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National climate hazard indices for health:

WHO technical report

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Acronyms and abbreviations

CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
DLS	Decorrelation length scale
ESGF	Earth System Grid Federation
ESM	Earth system model
ETCCDI	Expert Team on Climate Change Detection and Attribution
ET-SCI	Expert Team on Sector-specific Climate Indices
FDD	Full daily data
GCM	Global climate model
GPCC	Global Precipitation Climatology Center
GPCC-FDD	Global Precipitation Climatology Center – Full Daily Data
IPCC	Intergovernmental Panel on Climate Change
JRA	Japanese Reanalysis
RCM	Regional Climate Model
RCP	Representative concentration pathway
SIDS	Small Island Developing State
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organization
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

CHAPTER 1

Introduction

Climate change threatens health, both directly through exposures such as heat stress and extreme weather events, and indirectly through a number of exposure pathways including the transmission cycles of infectious diseases and the degradation of the environmental and social determinants of health (e.g. air, water, soil, security). There are significant differences in the health risks posed by climate change both between and within countries[1].

Countries are scaling up their work on health and climate change but are at different stages in this process. To develop comprehensive national assessments, plans and interventions, governments require national-level evidence to inform their decisions. The World Health Organization (WHO) has been working on climate change and health for over 25 years and supports Member States by strengthening evidence, monitoring, policy, and technical guidance and capacity-building.

In 2014, at the first WHO Global Climate Change and Health Conference, Member States requested WHO to continue to provide support to ministries of health with consistent information on the health risks from climate change, as well as further expanding work to achieve health benefits while cutting greenhouse gas emissions. Recognizing the diversity of health risks and opportunities between countries, United Nations Framework Convention on Climate Change (UNFCCC) Executive Secretary Cristiana Figueres and WHO Director-General Margaret Chan agreed that WHO should work with UNFCCC, and other relevant partners, to provide country-specific information on climate and health, in time to inform the negotiations of the UNFCCC agreement in Paris in December 2015.

The Health and Climate Change Country Profile project was launched as a joint WHO UNFCCC initiative under the guidance of a steering committee[2] comprised of key stakeholders and other UN agencies *(1, 2)*. The steering committee was chaired by the University of East Anglia, Tyndall Centre for Climate Change. The country profile project became a fundamental component of WHO's global monitoring of health sector response to climate change. The country profiles, developed in collaboration with national governments, summarize evidence of the climate hazards and health risks facing countries. They track national progress in addressing the health threats from climate change and highlight opportunities for gaining health benefits from climate mitigation action. The profiles provide an overview of key areas for taking action and provide links to available resources.

The specific objectives of the WHO UNFCCC Health and Climate Change Country Profile project were to:

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[1] Any further reference to ”country” and ”national” in this publication should be understood to refer to countries, territories and areas as well as national and local institutions, data and information. Use of the terms ”country” and ”national” does not imply the expression of any opinion whatsoever on the part of the World Health Organization concerning the legal status of any country, territory, city or area or of its authorities.

[2] Members of the steering committee included CDP, London School of Hygiene and Tropical Medicine, University of East Anglia, Tyndall Centre for Climate Change, University of Wisconsin Madison, Wellcome Trust, the World Meteorological Organization, the World Bank and the World Health Organization.

- provide ministers of health, and other decision makers, with a single snapshot of up-to-date, easily accessible, policy-relevant and reliable information on the impacts on climate change on health and the opportunities for health co-benefits in their own countries.

- present this information to support representation of the range of climate and health issues in national intersectoral policy discussions, and to provide an initial orientation of planning of climate and health programmes.

- establish a set of core indicators that will support countries to track their progress in reducing health vulnerability, and gain health benefits from mitigation policies in the future, including in relation to other countries.

To date, more than 80 countries (Annex 1, Table A.1) have participated in the Health and Climate Change Country Profile project since it began in 2015. The profiles are organized in three separate series *(2)*:

- the 2015–2018 global series

- the 2020–2021 Small Island Developing States (SIDS) series

- the 2021–2023 global series.

From the start of the project, the aim was to use available, comprehensive, standardized global datasets where possible. However, comprehensive, standardized national-level data on current and future climate hazards and health impacts from climate change do not exist for all Member States. Starting in 2015, WHO worked with leading researchers to develop country-specific climate hazard and health impact estimates for inclusion in the country profiles. WHO collaborated with the University of East Anglia, Tyndall Centre for Climate Change and the Climatic Research Unit on the development of climate hazard content. All analysis was conducted by the Climatic Research Unit, University of East Anglia.

This technical report outlines the methodology used in the selection and development of climate hazard indices for use in the country profiles. The work progressed under two main phases:

Phase 1 (2015–2016) involved the initial selection of four indices with health relevance and methods for their estimation. These indices were included in the first series of country profiles (2015–2018).

Phase 2 (2017–2019) involved a reassessment and selection of five indices with health relevance and strengthened methods for their estimation. These indices were included in the second series of country profiles for SIDS (2020–2021) and the third series of country profiles (2021–2023).

The report describes in detail the scope and underlying principles of the development of national climate hazard indices for use in the health and climate change country profiles (Chapter 2), the indices that were selected and why they are relevant for health (Chapter 3), the methodology used to develop climate hazard indices under high and low emissions scenarios (Chapter 4), a description of the data analysis, the time series plots, summary statistics, and how to interpret the findings (Chapter 5) and finally, some of the limitations of the data and areas for improvements (Chapter 6).

The data presented in this report are publicly available for 194 WHO Member States. Summary data and time-series plots for all five Phase II climate indices (Tmean, Ptotal, TX90p, R95ptot, SPI) are available on the Health and Climate Change Country Profiles webpage *(2)*[3] . The underlying data for the time-series plots are available on request at climatehealth@who.int.

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[3] The underlying data for the time-series plots are available in .xlsx data file format. Note that the data files contain multiple data sheets, and all values are unsmoothed.

CHAPTER 2

Scope and underlying principles

The scope and underlying principles for both phases of country profile development were determined by WHO through discussion with relevant experts and stakeholders. Those most relevant to the climate hazard content are summarized here.

- **Country-level**

Since one of the main objectives of the country profiles is to strengthen evidence at national level, support UNFCCC processes and monitor national progress, an early decision was made to provide both climate hazard and health data as country-level averages, regardless of the size of the country. This helps to ensure consistency of both climate and socioeconomic data. The latter, including health-related data, are typically provided at the country level in datasets with global coverage.

- **Consistent input data for all countries**

While many countries have the capacity to develop their own national climate information for in-depth analysis, there are many advantages and uses of information which is consistent across all countries. Such information facilitates comparison between countries and regions. It is also relevant for integrated impact assessment modelling for example, and for economic modelling such as the general equilibrium models used to explore the economic costs of climate change.

Consistency is achieved by using gridded observational data sets with coverage over all land areas and the same set of global climate modelling outputs (see Section 4.1).

- **Climate hazard indices with health relevance**

The definition of risk adopted by the Intergovernmental Panel on Climate Change (IPCC) in the Special Report on Extremes *(3)* and subsequent assessment reports views risk as a function of hazard, vulnerability and exposure. This implicitly recognises that the greatest societal impacts may not necessarily come from the most extreme meteorological or hydrological events and vice versa *(3, 4)*. Nonetheless, it is important to understand how climate hazards may change in the future. Due to climate change, many climate hazards and extreme weather events, such as heatwaves, heavy rainfall and droughts, are likely to become more frequent and more intense in many parts of the world *(5, 6)*.

While acknowledging that climate hazards and the critical thresholds in terms of impacts vary considerably from country to country, the guiding principle is to produce country profiles that are consistent in terms of content across all countries. To minimise the number of indices considered and to ensure a consistent approach for all countries, a limited set of four or five indices was selected for each phase of work from a larger set of indices of extremes. The latter indices are defined from a meteorological perspective and widely used by the physical climate change research community *(5, 6)*. The four or five selected indices used in the country profiles (see Section 3.1, Table 1) were identified based on their relevance for health impacts through discussion with health and regional experts (see Section 3).

- **Focus on temperature and precipitation**
The indices of extremes used in the country profiles are all defined based on temperature and precipitation alone. This means drought is considered from a meteorological rather than a hydrological or agricultural perspective, and heat stress in terms of temperature rather than additional factors such as humidity.

Where relevant, some of the country profiles include information about sea-level rise and tropical cyclones. This information was largely provided by other groups and is not discussed in this report.

- **Two emissions scenarios**
Climate hazard indices are provided for two different Representative Concentration Pathways (RCPs) which make different assumptions about greenhouse gas concentrations and the underlying emissions to reflect different possible climate change mitigation policies *(7–9)*.

The highest of the available emissions scenarios RCP8.5 is used together with the RCP2.6 scenario which was designed to meet the policy target of 2 °C global average warming compared to pre-industrial conditions. The radiative forcing associated with RCP8.5 peaks at 8.5 W/m^2 or about 940 ppm CO_2 in 2100 *(8)*, while that for RCP2.6 peaks at about 3 W/m^2 (about 400 ppm CO_2) before 2100 before declining to 2.6 W/m^2 (about 330 ppm CO_2) *(9)*.

These choices of a ‘business as usual’ high emissions scenario and a ‘two-degree’ scenario in which emissions decline rapidly were made when work on the country profiles started in 2015, based on available climate model simulations (see Section 4.1).

CHAPTER 3

Selection of indices and health relevance

3.1 Selection process

The climate hazard indices included in the country profiles focus on four (Phase 1) or five (Phase 2) aspects of mean and extreme climate considered important by the governments and health experts consulted during the WHO work. They were selected from a larger set of 27 indices (16 temperature-based and 11 precipitation-based) recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) *(10)*. The ETCCDI indices are widely used in studies of past and future changes in extremes, including IPCC assessments *(5, 6, 11)*.

It is important to consider extremes and not just changes in mean temperature and precipitation, since extremes and climate variability are often more important in terms of climate change impacts. On the other hand, information about changes in mean temperature and precipitation tends to be more robust, in part because spatial and temporal variability are lower than for extremes *(5)*. It is also informative to compare changes in mean and extreme values – to explore, for example, whether changes in the extremes are relatively larger than the changes in the mean. It is, however, generally easier to detect emerging signals in the means than in extremes because of the higher signal-to-noise ratio *(12, 13)*. Therefore, mean annual temperature and annual precipitation total are included in the set of indices used (Table 1).

To provide more complete information concerning the different characteristics of extremes, that is their magnitude, frequency and persistence *(4)*, nine or 10 indices of extremes were processed in total, including the four or five indices published in the country profiles (Table 1).

Table 1 indicates the index code as used in the ETCCDI archives (now managed through Climdex) *(14)*, a commonly-used descriptive name and a brief definition of how each index is calculated and the units in which it is expressed. The penultimate column shows the wording from the country profiles used to describe the relevance of the index from the perspective of risk and impact, such as heat stress, heatwaves, flood risk, drought or extreme rainfall.

TABLE 1

Summary of indices used in Phases 1 and 2

Index code	Descriptive name	Definition	Units	Calculated for phase 1/2	Included in profiles	Use in profiles as an indicator of
Tmean	Mean temperature	Mean annual temperature	°C	1, 2	1, 2	Mean annual temperature
Abs Hum	Absolute humidity	Estimated from Tmean and relative humidity	g/m^3	1	-	NA
Ptotal	Precipitation total	Annual precipitation total	mm	1, 2	2	Total annual precipitation
TN90p	Warm/hot nights	Number of days when TN > 90th percentile	Days	1, 2	** ***	Percentage of hot nights ('heat stress')
TN10p	Cold nights	Number of days when TN < 10th percentile	Days	1, 2	-	NA
TX90p	Warm/hot days	Number of days when TX > 90th percentile	Days	1, 2	2	Percentage of hot days ('heat stress')
TX10p	Cold days	Number of days when TX < 10th percentile	Days	1, 2	-	NA
CSDI	Cold Spell Duration Indicator	Annual count of days with at least 6 consecutive days when TN < 10th percentile	Days	1, 2	-	NA
WSDI	Warm Spell Duration Indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile	Days	1, 2	1	Days of warm spell ('heatwaves')
R10mm	Number of heavy precipitation days	Annual count of days when precipitation ≥ 10 mm	Days	1	-	NA
R20mm	Number of very heavy precipitation days	Annual count of days when precipitation ≥ 20 mm	Days	1, 2	1	Days with extreme rainfall ('flood risk')
CDD	Consecutive dry days	Maximum number of consecutive days with no precipitation (precipitation < 1 mm)	Days	1, 2	1	Consecutive dry days ('drought')
R95p	Very wet days	Annual total precipitation on days when precipitation >95th percentile	mm	1	-	NA
R95ptot	Percentage of total rainfall from very wet days	Percentage of annual total precipitation received on days when precipitation >95th percentile	NA	2	2	Contribution to total annual rainfall from very wet days ('extreme rainfall' and 'flood risk')

TABLE 1

Contd.

Index code	Descriptive name	Definition	Units	Calculated for phase 1/2	Included in profiles	Use in profiles as an indicator of
SPI12	Standardized Precipitation Index	Drought index expressing rainfall deficits/excesses over a 12-month period, relative to the average local conditions	Unitless*	2	2	Standardized Precipitation Index ('drought')

*SPI is unitless but can be used to categorize different severities of drought (wet): above +2.0 extremely wet; +2.0 to +1.5 severely wet; +1.5 to +1.0 moderately wet; +1.0 to +0.5 slightly wet; +0.5 to -0.5 near normal conditions; -0.5 to -1.0 slight drought; -1.0 to -1.5 moderate drought; -1.5 to -2.0 severe drought; below -2.0 extreme drought.
** TX90p used as an indicator of warm nights rather than WSDI as a heat stress indicator in the Phase 1 profile for the Philippines.
*** Plots not included in profiles, but text refers to hot nights – noting that similar changes are seen as for hot days.

3.2 Phase 1 indices

For Phase 1, three indices considered to be most relevant and informative for the health sector were selected for publication in the country profiles: Warm Spell Duration Index (WSDI) – as an indicator of heatwaves, R20mm (days of rainfall > 20 mm) – as an indicator of flood risk, and consecutive dry days (CDD) – as an indicator of meteorological drought (Table 1).

An additional seven indices of extremes were selected to provide more complete information concerning the different characteristics of extremes (see above). To complement the consideration of warm spells, Cold Spell Duration Index (CSDI) is included. WSDI is very sensitive to the threshold used (here the 90th percentile of maximum temperature) and to the day-to-day variability of maximum temperature. Furthermore, direct and indirect health impacts are not always related to spells of extremes, but to individual daily occurrences. Therefore, indicators of cold (TN10p) and warm (TN90p) nights and cold (TX10p) and warm (TX90p) days are also included. For some countries, a rainfall threshold of 20 mm is very rarely exceeded, so a threshold of 10 mm was also used (R10mm) to provide a more robust and appropriate index for such countries. While fixed thresholds (such as 10 mm and 20 mm for daily rainfall) are easily understood and so preferred by stakeholders and policy makers, as just noted, they are not universally applicable. Therefore, a percentile-based index of heavy rainfall (R95p) was also included.

There is evidence that temperature alone is not a good indicator of heat stress and human thermal comfort *(15)*, so, following the advice of health impact experts, absolute humidity was also provided for Phase 1.

3.3 Phase 2 indices and regional consultation in the Pacific and Caribbean

Following a lengthy process of iterative discussion including outreach to regional experts from the Pacific and Caribbean during 2017 and 2018, the University of East Anglia and WHO agreed how to develop updated and revised climate hazard indices for Phase 2 including the SIDS country profiles.

Based on this review and feedback, the original four climate indices published in the Phase 1 profiles were reassessed. While acknowledging that climate hazards and the critical thresholds in terms of impacts vary considerably from country to country, the desire of WHO to produce profiles consistent in terms of content across all countries remained the guiding principle. This review and reassessment resulted in indices being retained, replaced or added, according to Table 1 and the list below.

- **Tmean (mean annual temperature)** – retained.
- **Ptotal (total annual precipitation)** – added. This index is relevant for water resources for example, and so has potential implications for human health. In some regions, projected changes in Ptotal and extreme rainfall are in the opposite direction (i.e. a decrease in total precipitation is accompanied by an increase in heavy rainfall).
- **TX90p (percentage of hot days)** – an indicator of 'heat stress' as a replacement for WSDI used in the Phase 1 profiles. This change was made due to some concerns highlighted with the use of WSDI, particularly in tropical regions. As with WSDI, TX90p is based on the 90th percentile of the temperature distribution. Therefore, the temperature thresholds are specific to the location and baseline time period. TX90p, however, provides a more direct indication of over what proportion of time excessive heat exposure occurs. TN90p (percentage of hot nights) has also been calculated. This is not included in the country profiles, but the text provided for hot days notes that similar increases are seen in hot nights.
- **R95ptot (contribution to total annual rainfall from very wet days)** – an indicator of 'extreme rainfall' and 'flood risk' as a replacement for R20mm used previously. The advantage of R95ptot (the proportion of annual rainfall totals that falls during days that are at least as wet as the historically 5% wettest of all days) over R20mm is that it is based on the local distribution of rainfall rather than on a single fixed threshold (20 mm per day). The latter is not an appropriate threshold for heavy rainfall in all locations. As a climate change indicator, R95ptot is a proxy for the changing proportion of rainfall originating from extreme rainfall as opposed to non-extreme rainfall. The main disadvantage of this index is that its trends cannot easily distinguish whether the frequency or the intensity of hazards associated with extreme rainfall is expected to change. This is a critical caveat in terms of informing adaption options.
- **SPI (Standardized Precipitation Index)** – an indicator of 'drought risk' as a replacement for CDD used in Phase 1. SPI, rather than CDD, is perhaps the most widely used and World Meteorological Organization (WMO)-endorsed drought index for several reasons *(16–18)*. Firstly, SPIs are a way of expressing rainfall deficits/excesses over different timescales with relevance to different types of drought (e.g. meteorological, hydrological and socio-economic drought, in increasing order of duration). Secondly, it allows comparison of drought conditions between different locations despite their different rainfall climates. Thirdly, the index only necessitates rainfall as an input variable, so it is relatively easy to calculate from both observed and simulated data. Another advantage is that it shows both ends of the scale, that is how at the same time extremely dry and extremely wet periods change in frequency and/or intensity. It can be calculated for any time duration – for this work, 12 months was used (SPI12). One caveat for SPI projections is that the SPI will, by definition, not show any trend in the average unless annual rainfall totals change.

CHAPTER 4

Overview of input data and methodology

4.1 Input data

Climate hazard indices were produced for the historic past (back to 1901 where possible) using the gridded observed datasets listed in Table 2, and for the historic past and future out to 2100 using a large multi-model ensemble from the Community Model Intercomparison Programme – CMIP5 (see Table 3). Gridded data sets were used to provide, as far as possible, consistent information for all countries (see Section 2).

CMIP5 *(19)* is a project of the World Climate Research Programme's Working Group on Coupled Modelling. It has the advantage of including global climate models (GCMs) from many different modelling centres, allowing representation of modelling uncertainty as well as simulations for several scenarios, including RCP8.5 and RCP2.6 used here (see Section 2). CMIP, including CMIP5, outputs are used extensively in IPCC assessment reports *(20, 21)*. For the WHO work, advantage was taken of the work done by Sillman et al. *(22, 23)* who calculated ETCCDI indices of extremes from CMIP5 outputs and made these data freely available *(24)*.

For Phase 1, observed indices of extremes were taken from the HadEX2 data set, which provides a pre-calculated set of the required indices based on high quality series from more than 7000 temperature and 11 000 precipitation stations covering global land areas up to 2010 *(25)*. HadEX2 has been widely used in studies of observed trends in extremes *(25, 26)* and in comparisons of past and projected trends *(27, 28)*, including attribution studies *(29)*.

Among other things, the review process at the start of Phase 2 considered the most appropriate gridded observations to use for the representation of long-term trends and global climate model adjustment. The main motivation for this review, as well as extending the time series further forward, was that HadEX2 data for the indices of extremes were not available for many SIDS due to the lack of underlying station data for interpolation and gridding. Even where they exist, HadEX2 time series may contain missing values. While some consistency checking involving visual inspection of plots and removal of suspect HadEX2 values was undertaken for the published Phase 1 profiles (see Annex 2 for details), it was not practical to do this for all countries.

Based on these discussions and considerations, it was agreed to replace HadEX2 with these more recently available gridded data sets for Phase 2 (Table 2):

- Ptotal and SPI12 from the Global Precipitation Climatology Center (GPCC) *(30)*
- All other precipitation indices from GPCC full daily data (FDD) *(31)*
- All temperature indices of extremes from the JRA-55 Japanese reanalysis *(32)*.

In addition, Tmean was recalculated using the updated CRU TS 3.26 data set which extends to 2017, compared with 2013 for CRU TS 3.22 used in Phase 1 *(33, 34)*.

Further details of the input data from both observations and climate models are provided in Annex 2.

TABLE 2

Gridded observed datasets used to construct indices in Phase 1 and Phase 2

Index	Phase 1	Phase 2
Tmean	CRU TS 3.22: 1901–2013 http://catalogue.ceda.ac.uk/uuid/3f8944800cc48e1cbc29a5ee12d8542d	CRU TS 3.26: 1901–2017 https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_3.26/
Ptotal	CRU TS 3.22: 1901–2013 http://catalogue.ceda.ac.uk/uuid/3f8944800cc48e1cbc29a5ee12d8542d	GPCC: 1901–2016 https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html
Abs Hum	Calculated using temperature and relative humidity from CRU TS 3.22 (see above)	NA
TN90p, TN10p, TX90p, TX10p, CSDI, WSDI	HadEX2: 1901 (earliest date)–2010 http://www.metoffice.gov.uk/hadobs/hadex2/	JRA-55 Japanese reanalysis: 1955–2017 https://jra.kishou.go.jp/
R10mm, R20mm, CDD, R95p	HadEX2: 1901 (earliest date)–2010 http://www.metoffice.gov.uk/hadobs/hadex2/	GPCC-FDD: 1982–2016 https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html
R95ptot	NA	GPCC-FDD: 1982–2016 https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html
SPI12	NA	GPCC: 1901–2016 https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html

TABLE 3

Availability of CMIP5 global climate model outputs, and their spatial resolution, for calculating Tmean, Abs Hum, Ptotal and SPI12 (data available through https://esgf-node.llnl.gov/projects/esgf-llnl/) and indices of extremes (data available from https://climate-modelling.canada.ca/data/climdex/). P1: Phase 1; P2: Phase 2; Y: used P1 and P2.

Global climate model acronym	Resolution (number of latitude x longitude cells)	Tmean and Abs Hum	Precipitation data to calculate Ptotal and SPI12	Indices of extremes (from Sillman et al.) *(22, 23)*
CCSM4	192 x 288	Y	Y	Y
CNRM-CM5	128 x 256	Y	Y	Y
CSIRO-Mk3-6-0	96 x 192	Y	Y	Y
CanESM2	64 x 128	Y	Y	Y
FGOALS-s2	108 x 128	P2	P2*	Y*
GFDL-CM3	90 x 144	Y	Y	Y
GFDL-ESM2G	90 x 144	Y	Y	Y
GFDL-ESM2M	90 x 144	P2	Y	Y
HadGEM2-ES	145 x 192	Y	Y	Y

TABLE 3

Contd.

Global climate model acronym	Resolution (number of latitude x longitude cells)	Tmean and Abs Hum	Precipitation data to calculate Ptotal and SPI12	Indices of extremes (from Sillman et al.) *(22, 23)*
IPSL-CM5A-LR	96 x 96	Y	Y	Y
IPSL-CM5A-MR	143 x 144	Y	Y	Y
MIROC-ESM	64 x 128	Y	Y	Y
MIROC-ESM-CHEM	64 x 128	Y	Y	Y
MIROC5	128x256	Y	Y	Y
MPI-ESM-LR	96 x 192	Y	Y	Y
MPI-ESM-MR	96 x 192	Y	Y	Y
MRI-CGCM3	160 x 320	Y	Y	Y
NorESM1-M	96 x 144	Y	Y	Y
bcc-csm1-1	64 x 128	Y	Y	Y
bcc-csm1-1-m	160 x 320	Y	Y	Y
Total no. used		18 P1 20 P2	19 P1 20 P2	20 P1 20 P2

*Not used for precipitation indices in P2 due to very large model biases.

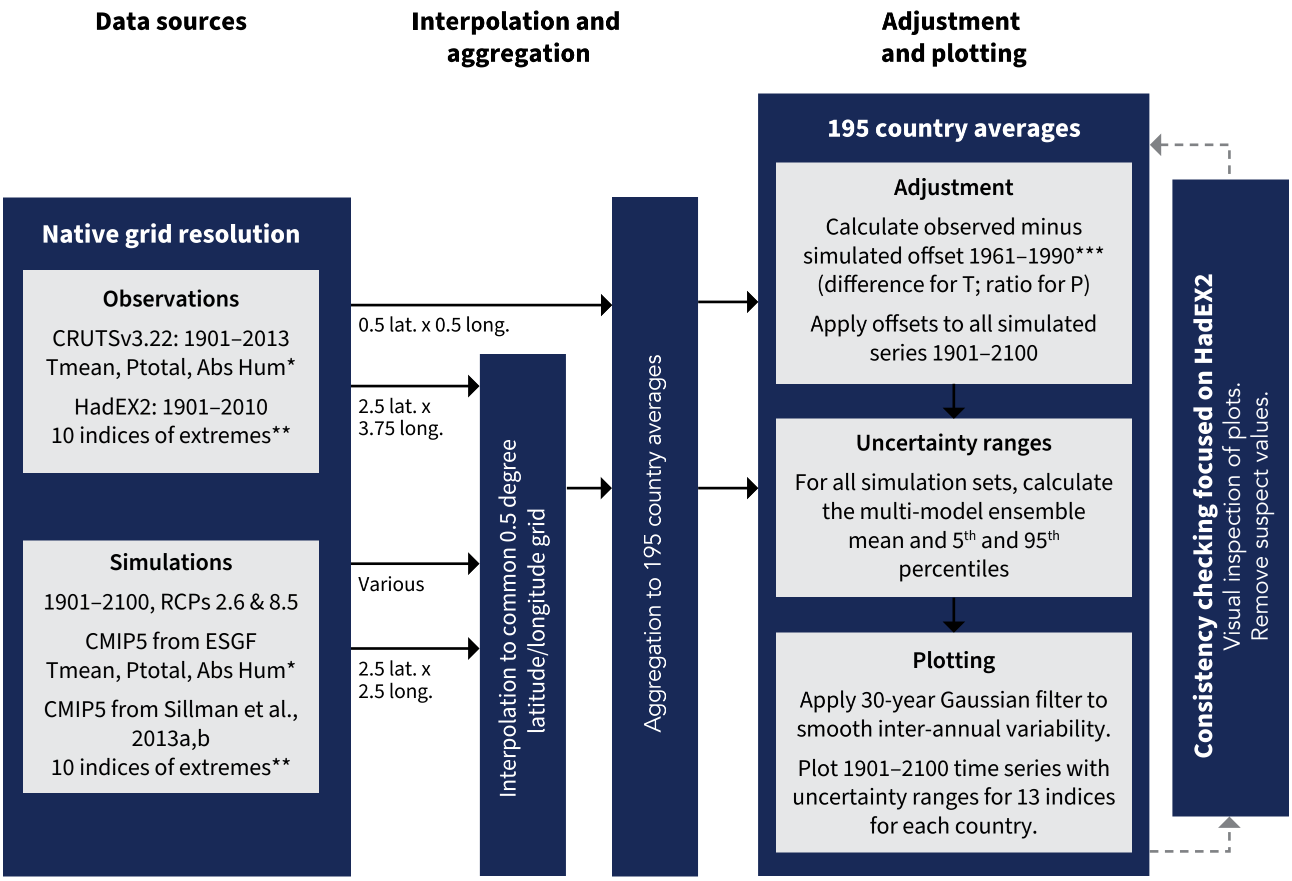
4.2 Methodology

The methodological steps of processing these data sets are summarized in workflow diagrams for Phase 1 (Figure 1) and Phase 2 (Figure 2).

After interpolation to a common grid and aggregation to the country level, offsets from observed values were used to adjust simulated values, before calculating uncertainty ranges and plotting time series. The process for Phases 1 and 2 is very similar. At the start of Phase 2, the mapping of grid boxes to countries was reviewed, focusing on the representation of SIDS, and a few minor modifications made. As a result of these modifications, averages were produced for 197 countries – two more than for Phase 1. As well as differences in the input observations (see Section 4.1), the main methodological differences between the two phases of work relate to how the simulated values were adjusted.

FIGURE 1

Flow diagram of data processing for Phase 1



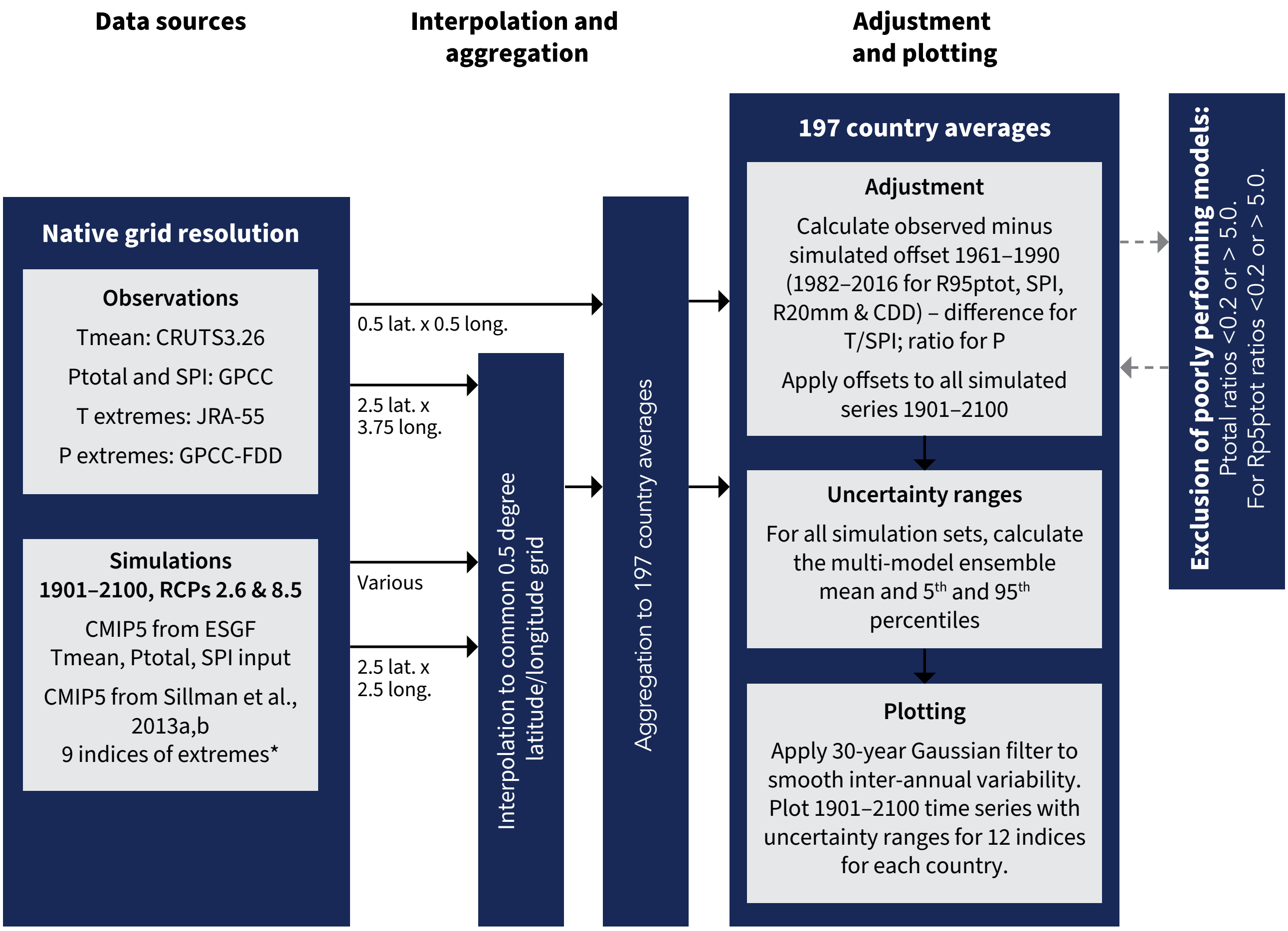
* Estimated from Tmean and Relative Humidity

** TN90P, TN10P, TX90P, TX10P, CSDI, WSDI R10mm, R20mm, CDD, R95P

*** If no observations, use multi-model mean

FIGURE 2

Flow diagram of data processing for Phase 2



* TN90P, TN10P, TX90P, TX10P, CSDI, WSDI R20mm, CDD, R95PTOT

To improve consistency between the observed and simulated data, a simple bias adjustment was used. In this approach, the GCM data are aligned with the observed baseline by using offsets between observed and simulated values for the baseline period as adjustment factors. These adjustment factors, or offsets, are then applied to the entire simulated series, on the assumption that model biases are stationary (i.e. they do not change over time). This assumption is inherent to all bias correction methods *(35, 36)*. For temperature-based indices and SPI12, observed minus simulated differences are applied in an additive way. For all other rainfall-based indices (including Ptotal and R95ptot), observed to simulated ratios are used.

In Phase 1, 1961–1990 was used in all cases as the baseline period. Where HadEX2 data were missing (see Section 4.1), the GCM ensemble mean was used. This no longer needed to be done in Phase 2, as the observed gridded data sets now being used were complete for the baseline periods. This removes a concern about the issue of systematic model bias. For temperature indices and Ptotal, the baseline period remains 1961–1990. For R95ptot and SPI12, 1982–2016 is used.

The Phase 2 bias adjustment or offset factors for SIDS were evaluated and screened for excessively high values, which can result in unrealistically high changes when applied to the future. From this assessment, it was concluded that there was no need to exclude any models for the temperature-based indices. However, several very large biases were evident for the precipitation-based indices (see Annex 2). A two-step process for automatically excluding models was therefore implemented:

1. Exclude all precipitation-based indices for models where Ptotal ratios are less than 0.2 (excessively wet models) or greater than 5.0 (excessively dry models);

2. For R95ptot, exclude models where ratios for this particular index are less than 0.2 or greater than 5.0.

In both phases of work, the same approach is used to indicate the range of uncertainty across the different climate models used (Table 3). For all simulation sets, the average of all models is calculated – this is the multi-model ensemble mean – together with the 5th and 95th percentiles. This allows identification of a 90% uncertainty or probability range, that is the range in which 90% of models fall.

In the final plotting stage, a 30-year Gaussian filter was used to smooth the year-to-year variability and time series for 1901–2100, plotted with probability ranges. The resulting figures are discussed in Section 5.

Further details of the methodology are provided in Annex 2.

CHAPTER 5

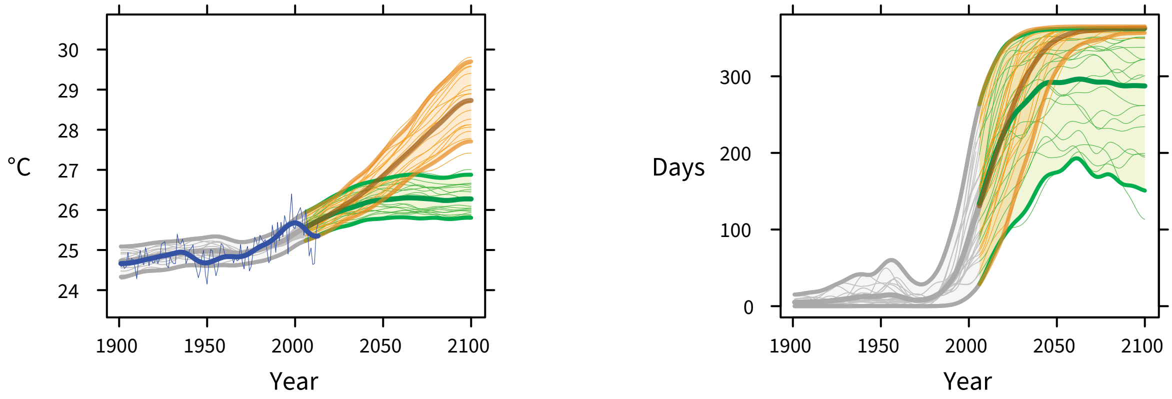
Presentation of data

5.1 Climate hazard plots

A standard layout is used to present and briefly describe the climate hazard indices in the country profiles. Examples for Jamaica are shown for Phase 1 (four indices – Figure 3) and Phase 2 (five indices – Figure 4).

FIGURE 3

Climate hazard indices from the Phase 1 country profile for Jamaica



a. Mean annual temperature

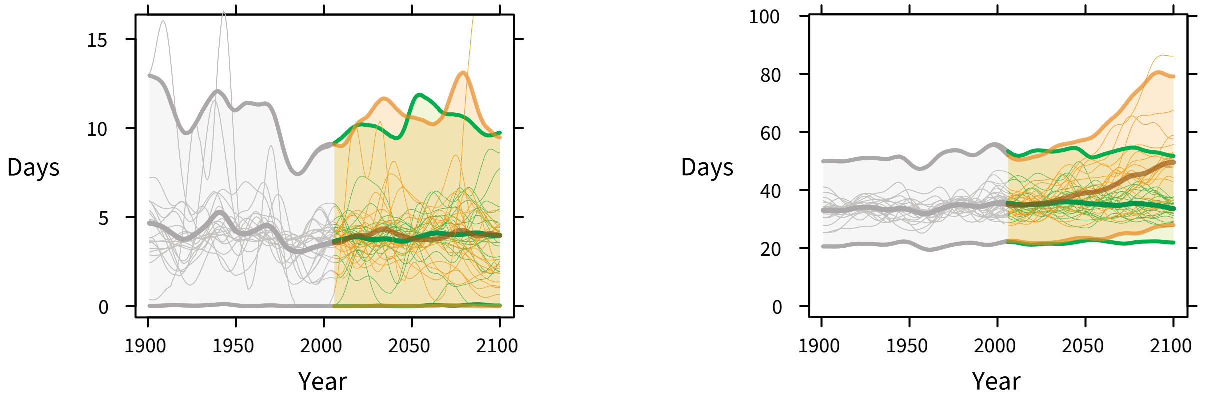
Under a high emissions scenario, mean annual temperature is projected to rise by about 3.6 °C on average from 1990 to 2100. If emissions decrease rapidly, the temperature rise is limited to about 1.1 °C.

b. Days of warm spell ('heatwaves')

Under a high emissions scenario, the number of days of warm spell is projected to increase from about 35 days in 1990 to about 360 days on average in 2100. If emissions decrease rapidly, the days of warm spell are limited to about 290 on average.

FIGURE 3

Contd.



c. Days with extreme rainfall (‘flood risk’)

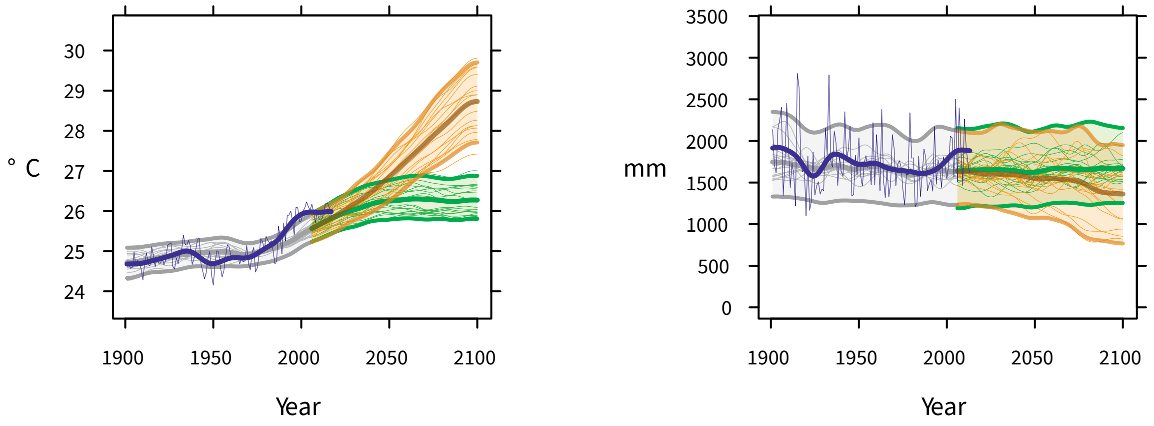
Under both high and low emissions scenarios, the number of days per year with very heavy precipitation (20 mm or more) is not expected to change much from an average of about 3 per year. The number of days with precipitation of 10 mm or more does however decrease somewhat under a high emissions scenario (from about 20 to about 15 days on average), with little change in such days and mean annual precipitation under a low emissions scenario.

d. Consecutive dry days (‘drought’)

Under a high emissions scenario, the longest dry spell could increase from about 35 days to about 50 days on average, suggesting greater persistence of droughts, with continuing large year-to-year variability and a few models indicating very large increases. If emissions decrease rapidly, there is no change on average. These changes are consistent with those in mean annual precipitation, which decreases by 15% on average under a high emissions scenario.

FIGURE 4

Climate hazard indices from the Phase 2 country profile for Jamaica



a. Mean annual temperature, 1900–2100

Under a high emissions scenario, mean annual temperature is projected to rise by about 3.0 °C on average by the end-of-century (i.e. 2071–2100 compared with 1981–2010). If emissions decrease rapidly, the temperature rise is limited to about 1.0 °C.

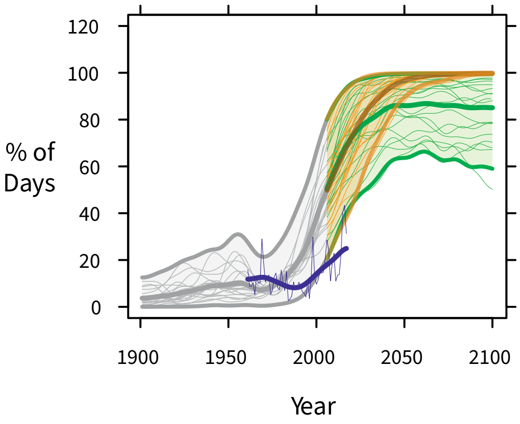
b. Total annual precipitation, 1900–2100

Total annual precipitation is projected to decrease by about 13% on average under a high emissions scenario, although the uncertainty range is large (-40% to +10%). If emissions decrease rapidly there is little projected change on average: with an increase of 2% and an uncertainty range of -8% to +13%.

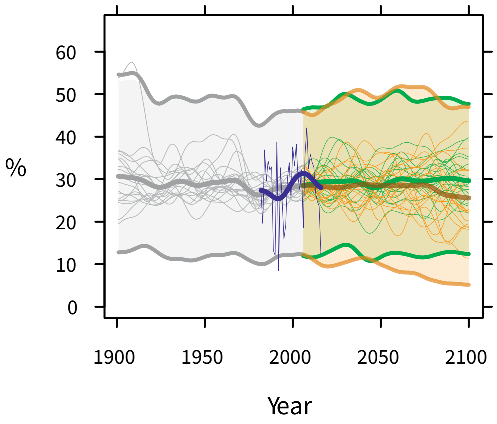
FIGURE 4

Contd.

c. Percentage of hot days ('heat stress'), 1900–2100



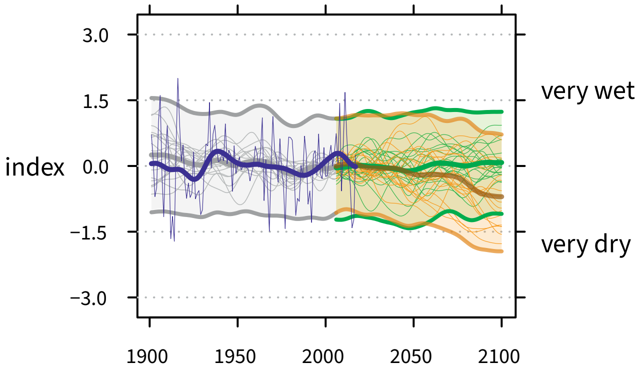
d. Contribution to total annual rainfall from very wet days ('extreme rainfall' and 'flood risk'), 1900–2100



The percentage of hot days is projected to increase substantially from about 10% of all observed days on average in 1981–2010. Under a high emissions scenario, almost 100% of days on average are defined as 'hot' by the end-of-century. If emissions decrease rapidly, about 85% of days on average are 'hot'. Note that the models over-estimate the observed increase in hot days (about 30% of days on average in 1981–2010 rather than 10%). Similar increases are seen in hot nights (not shown).

The proportion of total annual rainfall from very wet days (about 30% for 1981–2010) shows little change on average by the end-of-century, although the uncertainty range is somewhat larger particularly under a high emissions scenario (about 5% to almost 50%). Total annual rainfall is projected to decrease under a high emissions scenario (see Figure 4b). Under a high emissions scenario, mean annual temperature is projected to rise by about 3.0°C on average by the end-of-century (i.e. 2071-2100 compared with 1981-2010). If emissions decrease rapidly, the temperature rise is limited to about 1.0°C.

e. Standardized Precipitation Index ('drought'), 1900–2100



The Standardized Precipitation Index (SPI) is a widely used drought index that expresses rainfall deficits/excesses over timescales ranging from 1 to 36 months (here 12 months, i.e. SPI12). It shows how at the same time extremely dry and extremely wet conditions, relative to the average local conditions, change in frequency and/or intensity. SPI12 values show little projected change from an average of about -0.5, indicating little change on average in the frequency and/or intensity of wet episodes and drought events. Year-to-year variability remains large with both wet and dry episodes of varying intensity continuing to occur into the future.

A full set of time-series plots of all 13 (Phase 1) or 12 (Phase 2) indices (see Table 1) was produced using the same layout as the country profile plots, both before and after applying offsets or bias adjustment to the simulated data (see Section 4.2). Observed values are plotted in blue (see Table 2 for data sources). Simulated values (see Table 3 for data sources) are plotted in grey for the common historic period (1901–2005), and for the scenario period 2006–2100 in green for RCP2.6 and in orange for RCP8.5. As well as showing individual models (thin coloured lines), the multi-model mean is shown (thick coloured lines) and the 90% model range (shaded) as a measure of uncertainty.

Since the main purpose of these plots is to consider the longer-term evolution of climate over several decades, a 30-year filter is used to smooth the year-to-year variability (i.e. to smooth variations on timescales less than 30 years).

Note that in Phase 1 it was not possible to plot observed values for indices of extremes, including WSDI, R95p and CDD, for several countries, particularly SIDS such as Jamaica (Figure 3). This was due to issues with the HadEX2 data (see Section 4.1 and Annex 2 for further details).

5.2 Summary statistics

As well as summary time-series plots (Section 5.1), summary statistics were produced for Phase 2. These provide absolute average values and changes for historic and future 30-year time periods: 1961–1990, 1971–2000, 1981–2010, 2021–2050, 2035–2064 and 2071–2100.

These summary files allow a more systematic and quantitative description of the climate hazards plots for Phase 2 (Figure 4) compared with Phase 1 (Figure 3). The Phase 1 text provides an estimate of changes between 1990 and 2100, while Phase 2 quantifies the changes between the baseline period of 1981–2010 and 2071–2100. The latter period is referred to as the end-of-century. As well as giving the ensemble mean or average, the summary statistics include the 5th and 95th percentiles, allowing estimation of the 90% inter-model range, that is the uncertainty across the model ensemble.

5.3 Interpretation of the climate hazard projection plots

The text describing each climate hazard plot included in the country profiles follows a standard format (Figures 3 and 4). It is intentionally brief but nonetheless helps the reader to interpret each plot as well as providing some specific numbers, particularly for the Phase 2 profiles.

The strongest future trends in the climate hazards are seen for mean annual temperature and the temperature-related indices (Figures 3 and 4). For mean annual temperature, a clear distinction between the increases associated with RCP8.5 and RCP2.6 emerges after about 2050 (i.e. the orange and green shaded areas representing the 90% inter-model range no longer overlap). These ranges are provided as an indication of uncertainty across the particular set of 20 GCMs used here (Table 3). The latter, and indeed the full CMIP5 set of models, are a so called ‘ensemble of opportunity’. This means that the 90% inter-model range should be considered only as an indication of the possible modelling uncertainty.

The plots for the frequency of hot days show how the proportion of time each year that heat stress can occur increases very fast with a warming climate (Figure 4). For the high RCP8.5 emissions scenario, almost 100% of days on average are defined as ‘hot’ by the end-of-century for many countries. The changes are somewhat less for RCP2.6, though the inter-model range for the two emissions scenarios overlaps. Note that for some countries, the models tend to overestimate the observed increase shown in the Phase 2 plots – such cases are noted in the accompanying text (Figure 4).

The inter-model uncertainty range is generally larger for mean precipitation and precipitation-based indices of extremes, such as R95ptot and SPI12, than for temperature (Figure 4). The ranges for the two emissions scenarios always overlap for the precipitation indices. These ranges are quantified in the Phase 2 profile text for total precipitation and R95ptot. For many countries, the inter-model range extends from negative to positive, despite a negative or positive change on average. For Jamaica for example, the average change in total precipitation is a decrease of about 13%, with a 90% uncertainty range of -40% to +10% (Figure 4). Despite a tendency towards decreasing mean total annual rainfall, countries such as Jamaica do not show a decreasing trend in extreme rainfall, while other countries show a tendency towards more extreme rainfall despite little change in total precipitation. Note that some care is needed in interpreting trends in R95ptot as any trends may be due to changes in frequency or intensity of extreme rainfall (see Section 3.3).

SPI is unitless but can be used to categorize different severities of drought (wet):

- above +2.0 extremely wet
- +2.0 to +1.5 severely wet
- +1.5 to +1.0 moderately wet
- +1.0 to +0.5 slightly wet
- +0.5 to -0.5 near normal conditions
- -0.5 to -1.0 slight drought
- -1.0 to -1.5 moderate drought
- -1.5 to -2.0 severe drought
- below -2.0 extreme drought

It tends to show large year-to-year variability with both wet and dry episodes of varying intensity occurring in both the past and future. Countries such as Jamaica (Figure 4) show little change on average in SPI12, indicating little change on average in the frequency and/or intensity of wet episodes and drought episodes, while others show some tendency, particularly with a high emissions scenario, towards more positive (wetter) or negative (drier) index values – albeit with large inter-model uncertainty ranges.

Although several issues associated with both the choice of health-related indices (Section 3.3) and observed input data (Section 4.1) together with the handling of model biases (Section 4.2) were addressed in developing the Phase 2 country profiles, a number of caveats and acknowledged limitations remain. These are discussed in Section 6.

5.4 Data

Summary data and time-series plots for all five Phase II climate indices (Tmean, Ptotal, TX90p, R95ptot, SPI) are available on the Health and Climate Change Country Profiles webpage *(2)*.

The underlying data for the time-series plots are available on request at climatehealth@who.int. The data are available in .xlsx data file format. Note that the data files contain multiple data sheets, and all values are unsmoothed.

There are two versions of country summary files. The ‘indices summary’ files present 30-year means of the observations and the multi-model means, including 5th quantile, mean, and 95th quantile. The ‘delta summary’ files present 30-year means as percentage changes from 1981 to 2010, again with 5th quantile, mean, and 95th quantile of the models.

CHAPTER 6

Applications, caveats and limitations

The motivations for developing the WHO UNFCCC Climate Change and Health Country Profiles are outlined in Section 1, while the scope and underlying principles relating to the climate hazard information are listed in Section 2. Section 5.3 notes some of the issues to consider in interpreting the climate hazard plots, particularly in relation to the climate modelling uncertainty.

Some additional caveats and limitations are presented here, together with suggestions as to how these could be addressed in future phases of work.

Within-country variations

While there are many advantages in having consistent country-average climate data (see Section 2), care is needed in interpreting these values. For very large countries, such as Canada, Russia and China, the country averages may obscure large spatial variation across the country. Projected global warming is, for example, amplified at high latitude – with a strong gradient to greater warming moving northwards across Canada.

The provision of information about climate variability within countries would require the use of higher spatial resolution observations and climate model outputs. The latter could be sourced from Regional Climate Model (RCM) simulations performed as part of the World Climate Research Programme (WCRP) Coordinated Regional Climate Downscaling Experiment (CORDEX) programme. The standard CORDEX RCM simulations have a spatial resolution of between 12 and 50 km *(37, 38)*. A different set of RCMs and forcing GCMs tends to be used for different geographical domains, though a smaller set of consistent CORDEX-CORE simulations is now available *(39, 40)*.

As well as potentially giving improved representation of spatial patterns of change and variability within larger countries, the higher resolution of RCMs provides more realistic representation of the geography and topography of SIDS.

From CMIP5 to CMIP6

A new set of CMIP simulations, CMIP6 *(41)*, is now available *(42–44)*. Compared with CMIP5, the CMIP6 simulations make greater use of earth system models (ESMs), encompassing additional components of the coupled climate system, particularly those associated with the biogeochemical carbon cycle. The Working Group I report of the recently published Sixth IPCC assessment report *(20)* incorporates results from CMIP6, while the assessment of climate change impacts in the Sixth Working Group II report *(45)* is still largely based on CMIP5.

Future WHO work should encompass the more recent CMIP6 simulations, cognizant of the tendency for a number of the ESMs to have higher climate sensitivity than for the CMIP5 multi-model ensemble *(44)*. Downscaling of the CMIP6 GCM/ESM simulations using RCMs is underway, coordinated by CORDEX *(46, 47)*. Therefore, future work for the WHO profiles could combine the larger GCM/ESM ensembles with higher spatial resolution RCM simulations.

RCPs and policy targets

Both phases of the country profiles take an RCP-based time-series approach focusing on RCP8.5 (high emissions) and RCP2.6 (consistent with a 2 °C policy target). The emphasis on particular RCPs and associated shared socioeconomic pathways has shifted somewhat from CMIP5 to CMIP6 and from the Fifth to Sixth IPCC assessment reports *(48)*. This shift reflects changing understanding of current trajectories of emissions, current commitments with respect to mitigation, and a greater emphasis on a 1.5 °C policy target. It would be appropriate to review the choice of scenarios for any future phase of work.

Another possibility could be to move away from the RCP-based time-series approach to one focused on changes at the time at which global temperature reaches for example 1.5 °C, 2 °C, 3 °C and/or 4 °C above pre-industrial *(49)*. Such a move was discussed between the Climatic Research Unit and WHO at the start of Phase 2, but it was considered important to retain consistency with the Phase 1 profiles. It was also noted that the two selected RCPs (RCP2.6 and RCP8.5) clearly illustrate the co-benefits of mitigation.

Temperature extremes and heat stress

The regional consultation at the beginning of Phase 2 (see Section 1) highlighted some concerns with the use of WSDI (see Table 1) for SIDS, particularly those in tropical regions. The WMO Expert Team on Sector-specific Climate Indices (ET-SCI) held workshops in the Pacific in 2015 and the Caribbean in 2016 that calculated regional indices for, among other things, health applications. These indices encompass those from the earlier ETCCDI initiative including those used in the country profiles.

The newer ETC-SCI indices *(50)*, which can be calculated using the ClimPACT software *(51)* developed by ET-SCI, include a number of heatwave-related indices, such as heatwave amplitude (HWA), magnitude (HWM), duration (HWD), number (HWN), and frequency (HWF). These additional indices have not so far been widely adopted by the global health community. Therefore, for the Phase 2 country profiles it was agreed to replace WSDI with the relatively simple TX90p hot days index (see Section 3.3).

All the ETCCDI and newer ETC-SCI indices are based on maximum or minimum temperature only. In terms of human heat stress and thermoregulatory mechanisms however, humidity as well as temperature is important – particularly when considering changes in risk due to climate change *(15, 52–55)*. Several heat-humidity indices have been developed to capture both factors including Apparent Temperature (AT), Humidex (HD), Wet Bulb Globe Temperature (WBGT and Simplified WBGT – SWBGT) and the Universal Thermal Climate Index (UTCI) *(15, 56)*. These indices vary in complexity but are all more complex to calculate and require more input data than temperature-only heat indices, such as WSDI and TX90p. There may for example be issues with identifying humidity observations for all countries. Some heat-humidity indices also consider additional factors such as wind speed. The more direct health relevance of these indices may however justify the additional processing time and effort that would be required to calculate them for all countries.

Seasonal and year-to-year variability

Due to limited space and the principle of consistency between countries, all climate hazard indices are calculated on an annual basis, though it should be noted that the 10th/90th percentile thresholds used to calculate some of the indices (Table 1) take into account the seasonal cycle, that is the time of year. In terms of better understanding, quantifying and communicating health impacts however, it may be desirable to have information on a seasonal basis.

While the indices are calculated from daily time-series data, they are then presented as annual averages – with additional smoothing used to plot time series and to summarise average changes between 30-year periods (Section 5.2). This smooths temporal variability, including year-to-year variations. Such variability may impact on the capacity of health care systems to adapt and cope. Including some representation of this variability would, however, add to the amount and complexity of information provided. One possibility could be to present the range of the higher-frequency data instead of the inter-model range, with the latter provided in a separate plot.

Use of regional/country-specific and station data

It is acknowledged that many countries have produced more detailed climate and/or health information and assessments than are currently included in the country profiles. However, the use of observed gridded data sets with global coverage (Table 2) is preferred to the use of more local data sets and station observations. This is to maintain consistency across regions and with the grid-box averages produced by the climate models.

It is nonetheless also acknowledged that local data sets provide more relevant, representative and resonant data, particularly for many SIDS. Such data sets can also help in the interpretation of the gridded data, including reanalysis data currently used in the profiles, and to resolve any inconsistencies between observed and simulated trends. Given the need to scale-up, that is to produce profiles for all countries, it may however be problematic to automatically incorporate data that is in different formats, with varying start and end dates. Such data would also need to be subject to appropriate quality control and freely available for use in the published profiles.

CHAPTER 7

Conclusion

Despite the potential for improvement and/or provide more detailed information as outlined above, the climate hazard information provided to date in the Climate Change and Health Country Profiles meets the original purposes of empowering ministers of health and other decision makers to engage, advocate and act for health. This is particularly the case in national preparations and subsequent negotiations under the UNFCCC process (Phase 1 profiles) and as a monitoring mechanism, especially for SIDS (Phase 2 profiles). For this reason, the underlying data and supporting information for all countries, not just those with published profiles, are being made widely available through several WHO and WMO channels.

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ANNEX 1

Participation in country profile project

TABLE A1.1

Participation in country profile project. Published profiles available on project webpage (Health and Climate Change Country Profiles). Phase 1: 2015–2018 series; Phase 2: 2021–2023 series and SIDS 2020–2021

Countries and areas	2015–2018 series	2021–2023 series	SIDS 2020–2021
Algeria	🟠	–	–
Antigua and Barbuda	–	–	🟠
Austria	–	🟡	–
Bahamas	–	–	🟠
Bangladesh	🟠	–	–
Belarus	–	🟡	–
Belize	–	–	🟡
Bhutan	🟠	–	–
Botswana	🟠	–	–
Brazil	🟠	–	–
Brunei Darussalam	🟠	–	–
Bulgaria	–	🟠	–
Cambodia	🟠	–	–
China	🟠	–	–
Colombia	🟠	–	–
Croatia	–	🟡	–
Cuba	–		🟡
Cyprus	–	🟡	–
Czechia	–	🟠	–
Dominica	–	–	🟠
Dominican Republic	–	–	🟠
Egypt	🟠	🟡	–
Ethiopia	🟠	–	–
Fiji	🟠	–	🟠
Finland	–	🟡	–
France	🟠		–
Georgia	–	🟡	–
Germany	🟠	–	–

TABLE A1.1

Contd.

Countries and areas	2015–2018 series	2021–2023 series	SIDS 2020–2021
Ghana	🟠	–	–
Grenada	–	–	🟠
Guyana	–	–	🟠
Hungary	–	🟡	–
Iceland	–	🟠	–
Indonesia	🟠		–
Iran	🟠	🟠	–
Iraq	–	🟠	–
Israel	–	🟠	–
Italy	🟠	–	–
Jamaica	🟠	–	🟠
Jordan	🟠	🟡	–
Kenya	🟠	–	–
Kiribati	🟠	–	–
Kuwait	🟠	🟡	–
Lao People’s Democratic Republic	🟠		–
Lebanon	–	🟠	–
Lithuania	–	🟡	–
Madagascar	🟠	🟠	–
Malawi	🟠	–	–
Malaysia	🟠	–	–
Maldives	🟠	–	–
Malta	–	🟠	–
Mauritius	–	–	🟠
Mexico	🟠	–	–
Morocco	🟠	–	–
Mozambique	–	–	🟡
Myanmar	🟠	–	–
Nepal	🟠	–	–
Nigeria	🟠	–	–
occupied Palestinian territory, including east Jerusalem	–	🟠	–
Oman	🟠	🟡	–
Pakistan	🟠	🟡	–
Palau		–	🟡
Peru	🟠	–	–
Philippines	🟠	–	–
Romania	–	🟡	–
Saint Lucia	–	–	🟠
Samoa	–	–	🟡
Sao Tome and Principe	–	–	🟠
Slovakia	–	🟠	
Solomon Islands	–	–	🟠

TABLE A1.1

Contd.

Countries and areas	2015–2018 series	2021–2023 series	SIDS 2020–2021
South Africa	🟠	–	–
Sri Lanka	🟠	–	–
Sweden	–	🟡	–
Thailand	🟠	–	–
Timor-Leste	🟠	–	🟡
Trinidad and Tobago	–	–	🟠
Tunisia	🟠	🟡	–
Türkiye	–	–	–
Tuvalu	–	–	🟠
Uganda	🟠	–	–
United Arab Emirates	🟠*	–	–
United Kingdom	🟠	–	–
United Republic of Tanzania	🟠	–	–
United States of America	🟠	–	–
Vanuatu	🟠	–	🟠
Total number	**48**	**27**	**18**

🟠 Published profiles available 🟡 In process

* Uses Phase 2 indices with exception of SPI.

ANNEX 2

Detailed methodology

A2.1 Introduction

The data inputs and methodology used to construct climate hazard information for the Phase 1 and 2 country profiles are outlined in the main report (see in particular Section 4, Tables 1 to 3, and Figures 1 and 2).

Further technical details relating to both phases of work are provided here with respect to the data sources (Section A2.2), spatial interpolation and aggregation (Section A2.3), and bias adjustment of model simulations (Section A2.4). The technical evaluation undertaken for Phase 1 is also described (Section A2.5).

A2.2 Data sources

The observed and simulated data sets used are listed in Tables 2 and 3 respectively of the main report, including links to the data themselves. An overview of these data sets is provided in Section 4.1 of the report, with additional technical details provided below.

Observed historical record of mean temperature and precipitation – CRU TS

The CRU TS high-resolution (0.5 degrees latitude/longitude) data sets are based on monthly observations at meteorological stations across the world's land areas *(1–3)*. The number of stations used varies over time and by region and by variable. This information is provided to users alongside the gridded data. Each station series is required to have sufficient data for the base period of 1961–1990 (i.e. over 75% of non-missing values) to be used in the gridding. This allows calculation of a 30-year average (i.e. climatology) for each station, which is used to construct a time series of anomalies from this baseline for each station. Using anomalies rather than actual values helps to remove sampling biases associated with elevation. The station anomalies are then gridded in a complex process based on triangulated linear interpolation *(1)*. After gridding, the anomalies are converted to absolute values (in the case of temperature, by the addition of the gridded climatology for 1961–1990).

For the WHO Phase 1 work, mean annual temperature, precipitation and relative humidity (required to calculate absolute humidity) for 1901–2013 were taken from the gridded CRU TS 3.22 dataset. This dataset is still available although it has been superseded by more recent versions, including CRU TS 3.26 which was used to provide mean annual temperature for 1901–2017 for the WHO Phase 2 work. CRU TS 3.26 is the final version of CRU TS version 3 and is still available for download. Version 4 of CRU TS was released after completion of the WHO work. It is the first major update since Version 3 was first published in 2013 *(2)*. It features an improved interpolation process, which delivers full traceability back to station measurements. The station measurements of temperature and precipitation are provided as well as the gridded dataset and national averages for each country. Cross-validation was performed at station level, and the results can be examined in the paper *(2)* as a guide to the accuracy of the interpolation.

Observed historical records of extremes – HadEX2

For the Phase 1 WHO work, observed data for indices of extremes (Table 2 of main report) were taken from the HadEX2 gridded dataset *(4)*. These data are available on a 2.5 degrees latitude by 3.75 degrees longitude grid, extending from 1901 for the earliest series to 2010. Annual values were used for the WHO analysis, but monthly values are also available for appropriate indices.

The gridded values are based on high-quality series from over 7000 temperature and 11 000 precipitation stations covering global land areas. The HadEX2 team first calculated indices of extremes for all stations. Angular distance weighting was then used to interpolate from the station to the grid scale. Correlations were calculated for all station pairs not greater than 2000 km apart. From these values, the decorrelation length scale (DLS) was calculated for each index, that is the distance at which the correlation function falls below 1/exp (1). This is taken as the maximum search radius. It varies both by variable and region – reflecting inherent differences in spatial variability. For annual Tmax maxima (TXx) for example, DLS varies from about 400 to 800 km, while for maximum one-day rainfall (Rx1day) it was set to the minimum value of 200 km (see Figure 1 of Donat et al. *(4)*). Stations closer than the minimum distance are assigned a 'perfect' correlation of 1. A minimum of three stations were required to calculate a distance-weighted grid-box value. The weights decay exponentially from the centre of the grid box, with some consideration given to how bunched or isolated the stations used are by also considering the angle from the centre. Methodological details are given in Donat et al. *(4)* and references therein.

The HadEX2 dataset is available to download for non-commercial purposes from the UK Met. Office Hadley Centre. A full set of ETCCDI indices is available (16 temperature-related indices and 11 precipitation-related indices).

Observed historical record of mean temperature for calculation of temperature indices – JRA-55

JRA-55 *(5)* temperature data for 1955–2017 were used to calculate indices of extremes for Phase 2 of the WHO work (see Tables 1 and 2 of the main report). Time-series plots of mean annual temperature were also produced using JRA-55 and CRU TS 3.26 for SIDS and a few other countries (not shown). These plots indicate general agreement in trends from 1955 onwards, although there are systematic differences in the absolute magnitude of values from the two data sets for some locations.

The official page of the JRA-55 reanalysis provides summary information, access to the JRA-55 handbook, supporting reports and references, as well as information on usage and quality issues, together with access to the data. A quick summary, overview of benefits and limitations, and links to guidance and download pages is also available.

Observed historical record of precipitation for calculation of precipitation indices – GPCC and GPCC-FDD

Monthly precipitation data for 1901–2016 from the Global Precipitation Climate Center *(6)* were used to calculate Ptotal and SPI12 for Phase 2 (see Tables 1 and 2 of the main report). Total annual precipitation (Ptotal) for SIDS calculated from GPCC was found to show better agreement with Ptotal calculated from CRU TS 3.26 compared with JRA-55 (not shown), supporting the use of GPCC over JRA-55 for precipitation. All other precipitation indices for Phase 2 were calculated from the GPCC – Full Daily Data (GPCC-FDD) *(7)* for 1982–2016.

GPCC and GPCC-FDD are based on up to 50 000 quality-controlled station records – though as with all gridded data products, the number of stations used varies over time. The various gridded precipitation products produced by the GPCC are described in an internal report.

Model projections

The model projections are from CMIP5 *(8)* and encompass both global climate models as well as the newer generation of earth system models. For the WHO work, advantage is taken of the work done by Sillman et al. *(9, 10)* who calculated ETCCDI indices of extremes from CMIP5 outputs and made these data available. Indices were downloaded from this archive for 20 climate models for the historic 1901–2005 *(9)* and future 2006–2100 *(10)* periods. The original spatial resolution of these 20 models varies from around 8200 grid cells for the coarsest model – CanESM2

– to around 55 300 – CCSM4 (see Table 3 of the main report). All indices were, however, regridded by Sillmann et al. to a common 144 x 73 grid (2.5 degress latitude/longitude) using a first-order conservative remapping procedure *(9)*.

Data for mean temperature, total precipitation and relative humidity were downloaded directly from the Earth System Grid Federation (ESGF). For Phase 1, 18 models were available for temperature (and absolute humidity which was estimated using temperature and relative humidity – see below) and 19 for precipitation (see Table 3 of the main report). All 20 models were used for Phase 2 to calculate Tmean, Ptotal and SPI12 (see Tables 1 and 3 of the main report).

Absolute humidity (Abs Hum)

Since global datasets of observed absolute humidity are not available, and climate models do not routinely archive this variable, mean annual temperature (Tmean) was used to estimate absolute humidity (Abs Hum) in Phase 1 using the following three steps and formulae developed by Vaisala:

1. calculate saturated vapour pressure (vps)

If $\mathrm{Tmean} >= 0$

$$\mathrm{vps} = 6.107*\exp((17.38*\mathrm{Tmean})/(239.0+\mathrm{Tmean}))$$

(EQUATION 1)

if $\mathrm{Tmean} < 0$

$$\mathrm{vps} = 6.107*\exp((21.875*\mathrm{Tmean})/(265.5+\mathrm{Tmean}))$$

(EQUATION 2)

2. calculate actual vapour pressure (vp)

$$\mathrm{vp} = \mathrm{vps}*\mathrm{rh}/100.0$$

(EQUATION 3)

where rh is relative humidity

3. calculate absolute humidity (Abs Hum)

$$\mathrm{Abs\ Hum} = 2.16679*100.0*\mathrm{vp}/(273.15 + \mathrm{Tmean})$$

(EQUATION 4)

A2.3 Interpolation and aggregation

Interpolation to a common grid

CRU TS (all versions including 3.22 and 3.26 used here) is provided on the standard 'CRU' grid of 0.5 degrees latitude x 0.5 degrees longitude – with cell edges aligned with zero degrees latitude/longitude. This spatial resolution is considered an appropriate basis for aggregation to the country level. Therefore, all other observed and all CMIP5-based datasets were interpolated to this common grid, which consists of 360 (latitude) x 720 (longitude) cells, using CDO tools.

For interpolation of HadEX2 data, which has an original resolution of 2.5 degrees latitude by 3.75 degrees longitude – for land areas only, a distance weighted interpolation method was used (the *remapdis* function in CDO). A bilinear method was initially tried (as used for the climate model output at various initial resolutions (see Table 3 of the main report) taken directly from the CMIP5 archive), however land adjacent to coastlines was lost as the bilinear method requires the cell being interpolated to be surrounded by valid cells.

Aggregation from the common grid to country averages

Rcode scripts and a country 'look-up' grid were used to produce country averages from the common 0.5 degrees grid. Construction of the 'look up' grid is described by Mitchell et al. *(11)*. Each 0.5 degrees cell is allocated to a single country, then a weighted mean calculated for each country. Weighting (using the cosine of latitude of each cell) is necessary because the spatial area represented by each cell varies with latitude. The original 'look up' grid includes 289 'countries' encompassing 188 states then recognised by the UN and a further 101 islands and territories. Phase 1 work focused on 195 recognised states (as recommended by WHO), ignoring dispersed islands and territories – with two countries added for Phase 2.

For the observed HadEX2 data used in Phase 1, changes in station coverage over time cause some inconsistencies for some countries. These inconsistencies were minimised by working with anomalies from the 1961–1990 average, calculated using data only where at least 15 years of data are available during 1961–1990. Outside of this baseline range, the data were further constrained so that the number of grid boxes (cells) available for a particular year was always greater than 50% of the maximum number possible for that country and greater than 80% of the maximum number ever available for that country. As well as recording the number of available cells each year, the maximum number of possible cells and the maximum number of usable cells ever available were recorded for each country and for each of the indices of extremes. The second pair of conditions was applied primarily to remove unreliable early data. Overall, 70 countries (36% of all 195 countries) had at least one of the 10 indices of extremes set to 'missing' after application of these two conditions. Of these 70, 25 countries – all SIDS – had all indices set to 'missing'. Even where a particular index/country met both conditions, a visual consistency check revealed several issues relating to observed data quality (see Section A2.5).

A2.4 Adjustment for model bias

A simple 'bias adjustment' approach was used for both phases of work: climate model data were aligned using offsets between observed and simulated values for a baseline period. These offsets were then applied to the whole time period.

For Phase 1, 1961–1990 was used as the baseline period. Where HadEX2 observations were not available (see Section A2.3), the model ensemble mean was used instead. Figures A2.1 – A2.8 show the absolute magnitude of the adjustments for temperature and precipitation-based indices respectively, plotted as frequency distributions across 195 countries, for each index.

For temperature-based indices (Figures A2.1 – A2.4), observed minus simulated differences were applied in an additive way and the distributions of the adjustments generally appear to approximate to a normal distribution – more-or-less centred on zero for WSDI and to a lesser extent CSDI and TX90p. In the case of Tmean, many of the individual models are systematically too cold (i.e. the adjustments required are positive) or too warm (i.e. the adjustments required are negative), but overall, the multi-model distribution appears centred around zero.

For rainfall-based indices (Figures A2.5 – A2.8), observed to simulated ratios are used. While the adjustment distributions for precipitation are generally centred on one (indicating good agreement), they tend to be skewed to the right – reflecting the well-known and systematic tendency for GCMs to underestimate precipitation extremes (i.e. the magnitude and frequency of heavy rainfall and the persistence of dry spells).

FIGURE A2.1

Adjustment for Tmean index

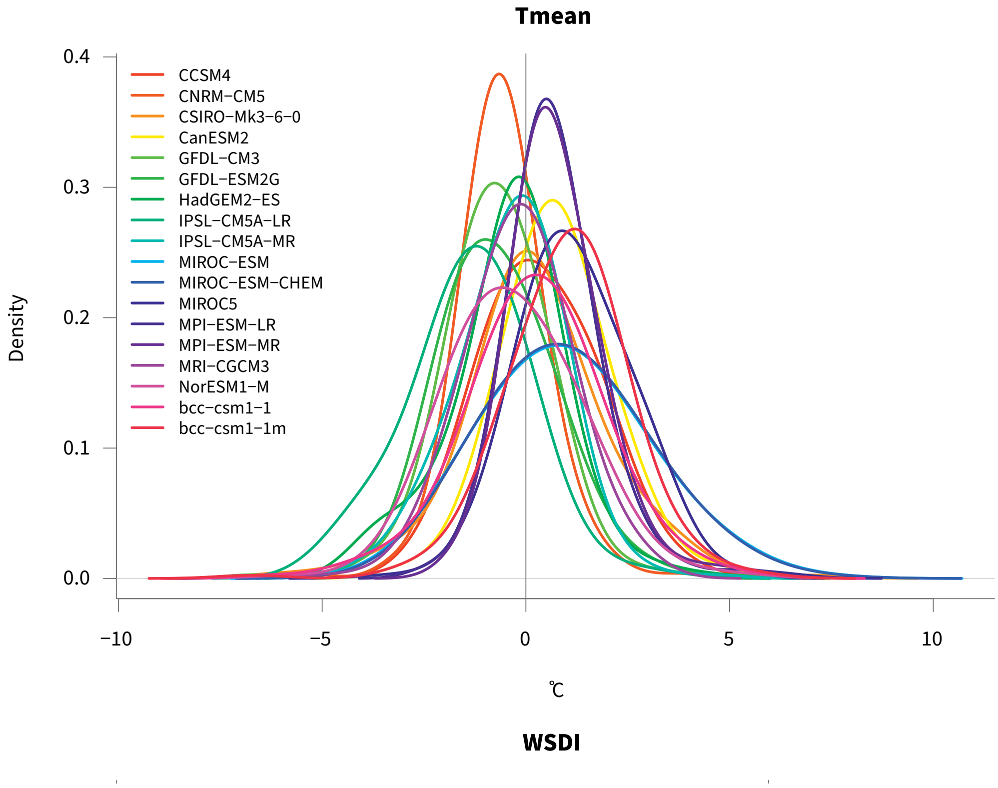


FIGURE A2.2

Adjustment for WSDI index

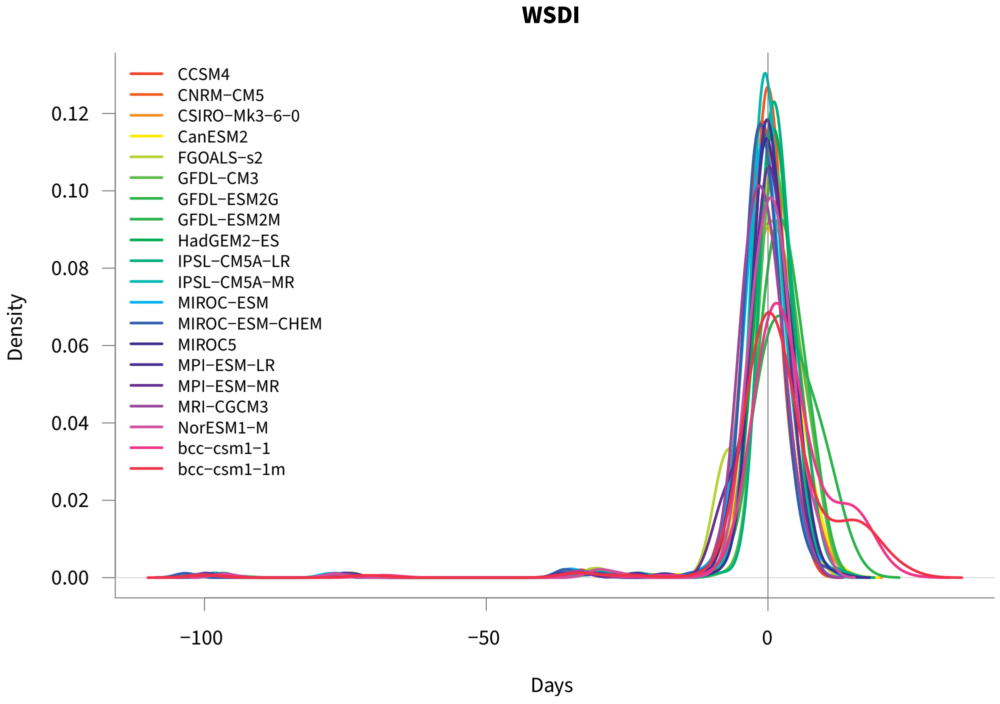


FIGURE A2.3

Adjustment for CSDI index

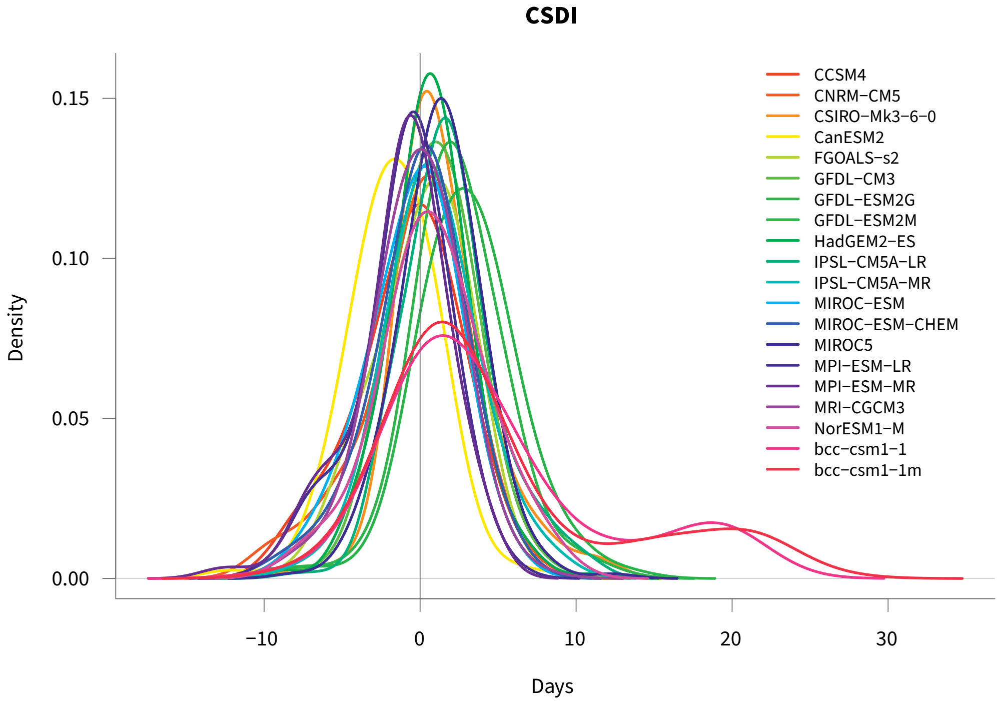


FIGURE A2.4

Adjustment for TX90p index

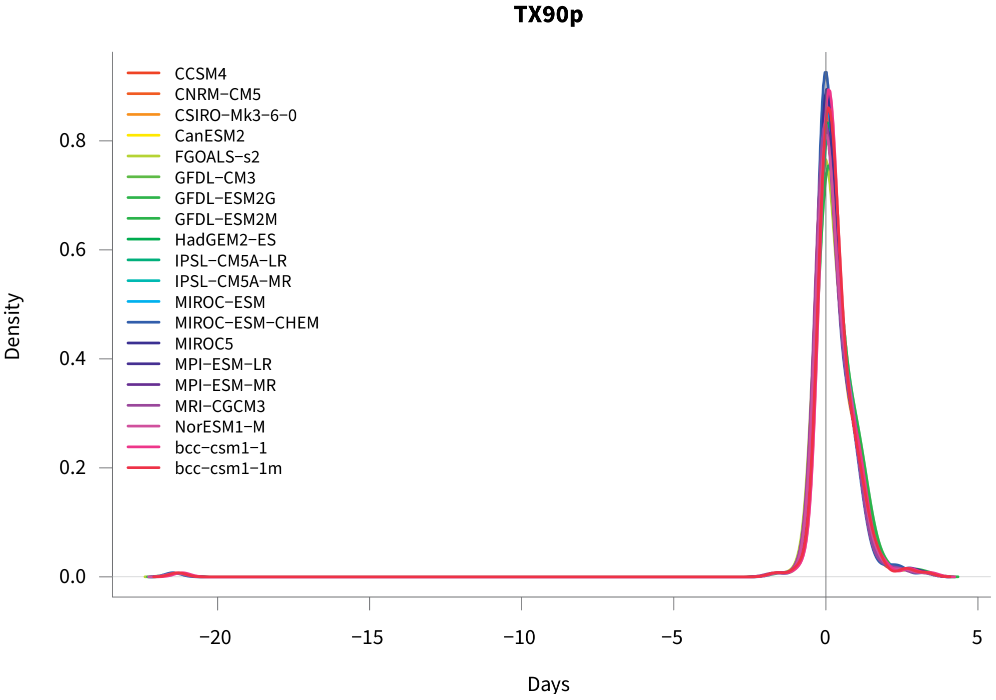


FIGURE A2.5

Adjustment for Ptotal index

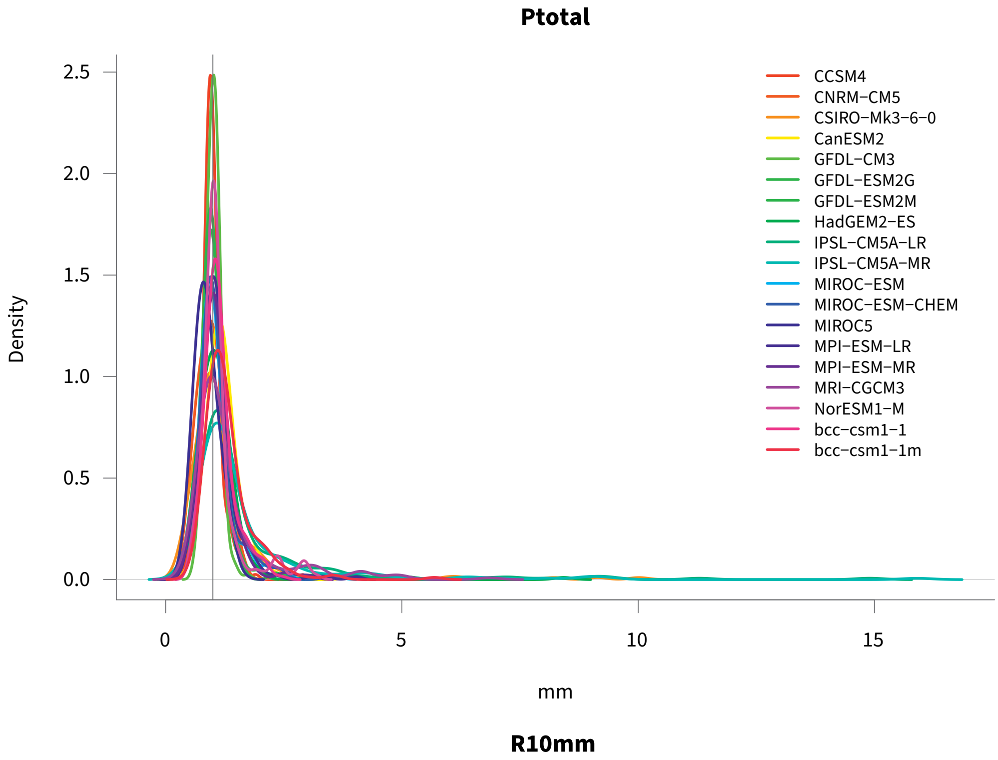


FIGURE A2.6

Adjustment for R10mm index

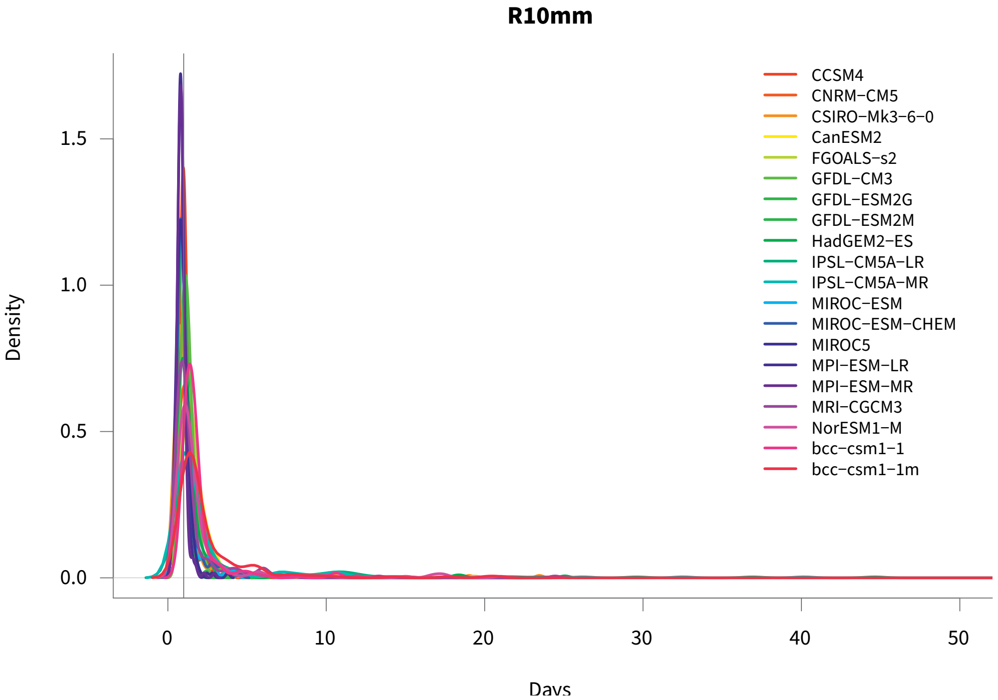


FIGURE A2.7

Adjustment for R95p index

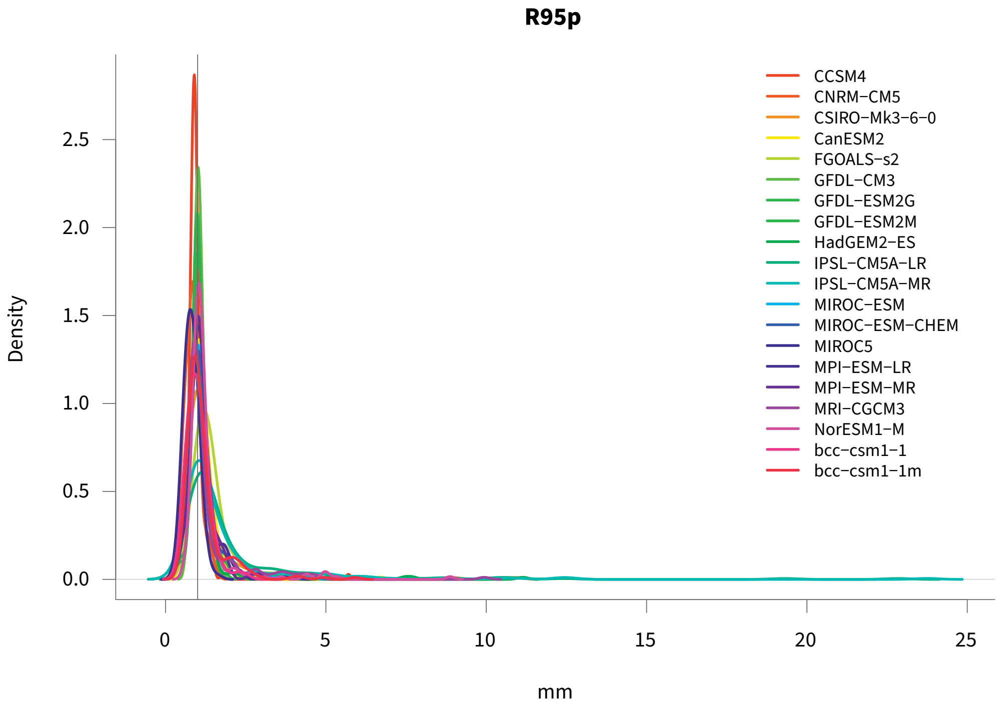
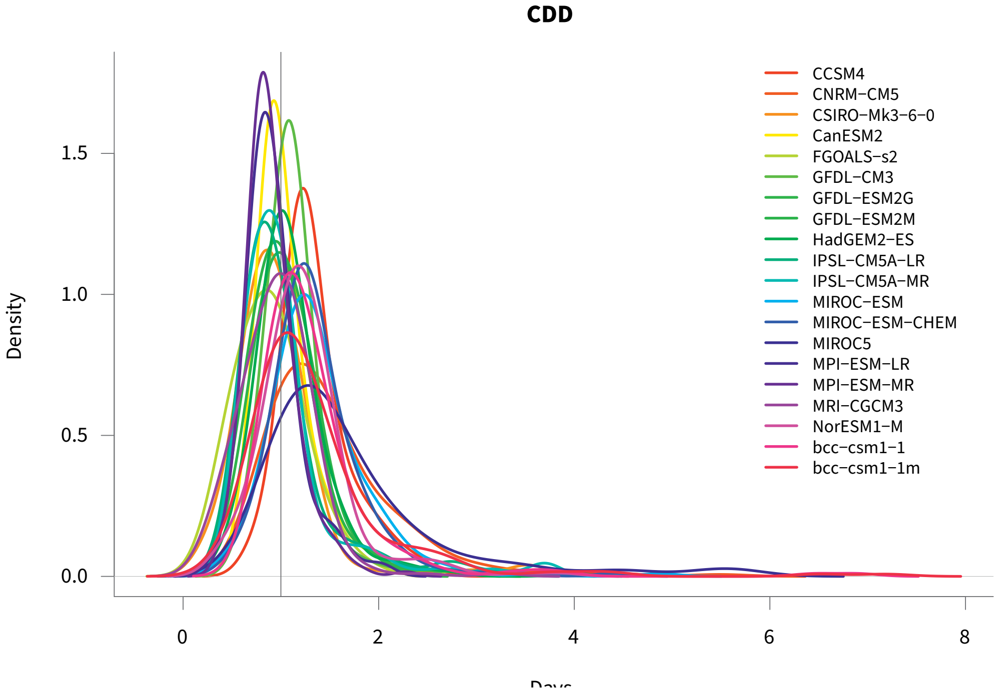


FIGURE A2.8

Adjustment for CDD index



A similar approach was adopted in Phase 2. One difference being that a baseline of 1982–2016 is used for R95ptot, SPI12 and other precipitation indices of extremes. Evaluation of the biases and adjustments required focused on SIDS (Figure A2.9 and Figure A2.10).

FIGURE A2.9

Evaluation of the biases and adjustments required for temperature indices for Small Island Developing States

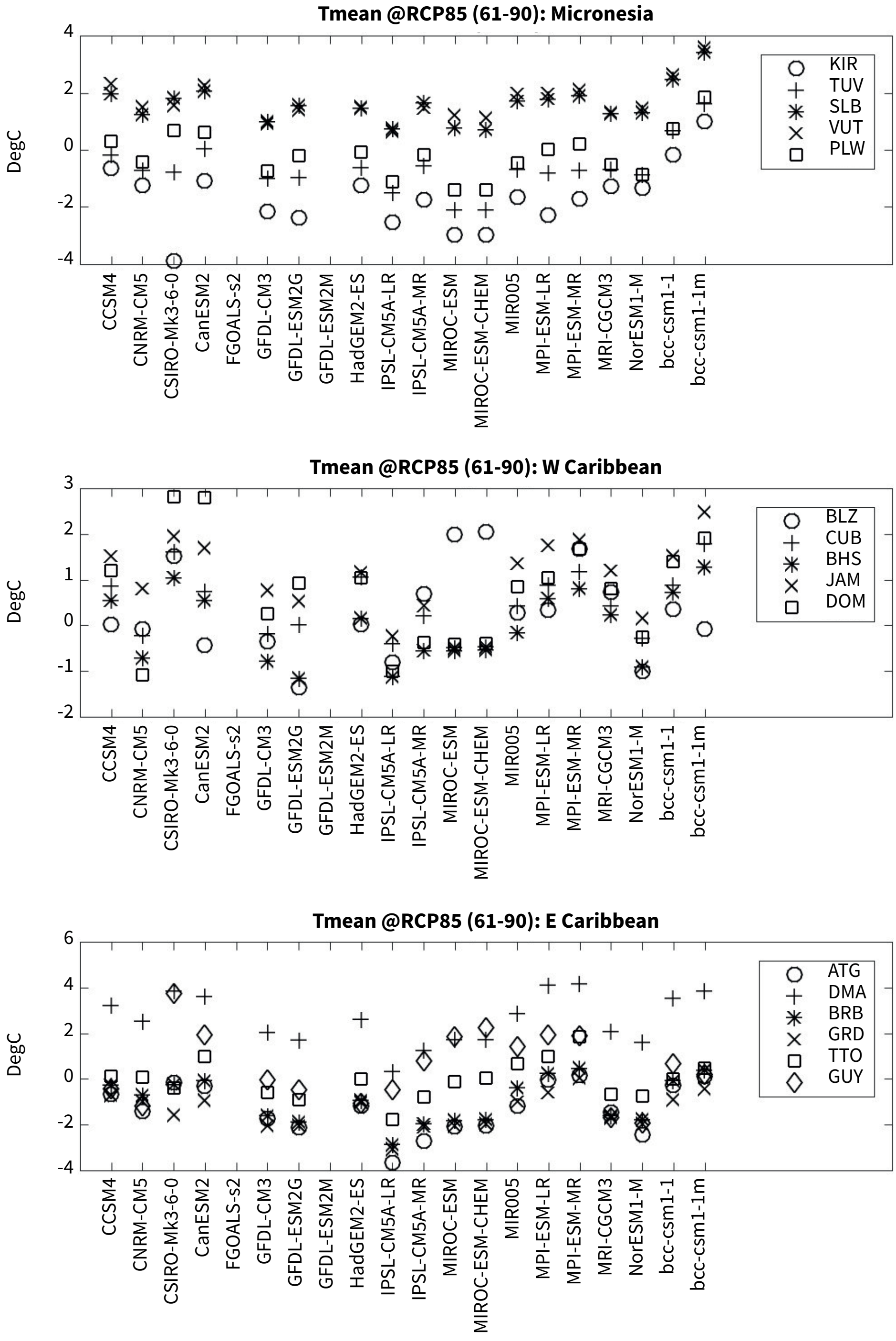
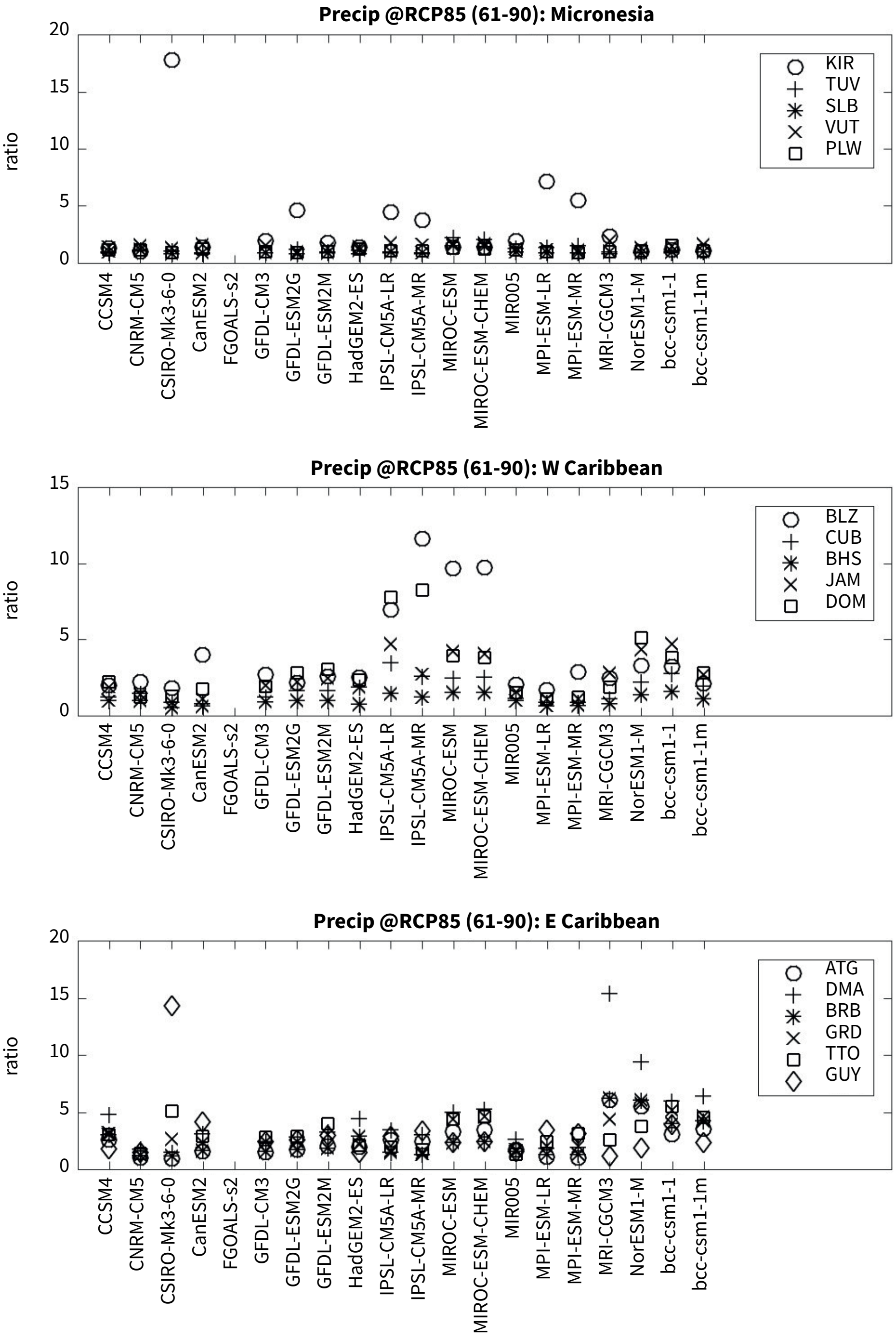


FIGURE A2.10

Evaluation of the biases and adjustments required for precipitation indices for Small Island Developing States



For temperature indices including Tmean (Figure A2.9) it was concluded that the biases were relatively small and would not have unexpected impacts on projected changes. This was not the case for Ptotal, where several SIDS had very large observed-to-simulated ratios (Figure A2.10) which resulted in implausibly large changes when applied to projections. It was therefore decided to automatically exclude all precipitation-based indices for climate models where Ptotal ratios are less than 0.2 (excessively wet models) or greater than 5.0 (excessively dry models). Figure A2.10 indicates that for SIDS in Micronesia and the Caribbean most exclusions were due to models being too dry, with ratios of 15 or more for Kiribati, Guyana and Dominica. After excluding these models, several unrealistically large projected changes in R95ptot were still seen. Therefore, the same exclusion criteria (less than 0.2 or greater than 5.0) were also applied to R95ptot. Numbers of excluded country/model pairs vary with variable and RCP scenario, ranging between 85 and 130. Additionally, one model (FGOALS-s2) was excluded for every country and precipitation variable.

A2.5 Phase 1 technical evaluation

Evaluation of HadEX2 observed data

For Phase 1, consistency checking, particularly of the observed HadEX2 data, was undertaken. Ideally this would be done in an objective and, because of the large number of countries and indices, automated way. In practice, as described below, this was not possible.

The HadEX2 data set was constructed by Donat et al. *(4)* using what were assessed by them and the data providers to be high-quality individual station records. HadEX2 is considered to have resolved some of the regional inconsistencies in the first version of this dataset (HadEX) by including additional station datasets, for example from Southeast Asia and Latin America. However, Donat et al. note that there are still large data gaps over regions such as Africa and northern South America *(4)*. It is also the case that the available network, and hence the stations used to derive any particular grid box value, changes over time. There is, however, no way for users of HadEX2 to know how many stations have been used to calculate each value, or the location of these stations. Both these characteristics will change over time and space; when the station density is higher it is expected that the stations used will be located at a closer distance to the grid cell centre.

As described in Section A2.3, constraints were applied concerning the number of years of data available, and the number of grid boxes (or cells) available to calculate a country average. As a result of applying these constraints, in addition to gaps in the underlying HadEX2 data, observed indices of extremes were not provided in some cases and gaps sometimes appeared in time series. While a minimum number of grid boxes was required to calculate a country average, it is important to recognise that, particularly for smaller countries, a grid box value may be used that was estimated in HadEX2 without using any stations from that country.

Given the lack of detailed and appropriate metadata, consistency checking had to be done in a more subjective and visual way. This made it time consuming. Here we describe the process and summarise the outcome for 47 countries. These countries were selected based on interest from a country's health ministry, rather than from any climate data consideration. They encompass countries with a broad range of sizes, including some SIDS, and with diverse geographical distribution. Therefore, they can be considered as a fairly random and representative sample with respect to the observational data issues likely to arise.

For each of these 47 countries, a visual inspection was undertaken, with the aim of identifying apparent jumps, or sudden changes in the range of variability, in the series that might be due to data issues. We also looked to see whether any trends and anomalous spikes were consistent across all precipitation indices and all temperature indices (both for the mean/total and extremes). Where potentially suspicious values were identified, they were further investigated.

In a few cases, it was found that the number of grid boxes used for calculating a country average was unstable during the earlier part of the record. This was found to be the case for WSDI for a group of neighbouring countries in Asia (Bangladesh, Bhutan, India, Nepal and Pakistan) where the number of cells used for averaging fluctuated in the earlier years of the HadEX2 series before stabilising from 1969 onwards. In the case of India, for example, the WSDI jumped from around five days prior to 1969 to around 50–60 days from 1969 onwards. In other potentially suspicious cases, the number of grid boxes was found not to vary – but as noted above, it could still be that the number and/or location of input stations is varying.

In some cases, it was possible to identify published studies confirming trends that had been identified as potentially suspicious. A systematic literature search was not, however, undertaken for all countries. After inspection of the time series, a few very large spikes were treated as missing (e.g. in CDD for Myanmar and Malawi). In contrast, the very large spike in CDD for Peru in 1984 was considered to be related to El Niño and was therefore retained.

Where problems were identified, the investigation conclusions and any modifications subsequently made to WSDI, R20mm and CDD were recorded[4]. Only these indices were modified (i.e. the values flagged as suspicious were subsequently treated as missing in the plots and data files) as they were the only indices of extremes included in the Phase 1 WHO country profiles.

Comparison of HadEX2 and model simulations

Reliable observations are essential not just for identifying past changes, but also for model validation. Sillman et al. *(9)* compared the GCM-derived indices of extremes with those from HadEX2 and four reanalysis data sets at the scale of 21 regions (five in North America, three in South America, two in Europe, four in Africa, six in Asia, and Australia). At this spatial scale, it was concluded that the "CMIP5 models are generally able to simulate climate extremes and their trend patterns" in comparison with HadEX2. Here, as described in Section A2.3, HadEX2-based values, where available, were used to apply a simple bias adjustment or offset factor. Figures A2.1 – A2.8 provide an indication of the variation in magnitude across models and countries in these adjustment factors.

A visual impression of the biases and the impact of the adjustment was obtained by comparing the unadjusted and adjusted time-series plots for individual countries (see Section 5.1 of the main report). While the HadEX2 observations were generally found to fall entirely or largely within the inter-model range for the historic period, there are some cases where they did not. This happens most frequently in the case of R20mm where the HadEX2 values lie entirely above the inter-model range for about 30% of countries. Both observed R10mm and R20mm (and often R95p) lie above the historical model range for about 9% of countries. This systematic underestimation of heavy rainfall extremes is consistent with the long right-hand tails in the distributions of the offsets used to adjust these variables (Figure A2.5 –A2.8).

In contrast, very few countries were found where the frequency of heavy rainfall extremes (Bolivia, Japan, Peru) and/or total precipitation (Bolivia, Burundi, Canada, China, Mongolia, Peru, Russia) are systematically overestimated by the models (i.e. where the observations lie below the model range). Some biases seem to be systematic for geographical regions. For example, Ptotal is systematically too high, but the frequency of R20mm underestimated, for several northwest/central European countries (Czech Republic, Denmark, Finland, France, Germany and Sweden). Ptotal is consistently underestimated across a large part of the Caribbean (10 islands including Barbados, Jamaica and Dominica, and Honduras and El Salvador). These systematic errors are likely to be associated in part with the relatively coarse

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[4] A table recording these investigations, together with tables giving HadEX2 cell counts for each country and countries with missing indices (see Section A2.3), is available on request from the authors of this report.

spatial resolution of the models compared with the size of such small island states *(12)*. In a few cases, simulated and observed WSDI values are strongly divergent (i.e. the HadEX2 observations lie some way above the model range). In the case of Bangladesh, India and Pakistan the number of warm days (TX90p) and warm nights (TN90p) are reasonably well simulated, indicating that the issue is primarily with simulating the persistence of warm spells. Whereas for New Zealand, warm days and warm nights are systematically underestimated along with the persistence (WSDI).

Inconsistencies between observed, particularly HadEX2 values used in Phase 1 of the WHO work, and simulated values may arise due to issues with the observations as well as the model simulations. Indeed, many of the issues identified during Phase 1 were, as described above, related to issues with the observations. Although detailed evaluation was not possible for Phase 2, it is anticipated that the improved observational datasets used (see Section 2 above and Section 4.1 of the main report) should have eliminated or reduced many of the earlier issues. The removal of models with particularly large biases in precipitation (see Section A2.4) should also help to ensure more reliable projections for Phase 2.

As with any time series, care is still needed in interpreting/extrapolating short records or trends. In some cases, where observed and simulated precipitation trends appear contradictory, these may simply reflect decadal variability rather than longer-term trends. Care is also needed in interpreting smoothed trends at the start and particularly the end of time series. The first/final 14 years of the climate hazard time series are smoothed by repeating the first/final time series values – following the now standard approach of Jones et al. *(13)*. Therefore, any strong upward or downward trend at the end of the series will be underemphasised and the direction of trend may even be reversed.

Users of the climate hazards information and data sets are encouraged to undertake their own evaluation and cross-checking for the countries in which they are interested. It may, for example, be helpful to look at all available indices (see Table 1 of the main report), rather than just a single temperature or precipitation index, to determine whether or not past and/or future trends are consistent.

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