SimClim AR6

Data and Methodology

Dr Chonghua Yin

January 2023

Updated Feb 2024

Reviewed by Drs Yinpeng Li
and Peter Urich

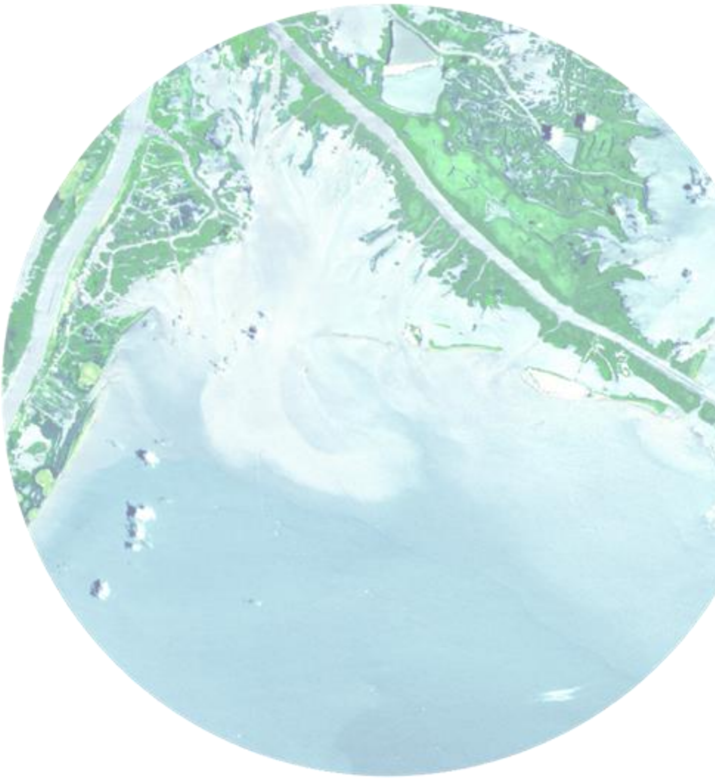

Table of Contents

Disclaimer - Limitations

This document was prepared for SimClim end users. The data and methods presented in this document represent ClimSystems' professional judgment based on information made available at the time of writing. They are true and correct to the best of ClimSystems' knowledge as at the date of this document's development.

ClimSystems did not independently verify either written or oral information provided during the development of this document. While ClimSystems has no reason to doubt the accuracy of the information provided, the document is complete and accurate only to the extent that the information provided was itself complete and accurate.

ClimSystems takes great care to ensure the climate information in this document is as correct and accurate as possible. The climate information provided is subject to the uncertainties of scientific and technical research, may not be accurate, current, or complete, is subject to change without notice and is not a substitute for independent professional advice. Users should obtain any appropriate professional advice relevant to their particular circumstances. ClimSystems does not guarantee the information provided and accepts no legal liability whatsoever arising from or connected to the use of any material contained therein.

Climate design data analytics is, by its nature, a dynamic and ongoing process. Therefore, it is recommended that the end-user routinely incorporate the latest climate data into all future planning.

ClimSystems recommends that the end-user uses their skill and care concerning their use of the climatic design information, and those users carefully evaluate the accuracy, currency, completeness, and relevance of the material for their purposes. Any use of the data is solely at the end-users' own risk. We understand that no party can rely upon the results of the assessments for planning purposes.

To the extent permitted by law, ClimSystems makes no representation or warranty (expressed or implied) as to the merchantability or performance of the data, about the fitness of the data for the permitted use, or that the data does not infringe the intellectual property rights or any other right of any person. The end-user indemnifies and releases ClimSystems against all claims, demands, suits, liability, loss or expense arising directly or indirectly from the end user's application of the data or any breach of this agreement by the end-user. This document does not purport to give legal advice. Qualified legal advisors can only give this advice.

This data has been prepared exclusively for licensed end users of the SimClim cloud-based tool and may not be relied upon by any other person or entity without ClimSystems' express written permission.

1. Introduction

Climatic data management, analysis, and visualisation are the most elementary functions of the SimClim software system. Climatic data may come from various sources and may have different characteristics: for example, spatial resolutions, data formations, and periods. According to specific cases, these data are post-processed, standardised, and then maintained by ClimSystems for inclusion in SimClim.

SimClim supports both spatial and site data. For the former, a region is used as the minimum data management unit, ranging from global to a relatively small river basin, state, province, or city. Whatever the spatial scale, climatic data can be divided into baseline and future climate change periods. A baseline period defines the observed climate with which climate change information is usually combined to create a climate scenario. When using climate model results for scenario construction, the baseline also serves as the reference period from which the modelled future change in climate is calculated.

Since SimClim follows the IPCC guidelines (currently the Sixth Assessment Report), SimClim AR6 mainly focuses on the IPCC CMIP6 datasets, and the baseline period generally ranges from 1991 to 2020 (centered on 2005). In SimClim AR6, the most basic spatial dataset (baseline and future) is run at the global scale of 0.5°×0.5° resolution. Higher spatial resolution study areas for other regions are generally derived from this dataset through nonlinear/linear interpolation methods.

As for the site data, they belong to the observational data set and are collected from global, publicly available observation networks or national Meteorological Departments. They are managed and visualised worldwide without using particular regions, as their spatial locations are defined by their latitude and longitude.

This manual presents the details of the data sources and the corresponding standardisation methods in two parts: Part 1 for spatial data and Part 2 for site data.

2. Spatial Data

2.2 Global Baseline Climatology

The original data populating SimClim AR6 represented by global baseline climatology of different variables were obtained from various publicly accessible data sources. The data sources were selected based on our best knowledge concerning the data quality. A ***bilinear interpolation*** method was applied to interpolate the data from their original resolution to 0.5°×0.5° degrees.

2.2.1 Temperature

Mean, maximum, and minimum temperatures for the land area are extracted from the gridded Climatic Research Unit (CRU) Time-series (TS) data version 4.05 data (i.e., CRU_ts4.05[1)]. The data are month-by-month variations in climate over the period 1901-2020, provided on high-resolution (0.5 x 0.5 degree) grids, produced by CRU at the University of East Anglia and funded by the UK National Centre for Atmospheric Science (NCAS), a NERC collaborative centre.

The temperature data for the ocean were derived from ECMWF Reanalysis v5 (ERA5[2]), the fifth generation ECMWF atmospheric reanalysis of the global climate covering the period from January 1950 to the present (1950-2023). The data cover the Earth on a 30km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80km.

Both datasets are extracted from 1991 to 2020 as the baseline period and then are transformed into monthly climatology for each temperature variable.

2.2.2 Precipitation

Land precipitations are extracted from CRU_ts4.05, while ocean precipitation is extracted from ERA5, just like the temperatures.

2.2.3 Wind speed

SimClim global wind speed baseline is a monthly climatology produced from ERA5 from 1991 to 2020.

---

[1] https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.05/

[2] https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

2.2.4Solar radiation

SimClim global wind solar radiation baseline is a monthly climatology produced from ERA5 from 1991 to 2020.

2.2.5 Relative humidity

SimClim global relative humidity baseline is a monthly climatology produced from ERA5 from 1991 to 2020.

2.2.6 Other variables

Other variables, such as Sea Surface Temperature (SST), can be transformed and inserted into SimClim AR6 data sets on demand.

1.2 Regional and county-specific historical climate data

An area whose spatial scale is smaller than the global scale is defined as a region in SimClim AR6. The most commonly used region is the country. Sometimes, a region can be drilled down into smaller areas, such as the Upper Mekong River Basin versus the Lower Mekong River Basin.

A regional data source and spatial resolution are typically derived through discussion between the end users of SimClim AR6 and the development team at ClimSystems. This consultation is conducted to provide the best data package to the end user. Generally, the smaller the region, the higher the spatial resolution. At the country level, the GCM projections and baseline data are provided at a 1km spatial resolution (about 0.008333333 degrees) in most cases.

For a specific region (country or area), producing a regional climate dataset depends on the availability of baseline and future climate change projection data from local agencies. For example, some countries (such as the USA and Australia) carry out downscaling projects to produce more detailed regional climate change projections. *The principle is that ClimSystems will adopt local data as much as possible* and then fill data gaps using publicly available data using the most appropriate interpolation method to generate a reasonable spatial resolution.

If there are datasets produced by national/local agencies, whenever possible or through the request of end users, ClimSystems will adopt local data for application in SimClim AR6. Taking the USA as an example, we have adopted

PRISM data as the baseline and applied the BCSD (a statistical downscaling method) generated GCM projections to produce climate change patterns for the USA. An incomplete list of country-specific baselines is presented in Table 1. Moreover, as more country-specific historical data become available, Table 1 will also be updated.

If there are datasets for the baseline period for a region but no climate change projection data, ClimSystems uses the pattern scaling method to produce the change patterns and then interpolates the data to a pre-defined resolution. On the other hand, if there are no historical data available for some regions, the data from the WorldClim Version 2[3] combined with CRU TS4.05 will be applied. The WorldClim data includes average monthly climate data for minimum, mean, and maximum temperature and precipitation at a high spatial resolution of about 1km. However, the data were created only for 1970-2000. Therefore, it was adjusted to 1991-2020 with the CRU TS4.05 through a spatial bias correction procedure. In a word, the baseline data may be produced from different data sources; however, we will use our professional judgment to select the most appropriate one (i.e., fit for purpose).

According to our rich experience, a good baseline is vital for successful regional impact assessments of climate change. We are always open and welcome our users to provide regional historical data.

Table 1: Samples of country-specific baseline data processed for SimClim AR6

Country and Climate variable	**Data sources**	**Spatial resolution (degree)**
USA		
Monthly climate data	USA: PRISM: https://prism.oregonstate.edu/normals/	0.0083333
Daily climate data	Daymet: https://daymet.ornl.gov/	0.0083333
Extreme	NOAA ATLAS14:	0.0083333

[3] http://www.worldclim.com/version2

precipitation	https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html	
Australia		
Monthly climate data	BOM: http://www.bom.gov.au/climate/data/	0.025
Daily climate data	BOM: http://www.bom.gov.au/climate/data/	0.05
New Zealand		0.05
Monthly climate data	NIWA: https://niwa.co.nz/climate/our-services/obtaining-climate-data-from-niwa	0.00833333
Daily climate data	NIWA: https://niwa.co.nz/climate/our-services/obtaining-climate-data-from-niwa	0.05
Daily (hourly) 30-year hindcast climate data	New Zealand Met Service: ▪ Precipitation ▪ Air temperature ▪ Solar radiation ▪ Relative humidity ▪ Potential Evapotranspiration ▪ Wind speed	0.03333332
Canada		
Monthly climate data	Daymetv4 (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=2129) NATURAL RESOURCES CANADA https://uwaterloo.ca/library/geospatial/collections/canadian-geospatial-data-resources/canada/climate-dataset-	0.1

	daily-10-km-grids	
Daily climate data	Daymetv4 (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=2129) NATURAL RESOURCES CANADA NATURAL RESOURCES CANADA https://uwaterloo.ca/library/geospatial/collections/canadian-geospatial-data-resources/canada/climate-dataset-daily-10-km-grids	0.1

Europe		
Daily climate data	EMO5 data: https://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/CEMS-EFAS/ E-OBS daily gridded meteorological data for Europe from 1950 to the present derived from in-situ observations: https://cds.climate.copernicus.eu/cdsapp#!/dataset/insitu-gridded-observations-europe?tab=overview	0.05
Germany	ftp://ftp-cdc.dwd.de/pub/CDC/help/gk3.prj	1km
Netherlands	https://dataplatform.knmi.nl/	Stations
Norway	https://thredds.met.no/thredds/catalog.html	1km
UK	https://catalogue.ceda.ac.uk/uuid/89908dfcb97b4a28976df806b4818639	1km

Spain	http://www.meteo.unican.es/en/datasets/spain02	0.1 degree
	UKCP data: https://catalogue.ceda.ac.uk/uuid/319b3f878c7d4cbfbdb356e19d8061d6	5km
China		
Daily Climate data	CMA: https://data.cma.cn/en/?r=data/index	0.5 degree
Russia	http://search.diasjp.net/en/dataset/APHRO_RU	0.25 degree
Japan	https://climatedataguide.ucar.edu/climate-data/aphrodite-asian-precipitation-highly-resolved-observational-data-integration-towards	0.05
Other Country-specific data for validation	Various international sources	

2.3 Global ESM Climate Change Data

SimClim AR6 ClimSystems follows the IPCC Sixth Assessment Report (AR6) and applies the corresponding CMIP6 data as its underlying future projections. The data under different Shared Socioeconomic Pathways (SSPs) for IPCC AR6 are publicly available. These data are generally produced and maintained by their respective research institutes. Moreover, these data have different spatial resolutions (Table 2). For the convenience of analyses, all data were processed by a ***pattern scaling*** method and then were re-gridded to a standard 720 × 360 grids (i.e., 0.5° × 0.5° spatial resolutions in longitude and latitude) using a ***bilinear interpolation*** method.

2.3.1 Shared Socioeconomic Pathways for IPCC AR6

The GCM data in SimClim is from CMIP6, the data source for IPCC AR6 climate change projections. For more information on CMIP6, please visit https://esgf-node.llnl.gov/projects/cmip6/.

When applying CMIP6, its ancestor, CMIP5, usually has to be mentioned as they share many common concepts. A short overview of the critical differences between CMIP5 and CMIP6 is provided. The vital difference between CMIP5 and CMIP6 is the future scenarios. The CMIP5 used the Representative Concentration Pathways (RCPs) to describe future scenarios such as RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The CMIP6 applies the Shared Socioeconomic Pathways (SSPs), including SSP 1-1.9, SSP1-2.6, SSP2-4.5, SSP4-6.0, and SSP5-8.5 (*Figure 1*).

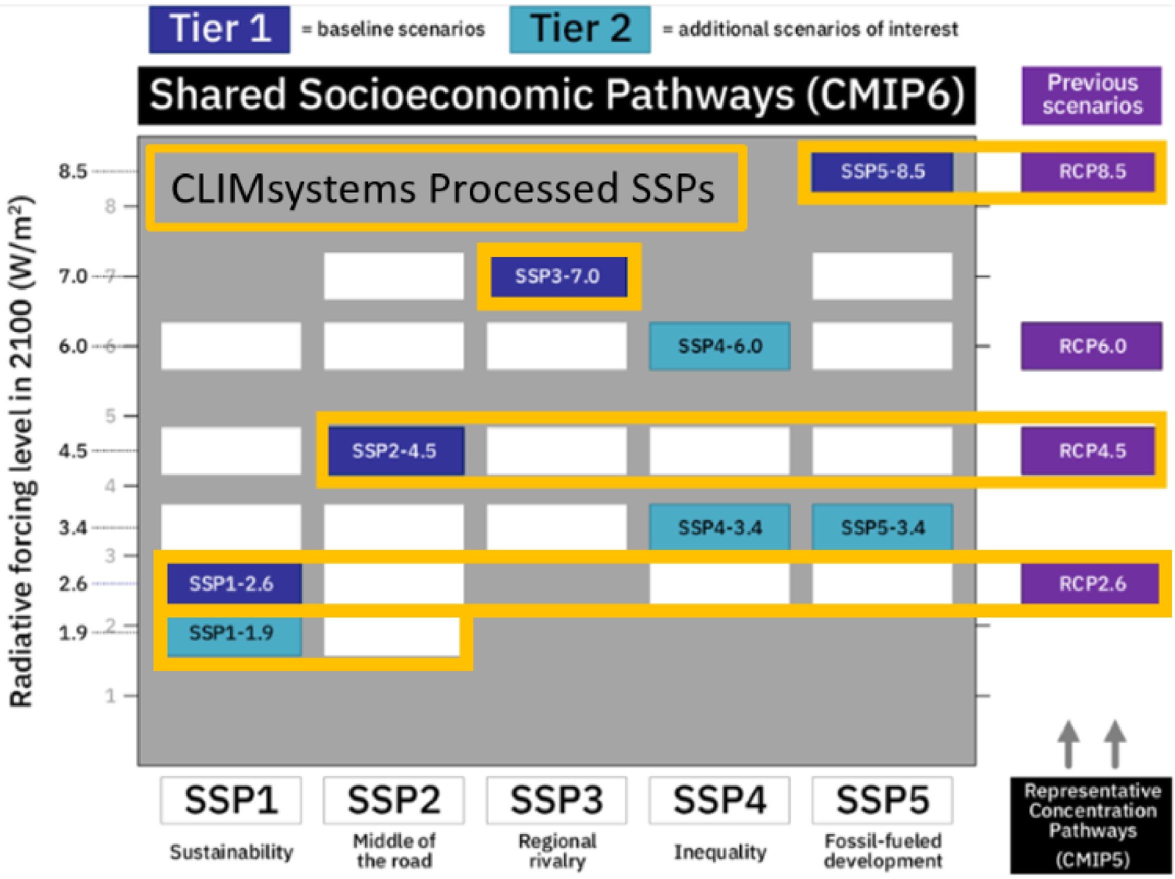

Figure 1: IPCC AR6 Shared Socioeconomic Pathways compared with CMIP5 Representative Concentration Pathways (RCPs)

For example, the broad SSP2 is a scenario in which the world follows a path where social, economic, and technological trends do not shift markedly from historical patterns. Comparably, SSP5 is a scenario where the world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress and the development of human capital as the path to sustainable development.

In general, several models have notably higher climate sensitivity than models in CMIP5. This higher sensitivity contributes to projections of more significant warming this century – around 0.4°C warmer than similar scenarios run in CMIP5 – though these warming projections may change as more models become available. Specifically, scenarios were chosen to provide a range of distinct end-of-century climate change outcomes.

Several new scenarios are also used for CMIP6 to give scientists a wider selection of futures to simulate. These scenarios are included in the chart below, which shows the radiative forcing levels to 2100. The new scenarios that can be applied for risk and vulnerability assessments are limited to the following five: ***SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5***.

A brief description of the five SSPs is presented as follows:

- ***SSP1***: The sustainable and "green" pathway describes an increasingly sustainable world. Global commons are being preserved; the limits of nature are being respected. The focus is more on human well-being than on economic growth. Income inequalities between states and within states are being reduced. Consumption is oriented towards minimising material resources and energy usage.
- ***SSP2***: The "Middle of the road" or medium pathway extrapolates the past and current global development into the future. Income trends in different countries are diverging significantly. There is certain cooperation between states, but it is barely expanded. Global population growth is moderate, leveling off in the second half of the century. Environmental systems are facing a certain degradation.
- ***SSP3***: Regional rivalry. A revival of nationalism and regional conflicts pushes global issues into the background. Policies increasingly focus on questions of national and regional security. Investments in education and technological development are decreasing. Inequality is rising. Some regions suffer drastic environmental damage.
- ***SSP4***: Inequality. The chasm between globally cooperating developed societies and those stalling at a lower developmental stage with low income and a low level of education is widening. Environmental policies are successful in tackling local problems in some regions but not in others.
- ***SSP5***: Fossil-fueled Development. Global markets are increasingly integrated, leading to innovations and technological progress. The social and economic development, however, is based on an intensified exploitation of fossil fuel resources with a high percentage of coal and an energy-intensive lifestyle worldwide. The world economy is growing, and local environmental problems such as air pollution are being tackled successfully.

2.3.2 Brief GCM Description

Global Climate Models (GCM)[4] solve budget equations numerically on a computer. The equations are based on energy conservation, momentum, and mass (air, water, carbon, and other relevant elements, substances, and tracers). Typically, they are solved in separate boxes representing specific regions of Earth's climate system components (Figure. 2). Along their boundaries, the boxes exchange energy, momentum, and mass. Exchange with the flow of water or air from one box to another is called advection. Prognostic variables such as temperature, specific humidity in the atmosphere, or salinity in the ocean, as well as three velocity components (zonal, meridional, and vertical), are calculated in each box. The momentum equations, which are used to calculate the velocities, are based on Newton's laws of motion, and they include effects of the rotating Earth, such as the Coriolis force. The temperature equations are based on the laws of thermodynamics. Thus, climate models represent the fundamental laws of physics as applied to Earth's climate system.

[4] https://open.oregonstate.education/climatechange/chapter/models/

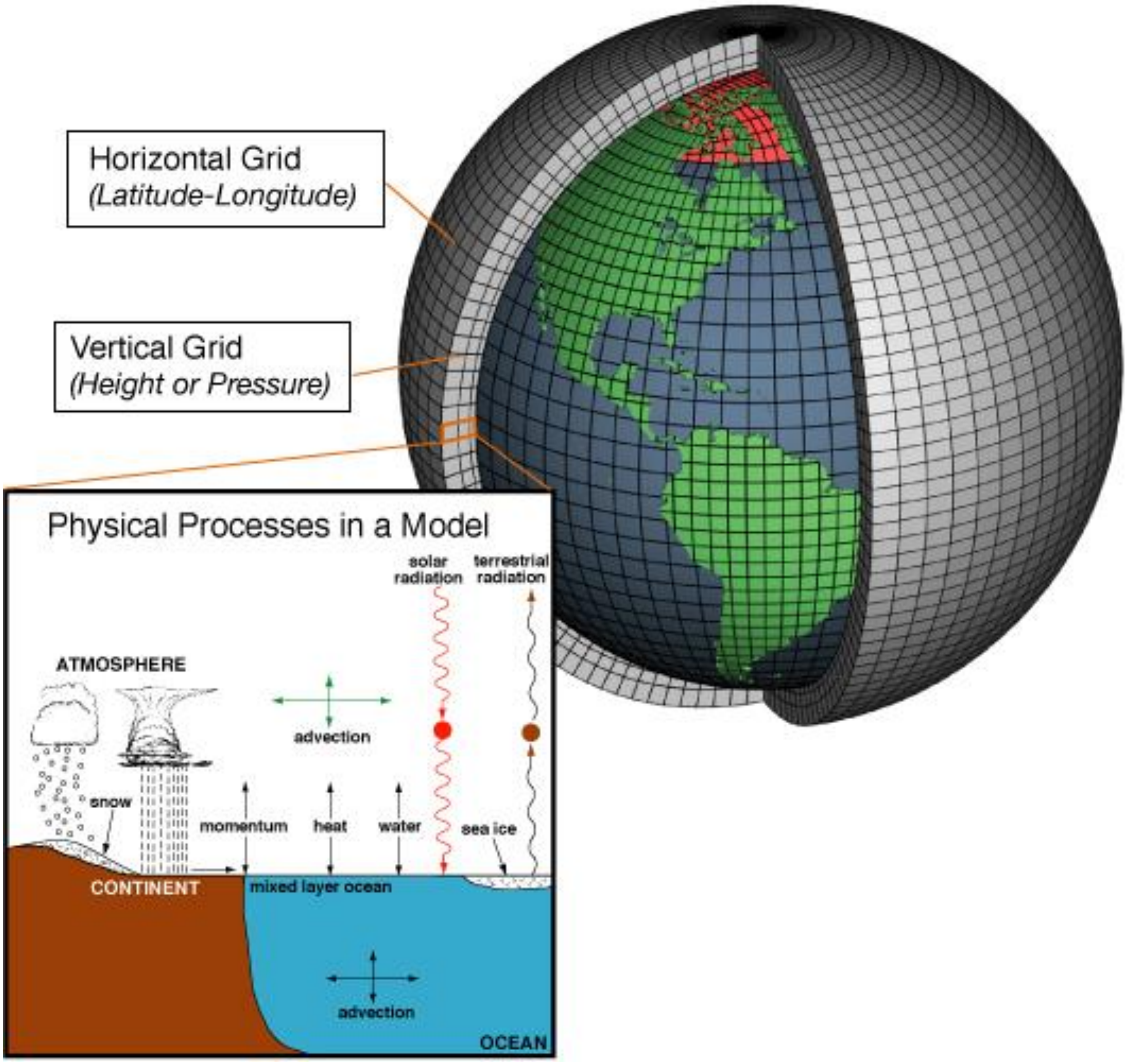

Figure 2: Schematic of a three-dimensional coupled climate model. From wikipedia.org.

Early GCMs only simulated one aspect of the Earth system – such as in "atmosphere-only" or "ocean-only" models – but they did this in three dimensions, incorporating many kilometres of height in the atmosphere or depth of the oceans in dozens of model layers. More sophisticated "coupled" models have brought these different aspects together, linking together multiple models to provide a comprehensive representation of the climate system. Coupled atmosphere-ocean general circulation models (or "AOGCMs") can simulate, for example, the exchange of heat and freshwater between the land and ocean surface and the air above.

The infographic below shows how modellers have gradually incorporated individual model components into global coupled models over recent decades (Figure 3).

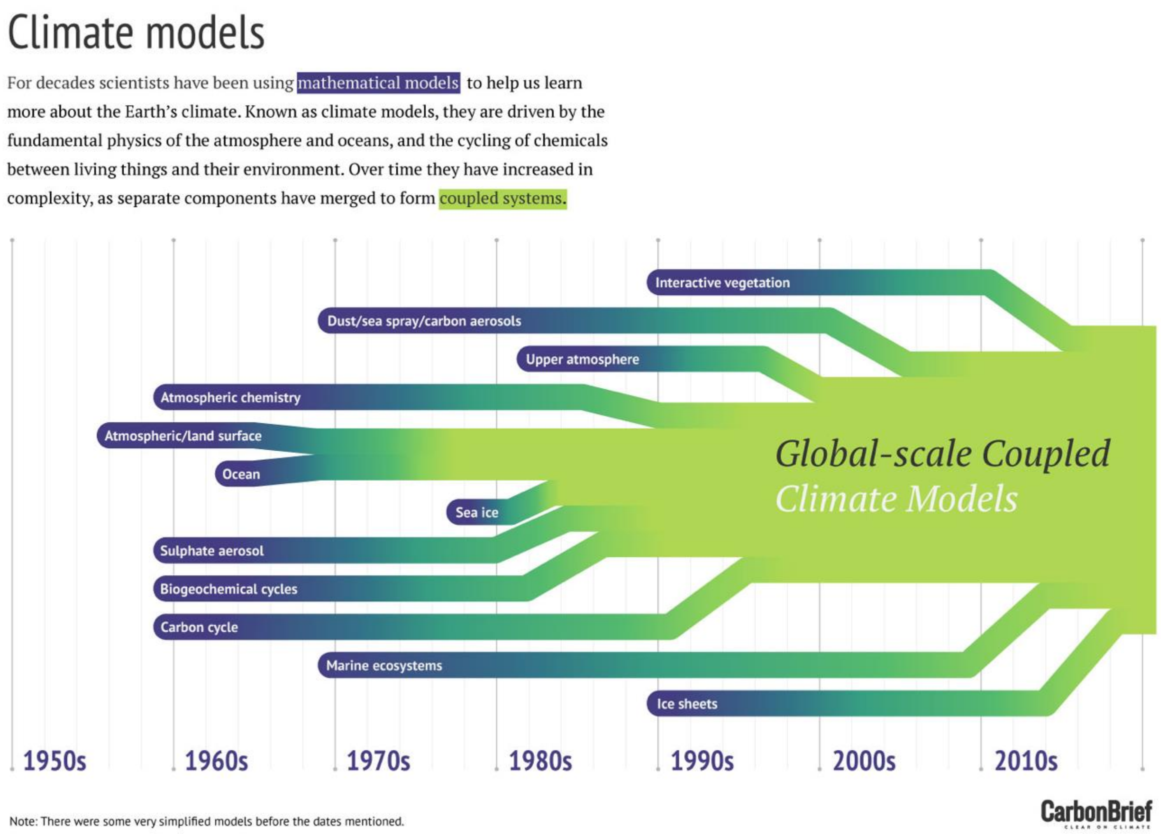

Figure 3: The Evolution of Climate Models[5]. Graphic by Rosamund Pearce; based on the work of Dr. Gavin Schmidt.

In SimClim AR6, GCM data were retrieved from the Earth System Grid (ESG) data portal for CMIP6. CMIP6 consists of the 'runs' from around 100 distinct climate models produced across 49 modelling groups. These models run several new and updated emission pathways that explore a much more comprehensive range of possible future outcomes than those included in CMIP5. The results from 44 monthly CMIP6 models were published at the time of developing this manual (Table 2, Table 3, and Table 4).

[5] https://www.carbonbrief.org/qa-how-do-climate-models-work/

Table 2: CMIP6 GCMs used in SimClim AR6

NO.	GCM	lat	lon	ssp245	ssp370	ssp585	Institution
1	ACCESS-CM2	144	192	ok	ok	ok	CSIRO-ARCCSS
2	ACCESS-ESM1-5	145	192	ok	ok	ok	CSIRO
3	AWI-CM-1-1-MR	192	384	ok	ok	ok	AWI
4	BCC-CSM2-MR	160	320	ok	ok	ok	BCC
5	BCC-ESM1	64	128		ok		BCC
6	CAMS-CSM1-0	160	320	ok	ok	ok	CAMS
7	CAS-ESM2-0	196	360	ok	ok	ok	CAS
8	CESM2	192	288	ok	ok	ok	NCAR
9	CESM2-WACCM	192	288	ok	ok	ok	NCAR
10	CIESM	192	288	ok		ok	THU
11	CMCC-CM2-SR5	192	288	ok	ok	ok	CMCC
12	CMCC-ESM2	362	292	ok	ok	ok	CMCC

13	CNRM-CM6-1	128	256	ok	ok	ok	CNRM-CERFACS
14	CNRM-CM6-1-HR	360	720	ok	ok	ok	CNRM-CERFACS
15	CNRM-ESM2-1	128	256	ok	ok	ok	CNRM-CERFACS
16	CanESM5	64	128	ok	ok	ok	CCCma
17	CanESM5-CanOE	64	128	ok	ok	ok	CCCma
18	EC-Earth3	256	512	ok	ok	ok	EC-Earth-Consortium
19	EC-Earth3-AerChem	256	512		ok		EC-Earth-Consortium
20	EC-Earth3-CC	256	512	ok		ok	EC-Earth-Consortium
21	EC-Earth3-Veg	256	512	ok	ok	ok	EC-Earth-Consortium
22	EC-Earth3-Veg-LR	292	362	ok	ok	ok	EC-Earth-Consortium
23	FGOALS-f3-L	180	288	ok	ok	ok	CAS
24	FGOALS-g3	80	180	ok	ok	ok	CAS
25	FIO-ESM-2-0	192	288	ok		ok	FIO-QLNM

26	GFDL-CM4	180	360	ok		ok	NOAA-GFDL
27	GFDL-ESM4	180	288	ok	ok	ok	NOAA-GFDL
28	GISS-E2-1-G	90	144	ok	ok	ok	NASA-GISS
29	GISS-E2-1-H	90	144				NASA-GISS
30	HadGEM3-GC31-LL	144	192	ok		ok	MOHC
31	HadGEM3-GC31-MM	324	432			ok	MOHC
32	IITM-ESM	94	192	ok	ok	ok	CCCR-IITM
33	INM-CM4-8	120	180	ok	ok	ok	INM
34	INM-CM5-0	120	180	ok	ok	ok	INM
35	IPSL-CM5A2-INCA	96	96		ok		IPSL
36	IPSL-CM6A-LR	143	144	ok	ok	ok	IPSL
37	KACE-1-0-G	144	192	ok	ok	ok	NIMS-KMA
38	KIOST-ESM	96	192	ok		ok	KIOST

39	MCM-UA-1-0	80	96	ok	ok	ok	UA
40	MIROC-ES2L	64	128	ok	ok	ok	MIROC
41	MIROC6	128	256	ok	ok	ok	MIROC
42	MPI-ESM-1-2-HAM	96	192		ok		HAMMOZ-Consortium
43	MPI-ESM1-2-HR	192	384	ok	ok	ok	MPI-M
44	MPI-ESM1-2-LR	96	192	ok	ok	ok	MPI-M
45	MRI-ESM2-0	160	320	ok	ok	ok	MRI
46	NESM3	96	192	ok		ok	NUIST
47	NorESM2-LM	96	144	ok	ok	ok	NCC
48	NorESM2-MM	192	288	ok	ok	ok	NCC
49	TaiESM1	192	288	ok	ok	ok	AS-RCEC
50	UKESM1-0-LL	144	192	ok	ok	ok	MOHC
	Total			**44**	**41**	**45**	

Table 3: The availability of climatic variables in CMIP6 GCMs used in SimClim AR6

Model	Precip	SolRad	Wind	RelHum	Tmean	Tmax	Tmin	SLR
ACCESS-CM2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ACCESS-ESM1-5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AWI-CM-1-1-MR	Yes	Yes			Yes	Yes	Yes	
BCC-CSM2-MR	Yes	Yes	Yes		Yes	Yes	Yes	Yes
BCC-ESM1	Yes	Yes	Yes		Yes	Yes	Yes	
CAMS-CSM1-0	Yes	Yes	Yes		Yes			Yes
CanESM5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CanESM5-CanOE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CAS-ESM2-0	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CESM2	Yes	Yes		Yes	Yes			Yes
CESM2-WACCM	Yes	Yes		Yes	Yes			Yes
CIESM	Yes	Yes			Yes	Yes	Yes	Yes
CMCC-CM2-SR5	Yes	Yes	Yes	Yes	Yes			Yes
CMCC-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

ESM2								
CNRM-CM6-1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CNRM-CM6-1-HR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CNRM-ESM2-1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
EC-Earth3	Yes	Yes		Yes	Yes	Yes	Yes	
EC-Earth3-AerChem	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
EC-Earth3-CC	Yes		Yes	Yes	Yes	Yes	Yes	Yes
EC-Earth3-Veg	Yes	Yes		Yes	Yes	Yes	Yes	
EC-Earth3-Veg-LR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
FGOALS-f3-L	Yes	Yes	Yes	Yes	Yes			
FGOALS-g3	Yes	Yes		Yes	Yes	Yes	Yes	Yes
FIO-ESM-2-0	Yes	Yes		Yes	Yes	Yes	Yes	Yes
GFDL-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	

ESM4								
GISS-E2-1-G	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
GISS-E2-1-H	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
HadGEM3-GC31-LL	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
HadGEM3-GC31-MM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
IITM-ESM	Yes	Yes	Yes	Yes	Yes			
INM-CM4-8	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
INM-CM5-0	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
IPSL-CM5A2-INCA	Yes	Yes	Yes	Yes	Yes			
IPSL-CM6A-LR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
KACE-1-0-G	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
KIOST-ESM	Yes	Yes	Yes	Yes	Yes			Yes
MCM-UA-1-0	Yes		Yes	Yes	Yes			

MIROC6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MIROC-ES2L	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MPI-ESM-1-2-HAM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
MPI-ESM1-2-HR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MPI-ESM1-2-LR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MRI-ESM2-0	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
NESM3	Yes	Yes	Yes		Yes	Yes	Yes	Yes
NorESM2-LM	Yes	Yes		Yes	Yes			Yes
NorESM2-MM	Yes	Yes		Yes	Yes			Yes
TaiESM1	Yes	Yes			Yes			Yes
UKESM1-0-LL	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
E3SM-1-1								Yes
GFDL-CM4								Yes

It is worth noting the abbreviated names in ***Table 3*** represent:

- Precip – Precipitation
- Tmean – Mean Temperature
- Tmax – Maximum Temperature
- Tmin – Minimum Temperature
- Wind – Wind Speed
- RelHum – Relative Humidity
- SorRad – Solar Radiation
- SLR – Sea Level Rise

In addition, ***Tables 2 to 4*** may be updated when new GCM simulations become available.

2.3.3 Data processing methodology – Pattern scaling

Pattern scaling is based on the theory that, firstly, a simple climate model can accurately represent the global responses of a GCM, even when the response is non-linear (Raper et al., 2001), and secondly, a wide range of climatic variables represented by a GCM is a linear function of the global annual mean temperature change represented by the same GCM at different spatial and temporal scales (Mitchell, 2003; Whetton et al., 2005). Pattern-scaling does not seem to be a very large source of error in constructing regional climate projections for extreme scenarios (Ruosteenoja et al., 2007); however, in applying pattern-scaling, two fundamental sources of error related to its underlying theory need to be addressed: 1) Nonlinearity error: the local responses of climate variables, precipitation in particular, may not be inherently linear functions of the global mean temperature change; and 2) Noise due to the internal variability of the GCM. Based on the pattern scaling theory, for a given GCM, the linear response change pattern of a climate variable to global mean temperature change represented by the GCM should be obtained from any one of its GHG emission simulation outputs.

Pattern scaling may be described as follows: for a given climate variable *V*, its anomaly ΔV^* for a particular grid cell (*i*), month (*j*), and year or period (*y*) under a representative concentration pathway RCP 4.5:

$$\Delta V_{yij}^{*} = \Delta T_y \cdot \Delta V_{ij}^{'} \tag{1}$$

ΔT being the annual global mean temperature change.

The local change pattern value ($\Delta V_{ij}^{'}$) was calculated from the GCM simulation anomaly (ΔV_{yij}) using linear least squares regression, that is, the slope of the fitted linear line.

$$\Delta V_{ij}^{'} = \frac{\sum_{y=1}^{m} \Delta T_y \cdot \Delta V_{yij}}{\sum_{y=1}^{m} (\Delta T_y)^2} \tag{2}$$

where *m* is the number of future periods used, from 2015-2100, namely 17 periods. The average of 5 years represents a period.

The global patterns are presented in 0.5°× 0.5° spatial resolutions in the latitude and longitude directions, which were interpolated from GCM's original resolution using a bilinear interpolation method.

Global patterns for other variables, including wind, solar radiation, relative humidity, and sea surface temperature, all use the same methodology. See Table 2 for the list of GCMs used in SimClim AR6 monthly precipitation and temperature patterns.

2.3.4 Mean sea level rise generator methodology

Global mean sea-level rise scenarios are readily available and are regularly updated by the IPCC. To date, most coastal impact and adaptation assessments have ignored regional variations in sea-level scenarios, mainly due to a lack of technical guidance and access to the necessary data in a usable form. This was rectified by the IPCC Report in 2011, which includes sea level rise outputs generated using the SimClim modelling system (Nicholls et al., 2011). Nevertheless, regional and local assessments would benefit from considering the components of sea-level change on a more individual basis since the uncertainty for sea-level change during the 21st century at any site is likely to be larger than the global mean scenarios suggest.

The regional pattern of thermal expansion under RCP forcing can be approximated using a pattern-scaling method similar to that previously applied for other climate variables (e.g., Santer *et al.*, 1990; Carter *et al.*, 2001). In applying the pattern-scaling method to sea level, "standardised" (or "normalised") patterns of regional thermal expansion change, as produced by coupled AOGCMs, are derived by dividing the average spatial pattern of change for a future period (e.g., 2081-2100) by the corresponding global-mean value of thermal expansion for the same period. The resulting standardised sea-level pattern is expressed per unit of global mean thermal expansion. The pattern-scaling approach has been formalised within an integrated assessment modelling system called SimClim AR6.

The following equation is employed to calculate the normalised sea surface elevation patterns (or sea surface height above the geoid, ZOS), termed ΔZOS *(unit: cm/cm $\Delta GSLR$)*:

$$\Delta ZOS_{ij} = \{(ZOS_{ij2090} - ZOS_{ij2005}) - \Delta ZOS_{global} + \Delta GSLR\}/\Delta GSLR$$

where ΔZOS_{global} is the global mean annual sea level change calculated directly from GCM gridded ZOS data; $\Delta GSLR$ is the global mean annual sea level change from ZOSGA dataset.

$$\Delta GSLR = ZOSGA_{2090} - ZOSGA_{2005}$$

where, $ZOSGA_{2090}$ is the global sea level height in 2090, and $ZOSGA_{1995}$ was the global sea level height in 2005. 2090 is the average of 2080-2100; 2005 is the average of 1996-2024; and *i, j* denotes the latitude and longitude of the studied location.

Note: Theoretically, ΔZOS_{global} should equal $\Delta GSLR$. However, during data processing, it was found that for some GCMs, these two variables are different, either owing to model drift or other unclear reasons, so these two variables were differentiated in the analysis to remove the drifting error in the ZOS dataset.

37 GCMs with local *ZOS* and *ZOSTOGA* data are used in SimClim AR6 (Table 4).

Table 4: CMIP6 GCMs for Mean Sea Level Rise in SimClim AR6

NO.	GCM	lat	lon	Institution
1	ACCESS-CM2	300	360	CSIRO-ARCCSS
2	ACCESS-ESM1-5	300	360	CSIRO
3	BCC-CSM2-MR	232	360	BCC
4	CAMS-CSM1-0	200	360	CAMS
5	CAS-ESM2-0	196	360	CAS
6	CESM2	180	360	NCAR
7	CESM2-WACCM	180	360	NCAR
8	CIESM	384	320	THU
9	CMCC-CM2-SR5	292	362	CMCC
10	CMCC-ESM2	292	362	CMCC
11	CNRM-CM6-1	294	362	CNRM-CERFACS
12	CNRM-CM6-1-HR	1050	1442	CNRM-CERFACS
13	CNRM-ESM2-1	294	362	CNRM-CERFACS

14	CanESM5	291	360	CCCma
15	CanESM5-CanOE	291	360	CCCma
16	E3SM-1-1	180	360	E3SM
17	EC-Earth3-CC	292	362	EC-Earth-Consortium
18	EC-Earth3-Veg-LR	292	362	EC-Earth-Consortium
19	FGOALS-g3	218	360	CAS
20	FIO-ESM-2-0	384	320	FIO-QLNM
21	GFDL-CM4	180	360	NOAA-GFDL
22	GISS-E2-1-G	180	288	NASA-GISS
23	HadGEM3-GC31-LL	330	360	MOHC
24	HadGEM3-GC31-MM	1205	1440	MOHC
25	INM-CM4-8	180	360	INM
26	INM-CM5-0	180	360	INM
27	IPSL-CM6A-LR	332	362	IPSL
28	KIOST-ESM	200	360	KIOST
29	MIROC-ES2L	256	360	MIROC

30	MIROC6	256	360	MIROC
31	MPI-ESM1-2-HR	404	802	MPI-M
32	MPI-ESM1-2-LR	220	256	MPI-M
33	MRI-ESM2-0	180	360	MRI
34	NESM3	292	362	NUIST
35	NorESM2-LM	385	360	NCC
36	NorESM2-MM	385	360	NCC
37	UKESM1-0-LL	330	360	MOHC

Vertical Land Movement (VLM) is important in estimating regional sea levels. The orders of magnitude are comparable, and VLM can either exacerbate or dampen the sea-level rise experienced at a coastal location. In a place where VLM is upward (rising, like Norway), the local experienced SLR is smaller (local SLR can even be negative: sea level going down). When VLM is downward (sinking, like Manila), local experienced SLR is stronger.

VLM velocity can be observed directly or inferred from related measurements. For example, direct observations are available through the SONEL initiative, while the Permanent Service for Mean Sea Level maintains indirect observations. However, as more and more GPS observation data are available, several VLM velocity data estimated from these data can also be directly applied. We constructed our global VLM data based on these peer-reviewed VLM datasets (Table 5).

Table 5: The information about peer-reviewed VLM site datasets

Name	Number of valid stations	Data cover range	Reference
JPL	366	1994 - 2019	Heflin et al., 2020
ULR	756	1995 - 2014	Santamaría-Gómez et al., 2017
GFZ	538	1994 - 2015	Deng et al., 2015
NGL	904 2357	1996 – 2019 1996 - 2022	Blewitt et al., 2016 Hammond et al., 2021

The four datasets provided the VLM velocities in a tabular format, including the information about Site (GPS station acronym), DOMES (GPS station number), Lon (longitude of the GPS station), Lat (latitude of the GPS station), T_GPS (Length of the GPS time series in years), Data (percentage of data in the time series), V_GPS (mm/year, GPS UP velocity), S_GPS (mm/year, GPS UP velocity uncertainty), and MODEL (stochastic model used to estimate uncertainty).

In the records among these datasets, it was found that there are duplicated sites. Therefore, the first step was to clean these sites to form a single data set with unique site names. The four datasets were combined with site names but filtered with T_GPS (Length of the GPS time series in years). That is to say, the site with the longest T_GPS was kept in the final combined VLM data.

To use VLM in places where it has not been observed, the VLM values at point locations (in Latitude and Longitude) need to be interpolated spatially over a regular grid. Therefore, the second step was to interpolate these site data from points to raster. The Inverse Distance Weighting (IDW) method was still employed as the interpolation approach in this version. The final resultant VLM at each grid includes mean values from V_GPS and the corresponding standard deviation from S_GPS based on the assumption that V_GPS follows a normal distribution.

2.4 Extreme precipitation change patterns

In SimClim AR6, site data are mainly managed on a daily scale and primarily used to study the changes in the frequency and intensity of extreme events. Combined with GCM future climate change scenarios, the data can be extended to investigate extreme events under a changing climate. Due to the availability of daily data, only the 26 GCMs in the CMIP6 archive were analysed for extreme precipitation change patterns (Table 6).

The following presents the procedure to process the historical and GCMs precipitation under CMIP6 projections. Firstly, precipitation with short durations was aggregated to longer durations with a rolling-sum method. For example, the raw GCMs provided 3-hourly precipitation. These 3-hourly precipitation data were aggregated for the duration of 6-, 12-, 24-, or 168-hours. Then, Depth-Duration-Frequency of Extreme Precipitation (DDF) was initiated.

2.4.1 Generalized Extreme Value Analysis

Extreme Value Theory (EVT) is a branch of statistics that deals with extremes and rare events. Common methods for analysing extremes include block maxima (i.e., maxima within a certain block of time, for example, a season or a year), points over a certain threshold (POT), and the Poisson point process description of the timing of exceedances above a threshold.

An annual maxima series (AMS), a block maximum, is of interest at each site. The Generalized Extreme Value (GEV) Distribution, one of the most common distributions for extreme value analysis, is employed to fit the AMS. The Generalized Extreme Value (GEV) distribution family is frequently used in Extreme Value Theory to model block (e.g., seasonal or annual) maxima of rainfall and is described by the following cumulative distribution function (Coles, 2001; Katz et al., 2002):

$$P(x \leq x) = F(x) = exp\left\{-[1 + \xi(\frac{x-u}{\sigma})]^{-1/\xi}\right\}$$

where μ, σ, and ξ are the location, scale, and shape parameters of the GEV. x can be rainfall intensity (i) or depth (D).

This distribution models the maxima of a series of independent and identically distributed observations and is an appropriate distribution for analysing extreme values. It encapsulates three distinct extreme value distributions utilising the shape parameter: Gumbel (ξ=0), which is light-tailed and unlimited; Fréchet (ξ>0), which has a lower limit at $\mu - \sigma/\xi$ and is heavy-tailed; and the reverse Weibull (ξ<0), which has an upper limit at $\mu - \sigma/\xi$ and is short-tailed.

The corresponding quantile function for the GEV is given by:

$$x(F) = \mu - \frac{\sigma}{\xi}[1 — \{-\ln{(1-p)}\}^{\xi}]$$

Where F is the annual non-exceedance probability (cumulative distribution function (CDF) value) and is equal to 1-P, P is the annual exceedance probability (AEP), which is related to the return period T by 1/P = T (i.e., F=1-1/T). If we define the parameter γ = σ/μ, then Equation 2 becomes:

$$x(F) = \mu * \{1 - \frac{\gamma}{\xi}[1 - (-lnF)^{-\xi}]\}$$

The L-moments method (Hosking et al., 1985; Hosking and Wallis, 1993, 1995) was applied to estimate the GEV distribution parameters (i.e., μ, σ, and ξ). Based on these fitted parameters, precipitation frequency estimates were computed from Equation 3 for the following average recurrence intervals (ARIs): 2, 5, 10, 25, 50, 100, 200, 500, and 1000 years. In addition, the confidence intervals of extreme values at a 0.1 significant level were obtained via bootstrapping 500 samples.

2.4.2 Change Factors – Mapping Future Projections

The GEV function parameters for the GCM baseline and future periods were estimated using the L-moments method for each GCM grid (x, y). The change of extreme precipitation in a future period compared to the baseline period corresponding to a specific return period (the estimated time interval between precipitation events of similar intensity) *T* is determined as:

$$\Delta P_{TFR(x,y)} = \frac{P_{TFR(x,y)} - P_{T(x,y)}}{P_{T(x,y)}} \times 100\%$$

where $P_{T(x,y)}$ is the baseline extreme precipitation value for the grid (x, y) attainted from applying the GEV function to GCM simulation for the baseline period $P_{TFR(x,y)}$ is the projected precipitation value for the future year *F* under a future scenario (i.e., RCP/SSP) R for the same grid. The future year F is the central year of a projected period (20 years in principle).

As global warming is driven by increased radiative forcing, the Pattern Scaling method applied can be described as: for a given P_T, its change ΔP_T^* in future year (*F*) under the future scenario (i.e., RCP/SSP) R for the grid (x, y) can be derived as:

$$\Delta P_{TFR(x,y)}^* = \Delta C_F \times \Delta P'_{T(x,y)}$$

where ΔC_F is the difference between the annual global mean temperature in future year F and that of the baseline period, and $\Delta P'_{T(x,y)}$ (unit: %/°C) is the change rate of P_T at grid (x, y) in response to that change of annual global mean temperature. Generally, the $\Delta P'_{T(x,y)}$ is also called the pattern of $\Delta P_{TFR(x,y)}^*$, while $\Delta P_{TFR(x,y)}^*$ is called the *change factor (CF)*, as it reflects the change of extreme precipitation between the future and baseline period.

The pattern scaling method assumes that, for a given GCM, $\Delta P'_{T(x,y)}$ can be obtained from any simulation run of that GCM. Pattern scaling does not pose the major source of error in constructing regional climate projections for extreme scenarios (Ruosteenoja et al., 2007). In applying pattern-scaling, two fundamental sources of error related to its underlying theory need to be addressed: 1) nonlinearity error (the local responses of climate variables, precipitation in particular), which may not be inherently linear functions of the global mean temperature change; and 2) noise due to the internal variability of the GCM. More profound studies of the relationships between the change rate of climate variables and the global mean temperature changes are required to obtain more accurate predictions of future climate. However, such further studies require extensive experiments with purposely designed inputs and outputs of GCM simulation, which current technologies do not provide.

To reduce the effects of the GCM internal variability from different SSPs and periods when calculating $\Delta P'_{T(x,y)}$, it is desirable to use all available GCM outputs for the calculation (including all scenarios as a kind of super ensemble). The calculation is based on a least-squares regression method, which has been employed in many studies (Ruosteenoja et al., 2007; Mitchell, 2003).

The pattern-scaling method was applied to the CMIP6 GCMs, which formed an ensemble of $\Delta P'_{T(x,y)}$. Then ensemble analysis can be carried out directly, where the ensemble percentiles of 50th (i.e., median), the range between 05th and 95th (i.e., 90% confident interval), as well as the range between 16th and 84th (i.e., about one standard deviation), were adopted hereafter to define the uncertainty of climate projections.

2.4.3 Future DDFs Generation

When a spatially aggregated pattern (i.e., $\Delta P'_T$) and a global ΔC_F at the target site (x, y) is provided, the future extreme precipitation value ($P_{TFR(x,y)}$) at the site can be obtained by the following equation:

$$P_{TFR(x,y)} = P_{OT(x,y)} \times \ (1.0 + \ \Delta C_F \times \Delta P'_{T(x,y)}/100.0)$$

where $P_{OT(x,y)}$ is the observed extreme value with an ARI of T (i.e., return period in years). Following the same process for all durations and ARIs, the future DDFs can be constructed. In summary, the future DDFs are constructed by mapping the future DDF changes to the observation DDFs.

Table 6: GCM list for daily extreme precipitation change patterns

NO.	GCM	ssp245	ssp370	ssp585	Institution
1	ACCESS-CM2	ok	ok	ok	CSIRO-ARCCSS
2	AWI-CM-1-1-MR	ok	ok	ok	AWI
3	BCC-CSM2-MR	ok	ok	ok	BCC
4	CanESM5	ok	ok	ok	CCCma
5	CMCC-CM2-SR5	ok	ok	ok	CMCC

6	CMCC-ESM2	ok	ok	ok	CMCC
7	CNRM-CM6-1	ok	ok	ok	CNRM-CERFACS
8	CNRM-CM6-1-HR	ok	ok	ok	CNRM-CERFACS
9	CNRM-ESM2-1	ok	ok	ok	CNRM-CERFACS
10	EC-Earth3	ok	ok	ok	EC-Earth-Consortium
11	EC-Earth3-Veg	ok	ok	ok	EC-Earth-Consortium
12	FGOALS-g3	ok	ok	ok	CAS
13	GFDL-ESM4	ok	ok		NOAA-GFDL
14	HadGEM3-GC31-LL	ok		ok	MOHC
15	HadGEM3-GC31-MM			ok	MOHC
16	IITM-ESM	ok	ok	ok	CCCR-IITM
17	IPSL-CM5A2-INCA		ok		IPSL
18	IPSL-CM6A-LR	ok	ok	ok	IPSL
19	KACE-1-0-G	ok	ok	ok	NIMS-KMA
20	KIOST-ESM	ok		ok	KIOST
21	MIROC6	ok	ok	ok	MIROC
22	MIROC-ES2L	ok	ok	ok	MIROC
23	MPI-ESM-1-2-HAM		ok		HAMMOZ-Consortium
24	MPI-ESM1-2-HR	ok	ok	ok	MPI-M
25	MPI-ESM1-2-LR	ok	ok	ok	MPI-M
26	MRI-ESM2-0	ok	ok	ok	MRI
27	NESM3	ok		ok	NUIST

28	TaiESM1			ok	AS-RCEC
29	UKESM1-0-LL	ok	ok	ok	MOHC
	Total	**25**	**24**	**26**	

3. Site Data: Historical site observational data

Unlike spatial data, site data is not managed according to regions. All site data are visualised onto the global domain according to their spatial coordinates (latitude and longitude).

3.1 Public sources

The site data in SimClim AR6 are built upon the Global Historical Climatology Network (GHCN) dataset daily. The dataset is being maintained at the National Oceanic and Atmospheric Administration's National Climatic Data Centre (NCDC[6]).

GHCN-Daily consists of more than 1 500 000 000 observations at over 90,000 land-based stations, some dating back to the mid-1800s. The primary meteorological elements represented include daily maximum and minimum temperature (TMAX and TMIN), 24-hour precipitation (PRCP) and snowfall (SNOW) totals, and the snow depth at a particular time of day (SNWD). The data originate from various sources, from paper forms completed by volunteer observers to synoptic reports from automated weather stations (Durre et al., 2010).

The GHCN-Daily dataset is updated with observations from more than 25,000 stations, usually within the last month. The dataset is frequently reconstructed from approximately 30 data sources to ensure its accuracy, typically weekly. This reconstruction process includes quality assurance checks applied to the entire dataset to maintain consistency with its expanding list of constituent sources.

It is worth noting that these site data are post-processed into SimClim AR6 's data format and then identified and maintained by ClimSystems. In addition, the GHCN-Daily dataset is also regularly updated in SimClim.

[6] https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00861

3.2 Customization

Besides the publicly available (GHCN)-Daily dataset, site data sets provided by end-users for a specific region can be formatted and ingested in SimClim AR6. However, the data must be pre-processed to follow the SimClim AR6 data format. Please get in touch with ClimSystems info@climsystems.com for instructions.

References

Blewitt, G., Kreemer, C., Hammond, W. C., & Gazeaux, J. (2016). MIDAS robust trend estimator for accurate GPS station velocities without step detection. Journal of Geophysical Research, 121, 2054-2068. https://doi.org/10.1002/2015JB012552

Blewitt, G., Hammond, W. C., & Kreemer, C. (2018). Harnessing the GPS data explosion for interdisciplinary science. Eos, 99. https://doi.org/10.1029/2018EO104623

Clarke, L., Edmonds, J., Jacoby, H., Pitcher, H., Reilly, J., & Richels, R. (2007). Scenarios of greenhouse gas emissions and atmospheric concentrations. Sub-report 2.1A of synthesis and assessment product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research.

Coles S. (2001). An introduction to statistical modelling of extreme values. Spinger, Berlin Heidelberg New York

Copernicus Climate Change Service (C3S). (2017). ERA5: Fifth-generation ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS). https://cds.climate.copernicus.eu/cdsapp#!/home

Deng, Z., Gendt, G., & Schöne, T. (2015). Status of the IGS-TIGA Tide Gauge Data Reprocessing at GFZ. In C. Rizos & P. Willis (Eds.), IAG 150 Years (pp. 411-416). Springer. https://doi.org/10.1007/1345_2015_156

Durre, I., Menne, M. J., Gleason, B. E., Houston, T. G., Vose, R. S., & Worley, S. J. (2010). Comprehensive automated quality assurance of daily surface observations. Journal of Applied Meteorology and Climatology, 49(8), 1615-1633. https://doi.org/10.1175/2010JAMC2364.1

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development, 9(5), 1937-1958. https://doi.org/10.5194/gmd-9-1937-2016

Fick, S. E., & Hijmans, R. J. (2017). Worldclim 2: New 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology, 37(12), 4302-4315. https://doi.org/10.1002/joc.5086

Fujino, J., Nair, R., Kainuma, M., Masui, T., & Matsuoka, Y. (2006). Multi-gas mitigation analysis on stabilization scenarios using AIM global model. Multigas Mitigation and Climate Policy, 24-35.

Heflin, M., Moore, A., Murphy, D., Desai, S., Bertiger, W., Haines, B., ... & Dietrich, A. (2019). Introduction to JPL's GNSS time series. Journal of Geophysical Research: Solid Earth, 124(8), 8244-8264. https://doi.org/10.1029/2018JB016835

Hosking, J. R. M., & Wallis, J. R. (2005). Regional frequency analysis: An approach based on L-moments. Cambridge University Press.

Hosking, J. R. M., & Wallis, J. R. (1993). Some statistics useful in regional frequency analysis. Water Resources Research, 29(2), 271-281. https://doi.org/10.1029/92WR02652

Hosking, J. R. M., & Wallis, J. R. (1996). Regional frequency analysis: An approach based on L-moments. Cambridge University Press.

Hosking, J. R. M., Wallis, J. R., & Wood, E. F. (1985). An appraisal of the regional flood frequency procedure in the UK "Flood Studies Report". Hydrological Sciences Journal, 30(1), 95-116. https://doi.org/10.1080/02626668509490939

Hurrell, J. W., Hack, J. J., Shea, D., Caron, J. M., & Rosinski, J. (2008). A new sea surface temperature and sea ice boundary dataset for the Community Atmosphere Model. Journal of Climate, 21(19), 5145-5153. https://doi.org/10.1175/2008JCLI2292.1

IPCC. (2001). Climate change 2001: The scientific basis. Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change (Eds. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, D. Xiaosu, X. Dai, K. Maskell & C.A. Johnson). Cambridge, UK: Cambridge University Press.

Katz, R.W., Parlange, M.B., & Naveau, P. (2002). Statistics of extremes in hydrology. Advances in Water Resources, 25, 1287-1304. https://doi.org/10.1016/S0309-1708(02)00056-8

Kriegler, E., et al. (2014). A new scenario framework for climate change research: The concept of shared climate policy assumptions. Climatic Change, 122, 401-414. https://doi.org/10.1007/s10584-013-0971-5

Krishnamurti, T.N., Kishtawal, C.M., Zhang, Z., Larow, T., Bachiochi, D., Williford, E., Gadgil, S., & Surendran, S. (2000). Multimodel ensemble forecasts for weather and seasonal climate. J. Clim., 13, 4196–4216. https://doi.org/10.1175/1520-0442(2000)013<4196:MEFFWAO>2.0.CO;2

Lambert, S.J., & Boer, G.J. (2001). CMIP1 evaluation and intercomparison of coupled climate models. Clim. Dynam., 17, 83–106. https://doi.org/10.1007/PL00013736

Martins, E. S., & Stedinger, J. R. (2000). Generalized maximum-likelihood generalized extreme-value quantile estimators for hydrologic data. Water Resources Research, 36(3), 737-744. https://doi.org/10.1029/1999WR900299

Min, S. K., & Hense, A. (2006). A Bayesian approach to climate model evaluation and multi-model averaging with an application to global mean surface temperatures from IPCC AR4 coupled climate models. Geophysical Research Letters, 33, L08708. https://doi.org/10.1029/2006GL025779

Mitchell, T. D. (2003). Pattern Scaling: An Examination of the Accuracy of the Technique for Describing Future Climates. Climatic Change, 60(3), 217–242. https://doi.org/10.1023/A:1026035305597

Moss, M., et al. (2010). The next generation of scenarios for climate change research and assessment. Nature, 463, 747-756. https://doi.org/10.1038/nature08823

New, M., Lister, D., Hulme, M., & Makin, I. (2002). A high-resolution data set of surface climate over global land areas. Climate Research, 21, 1-25.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., … van Ruijven, B. J. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change, 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Raper, S. C. B., Gregory, J. M., & Osborn, T. J. (2001). Use of an upwelling-diffusion energy balance climate model to simulate and diagnose A/OGCM results. Climate Dynamics, 17(8), 601–613. https://doi.org/10.1007/PL00007931

Raiahi, K., Gruebler, A., & Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change, 74(7), 887–935. https://doi.org/10.1016/j.techfore.2006.05.026

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., … Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Robertson, A. W., Lall, U., Zebiak, S. E., & Goddard, L. (2004). Improved combination of multiple atmospheric GCM ensembles for seasonal prediction. Monthly Weather Review, 132(11), 2732–2744. https://doi.org/10.1175/MWR2818.1

Rogelj, J., Meinshausen, M., & Knutti, R. (2012). Global warming under old and new scenarios using IPCC climate sensitivity range estimates. Nature Climate Change, 2(4), 248–253. https://doi.org/10.1038/nclimate1385

Ruosteenoja, K., Tuomenvirta, H., & Jylhä, K. (2007). GCM-based regional temperature and precipitation change estimates for Europe under four SRES scenarios applying a super-ensemble pattern-scaling method. Climatic Change, 81(Suppl 1), 193–208. https://doi.org/10.1007/s10584-006-9222-3

Santamaría-Gómez, A., Gravelle, M., Dangendorf, S., Marcos, M., Spada, G., & Wöppelmann, G. (2017). Uncertainty of the 20th century sea-level rise due to vertical land motion errors. Earth and Planetary Science Letters, 473, 24-32.

Smith, S. J., & Wigley, T. M. L. (2006). Multi-Gas Forcing Stabilization with the MiniCAM. Energy Journal, 27(3), 373–391.

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93(4), 485–498.

Tebaldi, C., & Knutti, R. (2007). The use of the multimodel ensemble in probabilistic climate projections. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1857), 2053–2075.

University of East Anglia Climatic Research Unit; Harris, I. C., Jones, P. D., & Osborn, T. (2021). CRU TS4.05: Climatic Research Unit (CRU) Time-Series (TS) version 4.05 of high-resolution gridded data of month-by-month variation in climate (Jan. 1901- Dec. 2020). NERC EDS Centre for Environmental Data Analysis. https://catalogue.ceda.ac.uk/uuid/c26a65020a5e4b80b20018f148556681

van Vuuren, D., den Elzen, M., Lucas, P., Eickhout, B., Strengers, B., van Ruijven, B., Wonink, S., & van Houdt, R. (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Climatic Change, 81(2), 119-159. https://doi.org/10.1007/s10584-006-9172-9

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., … & Nakicenovic, N. (2011). The representative concentration pathways: an overview. Climatic Change, 109(1-2), 5-31. https://doi.org/10.1007/s10584-011-0148-z

van Vuuren, D. P., et al. (2014). A new scenario framework for climate change research: The scenario matrix architecture. Climatic Change, 122(3), 373-386. https://doi.org/10.1007/s10584-013-0906-1

Whetton, P. H., McInnes, K. L., Jones, R. N., Hennessy, K. J., Suppiah, R., Page, C. M., ... & Durack, P. J. (2005). Australian climate change projections for impact assessment and policy application: a review. Climate Impact Group, CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia.

ANNEX Glossary

The following glossary is mostly extracted from the WMO Book of Climate knowledge for action: a global framework for climate services – Empowering the most vulnerable.

Adaptation: The process or outcome of a process that leads to a reduction in harm or risk of harm or a realization of benefits associated with climate variability and climate change.

Capacity building: The process by which people, organizations, and society systematically stimulate and develop their capacities over time to achieve social and economic goals, including through improvement of knowledge, skills, systems, and institutions. It involves learning and various types of training, but also continuous efforts to develop institutions, political awareness, financial resources, technology systems, and the wider social and cultural enabling environment.

Climate: Climate is typically defined as the average weather over a period of time. The quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense, is the state of the climate system, including its statistical description. For the purposes of this report, we have used the term climate to represent time periods of months or longer.

Climate change: Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. The Intergovernmental Panel on Climate Change uses a relatively broad definition of climate change that is considered to mean an identifiable and statistical change in the state of the climate which persists for an extended period of time. This change may result from internal processes within the climate system or from external processes. These external processes (or forcing) could be natural, for example volcanoes, or caused by the activities of people, for example emissions of greenhouse gases or changes in land use. Other bodies, notably the United Nations Framework Convention on Climate Change, define climate change slightly differently. The United Nations Framework Convention on Climate Change makes a distinction between climate change that is directly attributable to human activities and climate variability that is attributable to natural causes. For the purposes of this report, either definition may be suitable, depending on the context.

Climate change projection: A projection of the response of the climate system to emission scenarios of greenhouse gases and aerosols, or radiative forcing scenarios based upon climate model simulations and past observations. Climate change projections are expressed as departures from a baseline climatology, for example, that future average daily temperature in the summer will be 2°C warmer for a given location, time period and emissions scenario.

Climate model: A simplified mathematical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedbacks between them.

Climate variability: Climate variability refers to variations in the mean state and other statistics relating to the climate on all temporal and spatial scales beyond that of individual weather events. Climate can and does vary quite naturally, regardless of any human influence. Natural climate variability arises as a result of internal process with the climate system or because of variations in natural forcing such as solar activity.

Downscaling: The process of reducing coarse spatial scale model output to smaller (more detailed) scales.

Ensemble: A set of simulations (each one an ensemble member) made by either adjusting parameters within plausible limits in the model, or starting the model from different initial conditions. While many parameters are constrained by observations, some are subject to considerable uncertainty. The best way to investigate this uncertainty is to run an ensemble experiment in which each relevant parameter combination is investigated. This is known as a perturbed physics ensemble.

External climate forcing: One component of the Earth's natural climatic variability, is that due to external variability factors, which arise from processes external to the climate system, chiefly, volcanic eruptions and variations in the amount of energy radiated by the sun.

Extreme weather and climate events: Extreme events refer to phenomena such as floods, droughts and storms that are at the extremes of, or beyond, the historical distribution of such events.

Forecast: Definite statement or statistical estimate of the likely occurrence of a future event or conditions for a specific area. Generally used in reference to weather forecasts, and hence to weather a week or so ahead.

General Circulation Model (GCM): A General Circulation Model, or sometimes called a global climate model, is a mathematical model of the general circulation of the planet's atmosphere or oceans based on mathematic equations that represent physical processes. These equations are the basis for complex computer programs commonly used for simulating the atmosphere or oceans of the Earth. General

Circulation Models are widely applied for weather forecasting, understanding the climate, and projecting climate change.

Greenhouse gas: A gas within the atmosphere which absorbs and emits energy radiated by the Earth. Carbon dioxide is the most important greenhouse gas being emitted by humans.

Mitigation: Action taken to reduce the impact of human activity on the climate system, primarily through reducing net greenhouse gas emissions.

Observation: Observation, or observed data, refers to any information which has been directly measured. In climatology, this means measurements of climate variables such as temperature and precipitation.

Prediction: The main term used for estimates of future climatic conditions over a range of about a month to a year ahead.

Probability: Probability is a way of expressing knowledge or belief that an event will occur, and is a concept most people are familiar with in everyday life. Probabilistic climate projections are projections of future absolute climate that assign a probability level to different climate outcomes.

Projection: A Projection is an estimate of future climate decades ahead consistent with a particular scenario. The scenario may include assumptions regarding elements such as: future economic development, population growth, technological innovation, future emissions of greenhouse gases and other pollutants into the atmosphere, and other factors.

Regional Climate Model (RCM): A regional climate model is a climate model of higher resolution than a global climate model. It can be nested within a global model to provide more detailed simulations for a particular location.

Risk: Risk is conventionally defined as the combination of the likelihood of an occurrence of an event or exposure(s) and the severity of injury or cost that can be caused by the event or exposure(s). Understanding the risks and thresholds, including uncertainties, associated with climate is one principle of good adaptation.

Risk management: The systematic approach and practice of managing uncertainty to minimize potential harm and loss. Risk management comprises risk assessment and analysis, and the implementation of strategies and specific actions to control, reduce and transfer risks. It is widely practiced by organizations to minimise risk in investment decisions and to address operational risks such as those of business disruption, production failure, environmental damage, social impacts and damage from fire and natural hazards. Risk management is a core issue for sectors such as water supply, energy and agriculture whose production is directly affected by extremes of weather and climate.

Sea level rise: Sea level rise can be described and projected in terms of absolute sea level rise or relative sea level rise. Increasing temperatures result in sea level rise by the thermal expansion of water and through the addition of water to the oceans from the melting of ice sheets. There is considerable uncertainty about the rate of future ice sheet melt and its contribution to sea level rise.

Sustainable development: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Uncertainty: Uncertainty refers to a state of having limited knowledge. Uncertainty can result from lack of information or from disagreement over what is known or even knowable. Uncertainty may arise from many sources, such as quantifiable errors in data, or uncertain projections of human behaviour. Uncertainty can be represented by quantitative measures or by qualitative statements. Uncertainty in climate change projections is a major problem for those planning to adapt to a changing climate. Uncertainty in projections of future climate change arises from three principal causes: natural climate variability; modelling uncertainty, referring to an incomplete understanding of Earth system processes and their imperfect representation in climate models; and uncertainty in future emissions.

Variable: The name was given to measurements such as temperature, precipitation, etc. (climate variables), sea level rise, salinity, etc. (marine variables), and cooling degree days, days of air frost, etc. (derived variables).

Vulnerability: Vulnerability is the degree to which a system is susceptible to and unable to cope with the adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity. Vulnerability to climate change refers to the propensity of human and ecological systems to suffer harm and their ability to respond to stresses imposed as a result of climate change effects. The vulnerability of a society is influenced by its development path, physical exposures, the distribution of resources, prior stresses, and social and government institutions. All societies have inherent abilities to deal with certain variations in climate, yet adaptive capacities are unevenly distributed, both across countries and within societies. The poor and marginalized have historically been most at risk and are most vulnerable to the impacts of climate change.

Weather: The state of the atmosphere at a given time and place, with respect to variables such as temperature, moisture, wind velocity, and barometric pressure.

Acknowledgments

We would like to express our sincere thanks and gratitude *to Mr. Johnny Yu* and *Mr. Joshua Wu* for their fantastic work, not limited to

- Downloading, cleaning, and organizing raw CMIP6 GCM data
- Calculating and normalizing GCM patterns
- Downloading and preparing country-specific historical data
- Preparing country-level climate change patterns from the global dataset

Special thanks also go to *Mr. Matthew Dooley*, who has been developing and maintaining the excellent SimClim software.

We also express our great appreciation to Mrs. Sarah Bolton for providing valuable assistance with editing, reviewing, and providing feedback.