ECONOMIC AND SOCIAL COMMISSION FOR WESTERN ASIA (ESCWA)

ASSESSING THE IMPACT OF CLIMATE CHANGE ON WATER RESOURCES AND SOCIO-ECONOMIC VULNERABILITY IN THE ARAB REGION:

A METHODOLOGICAL FRAMEWORK FOR PURSUING AN INTEGRATED ASSESSMENT

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ABBREVIATIONS

ACSAD	Arab Center for the Studies of Arid Zones and Dry Lands
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
BHM	Basin-centred hydrological model
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
CSN	Climatological standard normals
DEM	Digital Elevation Model
ECV	Essential Climate Variable(s)
ENSO	El Niño-Southern Oscillation
ESCWA	United Nations Economic and Social Commission for Western Asia
FAR	IPCC First Assessment Report
GCOS	Global Climate Observing System
GHG	Greenhouse gases
GIS	Geographic information system
GCM	Global climate model
IM	Integrated mapping
ITCZ	Inter-Tropical Convergence Zone
IPCC	Intergovernmental Panel on Climate Change
LBC	Limiting boundary conditions
RCM	Regional climate model
RCD	Regional climate downscaling
RCP	Representative concentration pathway
RCOF	Regional Climate Outlook Forum
RHM	Regional hydrological model
SAR	IPCC Second Assessment Report
SRES	Special Report on Emissions Scenarios
TAR	IPCC Third Assessment Report
UNEP-ROWA	United Nations Environment Programme Regional Office for West Asia
UNFCCC	United Nations Framework Convention on Climate Change
VA	Vulnerability assessment
WMO	World Meteorological Organization

Introduction

The Arab region currently faces major water challenges related to the sustainable management of water resources and the delivery of water services for domestic, agricultural and industrial use. Climate change and climate variability can increase the risks and the costs of water resources management, impact the quantity and quality of water resources, and generate secondary effects that influence socio-economic vulnerability and environmental sustainability. A clear understanding of these risks and impacts is necessary to inform policy formulation and decision-making in support of efforts to achieve sustainable development in the Arab region.

Studies indicate that climate change is already underway. Early in the twentieth century there were already concerns that the climate was changing and that such changes were occurring because of the effect of human activity on the Earth's climate. However, these concerns remained unverified until the advent of powerful computer models in the 1970s that could represent complex interactions that influence the Earth's systems. Improved research, assessment and monitoring of natural phenomenon also increased scientific understanding of the contribution of human activity to the climate and climate variability.

By the end of the century, it became evident that global temperatures had increased over the last 150 years, and that this increase was dynamically changing climate patterns and the sustainability of land, marine and freshwater systems. While understanding the causes of these changes is an integral part of the global scientific and political debate, the urgent challenge facing the Arab region is to assess and adapt to these changes within the context of specificities, conditions and constraints that characterize the Arab region.

Such efforts must be firmly grounded in informed analysis and regional assessment of the impact of climate change on water resources now and in the future. This is achieved by applying a scientifically rigorous and regionally grounded methodology based on a shared set of assumptions and scenarios for generating data that are comparable across Arab countries. This in turn can forge a common understanding of the impact of climate change on water resources and foster regional dialogue and policy formulation to address socio-economic vulnerability and sustainable development in the Arab region.

1. *Justification for an Arab regional assessment on climate change and water*

To date, no study has been conducted to assess the impact of climate change on water resources in the Arab region as a geopolitical and geospatial unit using regional climate modelling and hydrological modelling tools. Additionally, no effort has been made to conduct an integrated assessment of the impact of climate change on freshwater resources and socio-economic vulnerability across Arab countries based on a common methodological framework. The previous four assessment reports issued by the Intergovernmental Panel on Climate Change (IPCC) were largely based on the outputs of global circulation models that modelled the global climate, and their analysis related to Arab countries was segmented between the Asian and African continents. Furthermore, IPCC findings that reference selected Arab countries and subregions were drawn from studies printed in peer reviewed journals that base their analysis largely on the magnification of coarse-resolution GCMs or the consolidation of disparate climate models conducted at the national or subregional level that were carried out using different models and assumptions.

As such, subregional and national studies involving selected Arab countries do not provide a comprehensive picture of the Arab region that is comparable across countries. Findings cannot be simply pieced together to provide a complete picture for the Arab region given differences in methods, models, scenarios, assumptions and data used for generating climate change projections and determining associated hydrological impacts. This is because most of these subregional and national studies simply magnify the outputs of **global climate models** (GCMs) to the regional or national scale without enhancing their resolution or introducing additional parameters that are normally incorporated in **regional climate models** (RCMs). GCMs and RCMs are also rarely attached to hydrological models, and have thus only offered coarse results related to the projected impacts of climate change on freshwater resources. This is problematic since the Arab region is characterized by water scarcity and is largely dependent on shared surface water and groundwater resources. Compared to other parts of the world, relatively small impacts on water resources in Arab countries can result in dramatic socio-economic and environmental consequences.

Conducting a regional assessment and considering specificities related to water resources are important steps towards informed intergovernmental dialogue, priority-setting and positioning on climate change impacts on water resources. River basins are not defined by political boundaries; surface and groundwater resources in the Arab region often cross international frontiers. Accordingly, climate change impact assessments on water resources in the Arab region need to consider the origins and flow of water resources in a transboundary context if the interactions between climate and hydrological systems are to be appropriately reflected. These interactions cannot be represented in a national assessment without drawing information from GCM or RCM. An Arab regional climate model and **regional hydrological model** (RHM) will provide the basis from which national and basin level assessment can be conducted based on dynamics affecting the regional climate and hydrological systems. Regional assessments can also set common assumptions, scenarios and development pathways to ensure consistency in the manner in which climate change projections are generated and applied to assess the impacts on freshwater systems across the Arab region. The resulting projections in turn provide the basis for identifying regional vulnerability hotspots and priorities for coordinated action on climate change adaptation.

2. *Origins of the Regional Initiative for the Assessment of the Impact of Climate Change on Water Resources and Socio-Economic Vulnerability in the Arab region*

In December 2007, the Arab Ministerial Declaration on Climate Change adopted by the Council of Arab Ministers Responsible for the Environment called for the development and dissemination of methodologies and tools that assess the impact of climate change to support the formulation of adaptation measures that are fully consistent with economic and social development goals. In response to this call, the twenty-fifth session of the United Nations Economic and Social Commission for Western Asia (ESCWA) adopted a resolution in May 2008 requesting the preparation of an assessment of the vulnerability of economic and social development to regional climate change, with particular emphasis on freshwater resources. In January 2009 the Arab Summit for Economic and Social Development accepted the preparation of a project to assess the impacts of climate change on water resources in the Arab region, and called for the preparation of a water security strategy for the Arab region. The ninth sectoral meeting of the League of Arab States, the United Nations and their specialized organizations held in Cairo in June 2009 focused on climate change and recommended the preparation of a joint assessment of vulnerability to climate change and its impact on water resources.

A conceptual framework for preparing the regional assessment was subsequently outlined during the expert group meeting Towards Assessing the Vulnerability of Water Resources to Climate Change in the Arab Region. The meeting was convened by the League of Arab States, ESCWA, the United Nations Environment Programme Regional Office for West Asia (UNEP-ROWA) and other partners in Beirut in October 2009. The framework was based on the following four pillars:

(a) Baseline review;
(b) Climate change impact analysis and vulnerability assessment;
(c) Awareness-raising and information dissemination;
(d) Capacity-building and institutional strengthening.[1]

A project brief including the components of the aforementioned conceptual framework was subsequently drafted by ESCWA and finalized following consultation with the meeting participants and a core group of partners in early 2010. Under the auspices of the League of Arab States Secretariat, the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD) subsequently submitted an Arabic version of

[1] ESCWA (2010a).

the project brief to the Arab Ministerial Water Council. The Council approved the project at its second session held in Cairo in July 2010 as a means to support integrated water resources management in the region and the implementation of its Arab Water Security Strategy.

Commitment and support for the project was further articulated by Arab member States as well as United Nations and the League of Arab States organizations at the expert group meeting on the Development of a Vulnerability Assessment for the Arab Region to Assess Climate Change Impacts on the Water Resources Sector in November 2010, which was hosted by ESCWA and the League of Arab States in Beirut in November 2010. This meeting transformed the project into the Regional Initiative for the Assessment of the Impact of Climate Change on Water Resources and Socio-Economic Vulnerability in the Arab Region. The Regional Initiative is comprised of various activities and components supported by different partner organizations. At the meeting, agreement was reached on the following parameters for implementing the Regional Initiative:

(a) The geographic scope of the regional assessment will be based on the delineation of an Arab Domain that will serve as the basis for running one or more RCMs;

(b) The RCMs will be based in large part on downscaling from GCMs;

(c) The climate change projections and outputs from one or more RCM will serve as the basis for generating an analysis of hydrological impacts;

(d) Socio-economic vulnerability to the impacts identified through the climate modelling and hydrological modelling components will be cross-sectoral in nature;

(e) Vulnerability hotspots will be identified through geospatial referenced maps of the Arab region; overlays could be used to conduct spatial analysis across different vulnerability parameters;

(f) Regional stakeholders, policy advisors, governmental decision makers partner organizations will be involved in capacity-building activities through different project components;

(g) Consultations will be regularly organized with regional stakeholders to discuss methods and preliminary findings at each stage of the assessment process.[2]

Based on the above, the Regional Coordination Mechanism through its Thematic Working Group on Climate Change, which is coordinated by UNEP-ROWA, mandated ESCWA to lead the implementation of the Regional Initiative in November 2010. The Regional Initiative was then further endorsed by the ESCWA Committee on Water Resources during its ninth session in March 2011. The Arab Ministerial Water Council at its third session held in Cairo in June 2011 received an update from ACSAD regarding the Regional Initiative and its role in assessing the impact of climate change on available water resources in the Arab region within the context of follow-up on the projects approved within the framework of the Arab Water Security Strategy.

The proposed methodological framework for implementing the Regional Initiative was discussed and endorsed at the expert group meeting on Assessing Climate Change Impacts on Water Resources and Socio-Economic Development in the Arab Region, which was organized by the League of Arab States, ESCWA and UNEP-ROWA in Beirut in July 2011. Donor and inter-agency commitments to support the Regional Initiative were announced during the meeting, and several scientific research institutions also expressed interest in collaboration. The expert group meeting resulted in the following findings and recommendations related to the impact assessment and vulnerability assessment component of the initiative:

(a) Models should be selected and fine-tuned to account for regional specificities, including wadis, sand storms, dust storms, deserts, salt water intrusion, salinity of water and land resources, palm trees, etc.;

[2] ESCWA (2010b).

(b) Most GCMs have too coarse a resolution to examine climate change effects at the regional, national or local level, and thus can be enhanced through the application of RCMs;

(c) RCMs provide an additional source of information for supporting national modelling efforts and can provide feedback for improving GCM outputs;

(d) RHMs that build upon RCM outputs can provide more detailed results on the impact of climate change on water resources;

(e) The results from multimodel ensembles reduce uncertainty associated with climate modelling outputs and hydrological modelling, including those of RCMs and RHMs;

(f) Climate change projections conducted within the framework of the Regional Initiative will be based on one or more representative concentration pathway (RCP), newly developed by IPCC for its Fifth Assessment Report (AR5), rather than those included in its Special Report on Emissions Scenarios (SRES), which were used as the basis for generating projections in its two previous assessment reports.

These recommendations and those resulting from the previous expert group meetings organized within the framework of the Regional Initiative, have contributed to the preparation of this methodological framework for assessing the impact of climate change on water resources and its associated implications for socio-economic vulnerability in the Arab region.

As coordinator of the Regional Initiative, ESCWA is working with Arab Governments, United Nations organizations, the Secretariat of the League of Arab States and its specialized organizations, international and regional institutions, donors, and research centres to implement the Initiative based on its four pillars and agreed upon structure. In support of this implementation process, this document presents the framework for preparing the climate change impact analysis and the vulnerability assessment components of the Regional Initiative based on an integrated assessment methodology. This document elaborates on the five constituent components of conducting an integrated assessment of the impact of climate change on water resources and the effect of those impacts on socio-economic vulnerability in the Arab region.

This integrated assessment methodology is based upon simulating climate change scenarios using various modelling and assessment tools, including: (a) GCMs, (b) RCMs, (c) RHMs, (d) socio-economic vulnerability assessment (VA), and (e) integrated mapping (IM), which are elaborated in the following chapters. These components draw upon various disciplines to present regional findings and foster regional dialogue, support regional contributions to global forums, establish a regional knowledge base, and inform Arab countries about common issues of concern to support action on climate change adaptation.

I. METHODOLOGICAL FRAMEWORK

A. Understanding integrated assessment

The Arab Water Security Strategy prepared under the auspices of the Arab Ministerial Water Council identifies climate change as one of the key challenges to sustainable development in the Arab region, and one of the major threats to water security.[3] Climate change exacerbates water-related socio-economic variables in the Arab region, which are already affected by unsustainable production and consumption patterns. High population growth rates, increased socio-economic activity in urban areas, overuse of water in agriculture, and reduced water quality due to pollution and salinity have increased pressure on scarce water resources. Dependence on shared water resources, particularly water resources originating from outside the Arab region, complicates management decisions and the formulation of responses to climate change.

The nexus between climate change, water resources management and food security justifies the preparation of an integrated assessment of the impact of climate change on water resources in the Arab region. The aim of the assessment is not only to identify the impacts of climate change on freshwater resources, but also the primary and secondary implications these pose for socio-economic vulnerability and sustainable development. An integrated assessment achieves this by using projections generated by climate change and hydrological impact assessment models to prepare socio-economic vulnerability assessments and identify vulnerability hotspots.

The integrated assessment pursues scientific analysis and informs policy development. It relies on mechanisms of climate change and hydrologic processes, accounts for their socio-economic linkages and outlines risks and possible mitigation policies. Such a duality has already been reflected in the United Nations Framework Convention on Climate Change (UNFCCC) and the Arab Water Security Strategy, which seek to assess and address the impact of climate change on water resources in view of advancing sustainable development. The integrated assessment methodology helps to build a bridge between:

- **Science** – whose role is to understand the mechanisms of climate change (physical sciences), hydrologic processes (physical and applied sciences), and their socio-economic linkages (social sciences), as well as to outline the nature of risks and to outline possible policies (applied and social sciences); and

- **Policy-making** – whose role is to decide on the level of acceptable risks, to define which ones are dangerous and should be avoided, and to agree on the course of action to be taken.[4]

Such an approach comes at a time of a growing demand for greater coordination between the science of climate modelling and the policy implications of climate change's impacts on societies, economies and ecosystems. This is evidenced by the formation of an Integrated Assessment Modelling Consortium under the auspices of IPCC in November 2006.[5] Furthermore, in its technical report on climate change and water, IPCC experts stressed the need to fill in knowledge gaps in terms of observations and research related to climate change and water, and noted that existing water management assessments and practices may not be sufficient to address the impacts of climate change on water.[6] This is partially because outdated models assume hydrologic stationarity, namely that the statistical parameters of hydrological variables do not change over time. However, increasing observations and empirical analysis have called this assumption into question. Water management assessment models thus require multidisciplinary, dynamic and integrated revision to better inform policy-making processes.

[3] League of Arab States (2010).

[4] Schneider (2006), p. 609.

[5] IPCC (2008a).

[6] Bates et al. (2008).

The integrated assessment approach takes into account all interactions between climate change and water resources to illustrate how "the nature of policy and decision-making, the climate system responses, and capabilities of model projections all change with time scale."[7] To do so, integrated assessments combine both formal mathematical modelling methodologies and empirical approaches within a policy-sensitive framework. Formalized mathematical models can be programmed into computers to simulate the dynamic behaviour of the Earth's complex climate systems, but cannot necessarily capture the complexities, subtleties, and ambiguities presented by the dynamic and iterative interactions that exist between climate, nature and society.[8] Those models are therefore complemented by empirical approaches and formulations that can also take into account the impact of socio-economic systems. By combining mathematical models with empirical approaches that take into account regional specificities related to water and climate, and primary and secondary effect that climate change may have on water resources and socio-economic vulnerability, an integrated assessment can be used to inform evidence-based policy-making processes in the Arab region.

This complementarity between disciplines is structured by incorporating impact assessment models and vulnerability assessment tools into an integrated assessment methodology. Impact assessment methodologies are applied to generate outputs regarding the effect of a determined set of natural or external forcing on a system. In the case of climate modelling, a greenhouse gas (GHG) emissions scenario or forcing embodied in a RCP is used as the basis for assessing the impact of different atmospheric changes on the climate cycle at the global and regional levels. The resulting projection is in turn interfaced with a RHM that can provide more specific detail regarding the effect of the climate cycle on the water cycle for a given duration of time and space based on the same scenario. An integrated assessment can then take the findings of the impact assessment to enhance understanding of vulnerability based on the same projection.

Socio-economic vulnerability assessments incorporate the human dimension into the integrated assessment. While there are different types of vulnerability assessments, the socio-economic vulnerability assessment component of the regional initiative is designed to address the implications of climate change for the social, economic and environmental aspects of sustainable development. Accordingly, the vulnerability assessment builds upon the outputs generated from the climate and hydrological impact analysis to provide the information necessary to address policy-oriented questions such as those related to water security, food security, poverty, health, employment, and biodiversity. Some integrated assessments can also be iterative in nature and allow such exogenous pressures as changes in human behaviour to be incorporated into the analysis, which in turn can support the development of a decision support system.

To generate such findings, the outputs of models developed by climate scientists, hydrologists, hydrogeologists, mathematicians and computer programmers are presented to economists, agricultural engineers, sociologists, health practitioners, gender specialists, environmentalist and other stakeholders within government and civil society to identify socio-economic impacts and assess vulnerability. The aim of this interdisciplinary process is to identify hotspots, costs, benefits, risks and other issues of common concern. These finding can then help to inform policy formulation, priority setting and decision-making for climate change adaptation.

[7] IPCC (2008).

[8] Yarnal (1998), p. 66.

Benefits of an integrated assessment

- Engages a cross-sector of stakeholders ranging from Government to civil society.
- Integrates scientific methodologies, traditions and standards into interdisciplinary analysis to bridge the gap between science and policy making.
- Links impact assessment to vulnerability assessment.
- Conducts analysis and assessment across relevant geographic scales and time scales.
- Recognizes and takes into account regional specificities.
- Accounts for scientific uncertainty, and seeks to reduce it through objective methods.

B. Methodological overview

This document focuses on the preparation of an integrated assessment of socio-economic vulnerability resulting from the impact of climate change on water resources in the Arab region. The document seeks to:

(a) Provide a systematic conceptual framework in which to structure present knowledge of GCM and RCM as related to the Arab region;

(b) Expose the linkages between climate modelling and hydrological modelling to identify the potential impacts of climate change on freshwater resources in the region and to expose the associated implications for the sustainability of water resources at the regional and basin levels;

(c) Review and propose methods for determining the socio-economic vulnerability of the Arab region to climate change impacts on water resources, to classify the relative importance and influence of the various climate and hydrological drivers on socio-economic vulnerability and sustainable development in a manner that is applied consistently across the Arab region;

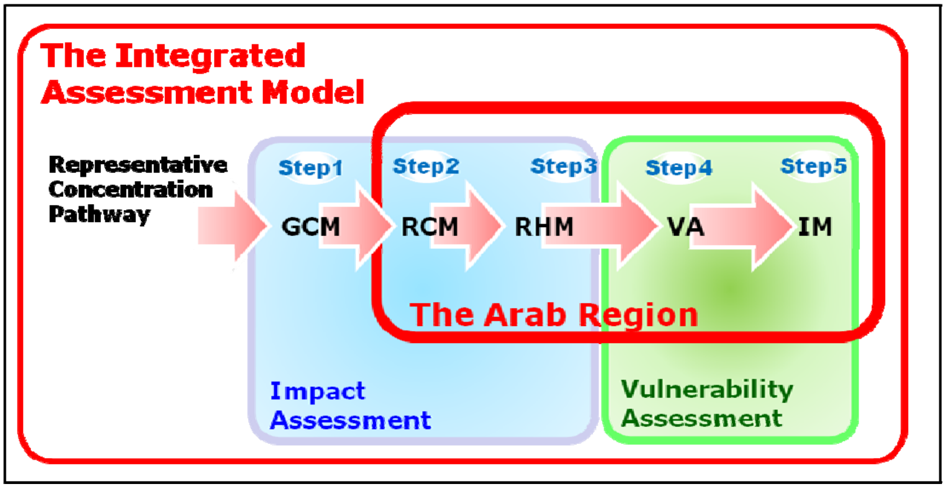
(d) Suggest methods, mechanisms, information systems and integrated mapping tools that can contribute to the development of decision support systems for assisting Arab countries engaged in adaptation at the regional and national levels.

These objectives are reflected in a five step methodology for implementing the integrated assessment. The approach combines impact assessment models (steps 1-3) with vulnerability assessment (step 4) and integrated mapping tools (step 5) for facilitating understanding and fostering policy dialogue on the expected impacts of climate change on water resources and socio-economic vulnerability in the Arab region.

The methodology starts by identifying which internationally accepted RCPs will be used as the basis for modelling the global climate through a GCM. One or more RCMs are then nested in one or more GCMs to determine how the global climate system influences the climate across the Arab region based upon that RCP. The outputs of the RCMs are then used to show how global and regional climate change affects the hydrologic regime in the region through RHM. The same process can then be repeated for another RCP that will result in another impact assessment scenario. Climate projections and resulting analysis of the impact of climate change on water resources in the Arab region can then be used to support the socio-economic vulnerability assessment. The assessment process is supported by integrated mapping tools that create visual representations of the potential implications of climate change for water resources and socio-economic vulnerability. It is expected that these findings and tools will improve decision-making on climate change adaptation and support progress towards sustainable development.

A more detailed review of these five steps of analysis is presented below and illustrated in figure 1. The steps are then elaborated in the subsequent chapters of this guidance document.

Figure 1. Integrated assessment methodology



Step 1: Modelling the global climate

Global assessments of projected climate change impacts are carried out using GCMs. This requires the following:

- ☑ Review of global climate trends based on observed data;
- ☑ Review available GCMs and selection of two or more GCMs to form the basis of the climate simulations in the region;
- ☑ Selection of at least one RCP to define the assumptions and range of the GCM simulations generated, which would be among the RCPs being used in the preparation of the IPCC's AR5;
- ☑ Consideration of which GCMs have generated outputs for which RCPs given their recent introduction;
- ☑ Clarification of the interface between the GCMs and RCMs under consideration;
- ☑ Recognition of the uncertainties and unexpected events at the global level in order to develop an appreciation of their implications at the regional level;
- ☑ Assurance that the current work fits in with future trends and developments in climate modelling and data collection.

The following are anticipated **outputs** of step 1:

- Identification of global climate change trends based on a specific set of parameters related to each RCP at specific time steps that would contribute the basic assumptions for RCM;
- Validation of GCMs to provide inputs into RCM, and selection of one or more RCP;
- Generation of coarse findings for a broad set of parameters at a resolution generally covering a 200 km x 200 km to 300 km x 300 km horizontal grid box.

Step 2: Regional climate modelling

RCMs will be nested in one or more GCM to support climate modelling at the scale of the Arab region. This requires the following:

- ☑ Consensus on the type of information sought from the regional climate modelling exercise, including agreement regarding the scope, resolution and time steps desired;
- ☑ Delineation of the Arab Domain based on a sensitivity analysis;
- ☑ Selection of one or more RCMs for application within the limits of the Arab Domain, that can draw upon information generated by one or more GCMs for areas outside the Arab Domain, in order to generate an ensemble of regional climate projections ;
- ☑ Decision on the time steps and resolution to be used for generating information from the projections;
- ☑ Downscaling from GCM to RCM;
- ☑ Consideration of uncertainties and unexpected events at the regional level, in the context of regional specificities;
- ☑ Data coordination and analysis in a regional framework, including provision of technical assistance for the development of long term daily homogenous climate databases and the collection and storage of data. Care should be taken to ensure data is stored in a reliable manner, and is easily and freely accessible.

The following are anticipated **outputs** of step 2:

- ➲ Identification of regional climate change trends and impacts based on a specific set of parameters resulting from a specific RCP at specific time steps, and the identification of more complex interactions between newly identified regional impacts than those drawn from GCM outcomes;
- ➲ Standardization of geospatial data sets for projected climate impacts in the Arab region from one or more RCMs based on specific parameters and time steps, resulting from the selected RCPs and generating higher resolution outputs based on a 50 km x 50 km to 25 km x 25 km horizontal grid box;
- ➲ Identification and assessment of data needs, data sources, data availability, and potential gaps needed to validate the climate model and calibrate the hydrological model to improve results at the regional scale.

Step 3: Regional hydrological modelling

RHMs will draw upon global and regional databases with a view towards producing a series of regional hydrological impact simulations for surface and groundwater systems for different climate projections. This requires the following:

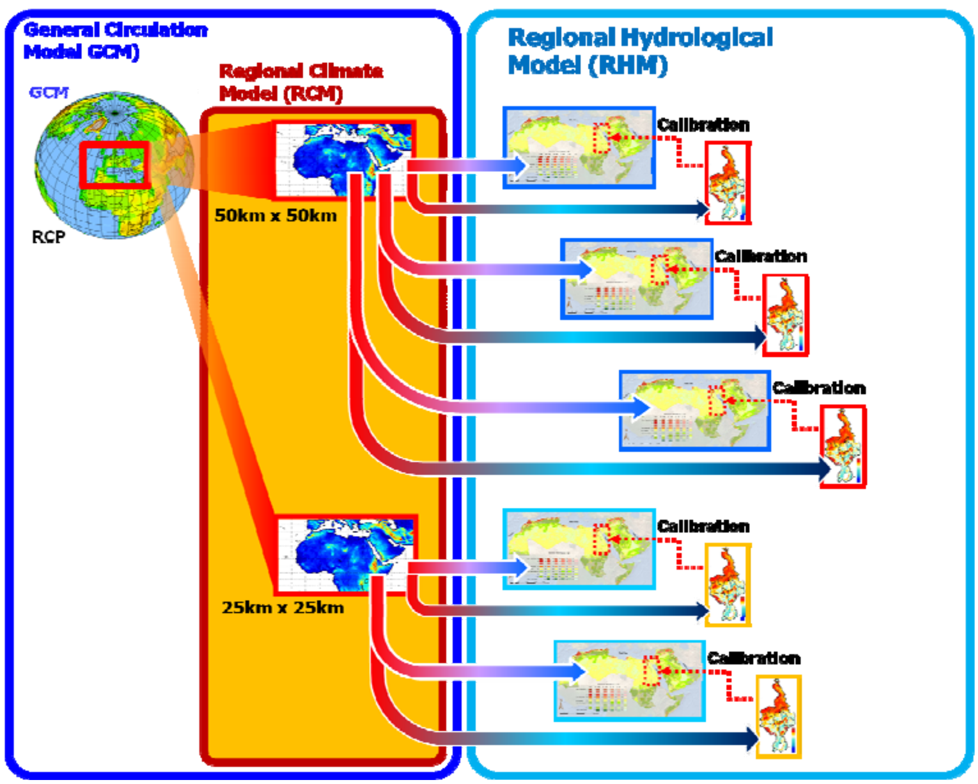
- ☑ Identification of criteria and requirements for pursing RHM in the Arab region based on regional and local specificities;
- ☑ Determination of the hydrological parameters that need to be computed to support the model;
- ☑ Selection of RHMs to be used to generate an ensemble of hydrological outcomes based on a projection generated by one RCM for a specific RCP, which can subsequently be repeated for other RCM projections and other RCPs. This includes the clarification and definition of the interface between RCMs and the selected RHMs, and assuring that the series of RHMs selected can be compiled to support an ensemble analysis and outcome;
- ☑ Selection and application of one or more basin-centred hydrological models in test basins to calibrate the RHMs and to handle cases where more detailed analysis may be needed for specific phenomena, such as droughts or floods. This requires the definition of the interface between RCM and basin-centred hydrological models to be used for calibration or possible case studies.

The following are anticipated **outputs** of step 3:

- An ensemble of standardized geospatial data sets for the projected impacts of climate change on regional water resources in the Arab region based on specific hydrological parameters and time steps associated with one or more RCP resulting from one or more RCM;
- More detailed hydrological data related to the water cycle and water resources that can be generated from GCM or RCM projections;
- Differentiation between primary impacts of climate change on hydrology in the region and the secondary impacts of climate change on specific socio-economic and environmental indicators in the Arab region;
- When needed, specific basins in the Arab region can be investigated with basin-centred hydrological models.

The linkages between GCM, RCM, RHM and basin-centred hydrological models are highlighted in figure 2, which shows how data flow from one level of the analysis to the other.

Figure 2. Illustration of the impact assessment component



Step 4: Vulnerability assessment

A socio-economic vulnerability assessment is carried out based on the outputs of the impact assessment by incorporating socio-economic and environmental parameters. This requires the following:

- ☑ Selection of the type or types of vulnerability assessments that are most appropriate for the integrated assessment methodology being applied, based on an understanding of the different vulnerability assessment methodologies and approaches used within the region;

- ☑ Determination of the scope and scale of the socio-economic vulnerability assessment based on interdisciplinary consultations with regional stakeholders. This includes the identification of the types of human responses and the threats to sustainable development to be targeted for assessment based on the outcomes of the impact analysis and the priorities identified by senior decision makers to support development planning and climate change adaptation;
- ☑ Identification of data needs, indicators, interdisciplinary analysis, and the specialized models to be applied to conduct the assessment based on the defined scope and scale of the vulnerability assessment, taking into account work already undertaken in the region;
- ☑ Preparation of the vulnerability assessment based on relevant parameters, consolidated data sets, empirical models and qualitative assessments.

The following are anticipated **outputs** of step 4:

- ➲ Consensus on the relevant socio-economic parameters and indicators that comprise and structure the vulnerability assessment and the identification of vulnerability hotspots;
- ➲ Standardized geospatial data sets of computed parameters and indicators of socio-economic vulnerability, associated with specific RCPs and RCM projections.

Step 5: Integrated mapping

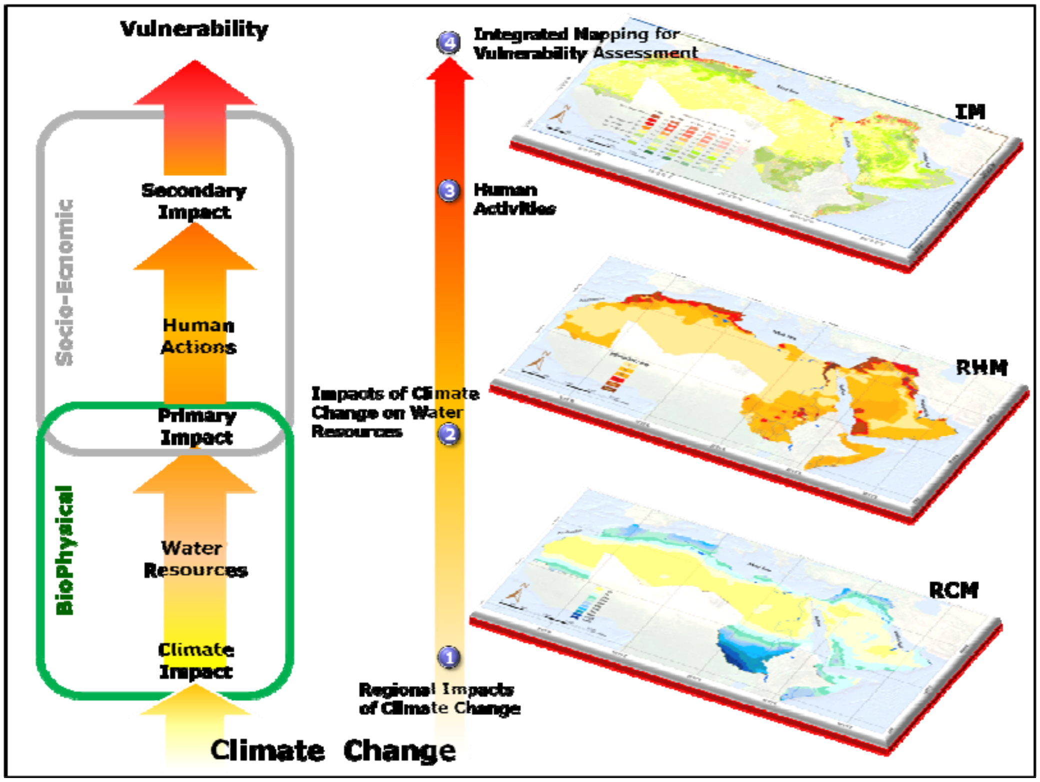
Integrated mapping of the outputs generated from the impact assessment (steps 1-3) and vulnerability assessment (step 4) will facilitate understanding and analysis of the findings. This requires the following:

- ☑ Establishment of a knowledge management hub for storing and disseminating information generated during the preparation of the impact assessment and vulnerability assessment components of the integrated assessment;
- ☑ Development of a harmonized database for the transfer of information onto a visual platform through a geographic information system (GIS) to produce maps across spatial and time scales and to integrate both discrete and continuous data types that are related to a selected set of parameters;
- ☑ Identification of vulnerability hotspots using integrated maps and overlays generated through GIS applications that represent the baseline and projected impacts of climate change on water resources in the Arab region and the socio-economic and environmental vulnerabilities associated to these impacts.

The following are anticipated **outputs** of step 5:

- ➲ Geographic representation of climate change impacts on water resources and socio-economic vulnerability hotspots visualized through integrated mapping tools;
- ➲ Accessible knowledge management hub supported by databases and GIS applications for disseminating information generated by the Regional Initiative.

Figure 3. Illustration of integrated mapping component



It is also envisioned that the integrated maps and knowledge management hub could contribute to the development of dynamic decision support systems that would inform climate change adaptation planning and priority-setting at the regional and national levels. In doing so, it could help to consolidate regional positions on common issues of concern that need to be advanced in global negotiations, such as those organized under the framework of the UNFCCC and other forums related to climate change adaptation and financing. The information generated through the project and made available through the knowledge management hub could also be drawn upon to prepare more specialized and lower resolution assessments at the national and local levels.

It is expected that these five stages will result in the preparation of an integrated assessment of the impact of climate change on water resources and its associated implications for socio-economic vulnerability in the Arab region. The integrated assessment will foster informed regional dialogue and decision-making on climate change and its implications for sustainable development in the region.

II. STEP 1: MODELLING THE GLOBAL CLIMATE

Short-term fluctuations (hourly and daily) define the weather, while longer term variations, trends and changes (over years and decades) define the climate. The global climate is driven by energy fluxes across the Earth's atmosphere. Most energy fluxes are mediated by water as it moves across its various states of liquid, vapour and ice, known as the **water cycle**. The water cycle moves incoming solar and thermal energy across the oceans, the terrestrial surface and the atmosphere, and it is now increasingly being affected by human actions. These anthropogenic effects influence climatic interactions in critical ways. Mankind now finds itself in an era of interaction between the Earth's natural systems and human activity which affect the climate together.

Scientists evaluate the interaction between these components by measuring the statistical parameters that characterize changes in the atmosphere, ocean and land. Doing so reveals the pattern of many of these interactions, thereby showing the relationship between human actions and the changes in the global climate over time. Scientists can evaluate past changes in the composition of the atmosphere against the level of economic activity experienced during the same period and compare this data to related historic climatic trends and observed climate data. They then use this understanding to project future changes in the composition of the atmosphere and related variations and changes in the climate.

A. REVIEW OF GLOBAL CLIMATE TRENDS

Changes in atmospheric patterns vary in both a deterministic and a chaotic manner. To scientists, **deterministic** systems are those whose future climate behaviour can be described by referring to the governing physical laws of nature. Systems are considered **chaotic** when small differences in the initial conditions of atmospheric parameters are found to yield widely diverging values.

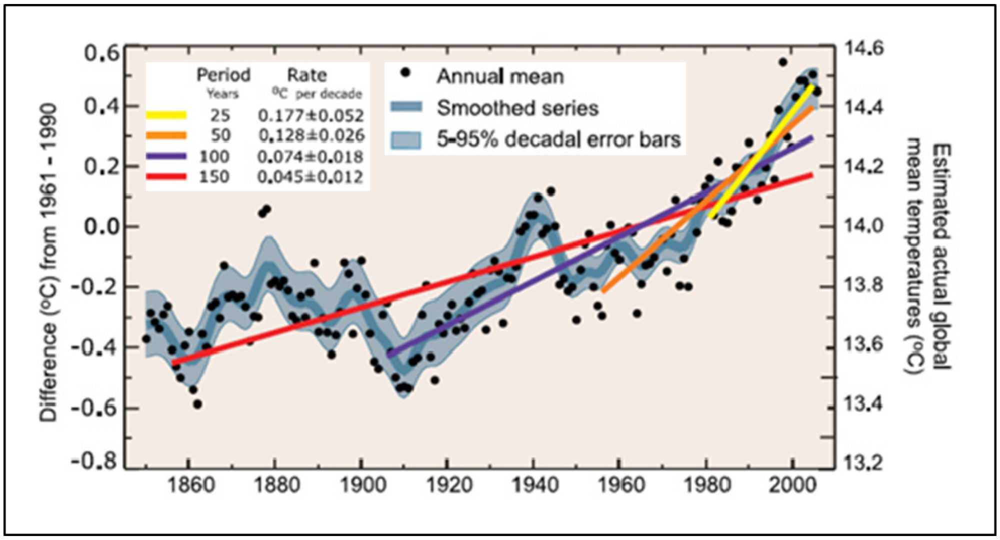
The extent of chaotic variation depends on the time scale considered. At the scale of the weather, the climatic system is very chaotic, and thus limits the accuracy of forecasts to a few days. However, as the time scale grows longer, daily and yearly chaotic variations in weather are largely overcome by averaging atmospheric statistics over consecutive time periods to identify climate patterns. As a result, while the weather of a given day cannot be predicted far into the future, trends in the prevailing future climate can be projected with relative accuracy.

It has been shown that consecutive time periods of 30 years are sufficient to clearly identify climate patterns. These time periods are defined by the World Meteorological Organization (WMO) and are called **climatological standard normals** (CSNs). CSNs represent a set of measured climatic parameters (temperature, precipitation, etc.) computed for a specific set of years, namely 1901-1930, 1931-1960, and 1961-1990. Going forward, they will be eventually computed for the next period running from 1 January 1991 to 31 December 2020.[9]

Based on available data extending back to the mid-nineteenth century, the fluctuations of CSNs show that, before the middle of the twentieth century, the climate had been oscillating in a relatively stable manner, with little variation from cycle to cycle (see figure 4). After the middle of the twentieth century, the climate appears to be warming from oscillation to oscillation, hinting that the CSNs for the current period that extends from 1991 to 2020 may be markedly higher than those manifested in the previous periods. Such a trend is evidenced in figure 4.

[9] Trewin (2007).

Figure 4. Changes in global mean temperature (1850-2010)[10]



For purposes of reporting climatologic observations, the climate is described by a set of **essential climate variables** (ECV) defined by the Global Climate Observing System (GCOS).[11] This set of variables defines the minimum set of variables needed to describe the climate system.[12] The variables define the parameters that climatologists need for their computerized climate models, and help to inform policy-making.[13] Established through a collaborative effort, the list of ECVs has expanded based on progress in research and reporting capability, and has grown from 44 variables when the IPCC's AR4 was issued in 2007, to about 50 variables in 2011 (see table 1).

[10]Solomon et al. (2007), p. 253.

[11]GCOS is a joint undertaking of the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU).

[12]Kuhn (2010), p. 18.

[13]Doherty et al. (2009), p. 503.

TABLE 1. LIST OF ESSENTIAL CLIMATE VARIABLES[14]

Domain	Sub-Domain	GCOS essential climate variables	
Atmospheric (over land, sea and ice)	Surface[a/]	• Air temperature • Wind speed and direction • Water vapour	• Pressure • Surface radiation budget
	Upper-air (up to the stratopause)	• Temperature • Wind speed and direction • Water vapour	• Cloud properties • Earth radiation budget (including solar irradiance)
	Composition	• Carbon dioxide • Methane and other long-lived greenhouse gases: nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), perfluorocarbons (PFCs)	• Ozone and aerosols, supported by their precursors, in particular nitrogen dioxide (NO_2), sulphur dioxide (SO_2), formaldehyde (HCHO), carbon monoxide (CO)
Oceanic	Surface[b/]	• Sea-surface temperature • Sea-surface salinity • Sea level • Sea state • Sea ice	• Surface current • Ocean colour • Carbon dioxide partial pressure • Ocean acidity • Phytoplankton
	Sub-surface	• Temperature • Salinity • Ocean current • Nutrients	• Carbon dioxide partial pressure • Ocean acidity • Oxygen • Tracers
Terrestrial	Surface[b/]	• River discharge • Water use • Lakes • Snow cover • Glaciers and ice caps • Ice sheets • Permafrost • Albedo	• Land cover (including vegetation type) • Fraction of absorbed photosynthetically active radiation (FAPAR) • Leaf area index (LAI) • Above-ground biomass • Fire disturbance
	Sub-surface	• Groundwater	• Soil carbon • Soil moisture

a/ Including measurements at standardized, but globally varying heights in close proximity to the surface.
b/ Including measurements within the surface mixed layer, usually within the upper 15 m.

Within the framework of UNFCCC and IPCC, climatologists developed climate projections of various parameters that are based on ECVs, by programming computer simulations to resolve their values at different elevations in the atmosphere. ECVs became a class of variables that have helped to define the parameters needed for climate projections to describe and assess key climatic driving mechanisms. Those mechanisms are related to the movement of energy fluxes across the Earth's atmosphere. While this is influenced by the

[14]GCOS (2011).

water cycle, the process is based on an **energy balance** between the incoming solar radiation of the sun and the outgoing infrared radiation of the Earth. The warming climate trend indicates that a key change is occurring in the balance between the influx and outflow of energy within the system.

In a static equilibrium environment, the climate would be stable over years and decades, and the CSNs would show little variation over time. The energy balance between inflows and outflows would thus vary little. As such, in the case of a stable climate, the value of climatic variables would oscillate around the average that would have corresponded to a static equilibrium. However, because the Earth and the socio-economic systems that operate upon it are dynamic, the equilibrium point between energy inflows and outflows is also dynamic. The current warming trend indicates that a key change is occurring in the balance of those fluxes, with the influx of energy outweighing the outflow. The average is thus moving upwards and becoming steeper, as illustrated in figure 4. This is reflected in value of key climatic parameters, which are also shifting to reflect the climate system's move towards a new and warmer state.

This change in the prevailing climate accelerates the rate at which water cycles through its different stages. The rates of evaporation and precipitation accelerate, modifying the availability of freshwater on the Earth's surface. This change in the water cycle is unprecedented in modern human history, and challenges the assumption of hydrologic stationarity.[15] In the water-scarce Arab region, the dynamics of climate change are undermining established water management assessment methods and practices. Within this changing environment, it is no longer valid to look exclusively at historical records when planning for the future since the frequency and intensity of weather-related events in the past may no longer be a reliable indicator of what may come in the future. A dynamic climate system can not rely on assumptions derived from past records of 100 year floods and 50 year drought cycles. Climate models and associated hydrological models based on these new conditions can provide water managers with a clearer picture of the evolution of the future climate and the implications this can have for water resources management.

B. Components of a global climate model

Scientists can describe the evolution of the climate by modelling deterministic interactions between parameters and running simulations based on a set of assumptions. They then examine the projected output to identify the main drivers of climate change. Throughout this process, climatologists determine what **forces** an otherwise stable climate to change by examining and postulating variations in key atmospheric parameters.

In the search for forcings that alter the Earth's global energy balance, climatologists ran various simulations that investigated the effect of all known significant parameters. They compared the results of their simulations against historic climate trends reconstructed from observed climate records that extend from 1850 onward. This allowed them to confirm that the increasing amount of GHGs found in the atmosphere is the most likely root cause of global changes in modern climate trends. GHGs tend to absorb the longer wavelengths of infrared radiations while being transparent to shorter wavelengths of visible light, most of which is emitted by the Earth's surface.

[15] Fowler et al. (2007) and Bates et al. (2008).

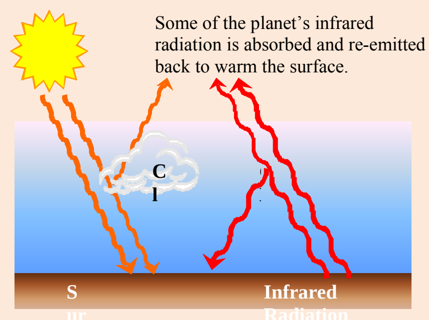
Greenhouse gases, aerosols and the greenhouse effect

Gases in the atmosphere tend to be transparent to shorter wavelengths of visible light and absorb the longer wavelengths of infrared radiations, most of which is emitted by the Earth's surface. The main GHGs include:[16]

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Halocarbons
- Ozone (O_3)
- Water vapour
- Aerosols: small particles present in the atmosphere with widely varying size, concentration and chemical position

GHGs have two noteworthy effects, namely the:

- **Greenhouse effect** – which is caused when GHGs absorb infrared radiation from the Earth's surface and reemit it back down. In this way, GHGs reflect some heat back to the surface that otherwise would have escaped into space, as shown in the figure to the right.
- **Global warming** – which is a rise in temperatures near the Earth's surface caused by an increase in the atmospheric levels of GHGs. Global warming is the result of the greenhouse effect.



The importance and the complex role of the greenhouse effect can best be illustrated by comparing the Earth to its two planetary neighbours, Mars and Venus, which illustrate the two extremes, relative to the Earth:

- On *Earth*, average surface temperatures would be an average of at least 15°C colder without the greenhouse effect. Temperature variations would be much less pronounced.
- The planet *Mars* is about half the size of Earth and can only retain a thin atmosphere; as such, little heat is captured and the average surface temperature is only -63° C, varying widely from -140°C to 20°C.
- *Venus* is about the same size of Earth, with a thick atmosphere and pronounced greenhouse effect that raised the planet's average surface temperature so high that water evaporated and was lost to space, GHGs such as CO_2 were released from the rocks further reinforcing planetary warming. The planet's temperature is now 477°C, hot enough to melt lead and twice as hot as it would be if Venus did not have an atmosphere.

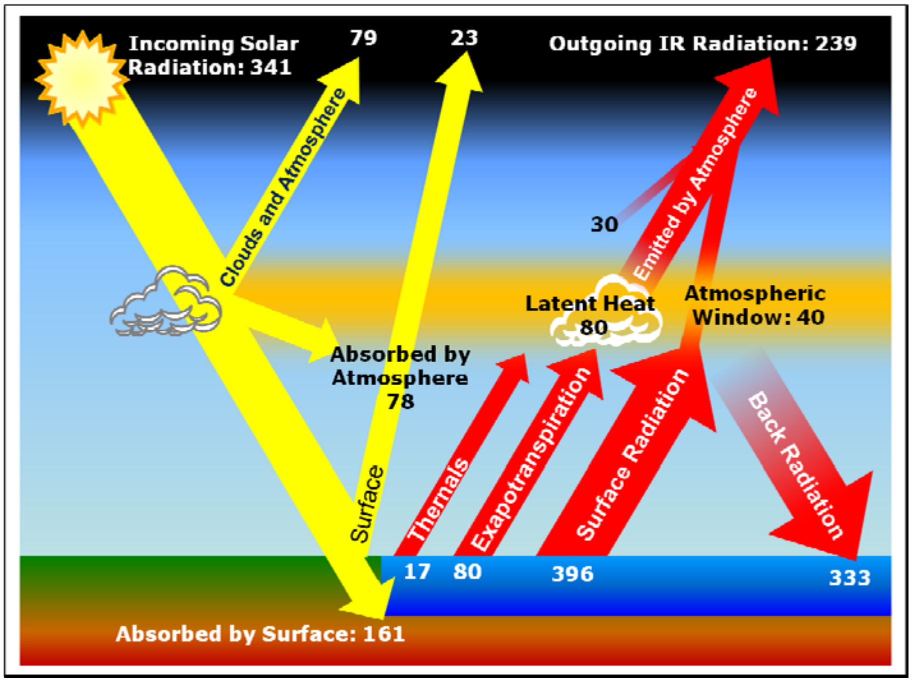
A dramatic increase in anthropogenic GHG emissions began during and has continued following the acceleration of Western industrialization after the nineteenth century.[17] Additional GHG in the atmosphere has enhanced the greenhouse effect, whereby thermal radiation is absorbed by gases in the atmosphere and reemitted back to the surface of the Earth. The greenhouse effect has resulted in warmer temperatures on the ground and in the lower atmosphere, as illustrated in figure 5. As previously shown in figure 4, since the

[16] IPCC, 2007.

[17] IPCC (2007a).

middle of the twentieth century, the accumulated effect of GHG generated by human activity has been to increase net irradiance through radiative forcing.[18]

Figure 5. Earth's energy balance (W/m²)[19]



The scientific investigation of future climatic change is based on the understanding that the observed change in CSNs is caused by GHG-related radiative forcing. Scientists model the climate system as an interaction of two basic sub-systems:

- **Biophysical systems** are defined by interactions between the Earth and the climate's physical systems such as the atmosphere, oceans, land surface and the planet's trees, vegetation and plankton. These interactions are largely modelled through deterministic equations that describe their various interactions through scientific relationships; GCMs and RCMs are used to describe these relationships.

- **Socio-economic systems** are defined by human economic interactions and their impact on the Earth's various biophysical systems. Most human economic activity results in GHG emissions; different development pathways result in varying emission concentrations in the atmosphere and thus different levels of radiative forcing. As human economic activity is highly chaotic and difficult to predict, human socio-economic systems are represented by postulated sequences of different future emission outputs, known as emission scenarios.

[18] This change in net irradiance is usually expressed in units of W/m².

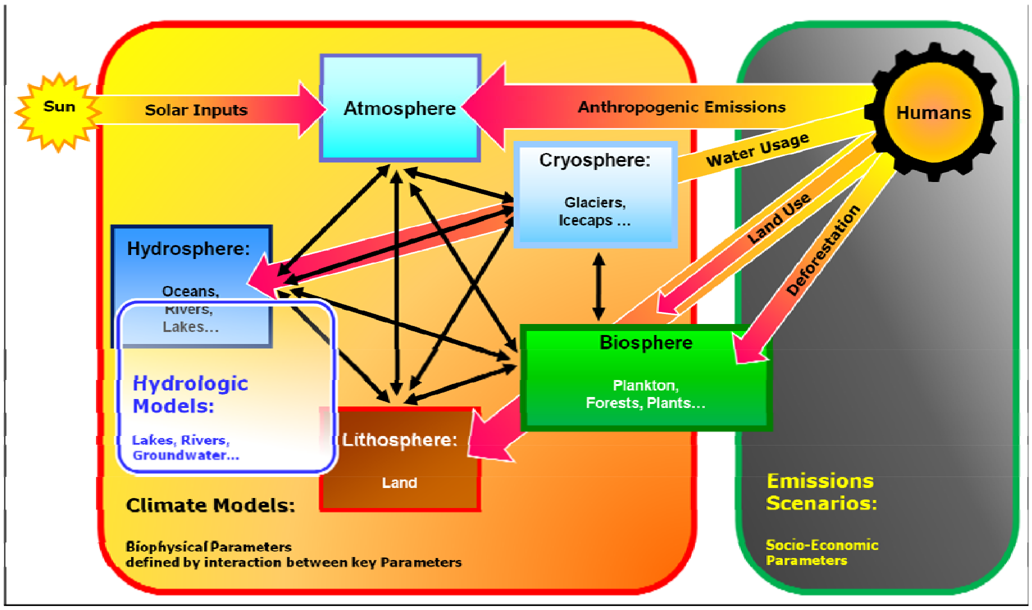
[19] Energy is measured in watts. Energy flows over the Earth surface are measured in m², and thus energy flows are expressed in W/m². The values shown here were measured between March 2000 to March 2004, as reported in Kiehl et al. (1997), p. 314.

Emission scenarios

An emission scenario represents a projected future concentration of GHGs in the atmosphere resulting from a combination of human socio-economic activities.

By focusing on these two sub-systems, climate scientists can model a **Whole Earth System** in which they investigate the interaction between the Earth's biophysical systems and socio-economic systems. Such a system is illustrated in figure 6, which exposes how relationships between atmospheric and topographic layers provide the platform for building models and emission scenarios for modelling the past, present and future climate.

Figure 6. The Whole Earth System: a platform for climate modelling and scenarios



C. Global climate models

In their investigation of the climate, scientists focus on the mathematical relationship between the energy fluxes within the Earth's various biophysical systems. Those energy fluxes are represented by Energy-Balance Models (EBM), which are composed of mathematical equations that rely on the physical laws of nature and incorporate relevant chemical and biological processes to test hypotheses on the workings of the planet. Energy-balance models reduce the interaction amongst the climate's various sub-systems into three basic classes of processes:[20]

- **Radiative processes** – transmit heat or electromagnetic radiation through the climate system by emission, absorption or reflection;
- **Dynamic processes** – transfer energy across the atmosphere in the horizontal and vertical transfer of energy by advection, convection, diffusion, etc.;
- **Surface processes** – describe the interactions between land, oceans, sea and ice, including the albedo, the emissivity of materials and surface-atmosphere energy exchanges.

[20] ESCWA (2009), p. 5.

This approach allows climate scientists to easily integrate the mathematical descriptions of those processes in computer models of the climate. Any time a process needs to be investigated, it is first classified as part of one of these three classes, and the equations that describe that process are then programmed into the computer model. The computer programmes that represent the climate of the Whole Earth System support the development of GCMs. As illustrated in figure 7, GCMs in turn divide up the Whole Earth System into manageable spatial units that can be examined across specific time scales.

On the spatial scale, the geography of the Earth is rendered in a three-dimensional grid-like pattern. Spatial discretization divides up the surface of the Earth, the oceans, and the atmosphere into a series of horizontal grid boxes that are stacked in vertical layers of varying height. Three-dimensional horizontal grid boxes in the model are delimited in terms of length and width and set the horizontal resolution of the model. Vertical levels are generally defined in terms of pressure and are expressed in hectopascal (hPa) levels to reflect the fact that the density of air decreases exponentially with height. In the vertical direction, climate models use 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans.[21]

Understanding pressure

Atmospheric air pressure is expressed as hectopascal (hPa). This pressure is due to the force (in newton, N) per unit area (square meters, m^2) resulting from the weight of air in the Earth's atmosphere that is above any surface. Under normal conditions, the air pressure at the surface, the **mean sea level**, is 1000 hPa, which corresponds to the older unit of 1 bar, or 1000 millibars.

The hPa level varies from 950-900 hPa near the surface to 0 hPa at the outer edge of the atmosphere. Pressure represents the mass of air in a given volume of the atmosphere, and decreases exponentially with elevation, resulting in a difference in height between 950 hPa and 900 hPa, or between 100 hPa and 50 hPa, even if the mass of air between those levels is the same.

Because of this difference in pressure at different levels of the atmosphere, the three-dimensional grid boxes that are used by climate modellers to generate output fields are not cubes, but boxes in a three-dimensional grid that have equal length and width horizontally, but may be of varying height between vertical layers, so as to contain the same mass of air.

In view of the above, modellers generally take care to concentrate the grid near the surface, where the data are of greater interest. Climate scientists develop equations that describe all the relevant processes in each one of these boxes. This is achieved by computing the energy fluxes in each grid box using:

- **Diagnostic** equations that estimate variables at any given time; and
- **Prognostic** equations that describe the evolution of the specified variables over time.

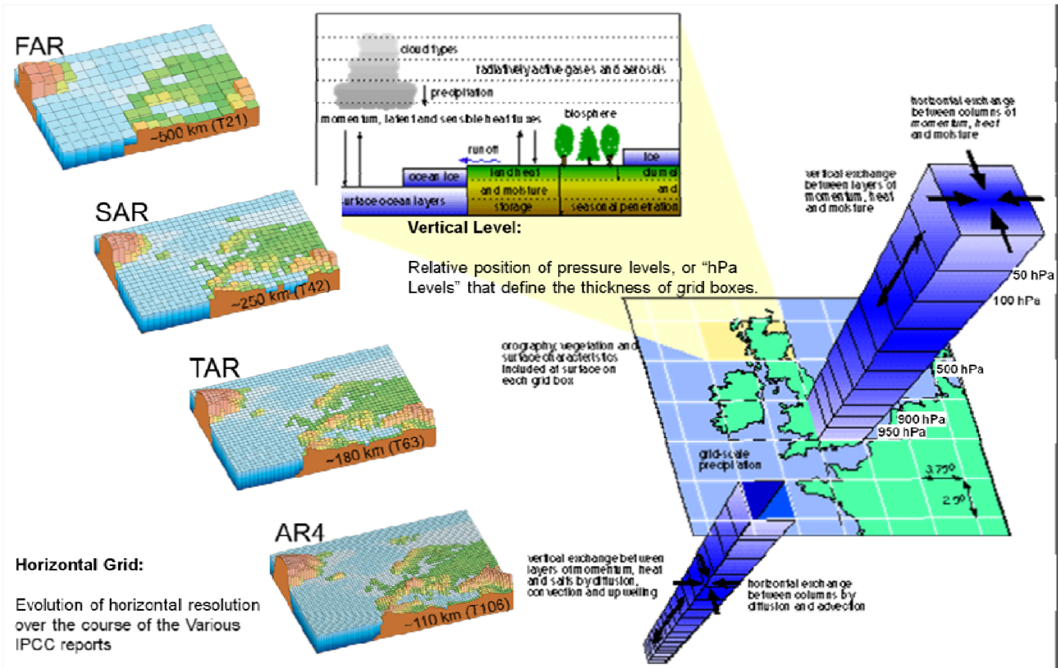
This requires that the solution be programmed to step forward in time and compute the energy fluxes in each box for each advancing time slice based on a predetermined **time discretization**. The time scale used is largely determined by political interests associated with planning over short and longer term time horizons.

Spatial and time discretization are central components of **Atmosphere-Ocean General Circulation Models**, which are commonly referred to as GCMs. Across both space and time, in each grid box and for each computational cycle, GCMs are designed to resolve a set of pre-defined equations that describe the key ECVs in the system. The equations and calculations developed may vary between GCMs due to different factors, and thus different GCMs may represent and project climate phenomenon differently. As shown in

[21] IPCC (2011).

figure 7, spatial resolution has improved over the course of the various IPCC reports, with grid sizes becoming smaller with each assessment report, namely the first, second, third, and fourth Assessment Reports (FAR, SAR, TAR, and AR4 respectively).

Figure 7. GCM spatial representation of the Earth and their evolution[22]



At the global scale, the various parameters make up a list of more than 100 variables that describe specific climate component (atmosphere, ocean, land or sea ice) or the interaction between them (radiative forcing fields). As shown in table 2, standard GCM output fields correspond to ECVs previously shown in table 1. For example, air temperature is an ECV whose mean values are computed at the surface and at different elevations in the air column, with daily maximums and daily minimums thus representing different **output model fields**. These are the field of parameters that constitute the outputs of a GCM run, which are used to carry out climate analyses on how ECVs respond to different anthropogenic influences.

Accordingly, prior to the start of each model run, climate scientist decide upon the GCM they will use and define the starting values for most of these parameters. This will define the initial climate that the simulation will compute and serve as the basis for projecting the future state of the climate system based on specified scenario. Based on spatial and time discretization, climatologists will determine the:

- **Resolution** of each model run; since GCM covers the Whole Earth System and normally generates coarse findings for a broad set of parameters at a resolution of 200 km x 200 km to 300 km x 300 km horizontal grid box.

- **Time steps** of the model based on political interests and technical constraints related to time and data storage. Time steps establish the temporal sampling rate at which the model output fields are calculated for each grid box. Depending on the GCM and computing capacity, parameters may be calculated every three to six hours, daily, or monthly.

[22] IPCC (2011) and (2007a).

TABLE 2. OVERVIEW OF CLIMATE MODEL OUTPUT FIELDS[23]

Domain		ECV	IPCC variable description as GCM output fields
Atmospheric (over land, sea and ice)	Surface	Air temperature	• Surface skin temperature • Near-surface (2 m): air temperature, daily-maximum, daily-minimum
		Wind speed and direction	• Eastward winds • Westward winds • Near-surface winds (10 m)
		Water vapour/ Precipitation	• Water evaporation flux from canopy, humidity (specific, relative) • Precipitation • Convective precipitation • Snowfall • Atmospheric water vapour content
		Pressure	• Air pressure on the ground surface and at sea level • Surface downward stresses due to wind
		Radiation budget	• Heat fluxes from the surface • Outgoing heat fluxes (long wave and shortwave) • Heat flux corrections • Prescribed heat flux (into slab ocean)
	Upper-air: (Up to the stratopause)	Not applicable	• Atmospheric boundary layer thickness (meters)
		Air temperature	• For each specified pressure elevation
		Wind speed and direction	• For each specified pressure elevation: Eastward and Westward winds, geopotential height
		Water vapour/Precipitation	• For each specified pressure elevation: cloud parameters (area fraction, ice content, water content)
		Radiation budget	• Heat fluxes incoming and outgoing (long wave and shortwave)
	Composition		• Mole fraction of ozone in air • Concentration of sulphate aerosols (NO_x, SO_x)
Oceanic	Surface	Sea floor depth below the geoid[24]	
		Temperature	• Sea surface temperature
		Precipitation	• Precipitation over ocean, water flux correction, water flux into ocean
		Salinity	• Sea water potential density
		Sea level	• Sea surface height above geoid • Sea level change (global average)
		Sea ice	• Area fraction • Thickness • Evaporation • Basal salt flux • Velocity
		Current	• Velocity, Eastward and Northward
	Sub-surface	Ocean layers	• Ocean mixed layer thickness
		Temperature	• Sea water potential temperature
		Salinity	• Sea water salinity • Northward ocean salt transport due to diffusion, gyre, overturning
		Current	• Upward sea water velocity • Ocean barotropic streamfunction • Meridional overturning streamfunction • Momentum flux correction
Terrestrials		• Surface runoff, snow (area fraction, amount, melt flux) • Glaciers (land ice area fraction) • Permafrost (soil frozen water content) • Soil moisture (content, content at field capacity, content of soil layer, root depth)	

[23] GCOS (2011), IPCC (2009) and WCRP (2004).

[24] The geoid is used to approximate the mean sea level as the height of the sea surface relative to the atmosphere is not equal across the Earth.

Output model fields are then calculated for each grid box at the resolution and time step established for the model run. The resulting GCM output fields, such as those listed in table 2, are used to carry out climate change analyses on how the climate responds to different anthropogenic influences.

D. Global emission scenarios

Despite their extensive level of detail, GCMs are only able to represent the interactions among biophysical parameters and accept as assumptions socio-economic emission scenarios for incorporating human activity. In the investigation of the future state of the climate, the computer models must be fed inputs that are exogenous from the natural system if the socio-economic effects of human activity are to be appropriately reflected in the analysis. This can be done by building scenarios based on different GHG emission concentrations in the atmosphere, or inputting a more general RCP that represents changes in radiative forcing that affects the atmosphere, without detailing the source or cause of that forcing. These two approaches allow the model to incorporate the socio-economic dimension.

Climate modelling rests on the study of forcing mechanisms on the Whole Earth System. This requires the use of emission scenarios that initially describe known historical climate records that are based on observations and that are projected into the future through an understanding of inferred spatial or temporal analogous conditions. In the case of:

- **Spatial analogues –** the output of climate models can theoretically be compared with data recorded from regions that closely resemble the area of interest to the study. In practice, however, few regions completely correspond to one another and thus the climate change impact assessment literature has generally recommended against this approach.[25]

- **Temporal analogues** – the output of climate models is compared with data derived from past climatic records, or reconstructed from fossil evidence or ice cores as a paleoclimate. This is the method most often used to validate climate models, and it has helped establish the fact that climatic changes of the past 100 years were largely due to human emissions of GHGs. This has been established by comparing model output against the record of past forcing such as variations in GHG concentration, solar cycle, and volcanic activity.

Developing projections of the future climate requires emission scenarios that describe the evolution of the main forcing mechanisms, most prominent among them anthropogenic GHG emissions. Emission scenarios used for climate modelling are either:

- **Equilibrium response scenarios**, or **doubled CO_2 scenarios** – which are relatively simple and therefore quick and inexpensive to run. However, they have limited physical realism, and are used chiefly to determine how sensitive temperature is to a change in radiative forcing. This climate sensitivity is then expressed as the temperature change associated with a doubling of CO_2 concentration in the atmosphere; or

- **Transient-model scenarios** – which are the most realistic emission scenarios. They are used to develop climate change assessments, by running a GCM to simulate a period of time with a time-varying forcing.

As an alternative to emission scenarios and the application of climate models, **synthetic scenarios**, have been used that simply assume that the climate is changed by a given amount. Synthetic scenarios can show what would happen under an arbitrary circumstance such as a precipitation decrease of 10 per cent or a temperature increase of 3 per cent.[26] While synthetic scenarios are academic exercises that can be supported

[25] IPCC (1990), Carter et al. (1994) and IPCC TGCIA (1999).

[26] For example, see Yarnal (1998).

by causal chain analysis and can provide maximum and minimum thresholds for framing policy discussions, they normally do not draw upon climate modelling methodologies. Instead they draw conclusions from a set of hypothetical assumptions that are then run through a hydrological model to estimate climate change impacts on certain parameters.

Equivalent carbon dioxide (CO2e)

Because it has been shown to be the primary GHG emitted from human socio-economic activity, carbon dioxide (CO_2) is used as a benchmark indicator for radiative forcing. There are two indicators:

- **Equivalent CO_2 (CO_2e)** is defined as the concentration of CO_2 that would cause the same level of radiative forcing as a given type and concentration of GHG.
- **Carbon dioxide equivalency (CDE)** is the amount of CO_2 that would have the same global warming potential as any given mixture and amount of GHG, measured over a given timescale.

In order to study the future climate, these scenarios need to estimate future emissions resulting from socio-economic systems. Such systems, while generally hard to model precisely, can still be accurately described based on clear rules defined by different patterns of economic growth, demography, and the types of technologies used. All socio-economic emission scenarios are therefore constructed based on five key criteria:

- **Consistency** with global projections of GHG emissions, which show a concentration of CO_2e ranging between 541 ppm and 970 ppm;
- **Physical plausibility** and strict adherence to physical laws, showing consistent changes across the globe and among different climate variables;
- **Applicability** of such impact assessment variables as daily to annual mean values of changes in temperature, precipitation, solar radiation, humidity and wind speed;
- **Representativity** – emission scenarios should be representative of the potential range of future regional climate change;
- **Accessibility** – emission scenarios should be straightforward to obtain, interpret and apply in impact assessments.

Emission scenarios therefore focus on describing a plausible range of socio-economic storylines that describe long-term socio-economic trends (ranging from several decades to a century) associated with different rates of GHG emissions. The estimates are based on well-established models and reflect expert judgments and understanding of socio-economic, environmental and technological trends.[27] Progress in socio-economic modelling led to improvements in IPCC frameworks for developing climate change projections from the initial emission scenarios developed during the 1992, to the more recent socio-economic storylines elaborated in the Special Report on Emissions Scenarios (SRES) used in the TAR and AR4, to the new RCPs that supersede them, and that will serve as the basis for climate change modelling analysis to be presented in AR5.

[27] Moss et al. (2010), p. 748.

IPCC emission scenario terminology

The IPCC in its Special Report on Emissions Scenarios issued the SRES terms of reference, which was used as the basis for preparing climate change projections in its third and forth assessment reports. These scenarios are described through the following terms, namely a:

- **Storyline**: a narrative description of an emission scenario (or a family of scenarios), highlighting the main scenario characteristics and dynamics, and the relationships between key driving forces.

- **Scenario family**: one or more emission scenarios that have the same demographic, politico-societal, economic and technological storyline.

1. *Special Report on Emissions Scenarios*

The Special Report on Emissions Scenarios (SRES) served as a basis for generating climate change projections in TAR and AR4. SRES was derived from a wide range of socio-economic activity that determined GHG and aerosol emissions, including population demographics, economic growth and energy use. Each scenario describes an alternative development storyline and is grouped into one or four emission scenario families:

A1: Rapid economic growth, with global population peaking around the year 2050, and the rapid introduction of new and more efficient technologies;

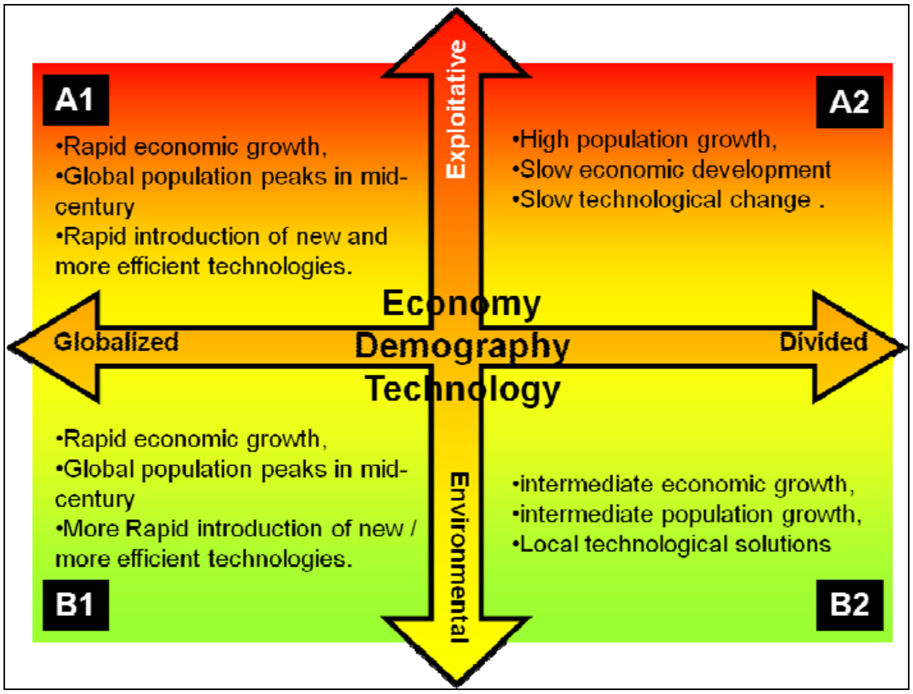
A2: Heterogeneous world, with continuously increasing global population; growth is regionally focused and more fragmented and slower than in other storylines;

B1: Convergent world with the same global population as in the A1 storyline, but with rapid changes in economic structures towards an economy with cleaner and efficient technologies that are less resource intensive;

B2: Relatively fragmented world economy with more emphasis on local sustainable development solutions. Population levels continue to increase, but a lower rate than in A2. Levels of economic development are intermediate.

In general, emission scenarios A1 and A2 describe a more polluting economy than B1 and B2 emission scenarios. Within each scenario family, A1 and B1 assume globalization, while A2 and B2 represent a more fragmented world economy. The relationship between the different scenario families is illustrated in figure 8.

Figure 8. The family of AR4 SRES[28]



2. *Representative concentration pathways*

Experience showed that applying SRES scenarios created confusion between the scientific and policy-making communities. This is because climate researchers perceived the SRES to simply represent a range of socio-economic storylines for simulating different combinations of human activity in an otherwise chaotic system, while policy analysis sought to determine what or who caused and contributed to each respective storyline.

IPCC therefore decided to decouple climate modelling and policy evaluation for the preparation of AR5. IPCC convened a workshop in September 2007 to discuss the development of a new set of scenarios that would cover a more representative range of possible futures. In this new process, the scientific and academic research community led the development of a new approach. IPCC limited its role to catalyzing the process and assessing the resulting peer reviewed literature for inclusion in AR5.

The effort resulted in the development of a series of **representative concentration pathways** (RCPs) that each embodied a specific radiative forcing trend over time that was fed into climate modelling applications. In doing so, RCP did not detail the types of socio-economic activities or propose the reasons for the variations in GHG emission concentrations in the atmosphere that caused the radiative forcing. As such, RCPs make no assumptions as to policy changes that may affect the climate; instead they only delimit the range of possible forcings that might occur. This facilitates the work of climate modellers, who now focus on the effect of a given level of radiative forcing on the climate without having to consider how to model permutations and changes in human behaviour over time.

For climate modelling, the radiative forcing trajectories represented by RCPs serve as the new starting point for climate change analysis. Policy analysts and researchers can work back from these trajectories to investigate what may cause them. For a given level of radiative forcing, researchers can determine the corresponding CO_2e concentration associated with each RCP and deduce the emissions that can cause them.

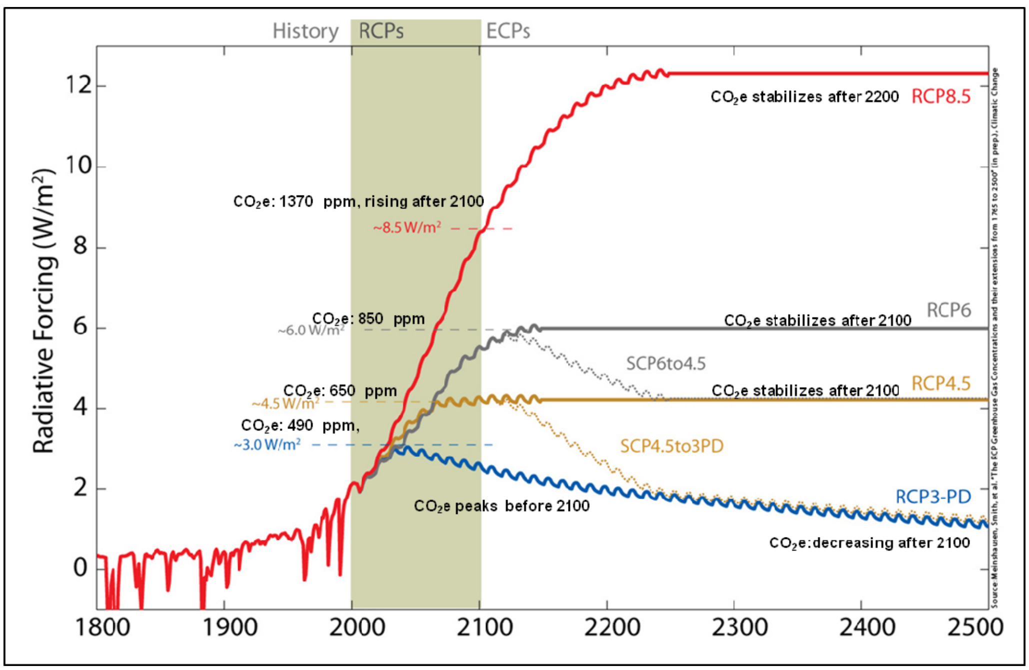
[28] ESCWA (2009), as adapted from Kropp et al (2009), p.47.

They can leave the challenge of identifying and analysing the policies that hinder or reinforce that level of radiative forcing to political scientists. This approach allows for more research into regionally-based socio-economic scenarios manifested in different parts of the world, and thus avoids generalizing human behaviour and response patterns across the globe. Different policy responses can then be simulated within the framework of a specific RCP to determine what leads or could lead to a given radiative forcing condition in the future.

For climate modellers, GHG emission scenarios have been superseded by radiative forcing trajectories that are detailed in RCPs. These trajectories currently correspond to four radiative forcings, each representing different peak levels of atmospheric CO_2 resulting from different development storylines, which could possibly incorporate the effect of mitigation policies.[29]

The range of radiative forcings is therefore currently defined by four RCPs whose broad outlines are expected to change little. There is general consensus that the maximum expected radiative forcing is unlikely to exceed 8.5 W/m^2 and the minimum radiative forcing achievable would not be less than 4.5 W/m^2. The four RCPs are known as RCP8.5, RCP6, RCP4.5 and RCP3-PD, named for the level of radiative forcing in W/m^2. The changes in radiative forcing would be equivalent to an increase in GHG emissions from a concentration of CO_2e of 455 ppm in 2005, to anywhere between 490 ppm and 1370 ppm by 2100.[30] Extended concentration pathways are simple extensions of RCPs beyond the year 2100.[31] This is illustrated in figure 9 and detailed below.

Figure 9. Representative concentration pathways and anthropogenic radiative forcing[32]



The difference between the four RCPs is based on whether the radiative forcing stabilizes, increases or decreases within a foreseeable future.

[29] Van Vuuren et al. (2009) and Moss et al. (2010).

[30] IPCC (2008), p. 34.

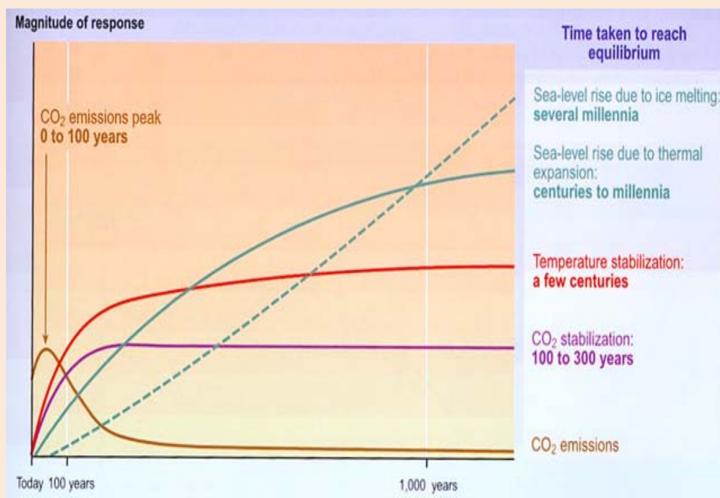
[31] Meinshausen et al. (2011).

[32] Ibid.

- **RCP8.5** shows the constant increase of radiative forcing, rising to more than 8.5 W/m^2 by 2100 and continuing to rise for some time thereafter. This concentration pathway represents the extreme case that applies in the case of little or no mitigation measures;
- **RCP6** reaches 6 W/m^2 in 2100, and then stabilizes at a higher level thereafter. An alternative pathway for RCP6 is one that peaks at 6 W/m^2 in 2100 and then declines, stabilizing at 4.5 W/m^2. The alternative pathway models the effect of delayed policy action and climate momentum;
- **RCP4.5** shows a stabilization in radiative forcing after a peak of 4.5 W/m^2 towards the middle and up to the end of twenty-first century. An alternative pathway for RCP4.5 peaks at 4.5 W/m^2 before 2100 and then declines after 2100 to follow the path of RCP3-PD. This shows the possibility of a delayed climate response to mitigation measures, reflecting the effect of delayed policy action and climate momentum;
- **RCP3-PD** represents an adapted emissions scenario, as it takes into account the positive effects of mitigation and emission reduction on GHG concentrations and therefore on radiative forcing; *PD* stands for the peak and decline that would result from aggressive immediate implementation of mitigation measures. Under this pathway, radiative forcing would still peak at approximately 3 W/m^2 before 2100 because of climate momentum, but it would decline thereafter. RCP-PD allows investigation into the reversibility of climate change and its impacts.

Climate change momentum

The current change in climate is due in part to a delayed reaction of the climate to past GHG emissions that have led to the increase in GHG concentrations over time. This results in the appearance that climate change gains momentum over time regardless of the current amount of emissions being released into the atmosphere. This is due to the thermal inertia of water, which causes the oceans (covering 70 per cent of Earth's surface) to store and release excess energy at a slower rate than the atmosphere.



Because of the ocean's thermal inertia, the climate is likely to adjust slowly to any mitigation efforts. The consequences of these relationships are illustrated in the figure above. Even if GHG emissions were reduced and the amount of CO_2 equivalent peaked within the next 100 years, climate change will likely continue to increase on its acquired momentum, with surface air temperature continuing rising for a century before stabilizing. The ocean's thermal inertia is such that their thermal expansion will continue, and ice cap melting will not stop right away. Both factors will continue to contribute to the rise in sea levels and changes in the climate.

Considering the slow progress in global compliance with reducing GHG emissions, RCP4.5 may represent a reasonable lower bound concentration pathway. Given ongoing efforts to curb increases in GHG emissions, RCP8.5 is a reasonable upper limit concentration pathway. Selecting these two RCPs would correspond with efforts being pursued by the Coordinated Regional Downscaling Experiment (CORDEX), whose members have agreed to run RCMs for those RCPs.[33] RCP4.5 and RCP8.5 were also selected as the highest priority for GCM simulations within the Coupled Model Intercomparison Project (CMIP), because they roughly correspond to the IPCC SRES emission scenarios B1 and A1, respectively.[34]

Representative Concentration Pathways – Helpful Hints

In view of positioning the Arab region within the global climate modelling community, the global dialogue on RCPs and in global negotiations over the coming decade, it is important that the Regional Initiative for the Assessment of the Impact of Climate Change on Water Resources and Socio-Economic Vulnerability in the Arab Region:

- Use RCPs as the basis for representing human socio-economic factors during climate modelling instead of the previously used emission scenarios detailed in the SRES;
- Determine which RCPs are most relevant for RCM implementation in the Arab region based on technical and political considerations;
- Identify which GCMs are available in the short term in which to nest RCMs for the Arab region and achieve results in the short term;
- Consider work being undertaken by the global community on the newly launched RCPs in view of benefiting and building upon lessons learned, including efforts being undertaken under CORDEX;
- Decide upon the one or more RCPs to be used as the basis for the based on the aforementioned considerations as well as time and resource constraints.

CORDEX members and other researchers engaged in dynamic downscaling must consider the availability of outputs being generated by GMC modellers for those RCPs. They must also consider the technical compatibility of GCMs running projections based on RCPs and RCMs that they would like to nest within them.

E. Dealing with scientific uncertainty

Climate policy-makers need to deal with uncertainty, and consider both climate surprises and the effect of approximations stemming from the practical limitation of computer modelling and data availability.[35] Two of the main approaches for dealing with uncertainty are addressed in this guide: using multimodel ensembles to reduce uncertainty and classifying uncertainties into a *typology of uncertainty*.

1. *Climate surprises*

To all those who model complex systems, *surprises* are probable events that lay outside the envelope of possibilities that have been considered. For climatologists, **climate surprises** are either related to the non-linear responses of the climatic system to anthropogenic forcing, or to possible events that would be too speculative to model.

[33] Gutowski (2010).

[34] Giorgi et al. (2009), p. 179.

[35] Moss et al. (2010), p. 747.

Because of its inherent chaotic nature, the climate can have non-linear responses to radiative forcing. These may manifest themselves as *tipping points* or by the path dependency of climate outcomes.

Climate **tipping points** occur when the climate shifts to a new equilibrium point. For instance, current climate change is happening and being modelled with a specified geographical domain within which all key processes and radiative forcing are relatively well understood. This is represented by inputting ECVs and generating model output fields, as detailed in table 2. Based on a consistent set of assumptions, relationships can be elaborated and well understood, even in the case of dramatic events such as an eventual melting of the Greenland Ice Sheet.[36] However, if emission concentrations and the rate of radiative forcing continue to increase, it may reach a critical threshold that is not previously known, and the climate could shift abruptly. This has happened frequently in the past, and the climatic history of the Earth suggests that when they occur, such shifts tend not to be smooth and could happen over a very short period of time. However, tipping points remain notoriously hard to predict.

Another important source of uncertainty is the **path dependency** of climate, in which the rate of change may be more important than the magnitude of that change. For example, an accelerated melting of the Greenland Ice Sheet could potentially lead to a sudden collapse in biophysical systems rather than a gradual withering away; it could also possibly shut off the Gulf Stream rather than merely slow it down. This could create a chain of adverse impacts that current climate models are ill-equipped to describe. On the global scale, the path dependency of the climate suggests that a faster rate of global temperature increases may magnify some climate impacts.[37]

The other type of climate surprise is based on **speculation** and is not well understood, even though the key processes that govern the projected outcomes of speculation can be properly modelled and known. Investigation based on speculation remains difficult because likelihood remains hard to determine, as was the case with the unexpected changes in the climate system of the Pacific Ocean. Based on present knowledge, it remains a policy decision as to whether to examine such potential events or not.

2. *Overcoming mathematical and physical limitations of models*

In computing climate model output fields, scientists face a practical limitation in programming climate processes related to constraints on the availability of computer power and storage. They address these challenges by carrying out approximations for their representations of real world processes of energy, momentum and mass conservation equations.

In practice, turning equations into computable idealized models requires both mathematical and physical approximations. As more processes have been added to GCMs, the systems have effectively grown to become composed of interacting model components, each of which simulates a different part of the climate system. These systems are either:

- **Resolved** mathematical approximations are pursued when the coupled non-linear equations that describe the various fluxes are replaced by discrete finite difference equations that are resolved numerically. Scientist resolve numerically those processes whose mechanisms are well described, as in the case of processes that transport heat, water, and momentum horizontally. Further approximations are due to the fact that the numerical solution depends on an arbitrary time scale that *bounds* different computation cycles. Even more approximations can result when interrelated parameters are resolved by iterative functions, thus requiring further loops based imperative repetitions that are sometimes defined by specific time steps that run before the programme steps forward.

[36] IPCC (2007b).

[37] ESCWA (2010b), p. 20.

- **Parameterized** processes are pursued when physical approximations are used for processes whose evolution is not well understood, or that are too resource-intensive to programme. Those processes rely on a mix of empiricism and fine-resolution to estimate and incorporate their effect. This is generally the case for processes that redistribute heat, water and momentum vertically and is also the case for sub-grid scale processes (within a grid box), which are too small to be resolved, or operate on time scales that are too fast.

Across all models, different numerical and physical techniques are used to resolve the values of the different classes of climate variables, and develop climate model output fields that cover the atmosphere, the ocean and the terrestrial surface.

The **atmosphere** is divided in two sub-domains, the atmosphere at the *surface* and the *upper air*, which are differentiated based on their composition. Climate simulations usually emphasize the troposphere and the lower stratosphere, representing a thin layer 20 km to 30 km thick that contains at least 95 per cent of the atmosphere's mass and virtually all of its water vapour.[38] While this layer is still affected by higher atmospheric levels, it is the one most relevant to the study of most weather phenomena.[39] Because of the disparity between scales, most climate models treat horizontal and vertical motions governing global and regional climate differently.

Such smaller scale phenomena as thunderstorms and turbulence can have a large scale impact on the upper regions of the atmosphere through the transfer of momentum. In the atmosphere, cloud formation tends to occur on the sub-grid scale, affecting such phenomena as cirrus and stratus cloud formation and dissipation, cumulus convection and turbulence. Because of the difficulty in calculating such sub-grid scale processes, scientists still struggle with the calculation of fractional cloud cover within a grid box. Either models predict cloud amounts diagnostically from the thermodynamic and hydrological state of the grid box at a given time step, or they compute cloud fraction as a prognostic, time-evolving variable. In both cases, climate models rely on sub-grid scale parameterizations for processes involving cloud formation, which has significant effects as the models are scaled down to represent smaller regional domains.

The **ocean** is *coupled* with atmosphere and ice models through processes that govern the exchange of heat, salinity and the momentum between them. The ocean is modelled similarly to the atmosphere, with much larger horizontal than vertical dimensions, and therefore a separation between the processes that control horizontal and vertical fluxes. However, unlike the atmosphere, ocean models need to account for a more complex three-dimensional boundary that includes enclosed basins, narrow straits, submarine basins, and ridges. Furthermore, the oceans are programmed with more parameterizations imposed both by the peculiar thermodynamic properties of sea water, and by the complexity of some of the processes that control the ocean. This is particularly the case of mixing near the surface, where processes can take place on very small scales, on the order of centimetres.

Because of its effect of heat transfers, this sub-grid scale mixing parameterization does not take into account the full spatial variations or differences between heat and salt in ocean waters. As models fail to accurately represent the real ocean's changes in deep temperatures, they do not properly treat the processes by which ocean currents give up their momentum. The net result is that the ocean is modelled like a viscous fluid unlike water. This affects the accuracy of circulation patterns over time scales of decades and longer, particularly because of the contribution of the mixing of its waters to its heat uptake and stratification. This contributes significantly to uncertainty in how the oceans interact with the global climate.[40]

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[38] Water vapour is the most significant GHG contributing to global warming.

[39] Pawson et al. (2000).

[40] Schopf et al. (2003).

An integral aspect of the climate system is the interaction between the **land surface** and the atmosphere. There, fluxes of mass, energy, water vapour and momentum occur near the interface. There are also biophysical and biogeochemical processes that control additional processes such as transpiration and carbon uptake. Those fluxes and additional processes are affected in turn by feedbacks between the atmosphere and the land surface, with important effects on the climate system. Initially, land models focused on vertical coupling of the surface with the overlying atmosphere, but they have recently been expanded to take into account more of the complexity of the effects of vegetation on exchanges of energy and moisture, plant transpiration, water flow through root systems, and carbon dioxide fluxes. Some models have recently been expanded to take into account horizontal water flows through river routing.

In general, algorithms become less and less dependent on approximations as computational resources continue to grow. However, in the present state of knowledge, the limitations of those approximations can still be easily overcome through the use of multimodel ensembles.

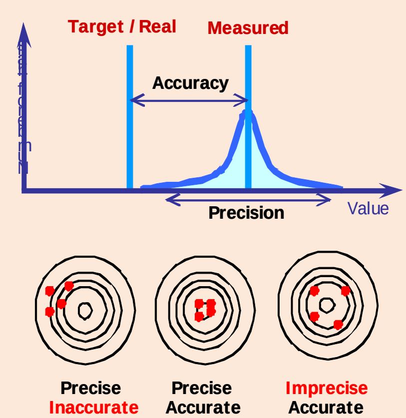
3. *Multimodel ensembles*

In multimodel GCM ensembles, any approximation errors are cancelled out through an averaging of the outputs of various models. In theory, such an approach is expected to work because, as more processes are included, choices will tend to differ across various models as to which ones to include, how to parameterize them and what to neglect. This approach is sufficient for the purposes of projecting the climate, and since the goal is to project the system's future state as closely as possible (which represents accuracy), agreement with other models (which represents precision) is not necessary.[41]

Accuracy and Precision

In climate science, it is more important to stress accuracy – the degree of veracity – over precision – the degree of reproducibility of an outcome. The difference can be illustrated on the normal probability distribution in the figure to the right.

Accuracy defines how close a measured or calculated quantity is to its actual true value, while ***precision*** is only a measure of reproducibility or repeatability that shows the degree to which measurements or calculations show similar results.



In climate modelling, the goal is to predict as closely as possible the system's future state. Furthermore, given chaotic influences on the climate systems, the same GCM run twice under the same conditions may not generate the same results. However, several runs of the same model under the same assumptions may increase its accuracy by creating a range of similar outcomes, which is why multimodel ensembles are often used.

The focus of climate modelling is therefore to reduce uncertainty by increasing the accuracy of outcomes.

[41] ESCWA (2009), p. 4.

While any model evaluation would be incomplete without an appreciation of its structure, intercomparison efforts are still very helpful. An increased amount of intercomparison effort has been taking place thanks to the wide availability of model simulation results in such databases as the **Coupled Model Intercomparison Project** (CMIP).

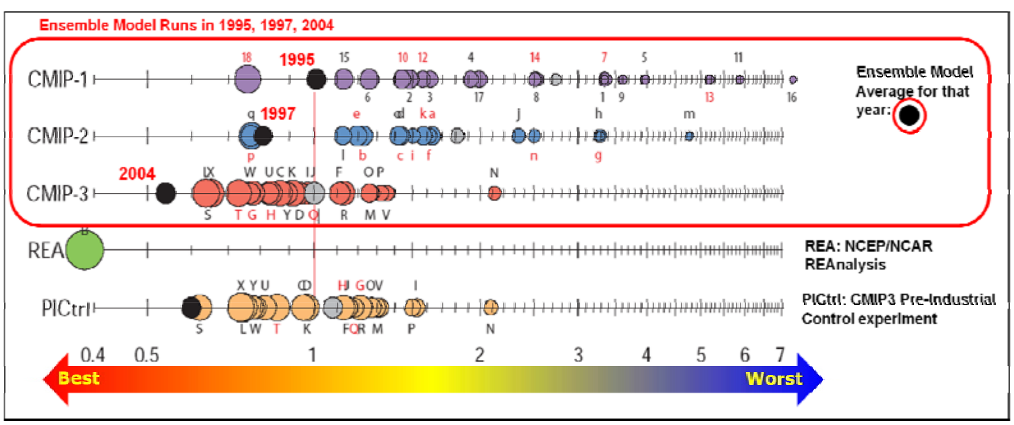
In general, evaluations that focus on specific aspects of the climate may not be adequate, and researchers have yet to agree on what aspects of the climate must be simulated to verify that future projections would be reliable. For example, a climate model that realistically simulates present-day precipitation in the Nile Basin may still not generate the most reliable projections of future precipitation in that region, not least because much of the rainfall in that area depends heavily on projected changes in the tropical Pacific Ocean.

However, evaluations that consider a model's overall strengths and weaknesses can provide adequate guidance. Researchers have started developing metrics to help objectively evaluate the ability of models to simulate a set of well-observed climate features, using the mean climate of the late twentieth century as a reference. By 2007, the CMIP database was in phase three (CMIP3), with over 35 terabytes of daily climate data archived, covering a variety of time intervals. In addition to AR4 and AR5 related experiments, the archive also stores control data covering a pre-industrial time period and the present day, the *Climate of the 20th Century Experiment* (20C3M) which covered the period from 1850 to the present, and a climate sensitivity experiment to test the climatic response to a doubling in CO_2 levels.

By the time of CMIP3, the dataset included daily climate data from 22 models from a variety of countries and institutions. This database allowed researchers to measure model performance in two ways: an intercomparison of the skill of different models in evaluating current climate and an evaluation of the overall progress of climate modelling and the validity of using multimodel ensembles.

The validity of the multimodel ensembles methodology was verified through an intercomparison of aspects of climate for which there were adequate climate observations with the outputs of various multimodel ensembles, resulting from CMIP1 in 1995, CMIP2 in 1997, and CMIP3 in 2004. As shown in figure 10, the intercomparison showed that the CMIP3 ensemble-mean (represented by the black dot), from the most recent ensemble model, had performed much better than any individual model.

Figure 10. Assessment of the relative skills of individual CMIP3 models[42]



[42]Gleckler et al. (2008), p. 8 and p. 20.

Ensemble modelling has also been improving over the years, with CMIP1 doing better than CMIP2, and CMIP3 doing better than most.[43] The following models are included in the archive of CMIP3:

- BCCR-BCM2.0 (Bjerknes Centre for Climate Research, in Norway);
- CGCM3.1 (T47 and T63) of the Canadian Centre for Climate Modelling and Analysis (Canada);
- CSIRO-Mk3.0 of the Atmospheric Research (Australia);
- CNRM-CM3 of Météo -France's Centre National de Recherches Métérologiques (France);
- ECHO-G, a joint effort of the Meteorological Institute of the University of Bonn (Germany) and Meteorological Research Institute of KMA (Korea);
- GFDL-CM2.0 and GFDL-CM2.1 Geophysical Fluid Dynamics Laboratory (United States);
- GISS-AOM, GISS-EH, and GISS-ER of NASA/Goddard Institute for Space Studies (United States);
- FGOALS-g1.0 LASG of the Institute of Atmospheric Physics (China);
- INM-CM3.0 of the Institute for Numerical Mathematics (Russia);
- IPSL-CM4 of the Institut Pierre Simon Laplace (France);
- MIROC3.2 (hires and medres) of the Center for Climate System Research at the University of Tokyo and JAMSTEC (Japan);
- MRI-CGCM2.3.2 of the Meteorological Research Institute (Japan);
- ECHAM5/MPI-OM of the Max Planck Institute for Meteorology (Germany);
- CCSM3 and PCM of the National Center for Atmospheric Research (United States);
- UKMO-HadCM3 and UKMO-HadGEM1 of the Met Office's Hadley Centre for Climate Prediction and Research (United Kingdom).[44]

As climate models continue to improve, it becomes necessary to quantify how any future design changes can affect overall performance. This is best done by continually evaluating model performance against a wide range of metrics, in addition to "striving for a single index of overall skill."[45] This is done by comparing GCM outputs with aspects of climate for which there are adequate observations. Those consisted of statistical measures of relative error that show how closely climate model output fields (table 2) agree with observations. Differences between simulated and observed climate data provide grades for the individual models, which are computed based on an average of the relative errors over all fields considered.

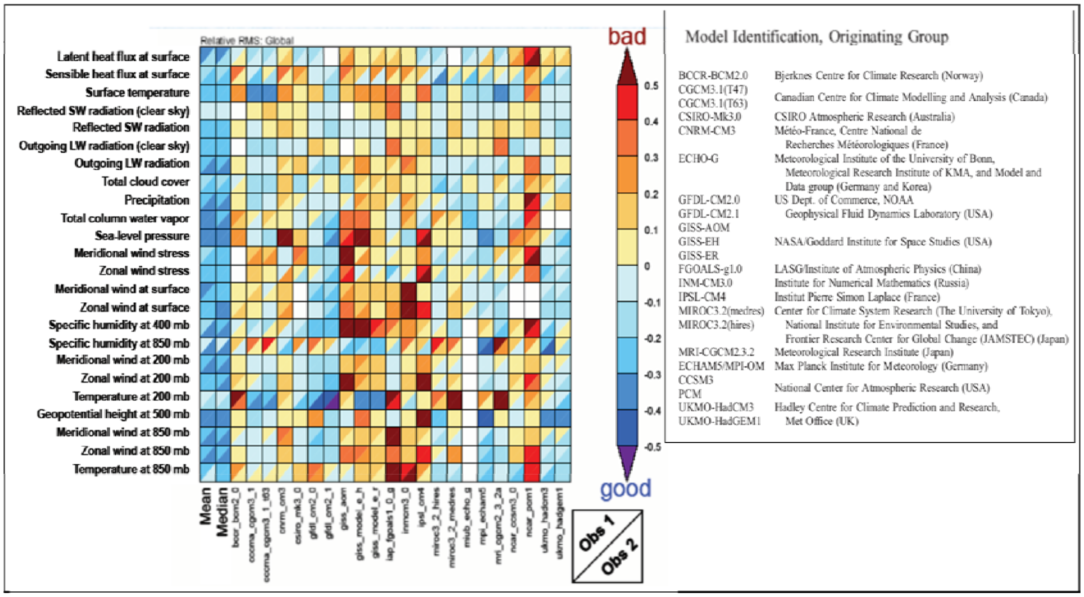
A comparison between the model output fields of different GCMs and climate observations is shown in figure 11. In the long run, any shortcomings can be overcome by using observations either to fine-tune the processes programmed, or to refine their parameterizations. Model intercomparisons reveal an interesting fact: even if models with the lowest error rate tend to do better than average in projecting most individual parameters, the model with the lowest total errors may not be the best choice for an individual application.

[43] Reichler and Kim (2008) and Gleckler et al. (2008).

[44] Gleckler et al. (2008).

[45] Gleckler et al. (2008), p. 18 and p. 20.

Figure 11. Intercomparison of GCMs prediction ability for some key parameters[46]



Such a result allows scientists to feel confident that the complexity of the true climate system can be more accurately rendered through ensemble models. Now that they have established that ensemble models can outperform any of the best single models, scientists can use them to develop more accurate projections of the future climate.[47]

Because those projections will depend on the accuracy of climatic data and the solution processes, scientists still have to focus on developing a specific treatment of uncertainty at the global scale, in addition to the collection and storage of local climatic data.

4. *IPCC's typology of uncertainty*

In spite of improvements in the performance of computer models, climate scientists are mindful of important fundamental limitations to their craft, not least because uncertainty lies at the heart of the physical sciences. Contrary to mathematics, where clear cut algorithms are used to prove the falsehood of a theorem physical theories are based on hypotheses which are tested by falsification, as a single result can falsify them. Because the validity of physical theories will remain uncertain, policy-makers follow either of two approaches: they can bound this uncertainty, or they try to manage it.

In controlled scientific studies, uncertainty can be **bound** by isolating the studied system or its components, then proceeding to identify, investigate and resolve unknowns one by one. However, in the study of climate change, the complexity of the system is such that the system cannot be broken up into core components. The only practical option is therefore to manage this uncertainty. In this case, scientists create models or representations of reality, and use those models to investigate a system's response to various disturbances under the various pressures caused by different concentration pathways.

Uniquely, however, climate scientists face a dual challenge: not only do they have few control scenarios to compare against, they must take into account the fact that uncertainty tends to increase with each

[46]Reichler and Kim (2008) and Gleckler et al. (2008).

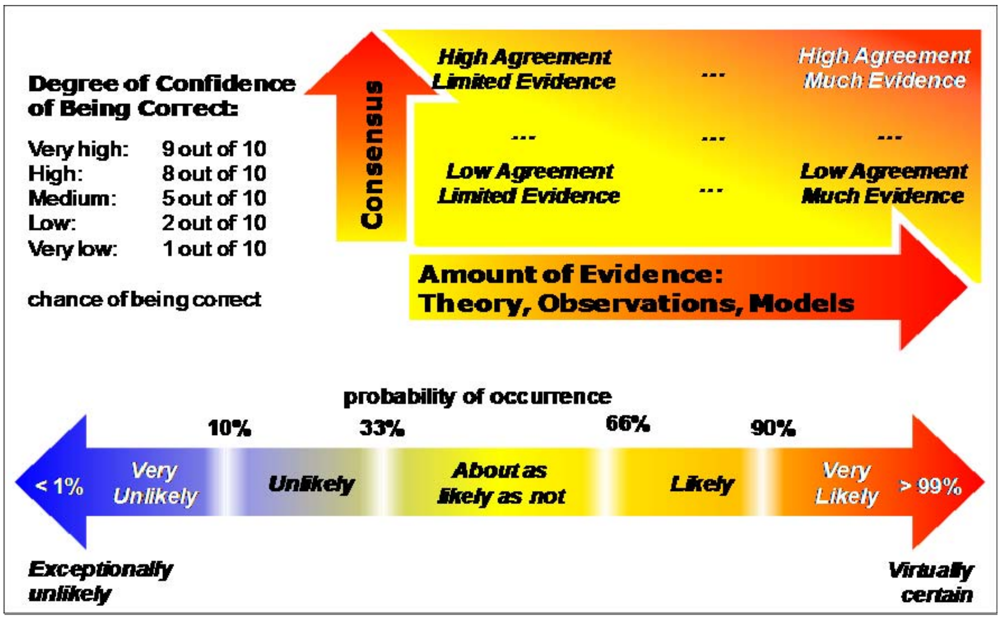
[47]Buser et al. (2009), p. 850.

level of measurement and each computing cycle.[48] As uncertainty accumulates through the sequence of computation cycles, they feed an *uncertainty explosion* composed of the following three ranges:

- **The first range** comprises all uncertainties of the climate system. This range includes climate surprises or events whose likelihood of occurring cannot be fully determined;
- **The second range** is one of judged uncertainty, defined by expert judgments;
- **The third range** is a narrower range of well-calibrated uncertainty, in which computer models allow experts to refine their judgments further.

It is within this well-defined range of well-calibrated uncertainty that climate science works to inform policy-making about the likelihoods of specific events. IPCC has therefore elected to focus on managing uncertainty by developing a typology of uncertainties that defines degrees of doubt about various climate outcomes, as presented in figure 12.[49]

Figure 12. IPCC's quantitatively defined levels of understanding and confidence[50]



It should be noted that IPCC's typology of uncertainty does not replace other tools for reducing uncertainty, such as the application of multimodel ensembles during climate modelling or hydrological modelling. Rather, the typology quantifies the degree of uncertainty, assisting researchers in determining how much confidence to place in outcomes and expressing the probability of the occurrence of future climate events.

[48] ESCWA (2009), p. 27.

[49] Moss and Schneider (2000), p. 38.

[50] IPCC (2010).

F. Future trends in global climate research

GCM capabilities have expanded since the first IPCC report due to growth in the scientific body of knowledge and advancements in information technology. Most of this progress is related to computer modelling and data acquisition. Progress in climatology allowed model programmes to create an ever clearer picture of the state of the future climate. More powerful computers allowed scientists to simulate an ever larger proportion of the climate system's interactive and iterative processes.

1. *State-of-the-art in computer modelling*

Thanks to the progress in computing power and programming techniques, most major climate models can now more accurately describe the interactions of the Earth's various biophysical systems than was the case five, ten or twenty years ago. Most climate scientists, however, still need to compromise high resolution from model runs to save on computing power.[51] Given constraints on storage and technical capacity, the length of the time steps is another compromise that is often necessary. While "the set of compromises has decreased" thanks to progress in computing power and programming techniques, scientists still face many obstacles.[52] The most dominant obstacles are limited computing power and the limits of scientific understanding, particularly concerning such fine scale processes that define the climate as evaporation or cloud formation. These limitations are being overcome by such research and development efforts as those in Japan, where GCM with a horizontal resolution of 3.5 km x 3.5 km to 10 km x 10 km has been developed.[53] Likewise, at King Abdullah University of Science and Technology in Saudi Arabia, new investments in state-of-the-art technologies has generated climate modelling outputs for the Arabian Peninsula by applying a fine resolution GCM rather than using RCMs.[54]

As these models reach smaller scales in space and time, their output data will grow to reach the order of hundreds of exabytes, which will create significant storage challenges that require additional financial and technical resources. These developments might also increase opportunities for cloud computing, where needed software and data storage is distributed across servers shared across the Internet. In any form, the generation of fine scale and shorter-term outputs will require a significant increase in computing capabilities, with systems at least a thousand times more powerful than the computers currently available.[55] Based on current trends, such systems could become available by 2030, but may require new computer architectures and technologies that overcome physical limitations of current designs.

Accordingly, for the near to medium term, most efforts to generate fine scale climate simulations and projections for the Arab region for the past and future require RCM downscaling from GCMs.

2. *Data sources and data collection*

An important part of climate change assessment is the collection of observed meteorological data, which can be obtained from both in situ and remote sensors. In situ sensors are distributed amongst a network of ground stations that measure weather information at the surface and in the upper-air at different atmospheric altitudes.

Data from meteorological stations has been collected, digitized, and standardized into the Historical Climatology Network, a database managed by the National Climatic Data Center (NCDC). NCDC was

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[51] ESCWA (2009), p. 6.

[52] ESCWA (2009), p. 6 and Shukal et al. (2009), p. 176.

[53] Shukla et al. (2009), p. 176.

[54] Zampieri (2011).

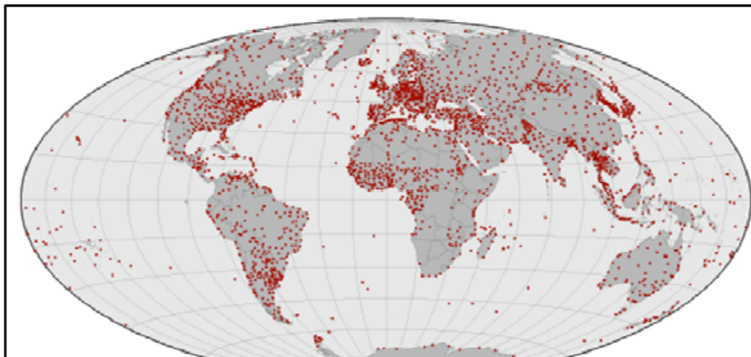
[55] Shukla (2009), p. 176.

established in 1951 as the records centre of the United States Department of Commerce and handles most of the data of the United States National Oceanic and Atmospheric Administration, a scientific agency focused on the condition of the oceans and the atmosphere. The NCDC reportedly has the largest record of historic climate data, with records extending back more than 150 years, and with 224 gigabytes of new information added each day.[56]

Yet, as shown in figure 13, some regions remain unsampled. This is mostly because most of the data obtained before the 1960s was obtained from ground stations. In significant areas of North Africa, particularly in and around the Sahara and large parts of the Arabian Peninsula, such stations were either not yet established or their records have yet to be digitized. This lack of integration of local data in the Historical Climatology Network database is a source of concern as it limits opportunities to assess and raise understanding about the impact of climate change and climate variability in the Arab region. This can be remedied thanks to projects such as the NCDC's Colonial Era Archive Data Project, which aims to find and digitize past records.[57]

Records can be dramatically improved not only because of the addition of new ground stations, but also because of increased resolution from remote sensing tools, both on the surface, and across the atmospheric column. Indeed, while ground-based stations can sample and collect observations directly, they can only measure atmospheric conditions at the discrete locations where they are placed. Across the surface of the globe, this leaves spatial gaps in the collected weather information that is equivalent to the spacing between ground stations, as illustrated in figure 13. Remote sensing tools can fill those gaps; once properly calibrated, they can measure weather information anywhere across the globe and along the atmospheric column. Such fine grained data thus provides a more complete and continuous picture of atmospheric conditions.

Figure 13. General locations of ground-based weather stations[58]



Source:
http://earthobservatory.nasa.gov/Features/GISSTemperature/giss_temperature2.php

Remote sensing tools can be both *active* and *passive*. Active sensors, such as radars, send electromagnetic energy and measure such parameters as the distribution of water vapour across the atmosphere. Those systems are now increasingly deployed on ground stations and some satellites, thanks to improvements in electronics and information technology. Passive sensors remain the most common types of remote sensing instruments and provide most of the fine grained, continuous picture of the atmosphere.

Passive sensors are calibrated for specific type of natural radiation emitted or reflected by the Earth, represented by *bands* of electromagnetic frequency. Radiometers and photometers collect reflected and

[56] Additional information about NCDC is available at: http://www.ncdc.noaa.gov/oa/about/whatisncdc.html.

[57] For more about the project: http://www.ncdc.noaa.gov/oa/climate/research/ghcn/colonialarchive.html.

[58] Peterson and Vose (1997).

emitted radiation in a wide range of frequencies and can provide detailed data on GHG concentrations in the atmosphere by detecting the emission spectra of those particles. At the global level, the bulk of this data is gathered by satellites.

Satellites outfitted with **passive sensors** can detect infrared, microwave, gamma ray, ultraviolet and waves in the visible spectrum. Each type of radiation can reveal a different type of information. For example, infrared radiation can reveal temperature, and can therefore help reveal irrigation intensity or evapotranspiration rates. They can also detect *multi-spectral* data, generating images in multiple wavelengths that convey a multiplicity of information. The data are used to create extensive thematic maps that describe land use patterns in detail. This allows for long-term and large-scale follow-up of desertification, deforestation, urbanization, and agricultural patterns. Satellites and airplanes can be used to collect geodetic data that show minute perturbations in the Earth's gravitational field due to changes in the planet's mass distribution. This can help reveal changes in groundwater. Finally, satellites can capture aerial images of the visible spectrum combined in stereographic pairs to create detailed topographic maps.

The quality of remote sensing data is defined by its spatial, radiometric and temporal resolutions:

- **Spatial resolution** is defined by the size of pixels in an image, and ranges from 30 cm to 1,000 m depending on the type of data collected.
- **Radiometric resolution** depends on the wavelength used by photometers and radiometers.
- **Temporal resolution** depends on the frequency of flyovers by satellites or airplanes, and is essential to reveal changes in land use, forest cover, desert area, or agricultural patterns. Any measure of a rate will depend heavily on this.

Measuring chemicals in the atmosphere

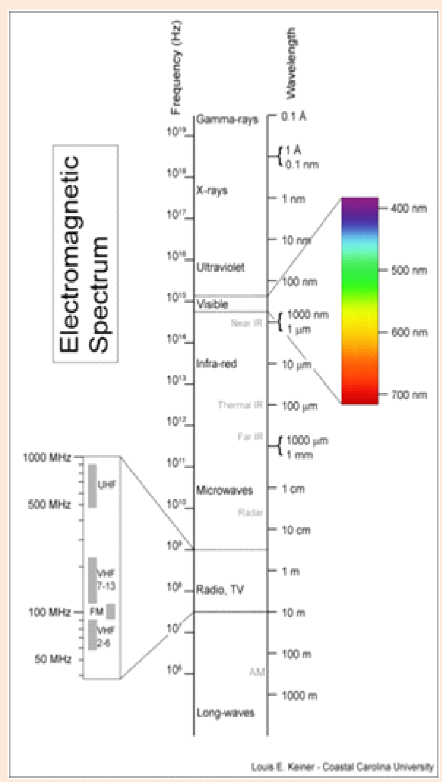
Thanks to the unique ways in which atoms react to electromagnetic radiation, the type of chemicals and their composition can be remotely measured.

The Sun and the Earth's energy are transmitted through space as **electromagnetic radiation**. This radiation is classified according to its wavelength, from the lowest frequency radio waves, to microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and the highest frequency gamma rays.

This range defines an **electromagnetic spectrum** of all the possible frequencies of this Electromagnetic Radiation.

When an atom absorbs energy, the electrons that orbit its nucleus move to a *higher orbit*, which corresponds to a higher energy level. As they *climb down* from that level, the energy is re-emitted by the atom. Each atom absorbs and emits specific levels of energy.

As a result, each type of chemical in the atmosphere has a unique **absorption band** and emits a specific spectrum of frequencies of electromagnetic radiation. Because each element's **emission spectrum** is unique, chemicals can easily be identified remotely, and the **chemical composition** of the atmosphere can be simply identified by measuring the emitted electromagnetic radiation.



Thanks to the profusion of satellites and the progress of information technology, there is a profusion of data sources, many of them available online.[59] The data in those archives is at varying levels of usability. Because data can be processed at different levels, the levels are codified from the most fundamental and onwards:

- **Level 0**: This is the raw data. The information consists of unprocessed instrument data such as the value of infrared radiation measured;
- **Level 1**: To all specialists except those operating the satellite, this is the most fundamental level of information. At this level, some or all the data have been processed to give a higher level information. For example, data on infrared radiation can be processed to give information about surface temperature. At level 1a, the process can still be reversed to the original data. At level 1b, the data are further processed and the basic information cannot be recovered;
- **Level 2**: The data here are used to derive geophysical variables the same resolution and location as level 1 source data. For example, infrared data could be used to derive soil moisture contents or ice concentration levels;
- **Level 3**: The data in level 3 are mapped at the resolution required by the end-user. At this level, more rules are applied to ensure completeness and consistency; missing points can be interpolated or outlying values disregarded;
- **Level 4**: This represents any variables derived from instrumental data. An example is measures of evapotranspiration rates. This data can then be compared to RCM or GCM projections for the time period considered.

An example of relatively raw satellite data (level 2) is NASA's "A-Train Data Depot," which provides distributed atmospheric measurements from its A-Train instruments.[60] More processed data (Level 4) provide information on specific parameters. One example is the Aerosol Robotic Network, an international collaboration centred on ground-based remote sensing tools to provide a "continuous and readily accessible public domain database".[61] Detailed information on specific climate events, such as weather and climate extremes, can also be obtained from such sources as the European Climate Assessment & Dataset project.[62]

In general, accessing the data is only part of the task, as the need for analysis and storage remains even for the highest level data. This is a particular concern for the Arab region, where there is an urgent need for available and accessible observed climate data to support global and regional climate modelling.[63]

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[59] For example, the Climatology Office of the University of Virginia maintains an online database available at: http://climate.virginia.edu/online_data.htm.

[60] Data available at: http://daac.gsfc.nasa.gov/atdd.

[61] Additional information is available at: http://aeronet.gsfc.nasa.gov/.

[62] Additional information is available at: http://eca.knmi.nl/.

[63] El-Asrag (2009).

CHAPTER RECAP

Running a **global climate model (GCM)** requires the:

- ☑ Review of global climate trends based on observed data;
- ☑ Review available GCMs and selection of two or more GCMs to form the basis of the climate simulations in the region;
- ☑ Selection of at least one RCP to define the assumptions and range of the GCM simulations generated, which would be among the RCPs being used in the preparation of IPCC's Fifth Assessment Report (AR5);
- ☑ Consideration of which GCMs have generated outputs for which RCPs given their recent introduction;
- ☑ Clarification of the interface between the GCMs and RCMs under consideration;
- ☑ Recognition of the uncertainties and unexpected events at the global level in order to develop an appreciation of their implications at the regional level;
- ☑ Assurance that the current work fits in with future trends and developments in climate modelling and data collection.

Completing the aforementioned actions contributes to the following **outputs**:

- ➲ Identification of global climate change trends based on a specific set of parameters related to each RCP at specific time steps that would contribute the basic assumptions for regional climate modelling;
- ➲ Validation of GCM models to provide inputs into regional climate modelling, and selection of one or more RCP;
- ➲ Generation of coarse findings for a broad set of parameters at a resolution generally covering a 200 km x 200 km to 300 km x 300 km horizontal grid box.

III. STEP 2: REGIONAL CLIMATE MODELLING

A. Downscaling from global to regional climate modelling

For all the progress in GCMs, important gaps remain in generating outputs on a smaller scale grid. In order to better understand those smaller scale processes, climate scientists *scale down* their models to describe limited areas of the world. There are generally two main downscaling approaches:

- **Statistical downscaling**, also known as empirical downscaling, involves developing statistical equations relating the output of a climate model from a GCMs or RCM to a national, subnational or local climate represented by atmospheric observations. These relationships can then be used to project local climate based on GCM or RCM projections.

- **Dynamical downscaling**, also known as numerical downscaling, refers to the use of RCMs. Typically, an RCM is nested within a GCM, which drives the RCM through an interface representing lateral boundary conditions.[64]

Statistical downscaling techniques are computationally cheap, but they are based on the assumption that climatic processes are stationary, which is unlikely to be the case in the medium to long term. As shown in table 3, the relative advantages of dynamical downscaling techniques makes them better suited for climate modelling. Statistical downscaling may still be useful for weather forecasting, which requires a shorter-term time horizon and has comparatively fewer computing requirements. Even in such a case, the reliability of statistical downscaling techniques is highly dependent on the quality of the meteorological observations used to develop their underlying relationships.

TABLE 3. COMPARISON OF DOWNSCALING TECHNIQUES[65]

	Advantages	**Disadvantages**
Statistical downscaling	• High resolution information possible • Some techniques allow for a diverse range of variables to be measured • Variables are internally consistent • Computationally inexpensive • Rapid application from multiple GCMs and scenarios possible	• Assumes that statistical relationships developed for the present day climate also hold for possible future climates • Needs access to daily observational surface and/or upper air data • Application is geographically specific; non-transferable to other locations
Dynamical downscaling	• Highly resolved information • Physically based • Relies on many variables • Better representation of large scale phenomena, including some weather extremes	• Computationally very expensive • Need for interface to ensure two-way nesting between RCM and GCM • Dependent on usually biased inputs from the forcing GCM • Fewer scenarios or RCP projections may be available

All downscaling techniques may still face one key limitation, which is forecasting the frequency and intensity of extreme weather events. In general, GCMs focus on providing the *mean* future climate state and do not necessarily produce the *extremes* around that mean. Furthermore, extreme weather events are not

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[64] Fowler et al. (2007).

[65] Adapted from Mearns et al. (2003).

normally reflected at the smaller regional level unless smaller time steps and more detailed climate observations are available to generate outputs. This aspect is an important factor to consider in the Arab region where endemic water scarcity makes countries sensitive to small changes in climate that can lead to extreme events. This has prompted the Regional Initiative to pursue additional RCM runs at smaller time scales to better support the prediction and projection of extreme events.

Higher resolution of RCM generally improves climate simulations for processes that have high spatial variability such as precipitation, and thus yield better predictions of distribution, inter-annual variability and intensity. Because of this, RCM setups often involve *two-way coupling* in which the nested RCM supplies part of its output back to its parent GCM in order to improve the accuracy of the model outputs. In this manner, RCMs improve GCM projections.

B. Regional climate model implementation

The first steps in RCM involves framing regional boundary conditions, identifying the relevant model output fields sought, establishing the interface between RCM and GCM in which it is nested, setting the resolution of the model and fixing the time steps to be applied for generating outputs.

1. *The Arab Domain*

Moving from GCM to RCM requires the delineation of the geographic domain within which RCM would be undertaken. Effort is thus underway within the framework of the Regional Initiative to establish an Arab Domain for structuring RCM within the region, and to propose it for inclusion within CORDEX, a coordinated international effort among climate centres to generate multimodel ensembles and improve RCM techniques.[66] Doing so requires that the standards and practices adopted under CORDEX be applied when establishing the limiting boundary conditions (LBCs) of the Arab Domain and running RCMs within it. This requires consideration of existing domains established under CORDEX to avoid duplication and facilitate access to finer regional climate information in shared boundary areas. Researchers will benefit from previous RCM runs generated in those shared boundary areas for supporting the validation of RCM outputs.

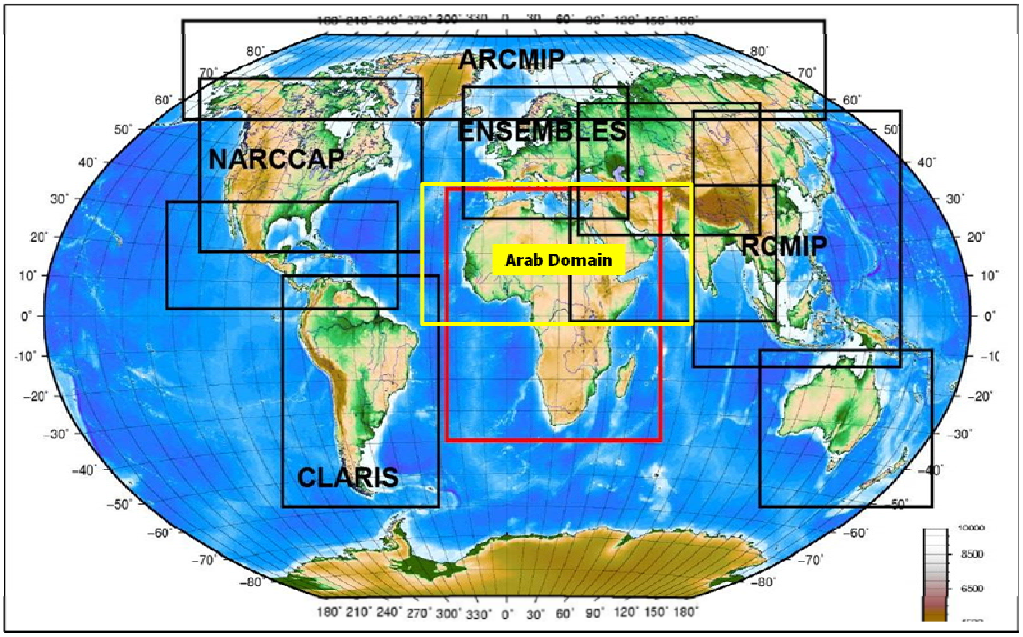
The actual extent of the Arab Domain will need to be determined based on a detailed sensitivity analysis. During this analysis, considerations should be given to the boundary conditions in the Africa Domain set up by CORDEX, and ascertain the extent of the domain boundary. This is because the implementation of downscaling requires the inclusion of a *buffer zone* around the nested RCM. By surrounding the domain of interest, this buffer zone serves to damp down the driving GCMs state towards RCM's boundary conditions provided by the field of LBC. This buffer zone needs to be large enough in both the horizontal and the vertical direction. In the horizontal direction, a *thin* buffer zone could suffer from phase errors in simulating such weather systems as storms that transfer across the world and this could lead to significant errors in the overall regional simulation. In the vertical direction, an incorrectly placed buffer zone for a region of rapidly varying topography can induce surface-pressure errors.

Within this framework, the boundaries of the Arab Domain should be selected so as to encompass all headwaters of shared water sources found in the Arab region. Because about 67 per cent of water resources in Arab countries originate from outside of the region, the Arab Domain should encompass a wider geographic area, extending from the headwaters of the Nile in the south, to the origins of the Tigris and

[66] This effort is being led by the Swedish Meteorological and Hydrological Institute (SMHI) in partnership with the WMO, ACSAD, League of Arab States and ESCWA as part of the project funded by the Swedish International Development Cooperation Agency (SIDA) to support the implementation of the Regional Initiative for the Assessment of the Impact of Climate Change on Water Resources and Socio-economic Vulnerability in the Arab Region. The SIDA-funded project supports all four pillars of the Regional Initiative, including the application of RCMs and RHMs in the Arab region, as well as the analysis of extreme weather events.

Euphrates in the north. A sensitivity analysis is also necessary to determine the exact extent of the boundary based on regional and global climate patterns and characteristics.

Figure 14. The CORDEX domains and the proposed Arab Domain[67]



Delineating the Arab Domain – Helpful Hints

The delineation of the Arab Domain involves:

- ☑ Defining its geographic boundaries;
- ☑ Considering and benefiting from the boundaries established under other CORDEX domains;
- ☑ Determination of the necessary grid size and grid distribution, as well as the parameters that will need to be measured and computed;
- ☑ Determination and standardization the subdivision of an Arab Domain into physiographic regions for hydrological modelling.

2. *RCM output fields*

The list of parameters tracked by RCM implementation will be largely defined by the archive of CORDEX. In its current version, the archive lists 57 variables that are needed to define a regional climate model output field. As shown in table 4, those variables correspond to GCM climate output field shown in table 2. CORDEX further groups them in three classes: Core, Tier 1 and Tier 2.[68] Core parameters are considered relevant to all communities, requiring RCM sampling of monthly and seasonal means. Tier 1 parameters require daily sampling of surface and some selected upper air data. Tier 2 parameters require a higher frequency sampling rate.

[67] Illustration adapted from Giorgi et al. (2009), p. 178, and CORDEX map available at: http://www.meteo.unican.es/en/projects/CORDEX.

[68] Christensen et al. (2011).

TABLE 4. REGIONAL CLIMATE MODEL OUTPUT FIELDS DEFINED BY CORDEX[69]

Domain		ECV	Description: minimal variable requirements	
			IPCC: GCM output fields	**CORDEX: RCM output fields**
Atmospheric (over land, sea and ice)	Surface	Air temperature	• Surface *skin* temperature • Near-surface (2 m): air temperature, daily-maximum, daily-minimum	Same as GCM output fields
		Wind speed and direction	• Eastward winds • Westward winds • Near-surface winds (10 m)	Same as GCM output fields
		Water vapour/ Precipitation	• Water evaporation flux from canopy, humidity (specific, relative) • Precipitation • Convective precipitation • Snowfall • Atmospheric water vapour content	Same as GCM output fields
		Pressure	• Air pressure on the ground surface and at sea level • Surface downward stresses due to wind	Same as GCM output fields
		Radiation budget	• Sensible & Latent Heat Flux • Upward/Downwelling heat fluxes (long wave and shortwave) • Heat flux corrections • Prescribed heat flux (into slab ocean)	• Sensible & Latent Heat Flux • Downwelling heat fluxes (long wave and shortwave) • Upward heat fluxes (shortwave) • Duration of sunshine
	Upper-air: (Up to the stratopause)	not applicable	• Atmospheric boundary layer thickness (meters)	Same as GCM output fields
		Air temperature	• For each specified pressure elevation	• At 850 hPa, 500 hPa, 200 hPa
		Wind speed and direction	• For each specified pressure elevation: Eastward and Westward winds, geopotential height	• At 850 hPa, 500 hPa, 200 hPa: Eastward and Westward winds • 200 hPa: geopotential height
		Water vapour/ Precipitation	• For each specified pressure elevation: cloud parameters (area fraction, ice content, water content)	• at 850 hPa : specific Humidity • Total Cloud Cover (Low, High, Medium) • Column Ice Water Content and Water Vapour
		Radiation budget	• Heat fluxes incoming and outgoing (long wave and shortwave)	• Flux at the top of the atmosphere • Outgoing long-wave • Short-wave (incident and outgoing)
	Composition		• Mole fraction of ozone in air • Concentration of sulphate aerosols (NO_x, SO_x)	Not specifically required

[69]GCOS (2011), IPCC (2009) and WCRP (2004).

TABLE 4. REGIONAL CLIMATE MODEL OUTPUT FIELDS DEFINED BY CORDEX *(continued)*

Domain	Description: minimal variable requirements	
	IPCC: GCM output fields	**CORDEX: RCM output fields**
Terrestrials	• Surface runoff, snow (area fraction, amount, melt flux) • Glaciers (land ice area fraction) • Permafrost (soil frozen water content) • Soil moisture (content, content at field capacity, content of soil layer, root depth)	• Surface runoff, Snow (Area fraction, amount, depth, melt) • Permafrost (Soil frozen water content) • Total moisture content

3. *Resolution and time steps*

In addition to setting the boundary conditions of the Arab Domain, the model must generate outputs based on a clearly defined resolution and time steps.

- **Resolution -** The Arab Domain map requires assessments at a horizontal resolution no larger than 50 km x 50 km given the interest of representing regional phenomenon at the national and subnational level, even in the smaller sized countries of the region. This is technically feasible because the resolution difference from the driving GCM data to RCM can be of the order of six to eight.[70] Since the horizontal resolution of GCMs are generally between 200 km x 200 km and 300 km x 300 km, the horizontal grid size for RCM covering the Arab Domain can be between 50 km x 50 km and 25 km x 25 km, or even less.

- **Time step -** RCMs can compute model output fields every 20-30 minutes, but the results are stored for a longer time scale normally beginning at three or six hour increments. A major determining factor affecting the analysis and distribution of results hinges on the storage and processing capacity of the computer system to handle such data.

The resolution and the time steps to be applied by the model are selected based on technical and political consideration and objectives.

With the grid scale defined, the climate model output fields that are required for implementation at the regional level can be agreed upon. It may not be necessary to track and record all climate model output fields defined by IPCC for GCM output in different regions. The final list of parameters will depend on the need to ensure that the outcomes of the integrated assessment fit in with global and regional efforts.

4. *Validation of the regional model for the Arab Domain*

On the regional level of the Arab Domain, the multimodel **ensemble** approach will be relevant for the reasons that make it necessary for the global domain. RCM will therefore be based on running two or more independent models that appropriately resolve the model output field that needs to be generated by the RCM simulation.

At first look, model independence should be easy to ascertain; provided various models are developed independently, choices will tend to differ across various models as to the process included and how they are programmed or parameterized. This leads to very different models and decreases chances of having many variants of the same model, and decreases chances of inbreeding, or having many variants of the same model.

However, the fact remains that, while the outputs of ensemble modelling efforts work well when the models have been developed and run separately, it is likely that some level of inbreeding may persist among

[70] Rummukainen (2010).

models. This is because of good scientific practice that leads scientists to share knowledge. Therefore, even when models have been developed relatively independently by different groups around the world, they tend to rely on a common pool of methodologies that resolve the same processes in a similar manner. Errors included by parameterization or unresolved processes could then be transferred across models and result in persistent biases in a multimodel mean.[71] However, doing so still allows for better comparison across outputs.

In spite of their higher resolution, RCM may also still need parameterizations for some sub-grid scale processes, particularly for boundary-layer dynamics, surface-atmosphere coupling, radiative transfer, and cloud microphysics. It may therefore be necessary to continuously verify the model as the regional implementation proceeds apace. In the long run, various shortcomings can be overcome by using observations either to *fine tune* the programmed processes, or to refine their parameterizations.

At the regional level where the implementation calls for two to three models, the effect of such persistent biases will be more significant than at the global level where more than 20 models can be considered. Additionally, because regional implementations resolve fewer key climatic parameters than those included in global climate assessments, it is important to ensure that models minimize errors in the resolution of those variables. An **ensemble** of region climate projections can be achieved by:

- Using different feeding GCMs when running an RCM more than once;
- Using different RCMs to run the same GCM;
- Implementing a model at different horizontal grid resolutions, e.g., at least one at a 50 km x 50 km horizontal grid resolution, and at least one at a 25 km x 25 km horizontal grid resolution;

RCM Implementation – Helpful Hints

- ☑ Review processes that are specific to the Arab region and incorporate them as needed;
- ☑ Coordinate an ensemble of regional climate projections and support intercomparison and diagnostics of models based on CORDEX protocols among climate research centers, based on one or more RCMs in order to reduce uncertainties, pool resources and save computing time;
- ☑ Develop regional observational datasets for use in regional climate prediction, climate change projection and downscaling;
- ☑ Archive of higher temporal frequency outputs to allow for detailed evaluation, ensuring that regional climate information needs to be easy to obtain, use, and validate;
- ☑ Investigate role of RCM implementation in future research aimed at producing more realistic future climate based on RCP; improving representation of driving forces and climate components, incorporate more processes such as biogeochemistry and the effect of deserts.

C. Uncertainty in the context of regional specificities

Fundamentally, approaches to uncertainty are similar for GCM and RCM implementations. Yet, at the regional level there are added sources of uncertainty, one related to downscaling, the other to extreme climate events.

The largest source of uncertainty is related to **downscaling**, and results from the mathematics and physics of the driving GCM and the way RCM is nested within it. The integration will allow for greater access to quality-controlled datasets of the recent historical past and twenty-first century projections. This could lead to a suitable set of regionally-specific metrics for downscaling evaluation that integrates well with

[71] Tebaldi and Knutti (2011), p. 2068.

a benchmark framework for model evaluation and assessment, thanks to the coordination of a range of RCM simulations for the defined domains.

However, solving those uncertainties may require additional changes in the way some processes are resolved or parameterized, to better account for regional specificities, particularly concerning large uncertainties that result from ill-defined extreme climate events. On the one hand, integration within CORDEX would allow for better control over uncertainties in regional climate change that are associated with different GCM simulations. The simulations are carried out to determine the impact of the forcing associated with various RCPs of GHG, taking into account natural climate variability. On the other hand, the regional impact of outside events would remain hard to model, especially when GCM themselves struggle to develop projections of those events.[72]

Understanding Likelihood

Although the concept of likelihood is well understood, it can be misinterpreted.

A case in point is reference to a “100 year event,” such as a “100 year flood event.” The term describes an event that it has been known to occur, on average, every 100 year or so. This is equivalent to saying that the event’s average chance of occurrence within any single year is about 1 per cent, or once every century. However, it also follows that the event has the same likelihood of occurring over 10 successive years and then not occurring for another 990 years after that over a 1,000 year period.

1. *Regional specificities*

Because GCMs struggle with resolving smaller scale, sub-grid processes, they cannot be simply scaled down and applied to finer grid sizes. Their parameterization needs to be modified to better incorporate smaller scale phenomena that are relevant at the regional level. Those phenomena require a different approach to the ways climate models resolve the atmosphere, the land surface, and the oceans.

In the **atmosphere**, clouds generated by cumulus convection tend to be largely based on empirical relationships. This is the case not only for the atmosphere, but also for turbulent transports near the surface, where scientists parameterize momentum, moisture, and energy. The fact that turbulent fluxes occur near the surface means that they depend on land conditions such as roughness, soil moisture, and vegetation, in addition to being affected by turbulent atmospheric flow and energy dissipation in the higher layers of the atmosphere.

At the **boundary interface** between the land and the atmosphere, scientist have to account for the effect of small scale hills, where non-turbulent pressure forces lead to momentum transfer between atmosphere and surface. These are a potential issue for the Arab Domain:

- Large desert areas have varying surface reflectivity, as the albedo of exposed sand surface may change significantly across space and time with varying levels of moisture. Some land surface models already account for variations in albedo, factoring in the *masking* that results from the interaction between vegetation and snow.

- In the large desert areas, the presence of dunes may be a source of concern as they could affect small scale phenomena. Dunes grow and move throughout the years, thus acting like *mobile hills* whose distribution changes across the surface. At smaller grid scales, moving dunes can have an effect on the desert’s surface roughness because of its vast expanses.

[72] Fowler et al. (2007), p. 1556.

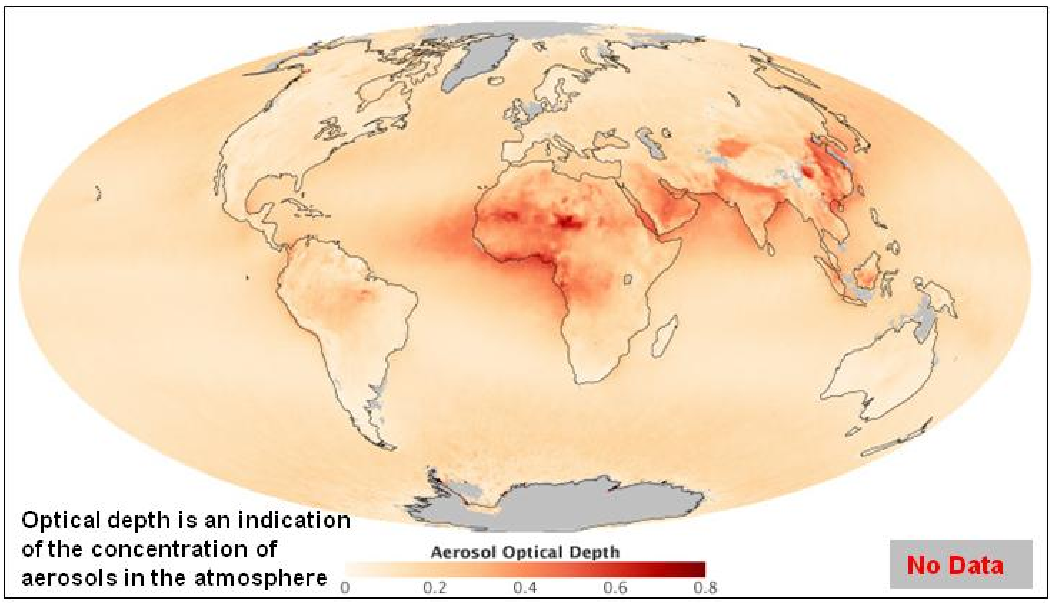
Albedo[73]

The albedo indicates the surface's reflectivity to sunlight, It is computed as a ratio of *diffusely reflected* to *incident* electromagnetic radiation. A higher albedo values mean more of the Sun's energy is reflected. Some sample albedo values are provided below:

Snow:	0.40 (old) to 0.85 (fresh)	Soils:	0.05 (dark/wet) to 0.35 (dry)	Desert:	0.25 to 0.29
Ice:	0.30 to 0.40	Asphalt:	0.04 (fresh) to 0.12 (worn)	Crops:	0.15 to 0.25
Water:	0.05 to 0.07	Concrete:	0.50 (new)	Forest:	0.05 to 0.15
Sand:	0.20 (wet) to 0.45 (dry)				

In addition, aerosols can magnify some local effects. **Aerosols** are fine hybrid particles made up of liquid droplets and/or solid particles that remain in suspension in the atmosphere. Figure 15 shows the average worldwide distribution of aerosols from June 2000 through May 2010. They originate mostly from such natural sources as dust storms in the great deserts of the Sahara and the Arabia Peninsula, volcanoes, forest fires, and human emissions (about 10 per cent of the total). Their cumulative effect can impact such critical phenomena as cloud formation, as demonstrated by recent studies using climate model simulations that show how past European aerosol emissions helped shift rainfall patterns away from the Sahel region, provoking a succession of devastating droughts in the region.[74]

Figure 15. Global concentration of atmospheric aerosols in 2006[75]



At the global scale, the effect of aerosols can also be significant, since the large majority of aerosols are generated by dust storms over the Sahara and the Arabian Peninsula. RCM implementation over the Arab Domain could therefore contribute to a proper understanding of their behaviour, thereby improving the characterization of their large scale impact.

[73] Data compiled from Hansen, 1993; Coakley, 2002.

[74] Kaufman et al. (2002), Sylla et al. (2009) and Held et al. (2003).

[75] Voiland (2010). Data measured by the Multi-angle Imaging SpectroRadiometer (MISR).

Within the ocean's stratified structure, vertical mixing takes place on scales from meters to kilometres, and is affected by variation in salinity and turbidity across the water column. In addition, there are very energetic currents and eddies that occur in the ocean on the scale of a few tens of kilometres. Rather than being resolved, those processes are generally parameterized for different reasons; while smaller scale processes are parameterized because they occur on sub-grid scales, larger scale processes impose heavy computer costs. Both those parameterizations introduce some uncertainties on the global scale.

- On the regional scale of the Arab Domain, this uncertainty may need to be addressed by resolving the Mediterranean Sea explicitly rather than simply parameterizing it.

- At the very least, the parameterization of turbulent mixing near the surface may need to be verified, particularly on the shallow seas such as the Strait of Hormuz or Bab-El-Mandab area.

- Parameterization may not be sufficient in the cases where geothermal processes are actively adding energy into the system, such as in the Arabian Sea near the Bab-El-Mandab area, or in the Atlantic across from Morocco.

RCM Implementation and Extreme Events – Helpful Hints

- Characterize region-specific processes to validate which processes need to be resolved, and which ones parameterized, taking into account the frequency, intensity and duration of extreme weather events and the possibility of climate surprises.

- Ensure observational datasets for extreme weather events are available for use in regional climate prediction and downscaling, including short-lived extreme weather events.

- Coordinate regional model intercomparison and diagnostics in accordance with protocols established within the CORDEX framework and in WMO Regional Climate Outlook Forums in order to facilitate research and exchange extreme weather events within the context of RCM implementation.

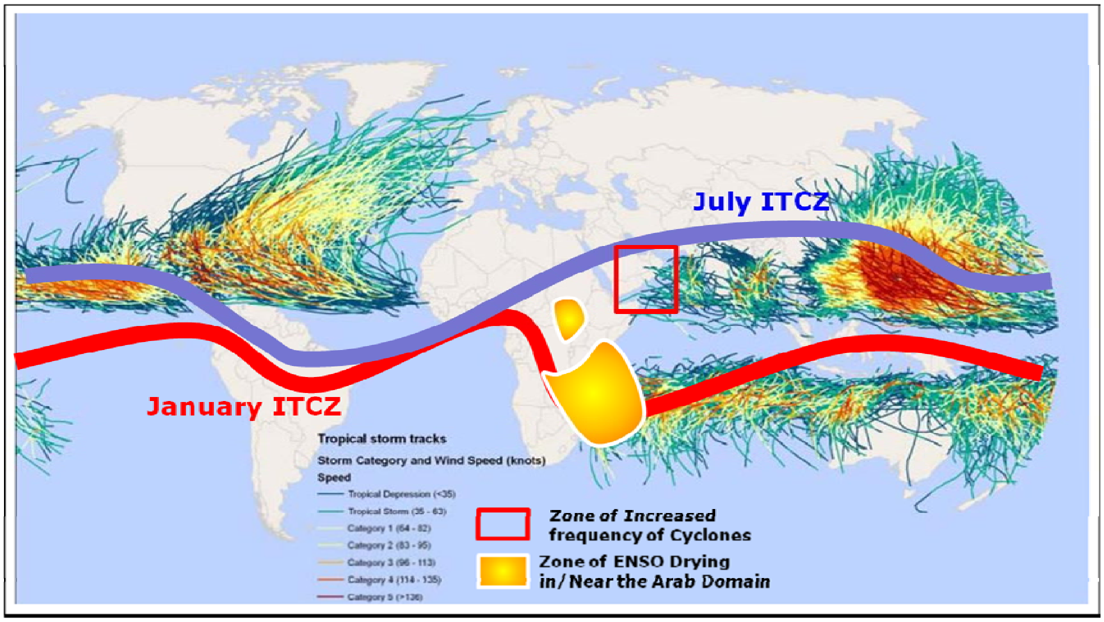
2. *Climate surprises*

In addition to the climatic surprises that GCMs cannot specifically predict, RCMs need to account for key climatic events that are not well understood at the global level. Some of those events may have significant effects on the region. Examples of such events include changes in the path of the Inter-Tropical Convergence Zone (ITCZ), and variations in the El Niño-Southern Oscillation[76] (ENSO). Figure 16 shows the outline of the known upper and lower extremes of the ITCZ, together with the zones that fall within the expected extent of the Arab Domain that tend to be most affected by ENSO.

ITCZ is an equatorial band of low pressure 10° latitude wide (about 1,100 km) in which both the northeast and southeast trade winds converge. It plays a key role in defining the climate of the Arabian Peninsula and the Nile Basin. In addition, those two regions are also affected by ENSO events, which affect the intensity of monsoon rains that feed the Upper Nile Basin. Indeed, variations in the flow of ITCZ can shift the path of rain clouds by up to 40° to 45° latitude away from the equatorial region of Africa. This is influenced by many local parameters, from land temperatures to atmospheric aerosols.

[76] Also known as "El Niño and La Niña".

Figure 16. ITCZ and the effect of ENSO over the Arab region[77]



More uncertainty, and potentially even climate *surprises* can result from the interaction between events outside the Arab region. For example, the interaction between aerosols and ITCZ can have effects on climatic patterns in the Arabian Peninsula that remain poorly understood. Indeed, aerosol formations such as the brown haze over South and East Asia appears to be playing a key role in the shift of tropical rainfall patterns southward, and they may be affecting mid-latitude systems in the region with potentially severe consequence as far away as Australia.[78]

In spite of overall improvement in GCM simulations, such events and their interactions remain poorly understood.[79] As a result, scientists cannot rely solely on the results of RCM simulation to understand those events. They need to investigate specific simulations that are designed to factor in the global impact of those events and show their local impact.

Reducing Uncertainty – Helpful Hints

- Within the CORDEX framework, explore different ways of generating ensemble simulations with RCMs, in order to better estimate uncertainty.

- Ascertain the projected impact of global climate changes at the local and national level by testing against historical databases, and drawing upon RCM outputs.

D. Data coordination in a regional framework

The establishment of an Arab Domain would allow researchers to conduct test simulations of the present climate to evaluate model performance. The large amount of information that will be generated by RCM requires coordination at the regional level, which is best done through the establishment of a regional

[77] Adapted from Thow and de Blois (2008), p. 14.

[78] Rotstayn et al. (2007).

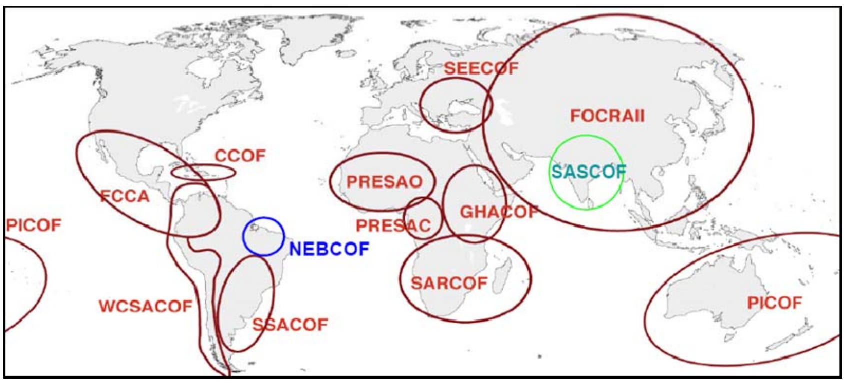
[79] IPCC (2007a), p. 592.

climate centre (RCC) or regional data centre.[80] In order to facilitate coordination and scientific inquiry, the information generated by the RCM simulation should be made available as open access. CORDEX and WMO protocols may be drawn upon to support climate modelling exercises at the regional level.

The coordination could be conducted through a network of RCCs working together to serve the Arab region, or through a regional climate outlook forum (RCOF), set up by various institutes working in the region to produce reliable information on seasonal forecasts, climate variability and climate change with the objective of providing high quality and high resolution climate services. These different institutional mechanisms fall within the scope of WMO Global Framework on Climate Services.

RCCs are already in the process of institutional strengthening and networking in Egypt, Morocco, Tunisia and Saudi Arabia, and are soliciting the guidance of WMO to secure its accreditation as climate service providers. RCOF in turn would help foster a better understanding of the links between the climate system and socio-economic activities.[81] This would be translated into an increasing demand for climate services, a greater awareness of the importance of climate information, and enhanced interactions and exchange of information between the climate scientists and users of climate information. Several RCOFs have already been established throughout the globe; their coverage is illustrated in figure 17.

Figure 17. Regional climate outlook forums worldwide[82]



RCCs or RCOF could provide a valid scientific foundation for decision-making by facilitating transmission and use of user-oriented climate information and enhancing an understanding of climate risks. Its climate services should be:[83]

- **Available**: at time and space scales that the user needs,
- **Dependable**: delivered regularly and on time,
- **Usable**: presented in user specific formats so that the client can fully understand,
- **Credible**: for the user to confidently apply to decision-making**,**
- **Authentic**: entitled to be accepted by stakeholders in the given decision contexts,
- **Responsive and flexible**: to the evolving user needs, and
- **Sustainable**: affordable and time consistent over time.

[80] El-Asrag (2009).

[81] Kolli (2010), p. 22.

[82] Kolli (2010), p. 13.

[83] Kolli (2010), p. 5.

Data Coordination in a Regional Framework – Helpful Hints

- Develop regional observational datasets and mechanism for improving climate services through improved technical capacity, networking and improved communications and exchange between data stakeholders; climate modellers, data collectors and analysts, local communities, and policy-makers.
- Leverage the CORDEX framework to ensure a standard experimental protocols and community participation, to better determine the resolution of regional climate information required and ensure quality and homogeneity of data.
- Assess the impact of new climate observation systems or changes to existing systems, and promote and coordinate the conversion of research observing systems to long-term operations.
- Facilitate the exchange of best practices and lessons learned from climate modelling in the Arab region.

CHAPTER RECAP

Running a **regional climate model** (RCM) requires the:

- ☑ Consensus on the type of information sought from the regional climate modelling exercise, including agreement regarding the scope, resolution and time steps desired;
- ☑ Delineation of the Arab Domain based on a sensitivity analysis;
- ☑ Selection of one or more RCMs for application within the limits of the Arab Domain, that can draw upon information generated by one or more GCMs for areas outside the Arab Domain, in order to generate an ensemble of regional climate projections;
- ☑ Decision on the time steps and resolution to be used for generating information from the projections;
- ☑ Downscaling from global climate modelling to regional climate modelling;
- ☑ Consideration of uncertainties and unexpected events at the regional level, in the context of regional specificities;
- ☑ Data coordination and analysis in a regional framework, including provision of technical assistance for the development of long term daily homogenous climate databases and the collection and storage of data. Care should be taken to ensure data is stored in a reliable manner, and is easily and freely accessible.

Completing the aforementioned actions contributes to the following **outputs**:

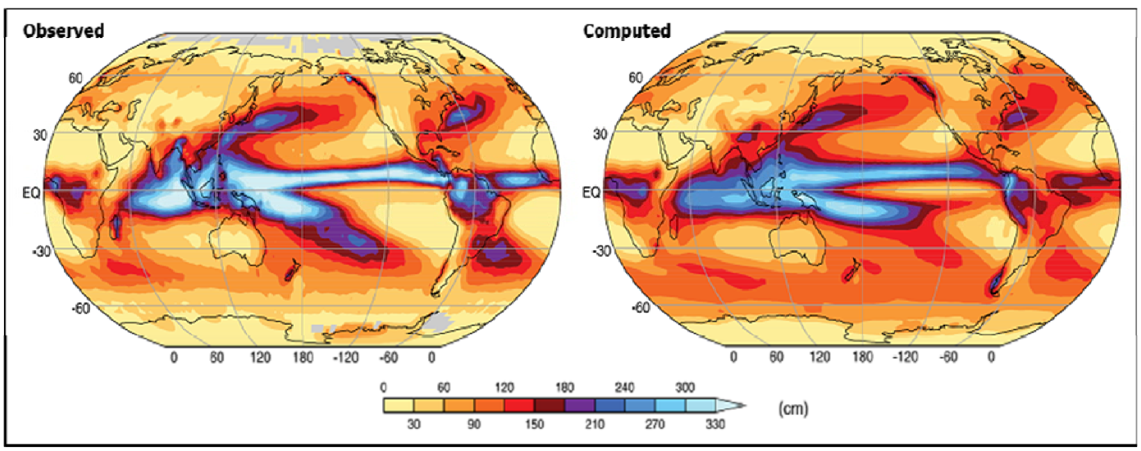
- ➲ Identification of regional climate change trends and impacts based on a specific set of parameters resulting from a specific RCP at specific time steps, and the identification of more complex interactions between newly identified regional impacts than those drawn from global climate modelling outcomes;
- ➲ Standardized geospatial data sets for projected climate impacts in the Arab region from one or more RCMs based on specific parameters and time steps, resulting from the selected RCPs and generating higher resolution outputs based on a 50 km x 50 km to 25 km x 25 km horizontal grid box;
- ➲ Identification and assessment of data needs, data sources, data availability, and potential gaps needed to validate the climate model and calibrate the hydrological model to improve results at the regional scale.

IV. STEP 3: REGIONAL HYDROLOGICAL MODELLING

As the climate changes, so will one of its key aspects: hydrology. This change in the prevailing climate accelerates the rate at which water is transformed through its different stages. For instance, climate change is likely to accelerate evaporation and precipitation rates, thus modifying the availability of fresh surface water. Dramatic changes in the water cycle are unprecedented in modern human history; indeed, the consistency of the water cycle has been the basis of the assumption of hydrologic stationarity, which is the principle upon which policy-makers and water resource managers have traditionally relied for planning water infrastructure and preventing risks for well over a century.[84]

Fundamentally, hydrological stationarity implies that the future will be statistically indistinguishable from the past. This may have been a useful operational hypothesis during the course of the past century, but is no longer valid in a context where specific characteristics of the climate system have changed. This has been reflected by GCMs simulations that have shown significant changes in the hydrologic cycle at the global scale. At such scales, scientists have been able to rely upon GCMs to accurately describe global expected changes in precipitation. The comparison illustrated in figure 18 below shows the consistency between observations and computer simulation of annual mean precipitation over the past century.

Figure 18. Agreement between observed and computed annual mean precipitation[85]

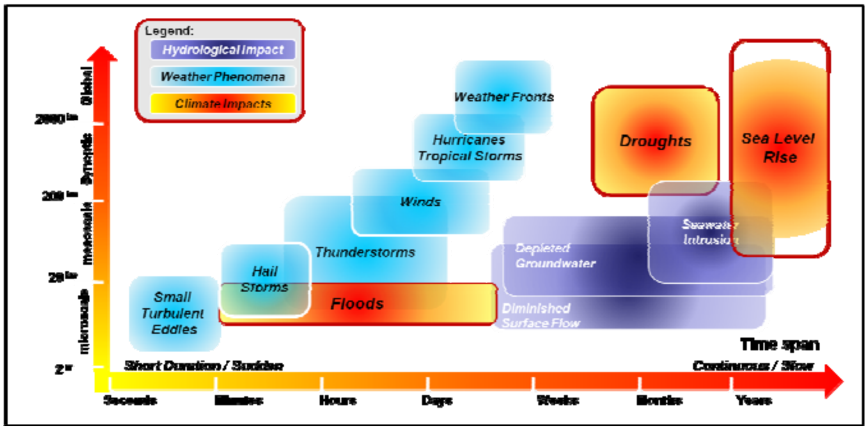


For all the improved accuracy of climate models at the global and regional scales, climate model output fields still cannot be used by themselves to accurately inform hydrological studies. This is because climate models are only designed to study the water cycle as part of the larger climatic system. Furthermore, climate models are generally sensitive to regional and local seasonal climatic variations that occur at spatial resolutions below those that they can model. As shown in figure 19, some climate phenomenon, particularly extreme weather events, occur over seconds, minutes and hours and impact much smaller geographic scales than currently can be modelled in a GCM or RCM, which store data at longer time steps (sub-daily, daily, monthly) and cover a 10 km x 10 km horizontal resolution. Accordingly, as the scale gets smaller, the various scales of hydrologic processes need to be considered more precisely in terms of both space and time.

[84] Fowler et al. (2007) and Bates et al. (2008).

[85] IPCC (2007a).

Figure 19. Different scales of typical climate-related phenomena



Additionally, such a difference in scale among various key processes means that, while the water cycle is essential to the climate cycle, the relevant aspects to be considered differ depending on the study focus. Because GCMs and RCMs focus on meteorological variables, they do not delve into the detailed aspect of the water cycle; as such the structure and accuracy of the data from their model output fields preclude *their direct use for hydrological impact studies*.[86] Accordingly, while those processes can often be satisfactorily parameterized for purposes of climate modelling, RHM is better suited to take such data and generate outputs necessary to inform hydrologic studies on runoff, recharge rates, snowpack, etc.

A. From climate models to hydrological models

At the global and regional level, results from GCM simulations show that climate change is expected to result in an increase in average temperatures, resulting in a sea level rise and an acceleration of the hydrologic cycle. The rise in temperature will very likely be in the range of 1.8°C to 4°C by 2100 depending on various emissions scenarios, with possible extremes of as little as 1.4°C and as much as 5.8°C. In general, warming is expected to be greatest over land and at most high northern latitudes. Already, because of rising average temperatures, *cold days, cold nights, and frost have become less frequent, while hot days, hot nights, and heat waves have become more frequent* over the last 50 years of the twentieth century.[87]

From a perspective of hydrology, it is now clear that rising temperatures will accelerate the hydrologic cycle because of how water acts as the atmosphere warms. Unlike other gases, water cannot significantly accumulate in the atmosphere as it warms.[88] Increasing temperatures will increase evaporation rates, causing clouds to form faster resulting in more frequent uneven rainfall. In this manner, the water cycle will be accelerated.

Increased temperatures feed more water into the hydrologic cycle and speed up the rate at which this water passes through the cycle of evaporation, condensation, and precipitation. This is suggested by recent studies based on GCM simulations, which show that any increased precipitation is more likely to come as heavier rainfall, akin to *cloud burst* events, rather than as more frequent rainfalls or falls of longer duration. Data collected towards the end of the twentieth century support the fact that the hydrologic cycle had already

[86] Fowler et al. (2007), p. 1557.

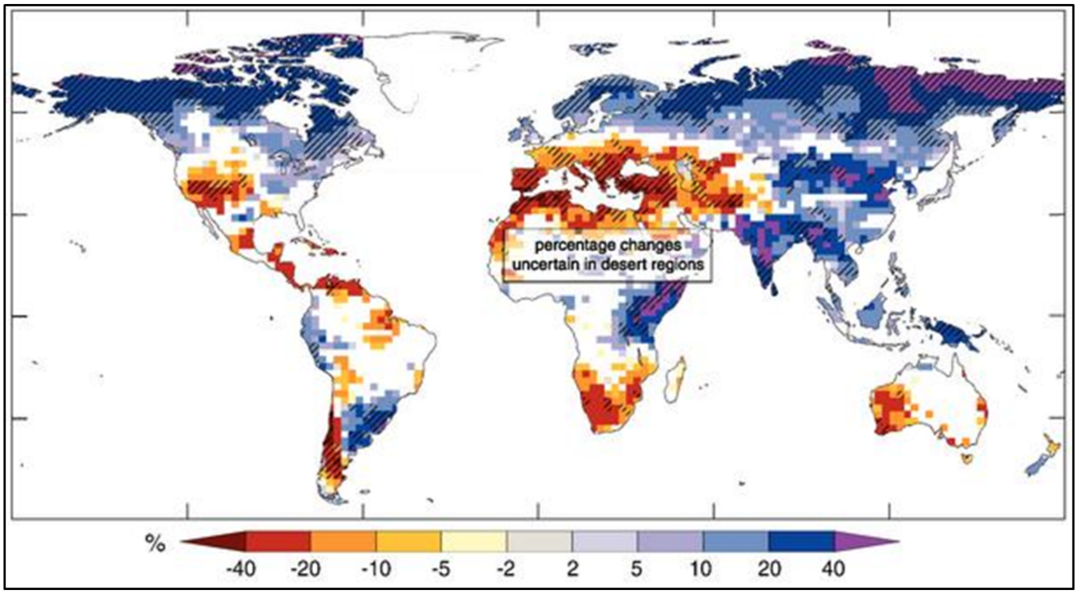
[87] IPCC (2007a).

[88] Kiehl and Trenberth (1997). Even if 36 to 75 per cent of the greenhouse effect is due to water in the atmosphere (two thirds of it due to water vapour, the rest to clouds), water's contribution remains generally unchanged. The contribution of the other GHGs can increase with increased temperatures, since there are no limits to their concentration in the atmosphere.

intensified. Data collected between 1900 and 2005 show an increase in the frequency of heavy precipitation events over most land areas.

However, as shown in figure 20, there are large gaps in this analysis, mostly because of scale limitations of climate models. Changes to runoff remain *uncertain* over the large arid and semi-arid areas that make up most of the Arab Domain. Such gaps are of particular concerns for semi-arid and arid regions, where a proper understanding of future hydrologic processes is essential. Any hydrological analysis cannot therefore rely exclusively on climate modelling, and requires specific hydrological modelling to describe regional hydrology.

Figure 20. Changes in annual runoff based on GCM[89]



RHMs, which investigate climate-induced changes to the water cycle at the regional level show how regional hydrology is impacted at scales relevant for water management. A model of hydrological systems at a fine resolution will *fill the gap* between climate modelling and regional hydrology. The hydrological models would use the relevant RCM generated regional climate output fields as input data, and generate predictions for the regional hydrology.

B. Inputs to the regional hydrological model

The implementation of RHM over the entire Arab Domain would complement RCMs and address the highlighted shortcomings, by providing an accurate description of local hydrology. RHM would be applied over the varied range of sizes of watersheds in the Arab Domain. In order to help address any uncertainties that may arise, different RHMs could be used as part of an ensemble RHM to investigate regional hydrology across the Arab Domain. This ensemble approach takes differences between large and small-scale basins into account when calibrating the hydrological model across the region.

Additionally, models used in RHM for the Arab region should have been applied in previous water-balance studies and thus have the ability to simulate all relevant hydrologic processes, particularly those that occur in semi-arid and arid areas. In general, this functionality would be defined by a large range of processes, such as:

[89] IPCC (2007b), p. 73.

- **Soil-vegetation processes** – including canopy rain interception and evaporation, fog drip, stem-flow, snowmelt, and evapotranspiration.
- **Soil moisture storage and runoff generation processes** – including infiltration and saturation, depression storage, shallow subsurface runoff, preferential flow, and overland flows.
- **Groundwater flow** – particularly in sandstone or karst formations.
- **Channel routing and human-induced effects** – such as road processes and structures, including hill slope runoff interception, precipitation interception, flow diversion and stream-crossing structures as culverts, in addition to other factors such as lakes, wetlands, and water control structures.

Interactions between surface water and groundwater flows, and processes related to evapotranspiration have the greatest relevance for RHM for the semi-arid areas of the Arab Domain. The model should be able to represent the river flow network of the region, which needs to be described at various scales. The quality of RHM implementation would depend on its ability to discretize or divide time and space.

Time discretization largely defines implementation complexity. When models perform simulations they do so at specific time intervals which can be sub-daily, daily, or monthly. The finer the temporal discretization, the more data and preparation are required. This has important implications for the integration of RCM with RHM, since the variables can be reported at different time rates. For example, while meteorological variables such as temperature and precipitation are often reported on a daily basis, hydrological variables such as flow rates may need to be evaluated on an hourly basis. When detailed results are needed, detailed information is required to obtain the relevant data. In RHM, data would be reported depending on implementation needs, and RHM would use data from various global databases particularly those where key climatic parameters are described as part of RCM output fields.

Space discretization is defined by a hydrological model's ability to discretize any given basin as lumped, semi-distributed, or distributed.[90]

- **Lumped hydrological models** are used to represent homogeneous areas where the spatial distribution of input variables or parameters is uniform. They often do not need a Digital Elevation Model (DEM);[91]
- **Semi-distributed hydrological models** are used in less homogeneous areas. They divide the watershed into areas that share similar hydrologic properties, such as elevation bands, hill slopes, or sub-basins. In addition, these models can create model-defined areas that share similar properties (land cover, elevation, slope, etc.) as Grouped Response Units, or Hydrologic Response Units. They typically require DEM to be able to define ground or hydrologic response units;
- **Distributed hydrological models** are used in the most heterogeneous areas and may be the most applicable. They tend to be computationally heavy, and require DEM as key input. Those models simply divide the watershed into equally sized grid cells, each implicitly representing a distinct Hydrologic Response Units with its own properties.

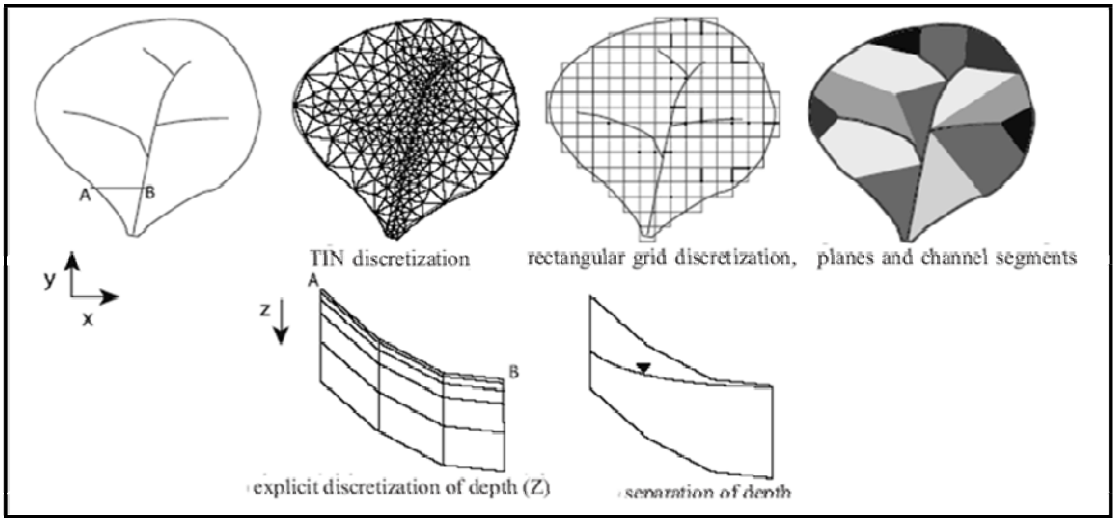
Typically, lumped hydrological models are used to represent homogeneous areas, where the spatial distribution of input variables or parameters is uniform. However, because the Arab Domain represents a heterogeneous area, RHM implementation would need to use a distributed modelling framework. RHM will therefore need DEM.

[90] Kampf and Burges (2007).

[91] DEMs are representation of the ground surface that excludes objects such as plants or buildings. Also referred to as Digital Terrain Model (DTM).

Additionally, hydrological models do not apply the same spacial discretization approach as climate models. Unlike the grid boxes of climate models, RHM can represent hydrological basins at a finer resolution and in a manner more reflective of watersheds and local characteristics, as illustrated in figure 21.

Figure 21. Hydrological model discretization[92]



RHM simulation model *detailed hydrological processes at high resolution simultaneously and homogenously across many river basins* by integrating forcing data from climate models with fine scale data about topography, soils and land cover.[93] In general, the inputs in RHM would be:

- **RCM outputs**, comprising data generated on precipitation, temperature and evaporation for each projection;
- **Elevation data**, which are used mainly to delimit watershed, and can be obtained by DEM;
- **Land parameters**, which are geographically referenced and need to include information on soil types and land use. Soil types include soil classifications and information on soil depth and soil profiles. Land use parameters include information on the extent of irrigated areas;
- **Hydrological data on surface water**, including information on rating curves, lakes, dams, channels and bifurcations, especially since the water may be taking a path different from the one that can be derived from topography.[94] RHM would also benefit from data on length of rivers and measurements of surface flows to help with any calibration;
- **Hydrological data on groundwater** including information about renewable groundwater resources, relevant aquifers, as well as water table level measurements and soil profiles.

By incorporating landscape elements and hydrological compartments at proper scale and along the flow paths, RHM can effectively simulate processes such as snowmelt, surface runoff, drainage and groundwater flow, as well as transport and transformation in rivers and lakes. Global databases could be relied upon, such as HydroSHEDS by the United States Geological Service, which provides geo-referenced

[92] Fowler et al. (2007).

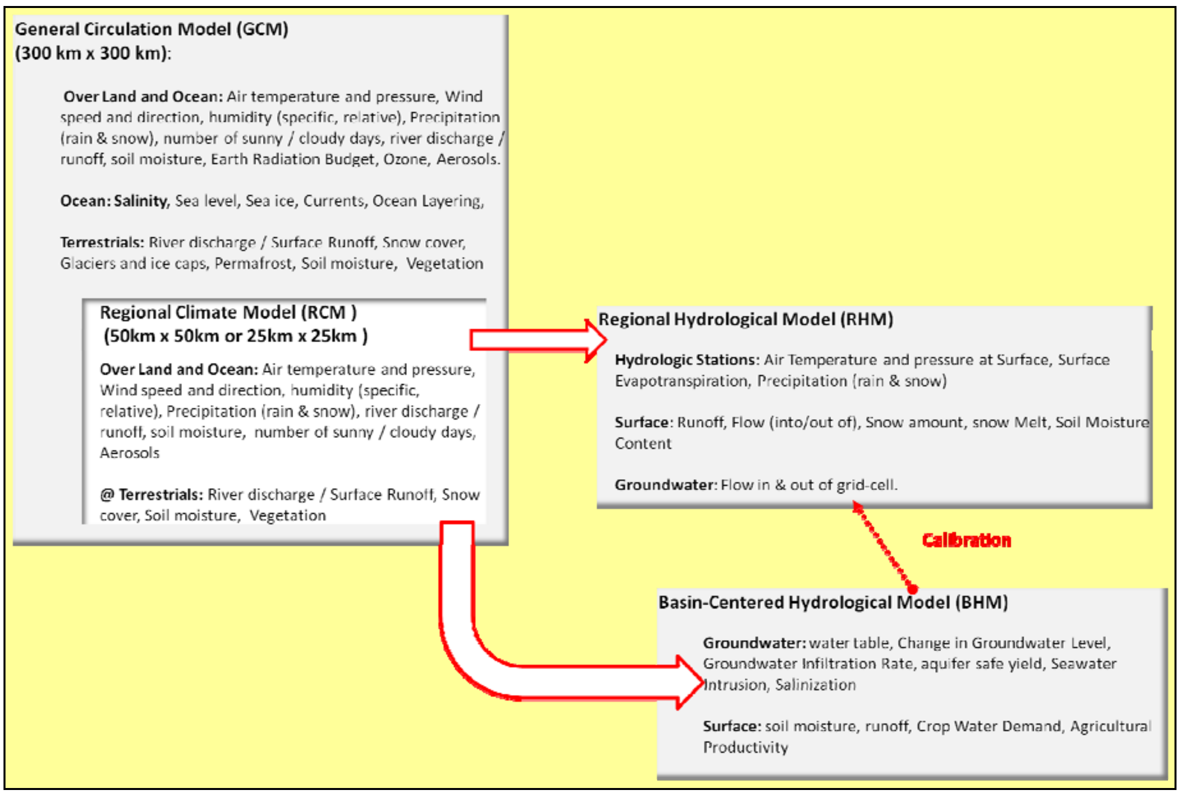
[93] Donnelly et al. (2010), p. 2.

[94] A rating curve is created from graphed data (derived from gauging stations) of a stream's discharge versus stage. The spatial discretization needed for the RHM implementation will define the actual size of relevant lakes.

datasets on watershed boundaries, drainage directions, flow accumulation and distances, and river topology based on elevation data.[95] Other databases could also be used such as the Global Lakes and Wetlands Database (GLWD) or the GlobCover Land Cover Map for land use. However, the importance of local data is crucial to the success of RHM implementation. For example, UNESCO's global *Soil Map of the World* could be used for input in RHM as it offers a 10 km x 10 km resolution; information from this database, however, could be complemented by regional level data and national and subnational soil type and land use surveys such as those compiled by ACSAD to provide higher resolution information on soil parameters and land use patterns that affect freshwater resources or sea level rise.

For the success of the implementation, RHM for the Arab region would benefit from regional databases for soil topography DEM and soil data. Furthermore, in order to ensure that the RHM is able to provide accurate data on regional hydrology, it is important that the model is calibrated with local data, particularly concerning river discharge and groundwater flow. This calibration is carried out by running proven or established Basin-centred hydrological models (BHM) on specific basins, and using their outputs to check or adjust the accuracy of RHM.[96] In this manner, RHM would integrate with RCM, and be calibrated with BHM, as shown in figure 22.

Figure 22. The regional hydrological model in context



Several RHMs are being considered for application in the Regional Initiative with the objective of selecting two to three RHMs as part of an RHM ensemble. However, hydrological modelling requires extensive regional observational data necessitating access to national hydro-meteorological data. To overcome potential data gaps, BHM will be used at test basins to calibrate RHM where adequate data are

95 Lehner et al. (2006).

96 Donnelly et al. (2010).

available; that information would then be used to extrapolate calibration parameters to other basins. It is recommended that at least one basin from each Arab country should be selected for calibrating RHM in the Arab region.[97]

Regional Hydrological Modelling – Helpful Hints

- Provide detailed physiographic data for model implementation, notably topography from Digital Elevation Models, and detailed soil data (Arab soils database).
- Provided digital file of hydrographical stations used to *feed* or calibrate the BHM.

C. Selecting regional hydrological models

As the GCM and RCMs to be applied during the climate modelling component of the project are selected, the selection of one or more hydrological models should also be undertaken to ensure that the best available hydrological models are selected. The selected hydrological models must be able account for the water-related specificities of the region and interface with the outputs generated by the selected RCMs. The following criteria have been identified by SMHI for determining which hydrological models to choose for application at the Arab regional level, namely that the model be:

- Applicable for a range of catchment sizes;
- Relevant for supporting water-balance studies;
- Adequate in sophistication to simulate all relevant hydrologic processes, including arid area processes;
- Sufficient to model interactions between surface water and groundwater flows, evapotranspiration, and river flow throughout the network;
- Able to produce daily output values;
- Dependent on minimum input data requirements (given data-poor catchments in the region);
- Able to use and interface with data drawn from various global databases;
- Readily and freely available with available documentation.[98]

The hydrological models selected should furthermore be able to accommodate the scale and scope of the Arab region and replicate surface and groundwater processes in both large and small basins. The uncertainty associated with regional hydrological modelling can in turn be reduced by incorporating basin-centred hydrological models in the analysis.

D. Basin-centred hydrological modelling

The basin-centred hydrological model (BHM) is applied for one of two purposes within the context of the integrated assessment: (a) to provide test basins to calibrate RHM, or (b) to conduct basin-level hydrological modelling based on RCM outputs.

1. *BHM for calibration of RHM*

Because the development of the field of hydrological modelling generally predates that of climate modelling, not all BHMs have been developed with the capacity to integrate with climate models. To properly calibrate with RHM, BHM selected should be proven to have the capacity to integrate properly with RCM.

[97] ESCWA (2011a).

[98] Johnell (2011)

TABLE 5. TYPOLOGY OF BASIN-CENTRED HYDROLOGICAL MODELS

	Lumped	Semi-distributed	Distributed
Soil layers	Conceptual representation	Explicit soil depths	Finite difference of finite element discretization
Vegetation layers	Two or more layers	Two layers	Single layer
Watershed processes	Empirical approaches	Analytical approaches	Physical approaches
Road hydrology	Empirical approaches	Analytical approaches	Physical approaches
Other features	Empirical approaches	Analytical approaches	Physical approaches
Data requirements	Monthly precipitation Monthly temperature	Daily precipitation Daily temperature	Hourly to daily precipitation Hourly to daily temperature
	No need for map data	Requires map data (DEM, soils, and forest cover)	Requires map data (DEM, soils, and forest cover)
	Parameters are experimentally based	Minimal number of calibration parameters	Medium to high number of calibration parameters

In the past, hydrologists operated in a context of a climate that was perceived as unchanging. One consequence of hydrologic stationarity is that, since climate parameters were not expected to vary over the course of time, models could reasonably programme some key parameters as constant. However, in a context of a changing climate, the key parameters are expected to change and thus adaptability of BHM becomes crucial. **Adaptability** defines how easily BHM programming can be modified to interface with climate models and handle variable climate data. Any BHM used for calibration therefore needs to have the ability to update new values for key climate parameters, take into account any land use and vegetation changes that may occur during the course of the simulation and possibly update key soil parameters to reflect such impacts as increase in salinity or wind erosion.[99]

The selection of BHMs must be based on a set of criteria and technical requirements, ensuring satisfactory integration with climate data. As shown in table 5, models that have the desirable criteria could be selected for use.

2. *BHM for basin-level outputs*

Statistical downscaling and dynamical downscaling from GCMs have typically provided information on climate change impacts on water resources in the Arab region based on the set of meteorological model output fields generated by climate models. In some cases, effort was also made to interface GCM outputs with a hydrological model at the basin-level to support national climate change assessments. However, generating reliable outputs has proven challenging given the significant variance between the spatial and temporal scales used to generate GCM outputs (at a 300 km x 300 km horizontal resolution) and assess hydrological processes at the basin level, which require a much finer resolution and can generate outputs down to a single kilometre.

With the development and application of an RCM for the Arab region, hydrological modelling of climate change impacts on water resources can interface with more detailed RCM output fields and thus

[99] Beckers et al. (2009), p. 14.

provide finer resolution data and inputs (specifically at a 25 km x 25 km horizontal resolution) that can better inform hydrological process and improve BHM outputs for subregional, national and basin-level hydrological assessments.

Basin-centred Hydrological Modelling – Helpful Hints

- Identify and classify physiographic regions from a perspective of discretization requirements, primary hydrologic regime, elevation, soil types, etc.
- Ideally use one BHM per Arab country to calibrate RHM for Arab region, taking into account differences between large and small-sized basins, when pursuing regional hydrological modelling.
- Interface RCM with BHM directly to generate outputs at the subregional, national or basin level.

E. Outputs of the regional hydrological model

The implementation of RHM would be centred on its integration with RCMs. Several RCM implementations will be nested in at least two GCMs. In turn, data generated by each of those implementations will be used to run various RHMs. When necessary, selected BHM implementation will be *fed* by RHM and run on specific basins. The results from these various RHM implementations will then be integrated and standardized across the Arab region.

Because climate change is a multifaceted problem, it has different types of impacts, largely defined by the interrelated nature of the various biophysical and socio-economic systems that are affected. The implication is that the hydrologic cycle cannot be viewed as driven only by physical forces, but also by human activities that impact water resources. The impact of climate change on water resources is therefore of two types: primary and secondary. Primary impacts are directly related to the biophysical effect of climate change. Those biophysical effects then cause human actions, which indirectly result in secondary impacts *mediated* through technology and infrastructure.[100]

1. *Primary impacts and extreme weather events*

Primary impacts are the direct effects of climate change on water resources. They are determined by deterministic biophysical relationships that are modelled by climate scientists and hydrologists. At the regional level, those impacts are either:

- **Meteorological impacts**, resolved by RCMs, and that may or may not have a direct impact on water resources,
- **Hydrological impacts**, resolved by the RHM as a result of meteorological impacts.

As shown in table 6, indicators for primary (biophysical) impacts are computed directly based on the outputs of computer models, whether RCMs, RHMs or BHMs. In the table, indicators that can be produced accurately by computer models are shown in blue, while indicators produced with low levels of accuracy are shown in grey diagonals. . Those indicators strive or aim to answer the following question: ***How is hydrology fundamentally impacted by climate change at scales of both space and time?***

[100] Füssel (2009) and Fünfgeld and McEvoy (2011).

TABLE 6. TENTATIVE INDICATORS OF PRIMARY IMPACTS

Impact area	Tentative indicators	Source		
		RCM	RHM	BHM
Surface	• Temperature • Evapotranspiration rate • Precipitation (snow, rain)			
	• River discharge • Runoff • Lake level • Lake area • Snow melt • Snow accumulation			
	• Soil moisture			
Subsurface	• Water table • Change in groundwater level			
	• Groundwater infiltration rate			
	• Aquifer specific yield • Aquifer specific storage			

Although output from hydrological models can be used to assess severity of droughts by analysing changes in climate and hydrological parameters over days, months and years, assessing extreme flooding events may prove more difficult. Extreme precipitation events and floods may be experienced over the course of days, if not hours. They may also be localized in nature. However, extreme variations in weather patterns may not be fully reflected in climate change projections that seek to expose shifts in climate averages and regional climate trends over a longer time horizon. Therefore, additional treatment and analysis is needed to leverage the outputs of RCMs and RHMs – which technically generate projections every three hours - to increase the sensitivity of analysis related to extreme events affecting the water sector. This requires greater time, effort and storage capacity to manage, analyse and validate data generated on shorter time steps and a finer resolution than those typically applied during climate change impact assessment.

The validation of outputs generated by RCM and RHM on a sub-daily basis also requires reference to more detailed historical data on extreme events than is normally available from meteorological institutions and water-related ministries. Collection of this data can enhance the regional knowledge base, assist countries to better prepare for future extreme events, and provide the quantitative and geospatial information necessary to increase the sensitivity of RCM and RHM outputs on a finer temporal and geospatial scale for determining the primary impacts of climate change on the frequency and intensity of extreme events.

2. *Secondary impacts*

Secondary impacts are the indirect result of climate change and result from human activities or responses to primary impacts. It is necessary to account for the effect of ongoing human activity on the hydrologic cycle and the water balance at the basin and regional levels. Human actions that affect water resources are mediated through technology and infrastructure within socio-economic systems.

Secondary impacts are therefore essentially due to existing socio-economic factors. Interactions among various socio-economic sectors (agriculture, industry, and domestic), effect water resources directly and indirectly.[101] Direct socio-economic impact on water resources is exemplified by agricultural activity's reaction to droughts, which depends on whether the land is rain-fed or not. Indirect socio-economic impacts occur when the provision of goods and services is affected, as in the case of energy production, which could depend on both water availability and ambient temperature.

[101] Fünfgeld and McEvoy (2011).

Table 7 lists tentative indicators of secondary socio-economic impacts of climate change that could help to classify these complex interactions. In doing so, one should ask a fundamental question: *all other things being equal, how are the primary projected impacts of climate change magnified over time and space, and how to they engender secondary impacts?*

TABLE 7. TENTATIVE INDICATORS OF SECONDARY IMPACTS

Impact area	Tentative indicators	Units
Agriculture	• Agricultural productivity	Yield: Tons/Ha
	• Crop water demand	m^3/Ha
Water	• Areas affected by secondary salination	m^2
	• Water abstraction rates	m^3/t
Land	• Storm water storage	m^2
	• Point source pollution	location

Note: t: Time Interval (year, month, or day).

Analysis of the primary and secondary impacts of climate change on water resources based on RCM and RHM outputs completes the impact assessment component of the integrated assessment and effectively informs the preparation of the socio-economic vulnerability assessment for the Arab region.

CHAPTER RECAP

The application of a **regional hydrological model** (RHM) requires the:

- ☑ Identification of criteria and requirements for pursing regional hydrological modelling in the Arab region based on regional and local specificities;
- ☑ Determination of the hydrological parameters that need to be computed to support the model;
- ☑ Selection of the RHMs to be used to generate an ensemble of hydrological outcomes based on a projection generated by one RCM for a specific RCP, which can subsequently be repeated for other RCM projections and other RCPs. This includes:
    - o Clarification and definition of the interface between the RCM and selected RHMs;
    - o Assurance that the series of RHMs selected can be compiled to support an ensemble analysis and outcome;
- ☑ Application of one or more basin-centred hydrological models (BHM) in test basins to calibrate the RHMs and to elaborate cases where more detailed analysis may be needed on smaller hydrologic units to detail specific phenomena, such as droughts or floods. This requires the:
    - o Selection of one or more BHMs for specific purposes based on a set of criteria and requirements;
    - o Definition of the interface between the RCM and the BHMs to be used for calibration or possible case studies.

Completing the aforementioned actions contributes to the following **outputs**:

- ➲ An ensemble of standardized geospatial data sets for the projected impacts of climate change on regional water resources in the Arab region based on specific hydrological parameters and time steps associated with one or more RCP resulting from one or more RCM;
- ➲ More detailed hydrological data related to the water cycle and water resources than can be generated from GCM or RCM projections;
- ➲ Differentiation between primary and secondary impacts of climate change on water resources in the Arab region.

V. STEP 4: VULNERABILITY ASSESSMENT

Vulnerability assessments depend largely on the definition used for *vulnerability* because the same term means different things to different scholars and institutions. Vulnerability research evolved from focusing mainly on geography and natural hazards and became a central concept in various other fields. Over the years, as the term has been associated with such diverse concept as exposure, sensitivity, coping capacity, criticality, robustness, resilience, marginality, susceptibility, adaptability, fragility, and risk. As a result, the same terms have been used in different policy contexts and in reference to different systems or challenges. This results in misunderstandings, particularly in the case of climate change in which scientific inputs from multiple disciplines need to be considered. This confusion has generated concern that vulnerability has become a term of "such broad use as to be almost useless for careful description at the present, except as a rhetorical indicator of areas of greatest concern."[102] Consequently, it is necessary for this study to adopt a clear definition of vulnerability to avoid contributing further to the confusion in terminology and concepts. In the following sections the widely used definitions of vulnerability and the one used for this study will be discussed.

Elements of a Vulnerability Vocabulary: Hazards and Impacts

Terms are sometimes used interchangeably, although they may mean different things in different contexts. This has been a cause of confusion with two terms commonly used in the climate change literature, namely the terms *hazards* and *impacts*.[103]

- **Hazards** are simply the source of adverse events. Some definitions associate this with the *likelihood,* the chance of a given event taking place, defining hazards as a *potentially damaging physical event, phenomenon or human activity*,[104] or *a physically defined climate even with the potential to cause harm*;[105]
- **Impacts** are defined as measurable effects such as the rate of sea level rise, changes in precipitation or temperature …etc.

This integrated assessment largely focuses on the impacts of climate change through the use of various modelling tools, internationally approved scenarios and projections.

A. Conceptualizing socio-economic vulnerability

While there is no right or wrong definition of vulnerability in the absolute sense, one conceptualization of the term is needed in the context of an integrated assessment. For present purposes, the focus is on determining the vulnerability of socio-economic systems to the impacts of climate change on water resources. Because climate is measured both across geographic locations and over time, the determination of vulnerability will need to be dynamic and cross-scale. Furthermore, it would need to consider the various aspects of both primary and secondary impacts of climate change on water resources. This focus will frame the concepts of vulnerability used.

In socio-economic vulnerability, the propensity of a system to be harmed would be assessed based on its exposure to stresses, sensitivity to exposure, and capacity to resist, cope with, exploit, recover from and adapt to the effects. The propensity to be harmed is not visible until the system experiences the effect of the stressor, and vulnerability then becomes a latent property that can only be observed through encounter with

[102] Füssel (2007), p. 155.

[103] Fünfgeld and McEvoy (2011), p. 37.

[104] UNISDR (2004).

[105] UNDP (2011).

a climate event.[106] Because vulnerability can be moderated by the system's adaptive capacity, the latter can be seen as an integral positive component of vulnerability.

A Frame of Reference for Vulnerability Assessment[107]

Consider the hypothetical question of attempting to determine which of two regions are more vulnerable to climate change:

⇒ **Region A** is a low-lying coastal region that is richer, warmer and more urbanized; or

⇒ **Region B** is a mountainous region that is poorer, colder, and that relies mostly on agriculture

- The low elevation exposes (**A**) to sea-level rise and the potential increased frequency of hurricanes. In addition, temperature rises may already exacerbate the effect of aridity;
- Region (**B**) has fewer resources for coping, and less scope for diversifying its income base. In addition, poverty may exacerbate administrative challenges.

When determining which of those regions are more vulnerable to climate change, the assessment will largely depend on the policy focus, as represented by the frame of reference through its geographic and temporal dimensions:

⇒ The **geographic perspective** focuses on the interaction between physical geography and socio-economic parameters;

- When the focus is on *human livelihoods*, the vulnerability assessment would consider (**B**) as the more vulnerable, because of extreme climate events may have a significant impact of on poorer people (i.e., droughts and subsistence farmers);
- When the focus is on *economic development*, then (**A**) could be the more vulnerable because of the substantial concentration of capital along the coastline would be impacted by hurricanes or sea-level rise;

⇒ The **temporal period** should also be considered, as this may highlight additional effects;

- For example, during the first half of the twenty-first century, climate changes may concern both (A) and (B). In the case (B), climate impacts may result in melting glaciers or decreased snow caps, thus leading to higher soil erosion or decreased groundwater storage; (A) would also be affected, since the impact of hurricanes is magnified by the rising sea levels, resulting in higher storm surges;
- In the long run, because of climate change momentum, (A) will continue to feel the impact of rising sea levels in the second half of the twenty-first century, long after the melting of the glaciers that had affected (B).

Proxy measurements of socio-economic vulnerability can be derived from several indicators. Some of these indicators, such as dependency on rain-fed agriculture, relate to processes that undermine the system's ability to sustain damage done by climate change. Other indicators, such as individual income and education, reflect an adaptive capacity to reduce vulnerability to the potential impact of climate change. Examples of socio-economic vulnerability include:

- **Social factors** including population density, percentage built area in floodplains, percentage child malnutrition and infant mortality;

[106] ESCWA (2010c), p. 9.

[107] Füssel (2007).

- **Economic factors** including energy prices, household access to water and sanitation, or factors that affect agricultural productivity such as crop water demand, domestic crop prices, agricultural subsidies, food imports, or market access;
- **Specific national policies** which contribute internal vulnerability factors and could be represented by complex indicators such as the level of application of integrated water resources management, the effectiveness of water demand management, or more straightforward indicators reporting on actual water storage capacity or share of households dependent on the agricultural sector.

The identification of vulnerability indicators should also be identified through consultative processes in view of responding to the interests and priorities of policy-makers and regional stakeholders.

B. measuring vulnerability

1. *Model-based approach*

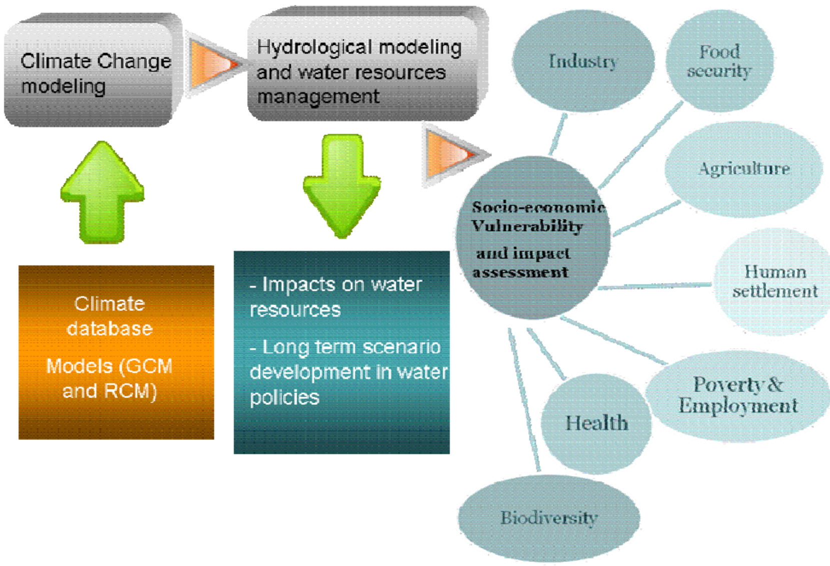
The socio-economic and environmental vulnerability associated with climate change impacts on water resources need to be identified and measured within a sustainable development context. This can be done by analysing impacts and mapping hotspots of affected subregions based on key issues of regional concern. For instance, crop yields and sensitivities to climate changes in the agricultural sector are key parameters that can be analysed and mapped using various scenarios and agro-economic models based on the outputs generated by hydrological models. This can be achieved by using agricultural models, land use models and water resources planning tools to draw conclusions for specific socio-economic sectors based on primary impacts and built upon secondary impacts that resulted from RHM.

These findings can then be used to inform the development of adaptation strategies and socio-economic policies deliberated at the regional and national levels. Response measures based on the impact assessment can then be fed back into a sector-based model to assess areas of weakness or strength in key sectors such as agriculture, tourism, industry, desalinization or employment.

Socio-economic vulnerability could then be assessed from the perspective of several parameters such as health and agricultural, labour and migration using sector-based models. For instance, modeling tools could contribute to estimating changes in vector-borne diseases caused by increasing temperatures or humidity in certain areas. Biodiversity loss could be assessed by models related to watersheds or wetlands that draw input data from RCM and RHM output fields. From an infrastructure and resource based perspective, this data could also be used to examine the vulnerability of water supply and sanitation services through engineering models that examine projected stresses on systems.

Through a model-based approach, vulnerability could express different parameters identified as priorities for consideration by policy-makers and regional stakeholders and include the response measures, as well as the socio-economic, financial and technical capacity to actually implement those measures. The vulnerability assessment could consider and model factors such as education, household income, gender, age disaggregation, endangered species and other regional specific factors that influence the capacity of communities to respond to projected impacts in the near and long terms.

Figure 23. Sector-based modelling approach to vulnerability assessment[108]



2. *Indicator-based approach*

A vulnerability assessment can alternatively be conducted based on sets of social, economic and environmental indicators. Analysis in this case is based on an examination of historical trends, a solid understanding of existing institutions affecting the current state of socio-economic development, and insight into local community responsiveness and resilience to external pressures. This historic analysis can then be used to help draw conclusions regarding present and future vulnerability based on the projections generated from RCM and associated outputs resulting from RHM.

An indicator-based study might consider vulnerability associated with water-related climate change hazards, such as floods, rainfall events, droughts, and water-borne epidemics. These could be represented by variables measuring their expected intensity, duration and frequency based on projected impacts. The positive or negative effects of those hazards on those indicators then enable the identification of regions, communities, groups and ecosystems that are more or less vulnerable to water-related hazards arising from climate change.

Using this approach, vulnerability can be seen as a function of exposure to hazard, sensitivity to hazard and adaptive capacity.[109] The latter represents a system's capability to reduce its vulnerability through adaptation to future hazards or those that occur over a long period of time. For example, the percentage of population living in flood-prone areas is an indicator of exposure to flooding hazards, while the percentage of those with inadequate shelter and/or drainage facilities is a measure of sensitivity to flooding. It should be noted that this vulnerability assessment approach is not aimed at conducting quantitative climate change risk assessment. Vulnerability indicators in this case are intended as tools to assess and monitor adverse conditions and to flag vulnerability pockets in order to inform decision-making on adaptation policies to climate change and pursue further action to investigate areas of concerns. Table 8 below shows some examples of the vulnerability indicators that can be used to support indicator-based vulnerability assessments.

[108] ESCWA (2011b), p. 8.

[109] A similar approach was developed by Adger et al. (2004).

TABLE 8. SAMPLE INDICATORS USED TO SUPPORT VULNERABILITY ASSESSMENT[110]

Category	Factor	Measure
Water resource planning and management	Application of IWRM	Level of application
	Efficiency of water demand management	Cost recovered from water fees (%)
	Water network losses	Water network losses (%)
	Water storage capacity	Water storage to total water resources (%)
	Status of strategic water reserves	Abstraction to total strategic water resources (%)
Economy	General state of the economy	Gross national income (GNI)
		Gross domestic product (GDP)
		Gross savings (% of GNI)
		Total reserves (% of total external debt)
		Total debt services (% of GNI)
		Lending interest rate (%)
	Population relative wealth	GNI per capita
		GDP per capita
		Unemployment (% of total workforce)
	Poverty	Population earning less than US$1.25 per day (%)
	Economic diversification	Value added – industry (% of GDP)
		Value added – services (% of GDP)
	Energy consumption	Electric power consumption (kWh per capita)
	Energy cost	Diesel fuel price
Demography and income	Population size	Total population
	Population growth	Population growth
	Population-female	Number of women to total population (%)
	Population density	Population per km^2
	High concentration of people in urban areas	Population in the largest city (% of total population)
		Population in urban agglomerations of more than 1 million (% of total population)
	Economically dependent population	Number of young and old to working-age population (%)
Agriculture	Dependency on agriculture	Agricultural land to total (%)
		Workforce in agriculture (%)
		Rural population (% of total population)
	Dependency on rain-fed agriculture	Rain-fed land (% of total)
	Level of land degradation	Degraded land (% of total)
Food security	Reliance on single or few crops	Top three strategic crops (% of total products)
	Reliance on locally produced food	Food produced locally (%)
	Food productivity	Cereal yield per hectare (kg)

C. From impact assessment to vulnerability assessment

The integrated assessment methodology pursues a linkage between impact assessment components related to climate modelling and hydrological modelling as a first stage, and vulnerability assessment and vulnerability mapping in a second stage. While the integrated mapping component is elaborated in the next chapter, it is important to review the different steps that have formed the integrated assessment.

[110] ESCWA (2011b), p. 9.

These relationships are reviewed in figure 24, which also details the major inputs and outputs that are generated during each step and each phase of the integrated assessment methodology through a linked process that feeds information from one stage into the other, and is described below:

⇒ **Climate modelling** requires inputs from RCPs to establish the development pathways under study and generates outputs from one or more models based on grids representing global surface topography and meteorological variables. GCM and RCMs both generate climate model output fields, but at different scales and resolution. Climate variables are drawn upon from the land and oceans, and such various terrestrial water bodies as river discharge and surface runoff. LBCs are established during the delineation of domains for running RCMs to support downscaling from GCMs.

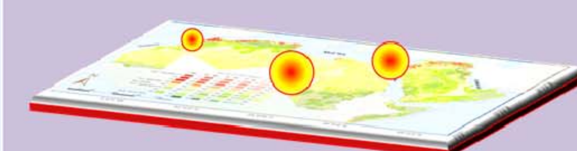
⇒ **RHMs** build a representation of regional topography through DEMs that sometimes show the location of hydrologic monitoring stations as well as information from soil databases that characterize soil and sub-soil profiles. The input they rely upon for climate data comes from RCM output fields, which are generally provided on scales of 50 km x 50 km or 25 km x 25 km, and normally describe key climate parameters such as air temperature and pressure, wind speed and direction, humidity (specific, relative), precipitation (rain and snow), river discharge and runoff, soil moisture, and the number of sunny or cloudy days. Based on those parameters, RHM outputs then generate additional and more detailed hydrologic parameters at the regional and basin levels such as surface runoff, flow into and out of the ground, soil moisture content, in addition to key groundwater information.

⇒ **Vulnerability assessments** are then carried out based on the outcomes of the impact assessment, taking into account both primary and secondary impacts. Primary impacts can be specified by RCMs in terms of surface temperature and pressure, precipitation, and data on extremes. Primary impacts are also specified by RHM in terms of surface runoff, snow amount, soil moisture content, water table, change in groundwater level, soil moisture, groundwater infiltration rate, aquifer safe yield, seawater intrusion and salinization. Secondary impacts can then be determined based on primary impacts and may elaborate on a range of such secondary effects as crop water demand or groundwater abstraction rates. Finally, sector-based models or additional socio-economic indicators can be taken into account, which draw upon the primary and secondary impacts generated and determine the vulnerability of certain sectors or communities to those projected impacts with a view towards their inherent capacity and resilience to overcome them. This in turn is mapped to support graphical analysis and identification of hotspots through collaborative and stakeholder based consultation, which are in turn presented in integrated maps for informing policy dialogue and decision-making on climate change adaptation, which is further detailed in the next chapter.

The final outcome of these consecutive steps results in a socio-economic vulnerability assessment based on the impact of climate change on water resources in the particularly scarce water environment that is characteristic of the Arab region.

Figure 24. From impacts to vulnerability[111]

	Impact Assessement				Vulnerability Assessment		
	Climate		Hydrology				
	General Circulation Model (GCM)	Regional Climate Model (RCM)	Regional Hydrological Model (RHM)	Basin Centered Hydrological Model (BHM)	Primary Impacts (from RCM, RHM, HM)	Secondary Impacts (Suggested)	Socio-Economic Indicators (Suggested)
INPUT	**RCP** **Global Surface Topography** (Digital Elevation Model)	**RCP** **Regional Topography** (Digital Elevation Model) CGM Data & LBC's : - Over Land and Ocean: Air temperature and pressure, Wind speed and direction, humidity (specific, relative), Precipitation (rain & snow), number of sunny / cloudy days, river discharge / runoff, soil moisture, Earth Radiation Budget, Ozone, Aerosols. - Ocean: Salinity, Sea level, Sea ice, Currents, Ocean Layering, - Terrestrials: River discharge / Surface Runoff, Snow cover, Glaciers and ice caps, Permafrost, Soil moisture, Vegetation	**Regional Topography** (Digital Elevation Model) **Hydrologic Stations** (number, Location) **Soil Data** (Soil Database) RCM Data (50km x 50 km): - Over Land and Ocean: Air temperature and pressure, Wind speed and direction, humidity (specific, relative), Precipitation (rain & snow), river discharge / runoff, soil moisture, number of sunny / cloudy days, Aerosols - Terrestrials: River discharge / Surface Runoff, Snow cover, Soil moisture, Vegetation	**Soil Topography** (Digital Elevation Model) **Basin Delineation** (Digital topographic data) **Soil Data & Subsoil Profile / Stratigraphy** (Detailed basin information) RCM Data (50km x 50 km): - Surface: Air Temperature and pressure at Surface, Precipitation (rain & snow), number of sunny / cloudy RHM Data (10km x 10km): - Hydrologic Stations: Air Temperature and pressure at Surface, Surface Evapotranspiration, Precipitation (rain & snow) - Surface: Runoff, Flow (into/out of), Snow amount, snow melt, Soil moisture content - Groundwater: Flow in & out of grid-cell.	RCM Daily Data(50km x 50km): Sruface Temperature and Pressure, Precipitation RCM Data on Extremes (50km x 50km): Growing season length, Maximum number of consecutive dry days, Heat wave duration index, Intra-annual extreme temperature range, Total number of frost days, No of days with precipitation > 10 mm/day, Maximum 5 day precipitation total, Simple daily intensity index, Precipitation Extremes, Sunshine Hours (per month, day) ... RHM Daily Data (10km x 10km): Surface Runoff, Snow amount, Soil Moisture Content HM Daily/Hourly Data: - Groundwater: water table, Change in Groundwater Level, Soil moisture, Groundwater Infiltration Rate, aquifer safe yield, Seawater Intrusion, Salinization - Surface: soil moisture, runoff, Crop Water Demand, Agricultural Productivity,	Water Availability / Person Crop Water Demand Water Abstraction Rate Areas affected by Sea Level Rise Area salinized by irrigation Agricultural Productivity	Energy Price on Location Ratio (Irrigated / rainfed area) Change in Property Prices Share (Off-Farm income) Access to water supply Access to Sanitation
OUTPUT	CGM Data : - Over Land and Ocean: Air temperature and pressure, Wind speed and direction, humidity (specific, relative), Precipitation (rain & snow), number of sunny / cloudy days, river discharge / runoff, soil moisture, Earth Radiation Budget, Ozone, Aerosols. - Ocean: Salinity, Sea level, Sea ice, Currents, Ocean Layering, - Terrestrials: River discharge / Surface Runoff, Snow cover, Glaciers and ice caps, Permafrost, Soil moisture, Vegetation	RCM Data (50km x 50 km): - Over Land and Ocean: Air temperature and pressure, Wind speed and direction, humidity (specific, relative), Precipitation (rain & snow), river discharge / runoff, soil moisture, Earth Radiation Budget (number of sunny / cloudy days), Aerosols. - Terrestrials: River discharge / Surface Runoff, Snow cover, Glaciers and ice caps, Permafrost, Soil moisture, Vegetation	RHM Data (10km x 10km): - Hydrologic Stations: Air Temperature and pressure at Surface, Surface Evapotranspiration, Precipitation (rain & snow) - Surface: Runoff, Flow (into/out of), Snow amount, snow Melt, Soil Moisture Content - Groundwater: Flow in & out of grid-cell.	HM Data: - Groundwater: Flow rate, flow path, water table, - Surface: soil moisture, runoff	**Socio-Economic Vulnerability through Integrated Mapping**		



[111] Füssel (2007), p. 158 and ESCWA (2010b).

Chapter Recap

Engaging in socio-economic and environmental **vulnerability assessment** (VA) based on the outcomes of the assessment of climate change impacts on water resources requires the:

- ☑ Selection of the type(s) of VA that is most appropriate for inclusion in the integrated assessment methodology being applied;
- ☑ Determination of the scope and scale of the socio-economic vulnerability assessment based on interdisciplinary consultations with regional stakeholders to identify the types of human responses and the threats to sustainable development to be targeted for assessment based on the outcomes of the impact analysis and the priorities identified by senior decision makers to support development planning and climate change adaptation;
- ☑ Identification of data needs, indicators, interdisciplinary analysis, and the specialized models to be applied to conduct the assessment based on the defined scope and scale of the VA, taking into account work already undertaken in the region;
- ☑ Preparation of the VA based on relevant parameters, consolidated data sets, empirical models and qualitative assessments.

Completing the aforementioned actions contributes to the following **outputs**:

- ➲ Consensus on the relevant socio-economic parameters and indicators that comprise and structure the VA, and the identification of vulnerability hotspots;
- ➲ Standardized geospatial data sets of computed parameters and indicators of socio-economic vulnerability, associated with specific RCPs and RCM projections.

VI. STEP 5: INTEGRATED MAPPING

Given the spatial nature of both the impact assessment and vulnerability assessment, outputs from these processes can be brought together into a spatially referenced information management and analysis system. Such a system facilitates integrated mapping of these outputs as depicted in figure 25 to identify and analyse critical areas arising from the potential impact of climate change on water resources. A geographic information system (GIS) would be an ideal platform to carry out this type of analysis as it provides powerful spatial analysis and visualization tools all supported by a well-established database system.

Geographic Information Systems (GIS)

GIS tools help to view the relationships between apparently unrelated information by indexing it by location (position in space; x, y, z coordinates representing, longitude, latitude, and elevation), and for each given time period (dates/times of occurrence). This information is then structured in any of three methods:

- **Raster**: in this data type, the map is represented as rows and columns of cells, with each cell storing a single value. This type of data can convey such continuous field information as elevation or precipitation;
- **Vector**: in this case, geographical features are expressed as geometrical shapes. Those shapes can be single points, lines or polylines, or polygons. They can be used to represent such discrete objects as wells (points), roads (lines), or farmed fields (polygons).
- **Hybrid**: in which point clouds combine data with colour information (RGB) to render a thematic three-dimensional colour image.

The integrated mapping component will depend on the establishment of a system to handle the large amount of data that is expected to be generated through the implementation of RCM, RHM, and the vulnerability assessment. This is ideally achieved through the establishment of a formal data retrieval, storage and sharing systems, with clear protocols that secure open access. The specifications of such a system would need to be outlined to reflect those needs, and to integrate within regional frameworks, as outlined in the next chapter.

Once the needs for data storage and handling are secured, integrated mapping can process the information to provide intuitive and informative maps. To do so, integrated mapping needs to be carried out in four basic steps:

Step A: Mapping of the impacts of climate change, using the output of the RCM implementation;

Step B: Mapping of the impacts of climate change on water resources, as determined by the RHM;

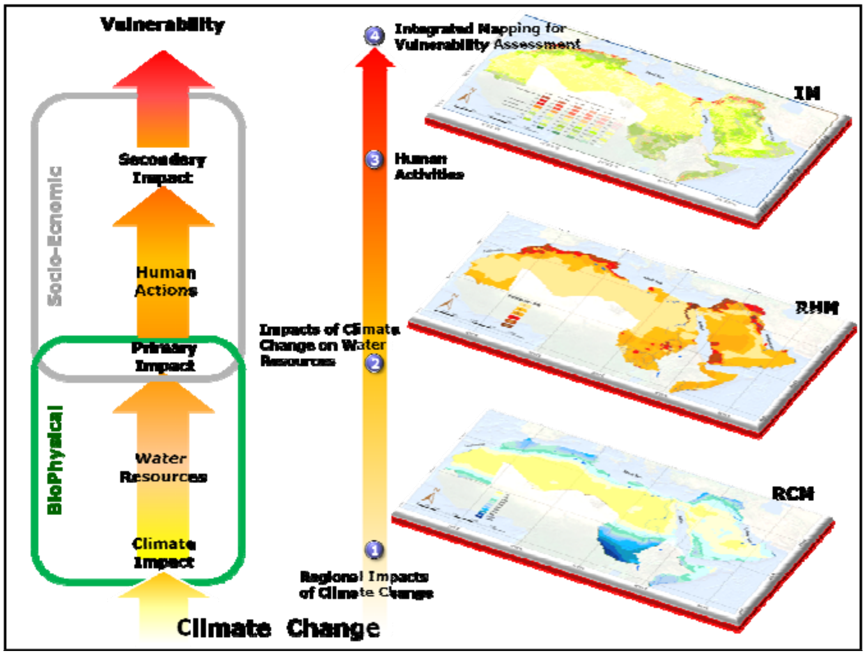
Step C: Mapping of socio-economic parameters that can be mapped and are likely to be affected by any impact of climate change on water resources. An example would be land use;

Step D: Combining the various maps showing impacts and socio-economic parameters, and creating through layering a picture of vulnerability by identifying and illustrating vulnerability hotspots.

This can be done by using *proxy data* to represent aspects of socio-economic vulnerability to the impact of climate change on water resources. For example, in regions where most of the domestic water supply is provided by wells, population density could serve as a proxy for groundwater abstraction rates. Another example is protected land areas as a proxy for biodiversity.[112]

[112] Yusuf and Francisco (2009), p. 3.

Figure 25. The steps of the integrated mapping in context



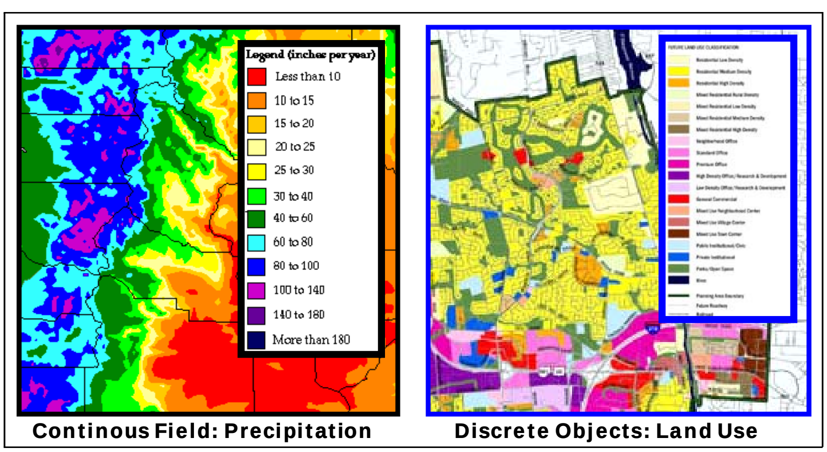
A. Developing geographically harmonized maps

In order to visualize the information about the spatial relationship and the exposed *items*, in this case water resources, spatial analysis would need to generate maps of indicators of socio-economic vulnerability and those representing the impact of climate change on water resources.

1. *The spatial scale*

Some parameters can be computed on a regular spatial grid, others are *placed* on a spatial representation, or map. For example, while some data such as temperature can be depicted on a regular grid pattern, other parameters such as crop yield or land value can best be represented through GIS using either of two *abstraction* types, as illustrated in figure 26.

Figure 26. Main types of geographic data relevant for the integrated assessment



- **Discrete objects** such as houses, land parcels, or roads. Those map objects describe the type of land use or land valuation.

  - ✓ Much of the socio-economic data relevant for Vulnerability Assessment is mapped by discrete objects. Even when *fine grained* data such as population density is represented, different land parcels are allocated certain population numbers.

  - ✓ Some of the information in discrete objects varies with time. For example, as people move in and out of neighbourhoods, the population numbers assigned to mapped land parcels changes.

  - ✓ Maps that show discrete objects will incorporate both numerical and non-numerical data:

    - ▪ Non-numerical, categorical data detail the presence or absence of a key feature, such as land use or land cover.

    - ▪ Numerical, integral data provides ranking or preference information, or may even represent counts of occurrences or observations.

Discrete objects are generally organized in **raster form**, consisting of single values stored in individual grid cells.

- **Continuous fields** represent information that varies with geographic location, such as rainfall amount or surface elevation. Some parameters are obtained computed at a regular spatial grid and at regular *time steps*, others are not.

  - ✓ Example of continuous field information that varies with time; rainfall rates and temperature. They change over different time scales.

  - ✓ Example of continuous field information that remains constant: surface elevation generally changes little with time. Except for large deserts where dunes move across the surface and alter the shape of the landscape, most topographic data changes little with time for all practical purposes.

  - ✓ Maps that show such continuous fields will incorporate data that is both *floating point* and *integral*:

    - ▪ Measured or computed floating-point data – those real values can represent either real surfaces such as elevation, or conceptual surfaces made up from *scalar functions* representing such values as precipitation or population density.

    - ▪ Numerical, integral data – such as computed indicators, or values indicating proximity to a key object or feature (such as a well), or to a vulnerability factor (such as the coast).

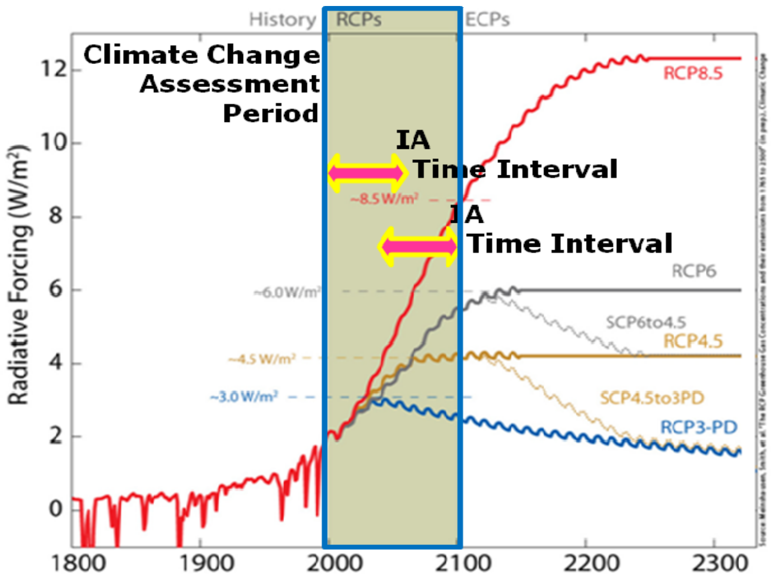
Continuous objects can be organized in either raster or vector form. While raster form can convey such simple information as the level of the water table in an aquifer, vector form can convey more complex information, as it is organized to represent *fields of direction*. For example, representation of groundwater can be organized in vector fields to represent the direction of flow.

2. *The time scale of climate change*

The rate at which the parameters are computed varies on the time scale. Some parameters can be obtained at regular *time steps* (minutes, hours, days) defined the computer simulation. However, many socio-economic parameters come at much coarser time scales (year). For the time scale, the time period also matters; while RCM simulations run for a specified periods of 30 to 100 years, planning is carried out on variable time frames and is often limited to spans of 5 to 10 years.

In general and due to shorter time scales required by policy cycles, the time interval applied when engaging in integrated assessment tends to be much shorter than the full duration the RCP simulations shown in figure 27. However, this may lead to hiding long term climate impacts that could occur beyond a policy-oriented time interval.

Figure 27. The study period and the time interval in context[113]



B. Identifying vulnerability hotspots

In most cases, vulnerability hotspots can be identified by with GIS mapping by constructing a series of maps and then overlapping them.[114] For maps to represent spatial-temporal data relevant to the analysis of socio-economic vulnerability they must place specific parameters on the geographic grid.

The variables defining those specific parameters must be transcribed as either continuous or discontinuous. This would require some additional modification of primary and secondary impact indicators, in addition to indicators of socio-economic vulnerability, taking care to exclude any type of parameters that cannot be transcribed on a set of map coordinates. A tentative list of such parameters is shown in table 9.

[113] Meinshausen et al. (2010).
[114] Yusuf and Francisco (2009), p. 4.

TABLE 9. SAMPLE PARAMETERS FOR INTEGRATED MAPPING

Impact area	Tentative indicators for mapping	Units	
		Continuous Variables	Discrete Variables
Primary impact			
Surface water	Temperature	C	
	Evapotranspiration rate	mm/t	
	Precipitation (snow, rain)	mm/t	
	River discharge, runoff, lake level, lake area	mm/t	
	Snow melt, snow accumulation	mm/t	
	Soil moisture	%	
Groundwater	Water table	M	
	Change in groundwater level	%	
	Infiltration rate	mm/t	
Secondary impact			
Agriculture	Agricultural productivity	Tons	Tons/Ha
	Crop water demand	m^3	m^3/Ha
Water	Areas affected by secondary salination		m^2
	Secondary salination	ppm	
	Water abstraction rates		m^3/t
Land	Areas affected by sea level rise		m^2
	Seawater intrusion	m	
Socio-economic vulnerability			
Energy	Energy consumption per capita		KgOE/t
Agriculture	Ratio (irrigated/rainfed area)		%
	Area is rainfed	(Boolean: Yes/No)	
Wealth	Change in property prices		%
	Share (off-farm income)		%
Water	Access to water supply		(Boolean: Yes/No)
	Access to sanitation		(Boolean: Yes/No)

Notes: t: Time Interval (year, month, or day).

KgOE: Kilograms of Oil Equivalent.

In this manner, GIS techniques can be used to identify hotspots through a comparison between different maps. This procedure is illustrated in figure 28, which shows how the general succession of maps is integrated. This can be done by **re-sampling** or interpolating the values at the centre of each grid cell in a given map to make them correspond to the value in the next map. The re-sampling method to apply can be determined based on a trade-off between the computational complexity that can be handled and the desired accuracy, and would depend on the type of data considered. From most to least complex, mapping re-sampling can use one of the following methods: nearest-neighbour, bilinear interpolation or cubic convolution. Each method has its advantages and disadvantages: The nearest-neighbour re-sampling method is computationally less intensive and works well with *discrete* data types; bilinear interpolation works better for *continuous* data fields.

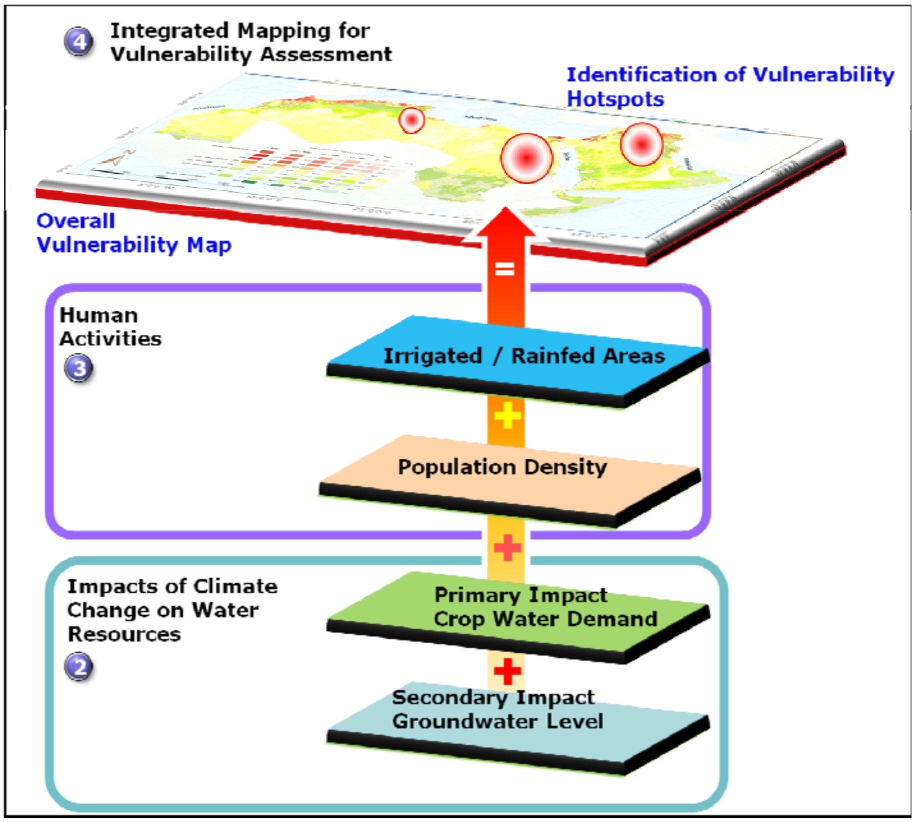
Alternatively, in the case when there are combined indicators, integrated mapping can simply be done by averaging them. It may be better to use simple averaging, since this would not prejudge the relative importance of each impact.[115]

[115] Yusuf and Francisco (2009), p. 5.

Mapping Vulnerability Hotspots – Helpful Hints
➢ Determine the method of reconciliation between parameters of different scales for indicators for secondary and primary impacts, and for endogenous/exogenous indicators of socio-economic vulnerability.   ➢ Define the parameters that can be meaningfully mapped or interpolated together.   ➢ Develop comparable/superposed GIS map structures to support hotspot identification based on maps illustrating different parameters.

It should be noted that re-sampling usually changes the statistical and spectral qualities of a GIS grid, resulting in the loss of the original mapping data. Because of that, it is better to re-sample to the smaller cell size among the various maps. While this would slow down computations, it would improve accuracy and minimize data losses.

Figure 28. Example of combining multiple maps to highlight vulnerability hotspots[116]



[116] Ibid.

CHAPTER RECAP

The application of **integrated mapping (IM),** based on the outputs generated from the impact assessment (steps 1-3) and vulnerability assessment (step 4), requires the:

- ☑ Establishment of a knowledge management hub for storing and disseminating information generated during the preparation of the impact assessment and vulnerability assessment components of the integrated assessment;
- ☑ Development of a harmonized database for the transfer of information onto a visual platform through a GIS;
  - o The database will need to produce maps across spatial and time scales;
  - o The maps would integrate both discrete and continuous data types that are related to a selected set of parameters;
- ☑ Identification of vulnerability hotspots using integrated maps and overlays generated information through GIS applications that represent the baseline and projected impacts of climate change on water resources in the Arab region and the socio-economic and environmental vulnerabilities associated to these impacts.

Completing the aforementioned actions contributes to the following **outputs**:

- ➲ Geographic representation of climate change impacts on water resources and socio-economic vulnerability hotspots visualized through integrated mapping tools;
- ➲ Accessible knowledge management hub supported by databases and GIS applications for disseminating information generated by the Regional Initiative.

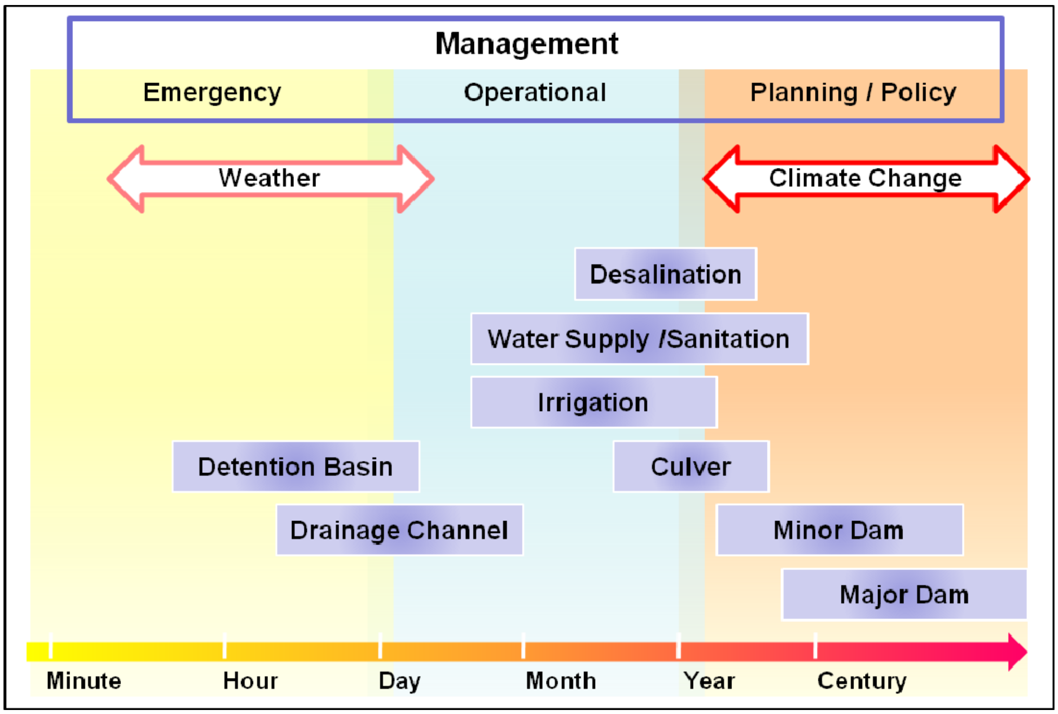
VII. NEXT STEPS

A. Implications of the integrated assessment

To scientists, the main challenge is the unprecedented level of complexity and the *multilevel* nature of environmental challenges. Causes, consequences, and responses span multiple levels from the local to the global. In addressing those challenges, scientists strive to integrate the current state of knowledge across various disciplines in a context of uncertainty.

Policy-makers also face a challenge in implementing a radical shift in the relationship between knowledge and action, away from centralized, top-down assessment efforts.[117] As shown in figure 29, at some levels, policy-makers can still respond within shorter time-frames; those are the domains of *emergency* and *operational* management. However, issues involving planning and policy relating to climate change require approaches that extend across multiple disciplines, levels and scales.

Figure 29. Management scales in the context of climate change



For this reason, the integrated assessment needs to take into account the complexity of those challenges and the time horizons. Specifically, the integrated assessment must do the following:

- Integrate research, assessment, and decision-making across multiple levels;
- Assess and address global change in the context of local consequences;
- Identify, assess, and respond to cross-level interactions between society and environment;
- Formalize the relationship between science and decision-making as a dynamic, iterative, two-way process.

[117] Cash and Clark (2001), p. 10.

B. Fostering regional cooperative frameworks

The integrated assessment will help foster informed intergovernmental dialogue, priority-setting and positioning on the impact of climate change on water resources at the Arab regional level. A regional perspective when conducting scientific research and pursuing integrated policies is necessary as climate and river basins are not defined by political boundaries, nor are the impacts of climate change on water resources limited to one country. Furthermore, because most surface and groundwater resources in the Arab region cross international frontiers, socio-economic vulnerability and stresses on natural resources will have regional implications.

The integrated assessment methodology is thus designed with a regional outlook in mind that takes into consideration three core components: impact assessment, vulnerability assessment and integrating mapping. By linking these three analytical tools together and basing the integrated assessment on the new RCPs that will inform the global debate over the coming decades, the Arab region has endorsed the preparation of joint and mutually reinforcing products that provide policy-makers with access to the evidence and projections needed to inform decision-making and negotiations at the Arab regional level over the near and long terms. This information can in turn be mainstreamed into regional and national decision-making to inform the development of adaptation strategies and measures.

c. Supporting climate change adaptation

The outcomes of the Regional Initiative for the Assessment of the Impact of Climate Change on Water Resources and Socio-Economic Vulnerability in the Arab Region and its associated integrated assessment methodology aims to support informed decision-making on adaptation policies and measures at the regional, national and local levels. The identification of climate change impacts and hotspots provides a better understanding of the underlying processes that influence socio-economic vulnerability and associated effects on the environment. This knowledge is necessary to inform the design, development and implementation of effective adaptation measures. For example, reliable estimation of the projected increase in duration and frequency of droughts in certain parts of the region can support the formulation long-term policies and actions on climate change adaptation in the water sector, including measures to enhance water use efficiency, develop adequate storage facilities and provide targeted social safety nets for vulnerable segments of society.

In doing so, the outcomes of this integrated assessment formalizes the relationship between science and policy-making, and fosters data exchange and investigation across multiple disciplines and research areas across the region and throughout the globe on the vulnerability of the Arab region to climate change. In this manner, the data obtained and the lessons learned comprise the basis of a regional knowledge base to inform and support policy dialogue, decision-making and negotiations on the implications of climate change for water resources and socio-economic and sustainable development in the Arab region.

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