RICCAR

Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region

Regional Climate Modelling and Regional Hydrological Modelling Applications in the Arab Region

TECHNICAL NOTE

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Available through:
United Nations Publication
E/ESCWA/SDPD/2017/RICCAR/TechnicalNote.1

Reference as:
Swedish Meteorological and Hydrological Institute (SMHI). 2017. Regional Climate Modelling and Regional Hydrological Modelling Applications in the Arab Region. RICCAR Technical Note, Beirut, E/ESCWA/SDPD/2017/RICCAR/TechnicalNote.1.

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PREFACE

The Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) is a joint initiative of the United Nations and the League of Arab States launched in 2010.

RICCAR is implemented through a collaborative partnership involving 11 regional and specialized organizations, namely United Nations Economic and Social Commission for Western Asia (ESCWA), the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD), Food and Agriculture Organization of the United Nations (FAO), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), the League of Arab States, Swedish Meteorological and Hydrological Institute (SMHI), United Nations Environment Programme (UN Environment), United Nations Educational, Scientific and Cultural Organization (UNESCO) Office in Cairo, United Nations Office for Disaster Risk Reduction (UNISDR), United Nations University Institute for Water, Environment and Health (UNU-INWEH), and World Meteorological Organization (WMO). ESCWA coordinates the regional initiative.
Funding for RICCAR is provided by the Government of Sweden and the Government of the Federal Republic of Germany.

RICCAR is implemented under the auspices of the Arab Ministerial Water Council and derives its mandate from resolutions adopted by this council as well as the Council of Arab Ministers Responsible for the Environment, the Arab Permanent Committee for Meteorology and the 25th ESCWA Ministerial Session.

Funding for this technical note was provided by the Government of Sweden through the Swedish International Development Cooperation Agency.

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ACRONYMS AND ABBREVIATIONS

ACSAD	Arab Center for the Studies of Arid Zones and Dry Lands
AR5	Fifth Assessment Report (IPCC)
BCIP	Bias Correction Intercomparison Project
CDD	Maximum length of dry spell
CMIP	Coupled Model Intercomparison Project
CNRM-CM5	Centre National de Recherches Météorologiques- Climate Model 5
CORDEX	Coordinated Regional Climate Downscaling Experiment
CRU	University of East Anglia Climatic Research Unit Time Series
CWD	Maximum length of wet spell
DBS	Distribution-Based Scaling
EC-EARTH	ECMWF based earth-system model
ECMWF	European Centre for Medium Range Forecasts
ERA-Interim	European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim
ERAINT	ERA-Interim-driven
ESCWA	Economic and Social Commission for Western Asia
ESGF	Earth System Grid Federation
ETCCDI	Expert Team on Climate Change Detection and Indices
FAO	Food and Agriculture Organization of the United Nations
GCM	Global Climate Model or General Circulation Model
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory-Earth System Model 2
GLWD	Global Lakes and Wetlands Database
GLC	Global Land Cover
GMIA	Global Map of Irrigation Areas
GPCP	Global Precipitation Climatology Project
GPCC	Global Precipitation Climatology Centre
GRanD	Global Reservoir and Dam Database
GRDC	Global Runoff Data Centre
GSFC DAAC	Goddard Space Flight Center Distributed Active Archive Center
HWSD	Harmonized World Soil Database
HIRLAM	High Resolution Limited Area Model
HEC-HMS	Hydrologic Engineering Center Hydrological Modelling System
HydroSHEDS	Hydrological data and maps from SHuttle Elevation Derivatives at multiple Scales
HYPE	Hydrological Predictions for the Environment
IPCC	Intergovernmental Panel on Climate Change
Km	kilometres
Km^2	square kilometres
MENA	Middle East North Africa
mm	millimetres
mm/day	millimetres per day
MIRCA	Monthly Irrigated and Rainfed Crop Areas
m^3/sec	cubic metre per second
NWP	Numerical Weather Prediction
PET	Potential Evapotranspiration
RCA3	Rossby Centre regional atmospheric model 3
RCA4	Rossby Centre regional atmospheric model 4
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
REMO	Regional Model, MPI, Hamburg
RHM	Regional Hydrological Model
RICCAR	Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region
R10	Annual count of days with precipitation greater than 10mm
R20	Annual count of of days with precipitation greater than 20mm
SDII	Simple Precipitation Intensity Index
SMHI	Swedish Meteorological and Hydrological Institute
SRTM	Shuttle Radar Topography Mission
SU	Number of summer days
SU35	Number of hot days
SU40	Number of very hot days
TR	Tropical nights
TRMM	Tropical Rainfall Measurement Mission
UDEL	University of Delaware Air Temperature and Precipitation
UNESCO	United Nations Educational, Scientific and Cultural Organization
VIC	Variable Infiltration Capacity
WCRP	World Climate Research Programme
WFDEI	WATCH Forcing Data methodology applied to ERA-Interim
W/m^2	Watts per square meter
°C	degree Celsius
%	per cent

1 INTRODUCTION

This Technical Note serves as an explanatory reference that describes the work undertaken on regional climate modelling and regional hydrological modelling within the framework of the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR). The intention is to provide technical clarification of the regional climate modelling methodology and regional hydrological modelling methodology applied by the Swedish Meteorological and Hydrological Institute (SMHI) to generate the regional projections and findings presented in the *Arab Climate Change Assessment Report- Main Report* and its Technical Annex, which are issued under RICCAR in coordination with the United Nations Economic and Social Commission for Western Asia (ESCWA) and the other RICCAR implementing partners.

2 DATA SOURCES

2.1 Meteorological Data

Climate datasets originate as measurements of sub-daily or daily weather variables collected over time and merged to create climate records. Point measurements taken in situ at observation stations are usually the most direct and therefore precise form of observation. For regional analysis, however, the point data may not be representative for larger regions, particularly where the terrain varies widely (e.g. mountains and coasts), and the measurement itself can also be error-prone. As an example, measured precipitation observations can be lower than the actual amount due to losses from wind or evaporation. Such limitations should be kept in mind when using observed climate data. Also, observation data can be organized into gridded datasets, similar to how data are organized in climate model outputs. It is an interpolation of available observed station data from non-uniform point data to the selected grid. An advantage of gridded data is that it can provide data at points where there are no observation stations, however the quality of the gridded data is always a function of the amount of station data that goes into it.

Due to the infrequency of reporting and quality assurance issues, it can be difficult and time consuming to work directly from station data. However, international research groups have created gridded observed datasets from such station data that are suitable for climate related studies and are freely available. These have gone through some type of quality control and further processing to improve their usability. Generating re-analysis data is a specific application that uses a Numerical Weather Prediction (NWP) model to incorporate all available meteorological observations (from ground weather stations and satellites) into a common structure over an observed period of time. This process is referred to as data assimilation.[1] The outcome is data that is evenly spaced in the gridded structure of the NWP model, both horizontally and at various vertical levels in the atmosphere. Since in these simulations large amounts of surface and upper-air observations are assimilated, they provide a close representation of reality, and are particularly useful for sites where there are no actual observations.

Re analysis data is seen as an important component for both testing and evaluation of climate models and is also used in combination with other observations to improve gridded observed datasets. However, as with all climate data, they have some limitations. An example is precipitation data from re-analyses, which have been shown to provide good representation of the temporal precipitation distribution, but can have large biases in precipitation magnitude. And this can also vary depending on location. Re-analyzed temperature data, on the contrary, generally shows a better agreement with observations.

Numerous historical meteorological datasets are available over the Arab region, with continuous developments as new methods for combining in-situ observations with numerical methods and remote sensing continue to evolve. Even though measurements for a wide range of parameters exist, none of these datasets individually give a perfect representation of the actual observations, and thus a combination of different datasets have been applied under RICCAR to make best use of their different characteristics. They include the datasets listed below.

- **University of East Anglia Climatic Research Unit Time Series (CRU v3.21):** It consists of datasets comprising month-by-month variations in climate starting from 1901 on 0.5-degree resolution grids. Variables include cloud cover, diurnal temperature range, frost day frequency, Potential Evapotranspiration (PET), precipitation, daily mean temperature, monthly average daily maximum and minimum temperature, vapour pressure and wet day frequency. Period of data used for RICCAR was until 2012 according to data available at the time of study.[2]

- **Global Precipitation Climatology Project (GPCP v1.2):** Version 1.2 provides a global monthly surface precipitation data at 60 arc-minute (1 degree) grid resolution from 1979 onwards.[3]

- **Global Precipitation Climatology Centre (GPCC v6):** This is the GPCC Full Data Reanalysis of monthly global land-surface precipitation based on the 67,200 stations world-wide. Data used at the time of analysis covered the period 1901-2010 at a spatial resolution of 0.5x0.5 degrees.[4]

- **University of Delaware Air Temperature and Precipitation (UDEL v3.01):** It comprises a series of gridded temperature and precipitation datasets based on station records starting from 1900 (data used for this study covered the period 1900-2010). It provides relatively detailed global land surface climatology of the two most essential variables in a spatial resolution of 0.5x0.5 degrees.[5]

- **Tropical Rainfall Measurement Mission Project (TRMM 3B42-v7):** Version 7 published by the Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC) provides daily precipitation data from 1997 onwards at a resolution of 0.25x0.25 degrees.[6]

- **European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim Reanalysis:** It is a global atmospheric reanalysis product that covers the period from 1979 onwards and is continuously updated in real time. It includes a set of 3-hourly surface parameters, describing weather as well as ocean-wave and land-surface conditions, and 6-hourly upper-air parameters covering the troposphere and stratosphere. The spatial resolution is approximately 80 km (T255 spectral) on 60 vertical levels from the surface up to 0.1 hPa.[7]

- **WATCH Forcing Data methodology applied to ERA-Interim (WFDEI):** The WFDEI observation dataset was used for setting up the hydrological models and for the bias correction of modelled precipitation. It is interpolated to a 0.5x0.5 degrees grid and is a combination of observations and re-analysis model data. As mentioned previously, the re-analysis uses a NWP to incorporate all available weather observations into a common structure over an observed period of time.[8] The WFDEI covers the period 1979-2012 and is based on monthly observed values from the CRU dataset that are distributed to daily values according to the temporal distribution coming from the ERA-Interim re-analysis.[9]

2.2 Water Resources Related Data Sources

2.2.1 Water basins delineation and drainage networks

The Hydrological data and maps from **SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS)** dataset was used for topography, watershed delineation and drainage networks. It is derived from elevation data of the Shuttle Radar Topography Mission (SRTM) elevation data at 3 arc-second resolution (GL3S). The original SRTM data have been conditioned in terms of hydrology using a sequence of automated procedures. Manual corrections were made where necessary.[10]

2.2.2 River discharge data

River discharge observations are point measurements representing the integrated sum of all runoff occurring upstream of the measurement point. They provide an important variable for analyzing changing hydrological, climatological and development conditions in the upstream basin. They also provide an important variable for calibrating and testing hydrological models. Access to observed river discharge data is however limited in the region. International sources from outside the region proved to be the main supplier for river discharge data, and it is of limited extent. Data from the **Global Runoff Data Centre (GRDC)** which comprises international archives of hydrological data[11] was made available to RICCAR, however, many discharge stations have only short periods of records ending in the early to mid-1980s. River discharge records were also obtained from various freely available reports and publications, such as a report published by the U.S. Geological Survey on the Tigris and Euphrates river basins.[12] A small number of records were also obtained locally through national collaborators. Access to long records of observed river discharge are lacking in this study.

2.2.3 Lakes and Reservoirs

The data sources on lakes and reservoirs used for the impact assessment are the following:

- **Global Lakes and Wetlands Database (GLWD):** It is published by the World Wildlife Fund and the Center for Environmental Systems Research, at the University of Kassel in Germany based on the combination of best available sources for lakes and wetlands on a global scale (1:1 to 1:3 million resolution), and the application of GIS functionality. It enabled the generation of a database focused on three coordinated levels: large lakes and reservoirs, smaller water bodies, and wetlands.[13]

- **Global Reservoir and Dam Database (GRanD):** This database is based on the compilation of global available reservoir and dam information with corrections and completion of missing information from new sources or statistical approaches. It initially included all reservoirs with a storage capacity of more than 0.1 km³, but many smaller reservoirs were additionally added depending on data availability.[14] This dataset was complemented with national data provided by the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD).

2.3 Topography and other Terrestrial Data Sources

Different sources were used as part as climate modelling in order to obtain terrestrial data with a varying level of detail depending on the different models applied. The WHIST program (World Hydrological Input data Set-up Tool)[15] was used as a set-up tool to prepare the baseline information for the models applied by SMHI in this study. Its function was to develop information for the hydrological models (such as the delineation of sub-basins, production of river routing and calculation related to proportions of soil and land use classes) based on the different source databases for topography, soil, land use and agriculture. The latter components are detailed in the sections below.

2.3.1 Topography

Topography data is based on the **HydroSHEDS Database** (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales)[16], which is the same used for drainage networks and watershed delineations.

2.3.2 Soils

Soil data was based on the **Harmonized World Soil Database (HWSD)**. Version 1.2 was used and is a 30 arc-second raster database with over 15,000 different soil mapping units that combines existing regional and national updates of soil information worldwide. It is based on four source-databases: The European Soil Database (ESDB), the Soil Map of China (1:1,000,000), various regional SOTER Databases (SOTWIS Database) and the FAO-UNESCO Soil Map of the World.[17]

2.3.3 Land Used

The **Global Land Cover (GLC 2000)** dataset was mainly used and was produced by an international partnership of 30 research groups coordinated by the European Commission's Joint Research Centre. The dataset is at 1 km resolution and contains two levels of land cover information—detailed, regionally optimized land cover legends for each continent and a less thematically detailed global legend that harmonizes regional legends into one consistent product.[18]

For modelling using the Hydrologic Engineering Center Hydrological Modelling System (HEC-HMS) model, land use data was based on the **Global Land Cover-SHARE (GLC-SHARE)**. It was published by FAO in 2014 and provides a set of eleven major thematic land cover layers resulting from a combination of best available high resolution national, regional and/or sub-national land cover databases. The database is produced with a resolution of 30 arc-second. The major benefit of the GLC-SHARE product is its capacity to preserve the available land cover information at the country level obtained by spatial and multi-temporal source data.[19]

2.3.4 Agriculture

The **Global Map of Irrigation Areas (GMIA)** Version 5 of GMIA published in 2013 by FAO was used. It shows the amount of area equipped for irrigation around the year 2005 in percentage of the total area as a raster with a resolution of 5 arc minutes. Additional map layers show the percentage of the area equipped for irrigation that was actually used for irrigation.[20] In addition, the **Global Monthly Irrigated and Rainfed Crop Areas (MIRCA)** dataset was used and provides both irrigated and rainfed crop areas of 26 crop classes for each month of the year with a spatial resolution of 5 arc minutes.[21]

3 BACKGROUND ON CLIMATE MODELLING

3.1 Global Climate Models

Global assessments of projected climate change impacts are carried out using Global Climate Models (also referred to as General Circulation Models or GCMs), which are numerical models that combine several components representing physical processes in the land surface, ocean, atmosphere and cryosphere to simulate the response of the global climate system to increasing greenhouse gas concentrations.

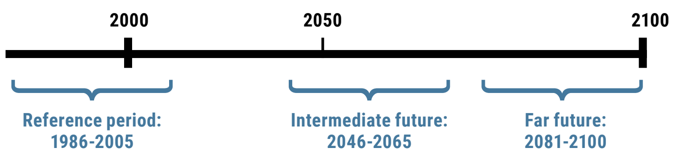
GCMs are used to study a variety of climate attributes such as surface temperature, atmospheric temperature profiles, rainfall, atmospheric circulation, ocean circulation, wind patterns, snow and ice distributions, as well as many other variables that are part of the global climate system. The various parameters make up a list of more than 100 variables at the global scale that describe specific climate components (atmosphere, ocean, land or sea ice, etc.) or the interaction between them (radiative forcing fields).

Global Climate Models, in conjunction with nested regional models, represent the most advanced tools to provide geographically and physically consistent estimates of regional climate change which are required in impact analysis. GCMs are continuously being improved as scientific understanding of climate develops and computational power increases. Over the years, a number of Coupled Model Intercomparison Projects (CMIPs) have produced a vast amount of GCM results that can be used to assess possible future climate changes of which the current CMIP5 model considered in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.[22]

3.2 Reference and Projection Periods

When creating future climate projections, climate models always cover a period of observed historical climate that is used as a “control period” (or “reference period”) to check how well the model represents the present climate. Biases with regard to climate models refers to the differences between the observed long-term mean for a region and the modelled long-term mean results from the control period over the same region. Within RICCAR, it was desirable to compare regional outcomes to the global outcomes presented in the latest IPCC assessment reports.[23] Therefore, it was decided to adopt the same reference and future time periods for analysis. These are 1986-2005 as a reference, and future periods of 2016-2035 (near future), 2046-2065 (intermediate future or mid-century) and 2081-2100 (far future or end-century). Results for the near future (2016-2035) were not presented in RICCAR reports but are available for further reference. Time periods considered for analysis are presented in Figure 1.

FIGURE 1: Time periods considered for analysis

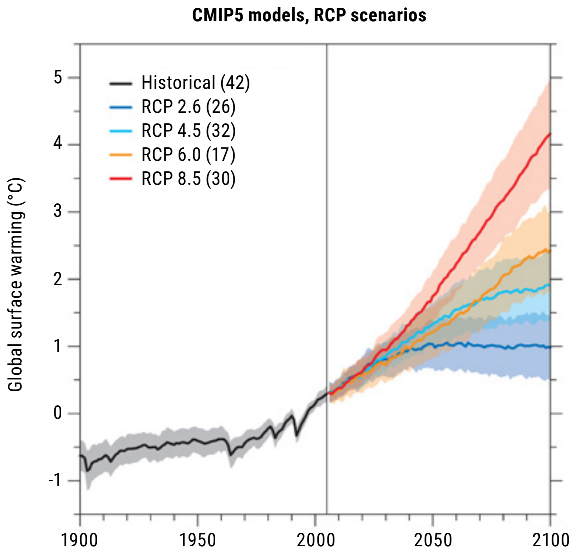


3.3 Representative Concentration Pathways

Climate change projections conducted within the framework of RICCAR are based on two of the four Representative Concentration Pathways (RCPs) developed by IPCC for informing global and regional climate modelling work presented in its Fifth Assessment Report (AR5). As shown in Figure 2, there are four RCP scenarios – RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 named in accordance with their expected radiative forcing expressed in watts per square meter (W/m^2). Each of them represents a trajectory of greenhouse gas concentrations from pre-industrial conditions and over time to reach a particular radiative forcing in the year 2100.[24]

The climate projections studied in RICCAR are based on RCP 4.5 (moderate case scenario) and RCP 8.5 (“business as usual” - worst case scenario). RCP 2.6 was examined to a lesser extent, where global greenhouse gas emissions peaks by 2020 and then decline thereafter.

FIGURE 2: Global temperature change projections for RCP scenarios run by CMIP5



Note: Mean global temperature change relative to 1986–2005 is shown as a colored line and one standard deviation is shown with colored shading. The number of models run is given in parentheses.

Source: Knutti and Sedláček, 2013

4 REGIONAL CLIMATE MODELLING

4.1 The Arab Regional Domain

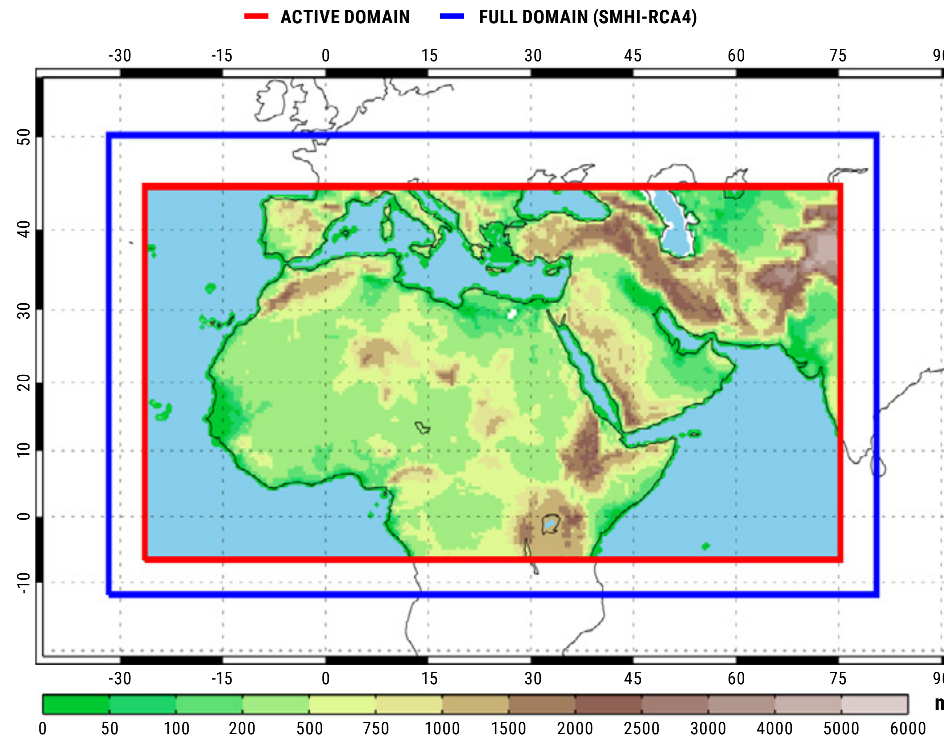
Despite the progress and rapid development of GCMs, important gaps remain in generating outputs on a smaller scale grid. In order to better understand those smaller scale processes, climate scientists downscale their models to describe limited areas of the world. Similarly, a core activity within RICCAR was to produce regionally downscaled future climate projections for the Arab Region. This involves the linking of models of different scales within a GCM to provide a more detailed analysis of regional conditions while using the general analysis of the global output as a driving force for the higher resolution model.

In this context, there is considerable global-wide cooperation and exchange to promote advancement in the science within the climate modelling community.[25] An initiative that is designed to enhance this cooperation is the Coordinated Regional Climate Downscaling Experiment (CORDEX) organized under the World Climate Research Programme (WCRP).[26] Through establishing a standardized approach, CORDEX aims to evaluate and improve regional climate downscaling models and techniques and produce coordinated sets of regional downscaled projections worldwide. An integral part of this approach is establishing common regional modelling domains to be used by all participating modelling groups. A common domain together with a common list of standard model outputs provides a framework for comparing model performance and future climate projections over these regions, and thus fosters better communication and exchange of regional climate information. Regional Climate Models (RCMs) are especially suitable to assess changes expected in terms of extreme weather events, which are of great importance to develop adaptation strategies as they better represent the local processes related to weather/climate extremes with respect to GCMs.[27] It was decided at the onset of RICCAR that following the CORDEX approach would enhance the outcomes of the study and provide a productive means for continued development beyond the project's lifetime.

The regional climate modelling approach was applied to dynamically downscale global climate model results to regional scales. This is usually done by first identifying a specific region of the globe in focus for the downscaling, referred to as the regional domain. For the case of RICCAR, the region of interest covers all of the Arab countries and their water resources. As the majority of water resources in Arab States originates from outside the region, it was thus necessary that the boundaries of the Arab Domain were selected so as to include all headwaters of shared surface water resources found in the region, which encompass a wider geographic area (extending from the headwaters of the Tigris and Euphrates Rivers in the north, to the headwaters of the Nile River in the south). In addition to the sufficient spatial coverage of the Arab region, the domain had to be extented to adequately represent prevailing circulation patterns that control the regional weather processes. Defining an appropriate regional domain is not a trivial task and a number of tests were required to determine the effects of different domain configurations. As a larger domain also implies larger computing needs and disk storage for the output, it was desirable to establish an appropriate size that provides satisfactory results without placing undue demands on computing resources.

With these considerations, the CORDEX "Region 13: Middle East North Africa (MENA)" regional domain or CORDEX-MENA regional domain (27W—76E, 7S—45N) was established as part of RICCAR within the WCRP[28] as shown in Figure 3. This is synonymous with the Arab Domain as referred to in the RICCAR Arab Climate Change Assessment Report.

FIGURE 3: CORDEX-MENA Domain



Note: The Active domain (red) contains the area where RCM results are considered usable. The Full domain (blue) indicates the actual area needed for the RCM (RCA4 in this case) to perform properly within the active domain. The area between Active and Full domain is a transition zone between the GCM driving boundaries and the RCM; using results from this zone should be avoided.

This is a result of the tests conducted together with recommendations from climate scientists in the region that had performed independent tests with other RCM models. According to the tests made, this choice provides robust representation of circulation, precipitation and temperature. It thus fulfills both the spatial and performance criteria set forth, while limiting the extent. Nevertheless, it should be noted that CORDEX-MENA is an extended domain that requires substantial computing resources for completing century-long simulations. It is also noted that the Comoros, while an Arab State, is not included in the Arab Domain given its geographic location. The Comoros can be studied drawing on high resolution global climate models or regional climate modelling outputs covering the CORDEX-AFRICA Domain.

4.2 Regional Climate Modelling Projections

The list of available RCM simulations over the CORDEX-MENA domain is shown in Table 1. It comprises all historical and future climate simulations thus far submitted to the CORDEX international archives at the Earth System Grid Federation (ESGF) portal.[29]

RCA4 is the regional climate modelling system developed by the Rossby Centre at SMHI and was the only regional climate model available for analysis for future simulations in RICCAR. It is built upon its predecessor RCA3 with substantial physical and technical improvements[30] and is developed from the Numerical Weather Prediction (NWP) High Resolution Limited Area Model (HIRLAM). There are three types of simulations identified from the table – evaluation, historical and scenario:

- ***The evaluation (or hindcast) simulation*** is used to assess how well an RCM can represent recent climate over the domain. It was created using ERA-Interim[31] as the driving GCM data at the boundaries, and is somehow considered equivalent to driving the RCM with observations.

- ***The historical simulation*** uses observed emissions data for the period that should statistically represent the historical period from 1950 to 2005.

- For the ***scenario simulation*** runs performed under RICCAR, downscaled simulations by RCA4 were driven by lateral boundary conditions from three different CMIP5 Global Climate Models, namely EC-EARTH[32]; CNRM-CM5[33] and GFDL-ESM2M[34]. As previously outlined, this report focuses on results for RCP 4.5 and RCP 8.5 scenario projections, which begin in 2006. The projection under the RCP 2.6 pathway has not been analyzed in detail, but is available for use in future research as needed.

TABLE 1: List of RCM simulations conducted over the CORDEX-MENA Domain by Rossby Centre, SMHI

RCM	Driving GCM/Reanalysis	Evaluation 1979-2010	Historical 1950-2005	RCP 2.6 2006-2100	RCP 4.5 2006-2100	RCP 8.5 2006-2100	RESOLUTION (Km)
RCA4	ERA-INTERIM	X					50
RCA4	EC-Earth		X	X	X	X	50
RCA4	EC-Earth		X			X	25
RCA4	CNRM-CM5		X		X	X	50
RCA4	GFDL-ESM2M		X		X	X	50
RCA4	GFDL-ESM2M		X			X	25
HIRAM	GFDL-ESM2M		X				25
REMO	MPI-ESM-LR		X				50

As seen in the table of simulations, there are a total of nine RCA4 projections listed. Seven of these are at 50 km resolution and two are at 25 km resolution. Six of the 50 km projections based on RCP 4.5 and RCP 8.5 scenarios have been used to create 3-member ensemble analyses in RICCAR.

4.3 Observation Datasets Comparisons

Comparisons with observation datasets (temperature and precipitation) for the MENA/Arab domain have been carried out for different seasons to provide a clearer view of how RCM simulation datasets perform with respect to observation datasets for the present climate.

The basis for comparison is the CRU dataset.[35] Results representing the recent past climate are presented for the RCM simulations of temperature in Figure 4 and Figure 5, and simulations of precipitation in Figure 6 and Figure 7. Both temperature and precipitation results are provided for June-July-August and December-January-February. In addition to the RCMs, they include two additional observations datasets for comparison and the RCA4 simulation driven by the ERA-Interim Reanalysis data, which represents a test of the RCM using the "perfect" boundary conditions based on observations.

Results of RCM driven by the GCMs show a common tendency for a cold bias in temperature that is more pronounced in winter than in summer. An exception is the warm bias in the south-east part of the Arabian Peninsula during summer. The GCMs exhibit the same pattern of bias, which indicates that the bias is carried over from the GCMs to the RCMs. This is supported by the fact that RCA4 driven by reanalysis shows more accurate temperature results (ERA-Interim). However, the warm bias for the Arabian Peninsula is apparent with this simulation as well. It is also worth noting that the largest differences between the two observational datasets (CRU and UDEL) also occur for the Arabian Peninsula, so uncertainties in the observational datasets may also be in play.

On the other hand, precipitation results show that most of the RCM simulations exhibit a dry bias over Central Africa during summer, but this appears more pronounced for RCA4. During winter, the dry bias also appears further north in the Atlas Mountains and in the headwaters of the Tigris and Euphrates Rivers. This is apparent for the GCM ensemble as well.

FIGURE 4: Comparison between different RCM results for mean seasonal temperature during June, July and August for the period 1980-2004

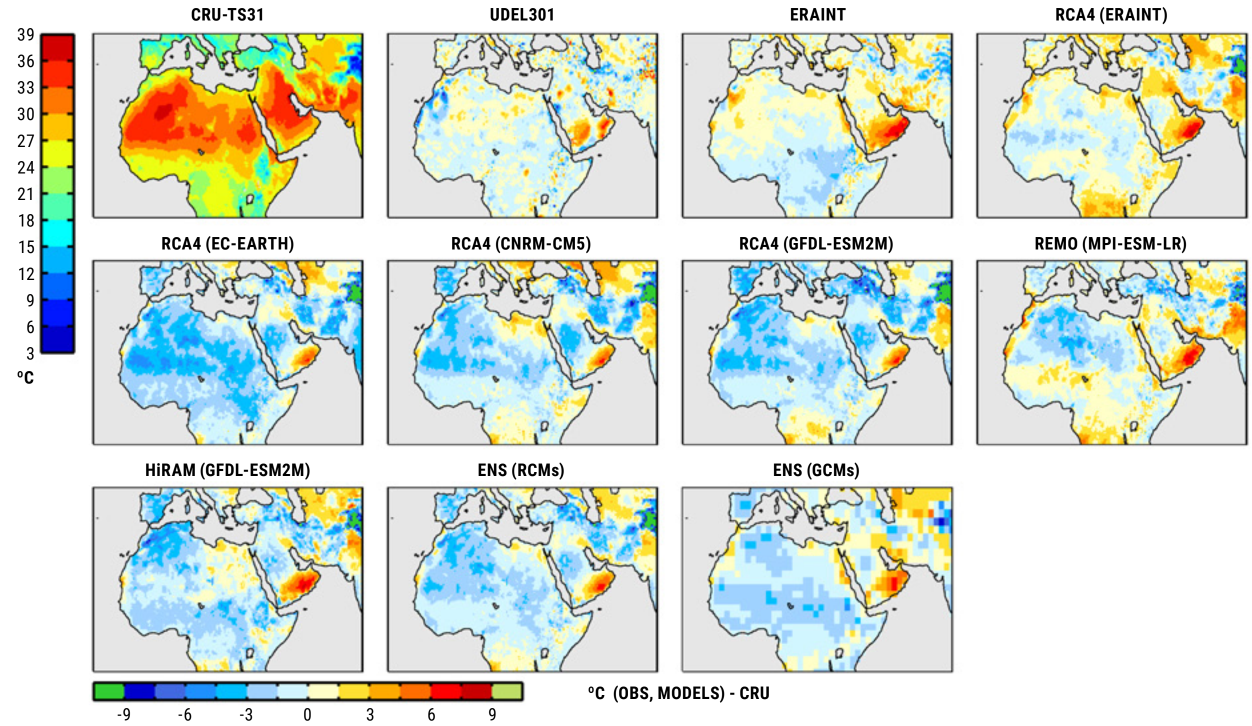
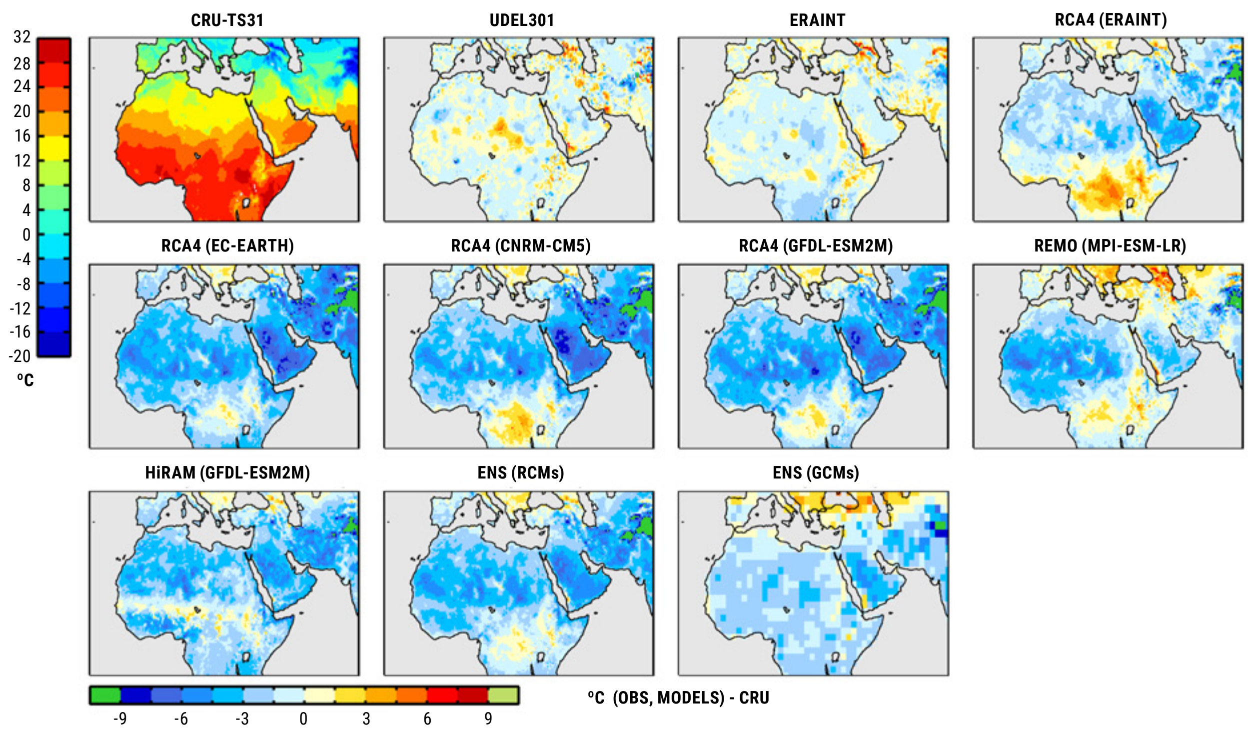


FIGURE 5: Comparison between different RCM results for mean seasonal temperature during December, January and February for the period 1980-2004



Notes:

- For each figure, top left image shows temperature observations from the CRU dataset; following are differences compared to CRU for the UDEL dataset, ERA-Interim data and RCA4 driven by ERA-Interim boundary conditions.
- Rows 2 and 3 show differences compared to CRU for different RCM simulations.
- The last two plots in row 3 are differences compared to CRU for the ensemble of the 5 RCMs analysed and the ensemble of the 4 GCMs used to drive these RCMs.
- The top left legend is for CRU only; the bottom legends pertains to all other plots.

FIGURE 6: Comparison between different RCM results for mean seasonal precipitation during June, July and August for the period 1980-2004

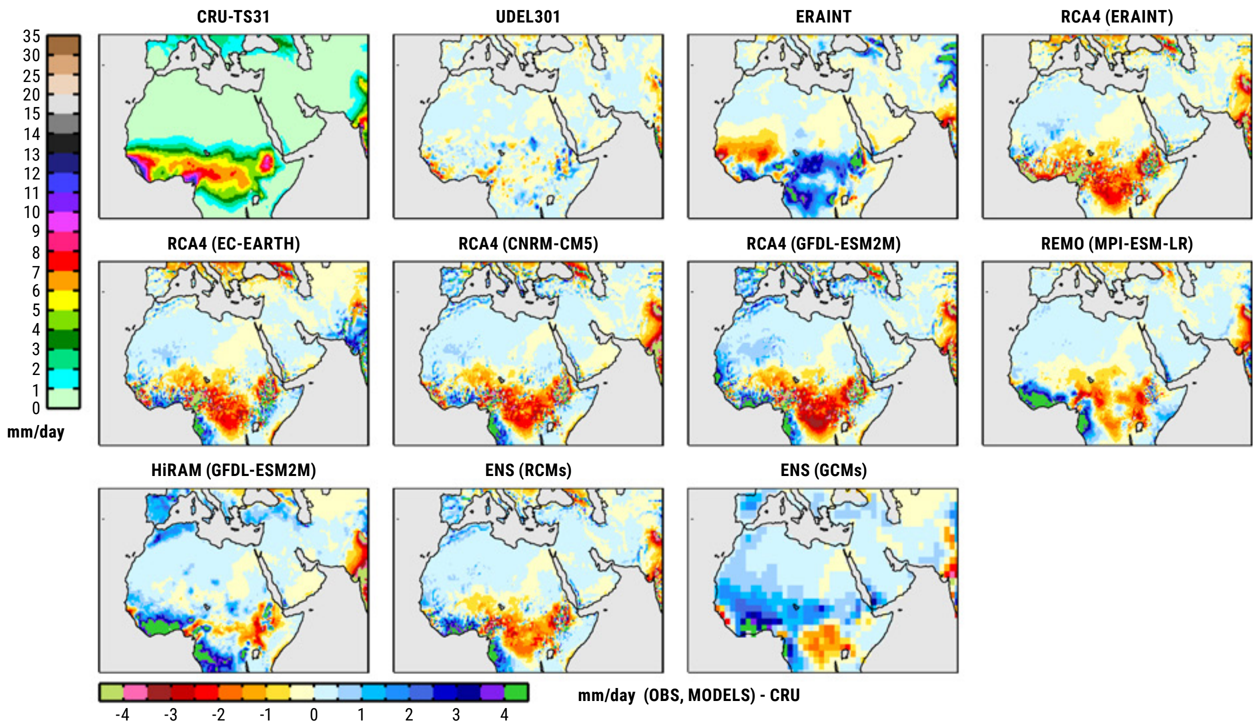
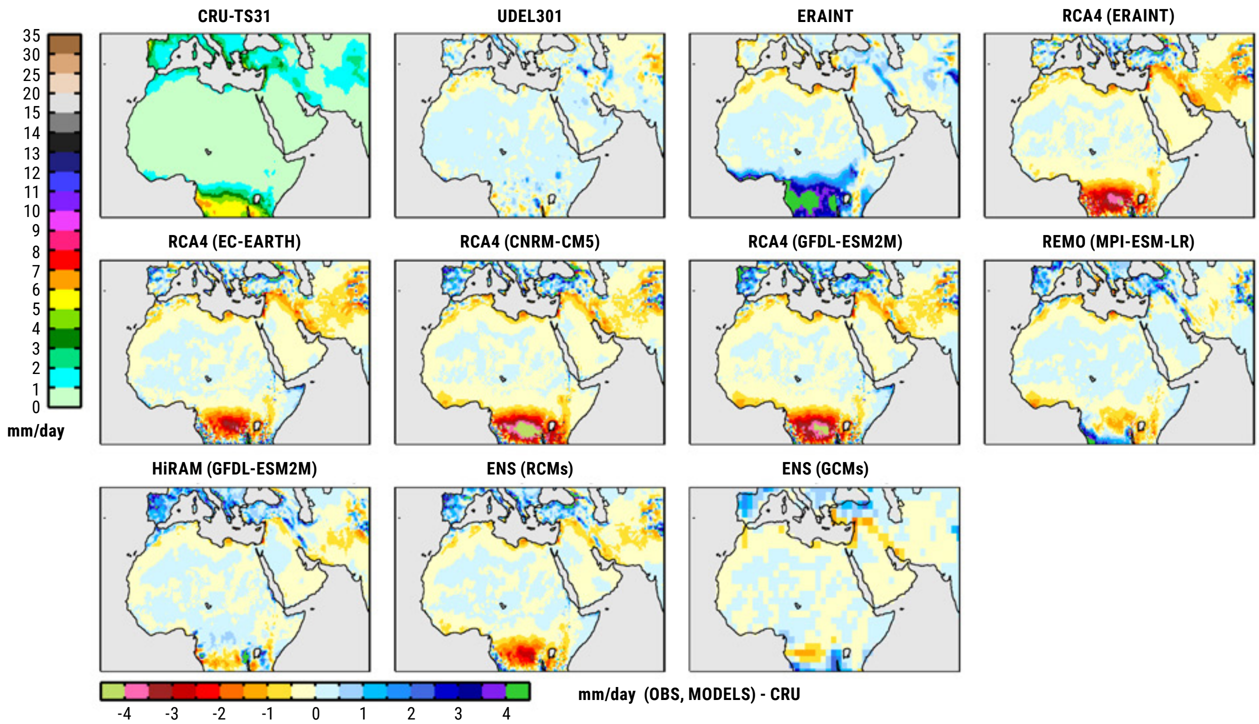


FIGURE 7: Comparison between different RCM results for mean seasonal precipitation during December, January and February for the period 1980-2004



Notes:

- For each figure, top left image shows temperature observations from the CRU dataset; following are differences compared to CRU for the UDEL dataset, ERA-Interim data and RCA4 driven by ERA-Interim boundary conditions.
- Rows 2 and 3 show differences compared to CRU for different RCM simulations.
- The last two plots in row 3 are differences compared to CRU for the ensemble of the 5 RCMs analysed and the ensemble of the 4 GCMs used to drive these RCMs.
- The top left legend is for CRU only; the bottom legends pertains to all other plots.

5 REGIONAL HYDROLOGICAL MODELLING

5.1 Background

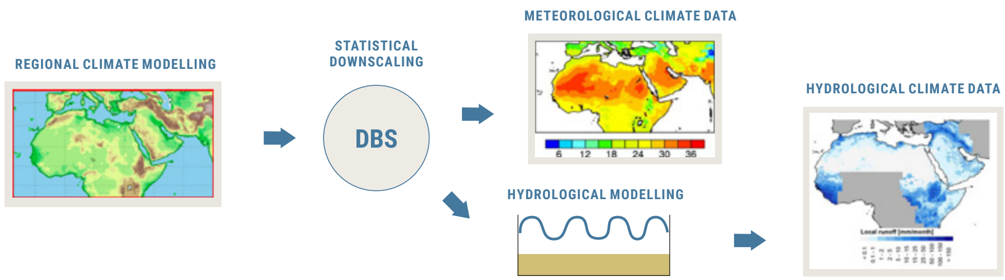
Although climate models include some representation of hydrological processes, they generally do not resolve the hydrological cycle at a level of detail suitable for hydrological applications. Hydrological models are thus used to further assess the impact of climate change on hydrological processes. The aim within RICCAR was to provide a large scale overview of hydrological effects over the entire Arab region. Hydrological modelling was carried out at this regional scale; we refer to this as "Regional Hydrological Modelling" (RHM). Producing perfect representation of river flows at local scales cannot be expected from such model applications. Efforts were thus made to produce reasonable representation of hydrological processes over regional scales given the sparse data available. This provides a consistent approach with a similar level of detail over the entire region. By providing a regional overview in this way, the regional patterns of projected hydrological change can be seen, and trends and areas that would be affected can be identified. It is important to note that the RHM approach does not replace the need to carry out local studies that address water resources management in more detail, but helps identify key areas that would potentially benefit from more detailed studies.

5.2 Bias Correction

Eventhough they are based on physical principles, information generated by global climate models also comprise numerical approximations, which may lead in some cases to biases resulting in deviations of the simulated climate from the observed one.[36] It is nowadays widely recognised that climate model results cannot be used directly as inputs to other more specialized impact models and an adjustment (bias correction) towards the observed climatology is necessary.

In particular, there are typically biases in the RCM statistics of key hydro-meteorological variables, such as precipitation and temperature.[37] Many of these biases originate from either the driving GCM model or the RCM used for downscaling. Since hydrological models are very sensitive to anomalies in rainfall amounts, direct use of RCM outputs in impact studies is therefore usually not appropriate and the hydrologically important variables precipitation and temperature need to first be adjusted before use in impact studies.[38] While several bias correction methods exist, all of the RCM projections in RICCAR were adjusted using the Distribution-Based Scaling (DBS) method developed by Yang et al. (2010) as shown in Figure 8.[39] More detailed information on different bias correction methods is provided in Nikulin et al.(2015).[40]

FIGURE 8: Scheme of modelling, downscaling and analysis within RICCAR

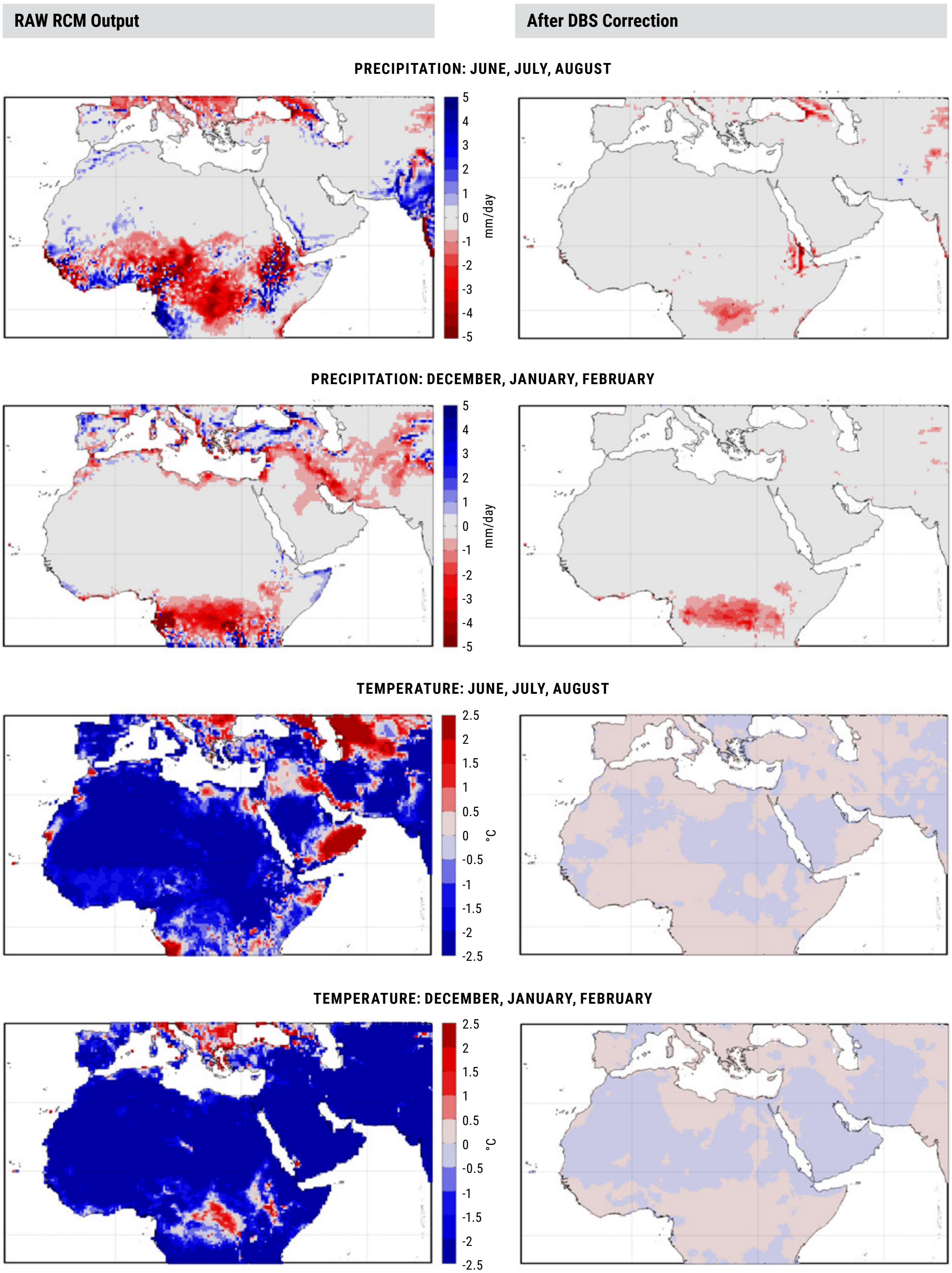


The following steps were performed with the DBS approach:

- Correction factors were derived by comparing the RCM output with observed climate variables for a similar control period.
- Correction factors were then applied to RCM outputs for the future climate period. This was done for precipitation and temperature for the entire regional domain.
- The WFDEI dataset was used as observed climate to define the DBS parameters for each RCM projection for the reference period 1980-2009.
- The DBS-corrected precipitation and temperature values were then used as inputs to drive the hydrological models and also in analysis of extreme events.

The original DBS approach was developed for applications over a wide range of climates in both Europe and Africa. It has been well-tested for areas that exhibit a positive bias in precipitation. For the RICCAR region, the climate projections showed tendencies for negative precipitation biases for many areas.[41] Additional focus was thus needed to further develop the DBS techniques to better account for negative precipitation biases. No additional development was needed for the temperature bias correction technique. An example showing precipitation and temperature biases both before and after the DBS bias correction is shown in Figure 9

FIGURE 9: Absolute bias in mean precipitation (mm/day) and temperature (°C) for raw RCM outputs and with DBS bias correction



Note: The example illustrates the absolute bias of RCA driven by EC-Earth relative to WFDEI for the period 1980-2009 over two seasons.

Biases are greatly reduced, improving the accuracy of these key climate variables relative to the observations data available. However, it is important to note that this approach assumes that the biases being corrected are systematic in nature and of similar magnitude for both present and future climate. Although bias correction is needed, it can to some extent also modify the climate change signal.

It is also worthy to note that applying bias adjustment to climate model simulations introduces a level of uncertainty in impact modelling, and thus care should be taken with respect to bias correction assumptions and unavoidable limitations in its application, as outlined in IPCC, 2015.

In this context, a Bias Correction Intercomparison Project (BCIP) has been recently established to:

(1) adress level of uncertainties bias adjustment introduces to workflow of climate information;
(2) advance bias-adjustment technique and
(3) provide the best practice on use of the bias-adjusted climate simulations.[42]

5.3 Hydrological Models Applied

Three different hydrological models (Table 2) were applied within RICCAR. The Hydrological Predictions for the Environment (HYPE) and Variable Infiltration Capacity (VIC) models were used to produce RHM results over the entire Arab region, and the Hydrologic Engineering Center Hydrological Modelling System (HEC-HMS) model was used to investigate hydrological impacts from changes in extremes at selected local scales. They all model rainfall runoff processes with primary focus on surface waters.

TABLE 2: Hydrological Models Applied under RICCAR

Hydrological model	Application	Set-up
HYPE	Regional approach	Runoff basins
VIC	Regional approach	Grid boxes, 50 km resolution
HEC-HMS	Local extremes	Runoff basins

Both HYPE and VIC are freely available open-source models. They were chosen as both have been designed for use in large-scale applications and have successfully been used in various regions around the world. Both have been applied to assessing hydrological change using future climate projections and can easily accommodate large datasets spanning timescales exceeding 100 years. HEC-HMS is also freely available and is a rainfall-runoff model that has been widely used for a variety of applications. It is not, however, specifically known for large-scale applications. The three models are briefly described below.

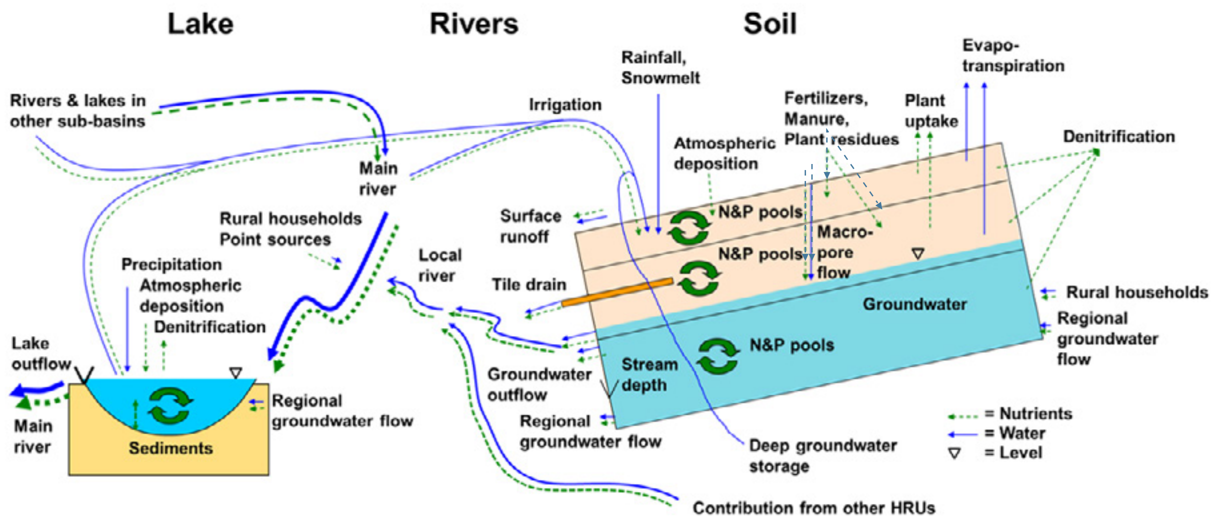
5.3.1 Hydrological Predictions for the Environment (HYPE) Model

The HYPE Model (Hydrological Predictions for the Environment) was developed at SMHI to better address environmental problems affecting hydrological systems, including nutrient transport and the effects of a changing climate.[43] HYPE is based on the widely-applied HBV model concept[44], and works on the basis of establishing sub-basins according to topographical data and then assigning different classes within each sub-basin to further represent heterogeneity.

These classes, or hydrological response units, are based on land use, soil type and elevation. The water balance for each class is calculated individually before being combined to generate the overall water balance in each sub-basin.

The HYPE model structure was designed to accommodate the large quantities of data needed for both modelling large areas and for long time periods, such as with climate change projections. It has successfully been applied in large and small scale applications, and serves both as a research tool and operational forecast model.[45] Components of this model are displayed in Figure 10 and its input data includes forcing data (precipitation, temperature) as well as static data (land cover, soil type, lakes and reservoirs).

FIGURE 10: Components of the HYPE model



Source: SMHI, 2016

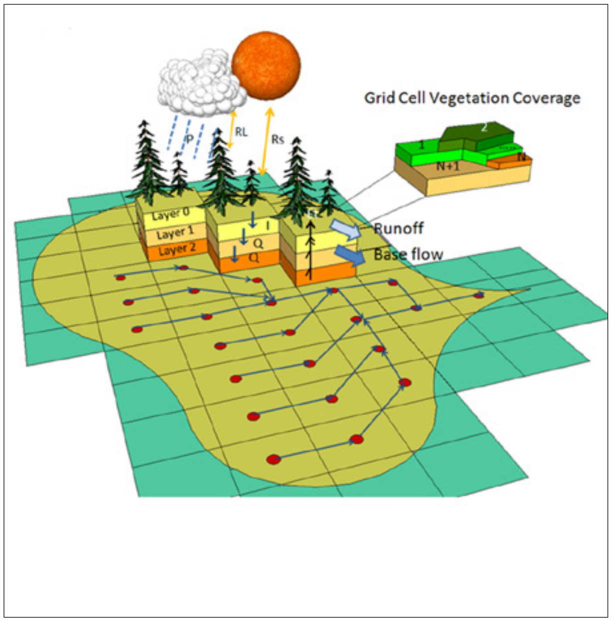
5.3.2 Variable Infiltration Capacity (VIC) Model

The VIC Model (Variable Infiltration Capacity) is a large-scale, semi-distributed hydrologic model and was originally developed as a macroscale hydrological model.[46] As such, it is typically applied on continental or subcontinental scales using a rectangular grid structure typically ranging from 0.125 to 2.0 degrees, although finer scale applications have been made in recent years.

Within each grid box, multiple land covers can be represented and variable topography is included through the use of elevation bands (Figure 11). VIC allows for two modes of calculation, either water balance mode with a 24-hour time step, or energy balance mode that allows for sub-daily time steps. The water balance mode was used for this application.

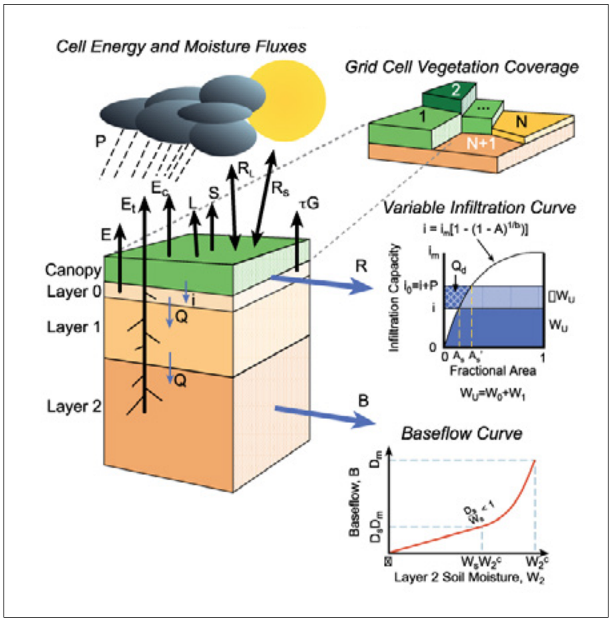
Each VIC grid cell is modelled independently to resolve different components of the water balance (Figure 12).[47] Represented processes include infiltration, percolation, evapotranspiration, snow accumulation and snowmelt (the following are not represented: lakes, irrigation, subsurface/groundwater flow and channel losses including seepage and evaporation). Representation of lateral flows between grid boxes can be done in a separate step for routing flows, but this was not included in this study. Input data for VIC includes daily precipitation, temperature and wind speed in 0.5° resolution from the WFDI dataset, as well as global VIC parameters comprising pre-processed soil and land cover data.[48]

FIGURE 11: VIC conceptual model



Source: Hamlet et al., 2010

FIGURE 12: Hydrologic processes in VIC model



Source: University of Washington Computational Hydrology Group, 2016

5.3.3 Hydrologic Engineering Center Hydrological Modelling System (HEC-HMS) Model

The HEC-HMS Model (Hydrologic Engineering Center Hydrological Modelling System) is a modelling package that is designed to accommodate varying hydrological applications over a range of geographic areas.[49] Depending on how it is set up, it can be used for both large river basin applications as well as urban conditions. It is often used in combination with other modelling tools for a number of water resources management applications. It supersedes the HEC-1 hydrological model from which it is based by offering a number of advancements and modelling options, including different ways to simulate the key variables of precipitation, evapotranspiration, and infiltration. This model was used by ACSAD in RICCAR in order to study hydrological impacts from changes in extremes at the local scale for three different basins, namely Wadi Diqah (Oman), Medjerda River (Tunisia/Algeria), and Nahr el Kabir (Lebanon/Syrian Arab Republic).

5.4 General Model Considerations

The drainage basins defining the HYPE Model setup vary in size but are on average 650 km^2 in area. The VIC Model was applied at the same grid resolution as the majority of the RCM climate projections, which is 0.44 degrees (approximately 50 km). Although neither of the hydrological models applied provides detailed operations of water resources systems such as dams and other diversions, the HYPE Model includes simple representation of such structures, allowing for some representation of dam regulations. It also includes functions that account for losses due to irrigation; this is based on crop-demand oriented calculations at basin scales and does not include other management factors such as distribution constraints for the irrigation water. Considerations for dams and irrigation are both highly dependent on the quality of observed data that is available. As such, including more detail for the RHM is not warranted until more detailed observed data is made available. As the version of the VIC Model used in this study does not explicitly include natural lakes or dams, the lag effects of storage and open water evaporation from such features are not represented. For this reason, lateral flows have not been calculated for the VIC Model and projection results for river discharge were not considered.

5.5 Calibration and Validation

For calibration and validation, the models were compared to the 107 monthly river discharge stations available. However, as noted above, the available discharge records are sparsely located and many contain only short periods of record. With such gaps, there was no common period of data for all the stations available to this project.

When working with hydrological models at a regional scale, the primary aim is to achieve a reasonable representation of the overall water balance. The ability to simulate individual events with high accuracy is not in focus. Furthermore, as many areas have no river flow observations, the concept of regional calibration is used. This means that estimation of model parameters is more aligned with physical characteristics of the hydrological areas than the more stringent approach of deciding the parameters solely through calibration techniques. However, calibration is done for selected areas that do have observations and then the calibrated parameters are applied in other areas according to their physical characteristics.

The Tigris, Euphrates and Medjerda river basins were used here as calibrating basins to ascertain representative parameters for other areas of the model domain.

For this work, more emphasis has thus gone into representing the overall hydrological variability and large scale water volumes than producing high values of commonly used efficiency criteria for hydrological applications, such as the Nash-Sutcliffe efficiency criteria. This approach is further necessitated due to the high hydrological variability across the large Arab Region and the extent to which the water resources are heavily managed for various human benefits. Due to the influence of dams and other diversions, analysis focused more on model outputs further upstream in many of the rivers.

5.6 Overall Model Performance

Looking at the large scale water balance, the median of the relative error, or volume error, for river discharge over the entire Arab Region is about 1%. Model performance in terms of this error metric is reasonable for much of the Mashriq region, but river discharge in West Africa is mostly overestimated. Results for North Africa and the Nile regions are mixed. This holds for both the HYPE and the VIC Models, but over-prediction in the VIC Model is more pronounced. A visual comparison of results from the HYPE Model compared to observations for selected basin stations is given in Figure 13.

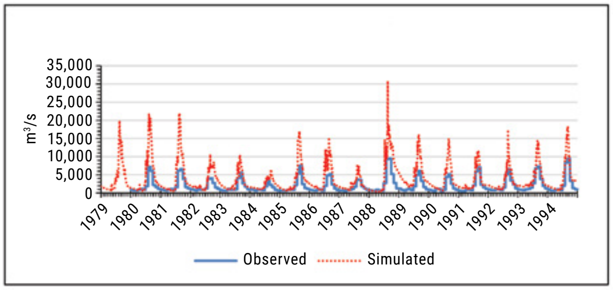
Comparison plots show that simulations follow the seasonal patterns of river flow reasonably well, with a tendency for overestimation apparent for some river basins (such as the Nile River or Faleme River tributary to the Senegal River) or underestimation for basins prone to flash floods such as Wadi Dayqah. A relatively good agreement between the model and observations is apparent for the Tigris River at Mosul, whereas differences are more pronounced further downstream at Baghdad. For the latter case, it is apparent that there are withdrawals from the river or other influences, such as additional storage capacity, that are not represented in the hydrological model.

There are several factors that can possibly explain the model discrepancies. One is irrigation withdrawals that are unaccounted for in the model. Another could be higher channel losses in some rivers that would lead to more of the surface water going to groundwater recharge. In some areas of the domain, such as Western Syria, there is also the presence of unusually large spring flows that are difficult to account for in a regional context. For these areas, underestimation in the models is generally the case. Furthermore, there is the observed climate database used as input to the models that has inadequacies, even though checks were made where possible to compare these inputs to other sources of data. The Wadi Dayqah is a case where the gridded climate database did not reflect the local precipitation extremes experienced during some observed flood events. These considerations have one thing in common; they require further input from local hydrological knowledge to be further investigated. The possibility for more detailed consultation or investigation is an area to prioritise in further studies.

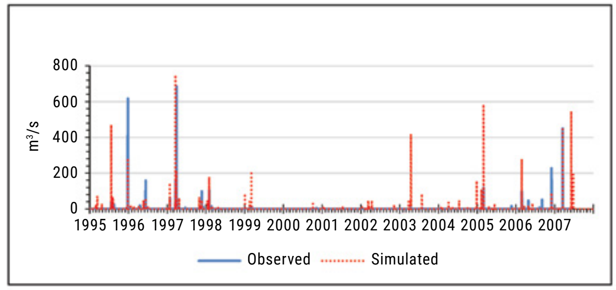
Regarding the hydrological model performance, it is recognized that there are deficiencies. Given the many unknowns in the region and the challenging characteristics of the regional climate, this is not an unexpected outcome. A key guideline in this respect is that analysis of the RHM results should focus on identifying the hydrological changes produced by the RHM simulations and not on specific magnitudes of variables produced in either the present or future climate.

FIGURE 13: Observed and HYPE simulated river discharge (m^3/s) at different river stations

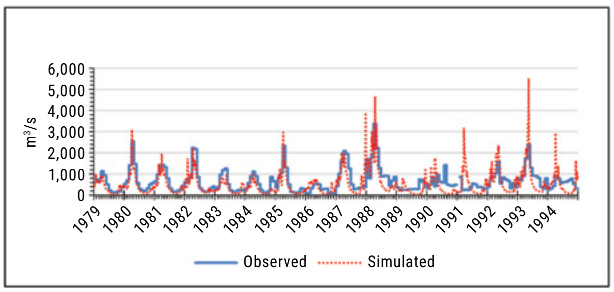
Nile River at Dongola (Sudan)



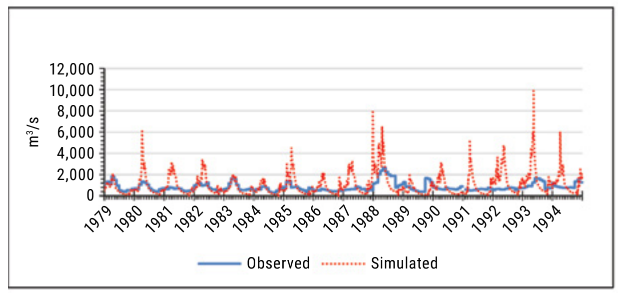
Wadi Dayqah near Daghmar (Oman)



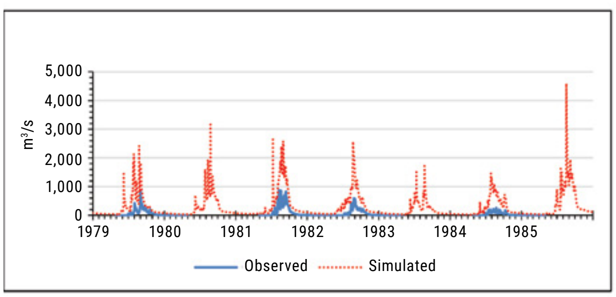
Tigris River at Mosul Dam (Iraq)



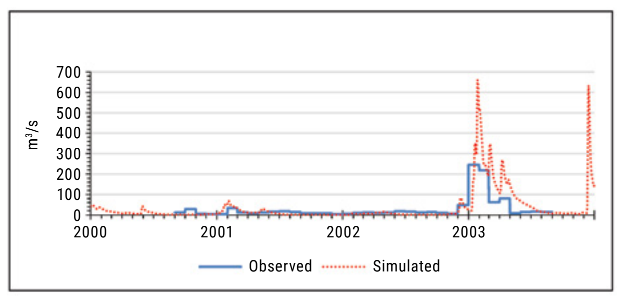
Tigris River at Baghdad (Iraq)



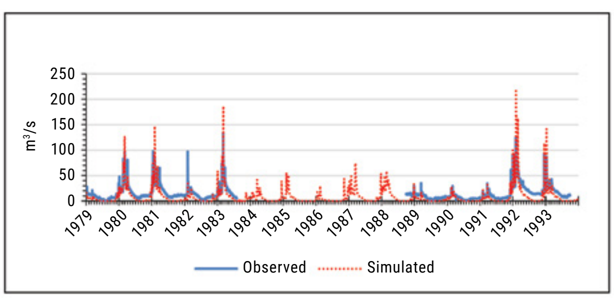
Faleme River at Kidira (Senegal)



Medjerda River at Sidi Salem (Tunisia)



Jordan River at Obstacle Bridge (Jordan)



6 ANALYSIS AND PRESENTATION OF RESULTS

6.1 Ensemble Analysis

To give the best possible estimate of the results from the different climate models, the ensemble method was used, whereby all model simulations based on the same emissions scenario and resolution are grouped and presented as mean values – an ensemble mean. As an ensemble should consist of at least three members, preferably more, the two 25 km resolution projections were not combined as an ensemble. Analysis for them consisted primarily of comparisons against the respective 50 km projections driven by the same GCM (EC-Earth, GFDL-ESM2M) as shown in Table 3. Such analyses show if and where there would be value added to using higher resolution.

TABLE 3: Description of the RCA4 ensemble members used in RICCAR

Ensemble	Resolution	Members
RCP 4.5	50 km	EC-Earth, CNRM-CM5, GFDL-ESM2M
RCP 8.5	50 km	EC-Earth, CNRM-CM5, GFDL-ESM2M

6.2 Common Model Outputs and Considerations

6.2.1 Outputs from Regional Climate Modelling (RCM)

The different climate models applied under RICCAR provide results of projections for specific variables and are expressed in terms of changes from the baseline period. The main variables primarily analyzed stem from the Regional Climate Modelling (RCM) and are *temperature and precipitation*. They are also subsequently used as an input to the Regional Hydrological Models (RHM).

An important consideration concerning the precipitation variable is that in many studies worldwide, changes in precipitation is often expressed as percent change from a base reference period, which provides an easy basis for comparison. However, using percent change can be problematic in regions that have extremely low precipitation. Given the small amounts of precipitation for the reference period in such areas, large percent changes can result even if changes in magnitude are relatively small. The Arab Region contains large climatic variation, particularly with regard to precipitation, which is extremely low over large areas. Projected changes in precipitation are thus primarily presented in terms of magnitude (mm) but also expressed as relative terms (%) in the report when deemed necessary. Concerning results, it is important to note that there are larger uncertainties for precipitation than for temperature outputs, whereby the precipitation change signal is more correlated with the driving GCM rather than the emission scenario.

6.2.2 Outputs from Regional Hydrological Modelling (RHM)

The key variable from RHMs is runoff. Complementary variables include: *soil moisture, evapotranspiration, river discharge*, as well as two discharge-derived variables namely *high flow and low flow values.*[50] RHM outputs are based on bias corrected results for temperature and precipitation generated by the RCMs. To be consistent through the entire results chain—from climate model to hydrological model to further analysis—results presented throughout the reports are also based on the bias-corrected outputs, unless otherwise noted.

As mentioned previously, due to the limited amount of hydrological data observations, uncertainties remain regarding the accuracy of the hydrological modelling outputs. In this regard, there are important issues to take into consideration as it relates to the RHM outputs, in particular regarding some variables.

It was envisioned to consider *groundwater recharge* as another variable stemming from hydrological modelling, however, the hydrological models used do not directly represent groundwater and in order to assess change in groundwater, the change in runoff is used as a proxy for change in groundwater recharge. As this is a coarse measure and other researchers are undertaking more detailed analysis on groundwater, results for this variable will not be presented.

When looking at projections of changes in runoff, consideration should be given to the fact that these are based on precipitation outputs, which exhibit high uncertainties. Runoff output projections also thus demonstrate high uncertainties for both the HYPE and VIC models. Moreover, for some river and streams pertaining to specific subdomains, no observation datasets on discharge were available to verify the model against. It is also worth pointing out that the higher the human influence on the river system (water regulation infrastructure, irrigation, etc.) compared to the size of the river, the higher the uncertainties in the results will be. These factors should be taken into consideration when interpreting and analyzing discharge-related results. Also, concerning results for discharge and related outputs, it is worth reminding that as the VIC Model used in this assessment does not take into consideration effects of storage and evaporation from reservoir features, discharge related outputs were only completed through the HYPE Model.

Another variable to be interpreted with caution in this context is *Soil Moisture*. Preliminary analysis showed that the soil moisture in the VIC Model simulations was not at equilibrium for all areas at model start-up, for dry areas in particular. Soil moisture content in such areas increased over the simulation time until it reached an equilibrium state in the model. This means that comparing future soil moisture states to reference period states does not give an accurate picture of how soil moisture will change in the future for these areas. Remedying this would require running the VIC Model for an extended time using present climate data to first reach a better soil moisture equilibrium, often referred to as “model spin-up,” and then perform a re-run to all of the VIC simulations. Note that model spin-up was performed for VIC, but this was apparently not sufficient for the dry areas of the domain. Given these issues, it was recommended that the HYPE results give a more accurate assessment of change in soil moisture for application in RICCAR, and thus results for this variable through the VIC Model were discarded.

A summary of variables studied under RICCAR from climate and hydrological modelling is presented in Table 4.

TABLE 4: Variables studied under RICCAR from RCM and RHM

Modelling source	Variable	Absolute/Difference unit
Regional Climate Modelling (RCM)	Temperature (daily mean, max, min)	Celsius
	Precipitation	mm
Regional Hydrological Modelling (RHM)	Runoff	mm
	Soil moisture *(only HYPE)*	High/Low
	Evapotranspiration	mm
	River discharge *(only HYPE)* - Mean discharge - High flow - Low flow	 m^3/s m^3/s m^3/s or number of days

As a further assessment of future change in soil moisture, the *low soil moisture* indicator was also applied for the HYPE Model results for the Arab Domain, which is defined as the mean of the lowest soil moisture occurring every year during the reference period (ie 1986-2005). Comparing future climate periods to the reference period, the change is identified as the mean number of additional days per year for each future period. For these two indicators, due to the high uncertainties in value changes in soil moisture, results are preferably read with a scale of “High” or “Low” change, to provide a general idea of these changes without giving exact values to avoid misinterpretation.

6.3 Extreme Events Indices

Although mean changes in the future climate are of interest for many applications, changes in extreme events are sometimes even more important whereby extreme weather events can have severe impacts on human health, built infrastructure, the natural environment, the transport sector and the economy at large. It is therefore necessary to study these events in order to provide the information needed to inform policy-making and decision-making on climate change adaptation and measures to enhance resilience across the Arab region.

A list of 27 indices has been developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) to provide metrics for extreme events.[51] The indices analyzed within RICCAR include eight from ETCCDI and two additional ones defined for application in the study (SU35 and SU40) using temperature thresholds defined to be more relevant for the region's climate. The ten indices are listed in Table 5.

TABLE 5: List of Extreme Events Indices studied in RICCAR

Index	Long name	Definition
EXTREME TEMPERATURE INDICES		
SU	**Number of summer days**	Annual number of days when daily maximum temperature > 25°C
SU35	**Number of hot days**	Annual number of days when daily maximum temperature > 35°C
SU40	**Number of very hot days**	Annual number of days when daily maximum temperature > 40°C
TR	**Number of tropical nights**	Annual number of days when daily minimum temperature > 20°C
EXTREME PRECIPITATION INDICES		
CDD	**Maximum length of dry spell**	Maximum number of consecutive days when daily precipitation < 1mm
CWD	**Maximum length of wet spell**	Maximum number of consecutive days when daily precipitation ≥ 1mm
R10	**Annual count of 10mm precipitation days**	Annual number of days when daily precipitation ≥ 10mm
R20	**Annual count of 20mm precipitation days**	Annual number of days when daily precipitation ≥ 20mm
SDII	**Simple precipitation intensity index**	The ratio of annual total precipitation to the number of wet days (≥ 1mm)

Source: Based on the work conducted by the WMO Expert team on Climate Change Detection and Indices (ETCCDI, 2009).

6.4 Seasons

Although change in annual mean values can be sufficient for some impact applications, it is often important to also see how future changes will likely occur over different seasons. As water is a key focus for this study, evaluating differences between "wet" and "dry" seasons is of considerable interest, and thus results were presented for two seasonal periods; namely April-September and October-March to assess how climate in the Arab region varies between seasons. This broadly represents dry and wet periods over the entire domain, although which period is wet and which is dry varies over different sub-regions.

Two seasons were chosen as robust time periods that could be applied over the entire domain to avoid more complicated analysis of how the length of seasons may change in different sub-regions in the future. In addition, some results were generated in terms of three boreal summer months (June, July, August) and three boreal winter months (December, January, February). This study of projected changes over time at the seasonal level was applied for most of the variables, except for the extreme events indices. Analysis of seasonal and inter-seasonal variability can be further examined from the RICCAR climate data that will be made available on the Regional Knowledge Hub.

6.5 Subdomains

The RICCAR Report provides results presented as both maps and plotted time series. The maps generally show the entire Arab Domain. On the other hand, the presented times series are area means summarized over specified subdomains. Selected subdomains have been chosen to give an overview of different areas of special interest over the region (Figure 14 and Table 6).

FIGURE 14: Location map showing subdomain areas chosen for highlighted climate analysis

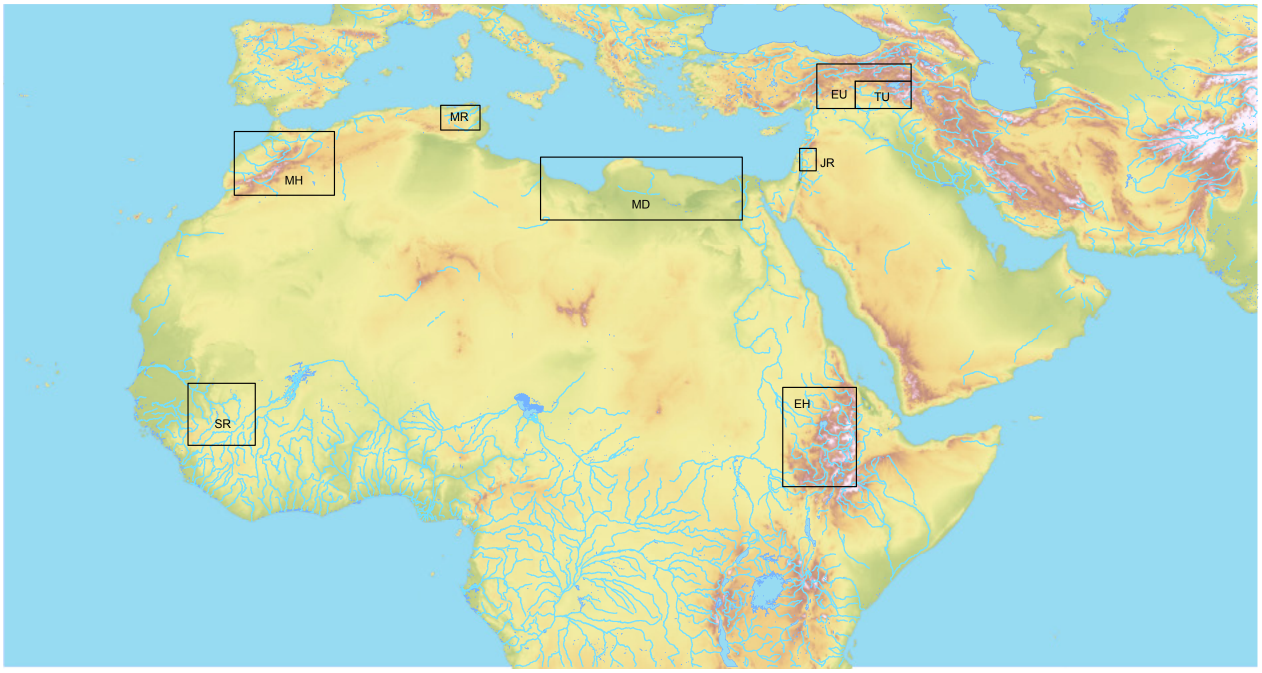


TABLE 6: List of subdomains considered for analysis

Subdomains	Identifier	Subdomain Name	Coordinates
Selected Subdomains	MH	Moroccan Highlands	9W 1W 30N 35N
	MD	Mediterranean Coast	15E 31E 28N 33N
Shared River Basins	EH	Ethiopian Highlands (Blue Nile Headwaters)	34E 40E 7N 15N
	TU	Upper Tigris (Tigris River Headwaters)	40E 44E 37N 39N
	EU	Upper Euphrates (Euphrates River Headwaters)	37E 44E 39N 40N
	MR	Medjerda River	15E 31E 28N 33N
	JR	Jordan River	35E 37E 32N 34N
	SR	Senegal River Headwaters	12W 7W 10N 15N

It should be noted that the Mediterranean Coast (MD) subdomain comprises 5 small rivers and the Moroccan Highlands (MH) subdomain includes three rivers (Moulouya, Oum-er-Rbia and Sebou rivers). Noteworthy, two additional subdomains were studied, namely the Sanaa River and the Wadi Diqah; however, they were not considered for analysis or presented for various reasons. For instance, Wadi Diqah was extensively studied by ACSAD in a separate analysis as part of the extreme events context. Nevertheless, modelling output for these subdomains will be available on the Regional Knowledge Hub for further analysis.

ENDNOTES

1. Uppala et al., 2005
2. CRU, 2013
3. Adler et al., 2003
4. Schneider et al., 2011
5. NCAR, 2014
6. TRMM, 2015
7. Dee et al., 2011
8. Uppala et al., 2005
9. Weedon et al., 2014
10. Lehner et al., 2008
11. GRDC, 2012
12. USGS, 2012
13. Lehner and Döll, 2004; WWF and CESR, 2004
14. GWSP, 2015; Lehner et al., 2011
15. SMHI, 2014
16. Lehner et al., 2008
17. Fischer et al., 2008; Batjes, 2012
18. Arino et al., 2008; JRC, 2000
19. Latham et al., 2014
20. FAO, 2013; Siebert et al., 2005
21. Portmann et al., 2010
22. Taylor et al., 2012
23. IPCC, 2013; IPCC, 2014
24. Meinshausen et al., 2011
25. Giorgi and Gutowski, 2015
26. Giorgi et al., 2009; WCRP, 2015a
27. Rummukainen, 2010
28. WCRP, 2015b
29. ESGF, 2015
30. Kjellström et al., 2016; Samuelsson et al., 2011; Strandberg et al., 2014
31. Dee et al., 2011
32. Hazeleger et al., 2010
33. Voldoire et al., 2012
34. Dunne et al., 2012
35. CRU, 2013
36. IPCC, 2015
37. E.g. Kotlarski et al., 2005; Kay et al., 2006
38. E.g. Graham et al., 2007; Lenderink et al., 2007
39. Yang et al., 2010
40. Nikulin et al., 2015
41. Bosshard et al., 2014
42. Nikulin et al., 2015.More detailed information on the bias correction methodology can be found in the sources mentioned in this section. Access to bias corrected datasets as they become available is provided by CORDEX on this link: http://www.cordex.org
43. Lindström et al., 2010
44. The HBV (Hydrologiska Byrans Vattenbalansavdelning) model is a conceptual model of catchment hydrology which simulates discharge using rainfall, temperature and estimates of potential evaporation.
45. SMHI, 2015
46. Liang et al., 1994
47. Gao, 2010 ; Devia et al., 2015
48. SMHI, 2016
49. US Army Corps of Engineers, 2000
50. The river discharge is the arithmetic mean discharge value. The high flow value represents the value with the 100 year return time (probability of 1% to occur or to be exceeded in any given year). The low flow value represents the arithmetic mean value for all days with values less than the 20th percentile (if expressed in m^3/sec) or the number of days with a value less than the 20^{th} percentile in the reference period (if expressed in number of days), noting that it is equal to 73 days in the reference period.
51. Peterson, 2005; Peterson and Manton, 2008

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