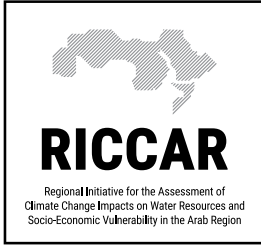


# Future climate projections for the Mashreq region: methodology



**TECHNICAL NOTE**

**SMHI**



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

**SMHI**

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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.

RICCAR was launched under the auspices of the Arab Ministerial Water Council in 2010 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 United Nations Economic and Social Commission for Western Asia (ESCWA) Ministerial Session.

RICCAR is implemented through a collaborative partnership involving regional and specialized organizations. The RICCAR Regional Knowledge Hub is managed by ESCWA in collaboration with the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD) with the Food and Agriculture Organization of the United Nations (FAO), which host the Arab/MENA Domain data portal. ESCWA coordinates the regional initiative under the umbrella of its Arab Centre for Climate Change Policies.

This technical note was prepared by Phil Graham, Peter Berg, Thomas Bosshard, Grigory Nikulin and Wei Yang at the Swedish Meteorological and Hydrological Institute (SMHI). Editing and design was provided by ESCWA as part of the RICCAR publication series.

Funding for the study was provided by the Government of Sweden through the Swedish International Development Cooperation Agency (Sida) under a project focused on water and food security in a changing climate context implemented by ESCWA. This project component provides regional climate projections to inform science-based assessments and analysis of climate impacts on water and agriculture in the Mashreq region.

# CONTENT

<b>PREFACE</b>	<b>III</b>
<b>EXECUTIVE SUMMARY</b>	<b>1</b>
<b>1 INTRODUCTION</b>	<b>3</b>
<b>2 OBSERVATIONS DATA</b>	<b>3</b>
2.1 Climate data	3
2.2 Terrestrial data	4
<b>3 BACKGROUND ON CLIMATE MODELLING</b>	<b>4</b>
3.1 Climate scenarios	4
3.2 Reference and projection periods	7
3.3 Climate variables	7
<b>4 MASHREQ REGIONAL CLIMATE MODELLING</b>	<b>7</b>
4.1 Previous RICCAR downscaling	7
4.2 The Mashreq Domain	8
4.3 RCM projections	8
4.4 RCM present climate	10
<b>5 MASHREQ BIAS-ADJUSTED RESULTS</b>	<b>15</b>
5.1 Why bias adjust?	15
5.2 Bias adjustment methodology	15
5.3 Summary analysis of adjusted biases	18
<b>6 ANALYSIS BACKGROUND AND TECHNIQUES</b>	<b>21</b>
6.1 Common model outputs	21
6.2 Extreme events indices	21
<b>7 RCM SUMMARY RESULTS FOR THE MASHREQ DOMAIN</b>	<b>22</b>
7.1 Temperature	22
7.2 Precipitation	22
7.3 Hot days	25
<b>8 SUMMARY CONCLUSIONS</b>	<b>26</b>
<b>REFERENCES</b>	<b>28</b>

## FIGURES

<b>FIGURE 1</b> SSP-RCP scenario matrix used for CMIP6 simulations	5
<b>FIGURE 2</b> Comparison of carbon dioxide, methane and total radiative forcing for the SSP and RCP scenarios from CMIP6 and CMIP5 GCM projections, respectively	6
<b>FIGURE 3</b> Arab Domain (aka CORDEX-Mena Domain)	8
<b>FIGURE 4</b> Mashreq Domain	9
<b>FIGURE 5</b> RCM results for mean seasonal temperature during June, July, and August for the period between 1981 and 2010	11
<b>FIGURE 6</b> RCM results for mean seasonal temperature during December, January, and February for the period between 1981 and 2010	12
<b>FIGURE 7</b> RCM results for mean seasonal precipitation during June, July, and August for the period between 1981 and 2010	13
<b>FIGURE 8</b> RCM results for mean seasonal precipitation during December, January, and February for the period between 1981 and 2010	14
<b>FIGURE 9</b> Illustration of the quantile mapping methodology with cumulative density functions that describe the value distributions of the historical and reference (observation) data sets	16
<b>FIGURE 10</b> Absolute bias in mean temperature for raw RCM outputs (top 2 rows, °C) and with MIdAS bias adjustment (bottom 2 rows, °C) relative to HydroGFD3 for the period between 1981 and 2010 during June, July, and August	19
<b>FIGURE 11</b> Absolute bias in mean precipitation for raw RCM outputs (top 2 rows, mm per day) and with MIdAS bias adjustment (bottom 2 rows, mm per day) relative to HydroGFD3 for the period between 1981 and 2010 during December, January, and February	20
<b>FIGURE 12</b> Mean temperature change (°C) from HCLIM-ALADIN driven by six different GCMs for SSP5-8.5 for the period between 2041 and 2060 compared to the baseline period between 1995 and 2014	23
<b>FIGURE 13</b> Mean precipitation change (mm/mon) from HCLIM-ALADIN driven by six different GCMs for SSP5-8.5 for 2041-2060 compared to the baseline period between 1995 and 2014	24
<b>FIGURE 14</b> Change in the annual number of hot days - defined as maximum temperature exceeding 35°C - from HCLIM-ALADIN driven by six different GCMs for SSP5-8.5 for the period between 2041 and 2060 compared to the baseline period between 1995 and 2014	25



## EXECUTIVE SUMMARY

This report was prepared for the Regional Initiative for the Assessment of the Impact of Climate Change on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR). It documents climate modelling and analysis done by the Swedish Meteorological and Hydrological Institute (SMHI) to produce finer resolution climate projections over the Mashreq region.

Building upon the regional knowledge generated under RICCAR for the entire Arab region (ESCWA, 2017), SMHI established the Mashreq Domain at 10 km grid resolution. Regional climate modelling (RCM) was performed to dynamically downscale global climate model (GCM) results and prepare a new ensemble of regional climate modelling projections for this Domain. The aim was to provide outputs at finer resolution – including bias-adjusted variables – that can be used by regional researchers to inform further climate analysis in the Mashreq region.

The main purpose of this technical note is to provide the methodological background that led to the Mashreq Domain setup and dynamical modelling work conducted under RICCAR and made available with the support of ESCWA on the RICCAR Regional Knowledge Hub. A separate SMHI technical report entitled “Future climate projections for the Mashreq region – Summary outcomes” focuses on the results generated from the projections and presents a summary of the ensemble outcomes for the projected future climate over the Mashreq Domain.

The high resolution HCLIMALADIN RCM was set up and applied over the Mashreq Domain at a 10 km grid resolution. Evaluation of the performance of this RCM over the Domain showed it to perform well. Deviations are seen when comparing modelled present climate results to observations, but they are within expectations from previous experience. Similar patterns of bias are seen in the GCM results, which indicates that the biases are carried over from the GCMs to the RCM.

As has become common practice for further application of climate model results, methods for adjusting biases in the projection results for temperature and precipitation were applied. The bias-adjusted datasets are appropriate for use in climate impacts studies, such as hydrology and agriculture that are highly affected by precipitation and temperature, or for calculation of climate change indicators that rely on absolute thresholds.

The Multi-scale bias AdjUstment (MIdAS) bias adjustment methodology was applied, rather than the distribution-based scaling (DBS) method used for the Arab Domain, to incorporate new developments in the field and more up-to-date observational databases. Even though MIdAS is based on similar techniques as applied for the Arab Domain, a major difference is that it is designed to better handle differences in scales for both space and time to take full advantage of finer RCM model resolution. It also employs an improved algorithm to deal with instances of a dry-frequency bias, i.e. if a climate model simulates too few rain days compared to the reference data. Results for temperature and precipitation before and after bias adjustment show that most of the bias has been removed at seasonal time scales.

After setup and testing, climate projections over the Mashreq Domain at 10 km horizontal resolution were produced using the HCLIM-ALADIN RCM for the period 1961-2070. Based on forcing data from the latest CMIP6 GCM projections for the SSP5-8.5 emissions scenario, the six-member ensemble of projections is compatible to the global projections presented in the latest IPCC AR6 report (IPCC, 2021a, 2021b). The higher resolution Mashreq projection results provide finer-scaled information that may be more suitable for application in impacts models, particularly over coastal and mountainous areas. These projections provide new results for the region, but they do not supersede the projections produced for the RICCAR Arab Domain. Rather, they can be seen as an enhancement to the previous projection results.

Regarding climate change trends, the RCM model results generally reflect similar trends to their GCM driving projections. This indicates that they maintain the large-scale global results over the Mashreq while providing the finer scale results desired over the coasts and mountains.

Temperature results from all six HCLIMALADIN projections show similar patterns of change. All of the projections agree on an increase of temperature over the region, and the magnitude of temperature change is similar to that seen from the Arab Domain projections. The southern part of the Domain along the south Arabian coast and the Horn of Africa show less temperature change than other parts of the Domain.

Precipitation results show more variability with considerable spread between projections in some areas. As with the previous Arab Domain projections, they do not agree completely on increases or decreases of precipitation over the region, such as over the headwaters for the Euphrates and Tigris rivers. However, the projections show a consensus for decreased wintertime precipitation along the relatively water rich areas of the Mediterranean coast and mountains by mid-century. Most of the



ensemble members show increased summertime precipitation over much of the dryland or desert areas. It should be noted that the amounts are small and not likely to have much impact on the overall water cycle in these already dry areas, with the exception of the more pronounced summertime increases along the south-west Arabian coast.

When comparing new results to previous ones, differences will always be encountered. One must keep in mind the many influencing factors at play for producing climate projections and look for where robust signals can be identified. Temperature trends are often easier to interpret, whereas precipitation typically shows a broader range of response according to different model setups, forcing conditions and more.

Only a few examples showing projected climate change results for the Mashreq Domain are shown in this methodological note. A more comprehensive overview of change results can be found in the complementary technical report on summary outcomes. Primary output variables from the modelled climate projections are available via the RICCAR Regional Knowledge Hub for further analysis. Regional researchers that work with impact studies can use the projections to carry out additional work that considers specific sectors in more detail, such as for hydrological, agricultural, or health impacts studies.

# 1 INTRODUCTION

This report was prepared for the Regional Initiative for the Assessment of the Impact of Climate Change on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR). It documents climate modelling and analysis done by the Swedish Meteorological and Hydrological Institute (SMHI) to produce finer resolution climate projections over the Mashreq region.

Building upon the regional knowledge generated under RICCAR for the entire Arab region (ESCWA, 2017), SMHI has established the Mashreq Domain at 10 km grid resolution. Regional climate modelling (RCM) was performed to dynamically downscale global climate model (GCM) results and prepare a new ensemble of regional climate modelling projections for this domain. The aim was to provide outputs at finer resolution – including bias-adjusted variables – that can be used by regional researchers to inform further climate analysis in the Mashreq region.

The purpose of this report is to provide technical background to the Mashreq Domain setup and modelling work in support of other reports prepared by the United Nations Economic and Social Commission for Western Asia (ESCWA), Arab States, and regional partners under the RICCAR publication series. Description and details of the overall initiative are not included here. More information is available on the RICCAR Regional Knowledge Hub (RKH).

A separate SMHI technical report entitled “Future climate projections for the Mashreq region – Summary outcomes” focuses more on the results generated from the projections and presents summary outcomes for the projected future climate over the Mashreq Domain.

## 2 OBSERVATIONS DATA

### 2.1 Climate data

The Mashreq Domain covers a region of Western Asia and North-eastern Africa that includes large reaches of sparsely populated, dry areas. This is reflected in the in-situ weather and water observations network characterised by a sparse network of stations, particularly in remote inland areas. From those existing observation stations, it is often difficult to access the data generated there, either due to technical reasons, protectionist attitudes, conflict zones, or a combination of these factors. However, research efforts over the years have resulted in various data sets that combine different observation sources into usable representative observations.

Climate data originates as measurements of daily weather variables (observations) that, when collected over time, create the climate record. Point measurements taken in situ at observation stations are probably the most direct and therefore precise form of observation. In some places, they also provide long records of observation. However, for regional analysis, the point data may not be representative for larger regions, particularly where the terrain varies widely (e.g. mountains and coast). Depending on the observed variable, the errors of areal estimates based on point data can be large. The measurement itself can also be error-prone. For example, precipitation observations are known to have “undercatch” errors, which means that the measured amount of precipitation is typically lower than what actually fell due to losses from wind or evaporation. Such limitations should be kept in mind when using observed climate data.

Observations data can be organised into a uniform horizontal grid with one data value at the centre of each grid box, similar to how data from climate models are organised. Gridded observed data is based on available observed station data (point data), interpolated from non-uniform points to the selected grid. An advantage of gridded data is its ability to provide data at points where no observation stations exist. However, the quality of the gridded data is always a function of the density of the station data that goes into it. Also, data from climate or numerical weather prediction models is always gridded.

Due to the infrequency of reporting and quality assurance issues, it can be difficult and time-consuming to work directly from station data. Yet, 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 quality control checks and further processing to improve their usability.

Furthermore, generating “reanalysis” data is a specific application that uses a numerical weather prediction model (NWP) to incorporate all available weather observations into a common structure over an observed period of time (e.g. Uppala and others, 2005). This is in essence a much more sophisticated type of interpolation. 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. Being based solely on

observed data, this model provides the closest representation of observations available, particularly for sites where no actual observations exist. Reanalysis data is seen as an important component for both testing and evaluation of climate models. It is also used in combination with other observations to improve gridded observed datasets. However, as with all climate data, it has its limitations. An example is reanalysed precipitation data, which has been shown to provide good representation of the temporal precipitation distribution but can have large biases in precipitation magnitude. Such data can vary depending on location. On the contrary, reanalysed temperature data generally shows good agreement with observations.

Moreover, there are numerous gridded datasets available for use over the Mashreq region and these continue to develop as new methods for combining in situ observations with numerical methods and remote sensing evolve. None of these datasets give a perfect representation of the actual observations, and thus a combination of different datasets has been applied to make best use of their different characteristics. These include:

- CRU (v4.03): University of East Anglia Climatic Research Unit Time Series (Harris and Jones, 2019)
- GPCC (v8): Global Precipitation Climatology Centre (Schneider and others, 2014, 2018)
- UDEL (v4.01): University of Delaware Air Temperature & Precipitation (University of Delaware, 2019)
- TRMM (3B42-v7): Tropical Rainfall Measurement Mission Project (Goddard, 2019)
- CHIRPS (v2.0): Climate Hazards Group InfraRed Precipitation with Station data (Funk and others, 2015)
- ERA-Interim: ECMWF ERA-Interim Reanalysis (Dee and others, 2011)
- ERA5: Fifth Generation ECMWF Reanalysis (C3S, 2020)
- WFDEI: WATCH Forcing Data methodology applied to ERA-Interim (Weedon and others, 2014)
- HydroGFD3: Hydrological Global Forcing Data (Berg and others, 2021)

The WFDEI dataset is a combination of observations and reanalysed model data, whereby monthly observed values are distributed into daily values according to the temporal distribution resulting from the ERA-Interim reanalysis. The result is a dataset of gridded daily observations, which is otherwise difficult to obtain as the actual daily observations are not widely available. The WFDEI dataset with a grid resolution of 0.5° (about 50 km) was used as the reference data to produce the bias-adjusted results from the RICCAR climate projections over the Arab region. It is mentioned here for comprehensiveness purposes.

The HydroGFD3 dataset has been developed more recently. At a grid resolution of 0.25° (about 25 km), it includes daily precipitation, and minimum mean, and maximum temperature. Similar to the WFDEI dataset, the HydroGFD3 dataset combines observations data with reanalysed model data to produce a dataset with global land area coverage, excluding the Antarctic and small islands. Based on the latest global reanalysis product ERA5, it covers the complete reanalysis time period starting in 1979 and is continuously updated to the present date minus 5 days. HydroGFD3 was used as the reference data to produce the bias-adjusted results from the RICCAR climate projections over the Mashreq Domain presented in this report.

## 2.2 Terrestrial data

Regional land cover information for RCM modelling was obtained from the ECOCLIMAP version 2.2 database at 1 km resolution (Faroux and others, 2013). Soil properties came from the Food and Agriculture Organization database (FAO, 2006).

## 3 BACKGROUND ON CLIMATE MODELLING

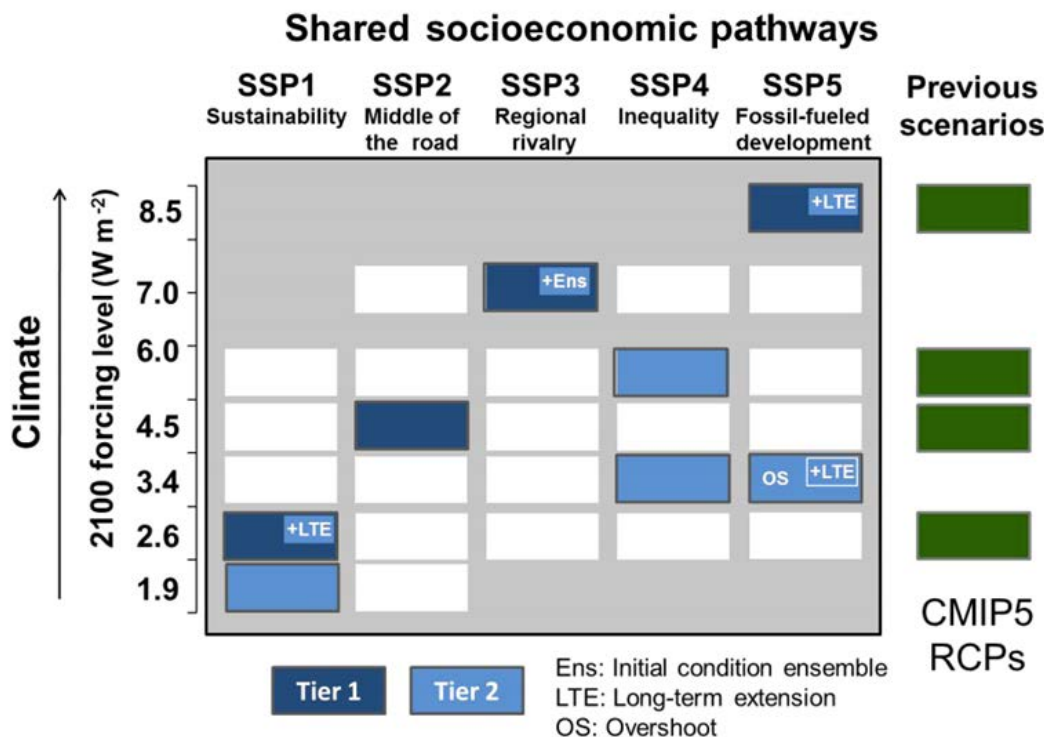
### 3.1 Climate scenarios

The previous IPCC fifth assessment report (AR5; IPCC 2013, 2014) was based solely on the Representative Concentration Pathways (RCPs) used in CMIP5, which cover the climate forcing dimension of different possible futures - i.e. in terms of radiative forcing. There was a parallel process of developing new scenarios by the climate research community that would include both the climate forcing and socioeconomic dimensions. However, the socioeconomic scenario dimension was not complete in time for AR5.

The emissions scenarios used in the latest IPCC sixth assessment report (AR6; IPCC, 2021a, 2021b) are referred to as the Shared Socioeconomic Pathways (SSPs). The SSPs constitute a new framework that combines the socioeconomic dimension of

scenarios with the RCPs into a scenario matrix architecture (Riahi and others, 2017). The SSPs provide different narratives that give a contextual description of how the future might develop in terms of societal trends that were used in integrated assessment models (IAMs) to produce a new set of global emissions and land use scenarios. These narratives of shared climate policy assumptions lead to different levels of radiative forcing, thus relating to the RCPs. Within CMIP6, five different combinations of SSP and RCP were chosen as a first tier of GCM experiments to guide the prioritisation of computing resources and provide projections to the AR6 work. A matrix table of these prioritised pathways is shown in figure 1 (O'Neill and others, 2016).

**FIGURE 1:** SSP-RCP scenario matrix used for CMIP6 simulations (O'Neill and others, 2016)



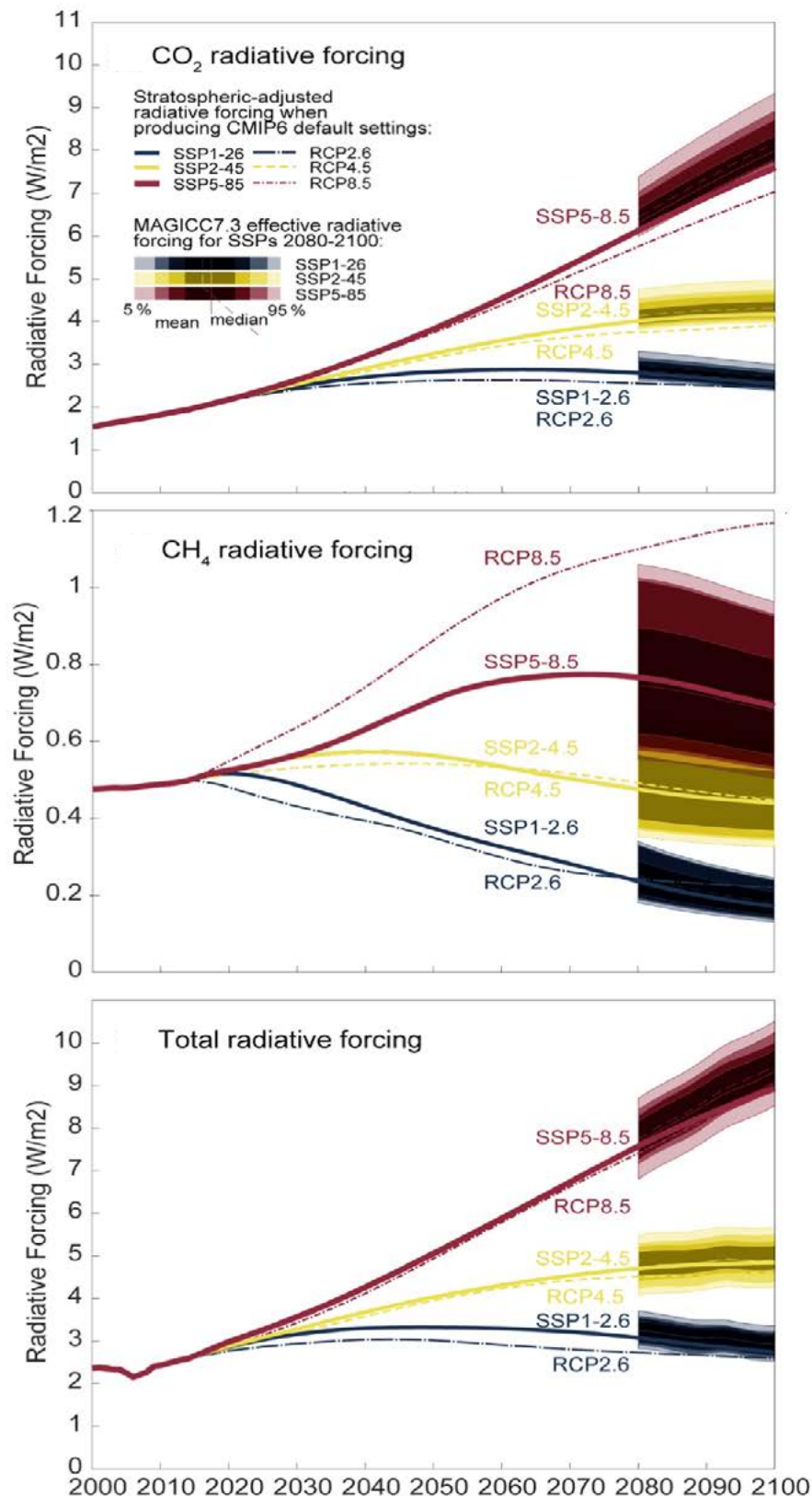
**Note:** Each cell in the matrix indicates a combination of socioeconomic development pathway (SSP) and climate outcome (RCP). The dark blue cells indicated as Tier 1 of CMIP6 are highlighted in AR6. The total radiative forcing corresponding to the CMIP5 RCPs is shown on the Y axis to the left.

Some of the SSP scenarios were chosen specifically to provide continuity with the RCPs, such as SSP12.6, SSP24.5, SSP46.0 and SSP58.5. Although these SSP scenarios lead to the same total radiative forcing amounts in 2100 as the RCP scenarios, as shown in figure 2, the assumed development to reach these values is not the same. Among other things, concentrations of the different greenhouse gases (GHG) – carbon dioxide, methane, and nitrous oxide – differ between the SSPs and RCPs (Tebaldi and others, 2021). The contribution to total radiative forcing from the different GHGs thus varies between the SSPs and the RCPs.

For this initial ensemble of climate projections produced for the Mashreq Domain, it was decided to focus on one scenario, which is the SSP5-8.5 scenario. This scenario is the SSP5 narrative categorised as “fossil-fueled development” that relates to the RCP 8.5 radiative forcing. Although this scenario represents the upper range of concentrations, it is not directly comparable to the RCP 8.5 scenario as modelled under CMIP5 and presented in AR5.

In general, it was expected that the new SSP scenarios under CMIP6 would lead to a somewhat colder climate globally through 2100 for equivalent levels of radiative forcing than that which resulted from the RCP scenarios under CMIP5 (Meinshausen and others, 2020). The first comprehensive evaluation shows the opposite, with a warmer climate resulting from the SSPs under CMIP6 (Tebaldi and others, 2021). However, regional differences are also to be expected.

**FIGURE 2:** Comparison of carbon dioxide, methane and total radiative forcing for the SSP and RCP scenarios from CMIP6 and CMIP5 GCM projections, respectively



**Note:** SSP scenarios are shown with solid lines for the CMIP6 ensemble mean and shaded areas for the spread of CMIP6 results at the end of the century. RCP scenarios are shown with dashed lines for the CMIP5 ensemble mean (Tebaldi and others, 2021).

## 3.2 Reference and projection periods

When creating future climate projections, the 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. Over the observed climate period, greenhouse gas emissions correspond to levels that were observed for the period in question. The climate model simulations are not expected to correspond directly with values from actual observed years, but they should ideally provide climate results during the control period that correspond with the statistics of observed climate over those years, such as 10 to 30-year mean values. The reference to biases in 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.

When analysing the climate change signal in the projections, “time slices” over future periods are selected for use in assessing how the climate change signal evolves over time. Results from these time slices are compared back to a time period in the same projection that represents the present climate or “baseline” condition. Periods to be compared should be of the same length and should span at least 20 years. The selection of periods to use varies and is subject to the specific needs of a study. Within RICCAR, it is desirable to compare regional outcomes to the global outcomes presented in the IPCC reports. When results from the Arab Domain were presented, the chosen time periods corresponded to the IPCC AR5 report.

For reporting on the Mashreq Domain, it was decided to adopt the same baseline and future time periods for analysis as used in the IPCC AR6 report. These are 1995-2014 as a baseline, and future periods of 2021-2040 (near future) and 2041-2060 (intermediate future). Results presented in this technical note and in the Summary Outcomes report were analysed using these adopted time periods. Regarding further impact studies, regional scientists can use these same reference periods or choose other periods that may be more relevant to their work or local region. It is, however, important that the chosen baseline period does not extend beyond 2014, as the modelled emissions scenarios start in 2015.

## 3.3 Climate variables

Climate models produce a full suite of different atmospheric variables, both near the earth’s surface and far up into the atmosphere. In addition, land surface and water body variables of varying complexity are also produced depending on the model used. However, the most common variables of interest remain temperature and precipitation near the surface (i.e. corresponding to observations at standard instrument height).

For water resources, runoff is the key variable of interest. Complementary variables include evapotranspiration and soil moisture, which are also produced while resolving the water balance.

For all variables concerned, mean changes are useful for showing change over time. However, it is not sufficient to define these changes on an annual basis only. Rather, it can be equally important to evaluate and understand how the changes will be spread out over different months of the year. Furthermore, to evaluate changes in extreme events, it is necessary to define specific thresholds in the form of indices as a basis for comparison between present-day and future conditions.

This technical note focuses on the following key variables:

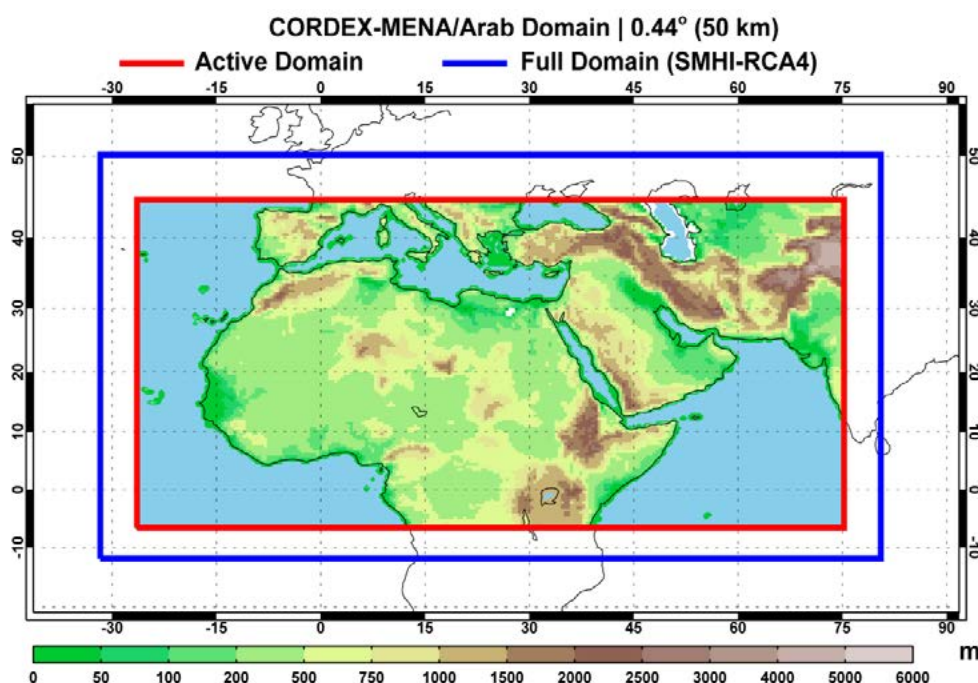
- Temperature
- Precipitation

# 4 MASHREQ REGIONAL CLIMATE MODELLING

## 4.1 Previous RICCAR downscaling

In previous RICCAR efforts, the Arab Domain (figure 3) – also known as the CORDEX-MENA Domain – was established and used to produce two ensembles of dynamically downscaled regional climate projections for the entire Arab region (ESCWA, 2017). The climate projections coming from this domain cover 21 Arab countries and the tributary river basins flowing into them, e.g. the headwaters of the Nile, Senegal, and Euphrates and Tigris rivers. This work forms an integral component of the RICCAR Regional Knowledge Hub ([www.riccar.org](http://www.riccar.org)) and informed the preparation of a region-specific integrated vulnerability assessment of climate change effects on freshwater resources and water-dependent sectors across the Arab region. A majority of the nine RCM modelling projections performed over the Arab Domain were at 50 km horizontal resolution, with two at 25 km resolution. Regional climate projection ensembles were generated for RCP 4.5 and RCP 8.5 for the full century covering the years 2006-2100, with the period 1986-2005 serving as the reference period.



**FIGURE 3:** Arab Domain (aka 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 the Active and the Full Domains is a transition zone between the GCM driving boundaries and the RCM; using results from this zone should be avoided.

## 4.2 The Mashreq Domain

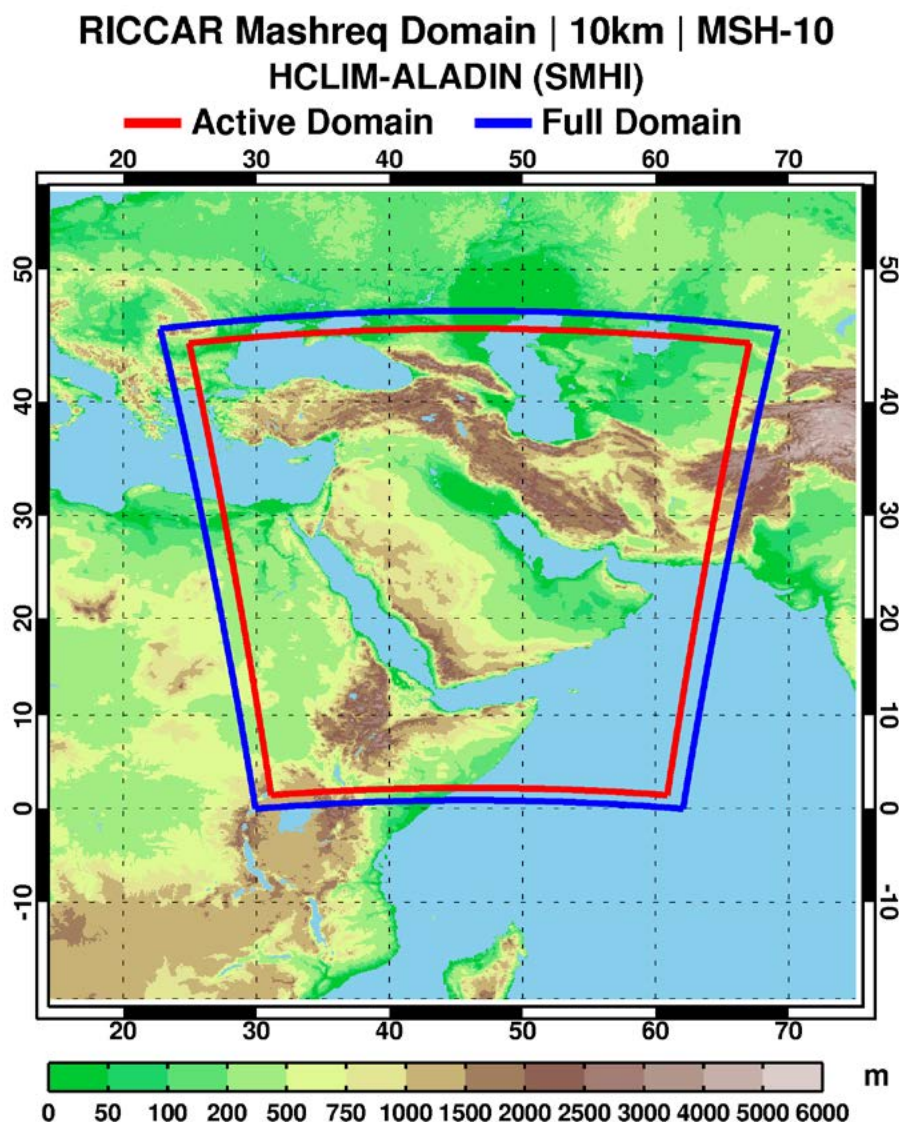
As the focus of the regional downscaling performed over the Arab Domain was to provide consistent impacts assessment for all Arab countries, the large size of the domain placed constraints on the RCM resolution that could be applied. Follow-up activities have been carried out to create additional climate projections at finer resolution to provide further detail for coastal and mountain areas over a smaller sub-region. The Mashreq Domain at 10 km grid resolution was established over the north-eastern parts of the Arab Domain, as shown in figure 4. This domain covers the Mediterranean coastal countries in the Levant and North-eastern Africa, the entire drainage basins of the Tigris and Euphrates rivers, and the entire Arabian Peninsula. RCM outputs from this dynamical modelling domain will be made available to regional researchers to further advance climate impacts assessment over the Mashreq region.

## 4.3 RCM projections

The HCLIM-ALADIN Regional Climate Model (RCM) was applied over the Mashreq Domain at 10 km horizontal resolution. HCLIM-ALADIN is part of the HCLIM38 system for regional climate modelling developed by a consortium of national meteorological institutes, including the Rossby Centre at SMHI and European partners. They have the specific aim to establish a comprehensive dynamical modelling system with appropriate configurations that can be applied across different scales to provide good results without additional region-specific tuning (Belušić and others, 2020). Within HCLIM38, HCLIM-ALADIN is intended for application with grid spacing close to or larger than 10 km (Termonia and others, 2018). ALADIN is an established regional model that has been used in climate mode for more than 10 years and that also appears in the configuration CNRM-ALADIN. Although the names and model configurations are similar, it is important to note that there are differences in the physical parameterizations between HCLIM-ALADIN and CNRM-ALADIN.

After having established and tested the Mashreq Domain, an ensemble of downscaled projections was produced based on the SSP5-8.5 emissions scenario (Riahi and others, 2017; O'Neill and others, 2016). Boundary conditions from six different Global Circulation Models (GCMs) were used to run the HCLIM-ALADIN model to produce regionally downscaled climate projections

FIGURE 4: Mashreq 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 (HCLIM-ALADIN in this case) to perform properly within the Active Domain. The area between Active and Full Domains is a transition zone between the GCM driving boundaries and the RCM; using results from this zone should be avoided.

from the respective GCM global projections. For ensemble analysis, a larger ensemble is always preferred over a smaller one. Even for the Arab Domain, a larger ensemble was planned whereby additional research institutes had intended to also provide RCM projections over the domain. However, due to various reasons, the other institutes were not able to provide their expected contributions in a format that could be incorporated into the ensembles for the Arab Domain produced by SMHI. The projections used for the Mashreq Domain are from the latest CMIP6 results that are part of the IPCC AR6 report, which was finalised for successive release during 2021-2022. A list of the six GCM projections used is shown in the table.

The choice for a subset of the CMIP6 GCM ensemble for downscaling over the Mashreq Domain was based on a combination of a number of criteria. These criteria include (i) time frames of the project, (ii) resources provided, (iii) availability of boundary forcing data, (iv) GCM resolution, and (v) a representative spread of climate sensitivity. It was decided that six GCMs could realistically be downscaled to fit the time frames of the project and resources provided. The first HCLIM-ALADIN simulations were started in Spring 2020 when just a few CMIP6 modelling centers had made their 6-hour boundary forcing data available through the Earth System Grid Federation (ESGF). Even as other CMIP6 modelling centers gradually made their forcing data available after spring 2020, the number of CMIP6 GCMs with fully available forcing data was still limited during the active phase of running or initiating the HCLIM-ALADIN simulations (through the end of 2020).



To avoid a large jump in resolution between the GCM forcing data and the 10 km target resolution for the Mashreq Domain, GCMs with higher resolution were prioritised. A number of coarse-resolution GCMs were thus excluded, such as CanESM5 (2.8 x 2.8 deg), MIROC-ES2L (2.8 x 2.8 deg) and ACCESS-CM2 (2.8 x 1.25 deg). Additional factors also impacted the selection such as, for example, a technical error in netCDF files with forcing data for CESM2 and the absence of the Red Sea in MIROC6 (no marginal seas included in MIROC6 ocean model).

The equilibrium climate sensitivity (ECS) is the expected long-term warming after a doubling of atmospheric CO<sub>2</sub> concentrations. It is an important indicator of how severe the impacts of future warming will be. It can be noted that analysis of CMIP6 models to date show that they tend to have higher climate sensitivity than the CMIP5 models used for AR5, which were characterised by an ECS range of 1.5C to 4.5C. Of the 40 CMIP6 models with ECS values available, the highest value reaches 5.6C and 14 have ECS values above 4.5C. The AR6 concludes that the best estimate of ECS is 3°C; it is likely (66-100 per cent) within the range 2.5 to 4°C and very likely (90-100 per cent,) within the range 2 to 5°C. As can be seen in the table, the ECS values for the six GCMs used for the Mashreq Domain range from 2.5C to 4.8C and fit within the AR6 very likely range of 2 to 5°C. The 6-member CMIP6 GCM ensemble for downscaling over the Mashreq Domain was an optimal choice in 2020 considering all the above factors.

List of RCM simulations conducted over the Mashreq Domain by Rossby Centre, SMHI

CMIP6 GCM	ECS	Horizontal resolution	
		LON (DEG)	LAT (DEG)
CMCC-CM2-SR5	3.5	1.25	0.94
CNRM-ESM2-1	4.8	1.4	1.4
EC-EARTH3-VEG	4.3	0.7	0.7
MPI-ESM1-2-LR	3.0	1.875	1.875
MRI-ESM2-0	3.1	1.125	1.121
NORES2-MM	2.5	1.25	0.95

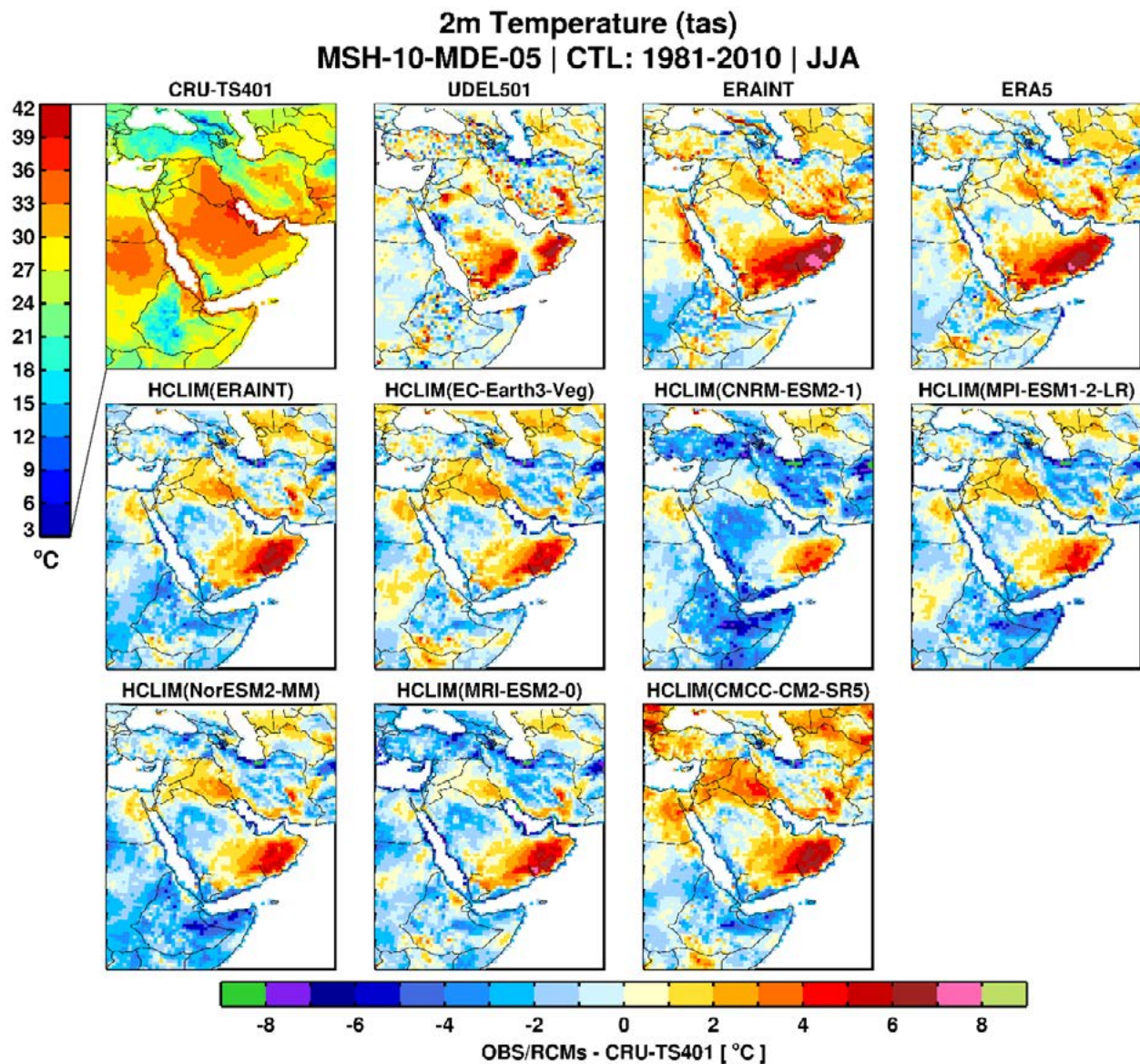
The projection simulations were carried out for the period 1961-2070, where 1961-2014 represents the historical period and 2015-2070 represents the emissions scenario period. In addition, an evaluation simulation using ERA-Interim reanalysis forcing was also carried out for 1981-2018. As ERA-Interim provides a proxy representation of observations over the entire domain, both at the surface and in the atmosphere, the ALADIN simulation forced by ERA-Interim provides an assessment of how well ALADIN can represent the present climate over the Mashreq Domain.

## 4.4 RCM present climate

Results for temperature and precipitation representing the present climate are presented for the RCM simulations in figures 5-8. In addition to the RCM simulations, they include two additional observations datasets and data from the two ERA reanalyses for comparison, and the HCLIM-ALADIN simulation driven by the ERA-Interim reanalysis data, which represents a test of the RCM using the “best available” observations.

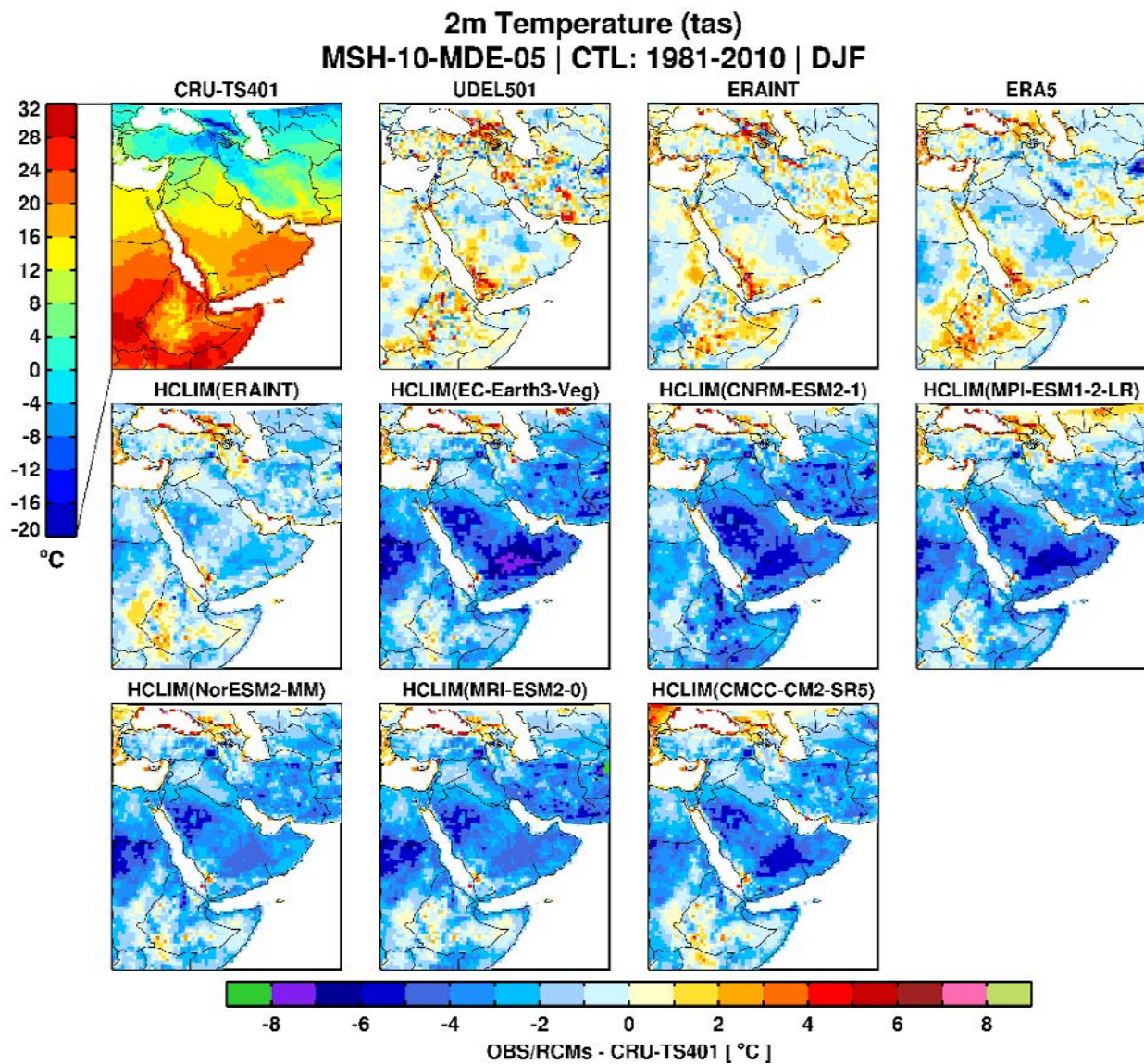
Looking at the RCM results driven by the GCMs, there is a common tendency for a cold bias in temperature that is more pronounced in winter than in summer (figures 5 and 6). An exception is the warm bias in the south-east part of the Arabian Peninsula during summer. The GCMs exhibit a similar pattern of bias, which indicates that the bias is carried over from the GCMs to the RCMs. This is reinforced by the fact that HCLIM-ALADIN driven by reanalysis shows less bias (ERA-Interim). However, the warm bias for the Arabian Peninsula is apparent with this simulation as well. It is worth noting that the largest differences between the two observations datasets (CRU and UDEL) and between the two reanalyses (ERA-Interim and ERA5) also occur for the Arabian Peninsula, which is in part a reflection of the sparse observations network there. It can also be noted that a similar pattern of temperature bias was exhibited for the RCM results over the Arab Domain.

Regarding precipitation, results from half of the RCM simulations exhibit dry biases over the domain during winter and all show wet biases during summer (figures 7 and 8). This varies spatially over the region but is apparent for the water rich headwaters of the Tigris and Euphrates rivers. In addition, as with the temperature observation datasets, there are considerable differences between the precipitation observation datasets over the domain.

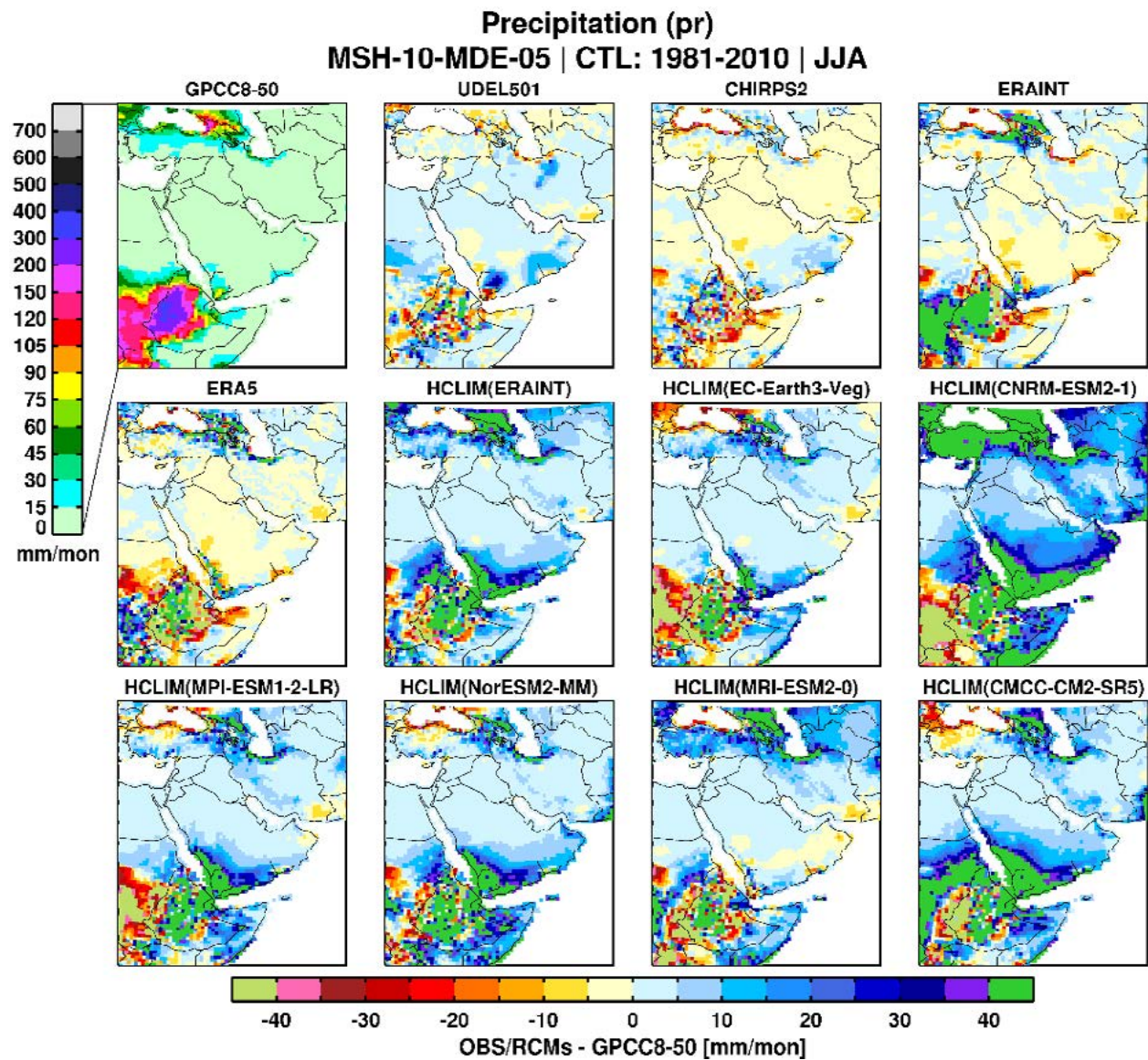
**FIGURE 5:** RCM results for mean seasonal temperature during June, July, and August for the period between 1981 and 2010**Note:**

- Top row left shows temperature observations from the CRU dataset; following are differences compared to CRU for the UDEL dataset, ERA-Interim data and ERA5 data.
- Rows 2 and 3 show differences compared to CRU for HCLIM-ALADIN driven by ERA-Interim boundary conditions and then the HCLIM-ALADIN simulations driven by six different GCMs.
- The top left legend is for CRU only; the bottom legend pertains to all other plots.



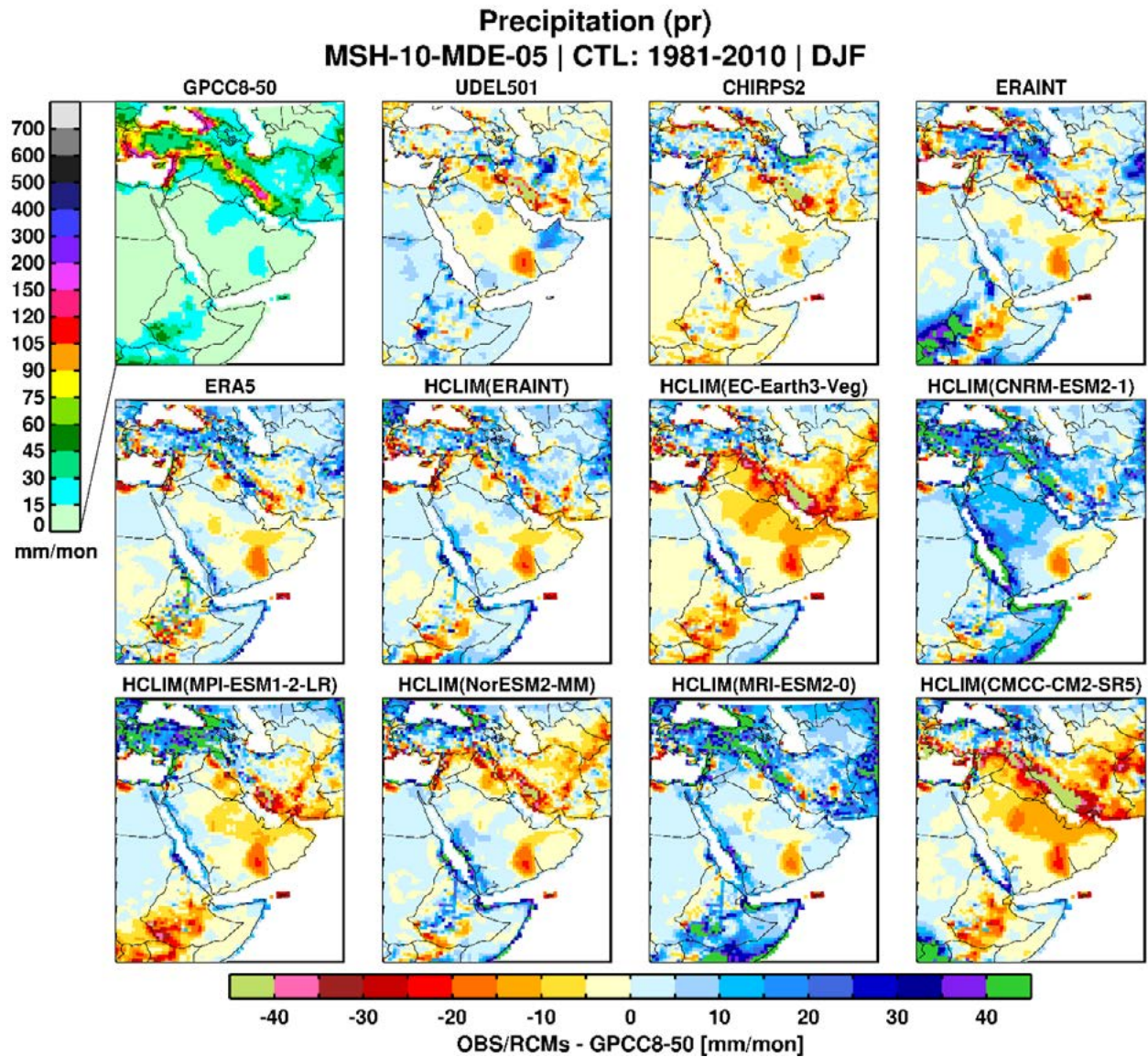
**FIGURE 6:** RCM results for mean seasonal temperature during December, January, and February for the period between 1981 and 2010**Note:**

- Top row left shows temperature observations from the CRU dataset; following are differences compared to CRU for the UDEL dataset, ERA-Interim data and ERA5 data.
- Rows 2 and 3 show differences compared to CRU for HCLIM-ALADIN driven by ERA-Interim boundary conditions and then the HCLIM-ALADIN simulations driven by six different GCMs.
- The top left legend is for CRU only; the bottom legend pertains to all other plots.

**FIGURE 7:** RCM results for mean seasonal precipitation during June, July, and August for the period between 1981 and 2010**Note:**

- Top row left shows precipitation observations from the GPCC dataset; following are differences compared to GPCC for the UDEL dataset, CHIRPS dataset and ERA-Interim data.
- Rows 2 and 3 show differences compared to GPCC for ERA5 data, HCLIM-ALADIN driven by ERA-Interim boundary conditions and then the HCLIM-ALADIN simulations driven by six different GCMs.
- The top left legend is for CRU only; the bottom legend pertains to all other plots.



**FIGURE 8:** RCM results for mean seasonal precipitation during December, January, and February for the period between 1981 and 2010**Note:**

- Top row left shows precipitation observations from the GPCC dataset; following are differences compared to GPCC for the UDEL dataset, CHIRPS dataset and ERA-Interim data.
- Rows 2 and 3 show differences compared to GPCC for ERA5 data, HCLIM-ALADIN driven by ERA-Interim boundary conditions and then the HCLIM-ALADIN simulations driven by six different GCMs.
- The top left legend is for CRU only; the bottom legend pertains to all other plots.

## 5 MASHREQ BIAS-ADJUSTED RESULTS

### 5.1 Why bias adjust?

There are typically biases in the RCM statistics of key hydro-meteorological variables, such as precipitation and temperature (e.g. Kotlarski and others, 2005; Kay and others, 2006). Many of these biases originate from either the driving GCM model or the RCM used for downscaling. Direct use of RCM outputs in impact studies is therefore usually not appropriate. It has become common procedure to first adjust the hydrologically important variables of precipitation and temperature before using them in impact studies or before calculation of climate change indicators that rely on absolute thresholds (e.g. Graham and others, 2007; Berg and others, 2012; Vrac and others, 2016).

### 5.2 Bias adjustment methodology

Bias adjustment is the collective term for the process of reducing biases in climate models in a post-processing step applied to model outputs. To take full advantage of the fact that the RCM setup over the Mashreq Domain is at higher resolution than the observational reference data, bias adjustment is performed at a coarser resolution than that of the RCM and then combined with detailed information that retains the high resolution features of the climate model, as further explained below. The bias adjustment methodology has been modified from that used for the Arab Domain and makes use of more up-to-date methods and observational databases.

It is important to note that bias adjustments correct only the climatological statistics over a longer period of time – most often 30 years. The different climate projections will still show their individual interannual variability. Bias adjustment is not perfect, and some remaining biases are to be expected, usually larger the more one looks towards the extremes of the distribution. Adjustment of the projection data is only done at similar resolution as the available observations. In this case, the HydroGFD3.2 dataset, and projection data at higher resolution, are added as anomalies to the bias-adjusted data at the coarser resolution. Hence, the high resolution data differs between the different projections, as well as between the projections and the reference data. See also further discussion below under spatial cascade.

It is standard practice in climate impact studies to use a 30-year period as reference period for the bias adjustment, although deviations from that occur. For the Mashreq Domain, the reference period of 1981-2010 was chosen to be close to the period used previously for the Arab Domain (1980-2009), and at the same time to comply with the WMO practice to start the definition of the 30-year period with the year one in a new decade. It is important to note that from 2015 onward, the SSP emissions scenarios start, and it would not be correct to include such years as part of the reference period.

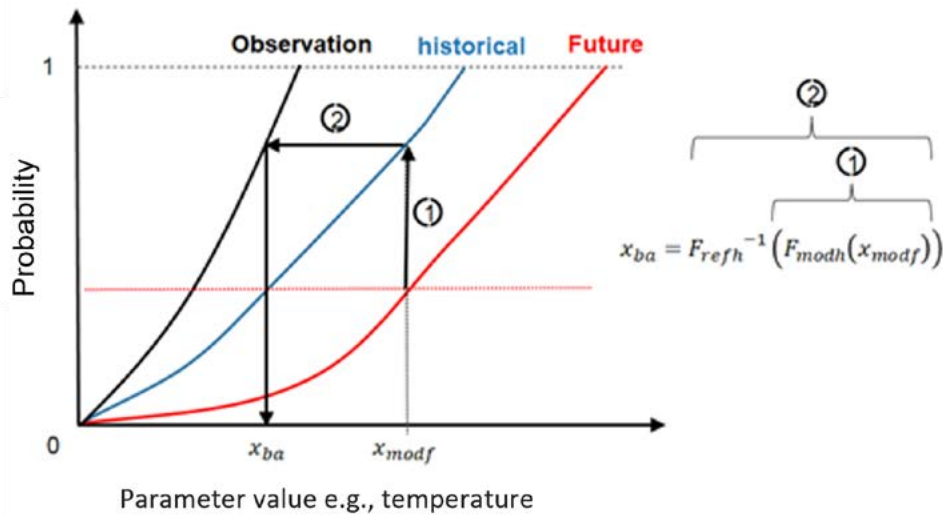
### Multi-scale bias AdjuStment (MIdAS)

The Multi-scale bias AdjuStment (MIdASv0.1) system was used for this work. It is a bias adjustment method in the quantile mapping family of methods (figure 9). Quantile mapping essentially consists of constructing a transfer function from the distribution of the model data values to those of the observed reference data. The transfer function is calibrated on the historical period (1981-2010), and the same function is then applied to the complete time series of the climate model projections. Application specifics of MIdAS depend on the variable being adjusted.

For the previous RICCAR work using the Arab Domain, the distribution-based scaling (DBS) method developed by Yang et al. (2010) was used for bias adjustment (also referred to as bias correction). DBS also makes use of quantile mapping, but in a different way. While DBS employs a parametric quantile mapping (i.e. fitting of a parametric distribution to the data), MIdAS uses a semi-parametric quantile mapping by fitting a spline function to the empirical cumulative distributions.

As a major difference from DBS, MIdAS is designed to be able to deal with differences in scales in space and time. For example, it is possible to do separate bias adjustment on the monthly and the daily time scales, which we call a cascade correction. By disentangling the biases on different scales in time and space, one prevents the interference of the biases on different time scales with each other, which in turn might affect the climate change signal in an implausible way. This also allows to bias adjust only on those scales where there are good observations. An example of this is for temperature where we adjust only the large scales ( $\geq 25$  km) but let the regional climate model steer the finer scales ( $< 25$  km). A traditional method would smooth the bias-adjusted temperature fields to the 25 km reference data. Furthermore, MIdAS uses an improved algorithm to deal with instances of a dry frequency bias, i.e. if a climate model simulates too few rain days compared to the reference data.

**FIGURE 9:** Illustration of the quantile mapping methodology with cumulative density functions that describe the value distributions of the historical and reference (observation) data sets



**Note:** A mapping is constructed such that the historical values are mapped on to the observation data at the same probability level (2). This mapping is then performed directly on any value  $x_{modf}$  outside the calibration period by identifying the mapping path for that value position (1) and adjusting it by the distance (2).

Regarding limitations, MIdAS has similar ones to DBS. Both assume bias stationarity over time; they are not targeted to adjust biases in correlation in time, space, and between variables, and assume a statistical model to extrapolate bias adjustment for values outside the value ranges in the reference period. Such characteristics are limitations that most – if not all – of the currently available bias adjustment methods have. MIdAS performed well in comparison to other methods in a pre-study that was done at SMHI (soon to be published).

## Precipitation

A general issue with climate models is a difference in the number of wet days, defined as days with precipitation strictly above zero, or above some low limit. An excess of wet days is straightforward to adjust by setting the wet days with the least precipitation to zero. In dry regions, however, the more complicated issue of too few wet days becomes more prominent. In this case one needs to create precipitation where the model had none. The Singularity Stochastic Removal (SSR) method proposed by Vrac and others (2016) was implemented in MIdAS. This method works essentially in four steps:

1. Set a threshold,  $P_{thres}$ , to the lowest precipitation value above zero in the reference of the model for the calibration period.
2. Set all zero precipitation values to a randomly generated value in the range  $(0, P_{thres})$ .
3. Perform the bias adjustment (here using MIdAS quantile mapping).
4. Bias-adjusted precipitation below  $P_{thres}$  are set to zero.

SSR is therewith promoting some of the randomly generated precipitation values below  $P_{thres}$  to a precipitation event above  $P_{thres}$  in the bias-adjusted time series.

## Temperature

For temperature, there is a known issue with quantile mapping methods that they sometimes affect the climate change signal. This occurs when a bias in the variance of the model differs from that of the reference data (Berg and others, 2012). Further, Haerter and others (2011) presented cases where a model has a different bias depending on the temporal resolution studied. For instance, it is illustrated in daily compared to monthly mean statistics, and where destructive interaction between the scales can occur such that the bias in monthly mean actually increase when the daily bias is adjusted. They presented the concept of

cascade bias adjustment to resolve this issue. The MIdAS adjustments for temperature time series (daily mean, minimum and maximum) employs two time scales for the adjustments with one cascade consisting of a 31-day running average (marked with an overbar),

$$\overline{T_{mod}(i)} = \sum_{k=i}^{i+30} T_{mod}(k) / 31$$

and another of daily anomalies from the running average (marked with a prime).

$$T'_{mod}(i) = T_{mod}(i) - \overline{T_{obs}(i)}$$

The model time series is adjusted separately for the two cascades, which are then merged to a complete time series,  $T_{adj}$ , again.

The bias adjustment is performed separately for the daily mean, minimum and maximum temperature. This generally works fine but can introduce some inconsistency whereby a bias-adjusted value for minimum becomes larger than the corresponding daily mean value, or vice versa for daily maximum temperature. This occurs for a few occasions in the bias-adjusted data and therefore such inconsistencies were corrected in a post-processing step after the bias adjustment.

## Spatial cascade

For temperature only, and in an extension to the temporal cascade adjustments of Harter and others (2011), the MIdAS method considers also spatial cascades. The grid resolutions for the HydroGFD3 observations reference data and the RCM differ with the observations grid spacing at 25 km and the RCM grid spacing at 10 km. The reference data can be interpolated to the higher resolution, but it would still not contain any of the high resolution features. For example, in mountainous terrain, such interpolated reference data would not contain the same level of spatial detail like elevation gradients as the model data. It is then better to trust in the finer resolution information from the RCM, as discussed by Berg and others (2015).

Here, the finer scale information of the RCM is retained by performing bias adjustment only on a coarse cascade scale. This coarse scale is produced by first interpolating HydroGFD3 to the regional climate model scale, then performing a 3x3 grid point smoothing of the reference and model grids. This smoothed data becomes the coarse model cascade. The anomaly cascade is calculated as the difference between data from the original model scale and from the smoothed coarse model scale. Bias adjustment is only performed on the coarse cascade, and then merged with the fine resolution cascade to produce the final bias-adjusted time series. The merging is done by adding the non-adjusted anomaly data to the bias-adjusted smoothed data.

$$T_{adj}^{merged} = T_{adj}^{smoothed} + T_{mod}^{anom}$$

## Bias adjustment post-processing

The bias adjustment is performed separately for the daily mean, minimum and maximum temperature. This works fine when the variables are used separately, but when they are used together it might introduce some consistency issues. Depending on the model bias for the different ends of the daily temperature spectrum, it can happen that bias-adjusted minimum ( $T_{min}$ ) becomes larger than the daily mean ( $T_{mean}$ ) value, or vice versa for daily maximum ( $T_{max}$ ) temperature. Although this is rare, post-processing for such physically inconsistent cases is carried out as follows. First, cases for which  $T_{min}$  ( $T_{max}$ ) was higher (lower) than  $T_{mean}$  were identified. Next, for each such case,  $T_{min}$  or  $T_{max}$  are replaced according to the equations below.

$$T_{adj}^{max,consist} = T_{mean}_{adj} + (T_{max}_{mod} - T_{mean}_{mod})$$

$$T_{adj}^{min,consist} = T_{mean}_{adj} + (T_{min}_{mod} - T_{mean}_{mod})$$

The procedure ensures that clearly non-consistent combinations of  $T_{mean}$ ,  $T_{min}$  and  $T_{max}$  do not occur, while at the same time imposing the bias-adjusted  $T_{mean}$  value as a reference from which the replacement values for  $T_{min}$  and  $T_{max}$  are derived. This



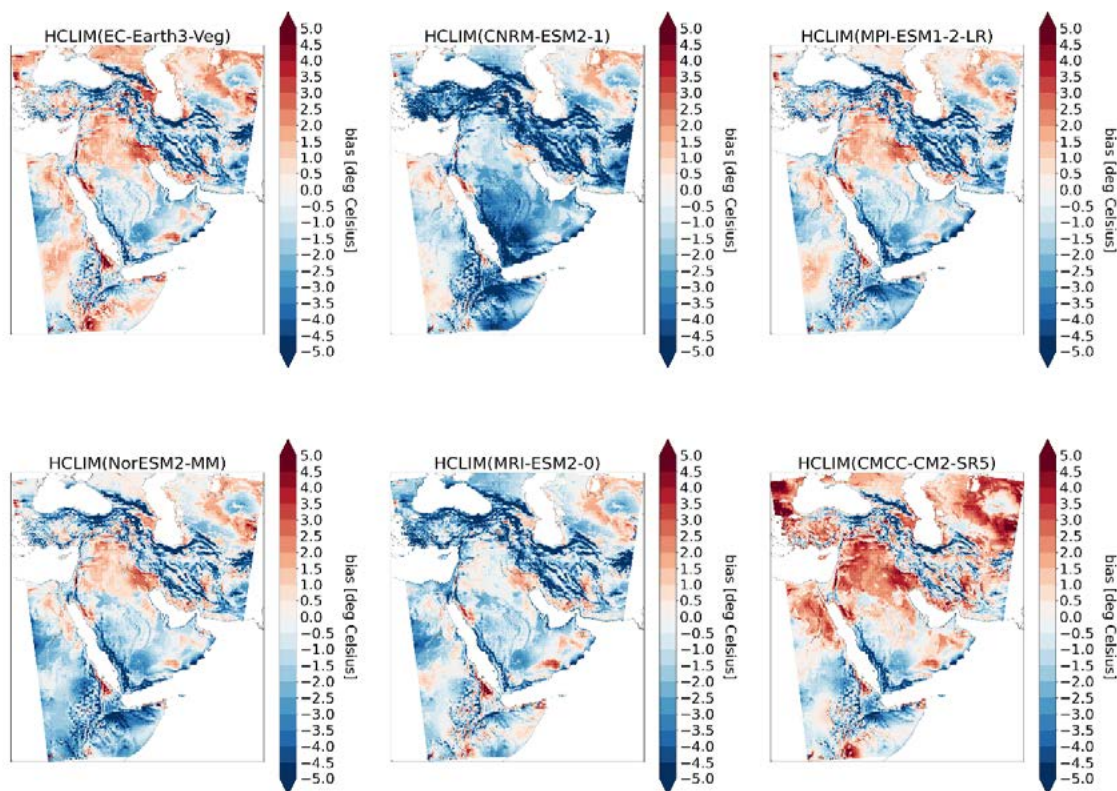
is conceptually equivalent to applying the same bias adjustment for T<sub>min</sub> or T<sub>max</sub> as for T<sub>mean</sub>. However, this is only done when needed to guarantee consistency amongst T<sub>mean</sub>, T<sub>min</sub> and T<sub>max</sub>. Otherwise, the bias-adjusted data are not post-processed, and each variable is bias adjusted individually with individual bias transfer functions. For the Mashreq Domain, such post-processing adjustments were only needed for a limited area of the domain, mostly along the south-eastern coast of the Arabian Peninsula, and accounted for less than 1 per cent of the T<sub>min</sub> and T<sub>max</sub> projection results.

### 5.3 Summary analysis of adjusted biases

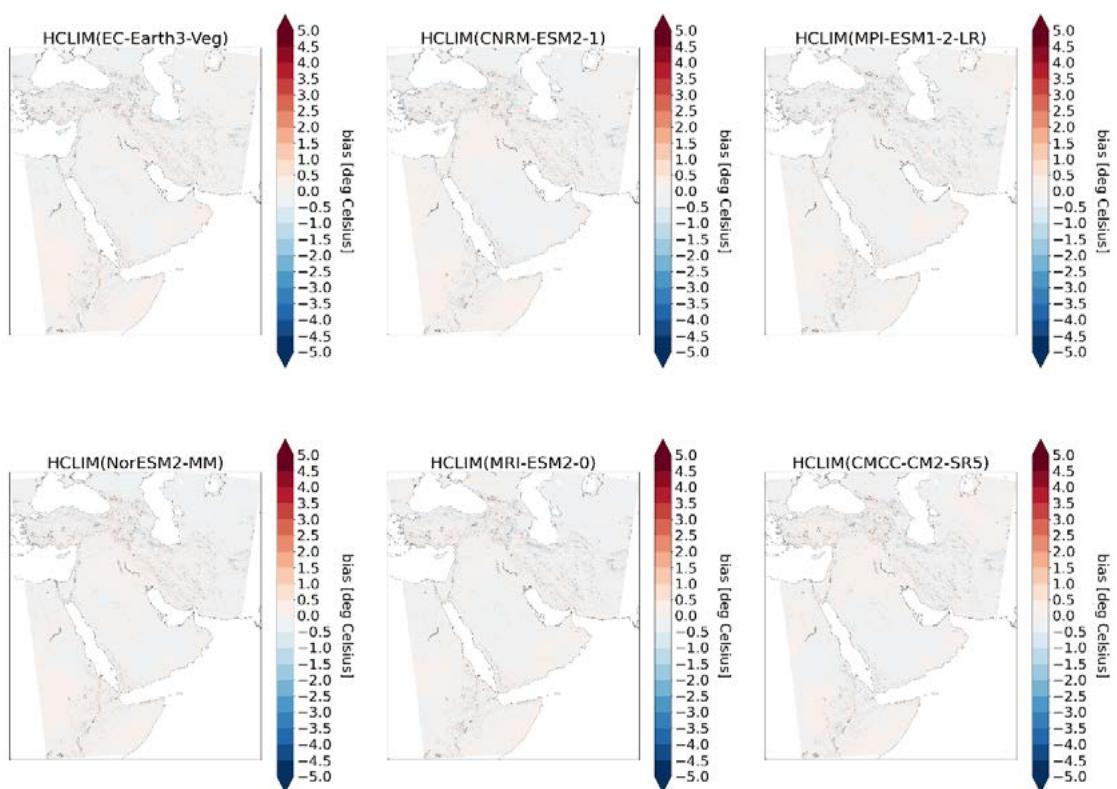
Examples of the results from bias adjustment are shown in figures 10 and 11 for temperature and precipitation, respectively. Each figure shows the biases before and after adjustment, which demonstrates how most of the bias has been removed.

**FIGURE 10:** Absolute bias in mean temperature for raw RCM outputs (top 2 rows, °C) and with MldAS bias adjustment (bottom 2 rows, °C) relative to HydroGFD3 for the period between 1981 and 2010 during June, July, and August

Temperature bias *before* adjustment

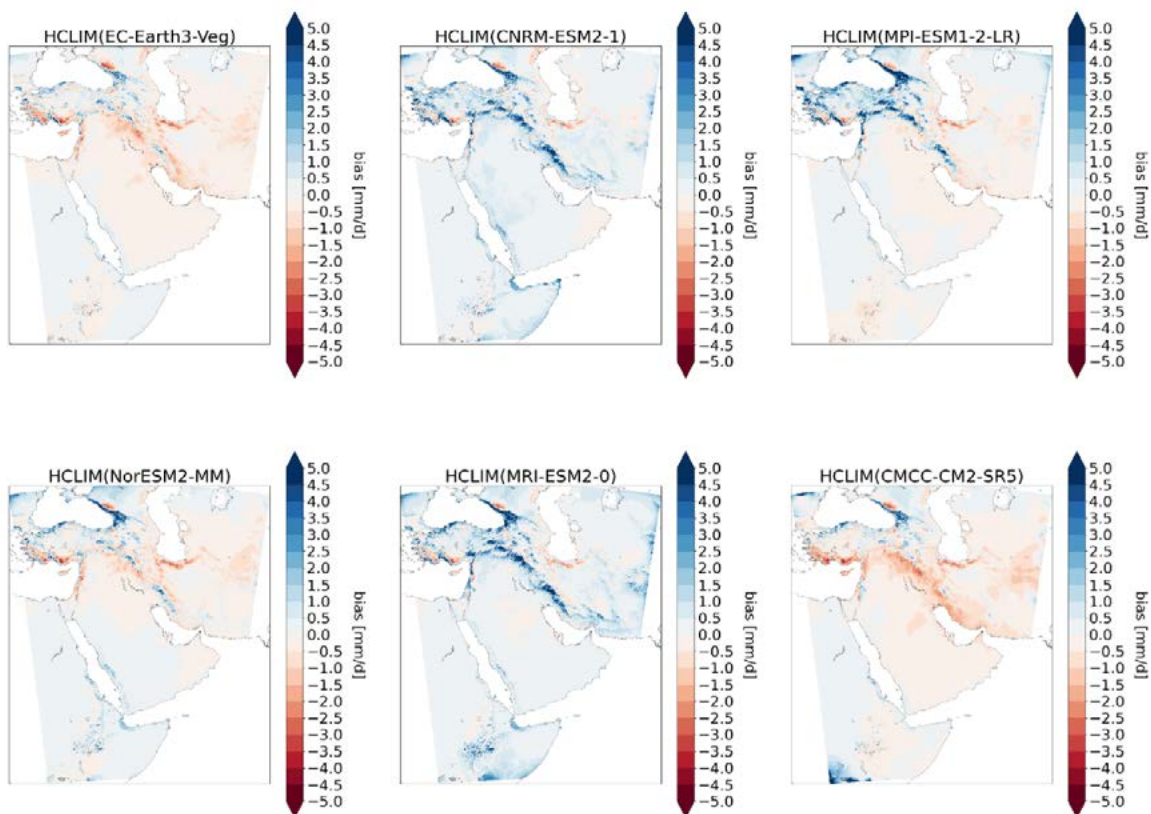


Temperature bias *after* adjustment

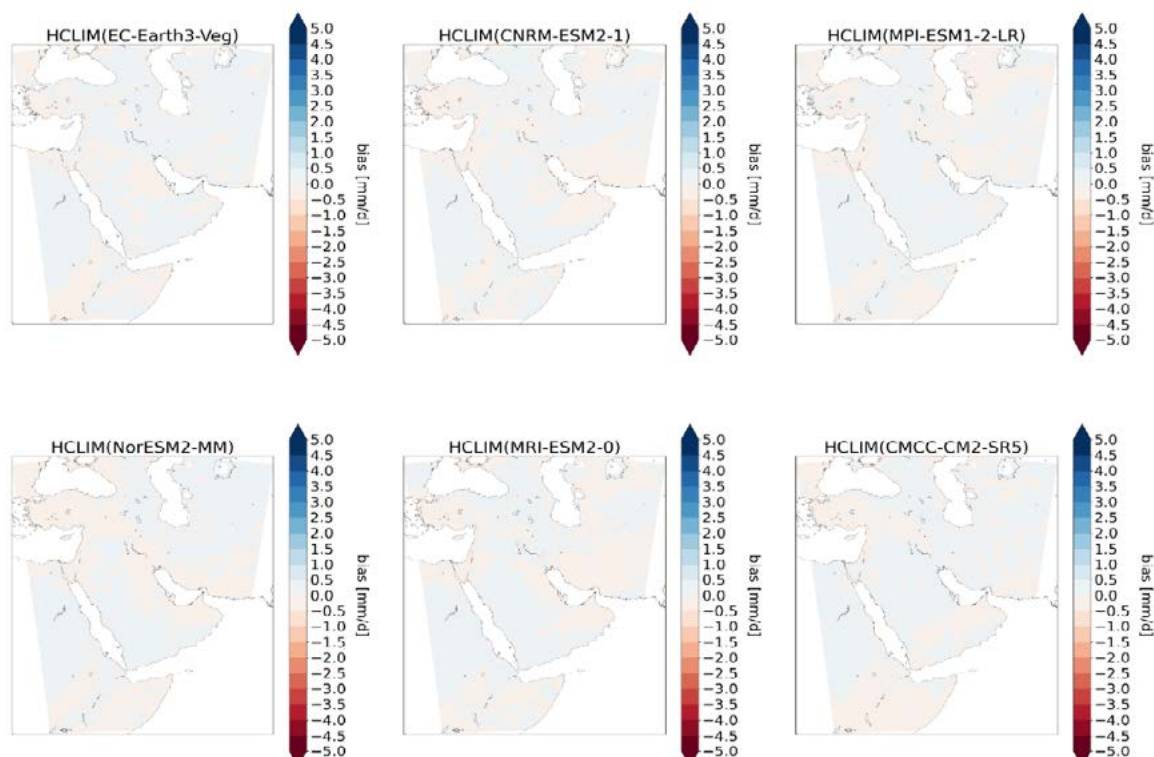


**FIGURE 11:** Absolute bias in mean precipitation for raw RCM outputs (top 2 rows, mm per day) and with MIdAS bias adjustment (bottom 2 rows, mm per day) relative to HydroGFD3 for the period between 1981 and 2010 during December, January, and February

Precipitation bias *before* adjustment



Precipitation bias *after* adjustment



## 6 ANALYSIS BACKGROUND AND TECHNIQUES

A number of projected model outputs have been analysed. Only a few are presented here for overview. A more comprehensive presentation of the modelled results is presented in the summary outcomes report. Many users of the projections will be mostly interested in the bias-adjusted results, as are presented in the summary outcomes report. Outputs from both the raw and the bias-adjusted RCM projections are shown here for comparison.

### 6.1 Common model outputs

The two most common model outputs of interest from the RCM projections are changes in precipitation and temperature. Changes in temperature are given in degrees Celsius. Precipitation is shown in mm over a given time. For water resources applications, runoff is the key variable of interest. Unlike for the Arab Domain, regional hydrological modelling (RHM) projections were not conducted over the Mashreq Domain. Changes in runoff coming directly from the RCM are therefore presented, but it is important to note that these can only be considered as indicative for trends. Runoff results are shown as mm over a given time and presented in the summary outcomes report.

Although all RCMs contain representation of the hydrological cycle, this cannot be compared to the level of detail from a calibrated hydrological model, particularly with consideration for biases in precipitation. To get more information on the expected magnitude of the change in runoff, more detailed analysis with hydrological models is needed.

### 6.2 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. A list of 27 indices was developed by the Expert Team on Climate Change Detection and Indices (ETCCDI; Peterson and Manton, 2008) to provide metrics for extreme events. Change in selected ETCCDI indices was analysed over the Mashreq Domain, whereby five indices were chosen as examples for the summary outcomes report, as listed below. Note that the SU35 index was defined in previous RICCAR work as more relevant for the climate in the region; an example using this index is presented below. The full list of 27 indices is given in Donat and others (2013) together with an analysis over the Arab region using historical observations.

<b>SU35</b>	<b>Number of hot days:</b> annual count of days when daily maximum temperature > 35°C {defined for application in RICCAR}
<b>TR</b>	<b>Number of tropical nights:</b> annual count of days when daily minimum temperature > 20°C.
<b>R20</b>	<b>Annual count of 20mm precipitation days:</b> when daily precipitation ≥ 20mm
<b>SDII</b>	<b>Simple precipitation intensity index:</b> defined as total precipitation amount ÷ number of wet days
<b>CDD</b>	<b>Maximum length of dry spell:</b> maximum number of consecutive days with daily precipitation < 1mm

## 7 RCM SUMMARY RESULTS FOR THE MASHREQ DOMAIN

Some summary results from the RCM projections for future periods are shown here. General outcomes on temperature and precipitation are presented. These are all based on the ensemble of 10 km projections. Additional results, including those for the above-mentioned ETCCDI indices, are presented in the summary outcomes report.

### 7.1 Temperature

Presented below are maps showing the projected temperature change over the Mashreq Domain for two seasons, June-August and December-February, for the mid-century period 2041-2060 (figure 12). The maps show changes both using direct results from the RCM and after these results have been bias adjusted.

Similar patterns of change for all six HCLIMALADIN projections can be seen. All of the projections agree on an increase of temperature over the region, and the magnitude of temperature change is similar to that seen from the Arab Domain projections. The southern part of the domain along the South Arabian coast and the Horn of Africa show less temperature change than other parts of the domain. As seen here, there is a slight reduction of the climate change signal after bias adjustment.

### 7.2 Precipitation

Presented below are maps showing the projected precipitation change over the Mashreq Domain for two seasons, June-August, and December-February, for the mid-century period 2041-2060 (figure 13). The maps show changes both using direct results from the RCM and after these results have been bias adjusted.

The change in projected precipitation shows considerable variability and the projections do not agree completely on increases or decreases of precipitation over the region. Most of the ensemble members show increased summertime precipitation over much of the dryland or desert areas, but it should be noted that the amounts are quite small and not likely to have much impact on the overall water cycle in these already dry areas. Summertime increases along the Southwestern Arabian coast are however more pronounced. The projections show a consensus for decreased wintertime precipitation through the relatively water rich areas of the Mediterranean coast and mountains. The precipitation change over the headwaters for the Euphrates and Tigris rivers is mixed among the climate projections, as it also was for the Arab Domain projections. However, evapotranspiration in the region plays an important role, which means that runoff can decrease even if precipitation increases somewhat.

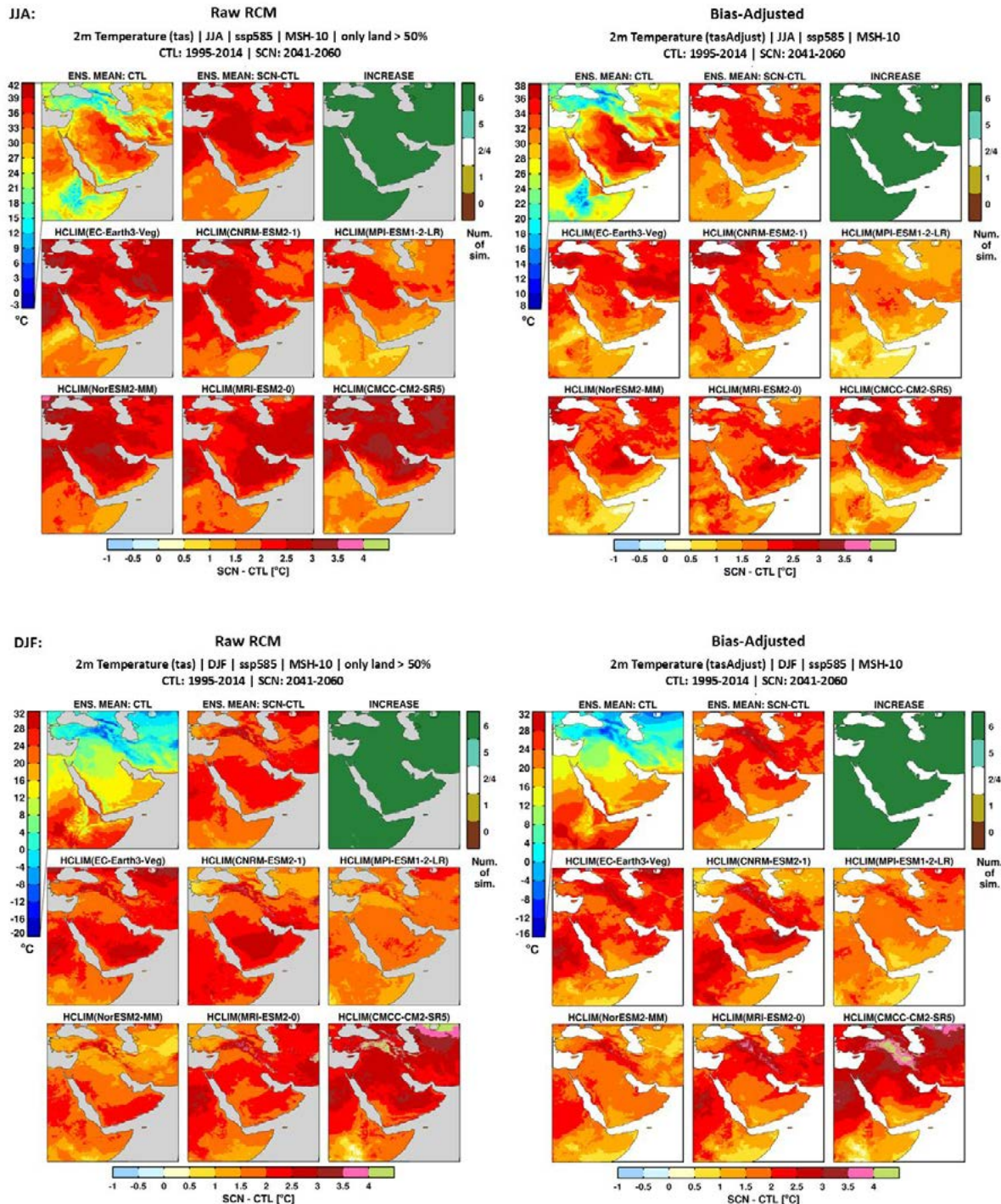
As with the temperature results, there are differences in the precipitation changes after bias adjustment. Yet, for precipitation, both reductions and increases of the climate change trends can be found after bias adjustment. It is however worth noting the agreement on decreased precipitation during the winter season along the eastern Mediterranean coast and increased precipitation along the Southwestern Arabian coast during summer.

### 7.3 Hot days

As an example of expected changes in extreme events, analysis of the change in hot days is included here. Presented below are maps showing the projected change in the number of days with maximum temperature exceeding 35°C over the Mashreq Domain for the mid-century period between 2041 and 2060 (figure 14). The maps show changes both using direct results from the RCM and after these results have been bias adjusted. The area along the southern Mediterranean coast, e.g. Sinai, stands out as one that will be highly affected.



**FIGURE 12:** Mean temperature change (°C) from HCLIM-ALADIN driven by six different GCMs for SSP5-8.5 for the period between 2041 and 2060 compared to the baseline period between 1995 and 2014

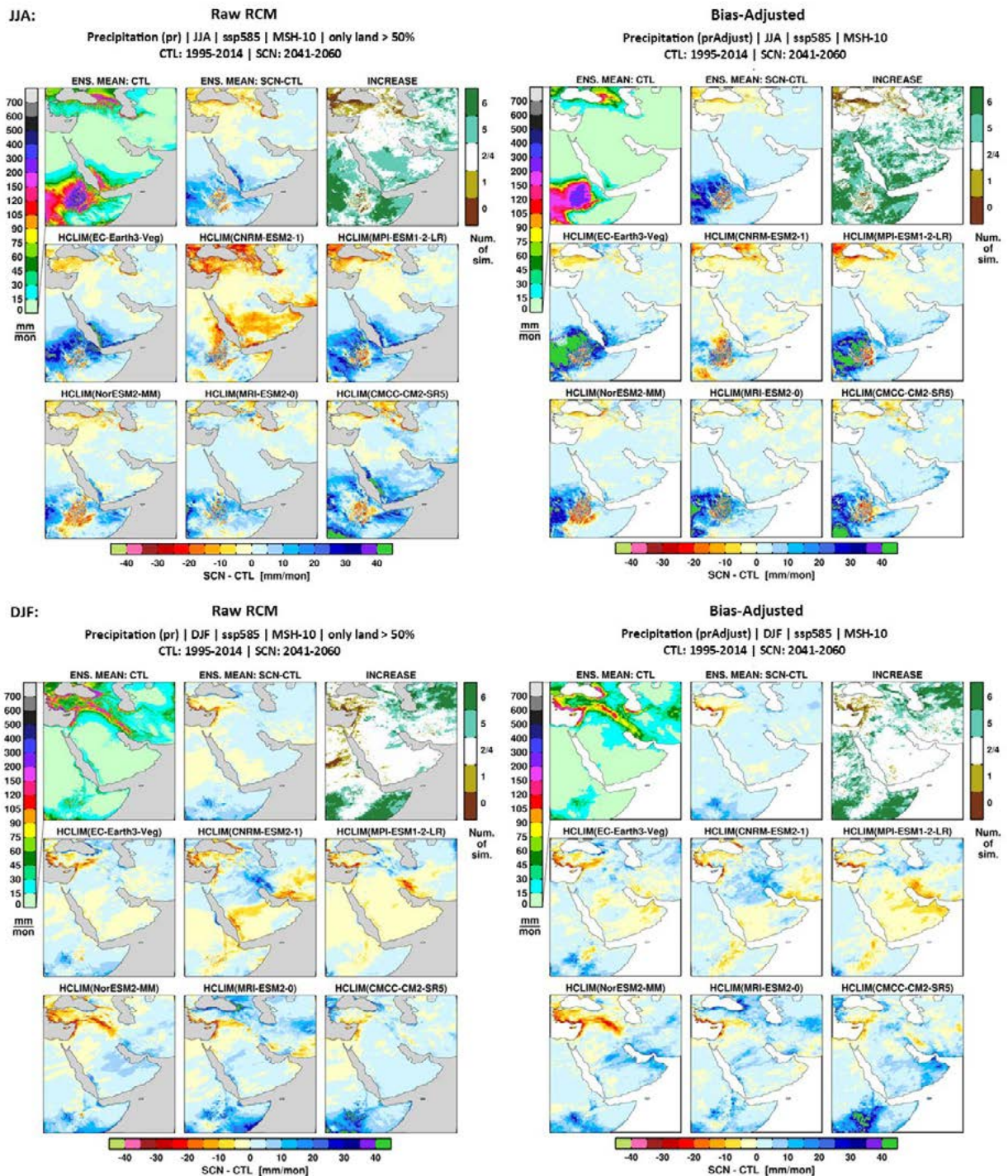


**Note:**

- The two left panels show the raw RCM projection results and the two right panels show the bias-adjusted projection results.
- In each panel the top row left plot shows the mean ensemble temperature for the baseline period, middle shows the ensemble temperature change and the right plot shows the level of agreement between the six projections.
- The 2nd and 3rd rows in each panel show the six individual HCLIM-ALADIN simulations. Top panels: June, July, August. Bottom panels: December, January, February.
- The top left legend in each panel is for mean ensemble temperature only; the top right legend is level of agreement only; the bottom legend pertains to all other plots.



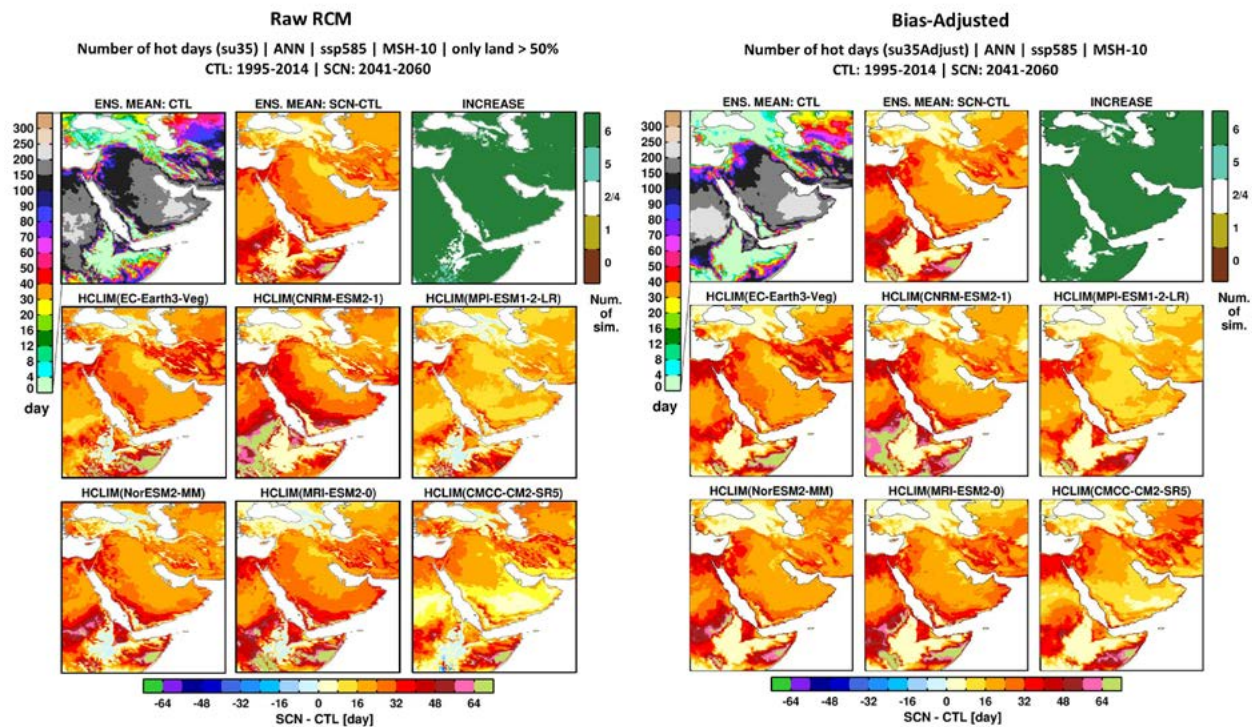
**FIGURE 13:** Mean precipitation change (mm/mon) from HCLIM-ALADIN driven by six different GCMs for SSP5-8.5 for 2041-2060 compared to the baseline period between 1995 and 2014



**Note:**

- The two left panels show the raw RCM projection results and the two right panels show the bias-adjusted projection results.
- In each panel the top row left plot shows the mean ensemble precipitation for the baseline period, middle shows the ensemble precipitation change and the right plot shows the level of agreement between the six projections.
- The 2nd and 3rd rows in each panel show the six individual HCLIM-ALADIN simulations. Top panels: June, July, August. Bottom panels: December, January, February.
- The top left legend in each panel is for mean ensemble temperature only; the top right legend is level of agreement only; the bottom legend pertains to all other plots.

**FIGURE 14:** Change in the annual number of hot days - defined as maximum temperature exceeding 35°C - from HCLIM-ALADIN driven by six different GCMs for SSP5-8.5 for the period between 2041 and 2060 compared to the baseline period between 1995 and 2014



**Note:**

- The left panel shows the raw RCM projection results and the right panel show the bias-adjusted projection results.
- In each panel the top row left plot shows the mean ensemble annual number of days for the baseline period, middle shows the ensemble change in number of days and the right plot shows the level of agreement between the six projections.
- The 2nd and 3rd rows in each panel show the six individual HCLIM-ALADIN simulations.
- The top left legend in each panel is for mean ensemble number of days only; the top right legend is level of agreement only; the bottom legend pertains to all other plots.



## 8 SUMMARY CONCLUSIONS

The Mashreq Domain at 10 km horizontal resolution has been set up for regional climate modelling as a complement to the previously established RICCAR Arab Domain covering the Arab region. Regional climate projections using forcing data from six global climate projections were produced with the HCLIM-ALADIN regional climate model. Based on the latest CMIP6 GCM projections for the SSP5-8.5 emissions scenario, this six-member ensemble of projections is compatible to the global projections presented in the latest IPCC AR6 report (IPCC, 2021a, 2021b). Such higher resolution projection results provide finer-scaled information that may be more suitable for application in impacts models, particularly over coastal and mountainous areas.

Evaluation of the performance of the HCLIM-ALADIN over the Mashreq Domain showed it to perform well. Deviations are seen when comparing modelled present climate results to observations, but they are within expectations from previous experience. For temperature, there is a common tendency for a cold bias over much of the domain that is more pronounced in winter than in summer. An exception is a warm bias in the south-eastern part of the Arabian Peninsula during summer. A similar pattern of bias is seen in the GCM results, which indicates that the bias is carried over from the GCMs to the RCM.

As always with such comparisons, considerations for the scarcity of observations networks should be kept in mind. In the case of the Arabian Peninsula, this is an area where differences between different observations datasets is largest, which indicates a higher level of uncertainty for the observations. It can also be noted that a similar pattern of temperature bias was exhibited for the RCM results over the Arab Domain.

Looking at the present climate for precipitation, results from half of the RCM simulations exhibit dry biases over the domain during winter, and all show wet biases during summer. This varies spatially over the region but is apparent – among others – for the water rich headwaters of the Euphrates and Tigris rivers. As with the temperature observation datasets, there are considerable differences between the precipitation observation datasets over the domain.

Regarding climate change trends, the RCM model results generally reflect similar trends to their GCM driving projections. This indicates that they maintain the large-scale global results over the Mashreq while providing the finer scale results desired over the coasts and mountains.

As has become common practice for further application of climate model results, methods for adjusting biases in the projection results for temperature and precipitation were applied. The bias-adjusted datasets are appropriate for use in climate impacts studies, such as hydrology and agriculture that are highly affected by precipitation and temperature, or for calculation of climate change indicators that rely on absolute thresholds.

The MIdAS bias adjustment methodology applied incorporates new developments and more up-to-date observational databases than DBS, which was used when applying bias adjustment to the Arab Domain. Even though MIdAS is based on similar techniques as DBS, a major difference is that it is designed to better handle differences in scales for both space and time to take full advantage of finer RCM model resolution. It also employs an improved algorithm to deal with instances of a dry frequency bias, i.e. if a climate model simulates too few rain days compared to the reference data. Results for temperature and precipitation before and after bias adjustment show that most of the bias has been removed at seasonal time scales.

Only a few examples showing projected climate change results for the Mashreq Domain are shown in this technical note. A more comprehensive overview of change results can be found in the complementary RICCAR technical report: Future climate projections for the Mashreq region – Summary outcomes.

Maps of projected temperature change over the Mashreq Domain for the mid-century period extending between 2041 and 2060 show similar patterns of change for all six HCLIM-ALADIN projections. All the projections agree on an increase of temperature over the region, and the magnitude of temperature change is similar to that seen from the Arab Domain projections. The southern part of the domain along the South Arabian coast and the Horn of Africa show less temperature change than other parts of the domain. Comparison of changes using both direct results from the RCM and after these results have been bias adjusted show some reduction of the climate change signal after bias adjustment.

Precipitation results for the mid-century period between 2041 and 2060 show more variability with considerable spread between projections in some areas. They do not agree completely on increases or decreases of precipitation over the region, although most of the ensemble members show increased summertime precipitation over much of the dryland or desert areas. It should be noted that the amounts are small and not likely to have much impact on the overall water cycle in these already dry areas. However, summertime increases along the Southwestern Arabian coast are more pronounced. The projections show a consensus for decreased wintertime precipitation along the relatively water rich areas of the Mediterranean coast and mountains. The precipitation change over the headwaters for the Euphrates and Tigris Rivers is mixed among the climate projections, as it also

was for the Arab Domain projections. Yet, evapotranspiration in the region plays an important role, which means that runoff can decrease even if precipitation increases somewhat.

Comparison of precipitation changes between direct RCM results and bias-adjusted results also shows some differences, as with temperature. However, for precipitation, both reductions and increases of the climate change trends can be found after bias adjustment. It is nevertheless worth noting the agreement on decreased precipitation during the winter season along the eastern Mediterranean coast and increased precipitation along the Southwestern Arabian coast during summer.

The fact that bias adjustment can influence climate change results in the projections is well known and not unique to this region (breakout group 3bis: IPCC, 2015). It is an area of ongoing research that will continue to be investigated in coming years. Aside from the bias adjustment methods applied, the choice of reference dataset for observed climate can also influence bias-adjusted outcomes. Although the best available observations and techniques are used in assembling them, the quality of such datasets at regional and local scale is a factor, particularly over data sparse regions such as the Arabian Peninsula. Bias adjustment is an additional source of uncertainty in the projection results, where the importance of its influence depends to some degree on the application at hand.

One example of changes in extreme events is shown in this report as the analysis of the change in the annual number of hot days – where maximum daily temperature exceeds 35°C. The area along the southern Mediterranean coast, e.g. Sinai, stands out as one that will be highly affected for the mid-century period between 2041 and 2060. Additional examples of extreme indices are found in the summary outcomes report.

The climate downscaling work performed over the Mashreq Domain extends the knowledge obtained from the RICCAR Arab Domain. The previous work was performed at 50 km resolution and included a mini-ensemble of three GCM-driven RCM projections for two RCP scenarios through end-century. The current work was performed at 10 km resolution and contains a larger ensemble of six GCM-driven projections for one SSP scenario through the year 2070. As such, there is now a larger combined ensemble of results over the Mashreq region from which to draw conclusions on upcoming trends for future climate. However, increasing the number of projections over any region will also increase insight over the spread of possible outcomes over that region.

Climate is complex with many interacting processes and producing climate projections is a continuously evolving science – both on global and regional scales. There are many factors to consider when processing and analysing future projections. Important points to remember when analysing the Mashreq Domain projections include the following:

- The domain is different, both in size and location.
- The resolution is different.
- The RCM used is different.
- The GCMs have been further developed, with higher climate sensitivity.
- The emissions scenarios are different – based on the AR6 SSP formulations.
- The techniques for bias adjustment have been further developed.
- The time scale focus is on mid-century and does not include late-century results where the climate signal may be more pronounced.

In comparing new results to previous ones, differences will be encountered. As mentioned above, one must keep in mind the influencing factors at play and look for where robust signals can be identified. Temperature trends from different model simulations are often easier to interpret, whereas precipitation is much more chaotic and variable, and typically shows a much broader range of response according to different model setups and forcing conditions. The new results do not negate or supersede the previous ones. Both are valid but should be considered in the context for how they were produced.

Further information on the climate projections generated for the Mashreq Domain and their use in hydrological and agricultural impact assessment studies conducted by ESCWA and regional partners is available on the RICCAR Regional Knowledge Hub ([www.riccar.org](http://www.riccar.org)).

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This report was prepared for the Regional Initiative for the Assessment of the Impact of Climate Change on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR). It documents climate modelling and analysis done by the Swedish Meteorological and Hydrological Institute (SMHI) to produce finer resolution climate projections over the Mashreq region.

Building upon the regional knowledge generated under RICCAR for the entire Arab region, SMHI has established the Mashreq Domain at 10 km grid resolution. Regional climate modelling (RCM) was performed to dynamically downscale global climate model (GCM) results and prepare a new ensemble of regional climate modelling projections for this domain. The aim was to provide outputs at finer resolution – including bias-adjusted variables – that can be used by regional researchers to inform further climate analysis in the Mashreq region.

