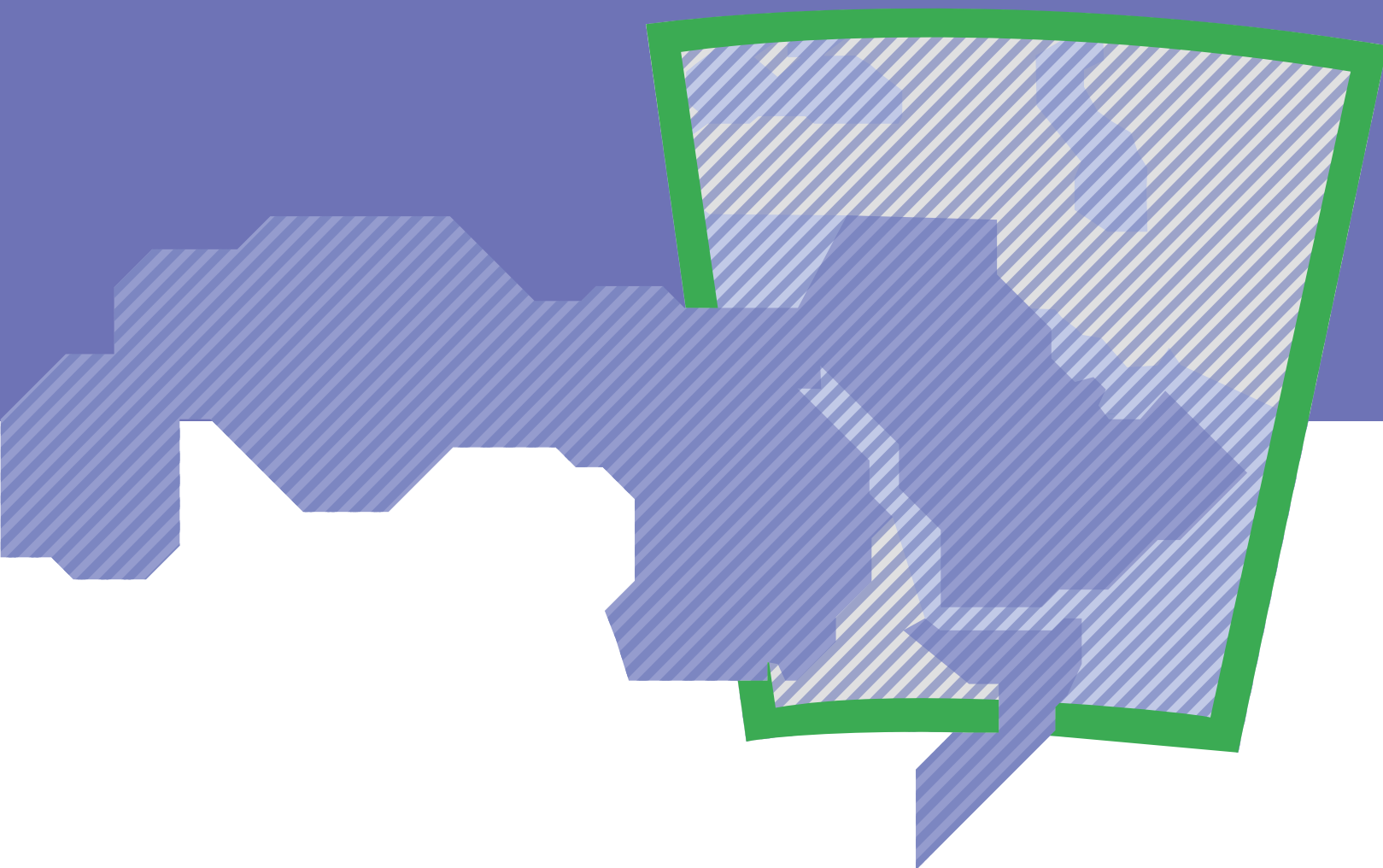




Future climate projections for the Mashreq region under the intermediate and high emissions scenarios



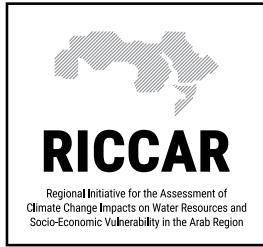
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Future climate projections for the Mashreq region under the intermediate and high emissions scenarios

TECHNICAL REPORT



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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 ESCWA Ministerial Session.

RICCAR is implemented through a collaborative partnership involving regional and specialized organizations. The RICCAR Regional Knowledge Hub includes an Arab/MENA Domain data portal and a Mashreq Domain data portal, which are managed by the Economic and Social Commission for Western Asia (ESCWA). ESCWA coordinates the regional initiative under the umbrella of its Arab Centre for Climate Change Policies.

This technical report was prepared by Grigory Nikulin, Aitor Aldama Campino, Peter Berg, Thomas Bosshard, and Wei Yang at the Swedish Meteorological and Hydrological Institute (SMHI) and Marlene Ann Tomaszewicz at ESCWA. 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 focusing on climate resilience for inclusive sustainable development through regional cooperation, implemented by ESCWA. This project component provides regional climate projections to inform science-based assessments and analyses of climate impacts on land and water resources in the region.

EXECUTIVE SUMMARY

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

The report provides an overview of key findings from a multi-model ensemble of regional climate simulations generated using HCLIM38-ALADIN (i.e. the HARMONIE-Climate regional climate modelling system cycle 38 with ALADIN physics) for the Mashreq Domain at a 10 km resolution. The ensemble is produced by dynamically downscaling six Coupled Model Intercomparison Project Phase 6 (CMIP6) global climate models (GCMs) under two widely-used climate change scenarios: the intermediate emissions scenario (SSP2-4.5) and the high-emissions scenario (SSP5-8.5).

The SSP2-4.5 scenario serves as the central planning scenario in most national adaptation strategies and financial risk assessments, reflecting a “middle-of-the-road” development pathway with moderate greenhouse gas emissions and policy trajectories broadly consistent with current global trends. In contrast, the SSP5-8.5 scenario represents a high-emissions and fossil fuel-intensive pathway, formally described as the “fossil-fueled development” pathway, characterized by rapid economic growth and sustained reliance on fossil fuels. Although recent policy and technological developments suggest that the extreme fossil-fuel growth assumptions embedded in the SSP5-8.5 scenario are becoming less plausible, the scenario remains essential for exploring the upper-bound climate risks and offering stress-testing for adaptation strategies. For this reason, many climate assessment and impact studies employ SSP2-4.5 and SSP5-8.5 as a scenario pair to provide a robust framing of the upper and moderate boundaries of the projected climate future.

The first six regional climate simulations of the Mashreq ensemble under the SSP5-8.5 scenario were generated in 2020 and 2021 (SMHI and ESCWA, 2021). Subsequent work focused on extending the Mashreq SSP5-8.5 ensemble by downscaling the same six CMIP6 GCMs under the SSP2-4.5 scenario, thereby allowing the consideration of a broader range of climatic futures. The Mashreq ensemble covers the 1961–2014 period of the historical CMIP6 experiment, based on observed forcings, and the 2015–2070 period of the scenario experiment, which incorporates assumptions about future trajectories of key human-related drivers of the climate system.

In line with established practice for subsequent applications of climate model projections, methods for adjusting biases in the climate projection results for temperature and precipitation were applied. The bias-adjusted datasets are appropriate for use in climate impact studies, such as hydrology and agriculture that are highly affected by precipitation and temperature, or for the calculation of climate change indicators that rely on absolute thresholds. Bias adjustment does not aim to improve climate projections but rather to reduce, to some extent, deviations of climate model data from observed climate conditions.

All Mashreq simulations agree on a consistent robust increase in temperature over the region compared to the 1995–2014 reference period. The magnitude (up to 1°C) and spatial pattern of warming are almost the same in the near-term (2021–2040) when both scenarios are similar in terms of radiative forcing. The magnitude of warming increases in the mid-term future (2041–2060) when radiative forcing between the two scenarios starts to diverge, reaching up to 2°C under the SSP2-4.5 scenario and up to 2.5°C under the SSP5-8.5 scenario over the central part of the region. The southern part of the domain along the South Arabian coast and the Horn of Africa shows less change in temperature than the other parts of the domain.

Precipitation results exhibit substantial variability, with considerable differences among individual projections in certain areas. As observed in previous Arab Domain projections, the results do not agree completely on increases or decreases in precipitation over the region. However, the Mashreq projections indicate a tendency towards drier future conditions along the Eastern Mediterranean coast and over central and western Türkiye, although a robust signal is observed only over small areas in 2041–2060 under the SSP5-8.5 scenario.

Regionally, there is a robust increase in precipitation over drylands or deserts for both winter and summer (e.g. parts of Egypt and the Sudan), evident as early as 2021–2040 under the SSP2-4.5 scenario. This increase in precipitation over dry regions with a few rainy days and small amounts of precipitation should be interpreted with caution and requires detailed analysis. A robust increase in precipitation in April–September along the western coast of Yemen is already visible during 2021–2040 under the SSP5-8.5 scenario and subsequently extends along the southern coast of Yemen in 2041–2060 under the same scenario. This increase may be linked to changes in the northward migration of the Inter-Tropical Convergence Zone (ITCZ) rainbelt during the summer, which is also reflected in the projected wetter conditions over the Great Horn of Africa.

Runoff also exhibits considerable decadal and multi-decadal variability. Nevertheless, the Mashreq ensemble projects an increase in runoff during April–September along the Southwestern Arabian coast, which is already evident during 2021–2040. The increase becomes more robust over time and extends to southern Yemen in 2041–2060 under the SSP5-8.5 scenario. A pronounced and robust decrease in April–September runoff is projected for the Euphrates and Tigris headwaters under both the SSP2-4.5 and SSP5-8.5 scenarios. Runoff data in this report are based on direct outputs from a regional climate model and therefore contain inherent biases. Calibrated hydrological models that more accurately represent hydrological details should therefore be used to provide deeper insight into the impacts of climate change on runoff and river flows in the Mashreq region.

When comparing new results to previous ones, differences will always be encountered. These Mashreq Domain projections complement the previously established RICCAR Arab Domain projections for the wider Arab region.

It is important to consider the multiple factors influencing climate projections and to identify areas where robust signals emerge. Regional temperature trends are often easier to interpret, whereas precipitation typically exhibits a wider range of responses depending on different model setups, scenarios, the number of projections and other factors.

This technical report provides a detailed description of the Mashreq ensemble and methodology used to create it. However, the results presented in the report present only a general overview of future climate change across the Mashreq region, focusing on a limited set of variables, indices and river basins. The report is intended primarily as a reference for the Mashreq ensemble to support detailed assessments and studies that focus on specific sectors in more detail, such as hydrological, agricultural or health impact studies. Primary output variables from the modelled climate projections are available through the RICCAR Regional Knowledge Hub for further analysis.

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ABBREVIATIONS AND ACRONYMS

AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CMIP7	Coupled Model Intercomparison Project Phase 7
ECS	equilibrium climate sensitivity
ESCWA	Economic and Social Commission for Western Asia
ESM	earth system model
GCM	global climate model
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
RCM	regional climate model
RCP	representative concentration pathway
RICCAR	Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region
SMHI	Swedish Meteorological and Hydrological Institute
SSP	shared socioeconomic pathway

1. INTRODUCTION

This report was developed as part of the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR). It presents regional climate modelling and analysis conducted by the Swedish Meteorological and Hydrological Institute (SMHI) based on high-resolution regional climate projections for the Mashreq region under two future climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), namely the intermediate SSP2-4.5 and the high-emissions SSP5-8.5.

Building on the Arab Climate Change Assessment Report (ESCWA and others, 2017) and the regional knowledge base generated under the RICCAR initiative for the entire Arab region, SMHI established the Mashreq Domain in 2020 to conduct regional climate modelling projections for this sub-region at a higher resolution, moving from the 50 km horizontal scale applied for the Arab region to a 10 km horizontal resolution for the Mashreq region. The regional climate model HCLIM38-ALADIN (i.e. the HARMONIE-Climate regional climate modelling system cycle 38 with ALADIN physics) was employed to dynamically downscale a subset of global climate projections for this domain under the SSP5-8.5 scenario. This initial ensemble of projections is presented in the RICCAR technical report entitled *Future climate projections for the Mashreq Region: Summary outcomes*, published by SMHI and ESCWA in 2021. The report provides regional climate projections at high resolution, including bias-adjusted variables, which can be used by regional researchers to inform further climate analyses in the Mashreq region under this high-emissions scenario.

This 2026 technical report builds on the previous report, expanding downscaling efforts and ensemble outputs to include the intermediate SSP2-4.5 climate scenario, and providing comparative analysis between the SSP5-8.5 and SSP2-4.5 scenarios as well as additional information on the methodology applied for conducting the analysis. These results are not intended to provide a comprehensive assessment of the domain. A full description of the overall initiative and associated resources are available on the [RICCAR Regional Knowledge Hub](#) data portal as well as its [Mashreq Domain data portal](#) and [data catalogue](#).

This report and its findings support other analyses and reports prepared under the RICCAR publication series by the United Nations Economic and Social Commission for Western Asia (ESCWA), SMHI and regional partners. The results have been used by Arab States to inform national and regional climate priority-setting, policy development, strategy formulation, and reporting under the United Nations Framework Convention on Climate Change.

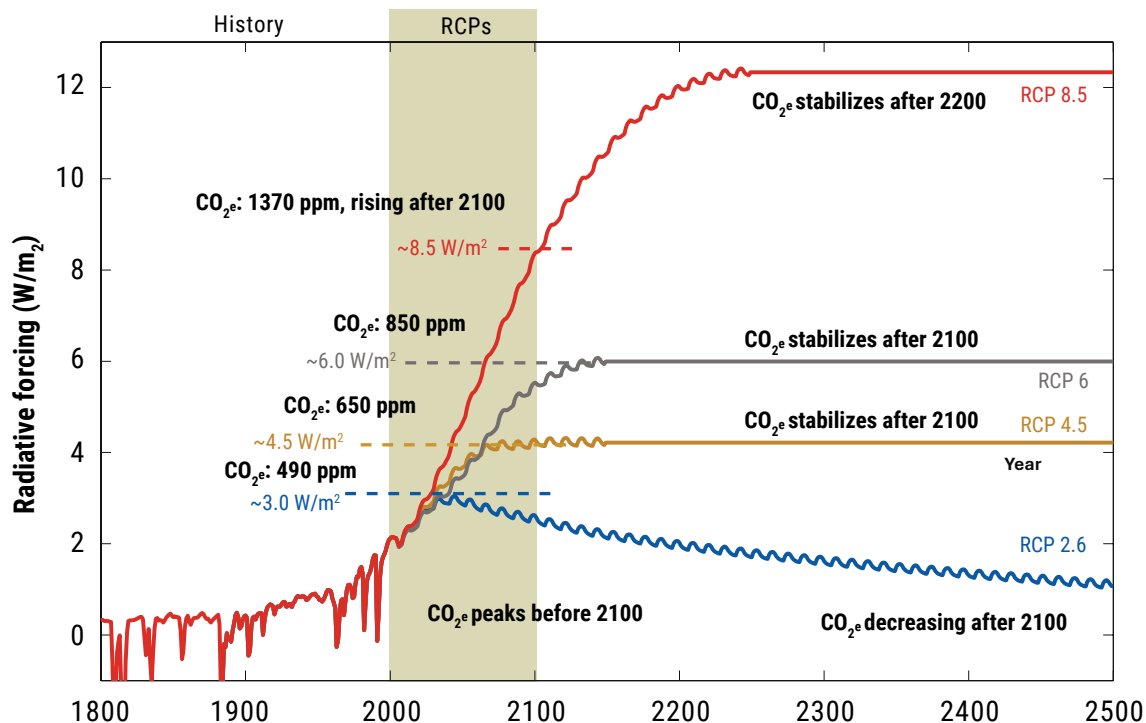
2. BACKGROUND

A. Climate change scenarios

Climate change scenarios encompass a range of plausible futures and are based on assumptions about trajectories of key human-related drivers of the climate system, such as greenhouse gas (GHG) emissions, land-use changes and socioeconomic factors. Various approaches to develop future climate scenarios have been used over time, including a 1% per year increase of atmospheric carbon dioxide (CO_2) concentration in the Coupled Model Intercomparison Project (CMIP) Phase 2 (CMIP2) (Covey and others, 2003) and advanced combinations of GHG emissions and socioeconomic factors in the latest CMIP6 (Eyring and others, 2016).

The fifth assessment report (AR5) of IPCC (IPCC, 2013; IPCC, 2014) was based solely on the Representative Concentration Pathways (RCPs) (van Vuuren and others, 2011) used in CMIP5 (Taylor and others, 2012). The RCP scenarios are named in accordance with their expected radiative forcing expressed in watts per square metre (W/m^2), e.g. RCP2.6, RCP4.5, RCP6.0 and RCP8.5. Each represents a trajectory of GHG concentrations over time to approximately reach a particular radiative forcing in the year 2100 (figure 1). As such, RCPs make no assumptions related to policy changes that may affect the climate; instead, they only delimit the range of possible forcings that might occur. Policy analysts and researchers can work back from these trajectories to investigate what may cause them. In this approach, each RCP could result from different combinations of economic, technological, demographic, policy and institutional futures. Two of the CMIP5 RCP scenarios – RCP4.5 (medium stabilization scenario) and RCP8.5 (high-emissions scenario) – were used in the Arab Climate Change Assessment Report (ESCWA and others, 2017).

Figure 1. Representative concentration pathways



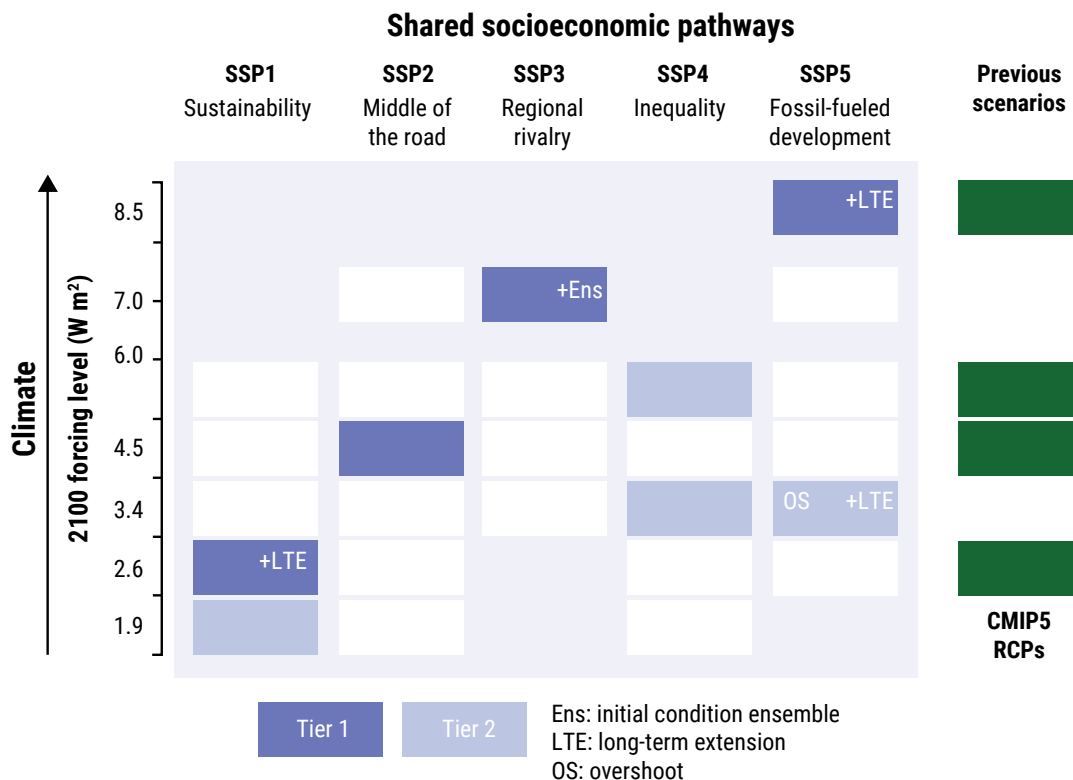
Source: Meinshausen M. and others, 2011.

The climate change scenarios used in the sixth assessment report (AR6) of IPCC (IPCC, 2021a; IPCC, 2021b) are referred to as the shared socioeconomic pathways (SSPs). SSPs constitute a new framework that links the socioeconomic dimension of scenarios with RCPs within a scenario matrix architecture (O'Neill and others, 2016) (figure 2). They provide different narratives that describe how the future might unfold in terms of societal trends which were used in integrated assessment models (IAMs) to generate a new set of global emissions and land-use scenarios. These narratives, which are based on shared climate policy assumptions, result in different levels of radiative forcing and are therefore linked to RCPs. Within CMIP6, five SSP-RCP combinations were selected as a first tier of global climate model (GCM) experiments to guide the prioritization of computing resources and provide projections for the sixth assessment report.

Although SSP scenarios lead to the same total radiative forcing values in 2100 as RCP scenarios, the assumed development to reach these values is not the same. For instance, GHG emissions (carbon dioxide, methane and nitrous oxide) differ between SSPs and RCPs (Tebaldi and others, 2021). The contribution of different GHGs to total radiative forcing thus varies between SSPs and RCPs. Some of the SSP scenarios were chosen specifically to provide continuity with RCPs, such as SSP1-2.6, SSP2-4.5, SSP4-6.0 and SSP5-8.5. However, CMIP5 RCPs are based on earlier emissions and land-use scenarios (van Vuuren and others, 2011). Therefore, the regional pattern of climate change resulting from a climate simulation conducted under an RCP would not be identical to that obtained from a simulation based on an SSP with the same RCP counterpart, even if both simulations follow a similar global forcing pathway. Additionally, comprehensive evaluation shows a warmer climate under SSP-RCP pairs than their RCP counterparts in CMIP5 (Tebaldi and others, 2021; Wyser and others, 2020).

The initial Mashreq climate ensemble (SMHI and ESCWA, 2021) focused solely on the SSP5-8.5 scenario, which is based on the socioeconomic pathway characterizing a “fossil-fueled development” narrative that corresponds to the high end of radiative forcing levels, although it is not directly comparable to RCP8.5 in CMIP5. Recent work expanded the analysis by adding new SSP2-4.5 simulations, enabling assessment of a broader range of future climate conditions.

Figure 2. SSP-RCP scenario matrix used for CMIP6 simulations



Source: Adapted from O'Neill and others, 2016.

Note: Each cell in the matrix indicates a combination of SSP and 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.

SSP2-4.5 represents a middle-of-the-road pathway with intermediate GHG emissions, where CO₂ levels and other GHG emissions remain near today's values until mid-century and then decline without reaching net zero by 2100. These two scenarios are widely used in national adaptation planning and financial risk assessments to provide the upper and lower boundary of what is considered plausible. Although current policy and technology trends make the SSP5-8.5 pathway less likely, it remains essential for exploring upper-bound climate risks and testing the resilience of adaptation strategies. For this reason, SSP2-4.5 and SSP5-8.5 are often used together to represent a central future and a high-risk future in climate impact studies.

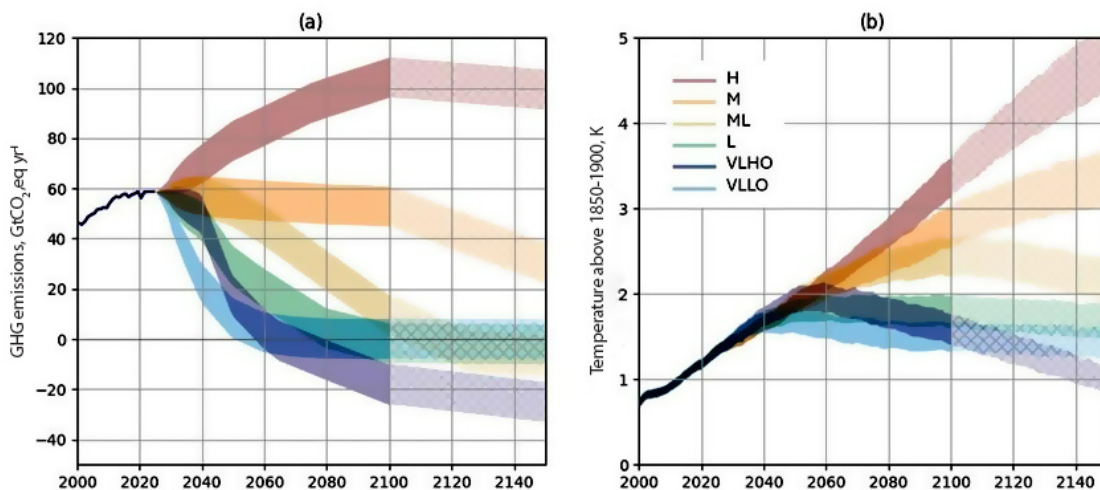
The forthcoming CMIP7 focuses on emission-driven scenarios, in which the carbon cycle represented in Earth System Models (ESMs) determines the resulting atmospheric carbon dioxide concentrations from prescribed emissions. Nevertheless, CO₂ concentrations will also be provided for ESMs/global climate models (GCMs) that operate only in concentration mode and do not include an active carbon cycle.

Six entirely new scenarios (figure 3) are included in the CMIP7 Fast Track (FT), which aims to provide, in a timely manner, a subset of CMIP7 experiments, including climate projections under the new scenarios, for IPCC AR7.

The CMIP7 scenarios start in 2025 (scenario experiment) and represent a wide range of policy-relevant emission trajectories considered to be plausible, namely: High (H), Medium (M), Medium-Low (ML), Low (L), Very Low with Limited Overshoot (VLLO) and Very Low after High Overshoot (VLHO) scenarios. A set of scenarios at the low end would inform policies in line with the Paris Agreement (i.e. global warming range from 1.5 to below 2°C).

As of 2025, all new CMIP7 scenarios are under development and are expected to be released sometime in 2026 or later. In CMIP6, one of the stated goals of the scenario design was to facilitate comparison between the new SSP scenarios and the earlier RCP scenarios used in CMIP5. In CMIP7, however, the new scenarios are not necessarily intended to be consistent with the CMIP6 SSPs.

Figure 3. Draft CMIP7 scenarios



Source: Adapted from van Vuuren and others, 2025.

Note: (a) GHG emission pathways as a function of time for each of the proposed scenarios and (b) the expected global average temperature outcomes.

B. Mashreq Domain regional climate model projections

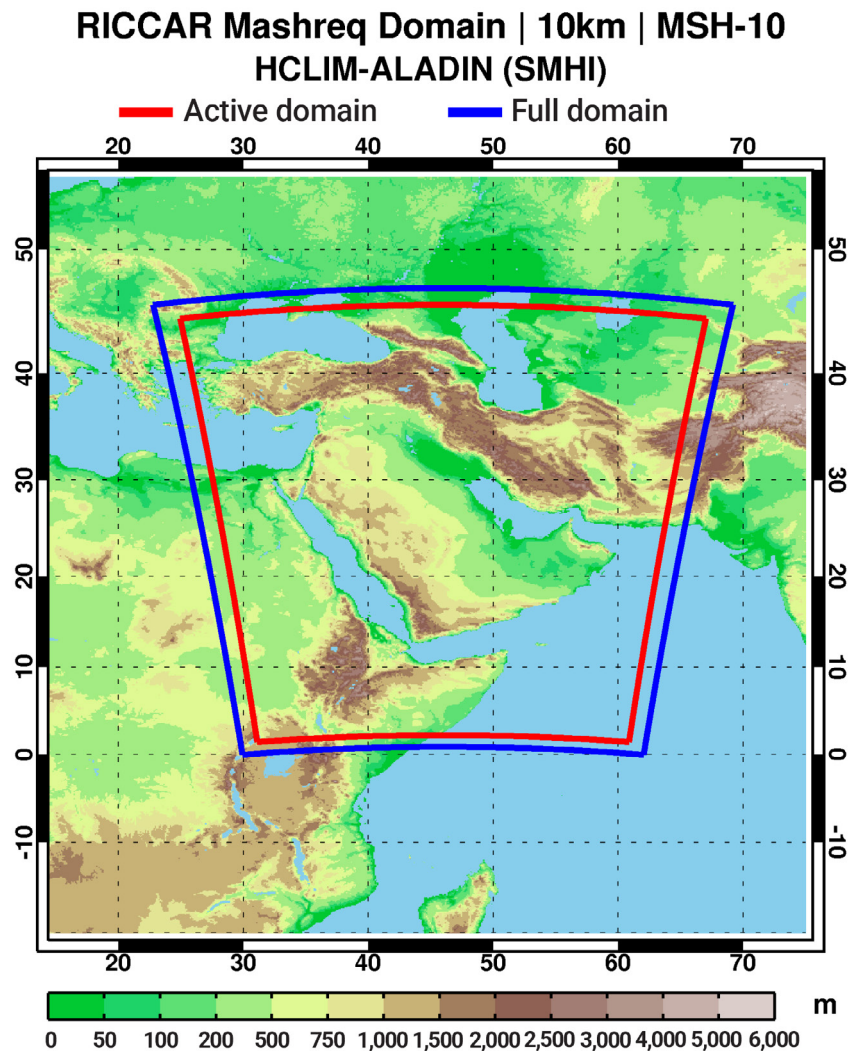
The Mashreq Domain for high-resolution regional climate projections (figure 4) was established in 2020 (SMHI, 2021) in the north-eastern parts of the Arab Domain (ESCWA and others, 2017). It covers the Mediterranean coastal countries in the Levant and north-eastern Africa, the entire drainage basins of the Tigris and Euphrates rivers, and the entire Arabian Peninsula. Defining an appropriate regional domain is a complex task that requires multiple tests to assess the ability

of different configurations to accurately represent the regional climate. Testing various domain sizes for the Mashreq Domain revealed that extending the domain sufficiently to the east is essential to capture the prevailing circulation patterns originating from the Indian Ocean.

The first ensemble of six high-resolution regional climate projections for the Mashreq Domain was generated in 2020 and 2021. HCLIM38-ALADIN (Belušić and others, 2020) was utilized to downscale six GCMs from CMIP6 over the Mashreq Domain at 10 km horizontal resolution under the SSP5-8.5 scenario (SMHI and ESCWA, 2021).

HCLIM is a seamless regional modelling system developed by a consortium of European national meteorological services, including the Rossby Centre at SMHI (Wang, 2024). HCLIM represents a comprehensive dynamical modelling system with a suite of three different regional climate models (ALADIN, ALARO and AROME) designed for a range of horizontal resolutions from tens of kilometres to convection-permitting scales of 1–3 km. ALADIN is one of the three models used for simulations with grid spacing close to or larger than 10 km. It is the limited-area version of the global model ARPEGE, from which it inherits all dynamics and physics options, as detailed in Termonia and others (2018).

Figure 4. Mashreq Domain



Source: Authors.

Note: The active domain (red) contains the area where the regional climate model (RCM) results are considered usable. The full domain (blue) indicates the actual area needed for the RCM (HCLIM38-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.

ALADIN is also used by Météo-France – CNRM (*Centre National de Recherches Météorologiques*) or the National Centre for Meteorological Research and is known as CNRM-ALADIN. Although the names and model configurations are similar, it is important to note that HCLIM38-ALADIN and CNRM-ALADIN are two different regional climate models.

The initial selection of a subset of the CMIP6 GCM ensemble for downscaling the SSP5-8.5 scenario for the Mashreq Domain was based on a combination of criteria. These included: (i) project time frames, (ii) available resources, (iii) availability of boundary forcing data, (iv) GCM resolution, and (v) a representative range of climate sensitivity (SMHI and ESCWA, 2021). Ensemble outputs were based on six CMIP6 downscaled models (table). The primary objective of the more recent work was to extend the Mashreq SSP5-8.5 ensemble by downscaling the same six CMIP6 GCMs under the SSP2-4.5 scenario, allowing consideration of a broader range of climatic futures.

However, one of the six GCMs (MRI-ESM2-0), which was initially downscaled under the SSP5-8.5 scenario, did not provide boundary conditions (forcing) to drive HCLIM38-ALADIN under the SSP2-4.5 scenario. Boundary conditions for only two scenarios (SSP1-2.6 and SSP5-8.5) were available for this model. This situation was impossible to foresee in 2020 when MRI-ESM2-0 was selected for downscaling since the main focus was only on SSP5-8.5. Therefore, another CMIP6 GCM needed to be selected to provide the boundary conditions for both the SSP2-4.5 and SSP5-8.5 scenarios. For consistency with the SSP5-8.5 ensemble, the selection of an additional GCM projection for downscaling was based on the same criteria described above. Considering all criteria, the IPSL-CM6A-LR global climate model was selected for downscaling over the Mashreq Domain under both the SSP2-4.5 and SSP5-8.5 scenarios, replacing MRI-ESM2-0 to facilitate comparative ensemble analysis. The predecessor of this model from CMIP5 activities (IPSL-CM5A-LR) was widely downscaled in CORDEX by various regional modelling groups over different domains. The current version (IPSL-CM6A-LR) used in CMIP6 has also been selected in Euro-CORDEX as one of the recommended CMIP6 GCMs for downscaling following a comprehensive evaluation of all CMIP6 GCMs (Sobolowski and others, 2023).

One of the selection criteria is the climate sensitivity of CMIP6 GCMs, expressed as the Equilibrium Climate Sensitivity (ECS). ECS represents the expected long-term global warming resulting from a doubling of atmospheric CO₂ concentrations. Different GCMs have different ECS values depending on their configuration. A representative subset of CMIP6 GCMs should include models with low, medium and high ECS values. IPSL-CM6A-LR has higher ECS (4.6°C) than MRI-ESM2-0 (3.1°C), and the new ensemble is slightly biased to higher values of ECS (table). The higher ECS value for IPSL-CM6A-LR may result in a stronger projected warming signal over the Mashreq region in the updated Mashreq ensemble compared with the initial ensemble generated under the SSP5-8.5 scenario. However, the impact of a single simulation is expected to be small within the ensemble of six simulations, and regional warming may differ from the global warming defined by ECS. The table shows that the ECS values for the six GCMs, including IPSL-CM6A-LR, range from 2.5°C to 4.8°C, remaining within the AR6 very likely range of 2°C to 5°C (SMHI and ESCWA, 2021). The final six-member CMIP6 GCM ensemble for downscaling over the Mashreq Domain is an optimal choice, given that the generation of high-resolution regional climate projections for the Mashreq region was carried out in two phases (2020–2021 and 2022–2023) with a break in between. The selection of a subset of GCMs for downscaling is inherently subjective, balancing multiple relevant criteria.

List of CMIP6-driving GCMs and scenarios downscaled by HCLIM38-ALADIN over the Mashreq Domain at 10 km resolution

CMIP6-driving GCMs	ECS (°C)	SSP2-4.5	SSP5-8.5	Reference
NorESM2-MM	2.5	✓	✓	Seland and others, 2020
MPI-ESM1-2-LR	3.0	✓	✓	Mauritsen and others, 2019
CMCC-CM2-SR5	3.5	✓	✓	Cherchi and others, 2019
EC-Earth3-Veg	4.3	✓	✓	Döscher and others, 2022
IPSL-CM6A-LR	4.6	✓	✓	Boucher and others, 2020
CNRM-ESM2-1	4.8	✓	✓	Séférian and others, 2019
MRI-ESM2-0	3.1	✓	no forcing	Yukimoto and others, 2019

HCLIM38-ALADIN 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.

C. Baseline and projection periods

There are no standard periods for assessment of future climate changes. The World Meteorological Organization (WMO) recommends 30-year periods which provide sample sizes relevant to calculating changes in statistics other than the mean. The current normal period defined by WMO and operationally used by national meteorological centres is 1991–2020. The latest IPCC AR6 uses 20-year periods: 1995–2014 as a baseline reference period and 2021–2040, 2041–2060 and 2081–2100 as near-, mid- and long-term future reference periods. For reporting on the Mashreq Domain, the same reference and future periods for analysis were adopted as those used in IPCC AR6, namely 1995–2014 (baseline), 2021–2040 (near-term future) and 2041–2060 (mid-term future). Results presented in this summary outcome report and in the technical note were analysed using these adopted time periods. Regarding further impact studies, regional scientists may use these same periods or choose other periods that may be more relevant to their work or local region. Daily and monthly datasets from 1961–2070 for all variables are available through open source from the RICCAR Regional Knowledge Hub.

D. Global warming levels

Another way to assess the impact of possible future climate change is global warming levels. Global warming levels refer to specific thresholds of average global warming established at various United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) meetings, including 1.5°C and 2°C, as well as higher levels such as 2.5°C, 3°C, 3.5°C and 4°C. The timing of a global warming level is typically defined as the central year of a sufficiently long period (20 or 30 years) during which the global mean temperature reaches predefined anomalies (1.5°C, 2°C, 2.5°C etc.) relative to pre-industrial levels. According to IPCC AR6 (IPCC, 2021a), a future climate simulation is considered to reach a specific global warming level when its global-mean temperature change, averaged over successive 20-year periods, first attains that level relative to the 1851–1900 simulated climate, which serves as the pre-industrial baseline period. Even under the same scenario, individual global warming levels are reached at different times, depending on the climate sensitivity of the GCM. For example, information on the timing of different global warming levels used in IPCC AR6 is provided in the IPCC AR6 Atlas repository (Iturbide and others, 2022). After identifying all individual GCMs that reach a given global warming level under different scenarios, the climate response at that global warming level is estimated by taking into account all models and scenarios. A key advantage of the global warming level approach is that averaging across many models and scenarios reduces uncertainties in the regional climate response associated with the scenarios and the climate sensitivity of the GCM. For regional climate model (RCM) projections driven by GCMs, the timing of global warming levels is defined according to the global warming level timing in the respective driving GCMs. Climate projections at the 1.5°C and 2.0°C global warming levels provide information to society and policymakers on how the climate may change under global warming levels consistent with the objectives of the Paris Agreement, while higher global warming levels (for example, 2.5°C or 3.0°C) show the consequences of failing to meet these objectives. Assessments of future climate change at different global warming levels are not part of this technical summary report.

E. Significance and robustness of projected climate changes

The significance and robustness of the climate change signal can be defined using different methodologies (for example, Nikulin and others, 2018). In this report, the IPCC AR6 approach to mapping uncertainties and robustness is adopted, which distinguishes three categories: “robust change”, “conflicting change”, and “no change or no robust change” (Gutiérrez and others, 2021). According to IPCC AR6, these three categories are defined as follows:

C.1 “robust signal”: when more than 80% of simulations (at least five of the six) agree on the sign of the change and more than 66% of simulations (at least four of the six) show change greater than variability threshold γ .

C.2 “no change or no robust signal”: when less than 66% of simulations show change greater than variability threshold γ .

C.3 “conflicting change”: when more than 66% of simulations show change greater than variability threshold γ and less than 80% of simulations agree on the sign of the change.

The variability threshold γ is defined as:

$$\gamma = \sqrt{2/\text{len}} * 1.645 * \sigma_{1\text{yr}},$$

where $\sigma_{1\text{yr}}$ is the interannual standard deviation measured in a linearly detrended baseline period and len is the number of years in a baseline period (20 in our case).

F. Climate variables

Climate models produce a full suite of atmospheric variables, both near the surface of the earth and further up in the atmosphere. Land surface and water body variables of varying complexity are also produced depending on the model used. The most common variables are temperature near the surface (i.e. corresponding to observations at standard instrument height) and precipitation. For water resources, runoff is the key variable of interest. Complementary variables include evaporation and soil moisture, which are also generated as part of the water balance calculations. It should be noted that runoff, soil moisture and evaporation analysed in the report are not outputs from a calibrated hydrological model but direct outputs from HCLIM38-ALADIN and have their own biases. The bias adjustment of such variables is not possible due to the absence of reference observational datasets. Projected future changes in these three variables from HCLIM38-ALADIN can be relevant as initial estimates of the hydrological cycle under future climate conditions. This report focuses on the following key variables which can be used to facilitate climate analysis and resulting impact in different sectors:

- Temperature
- Precipitation
- Runoff (total)
- Evaporation (including transpiration)
- Soil moisture (total)
- Dust uplift potential (DUP).

Other climate variables selected for the Mashreq Domain include:

- Surface air pressure
- Near-surface relative humidity
- Near-surface wind speed
- Daily maximum wind speed of gust
- Duration of sunshine
- Surface downwelling shortwave radiation.

All datasets are available in the RICCAR Regional Knowledge Hub and its data catalogue.

G. Extreme event indices

Although mean changes in future climate are relevant for many applications, changes in extreme events are often of even greater importance. A list of 27 indices was developed by the Expert Team on Climate Change Detection and Indices (Peterson and Manton, 2008) to provide metrics for extreme events. Changes in selected indices were analysed over the Mashreq Domain, whereby five indices were chosen as examples for the summary outcome report for the Mashreq ensemble under the SSP5-8.5 scenario (SMHI, 2021). The SU35 index was defined in earlier RICCAR work as being particularly relevant to the regional climate. The full list of 27 indices is presented in Donat and others (2013), alongside an analysis over the Arab region using historical observations.

- SU35 – Number of hot days: annual count of days when daily maximum temperature $>35^{\circ}\text{C}$ (defined for application in RICCAR given its relevance for Arab States and the Mashreq Domain).
- TR – Number of tropical nights: annual count of days when daily minimum temperature $>20^{\circ}\text{C}$.
- R20 – Annual count of 20 mm precipitation days: when daily precipitation ≥ 20 mm.
- SDII – Simple precipitation intensity index: defined as total precipitation amount divided by number of wet days.
- CDD – Maximum length of dry spell: maximum number of consecutive days with daily precipitation <1 mm.

H. Mashreq bias-adjusted results

Climate data generated by climate models are subject to a number of uncertainties, including limitations in their ability to accurately simulate the complexity of the climate system. All models represent approximations of the real climate system and exhibit different errors (biases), which result in deviation between simulated and observed climate conditions. It is widely recognized that climate model outputs, when used as inputs to impact models, cannot always be applied directly and therefore require adjustment to align with observed climatology. Accordingly, bias adjustment has become an integral component of the pre-processing of climate simulations for use in impact modelling studies.

However, bias adjustment is, in general, a statistical approach that lacks physical arguments, and its application to climate model simulations may introduce additional uncertainties (IPCC, 2015). Bias adjustment can, for example, affect the climate change signal. Several bias-adjustment methodologies are designed to preserve the mean climate signal; nevertheless, they may still affect the climate signal of extremes. Natural variability, presented in all climate model simulations, does not constitute a bias and should not be subject to bias adjustment. However, separating natural variability from biases in climate simulations is not straightforward and, in many cases, is not possible. It is also important to note that bias adjustment does not aim to improve climate projections, but rather to reduce, to some extent, deviations of climate model data from observed climate conditions prior to their use in impact studies or in the calculation of climate change indicators that rely on absolute thresholds. In addition, bias adjustment corrects only climatological statistics over longer time periods, most often 20 or 30 years. Bias adjustment is not without limitations, and some remaining biases are to be expected, typically increasing towards the extremes of the distribution. In general, it is strongly recommended to assess future climate change using both original and bias-adjusted data and to intercompare the results. This is particularly important for dry regions with few rainy days, where data are not sufficient to support robust bias-adjustment and a number of simplified approaches are applied.

Daily mean precipitation, as well as mean, maximum and minimum temperatures, for all new simulations have been bias-adjusted using the same bias-adjustment methodology (MIdAS) and the same reference observation dataset (HydroGFD3.2) as applied to the SSP5-8.5 ensemble provided in 2021. Details of the bias-adjustment methodology are provided in SMHI, 2021 (pp. 15–18). Extreme event indices are presented using the bias-adjusted temperature and precipitation outputs.

I. High-resolution climate data: benefits and limitations of different methods and tools

GCMs are the primary tools used to produce future climate projections by simulating climate change under a range of future GHG emission scenarios. Despite rapid advances in high-performance computing, most GCMs that produced

future climate projections in the latest CMIP6 have a horizontal resolution of order 100–200 km. This resolution is not fine enough to accurately simulate local-scale processes and extreme events or to provide regional climate data with the high spatial detail required for impact assessment and adaptation planning. Nevertheless, GCM horizontal resolution has been gradually increasing for the past decades, and new modelling activities focusing on GCMs with high spatial resolution have recently emerged. A new High-Resolution Model Intercomparison Project, HighResMIP, (Haarsma and others, 2016) has contributed to CMIP6 by generating global climate projections at horizontal grid spacings of 25–50 km. The World Climate Research Programme Digital Earths Lighthouse Activity and the European Union Destination Earth (DestinE) initiative aim to develop high-resolution (km-scale) ESMs. However, most of these activities remain experimental and currently do not provide large ensembles of multi-decadal climate projections with a resolution of 10 km or finer.

A common approach for providing high-resolution climate data in the future climate projection framework is to supplement GCMs by empirical-statistical downscaling (ESD) or dynamical downscaling (DD) techniques. To derive regional climate data, the ESD approach assumes that larger-scale atmospheric processes are dominant drivers of local-scale climate and applies a statistical relationship between information from global models (large-scale predictors) and local-scale processes (predictands) (Maraun and others, 2010). ESD is a relatively fast and computationally efficient approach, but it strongly depends on the availability of observations and is limited to a few variables. Another potential limitation of ESD is the non-stationarity of the climate system, which refers to whether the relationship between the local-scale predictand and the large-scale predictors remains constant over time.

There are numerous ESD methods of varying complexity, including modern machine learning techniques, which can emulate the behaviour of dynamical models or establish relationships between large-scale atmospheric conditions and local-scale processes (Rampal and others, 2024). In parallel, there are several basic methods that interpolate climate projections from coarse-resolution GCMs (100–200 km) to high-resolution grids (e.g. 1 km) and subsequently apply a basic bias adjustment, such as the delta method, combining these interpolated GCM projections with high-resolution observations to represent future climate conditions at kilometre-scale resolution, such as the WorldClim dataset. These high-resolution products appear attractive for many applications. However, despite their high resolution, they only reflect future climate change at the 100–200 km native resolution of the input GCMs, which can create a misleading impression of precision and confidence among users. Nevertheless, such datasets may be used in applications where “large-scale” GCM-based climate projections, interpolated to a high resolution with a basic bias adjustment, are acceptable. A critical concern with many similar datasets is that their limitations and associated uncertainties are not well documented, if documented at all, and are not communicated to potential users.

Dynamical downscaling uses RCMs driven by GCMs (Rummukainen, 2010). RCMs are computationally expensive and require substantially more resources than ESD, for example, to store the extensive set of driving boundary conditions from GCMs. However, in contrast to the ESD approach, RCMs can provide a larger number of variables in a physically consistent manner, including regional and local feedback that may be important in a changing climate. While RCMs are not as critically dependent on observations as ESD, observations are still very useful to improve the ability of RCMs to simulate past or present climate conditions. One advantage of dynamical downscaling is that high-resolution RCM outputs can be archived at sub-daily (e.g., 1 hour) or even at sub-hourly (e.g., 15 min) frequency for an RCM domain. Archiving the same high-frequency output at the same horizontal resolution globally is a challenge for GCMs. In turn, to generate similar high-frequency temporal outputs, ESD requires observations at the same frequency, which are either unavailable in many regions or available only for short periods that are insufficient for establishing an ESD method.

Dynamical downscaling has several limitations. RCMs, like GCMs, cannot always accurately simulate all physical processes and feedback, which can result in errors in the simulated climatology. Such errors are commonly called biases within the climate modelling community. Additionally, RCMs driven unidirectionally by GCM boundary conditions do not capture two-way interactions between regional and local processes simulated by RCMs and the large-scale or global processes simulated by GCMs. RCMs can develop their own internal variability and simulate large-scale climatology within their computational domain, which may deviate from that of the driving GCMs. This feature may be considered an advantage, as it allows RCMs to better represent large-scale processes while providing improved resolution of regional- and local-scale processes within the domain.

3. RESULTS FOR THE MASHREQ DOMAIN

Ensemble mean maps from RCM projections under the two scenarios (SSP2-4.5 and SSP5-8.5) for the periods 2021–2040 and 2041–2060 are presented here, compared with the baseline period 1995–2014. These same time periods were adopted by IPCC in AR6. Consistent with previous RICCAR reports, bias-adjusted RCM ensemble outputs are provided for temperature, precipitation and extreme events indices, while the remaining climate variables are based on the raw (non-bias-adjusted) modelling outputs.

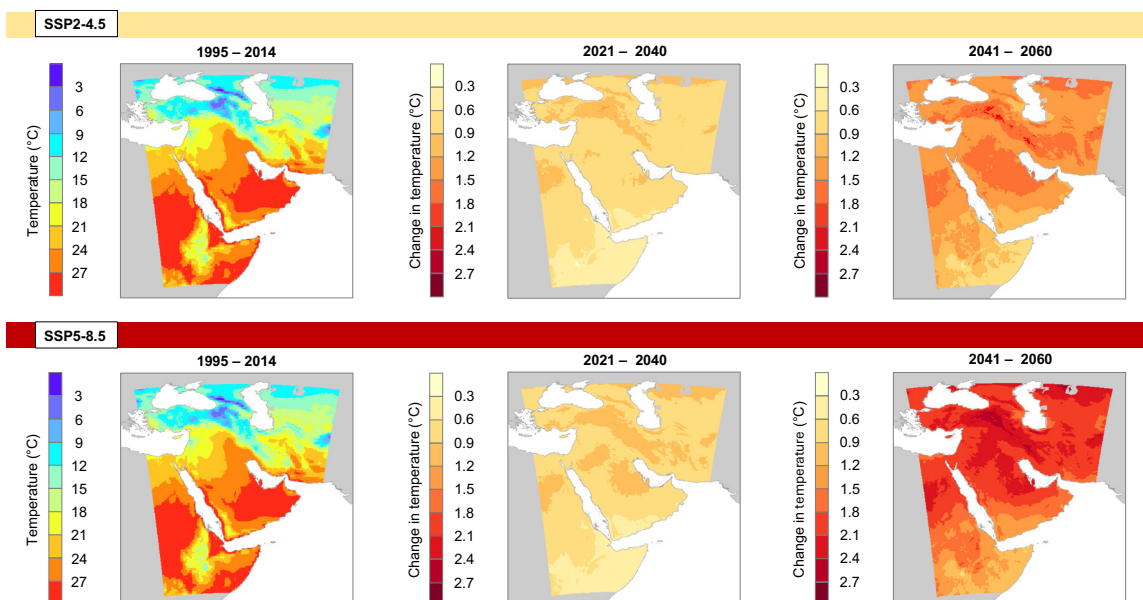
A. Temperature

Projected changes in annual mean temperature (figure 5) over the Mashreq Domain exhibit a similar spatial pattern, with warming of approximately 0.5°C to 1.0°C during 2021–2040 under both SSP2-4.5 and SSP5-8.5. The two scenarios begin in 2015 and are very similar in terms of radiative forcing for the first 10–15 years of the scenario period, resulting in almost the same warming magnitude and pattern across the domain. The magnitude of warming increases in 2041–2060, reaching up to 2.5°C in the central and northern parts of the Mashreq Domain under SSP5-8.5. Radiative forcing between the SSP2-4.5 and SSP5-8.5 scenarios diverges progressively after approximately 2030, with the stronger forcing under SSP5-8.5 explaining the greater warming in the SSP5-8.5 ensemble. The projected warming signal remains robust over the Mashreq Domain for both periods and scenarios.

Changes vary across the Domain because different parts of the region respond differently to global warming due to their geography, atmospheric dynamics, land-sea interactions and local climate patterns. For example, the southern part of the Domain along the South Arabian coast and the Horn of Africa shows less change in temperature than other areas. Coastal regions may warm more slowly but face increased humidity and heat stress. Conversely, northern and interior regions often show stronger warming due to continentality and low moisture. Mountainous areas may experience distinct seasonal shifts, affecting agriculture and water resources.

Although the general trends between the previously released Arab Domain ensemble (ESCWA and others, 2017) and the Mashreq Domain outputs are similar, there are some notable differences. For example, in certain areas, such as the lower

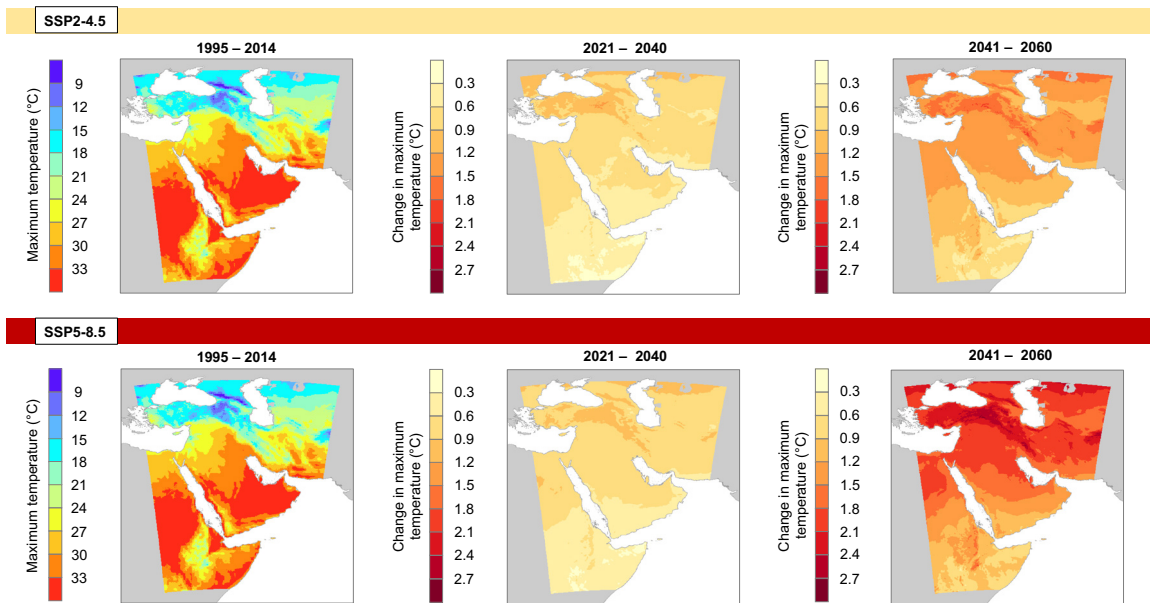
Figure 5. Change in mean annual temperature (bias-adjusted) for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

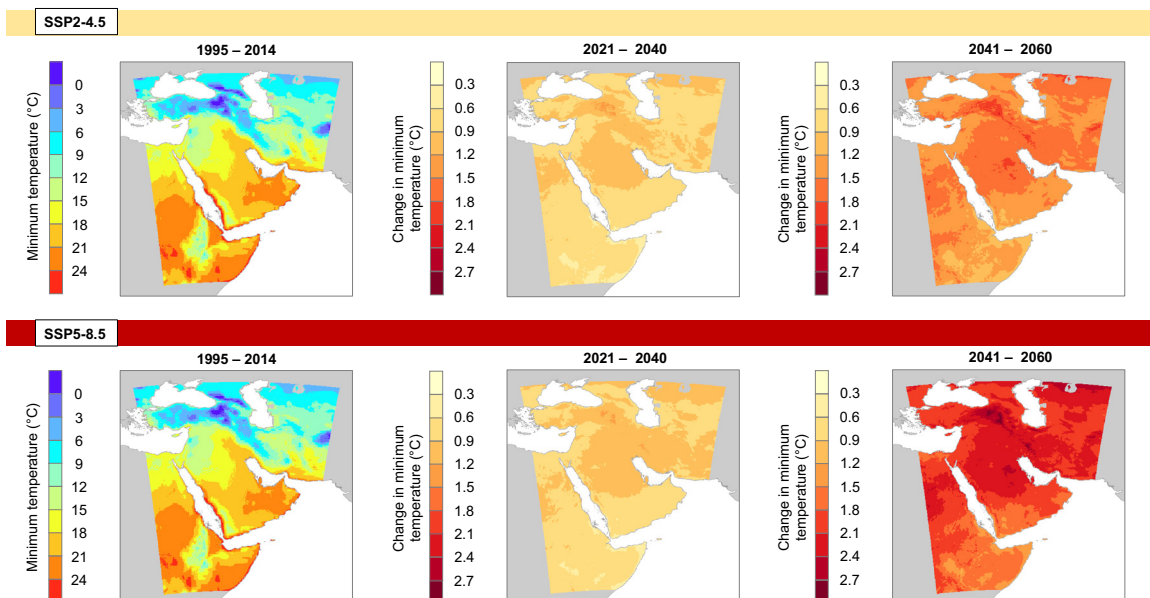
Euphrates and the upper and lower Tigris basins, the Arab ensemble projections show slightly weaker warming during the mid-term period (2041–2060) compared to the Mashreq ensemble. This difference can be attributed to several factors, including higher climate sensitivity of the CMIP6 GCMs used in the Mashreq ensemble compared to the CMIP5 models in the Arab projections, as well as the use of different climate scenarios in CMIP6 and CMIP5, and the use of different regional climate models to generate the Mashreq and Arab projections.

Figure 6. Change in annual maximum temperature (bias-adjusted) for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

Figure 7. Change in minimum annual temperature (bias-adjusted) for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

Similar to annual mean temperature, projected changes in annual maximum temperature have approximately the same spatial pattern and magnitude of warming in 2021–2040 under both SSP2-4.5 and SSP5-8.5 (figure 6). The magnitude of warming increases in 2041–2060, reaching up to 2.0–3.0°C in the central and northern parts of the Domain under SSP5-8.5. The projected warming signal in maximum temperature remains robust over the Mashreq Domain for both periods and scenarios, with the exception of a small spot in western Ethiopia in 2021–2040 under SSP2-4.5. This regional exception reflects the impact of natural variability, which may dominate the warming signal in the near-term future.

The spatial pattern and magnitude of annual minimum temperature changes in 2021–2040 are similar under both SSP2-4.5 and SSP5-8.5 (figure 7), with slightly larger areas experiencing the strongest warming (up to 1.5°C) under SSP5-8.5. The warming becomes more pronounced in 2041–2060, reaching 2.5–3.0°C in the central and northern parts of the Mashreq Domain and up to 2.0°C in the southern part of the Domain in the SSP5-8.5 ensemble. The projected warming signal in minimum temperature remains robust across the Mashreq Domain for both periods and scenarios.

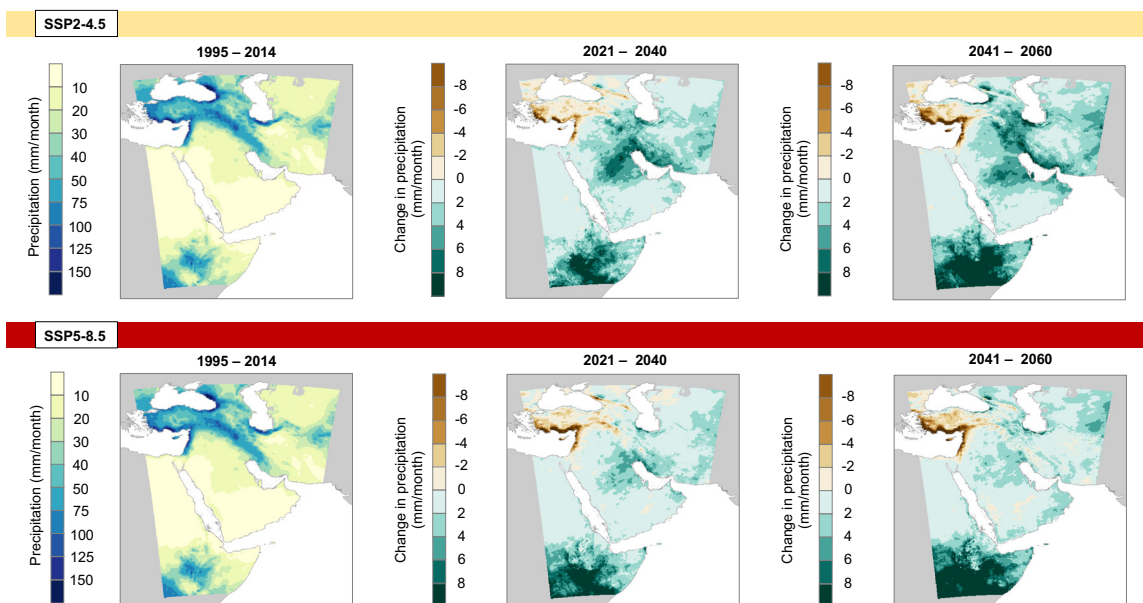
B. Precipitation

Hydrological variables, including precipitation, are best evaluated seasonally to capture shifts between the broadly defined wet winter period (October to March) and the dry summer period (April to September). Projected precipitation exhibits substantial variability on both decadal and multi-decadal timescales, with notable discrepancies among individual projections in some regions.

Seasonally, several small regional areas exhibit a robust increase in precipitation in October–March (figure 8) over the Arabian Peninsula and surrounding regions, including wetter conditions in Kuwait and areas to the west of Kuwait, during 2021–2040 under SSP2-4.5. However, this increase is not seen under SSP5-8.5 in 2021–2040 or 2041–2060 when radiative forcing is stronger under both scenarios. This near-term signal under the intermediate SSP2-4.5 scenario likely reflects strong internal precipitation variability rather than the impact of global warming.

A notable feature in both periods and under both scenarios is a significant increase in precipitation over Egypt, extending into the Sudan during 2041–2060 under SSP5-8.5. However, these increases in typically dry regions with few or no rainy

Figure 8. Change in seasonal mean precipitation (bias-adjusted) in October–March for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)

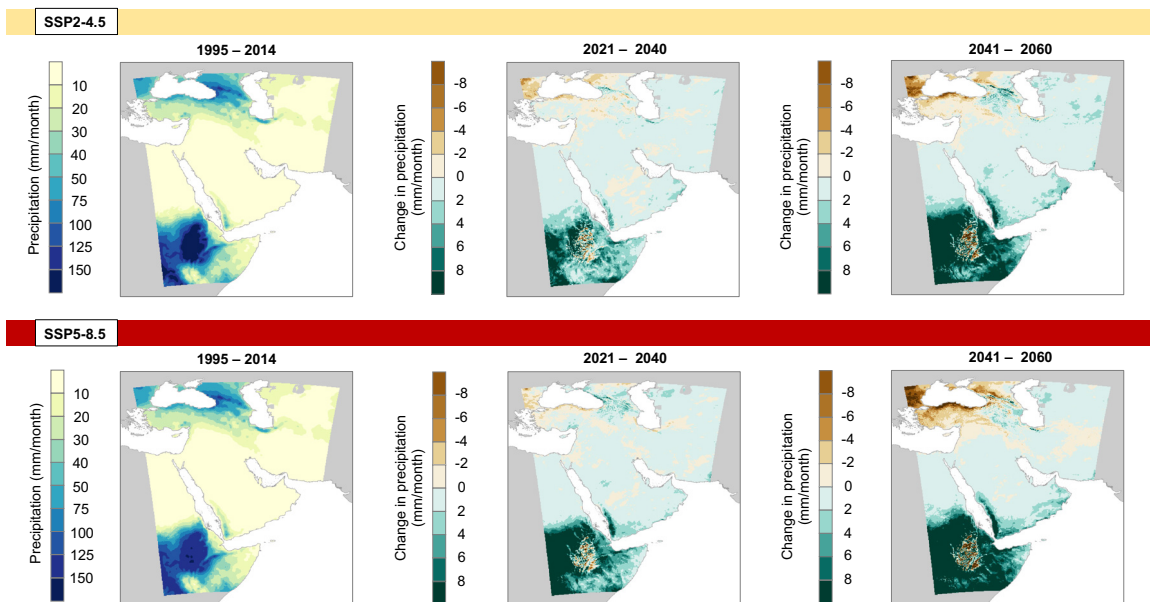


Source: Authors.

days should be interpreted with caution. For instance, even a small increase in precipitation over a dry region may result in a robust signal that is not necessarily relevant for many applications. Additionally, these results are based on bias-adjusted data, which can influence the climate change signal. Therefore, a detailed analysis is essential in these cases. Another notable feature is a robust increase in precipitation over Ethiopia, in the southern part of the computational domain, which gradually emerges from internal variability over time and becomes particularly pronounced in 2041–2060.

In April–September (figure 9), there is a tendency towards drier future conditions over the Eastern Mediterranean coast and Türkiye during both periods. However, as in the October–March period, this signal is not significant. Meanwhile, projected precipitation changes over the headwaters of the Euphrates and Tigris rivers vary across the Mashreq projections, mirroring the mixed signals found in the Arab Domain projections (ESCWA and others, 2017). In contrast, a robust increase in precipitation along the western coast of Yemen is evident as early as 2021–2040 under SSP5-8.5, gradually intensifying and extending to southern Yemen by 2041–2060 under the same scenario. This increase may be linked to changes in the northward migration of the Inter-Tropical Convergence Zone (ITCZ) rainbelt during the summer, which is also reflected in the projected wetter conditions over the Great Horn of Africa. Similar to the October–March period, a strong increase in precipitation over Egypt and the Sudan is evident as early as 2021–2040 under SSP2-4.5. However, such an increase in dry regions should be interpreted with caution and requires detailed regional analysis. A pronounced and robust increase in precipitation is also projected over western Ethiopia and South Sudan.

Figure 9. Change in seasonal mean precipitation (bias-adjusted) in April–September for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

C. Runoff

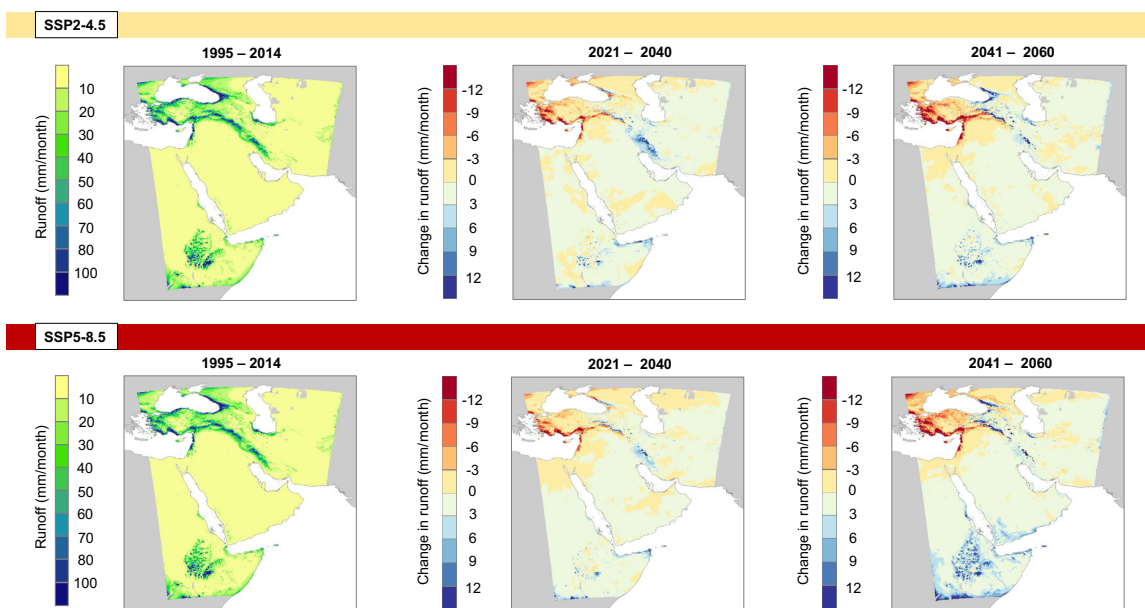
Total runoff is the total volume of water flowing from land into water bodies as a result of precipitation. It differs from discharge, which is the volume of water flowing through a river or wadi. Total runoff includes the following components:

- Surface runoff: water that flows over the land surface after rainfall.
- Interflow: water that infiltrates the soil and moves laterally towards stream channels.
- Base flow: groundwater that discharges into streams, particularly during dry periods.

Runoff, much like precipitation, displays significant decadal and multi-decadal variability. It is also presented seasonally.

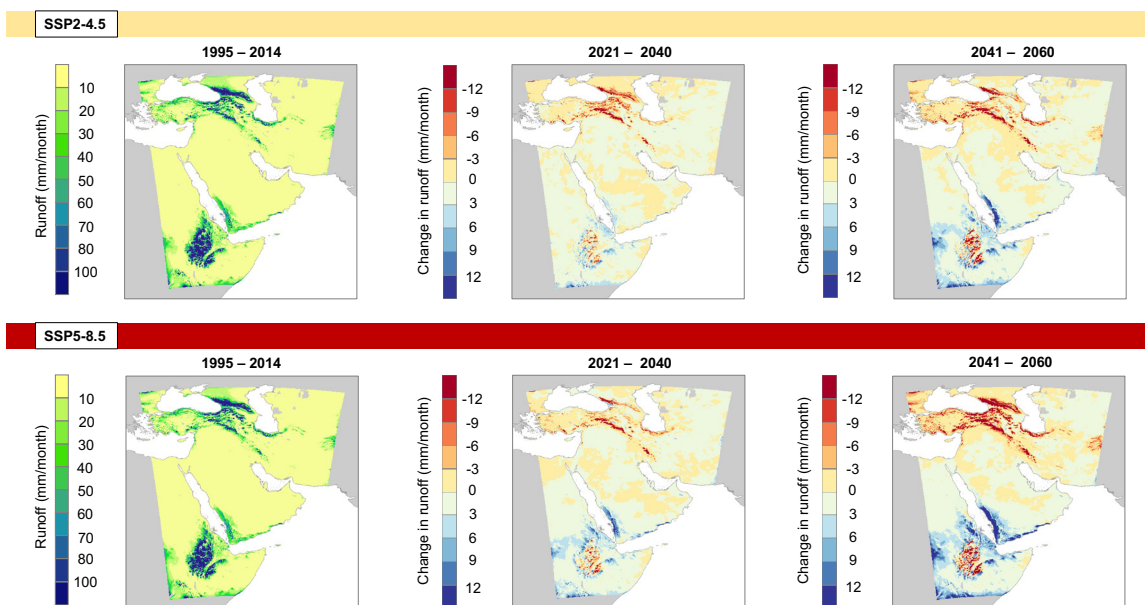
A common feature across both periods and scenarios is a pronounced decrease in runoff in October–March (figure 10) over the eastern Mediterranean coast and central and western Türkiye. However, this decrease only exhibits regional signs of robustness in 2041–2060 under SSP5-8.5. In contrast, runoff tends to increase across the rest of the Mashreq Domain, primarily in dry regions, with the largest area of robust signals appearing in 2041–2060 under SSP5-8.5.

Figure 10. Change in seasonal mean runoff in October–March for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

Figure 11. Change in seasonal mean runoff in April–September for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

Projected climate changes indicate a decline in runoff in April–September (figure 11) across the northern Mashreq region, with robust trends emerging during 2041–2060 under the SSP5-8.5 scenario. In contrast, runoff along the western coast of Yemen increased during 2021–2040, a trend expected to intensify and extend into southern Yemen by 2041–2060. Another notable feature is the pronounced and robust decrease in runoff in April–September for the Euphrates and Tigris headwaters under both scenarios, likely due to a decrease in winter snowpack.

It is important to note that runoff data presented in this report are direct outputs of a regional climate model and therefore contain inherent biases. Calibrated hydrological models that better represent hydrological details should be used to provide more insight into the impacts of climate change on runoff and river flows.

D. Evaporation

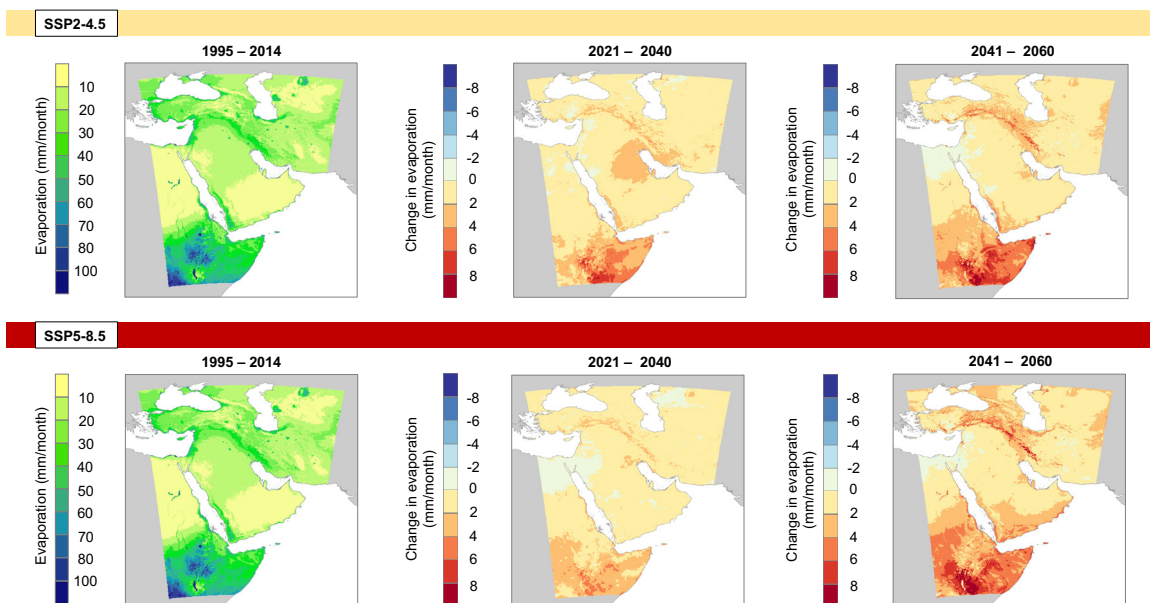
Evaporation specifically refers to the transfer of water from non-vegetated surfaces, including soil, lakes and wet ground, into the atmosphere. Evaporation is represented as part of the surface energy balance and hydrological cycle, and is often influenced by factors such as temperature, humidity, wind speed and solar radiation.

Evaporation differs from evapotranspiration, which encompasses evaporation as well as transpiration from plants and canopy interception loss. However, the two terms are sometimes used interchangeably in RCMs, where evaporation is assumed to implicitly include transpiration. This assumption is applied to the Mashreq Domain.

A common feature across the Mashreq Domain is an increase in evaporation in October–March (figure 12), with the first regional signs of robustness emerging as early as 2021–2040 under both scenarios, particularly in southeastern Türkiye. This trend intensifies by 2041–2060, with the robust signal expanding to cover larger areas, including the entire Tigris basin and the Great Horn of Africa.

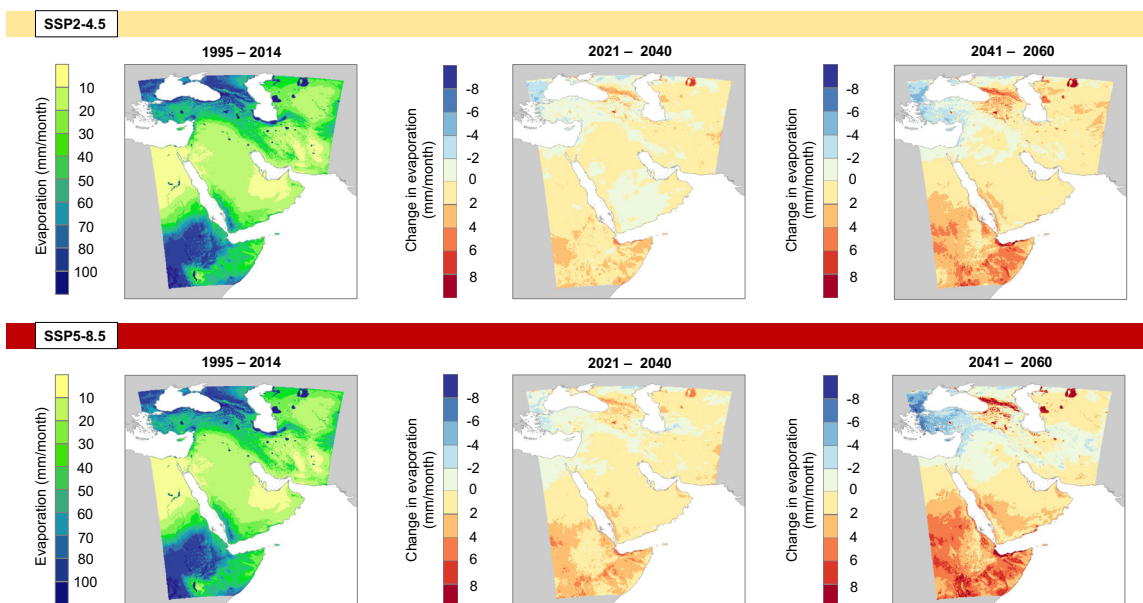
No significant changes in evaporation in April–September (figure 13) are projected for 2021–2040. However, by 2041–2060, under the SSP5-8.5 scenario, a notable decrease is expected over eastern and central Türkiye and eastern Mediterranean, despite rising temperatures, due to decreasing water availability in the hydrological cycle. A significant increase emerges elsewhere across the Domain, particularly in eastern Africa and the southern Arabian Peninsula.

Figure 12. Change in seasonal mean evaporation in October–March for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

Figure 13. Change in seasonal mean evaporation in April–September for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)

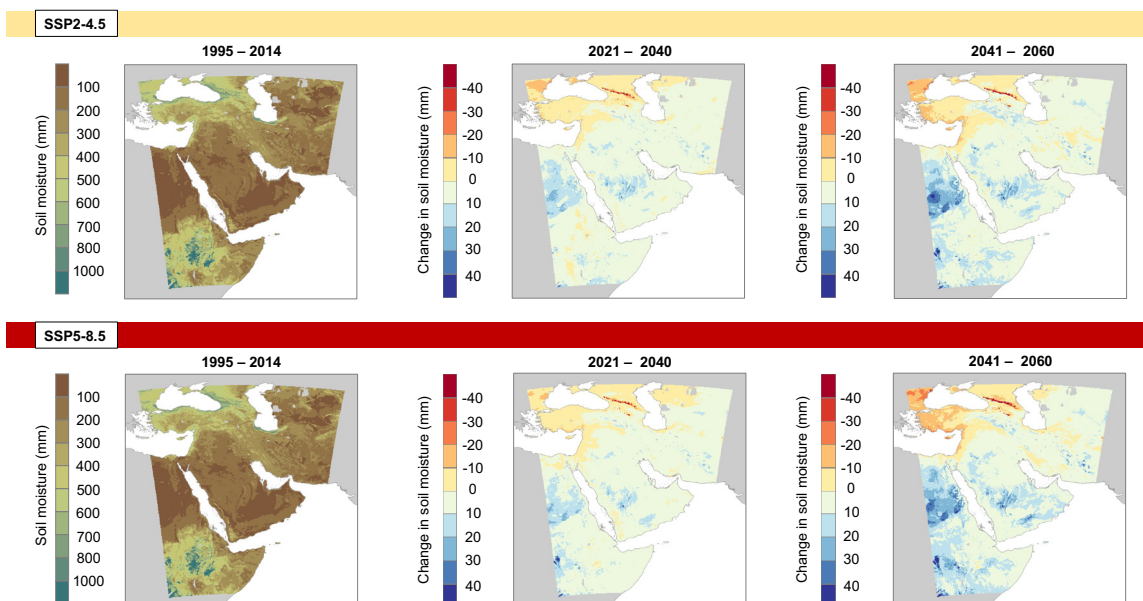


Source: Authors.

E. Soil moisture

Soil moisture is the amount of water retained in the soil at various depths and is a critical variable for simulating land-atmosphere interactions. It is closely linked to precipitation, often exhibiting similar patterns, and is affected by evaporation and runoff.

Figure 14. Change in seasonal mean soil moisture in October–March for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)

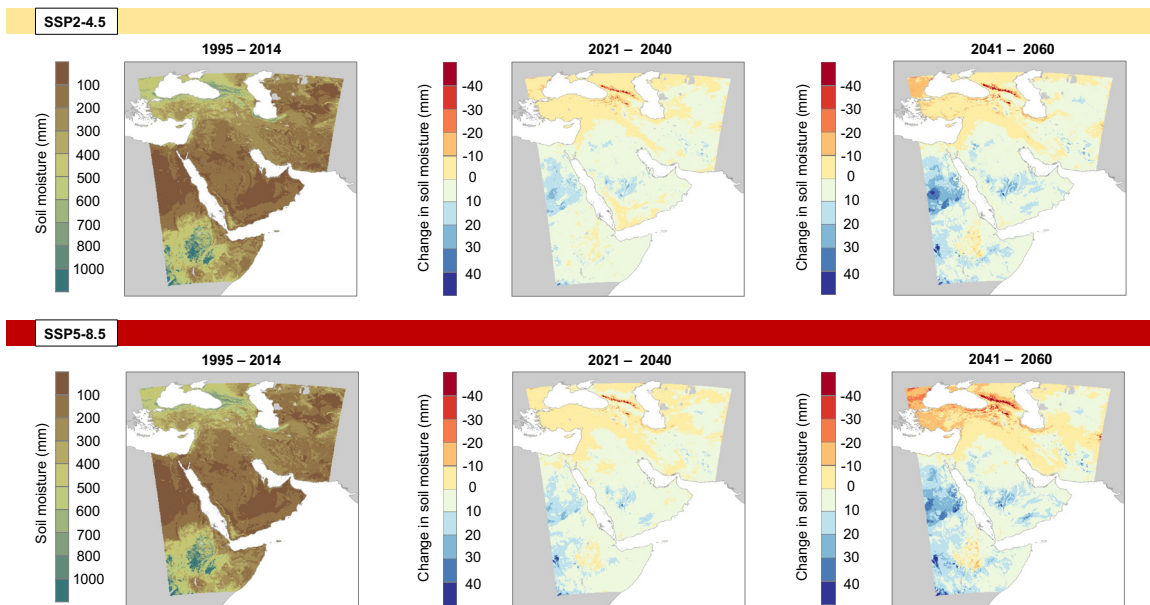


Source: Authors.

During the October–March season, soil is projected to become drier in the northeastern part of the Mashreq Domain (figure 14), with a robust decrease in soil moisture over eastern Türkiye during 2041–2060 under SSP5-8.5. The largest absolute and robust increase in soil moisture is expected over dry regions in Egypt and the Sudan for both periods and scenarios. Conversely, soil moisture is projected to increase over the southwestern Arabian Peninsula and eastern Africa by 2041–2060 under SSP5-8.5.

Projected changes in soil moisture in April–September (figure 15) generally mirror those of October–March. A robust decline is expected across all of Türkiye during 2041–2060 under SSP5-8.5, while a robust increase is projected in the dry regions of Egypt and the Sudan across both periods and scenarios. Soil moisture is expected to rise in the southeastern Arabian Peninsula and eastern Africa by 2041–2060 under SSP5-8.5.

Figure 15. Change in seasonal mean soil moisture in April–September for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

F. Dust uplift potential

Dust uplift potential (DUP) has been proposed as a dynamical proxy for predicting sand and dust storm activity in climate simulations. It can be calculated using wind speed coupled with soil moisture, vegetation cover and surface roughness. Based on a review of the scientific literature, the most suitable methodology calculates DUP using 10 m wind (Marshall and others, 2011):

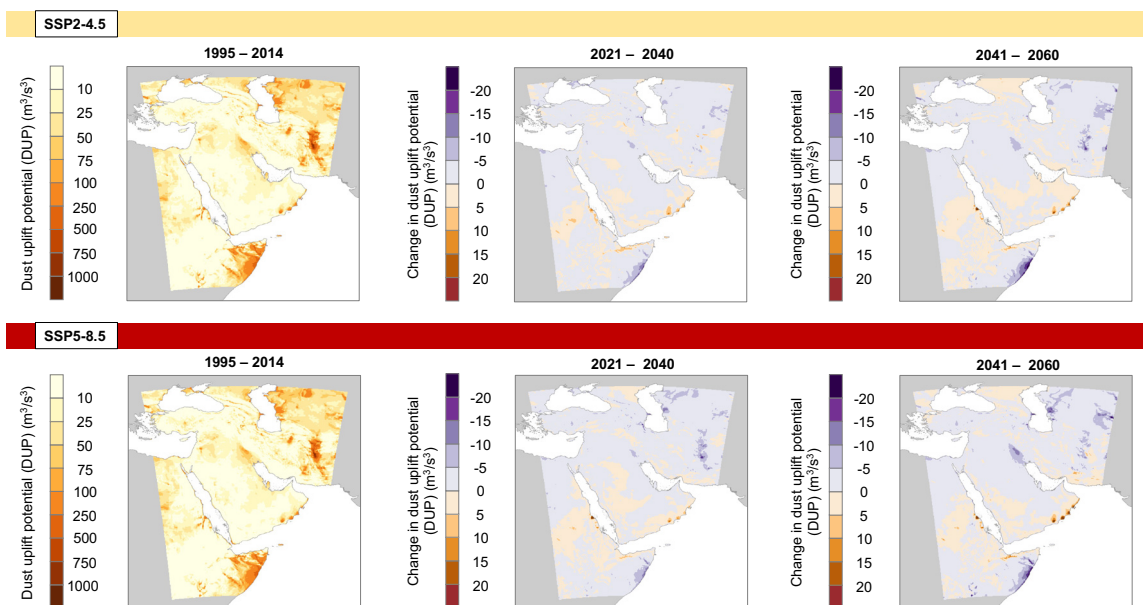
$$DUP = U^3 \left(1 + \frac{U_t}{U} \right) \left(1 - \frac{U_t}{U} \right)$$

where U is the 10 m wind and U_t is the threshold 10 m wind (7 m/s). If $U \leq U_t$, then DUP is equal to zero. The DUP index based on 1-hourly 10 m wind has been calculated for all 10 km Mashreq simulations.

RCM outputs do not project a robust change in DUP over much of the Mashreq Domain (figure 16), particularly in the near-term (2021–2040). However, localized changes emerge by mid-term (2041–2060), signalling an increase along the southern Arabian Peninsula coastline and a decrease over Kuwait and areas east of the Caspian Sea.

Due to the DUP calculation methodology, results are largely correlated with wind speed outputs. Additionally, because sand and dust storms are a complex phenomenon influenced by multiple climatic and environmental factors, the use of DUP as a proxy indicator for sand and dust storms should be approached with caution.

Figure 16. Change in annual mean dust uplift potential for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

G. Extreme event indices

Extreme event indices are metrics used to describe the frequency, intensity and duration of climatic extremes. The indices selected for this report are presented herein, while outputs from other indices are available on the RICCAR Regional Knowledge Hub. All indices were calculated using bias-adjusted temperature and precipitation outputs.

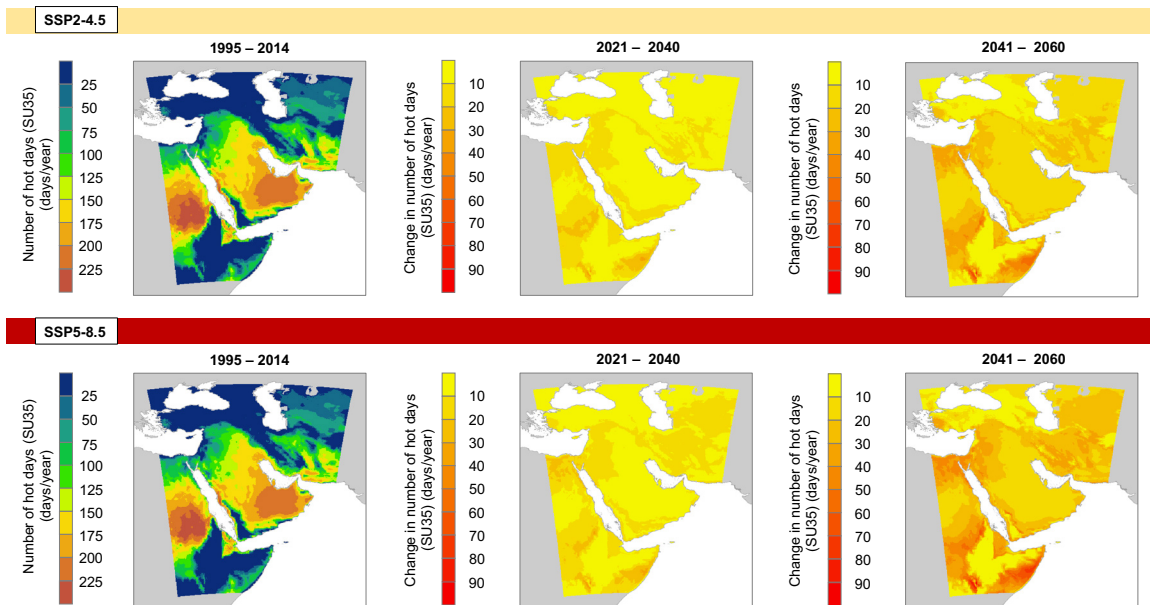
Projected climate changes in the number of hot days (SU35) indicate a robust increase in the number of hot days across the entire domain, with a small exception in southern Sudan during 2021–2040 (figure 17). This exception reflects strong natural variability, which dominates the 2021–2040 warming near the domain's boundaries. As expected, the increase in SU35 becomes more pronounced in 2041–2060 under the high-emission SSP5-8.5 scenario. Mountainous regions in Yemen, Türkiye and Ethiopia, which historically experience the fewest hot days, show the smallest projected changes. Even by 2041–2060 under SSP5-8.5, days with maximum temperatures above 35°C remain rare in these areas.

Projected changes in the number of tropical nights (TR) indicate a robust and gradual increase across the Mashreq Domain for both periods and under both scenarios (figure 18). The largest increase is expected during 2041–2060 under the high-emission SSP5-8.5 scenario. The smallest changes are found in regions already experiencing more than 300 tropical nights per year, such as the southeastern Arabian Peninsula and low-elevation tropics in Africa. In these areas, despite rising minimum temperatures, the number of tropical nights remains nearly unchanged, as most nights were already classified as tropical during the reference period.

Similar to precipitation, projections indicate a robust increase in very heavy precipitation days (R20) over Egypt as early as 2021–2040 under the intermediate SSP2-4.5 scenario (figure 19). This increase extends southward over time, becoming most pronounced in 2041–2060 under the high-emission SSP5-8.5 scenario. However, as with precipitation,

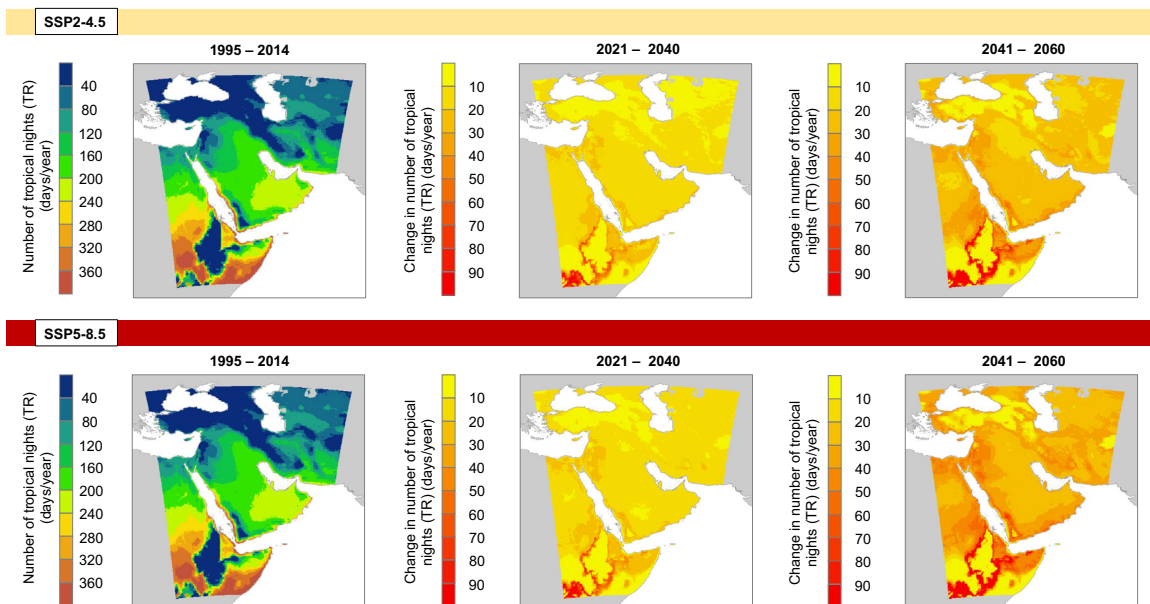
such a notable increase in 20 mm rainfall days over arid regions with few wet days should be interpreted with caution and requires detailed analysis. Across the rest of the domain, an increase in heavy precipitation days is generally expected, although these changes are mostly small and not statistically robust. The exception is southwestern Yemen, where a significant increase is projected for 2041–2060 under SSP5-8.5. Conversely, there are indications of a possible decrease in R20 along the Mediterranean coast, but this decrease is not robust.

Figure 17. Change in annual number of hot days (SU35) (bias-adjusted) for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



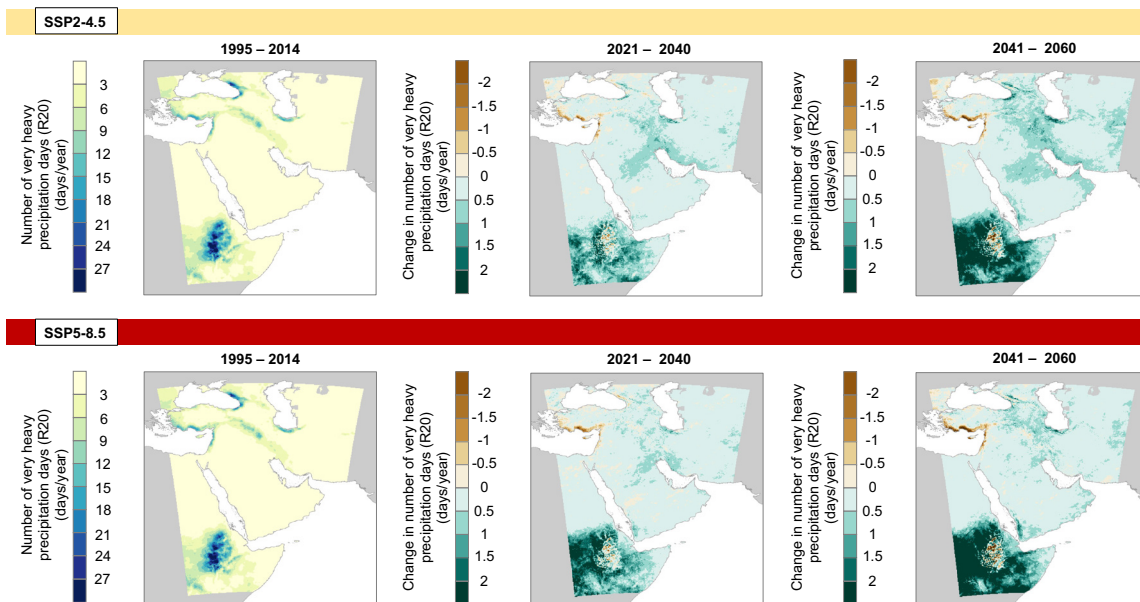
Source: Authors.

Figure 18. Change in annual number of tropical nights (bias-adjusted) for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

Figure 19. Change in annual number of very heavy precipitation days (R20) (bias-adjusted) for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

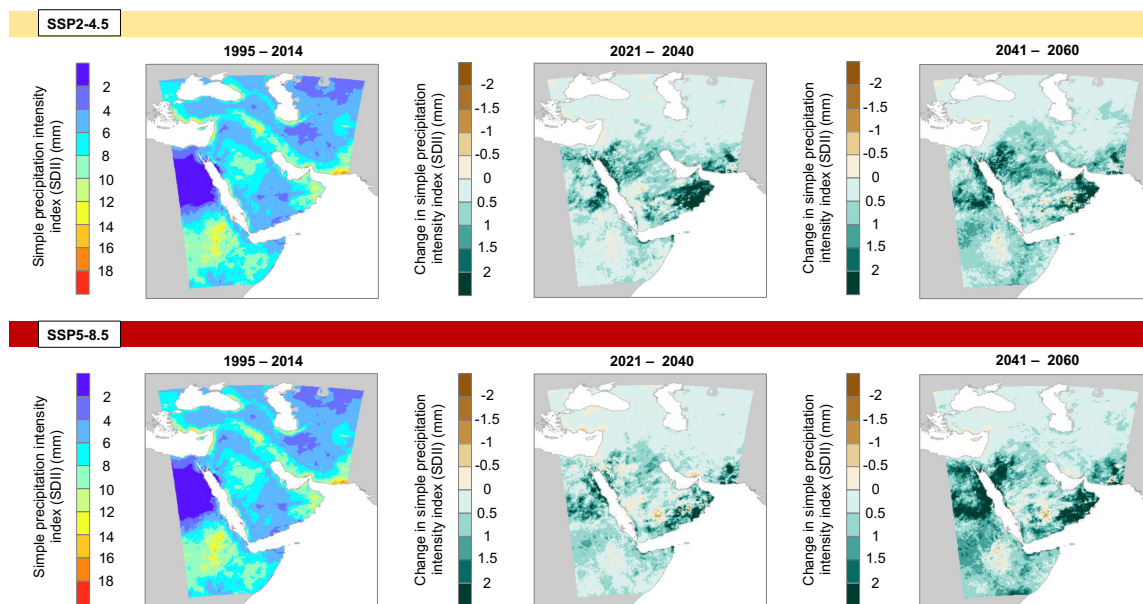
The simple precipitation intensity index (SDII) is the total sum of precipitation during wet days (days with >1 mm of precipitation) divided by the number of wet days during the same period. Results are equivalent to zero in locations with zero defined wet days. The index provides a simplified approach to evaluate projected changes in precipitation intensity.

SDII is projected to increase across almost the entire Mashreq Domain, with only a few isolated areas showing a decrease, although these declines are not statistically robust (figure 20). The most significant and robust increases are seen over the African part of the domain, particularly during 2041–2060 under the high-emission SSP5-8.5 scenario, consistent with trends seen in other precipitation-related metrics.

For the rest of the domain, a robust increase in SDII is evident over smaller regions, becoming more pronounced in 2041–2060 under SSP5-8.5. Notable areas of increase include parts of Türkiye and the coastal regions of southern and western Yemen. This widespread trend suggests that precipitation events will become more intense compared with the baseline period, even in regions where the number of wet days is projected to decline, such as Türkiye.

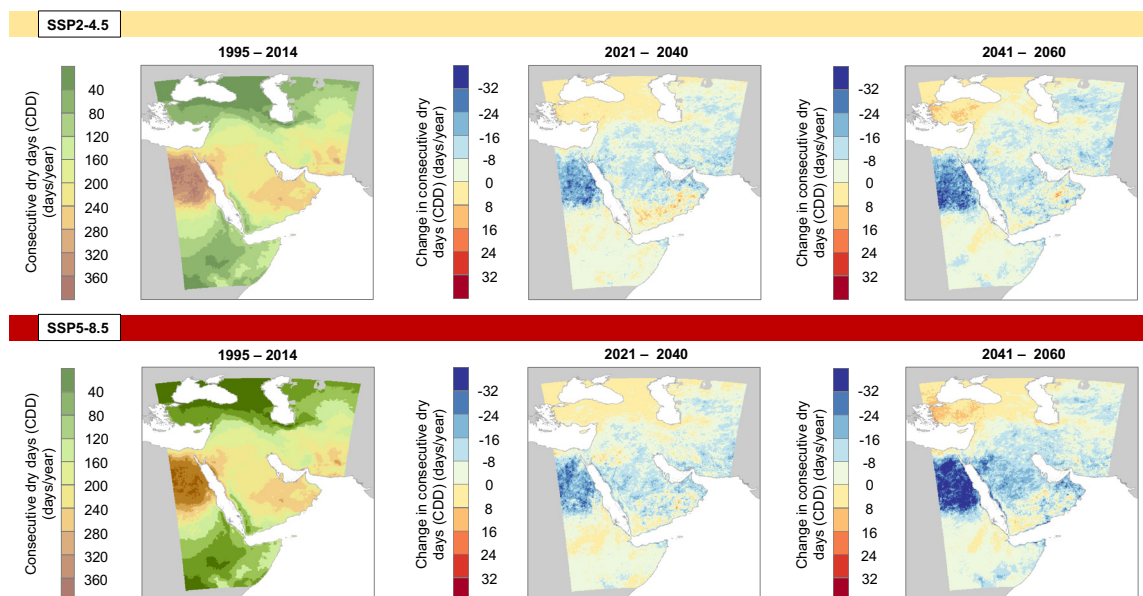
A robust decrease in the maximum length of dry spell (CDD) (previously referred to as consecutive dry days) is projected over Egypt for both periods and under both scenarios, with the largest decrease in 2041–2060 under SSP5-8.5 (figure 21). This is particularly noteworthy given that Egypt is a predominantly arid region, where the maximum length of dry spell exceeds 300 days per year in the reference period. There are indications of an increase in CDD over Türkiye, with a robust signal emerging locally during 2041–2060 under SSP5-8.5.

Figure 20. Change in simple precipitation intensity index (SDII) (bias-adjusted) for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

Figure 21. Change in annual maximum length of dry spell (CDD) (bias-adjusted) for near-term (2021–2040) and mid-term (2041–2060) compared with the baseline period (1995–2014)



Source: Authors.

4. CONCLUSION

An ensemble of high-resolution regional climate projections over the Mashreq Domain was generated using the HCLIM38-ALADIN regional climate model at a 10 km horizontal resolution. This ensemble is based on downscaling six GCMs from the latest CMIP6 projections under two climate change scenarios: SSP2-4.5 (an intermediate emissions scenario) and SSP5-8.5 (a high-emissions scenario).

These high-resolution projections provide more detailed regional climate change information compared to coarser resolution climate models, making them particularly valuable for assessing climate change impacts and for use in impact models. They are especially beneficial for analysing climate change in coastal and mountainous regions, where finer spatial details are crucial.

The first six regional climate simulations of the Mashreq ensemble under SSP5-8.5 were generated in 2020 and 2021 (SMHI and ESCWA, 2021). Subsequent work focused on extending the Mashreq SSP5-8.5 ensemble by downscaling the same six CMIP6 GCMs under the SSP2-4.5 scenario, allowing the consideration of a broader range of climatic futures. The Mashreq ensemble covers the 1961–2014 period of the historical CMIP6 experiment, with observed forcings, and the 2015–2070 period of the scenario experiment, with assumptions about future trajectories of key human-related drivers of the climate system.

Although some background information on the climate projections presented in this report is provided, additional documentation on bias adjustment and other details can be found in the complementary RICCAR technical note: Future climate projections for the Mashreq region: methodology (SMHI, 2021).

The Mashreq ensemble provides new high-resolution projections for the region, but it does not replace the projections produced for the Arab Domain. Results from the Arab Domain were developed to support regional cooperation, whereas the Mashreq ensemble provides additional information on possible outcomes. In general, for climate change assessments, a larger ensemble is preferred over a smaller one. Increasing the number of projections for any region enhances understanding of the range of possible outcomes over that region.

Climate is a complex system with many interacting processes, and the production of climate projections is a continuously evolving science at both global and regional scales. Numerous factors must be considered when processing and analysing a new ensemble of regional climate projections. This is particularly important when comparing the Mashreq Domain projections to those from the Arab Domain. These factors include the following:

- The domains are different, both in size and location.
- The resolution is different: 10 km for the Mashreq Domain and 50 km for the Arab Domain.
- The RCMs used are different: HCLIM38-ALADIN and RCA4.
- The driving GCMs are different (the latest CMIP6 GCM generation for the Mashreq Domain and the previous CMIP5 GCMs for the Arab Domain).
- The ensemble size is different: 6 projections under one scenario for the Mashreq Domain and 3 projections under one scenario for the Arab Domain.
- The climate change scenarios are different: the latest CMIP6 SSP scenarios for the Mashreq Domain and the previous CMIP5 RCP scenarios for the Arab Domain.
- The techniques for bias adjustment have been further developed.
- The Mashreq Domain focuses on the near- and mid-term future (2021–2040 and 2041–2060) and does not include late-century results, where the climate signal may be more pronounced.

When comparing new results with previous ones, differences are expected to emerge. It is important to consider the influencing factors and to identify areas where robust signals can be detected. Temperature trends from different model simulations are generally easier to interpret, whereas precipitation and runoff are considerably more variable, typically exhibiting a wider range of responses depending on model setups and forcing conditions.

It is widely recognized that climate model projections cannot always be used directly, and that adjustment to the observed climatology is necessary. Bias adjustment has become an integral part of the pre-processing of climate simulations for use in impact modelling studies or for the calculation of climate change indicators that rely on absolute thresholds. Most of the summary outcome results presented in this report are based on the bias-adjusted variables of temperature and precipitation. Bias adjustment does not aim to improve climate projections but rather to reduce, to some extent, deviations of climate model data from the observed climate.

Unlike the Arab Domain, projections over the Mashreq Domain do not include regional hydrological modelling. Therefore, this report presents runoff, evaporation and soil moisture directly derived from the RCM outputs. These results should only be interpreted as indicative of trends. Further studies using calibrated hydrological models are needed to provide more detailed information, such as the magnitude of hydrological changes in specific areas.

Projected climate changes over the Mashreq Domain for both the near-term period 2021–2040 and the mid-term period 2041–2060 are presented in this report in relation to temperature, precipitation, runoff, evaporation, soil moisture and five extreme event indices. The indices are the same indices used for the first overview analysis of the Mashreq ensemble under SSP5-8.5 (SMHI and ESCWA, 2021) and represent only a subset of the established indices serving as examples for such analyses.

All Mashreq simulations consistently project a robust increase in future temperatures across the region compared to the 1995–2014 baseline period. In the near-term (2021–2040), the magnitude of warming reaches up to 1°C, with a similar spatial pattern under both SSP2-4.5 and SSP5-8.5, as the scenarios exhibit comparable radiative forcing during this period. The magnitude of warming increases in the mid-term (2041–2060), as the radiative forcing between the two scenarios starts to diverge progressively, and reaches up to 2°C under SSP2-4.5 and up to 2.5°C under SSP5-8.5 over the central and northern parts of the domain.

The southern part of the domain, including the South Arabian coast and the Horn of Africa, is projected to experience smaller temperature changes compared to other regions. In certain areas, such as the lower Euphrates and the upper and lower Tigris basins, the Arab ensemble projections show slightly weaker warming during the mid-term period (2041–2060) compared to the Mashreq ensemble. This difference can be attributed to several factors, including higher climate sensitivity of the CMIP6 GCMs used in the Mashreq ensemble compared to the CMIP5 models in the Arab projections, as well as the use of different climate scenarios in CMIP6 and CMIP5, and the use of different regional climate models to generate the Mashreq and Arab projections.

Projected precipitation exhibits substantial variability on both decadal and multi-decadal timescales, with notable discrepancies among the individual projections in some regions. Similar to the earlier Arab Domain projections, there is no clear consensus on robust, widespread increases or decreases in precipitation across the entire region. However, several sub-regions with robust projected changes in precipitation can be identified. For instance, the Mashreq projections indicate a trend towards drier future conditions along the Eastern Mediterranean coast and in central and western Türkiye, though a robust signal is seen only over small areas in 2041–2060 under the SSP5-8.5 scenario. Meanwhile, projected precipitation changes over the headwaters of the Euphrates and Tigris rivers vary across the Mashreq projections, mirroring the mixed signals found in the Arab Domain projections. Certain regions, notably parts of Egypt and the Sudan, exhibit a robust increase in precipitation over drylands or deserts during both winter and summer, evident as early as 2021–2040 under the SSP2-4.5 scenario.

This robust increase in precipitation over dry regions with a few rainy days and small amounts of precipitation should be interpreted with caution and requires further analysis. Under the SSP5-8.5 scenario, a robust increase in April–September seasonal precipitation is already evident along the western coast of Yemen during 2021–2040, extending to the southern coast of Yemen by 2041–2060. This projected increase may be linked to changes in the summertime northward migration of the Inter-Tropical Convergence Zone (ITCZ) rainbelt, which is also reflected in the projected wetter conditions over the Great Horn of Africa.

Runoff and other hydrological variables also exhibit considerable decadal and multi-decadal variability. Nevertheless, the Mashreq ensemble projects an increase in runoff during April–September along the Southwestern Arabian coast, which is already evident during 2021–2040. The increase becomes more robust over time and extends to southern Yemen in 2041–2060 under the SSP5-8.5 scenario. A pronounced and robust decrease in April–September runoff is projected for the Euphrates and Tigris headwaters under both the SSP2-4.5 and SSP5-8.5 scenarios. Runoff data in this report are based on direct outputs from a regional climate model and therefore contain inherent biases. Calibrated hydrological models that more accurately represent hydrological details should therefore be used to provide deeper insight into the impacts of climate change on runoff and river flows in the Mashreq region.

Results presented in this report provide only an overview of climate change trends from the Mashreq Domain ensemble for a few selected indicators. Primary output variables from the modelled climate projections are available in the RICCAR Regional Knowledge Hub for further analysis. Regional researchers who work with impact studies can use the Mashreq projections to carry out additional work that considers specific sectors in more detail, such as hydrological, agricultural or health impact studies.

Many users of the Mashreq Domain projections are primarily interested in the bias-adjusted simulations, as these can provide more realistic results for the historical period, which in turn are consistent with the results that the impact models will produce for the future period. Bias-adjusted results should also be used for analysing indicators or indices based on threshold values, such as rainfall exceedance or temperature indices.

It is important to note that differences can arise between the change values produced by raw and bias-adjusted projections. The influence of bias adjustment on climate change results is well-recognized and not unique to this region (IPCC, 2015). In addition to the bias adjustment methods applied, the choice of reference dataset for observed climate can also affect bias-adjusted outcomes. While the best available observations and techniques are used in assembling these datasets, their quality and resolution at regional and local scales remain important factors, particularly over data-sparse regions such as the Arabian Peninsula. Bias adjustment represents an additional source of uncertainty in projection results, with the extent of its influence depending, to some degree, on the intended application.

When reviewing the results presented in this report, it is important to note that the reference periods used are different from those presented in the Arab Domain main report (ESCWA and others, 2017). The latter used the 1986–2005 reference period adopted by AR5. The Mashreq Domain uses the reference period 1995–2014 as presented in AR6. Thus, projected temperature changes vary depending on the reference period used.

The primary purpose of this report is to provide an overview of summary outcomes from the Mashreq Domain climate modelling work. While the report includes selected example analyses from the Mashreq climate projections, it is not intended to provide a comprehensive assessment of results for the domain. Rather, it serves as a background document to support evidence-based analysis and inform regional action. Additional analyses and datasets from the regional climate projections and ensemble outputs for both scenarios are available on the RICCAR Regional Knowledge Hub.

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The present technical report, prepared under the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR), presents regional climate modelling and analysis done to produce high-resolution climate projections over the Mashreq region. Led by the Swedish Meteorological and Hydrological Institute in collaboration with ESCWA, the report summarizes the outcomes derived from an ensemble of regional climate simulations produced at a 10 km resolution, based on the downscaling of six CMIP6 global climate models under two scenarios: SSP2-4.5 and SSP5-8.5.

The Mashreq Domain ensemble spans the period 1961–2070, with an emphasis on near-term (2021–2040) and mid-term (2041–2060) conditions, analysed against a 1995–2014 reference period. Temperature and precipitation outputs, and related extreme indices, are presented using bias-adjusted datasets to support climate impact studies related to the water and agricultural sectors.

