals that ~27×10^6 cubic meters of rock and glacier ice collapsed from the steep north face of Ronti Peak. The rock and ice avalanche rapidly transformed into an extraordinarily large and mobile debris flow that transported boulders greater than 20 meters in diameter and scoured the valley walls up to 220 meters above the valley floor. The intersection of the hazard cascade with downvalley infrastructure resulted in a disaster, which highlights key questions about adequate monitoring and sustainable development in the Himalaya as well as other remote, high-mountain environments.

4. Rock Glaciers, future water supplies and impacts.

While much has been written on the effect of climate change on glaciers in the Himalaya and its impact on sustainability, almost nothing has been published on rock glaciers in the wider region and their role in maintaining water supplies as the climate warms. Rock glaciers are important components of the HMA hydrological system because they are present in almost all regions of HMA and are climatically more resilient than other glacier types owing to an insulating layer of debris cover (Harrison et al 2021; Jones et al 2021). Research from other mountain regions shows that they contain potentially important water stores, although in HMA there is almost no information on their number, spatial distribution, and response to future climate change. As a result, more research needs to be focused on Asian rock glaciers to assess their hydrological significance to underpin climate change adaptation strategies.

The only major assessment of their importance (Jones et al. 2021) show that rock glaciers in the central Himalaya (volume of water is 31.80 ± 6.36 km^3) and east Himalaya (volume of water is 5.06 ± 1.01 km^3) constitute considerable long-term water stores, although their relative hydrological contribution vs other hydrological inputs (i.e. precipitation) diminishes their hydrological significance when considered at the sub-regional spatial scales.

They argue that the proportional contribution of glacial [and rock glacial] melt inputs to runoff generally increases with proximity to the source (i.e. water inputs are less diluted by precipitation), the importance of which is influenced by the distribution of water demand and pre-existing levels of water stress. Therefore, in basins with higher population densities in their upper ranges glacial melt has greater comparative hydrological value than basins where the populations predominantly occupy lowland plains. They show that rock glacier: glacier Water Volume Equivalent (WVEQ) ratios, mask their actual hydrological significance. Arguably, rock glaciers located in the western Himalaya (1:34) are the most hydrologically significant. However, rock glacier: glacier WVEQ ratios are not reflective of rock glacier hydrological significance at smaller spatial scales; for example, 1:3 and 1:5 in the West and Far-west regions of Nepal, respectively.

Representative papers

Mölg, N., Bolch, T., Rastner, P., Strozzi, T. and Paul, F., 2018. A consistent glacier inventory for Karakoram and Pamir derived from Landsat data: distribution of debris cover and mapping challenges. *Earth System Science Data*, *10*(4), pp.1807-1827.

As a contribution to the Randolph Glacier Inventory (RGI) and the Global Land Ice Measurements from Space (GLIMS) glacier database, we have produced a homogeneous inventory of the Pamir and the Karakoram mountain ranges using 28 Landsat TM and ETM+ scenes acquired around the year 2000. We applied a standardized method of automated digital glacier mapping and manual correction using coherence images from the Advanced Land Observing Satellite 1 (ALOS-1) Phased Array type L-band Synthetic Aperture Radar 1 (PALSAR-1) as an additional source of information; we then (i) separated the glacier complexes into individual glaciers using drainage divides derived by watershed analysis from the ASTER global digital elevation model version 2 (GDEM2) and (ii) separately delineated all debris-covered areas. Assessment of uncertainties was performed for debris-covered and clean-ice glacier parts using the buffer method and independent multiple digitizing of three glaciers representing key challenges such as shadows and debris cover. Indeed, along with seasonal snow at high elevations, shadow and debris cover represent the largest uncertainties in our final dataset. In total, we mapped more than 27 800 glaciers >0.02 km^2 covering an area of 35 520±1948 km^2 and an elevation range from 2260 to 8600 m. Regional median glacier elevations vary from 4150 m (Pamir Alai) to almost 5400 m (Karakoram), which is largely due to differences in temperature and precipitation. Supraglacial debris covers an area of 3587±662 km^2, i.e. 10 % of the total glacierized area. Larger glaciers have a higher share in debris-covered area (up to >20 %), making it an important factor to be considered in subsequent applications (https://doi.org/10.1594/PANGAEA.894707).

Jones, D.B., Harrison, S., Anderson, K., Shannon, S. and Betts, R.A., 2021. Rock glaciers represent hidden water stores in the Himalaya. Science of The Total Environment, 793, p.145368.

In the high mountains of Asia, ongoing glacier retreat threatens human and ecological systems through reduced water availability. Rock glaciers are climatically more resistant than glaciers and contain valuable water volume equivalents (WVEQ). Across High Mountain Asia (HMA) the WVEQ of rock glaciers is poorly quantified, and thus their hydrological significance versus glaciers is unknown. Here we present the first systematic assessment of Himalayan rock glaciers, totalling ~25,000 landforms with an areal coverage of ~3747 km^2. We calculate the WVEQ of Himalayan rock glaciers to be 51.80 ± 10.36 km^3. Their comparative importance versus glaciers (rock glacier: glacier WVEQ ratio) is 1:25, which means that they constitute hydrologically valuable long-term water stores. In the context of climate-driven glacier recession, their relative hydrological value will likely increase. These cryospheric stores should be included in future scenario modelling to understand their role in sustainable water management for HMA

Hassan, J., Chen, X., Muhammad, S. and Bazai, N.A., 2021. Rock glacier inventory, permafrost probability distribution modeling and associated hazards in the Hunza River Basin, Western Karakoram, Pakistan. Science of The Total Environment, 782, p.146833.

The destabilization of rock glaciers and permafrost variations is of great importance to the safety of the population and infrastructure in the Karakoram region because of their effects on land stability and river obstructions. In this study, we compiled the first complete rock glacier inventory for the Hunza Basin, western Karakoram, of 616 rock glaciers with an area of 194 km^2 between 2800 and 5700 m a.s.l. We categorized the rock glaciers as intact or relict, and their distributions and destabilization were further analyzed and used along with in situ climate and elevation dataset to model the permafrost probability distribution. The modeled areas where the permafrost zonation index (PZI) is 0.5–1.00 indicate that permafrost occurs over 85% of the catchment area and lies above 3525 m a.s.l., which closely matches the zero-degree isotherm of 3800 m a.s.l. Based on the sensitivity analysis of the independent variables, elevation is the most sensitive variable, followed by net radiation, for predicting the probabilities of the presence and absence of permafrost. The model distributions are quite precise, with median posterior areas under the curve of 0.98 and 0.96 for model training and testing, respectively. We analyzed the rock glacier destabilization for 68 rock glaciers that interacted with river channels, of which 50 blocked or diverted river channels. Destabilized rock glaciers can be closely linked to the 0 °C isotherm between 3400 and 4600 m a.s.l. The significant damage caused by periodic floods from the subsequent blockage of river channels by landslides can be attributed to variations in permafrost. Which demolished infrastructure, including a hydropower plant, suspension bridge and water supply system in Hassan-abad catchment. Quantification of rock glacier dynamics and permafrost in the region can further improve policies related to the reduction in disaster risk and mitigation of associated hazards.

Recommendations

1 Improve data availability to assess climate trends in the Karakoram. There are few observational data sets from high elevations so the role of winter precipitation, westerly atmospheric flows or monsoonal influences in producing the Karakoram Anomaly is not clear.

2 Assess the climate lags in driving GLOFs. Assess glacier lake development and evolution, and critically assess which lakes are dangerous, and which lakes are not. There are a number of risk analysis protocols that could be adopted here, and a systematic assessment of these would be very valuable.

3 Investigate the ways in which ice glaciers are transitioning to debris-covered glaciers, and which of these further transition to rock glaciers. Which ones are doing this, and how quickly? Understanding this will enable a proper assessment of future water sources to be obtained. Investigate the ice content of contemporary rock glaciers and their likely contribution to hydrological resources.

4 Identify vulnerable populations and infrastructure at risk from rock slope failures, which will probably be catastrophic in nature.

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