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**REVIEW OF METHODOLOGIES AND POSSIBLE SCENARIOS
FOR CONDUCTING VULNERABILITY ASSESSMENTS
TO CLIMATE CHANGE**

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Preface

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EXECUTIVE SUMMARY

The Arab world today faces all of the four major water problems in the world today; providing safe drinking freshwater; satisfying the requirements for agriculture and industry; ensuring the sustainability of development projects; appropriately managing shared water resources. This is partly due to the long history of development in the region, as many Arab population centres predate all others, often extending back to the dawn of written history. Population pressures that have been growing ever since are now accelerating because of the increased demands of the modern age, so much so that the sustainability of further development projects is now the most critical challenge faced by the region, as climate change exacerbates the region's freshwater scarcity.

In order to meet this challenge, Arab policy makers will need reliable estimates of the detailed impact of climate change over the region. This will allow them to make informed decisions regarding how to address the crisis in water quantity and quality, as well as confront the threats to the region's fragile ecosystem. Decisions can only be based on objective and "actionable" vulnerability assessments that can be easily updated to reflect scientific/technical characterization of the specific impacts of climate change on the Arab region.

This requires "region-specific" forecasting tools based on Climate "Models", computerized simulations that are tailored to describe the impact of climate change on the region. Thanks to advances in technology, it is now increasingly possible to adapt existing models, albeit with key modifications to take into account the Arab region's unique mix of topographic features and human development patterns.

However, regional climate models are insufficient by themselves. They need to be validated against climate scenarios that are not only specific to the Arab region, but that "scaled down" to represent the various small scale processes that play a crucial role in determine local weather patterns.

The combination of regional model and scenarios will provide Arab policy makers with reasonably accurate forecasts on which they can then assess vulnerabilities of various regions. This will allow them to prioritize actions aimed at either mitigating climate change or adapting by building up resilience, by targeting the risks that were considered most likely at the time. Because uncertainties will remain, the approach will necessarily be iterative and will need to be often revised to take into account new information or knowledge about both past climate histories and physical mechanisms.

I. UNDERSTANDING CLIMATE

The Earth is a dynamic system¹ made up of many interdependent subsystems. Over various periods during the course of the planet's history, the interaction between all those systems reached states of equilibrium that lasted over a given period of time. In the Earth's recent geologic history, such equilibriums were mostly Climate-related, with the planet experiencing generally stable patterns of variations in weather, conventionally defined over a 30 year period.

It is therefore important to understand those effects in order to comprehend how we can adapt to them, or may be mitigate their effects. This requires understanding both weather and climate, which result from the complex interaction amongst the Earth's main systems within the Atmosphere as they interact with the other subsystems such as hydrologic cycle, in addition to the Biosphere, Lithosphere, the Cryosphere, etc.

Note:

Biosphere: Earth's global ecosystem, or the sum total of all of earth's ecosystems. Most component elements of the biosphere are linked in some form or another, mostly dependent on the sun's energy (photosynthesis), either directly (plants, algae), or indirectly (animals). Some other forms of life that are unrelated to photosynthesis derive chemical energy from rocks (deep crust bacteria) or volcanic activity (colonies around deep sea "black smoker" vents).

Lithosphere: The solid outermost thin shell that tops the Earth, a 12,756 km diameter ball of molten magma. This thickness of "top crust" varies between 50 km and 100 km, and floats atop the more flexible uppermost part of the mantle, the "convecting mantle". It acts as a conductive lid, regulating heat transport across the Earth's surface through faults that criss-cross it and the volcanoes that "puncture" it. The rocks in the Lithosphere also interact chemically with the atmosphere; absorbing or rejecting gases.

Cryosphere: All the places on the Earth's surface that contain water in solid form; snow, the various forms of ice (sea ice, lake ice, river ice, glaciers, ice caps, ice sheets), frozen ground ("permafrost"), and deep-oceanic frozen methane ("methane hydrates"). These components play a role in the physics of heat transport and storage, and the chemistry of greenhouse gases ("locked" in permafrost and methane hydrates).

I.A WEATHER AND CLIMATE

Weather is determined on shorter time scales, a detailed mix of events that happen in a particular locality on any particular day, determined by measuring daily atmospheric statistics such as temperature, precipitation, wind velocity. Because of the short time scales during which the interaction is taking place, weather is a chaotic system whose exact pattern is therefore hard to forecast. This unpredictability arises from the system's "sensitivity" to variations in the initial conditions of any of the variables under consideration.

Note:

Chaotic Systems are those whose solution displays "sensitive dependence on initial conditions on a closed invariant set" (Wiggins, 1990), and "whose evolution through phase space appears to be quite random" (Tabor, 1989). In climate models, chaos is an "**Intrinsic**" or "**Unforced Variability**", because it is related to unpredictable changes arising from dynamic interactions between subsystems (oceans, atmosphere...).

On the other hand, Climate is a "big picture" concept, defined on longer timescales as an "average weather", with atmospheric statistics averaged out over a period of 30 years². While chaos remains an "Intrinsic" feature of climate models, the "Unforced Variability" that it causes occurs within a relatively narrow range, its impact limited on the longer time scales by constraints imposed by the major factors

¹ A system in which one physical state develops into another one over the course of time, often under the effect of extraneous influences ("forcings").

² This time scale, as defined by the World Meteorological Organization, is adequate for most short-term purposes. However, it may prove too "coarse" a definition for longer term needs such as climate forecasting, especially because it fails to properly reflect large episodic variations.

influencing climate³. Because small-scale variations are evened out, such a system is much less chaotic and therefore easier to predict. As a result, while the weather of any given day cannot be predicted in the far future, the prevailing climate can be forecast with relative accuracy, thanks to models “based on well-established physical principles [that] have been demonstrated to reproduce observed features of recent climate⁴”. Essential Climate Variables are defined of over three core domains; atmosphere, oceans, and land.

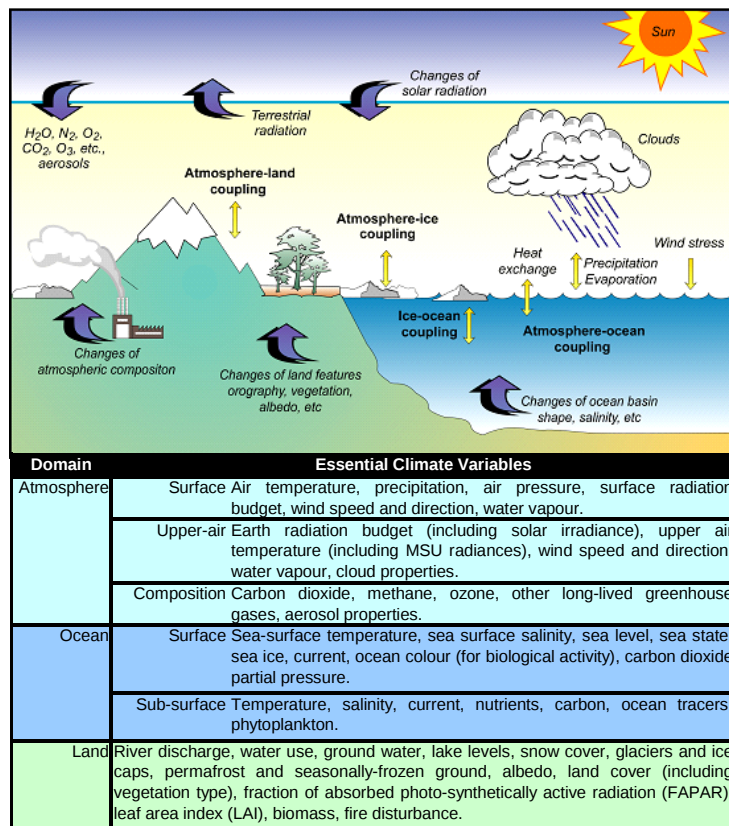


Figure 1. Main Climate Variables and their interactions⁵.

In general terms, the climate of each of the Earth's regions is commonly defined as function of three main parameters; temperature (winter, summer), moisture levels (rainfall), and ambient light (Bright skies vs. cloudy, overcast skies, Sun angles). The prevailing climate over most of the Arab world would then be classified as arid and semi-arid⁶; extremely hot and humid in the 7 to 9 month long summertime. During the summer, temperatures could exceed 50°C, and humidity exceeds 90 % in coastal areas. Precipitation rates over most of the region are low, in the range of 50 mm to 150 mm⁷. The exception is coastal strips adjacent to the Mediterranean Sea or the Atlantic Ocean, where temperature is less than the inland temperature, the air is more humid, and precipitation rates much higher.

³ For example, while this variability may make some winters bit a warmer in a given region, it cannot make winters warmer than summers. In a similar manner, a small succession of warmer winters may be due to unforced variability rather than global warming.

⁴ IPCC, 2007; p. 591.

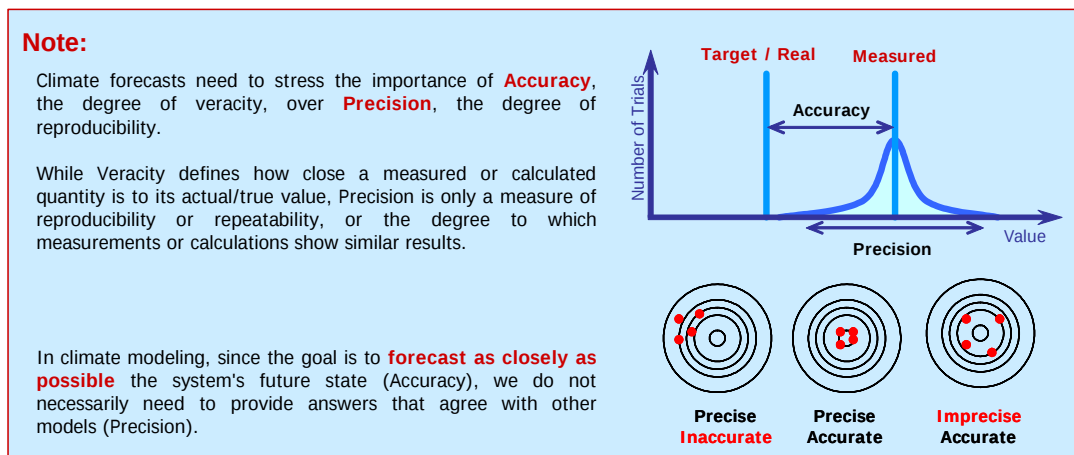
⁵ GCOS, 2003; Hennessy, 2003.

⁶ According to the Köppen climate classification, the types of climate are; Tropical, Dry (arid and semi-arid), Temperate, Continental, and Polar. In Dry climate regions, precipitation is less than potential evapotranspiration.

⁷ UN-ESCWA, 2007

I.B ACCURACY AND PRECISION

Climate modellers are in constant search for greater accuracy and for ways to better account for the effect of Unforced Variability. In climate modeling, the choice of the relevant mathematical method should be largely defined by Physical considerations. However, this is often not done in practice⁸, as far too many prioritize **precision** at the expense of **accuracy**.



There will necessarily be relative errors because of approximations introduced by modellers to simplify the intricate nature of climate interactions. Those approximations are essentially deliberately introduced mathematical or physical “errors”.

- **Mathematical errors:** caused by the approximate nature of numerical solution methods. In climate modeling, since the goal is to forecast as closely as possible the system's future state (Accuracy), agreement with other models (Precision) is not necessary. Because different numerical solutions will yield different errors, provided models are developed independently, a closer forecast can be obtained by averaging their results.
- **Physical errors** are of two types.
 - Physical errors introduced in order to “focus” representations of the problem considered on the parameters that are relevant for scale or case considered.
 - Physical errors caused by the limitations our current knowledge. As some processes remain insufficiently well-known, their detailed behaviour cannot yet be included in models. A remedy is to design parameterisations, based on empirical evidence and/or on theoretical arguments. However, because such parameterisations reproduce only “first order effects”, they cannot be extrapolated to all possible conditions encountered by the model, therefore increasing uncertainty.

Because the parameters considered are inter-related, modellers need to implement a procedural approach to solve the climate once they decide on the mathematical representation. In practice, this involves two methods.

- Models are run repeatedly, each time with different starting conditions.
- Models are verified against “scenarios”.

Scenarios are sometimes based on climate history, a “palaeoclimate” that is either directly obtained from historical records, or indirectly inferred from archaeological or paleontological evidence. However, because

⁸ Randall, 2000.

of the need to make forecasts on unprecedented future conditions, some scenarios are developed on the basis of the current understanding of socio-economical effects on some key climate parameters.

However, in spite of the progress made during the course of the past 50 years, climate model development remains a major objective. Models continue to struggle to describe accurately the behaviour of such subsystems as cloud formations. This is exacerbated by the complexity inherent to modelling the climate system in which various “Forcings” and the model’s inherent “Unforced Variability” are interrelated. In such systems, models can never fully describe the unfolding reality with precision and describe the *precise* variation of temperature at any time in the future. However, the objective of climate models is not as much “predicting the exact time and location of a specific small-scale event” but rather the development of an understanding and prediction of “the statistical behaviour of the system”, i.e. its “mean and variance”⁹.

I.C CLIMATE MODELS

Most major climate modelling algorithms can provide an **accurate** forecast of “the state of the future climate”¹⁰. Any obstacles that remain are either related to technology or knowledge; even when considering “the potential predictability of” smaller scale events such as “intra-seasonal and seasonal variations”, the “dominant obstacle” remains inaccurate models, rather than an intrinsic limit¹¹ of the scientific understanding.

Climate models therefore strive to “cover” as many processes as can be possibly investigated given the state of available technology. They **abstract** the earth’s climate through mathematical representations of those various physical interactions that divide the basic processes of the Whole Earth System among three categories;

- **Radiative** processes are those that transfer radiative energy (heat, 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...
- **Surface** processes are those that involved the interaction of land, ocean, and ice, taking into account the effect of Albedo, emissivity, and surface-atmosphere energy exchanges.

Note:

Albedo indicates the surface's reflectivity to sunlight, it is computed as a ratio of “diffusely reflected” to “incident” electromagnetic radiation. Higher Albedo values mean more of the Sun's energy is reflected:

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
Sand: 0.20 (wet) to 0.45 (dry)	Concrete: 0.50 (new)	Forest: 0.05 to 0.15
Water: 0.05 to 0.07		

In analysing those interactions, models rely on physical laws (energy and mass conservation, Newton’s second law of motion) and incorporate relevant chemical process and biologic processes. This allows those “Energy-Balance Models” (EBM) to simulate the interplay among basic processes of Forcings, Feedbacks, and Responses, they can test hypotheses on the workings of a “Whole Earth System” and its main systems (oceans, atmosphere...), subsystems (role of clouds in tropical intra-seasonal variability...), as well as inter-system interactions. The capabilities of those models expand with the growing body of knowledge.

⁹ Kiehl, 2006; p.2.

¹⁰ Kiehl, 2006; p.13.

¹¹ Shukla, 2008, slide 20 of 48.

Note:

Forcings are mechanisms that alter the Earth's global energy balance between incoming energy from the Sun and outgoing heat from the Earth is upset. They can be:

- Natural:** changes Earth's orbit, variations in ocean circulation, changes in the atmosphere's composition due to volcanic activity...
- Anthropogenic:** man-made emissions of gases that change the atmosphere's composition in unprecedented ways

In **Feedbacks**, part of a system's output is returned as input, and further affects the system's performance. There are two type of **Feedbacks**:

- Negative:** as the atmosphere warms, its moisture content increases, increasing the number of clouds, which then reflect more sunlight, thereby reducing warming.
- Positive:** as the atmosphere warms, its moisture content increases, increasing the number of clouds, which then reflects or traps more of the earth radiated energy, thereby increasing warming.

Because of limitations in the available state of technology, modelling will always remain a set of compromises between the need to simplify climate's very complex systems and the necessity for accuracy. With the progress of technology, the set of compromises has decreased.

Such simplifications are not only due of our limited understanding of the climate system, but also the result of computational restraints. Algorithms that are developed to investigate the physics of the problem are therefore developed with considerations for the "scale of interest" (time and space), the level of accuracy required, or the available computing power. Simplification may then be achieved in terms of spatial dimensionality, space and time resolution, or through parameterization of the processes that are simulated. As a result, climate models are organized into a "hierarchy"¹², based on the number of spatial dimensions explicitly modeled.

¹² Harvey, 2000.

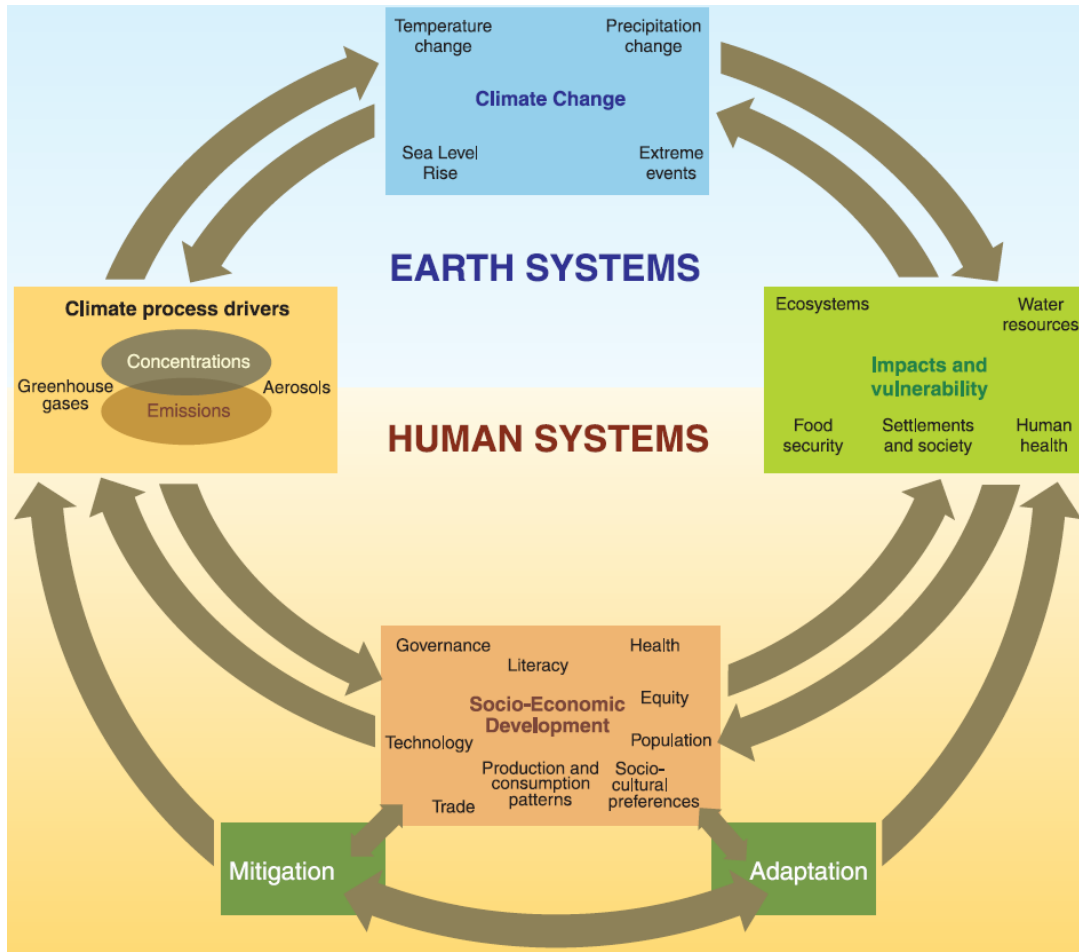


Figure 2. The “Whole Earth System”¹³.

I.C.1 Zero Dimensional Energy Balance Models

Zero Dimensional (0-D) models are the simplest of EBM’s. They represent globally annually averaged conditions of the energy balance of systems such as the coupled atmosphere–ocean system in a linearized, time-dependent form. Such models are useful for understanding processes that control the overall time scale of the entire climate system, as opposed to the time scale of individual components of the system.

I.C.2 One Dimensional Radiative-Convective Models

One-dimensional (1-D) climate models investigate time-scale processes along one direction. Those “Radiative-Convective Models” allow study of the balance of the Whole Earth System, where the electromagnetic waves transmitted through space interact with convective energy of our planet’s atmosphere.

Radiative-Convective Models track the “Global Radiation Cascade”, in which radiative and convective processes interact along the vertical direction. Those radiative processes are a “Shortwave Radiation

¹³ IPCC, 2007b.

Cascade”, from the Sun¹⁴, and an outgoing “Longwave Radiation Cascade”, outgoing from the Earth¹⁵. The energy they impart to the atmosphere contributes to and interacts with a convective process in which trace “Greenhouse Gases” (GHG) are playing an increasingly prominent role.

Note:

The “Greenhouse Gases” considered by the IPCC are;

Carbon Dioxide (CO ₂)	Non-Methane Hydrocarbons (NMVOC's)	Sulfur Dioxide (SO ₂)
Carbon Monoxide (CO)	Hydrofluorocarbons (HFC's)	Sulfur Hexafluoride (SF ₆)
Hydrochlorofluorocarbons (HCFC's)	Methane (CH ₄)	
Hydrofluorocarbons (HFC's)	Nitrous Oxide (N ₂ O)	
Methane (CH ₄)	Nitrogen Oxides (NO _x)	
Nitrous Oxide (N ₂ O)	Non-Methane Hydrocarbons (NMVOC's)	
Nitrogen Oxides (NO _x)	Perfluorocarbons (PFC's)	

In addition to those gases, water vapour plays a role in trapping heat and warming up the atmosphere (IPCC, 2007).

I.C.3 Two-Dimensional Statistical-Dynamical Models

Two-dimensional (2-D) “Statistical-Dynamical Models” (SDM) are “deeper” climate models that combine horizontal-energy transfers modelled by 0-D EBM’s with the radiative-convective approach of 1-D Radiative-Convective Models, in addition to empirically-derived statistical relations that describe parameters such as wind speed and wind direction. SDM models are used for studies such as the circulation in the atmosphere (stratospheric circulations and chemical interactions), or the ocean (Sensitivity of the thermohaline circulation to external Forcings).

The energy transfer is easily modeled along the latitudinal (East-West) direction, where radiation exposure tends to remain constant. However, when considering equator-to-pole energy transfers along the longitudinal (North-South) direction, radiation exposure varies not only geographically, but also temporally, among the seasons. More sophisticated tools are developed, based on theoretical and empirical relationships of the cellular flow across latitudes.

Because of the complexity of such horizontal energy transfers, SDM models face limitation in their investigation of the Global Radiation Cascade because of the effect of convection in the atmosphere. They modify Radiative-Convective Models to incorporate a meridional direction that can investigate convective processes that form “traps” for Outgoing Longwave Radiation (OLR). In general, those traps result from either optically thick clouds that result from convective processes, or increased high-altitude moisture levels. As those “traps” retain heat, surface warming increases, thereby furthering sea-ice loss¹⁶, which in turn contributes to greater moisture. Because this sea-ice feedback can amplify radiative effects¹⁷, the system’s complexity becomes such that modellers still “have a long way to go before successfully modeling the excess cloud absorption¹⁸”.

¹⁴ The earth infrequently receives energy from high-energy cosmic rays” that play a role in increasing in global temperatures (Ogurtsov, 2007). However, they occur too episodically and infrequently to be a significant cause for the current warming, but they can magnify its effects.

¹⁵ In space, colder bodies such as the earth tend to emit energy in the Infrared portion of the radiation spectrum, a longwave radiation with wavelengths greater 4 µm.

¹⁶ Abbott et Al., 2009.

¹⁷ Lian and Cess, 1977.

¹⁸ Schneider et Al., 1995.

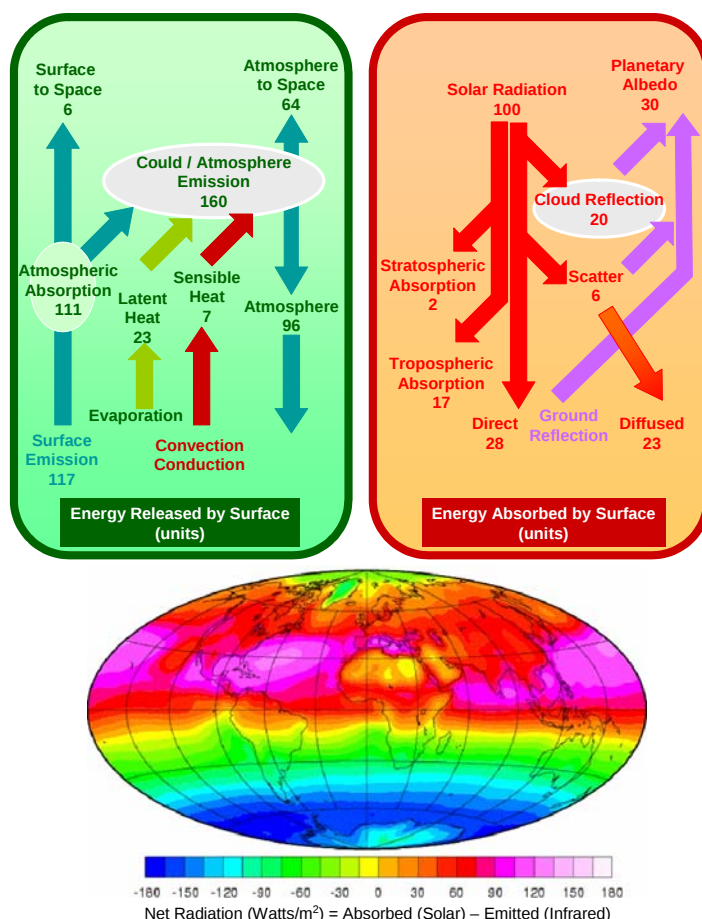


Figure 3. The Radiation Cascade¹⁹.

II . GLOBAL CLIMATE MODELS (GCM)

With improvements in computer power, General Circulation Models (GCM's) were developed to investigate the full three-dimensional equations for momentum, energy, and mass. Also known as Atmosphere-Ocean General Circulation Models (AOGCM), they are now increasingly referred to as Global Climate Models, or "coupled" GCM.

They are based on a Three Dimensional (3-D) spatial representation of the earth on which "the numerical and computational solution of evolution equations" that describes the fundamental laws of physics in addition to characterizing "the system components and the coupling of these components"²⁰. This level of detail allows GCM's to simulate global and continental scale processes such as the effects of mountain ranges on atmospheric circulation in detail.

Relevant GCM's are part of the "Climate Model Diagnosis and Inter-comparison" (PCMDI), established in 1989 at the Lawrence Livermore National Laboratory (LLNL). The PCMDI works on both the scientific

¹⁹ Ahrens, 2001. The map was developed by Dr. Ostermeyer for the time period June, July, August 1985-1986.

²⁰ Kiehl, 2006; p.15.

aspects of climate change projects and infrastructural tasks (data management, visualization, and computation), and supports modeling studies initiated by the IPCC²¹.

Table 1. The PCMDI Global Climate Models.

Model Name	Originating Group(s)	Country
BCC-CM1	Beijing Climate Center	China
BCCR-BCM2.0	Bjerknes Centre for Climate Research	Norway
CCSM3	National Center for Atmospheric Research	USA
CGCM3.1(T47) CGCM3.1(T63)	Canadian Centre for Climate Modelling & Analysis	Canada
CNRM-CM3	Météo-France / Centre National de Recherches Météorologiques	France
CSIRO-Mk3.0 CSIRO-Mk3.5	CSIRO Atmospheric Research	Australia
ECHAM5/MPI-OM	Max Planck Institute for Meteorology	Germany
ECHO-G	Meteorological Institute of U of Bonn, Meteorological Research Institute of KMA	Germany / Korea
FGOALS-g1.0	LASG / Institute of Atmospheric Physics	China
GFDL-CM2.0 GFDL-CM2.1	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA
GISS-AOM GISS-EH GISS-ER	NASA / Goddard Institute for Space Studies	USA
INGV-SXG	Istituto Nazionale di Geofisica e Vulcanologia	Italy
INM-CM3.0	Institute for Numerical Mathematics	Russia
IPSL-CM4	Institut Pierre Simon Laplace	France
MIROC3.2(hires) MIROC3.2(medres)	Ctr for Climate Sys Research / The U of Tokyo, Nat Inst for Enviro Studies, Frontier Research Ctr for Global Change (JAMSTEC)	Japan
MRI-CGCM2.3.2	Meteorological Research Institute	Japan
PCM	National Center for Atmospheric Research	USA
UKMO-HadCM3 UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research / Met Office	UK

There were much improvements since the IPCC's 3rd Assessment Report (TAR), allowing the authors of the 4th Assessment Report (AR4) to consider it “likely²² that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica”, since “observed patterns of warming” were only “simulated by models that include” such human effects²³. The models reviewed here were part of PCMDI, and most were relied on for IPCC-AR4.

II.A REPRESENTING THE EARTH

GCM's are generally designed to receive inputs from observations or other model studies, their coarseness largely defined by available computing power. For example, climate models that describe nearly all the components of the system require a relatively small amount of data, but they will be limited in time span and/or space. On the other hand, limited models such as those that focus on the explicit representation of the physics of the atmosphere and the sea will require inputs on “boundary conditions” such as the distribution of vegetation, the topography of mountains, local hydrologic variables...

²¹ <http://www-pcmdi.llnl.gov/>

²² The IPCC has developed formal definitions of likelihood.

²³ Trenberth et Al., 2007.

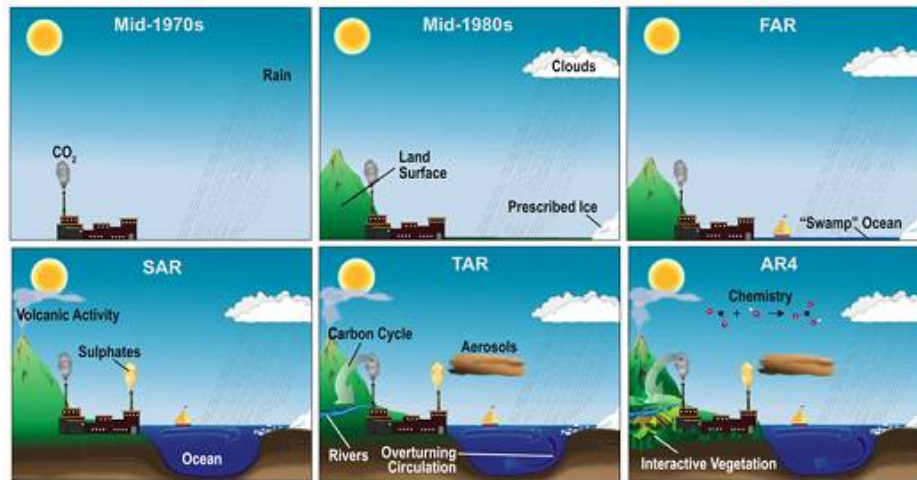


Figure 4. Progress in Climate Modeling²⁴.

In GCM's 3-D spatial representation, the Earth is "discretized" in both space and time. Spatially, the Earth is approximated into a series of "boxes" based on discrete points of a grid. The 3-D grid is based on a horizontal grid projection of the Earth (at least 5° latitude by 5° longitude) that is then layered times in the vertical direction. In each grid, equations that describe the evolution of the Earth's climate are resolved. This combination of spatial and time discretization is defined as a "scheme".

One common scheme is based on the "Finite-Difference Method" (FDM), or "Grid-Point Scheme", in which the flow of energy across the Earth is represented by those time-derivative equations that are approximated in terms of differences involving neighbouring grid-point values. One major alternative to FDM is the "Spectral Method", in which model fields are expanded in terms of weighted sums of continuous basis functions. However, it is still under improvement, and its impact was limited on the Global scale at the time of IPCC AR4.

In either scheme, the equations are solved by a variety of iterative approaches on two scales; a time scale, and a geographic scale.

It should be noted that Iteration introduces climate model "biases" that ultimately depend on "starting" conditions. Modeling is a constantly updated work where models are verified against measured historic data from a "control climate".

²⁴ FAR: First Assessment Report, SAR: Second Assessment Report, TAR: Third Assessment Report, AR4: Fourth Assessment Report.

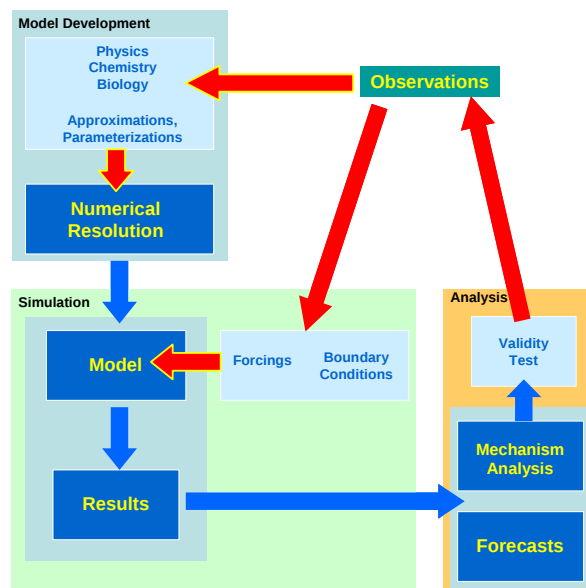


Figure 5. Model Development

Furthermore, the data in recent instrumental past tends to be associated with more information about Forcings since current changes in climate are of “a magnitude that [has] not occurred in the instrumental past”. Because older Historic data may not replicate the current Forcings, there is a degree of certainty about which could lead models risk underestimating the impact of climate change; even a CGM that “perfectly reproduces the current climate” cannot be guaranteed to “exhibit the true climate sensitivity”. This limitation is addressed by separately validate summer and winter seasons²⁵, and the model’s “fidelity” is then defined by its accuracy in replicating the seasonal cycle.

Note:

Fidelity is a measure of realism, defined as the degree to which a climate model is able to reproduce the past behaviour of a given climate system. There are many methods to describe fidelity, but the issue of developing reliable by “metrics” to measure it was “just beginning to be addressed” by the time of the IPCC AR4 (Randall et al., 2007).

II.A.1 Time Scale

In Climate models, the Time scale is important in two key respects; the “time-steps” in which the basic equations are solved, and the period explored. Variables that are important for the prediction of climate are based upon four key laws; conservation of energy, conservation of momentum, conservation of mass, and the Ideal Gas Law.

Conservation of energy leads to “predictive equations” for the constituent components of such systems as the Atmosphere and the oceans. Models for the other systems (land, chemical processes, and ecological systems) are based on “parametric relationships that relate key predictive quantities to large scale forcing factors (i.e., precipitation)”. While they are not based entirely on explicit conservation laws, the mathematical models that describe them “are not purely empirical” because they remain “linked to fundamental understanding of physical and chemical principles²⁶”.

²⁵ Meehl et al. 2007.

²⁶ Kiehl, 2006; p.13.

Note:

Predictive Equations are not mathematical expression whose resolution can lead to a prediction of the climate. Predictive Equations are those “**closed-form**” mathematical formulations that have been developed either empirically or theoretically, and expressed in terms well-known functions and parameters

a **closed-form** expression is one that can be expressed analytically in terms of a bounded number of certain “well-known” functions or parameters. Predictive climate equations have almost never any closed-form solution.

Many of those are “prognostic” equations that describe time-related processes, in contrast with “diagnostic” equations that do not contain time derivatives. Because the equations that describe them are “non-linear” and interrelated, no “closed-form” solution can be derived, and they can only be solved by “Iterative” processes. First, external parameters (i.e. the radius of the Earth) are imposed on the model, and time-dependent prognostic variables assigned initial conditions. Then, prognostic equations are solved iteratively by numerical time integration techniques, and the diagnostic variables of a model are also determined. The process is an iterative one in which the equations are solved in “time steps” across cells, and the results averaged over specific time periods.

Those time-steps cut short an iterative cycle that would otherwise infinite continue infinitely, therefore potentially resulting in a “truncation error [that] can be a substantial component of total forecast error of the model²⁷”; different time-steps may lead to different model climates, and potentially to different regimes. While this problem is well understood, with modellers implementing various methods to estimate and control it, concerns remain when integrating various components that rely on different time-steps.

II.A.2 Grid Point Schemes

Current GCM models are based on square grids, with lengths varying between 50 km and 200 km in the horizontal and 100 m to 2 km in the vertical. This structure allows the explicit resolution of dynamic motions and processes with scales greater than the specified spatial grid-scale.

Initially, the nature of GCM’s square grid imposes limits on how the model represents the homogeneity and isotropy of the atmosphere. this is because, of the three theoretically possible types of regular polygons (triangular, square, and hexagonal) that can be used to divide a horizontal plane, only the hexagonal polygon offers the highest symmetry. While all neighbours of a given hexagonal cell are located across its walls, some neighbours are found across “corners”, or “cell vertices” in the case of either triangle or square grids.

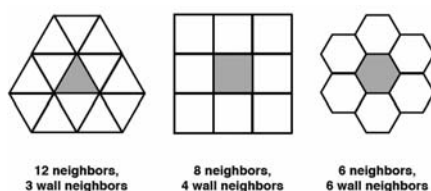


Figure 6. Regular Polygons and Grid Representations.

A crucial advance was made in the late 1960’s that allowed FDM models based on square grids to sidestep this limitation. Those models now carry out two different computations, one for “wall neighbours”, and one for “vertex neighbours”, as in the “Arakawa Jacobian Grid²⁸”.

For the time being, the computational needs of standard FDM models are adequate for purposes of modeling regions such as the Arab world. However, “finer” precision will soon be required, and less computationally “hungry” methods will need to be developed and implemented; in order to compute the basic atmospheric variables at each grid-point, GCM models already need to store, retrieve, recalculate, and

²⁷ Teixeira et al., 2007.

²⁸ Arakawa, 1966; Arakawa and Lamb, 1977.

re-store about 10^5 figures at every “time-step”. Furthermore, on the global scale, gridlines would converge towards the poles, creating a “singularity” that could lead to computational instabilities. The singularity is currently treated by a variety of methods; filtering model variables along latitudes as they get closer to the poles, creating an artificial Island (BCC-CM1, FGOALS-g1.0, MIROC3.2-medres), or using a modified/rotated grid where the North Pole is shifted onto a nearby landmass (Greenland; CCSM3, ECHAM5/MPI-OM, PCM). Alternatively, some models use a “Quasi-Isotropic Tri-polar Grid” which results in 2 North Poles (over Canada and Siberia; INM-CM3.0, IPSL-CM4).

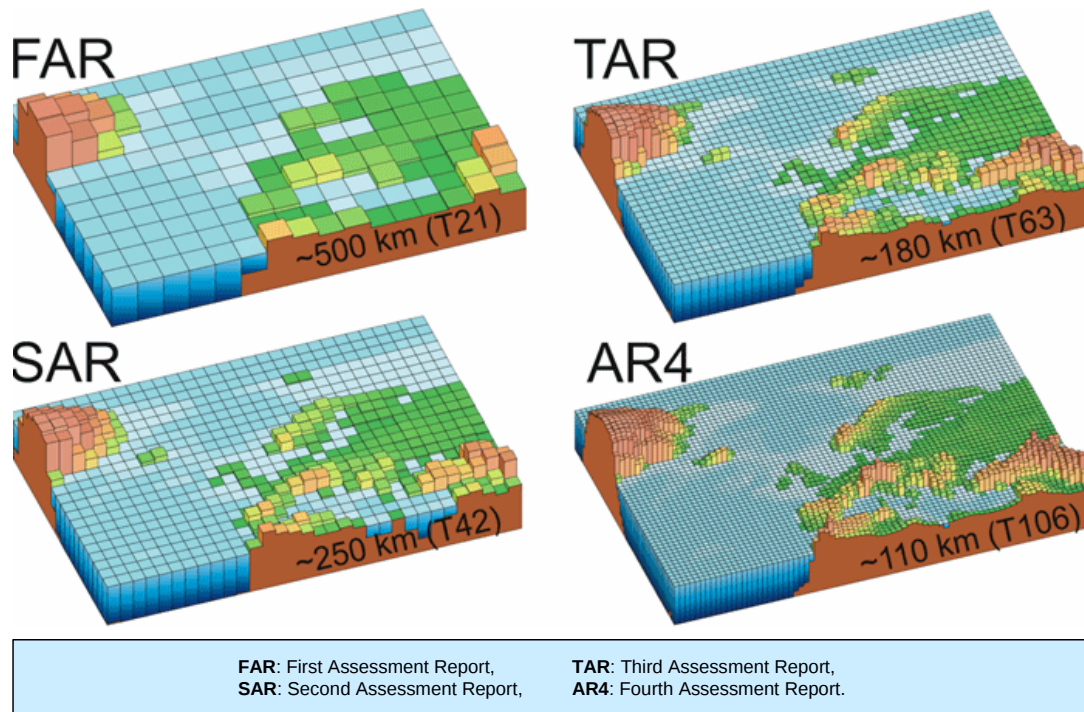


Figure 7. Evolution of Parameterization and Resolution.

Models based on the Spectral Method do not suffer from this problem; not only do they allow for a more straightforward implementation of key physical laws, but they did not need to apply such “tweaks” as “polar filtering” to increase time-steps. This would diminish the amount of computing time required. The Spectral Method has therefore been incorporated in some regional atmospheric models for which it is considered “more suitable [...] than for an oceanic model²⁹”. However, as of 2000, modellers were still struggling with overcoming the method’s problems with “discontinuous fields” on medium scales, which resulted in non-physical phenomena such as “spectral rain”. As of 2005, the method still worked poorly on medium scales, near regions of where flat landscapes rise rapidly to meet steep topography³⁰, as in the Anatolian and Zagros chain of mountains, North Africa’s Atlas chain, Saudi Arabia’s Hejaz, or the Levant’s Mount Lebanon chain. However, the method is giving very useful results on smaller scales, and could be useful to model either microclimate regions or to track climate change over small countries.

²⁹ Mote and O’Neill, 2000; p. 3.5

³⁰ At present, tests have been carried out on Greenland and the Andes.

All those effort are still contributing to accelerating the pace of development in climate modeling; thanks to steady improvements in various fields, models could potentially run as much as 50% faster in 2008 than in 2006³¹.

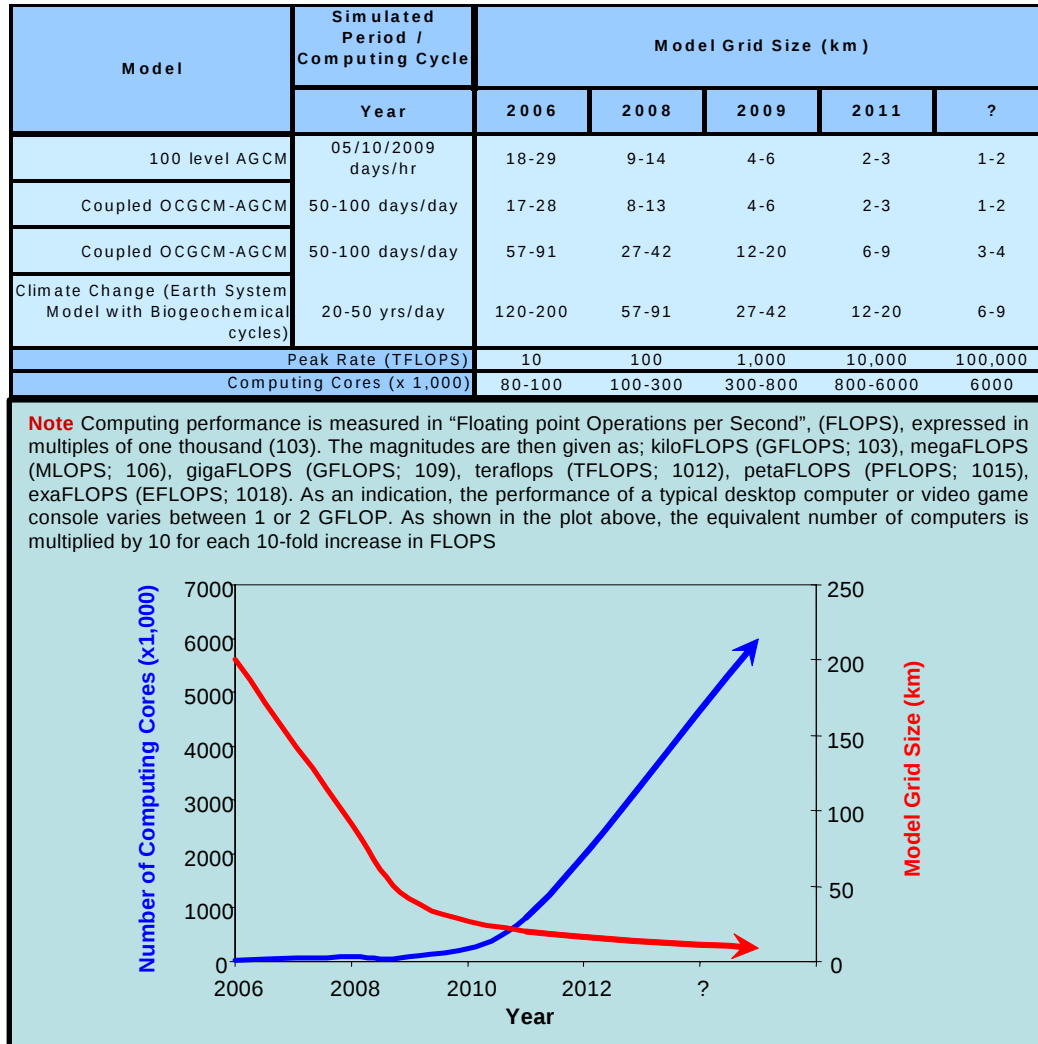


Figure 8. Evolution of Computing Capability and Model Scale³².

Boundary Conditions

In climate models, the extent of the problem imposes "boundary conditions" that correspond to either physical or mathematical entities. Physical boundaries are actual regions, which can be grouped in two types.

The first type is defined by a given geographic area, such as the Middle East. The second type of region is defined when the focus is on a single physical system such as the atmosphere, and "inputs" from other systems such as the sea or the hydrologic cycle are evaluated separately and "fed" into the model. In either case, variations in the initial values of those "boundary elements" will greatly affect the model's outcome.

³¹ Giraldo and Restelli, 2008.

³² After Shukla, 2008.

Furthermore, in cases when the spatial resolution is limited in the vertical dimension, boundary layer processes must be parameterised.

Scale Differences

When considering regional climate, the description of “finer” processes becomes more important. However, since it occurs on smaller scales, it remains spatially unresolved; the “time step” of those processes is shorter than that of GCM models. The time-step is essentially the ratio of the grid size to the maximum velocity; since information cannot propagate faster than this maximum velocity across the grid, time steps are limited by this ratio, lest the model result in “numerical instabilities”.

Each of the components of Earth’s climate system is itself a “non-linear”, “spatially non-local” system with its own characteristic time scale³³. Because of this, many GCM’s still struggle to represent key “smaller scale” phenomena, that occur either across distances smaller than the model’s grid, or within short time spans. This is the case of tropical storms, localized meteorological phenomena that nonetheless play an important part in latitudinal transfers of energy and momentum. This is also the case of hydrologic processes such as water flow, which are studied on far smaller grid-scales and time-scales than any climate model (cm to m versus km, and hour or day versus year or century, respectively). In order to properly reflect the information from those finer processes, the data is often “parameterized” rather than computed, i.e. implicitly included in the model.

The net result of all this is that model outputs cannot be rigorously compared without prior consideration to their methodology. An additional limitation comes from the nature of inputs. Those are either fixed boundary or variable external Forcings, and some regions such as the Arab world may require deep adjustments to models that may work well on others.

II.B COUPLING

As climate models were developed, different components were first integrated separately, tested, and then “coupled” into comprehensive climate models. Those models then provide a solution that is discrete in both time and space. This discretization defines a “numerical grid”; the model’s “resolution”. The coarseness of the model’s “resolution” may not necessarily affect its accuracy, but it will largely impact how closely smaller-scale processes are described.

In general, greater accuracy is achieved by taking into account a wider range of processes. Basic GCM models consist of a “dynamic” core that relates material properties (temperature) to dynamic properties (pressure, velocity). Those models are limited to the study of limited atmospheric processes and cannot evaluate complex climate processes. This is the case of cloud formation, which involves coupling across components through the transfer of fluxes of momentum, energy, mass, often on smaller scales and across various vertical locations. In the past, those flux flows had to be adjusted, but recent progress is such that only 4 of the 23 models considered for IPCC-AR4 reportedly still used some flux adjustments; BCC-CM1, ECHO-G, IMM-CM 3.0, MRI-GCM2.3.2. It should be noted here that the IMM-CM 3.0 only requires flux adjustment of water in the arctic Barents and Kara Seas, which could possibly be an artefact of its tripolar grid implementation. All other models “no longer use flux adjustments³⁴”, even if some still use separate components to handle such issues.

³³ Kiehl, 2006; p.1.

³⁴ IPCC, 2007; p. 591.

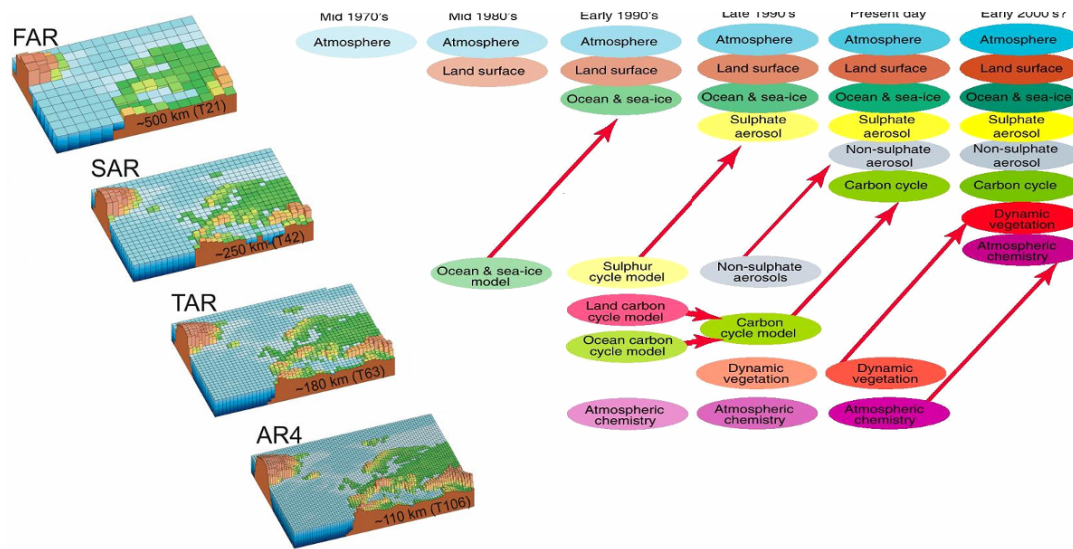


Figure 9. Model Coupling³⁵.

However, it is possible that such adjustments could still be needed on the smaller scale, where otherwise negligible process may play a larger role. In addition, small imbalances may be magnified when focusing on regions in which there are large uniform areas (deserts, ice sheets...). At larger scales, it may be hard to tease out such imbalances from normal “rounding” errors, and few models have reported the investigation of such possible imbalances; in the case of Antarctica, some models report small imbalances in freshwater (UKMO-HADCM 3, UKMO-HadGEM 1). It is possible that other models may encounter similar issues.

Integrating various components in a single model is not always feasible, particularly since boundary conditions and process description may not be “complementary”. In addition, the “forcing” of one model could be a key state variable of another; as an example, changes in CO₂ concentration that are prescribed in some models may be directly computed in others.

The current consensus appears to be that coupling is the optimal solution; it links Atmospheric GCM’s and Oceanic GCM’s, into coupled atmosphere-ocean GCM’s. Various GCM implementations differ in how this coupling is done (**Error! Reference source not found.**).

II.B.1 Atmospheric GCM (AGCM) and Oceanic GCM (OGCM)

In general, Atmospheric GCM (AGCM) model simulate only the atmosphere, but some also contain a land-surface model. Since 1990, AGCM models are constantly being evaluated as part of the “Atmospheric Model Inter-comparison Project” (AMIP) standard experimental protocol³⁶.

In AGCM’s, a “dynamic core” integrates the equations of fluid motion for surface pressure, velocity (horizontal components in layers), temperature, and water vapour. Other effects are taken into account by code that evaluates the effect of radiation code (short wave and long wave). They also include computation or parameterizations for convection, land surface processes, albedo, hydrology, and cloud cover. Among the coupled models considered, there are 14 clearly identified individual AGCM’s.

AGCM models interact with associated Oceanic GCM’s (OGCM). Among the coupled models considered, there are 10 clearly identified individual OGCM’s.

³⁵ IPCC, 2001; Box 3, Figure 1.

³⁶ <http://www-pcmdi.llnl.gov/projects/modeldoc/amip2/>

The interaction between AGCM and OGCM models follows a cyclical iteration. At the end of each computational cycle, AGCM models require inputs such as sea surface temperatures (SSTs), which they use as part of their computation. OGCM's also require input from AGCM models, particularly fluxes from the atmosphere. Both models also interact with other specific models for Sea Ice, Land, and deserts. The data is passed back and forth in a predetermined manner, with the type of parameters varying among models (**Error! Reference source not found.**).

II.B.2 Coupled Atmosphere-Ocean GCM (AOGCM)

AOGCM combine both AGCM and OGCM models to internalise as many processes as possible. This allows them to remove the need to manage the flow of inputs and outputs externally, thereby diminishing the potential for error. As such, those models are optimal tools to generate regional analyses, where the interconnection among processes is a larger issue than on the global scale.

III . REGIONAL CLIMATE MODELS (RCM)

To represent finer processes, "Regional Climate Models" (RCM) are developed that focus on a limited geographic area and "use GCM output as their driving boundary conditions"³⁷. Given similar computing capabilities, RCM's are able to have finer grid scales than GCM's. Current FDM methods allow square grids to represent the global dynamics of the atmosphere and ocean to a very high degree of accuracy, and it appears to be sufficient for representing regional climate.

III.A AN RCM FOR THE ARAB WORLD

As the global climate prediction initiative progresses forwards, it is increasingly clear that small-scale weather regional effects will impact larger scale climate events, as in the case of the El Niño-Southern Oscillation (ENSO). This is leading to a consensus among researchers that the success of predictions will be "critically" dependent on "significantly enhancing" predictions "of weather and climate variations were including the prediction of changes in the probability of occurrence of regional high-impact weather"³⁸. However the development of RCM's for the Arab World has two aspects; managerial and technical.

Like GCM models, RCM's will need to be validated against past climate records in the Arab region. This task may prove easier that it first appears, not only because of the long history of human presence in the region, but also due to the recent discoveries regarding the climate of ancient, pre-historic times.

Deriving RCM's from GCM's involves more than mere scaling down. RCM's need to incorporate the finer processes encountered on the local scale. Regional models may need to be adjusted by revising assumptions, improving cloud modeling and precipitation forecasting, and taking into account processes that tend to be neglected on the global scale. RCM's may also require some key modifications to reflect region-specific features or variations, particularly concerning boundary conditions.

III.A.1 Adjusting Assumptions

The finer scales of RCM's may require modellers to revise their assumptions and approximations. This is necessary because of the need to ensure that not only assumptions can "scale down" to the regional level, but that decisions on mathematical detail are still valid.

Scaling down to the Regional Level

When models are scaled down, approximations that were valid on the larger scale may no longer apply, and regional effects may be magnified by some key local parameters:

³⁷ Busier et al., 2009.

³⁸ Shukla, 2008.

- **Changing Topography:** Unlike other regions, the Arab world is one of rapidly changing and varying topography, with potential importance to regional climate models:
 - On the larger regional scale, the movement of dunes over the large desert areas in Arabia and the Sahara may have a cumulative effect on surface winds,
 - Over smaller regions, rapid urbanization and increased concentration is modifying local conditions in unique ways. Their impact on local cloud formations, wind patterns and freshwater need to be incorporated,
- **Albedo Variations:**
 - The spread of deforestation and land degradation is modifying the surface reflectivity on the local scale, potentially altering local rainfall patterns and freshwater availability,
 - GCM models may not have needed to factor in Albedo changes over the seasons. However, on the regional level, the desert's reflectivity changes seasonally because of rain or permanently because of the pollution resulting from extraction industries. This will likely have an effect, if not regionally, then at least cumulatively.
- **Heat Islands:** The rapid expansion of urban areas in the Arab world's arid regions is unprecedented in its scale and breadth. The effect of such an expansion on local climate patterns needs to be taken into account, and is already being felt on local rainfall patterns in such arid cities such as Riyadh in Saudi Arabia³⁹. However, the use of regional climate models is necessary for the observation to be put in a proper context.
- **Water Table depletion,** by decreasing the amount of water available for evaporation, may have an effect on the radiation cascade at the regional level, thereby affecting cloud formation.
- **Population movement:** More people may need to "climigrate", i.e. move to another area because the effects of climate change have become far too pronounced in their local region. This may modify land pattern uses, and potentially exacerbate other effects:
 - Land degradation, as a sudden influx of refugees increases pressures on some regions,
 - Heat Islands, as the populations of urban centers swell under the influx of displaced people looking for work.

III.A.2 Clouds and Precipitation

Because of computing power limitations, most global models make some form of "hydrostatic assumption", in which the atmosphere is assumed to be in a state of "hydrostatic equilibrium". This approximation facilitates the computation of atmospheric pressure, relating it to height and the unit weight of the atmosphere.

However, the atmosphere is a complex and dynamic "mesoscale", where the scale of phenomena ranges from meters to several hundred kilometres. Small-scale processes such as evaporation or cloud formation precede larger scale systems such as thunderstorms or squall lines, which then activate even larger weather fronts, precipitation bands, which then create tropical depressions or cyclones... In addition, topography plays a role in either generating or catalyzing those processes, which also interact with one another in a swinging day-night cycle, a "pendulum day".

Global models attempt to correct this fundamental shortcoming by a variety of means, but they remain very approximate in this respect. As a result, and in spite of much progress, there is still variation among models when investigating cloud formations, particularly "boundary-layer clouds, and to a lesser extent

³⁹ Shepherd, 2006.

midlevel clouds⁴⁰”. Observations have not yet been able to ascertain “which estimates of the climate change cloud feedbacks are the most reliable⁴¹”.

On smaller scales, computer needs are more manageable, and “non-hydrostatic” weather models that do not make this assumption are able to generate better forecasts. Thanks to improvements in computer power since the late 1990’s, attempts were being made to “scale up” this “non-hydrostatic” approach to mesoscale modeling by researchers⁴² at the Met Office⁴³, and the Canadian Meteorological⁴⁴. By 2008, the “closest attempt⁴⁵” to a global cloud resolving model has been developed at the Frontier Research Center for Global Change of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), which are partners in the MIROC class of models.

By 2008, the NICAM model was run on an “aqua planet experiment”, assuming an ocean-covered Earth with a 54-layer atmosphere, 40 km thick. This experiment allowed the modellers to confirm that the NICAM model was able to replicate precipitation similar to “that observed on an open ocean”, given them the confidence to start a “global cloud resolving experiment under a more realistic condition” of a “real” Earth.

However, in contrast to the MIROC, their “Non-hydrostatic ICosahedral Atmospheric Model” (NICAM) is based on a triangular geodesic grid. It is therefore not clear if the two models will be integrated in a coupled model, and how that will be achieved.

In the context of semi-arid areas such as the Middle East and North Africa (MENA) region, this is more than “reason for some concern⁴⁶”, because proper understanding of cloud formation is essential to forecasts of precipitation rates. By causing local variations in the distribution and frequency of precipitation, climate change “will transform the hydrological patterns that determine the availability of water”; with “many of the world’s most water-stressed areas [getting] less water, and water flows [becoming] less predictable and more subject to extreme events⁴⁷”. This may already be the case in the region; in North-Eastern Syria, increased frequency of drought has caused farmers to deplete the water table. The government had recently to evacuate about 160 villages. Proper forecasting of cloud formation and precipitation rates will help local policy makers to coordinate and prioritize such adaptation measures.

III.B BOUNDARIES: DYNAMIC DOWNSCALING

By their very nature, RCM models are focused on a given region and do not evaluate nor simulate processes that occur outside their bounds. The result of those processes comes from the GCM’s through “downscaling” to RCM’s.

- **Dynamic Downscaling:** The GCM’s “broad-scale” projections are treated as “inputs” at the RCM’s “boundaries”. This technique tends to be computationally intensive and requires very careful coordination, especially since “time dependent” GCM variables that are needed “are not routinely stored because of the implied mass-storage requirements⁴⁸”.
- **Statistical Downscaling:** Observed statistical relationships between broad-scale and local climate are applied in the RCM. While this technique is computationally cheap, it has two main disadvantages:

⁴⁰ IPCC, 2007; p. 593.

⁴¹ IPCC, 2007; p. 593.

⁴² Semazzi, et al., 1995; Qian et al., 1998.

⁴³ Cullen, 1997.

⁴⁴ Yeh et al., 2002.

⁴⁵ Shukla, 2009.

⁴⁶ IPCC, 2007; p. 593.

⁴⁷ UNDP, 2006; p.7

⁴⁸ Mearns et al., 2003.

- o Errors can be introduced by statistical relationships, especially in cases where there is a poor record of instrument data, as in the Arab World.
- o There is no scientific reason why processes that appear to be statistically correlated in the past will remain so under future conditions, especially under high rates of climate change.

In either case, any “errors introduced by the GCM large scale representation are transmitted to the RCM⁴⁹”. This could have significant consequences, particularly in the context of the Arab world, because the impact of both “El Niño-Southern Oscillation” (ENSO) and the “Inter-Tropical Convergence Zone” (ITCZ) remain poorly understood on the global scale.

III.B.1 El Niño-Southern Oscillation (ENSO) Event

ENSO events are a crucial element of any model that aims at simulating the climate in the Arab world, particularly in East Africa and Egypt. Indeed, of 80% of the Nile waters that flow into Sudan and Egypt are generated by monsoon clouds that fall over the Ethiopian highlands.

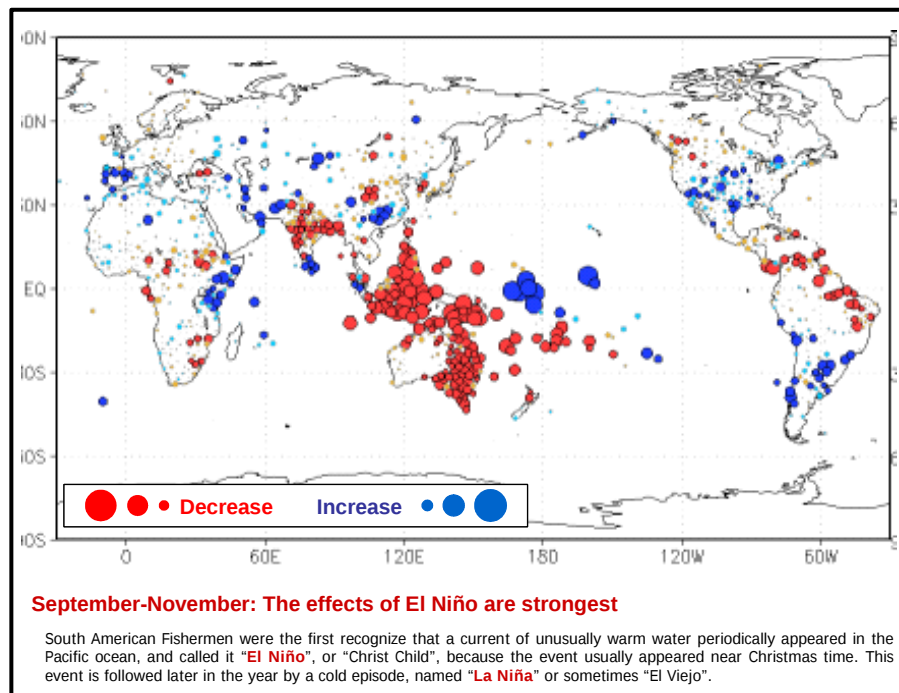


Figure 10. Global Impact of El Niño on Precipitation⁵⁰.

The formation of those clouds starts far from the region, as they are carried by the “Inter-Tropical Convergence Zone” (ITCZ), a 10° (about 1,100 km) wide equatorial band of low pressure in which both northeast and southeast “trade winds” converge. Near the Arab region, trade winds blow westward, steering tropical storm that form over the Pacific and Indian Oceans towards making landfall in Southeast Asia, India, and East Africa. As it reaches East Africa, the ITCZ brings in rain clouds over the Ethiopian highlands and across them to the southern Sahel desert, about 10° south of the equator. The flow of the ITCZ is not constant, as it can shift 40° to 45° of latitude away from the equatorial region of Africa under the effect of either variation in land temperatures, or an increase in atmospheric aerosols.

⁴⁹ Mearns et al., 2003.

⁵⁰ Royal Netherlands Meteorological Institute: http://www.knmi.nl/research/global_climate/enso/effects/

Note:

Aerosols are fine solid particles that are “suspended” (float) in the atmosphere. They used to occur though natural process of forest fires or volcanic activity, but nowadays are typically generated as the burning of various fuels creates smoke, air pollution, or smog.

The ICTZ is also related another climate processes such as the ENSO events that interact with sea surface temperature variations over other ocean basins, especially the Indian and South Atlantic Oceans⁵¹.

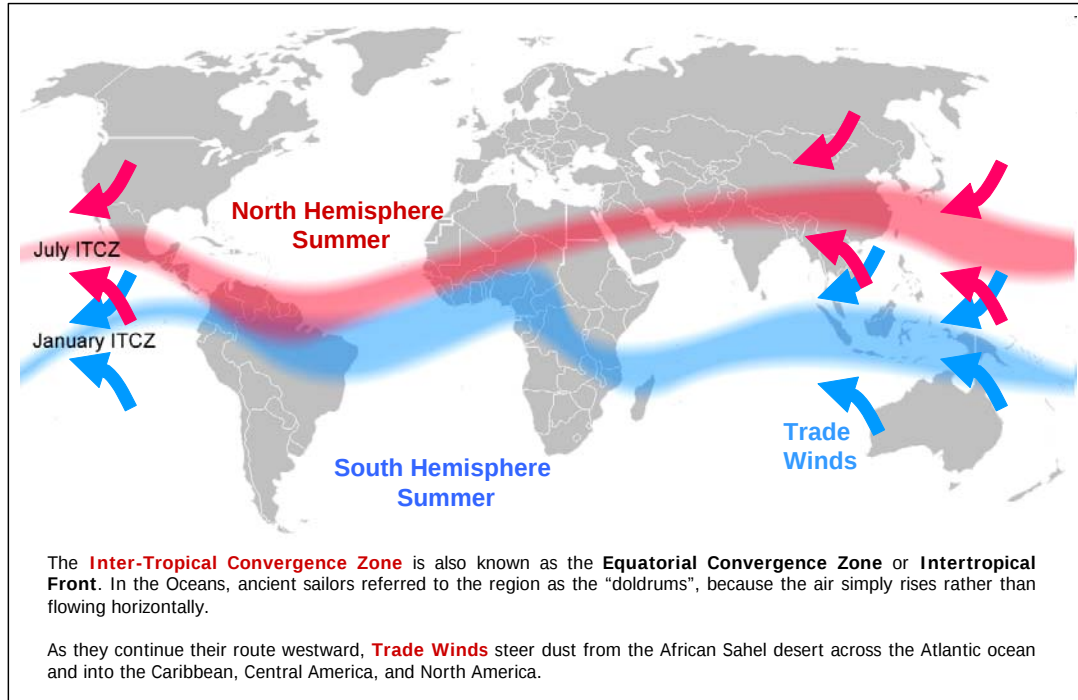


Figure 11. The Inter-Tropical Convergence Zone (ITCZ).

In the present state of knowledge, in spite of “overall improvement in the AOGCM simulation of the spatial pattern and frequency of ENSO”, problems remain “in simulating its seasonal phase-locking and the asymmetry between El Niño and La Niña episodes⁵²”.

Note:

A “**phase-locked**” loop is a type of “**negative feedback**”, where a system's output counter-balances the inputs, thereby attenuating changes and “stabilizing” the interaction. The El Niño-La Niña episodes are an example of such a negative feedback; the “stability” in this context describes the recurring nature of the two episodes

Further progress may depend on improvements in modeling the climate on the smaller scale of regions that are affected by ENSO and the ITCZ, such as the Nile Basin, the Sahara Desert, and the Arabian Peninsula.

III.B.2 Implications for the Arab World

The implications for the Arab world are two fold; on the global level, and on the local level.

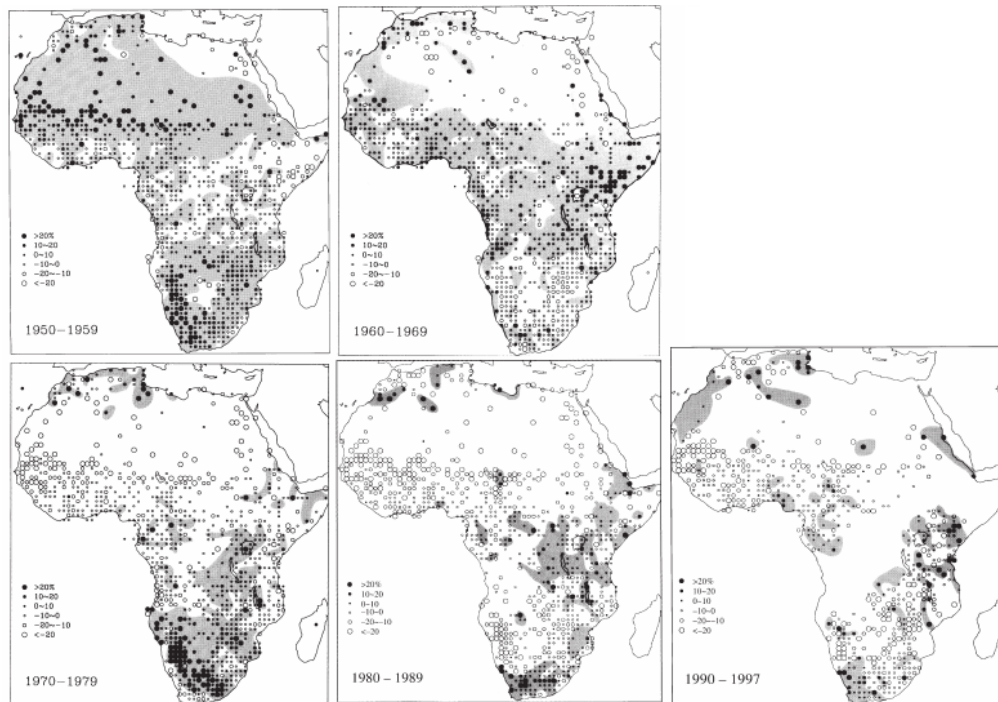
⁵¹ Camberlin, 2009.

⁵² IPCC, 2007; p. 592..

On the **global level**, there is much evidence for the importance of RCM modeling in understanding such crucial global processes as ENSO and ICTZ. The evidence for that comes from various small scale models for storm-tracking, which show links between small variations within the system to the system's overall trend⁵³. Those systems act much like a swing whose sway is sustained by small, random blows; this trend is evidenced in simulations of ENSO, where random atmospheric disturbances play an important role in defining the extent of the event⁵⁴. Recent evaluations of current models show that “control on the ENSO-rainfall teleconnection by the ENSO amplitude is systematic, highlighting the importance of realistically simulating this attribute⁵⁵”. Further complicating matters is the fact that a comparison between models and observation suggest that “the Indian Ocean has variability beyond ENSO⁵⁶”.

On the **local level**, the need to better understand those processes is crucial because of the need to “input” ENSO related parameters from GCM's.

- In the regions closest to this “boundary”, such as the Upper Nile Basin and the Arabian Peninsula, this could lead to mistaken estimates of rainfall rates; the increases predicted by most models may simply be a case of “model rain”.
- Historical evidence indicates frequent drought episodes when precipitation over Africa decreased by as much as 50% compared to the average between 1951 and 1997.
- The same evidence suggests that, from drought to drought, while the decrease in rainfall departed less and less from the mean over the continent in general, conditions worsened over the rest of the continent.



⁵³ DelSole and Shukla, 2009.

⁵⁴ Kirtman and Schopf, 1998; Fedorov, 2003.

⁵⁵ Cai et al., 2009.

⁵⁶ Cai et al., 2009.

Figure 12. Historic Evolution of Mean Rainfall Rates over Africa⁵⁷.

The recent relative improvement over North Africa and the Sahel may be misleading; past droughts may have been worsened by European aerosol emissions⁵⁸, with current increases in rainfall “starting” from already “low base”. Indeed, European aerosol emissions appear to have had little effect over the rest of the continent, in Southern Africa East Africa, and the Nile Basin. There, the worsening conditions appear to reflect long-term trends in precipitation decline and worsening droughts.

This deficiency would also pose a problem when comparing the performance of regional models with historic data. Because of the linkages, it will be hard to evaluate the performance of an RCM’s attempt at simulating precipitation over the Nile Basin, since it will ultimately depend on a GCM’s representation of ENSO. In the current state of knowledge, there are two ways to address this issue:

- New tools such as the new NICAM model are under development, but it remains to see how closely it correlates with the data. This is important for the implementation of RCM for the Arab world will always be dependent on proper modelling of ENSO because of its role in regulating precipitation in the Nile Basin.
- At the present time, RCM models have little choice but to rely on GCM’s that better simulate tropical heating, since those with “high deficiencies in simulating tropical heating produce highly deficient extra-tropical response to ENSO⁵⁹”. This appears to be the case of the regional model implementation by the Hadley Centre. However, a better understanding is still needed for the ENSO and the ITCZ before one is sure that the forecasted increases in rainfall rates are likely to be real.

It is crucial for the Arab world that such linkages be better understood; not only do current models still poorly describe ENSO events, but there is little consistency among them as “systematic biases have been found in most models’ simulation of the Southern Ocean”, which is “important for ocean heat uptake⁶⁰”. The successful modeling of RCM’s for the Arab Region will therefore be essential for a better understanding of the global climate, and may result in improved understanding of such crucial events as ENSO and ITCZ.

IV. MODEL VALIDATION

At present, there is no formal theoretical process for evaluating or validating uncertainty from climate models⁶¹. However, the consensus is that a statistical comparison may be applicable since different models are “quasi-independent”; they were independently developed at different institutions and the processes programmed rely on different references. This led to various comparative efforts since the late 1990’s such as the European Union’s “Prediction of Climate Variations on Seasonal to Inter-annual Timescales” (PROVOST) or the United States’ “Dynamical Seasonal Prediction” (DSP).

In those projects, the output from different models was compared against real observations. The consensus among those comparisons appears to be that the accuracy of a given full multi-model ensemble was generally higher than that of any of the single-model ensembles⁶² considered. This led to the “Development of a European Multi-model Ensemble system for seasonal to inTERannual prediction” project (DEMETER), a project funded under the European Union 6th “Framework Environment Programme”. The

⁵⁷ Hulme, 1999; Nicholson, 2001.

⁵⁸ Recent climate model simulations on (GFDL CM2.x) indicates that the general drying trend in the Sahel is at least partially attributable to an increase in atmospheric aerosols (Held et al., 2005).

⁵⁹ As determined by the European Centre for Medium-Range Weather Forecasts (ECMWF), (NCEP), (GFDL), (COLA). Reported in Shukla et al., 2007.

⁶⁰ IPCC, 2007; p. 591.

⁶¹ Palmer et al., 2004; Trenberth et al., 2007.

⁶² Barnett et al., 1997;

IPCC TAR and AR4 efforts are based on a similar concept; rather than relying on a few models, they are following a multi-model integration approach.

Subsequent evaluations validated this approach; the certainty of the IPCC's AR4 in the effect of GHG emissions on climate appears to be reinforced by the fact that those models that more accurately simulated the climate of the past 100 years also tended to produce higher values for global warming⁶³.

It is likely that the same would apply for RCM's ability to describe a given region, provided they are also developed independently. This may prove to be crucial for the Arab world where many regions, already on the brink of freshwater scarcity, are extremely vulnerable to climate change. While no multi-model configuration can provide a precise description of the region's climate, a wider array of models would allow for increased accuracy, therefore affording greater guidance to policy makers.

V . SCENARIOS AND VULNERABILITY ASSESSMENT

The Arab world covers a vast expanse of physical territory, extending from the Atlantic Ocean to East to the Indian Ocean to the West. Across this vast landscape, the Arab world is facing the challenge of a complex sustainability challenge generated by the interaction of climate (physics, chemistry), geology, ecosystem, and human activity (economic, cultural).

Because of the growing urgency of climate change, climate modeling will have to be closely coordinated scenario building, and policy making and implementation. More than in other cases, the evaluation of the "Whole Earth" system in the Arab context will have to be a multidisciplinary effort across those three competency "domains".

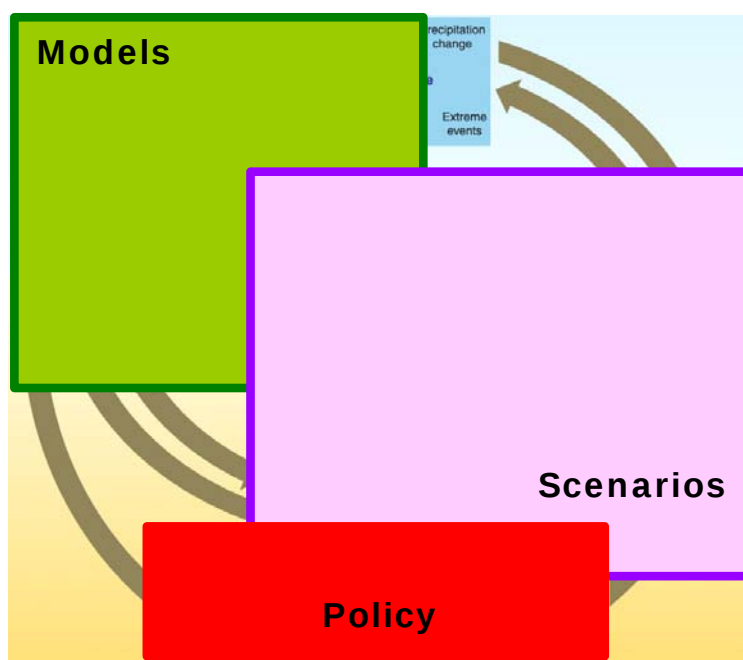


Figure 13. The “Whole Earth System”: Domains of Models, Scenarios, and Policy.

In order to assess the impact from such a diversity of elements, policy makers need to rely on formal evaluation tools that consider various fields of study; the social and economic factors that drive the emission

⁶³ Shukla et al., 2006.

of greenhouse gases, the biogeochemical cycles and atmospheric chemistry that determines the fate of those emissions, and the resultant effect of greenhouse gas emissions on climate and human welfare.

Some of those formal tools are “Integrated Assessment Models” (IAM) that bring together and contextualize information from diverse fields of study.

However, IAM’s are often biased by assumptions made on complex information with little context or understanding of their long-term implications. Typically, IAM’s treat the future impacts from climate change in the same manner as risky, short-term financial decisions, and thus discount them at relatively high rates. This leads them not only to mistakenly undervalue the future value of early efforts at adaptation, but also to ignore any potentially valuable technological innovation that could result from mitigation efforts. Their most critical failing, however, is their attempt to speculatively price the costs of climate change while downplaying scientific uncertainty about the extent of expected damages⁶⁴.

Rather than engaging in such speculations about relative costs, the IPCC AR4 has chosen to follow a dual approach. First, it simply established a “Topology” of the uncertainties related to the current state of knowledge, largely based on a description of the risks associated with climate change. Then it developed various scenarios of climate change, and evaluated their impact, without attempt to associate cost any of the outcomes, or to price any of the decisions.

In this manner, the various likelihoods would become clear to policy makers, and they can evaluate the impact of their decisions in the context of a few key possible scenarios.

V.A RISKS AND LIKELIHOODS

Formally, the notion of Risk defines the “Uncertainty of Outcome”, computed as the product of the probability of a given event with its impact, or cost.

This means that risks can be categorised in four types, depending on whether the impact is limited or complex, and whether the probability can be ascertained from Normal Distribution functions, or belongs to a “Fat Tail” domain. As a result, decisions on adaptation or mitigation would **in theory** be defined by both the type of impact and the existence of probability estimate. However, **in practice**, such probability estimates cannot be determined with any certainty in many cases, particularly those concerning the climate; while global warming is now a certainty, the extent of exposure is harder to ascertain.

V.A.1 The Fourth Quadrant

Risks associated with such complex “Fat Tail” probability domains are therefore said to belong to a “Fourth Quadrant”⁶⁵, where neither mitigation nor adaptation are possible.

⁶⁴ Ackerman et al.,

⁶⁵ Taleb, 2008.

Table 2. The “Fourth Quadrant” Problem.

Impact		Simple	Complex
Probability	Normal “Thin Tailed”	Mitigation Affordable Risk	Adaptation Manageable Risk
	“Fat Tailed”	Adaptation Potentially Unaffordable Risk	No Adaptation No Mitigation Unaffordable Risk

Note:

In **well understood domains** such as the height of people or their age, probabilities belong to a “normal”, or “Gaussian” distribution, a bell-shaped curve. In those domains, there are upper limits to parameters, such as how tall a person can be or how old they can grow.

However, there are **many other domains** where parameters either **do not have upper or lower limits** (“tails”), or where the frequency of the occurrence of the higher values is not well known. Those are parameters such as surface temperatures or stock prices. In order to address those, probability distributions were developed with more allowance for upper or lower limits. However, those are no more than “deformations” of the bell-shaped curve that give it a “fat tail”, and their use has often resulted in misidentification of risks, notably in the stock market

This “Fourth Quadrant Problem” is one principal reason for the shortcomings of vulnerability assessments based on IAM models. IAM models can be useful in investigating problems that fall in the first and third quadrant where the likelihoods are known. To some extent, because of its limited impact, policy makers could also rely on IAM models for problems that fall in the second quadrant. In general, climate change belongs to that Fourth Quadrant, since we are now certain that it is occurring but we cannot determine when specific events will occur;

- The probability of occurrence of *specific weather* events cannot be determined with any certainty. For example, in the current state of knowledge, there is no doubt that the Arab world will experience a rise in average temperatures, which will result in an increased frequency of extreme weather events such as droughts. However, there is no way of determining when those droughts will occur. Furthermore, it is possible that the region may experience a continuous period of rainy years, thereby giving policy makers a false sense of security until the drought cycle starts again.
- On average, only overall climate trends can be understood. However, because of poorly understood feedbacks between climate processes, there can be few certainties about the likelihood of a given outcome. For example, while RCM can eventually describe accurately future climate patterns over the Arab Region, they will remain dependent on proper forecasting of events outside the region, such as ENSO and ITCZ. Those events, and the feedbacks among them, remain themselves poorly understood.

When considering the “complex tradeoffs at larger scales” that occur in the Fourth Quadrant, no reliable probability estimate of the likelihood of impacts is available⁶⁶.

V.A.2 Decision Making and Uncertainty

In addition to the lack of information about probabilities, policy makers are confronted with the fact that the “knowledge base” in this domain is still “formative”, as “the knowable remains undetected because of the

⁶⁶ Wilbanks, 2004.

assumptions that frame the question or methods of analysis”. This lack of information leads to disagreement about the known and the knowable and thus further increases uncertainty.

Note:

This is illustrated by the discovery of the “**Ozone Hole**” over the South Pole. It was discovered only after British Scientists pointed out to a link between “outliers” in ground-based readings of ultraviolet radiation and a “possible decrease in the ozone in the Southern Hemisphere springtime from the mid-1970’s to the mid-1980’s”. As a result of this **unexpected finding**, computers were reprogrammed to analyze all data points”, revealing “a deep hole in the ozone over the Antarctic continent, which was growing in intensity over time and drifting over nearby oceans and continents” (Schneider and Kuntz-Duriseti, 2002)

In considering this “systemic” uncertainty that extends from science to affect the policy arena, there are two options:

- **Bound the Uncertainty.** In normal scientific study, uncertainty is overcome by identifying unknowns and resolving them. However, in considering climate change, the “unknowns” are far too many, arising from statistical variations, measurement errors, variability, approximation, subjective judgment, and even disagreement. The uncertainty is magnified by the simple fact that no “before-the-fact” experimental controls are possible in studying the climate change.
- **Manage Uncertainty.** In this context, the focus is on creating models to investigate the system’s response to various disturbances under various scenarios.

Table 3. Examples of Sources of Uncertainty⁶⁷.

Problems with Data	
	• Missing components or errors in the data • “Noise” in the data associated with biased or incomplete observations • Random sampling error and biases (nonrepresentativeness) in a sample
Problems with Models	
	• Known processes but unknown functional relationships or errors in the structure of the model • Known structure but unknown or erroneous values of some important parameters • Known historical data and model structure but reasons to believe that the parameters or model structure will change over time • Uncertainty about the predictability (e.g., chaotic or stochastic behavior) of the system or effect • Uncertainties introduced by approximation techniques used to solve a set of equations that characterize the model
Other Sources of Uncertainty	
	• Ambiguously defined concepts and terminology • Inappropriate spatial or temporal units • Inappropriateness or lack of confidence in underlying assumptions • Uncertainty caused by projections of human behavior (e.g., future consumption patterns or technological change), which is distinct from uncertainty from “natural” sources (e.g., climate sensitivity, chaos)

V.A.3 The IPCC Approach

The IPCC has therefore elected to focus on “managing uncertainty” and not base its estimates of climate change on statistically based claims and developed guidelines to help ascertain the type of Climate Risk by developing a “Topology of Uncertainties⁶⁸” to use when investigating Fourth Quadrant issues; Unpredictability, Structural Uncertainty, and Value Uncertainty.

Based on this classification, a formal definition was developed to define the prevailing consensus among experts and ascertain their level of confidence. This approach allowed the IPCC to identify the most relevant computer simulations and develop a consensus among them. The uncertainty could then be quantified

⁶⁷ Moss and Schneider, 2000.

⁶⁸ IPCC, 2005.

through formally outlined “Degrees of Doubt”⁶⁹, where terms such as like “likely” and “very likely” are expressed in terms of percentage probability.

Table 4. The IPCC’s Varying “Degrees of Doubt”.

Virtually Unlikely	Very Unlikely	Unlikely	“Medium”	Likely	Very Likely	Virtually Certain
< 1%	1 - 10	10 - 33	33 - 66	66 - 90	90 - 99	> 99%

As the IPCC investigated the reasons behind the current climate trend, two key conclusions were reached;

- Human emissions of GHG’s, which “have grown since pre-industrial times” by “70% between 1970 and 2004”, are “*very likely*” the cause of “most of the observed increase in global average temperatures since the mid-20th century”⁷⁰.
- As a result, the “warming of the climate system is *unequivocal*”⁷¹, and it “has *likely* had a discernible influence at the global scale on observed changes in many physical and biological systems”⁷².

As a result, the debate is not one of determining **whether** there is an ongoing climate change, but *how* this change will affect various regions and **what** will its extent be.

V.B SCENARIOS: DEVELOPING IMAGES OF THE FUTURE

By definition, any evaluation of “change” in climate involves comparison between states. Those “scenarios” are arbitrary or synthetic constructs that simulates discrete variations between climate parameter over time; for example, incremental changes in mean temperature or precipitation amounts and their occurrence.

Such “time series data” can provide modellers with information on a range of possible changes and the inter-linkages between parameters and processes. However, those data are seldom realistic unless they are compared to a “baseline” daily climate database that contains real measurements either from previous history or physical reality.

V.B.1 Analogue Scenarios

Scenarios that are based on previous history are known as “Analogue Scenarios”. They are either “temporal analogues” that use of past warm climates as scenarios of future climate, or “spatial analogues” that use current climate in another location as scenario of future climate in the study area.

In **Temporal Analogues**, past climate data is reconstructed from past:

- “Palaeoclimate”, in which past climatic data reconstructed from fossil evidence or ice cores is used as an “analogue” for the future climate.
- Historic climate extracted from the “instrumental record”, a record of temperature variations that extends to 1850 on the global scale⁷³. The most recent GCM experiments made use “Temporal

⁶⁹ IPCC, Climate Change 2007: Supplementary Materials: Global Climate Projections, p. SM. 10.8

⁷⁰ IPCC, Climate Change 2007: Synthesis Report, Summary for Policymakers, p. 8.

⁷¹ IPCC, Climate Change 2007: Synthesis Report, Summary for Policymakers, p. 2.

⁷² IPCC, Climate Change 2007: Synthesis Report, Summary for Policymakers, p. 6.

⁷³ Brohan et al., 2006. The Central England temperature data series is a longer running record, dating as far back as 1659, but it is limited in geographic scope.

Analogues” that used data from the “Instrumental Record” to compare the output of the models with data over the same period.

Using Palaeoclimate data has an advantage over the “instrumental record” because the large differences between the distant past and current climate may be more consistent with potential future changes. However, use of past climate data has two main disadvantages; not only are there concerns about the quality and availability of palaeoclimate reconstructions, but they could correspond to periods when the causes of climate change are either dramatically different from today’s, or poorly understood.

Spatial Analogues have the advantage of relying on recorded data from clearly understood time periods, over regions that closely resemble the area of interest to the study⁷⁴. However this approach is restricted because few regions completely correspond to one another; even if climate patterns are similar, future climate are unlikely to be similar⁷⁵. Because of this, “the climate change impacts assessment literature has generally recommended that these types of scenarios should not be used⁷⁶”.

V.B.2 Global Climate Model Scenarios

In order to investigate the various possible outcomes, the IPCC has focused on developing climate change “scenarios” based on the current understanding of climate and population dynamics.

The scenarios do not rule out very probable “surprises” due to “rapid, nonlinear responses of the climatic system to anthropogenic forcing⁷⁷”. Those surprises can be of two types;

- Climate outcomes appear to be “path dependent”; some impacts may be greater depending on how rapid the change is. Research shows that a faster rate of temperature increase may create a worse impact than forecasted.
- Possible events such as the probable collapse of Greenland Ice Sheet, leading to perturbations in the North Atlantic Ocean “conveyor” belt that could have catastrophic effects on natural and human ecosystems, in addition to potentially increasing sea levels by up to 7 m⁷⁸.

The approach followed by the IPCC may underestimate the impact of such surprises, but it is the most rigorous under the current state of knowledge. Rather than investigating such “imaginable surprises⁷⁹”, those “synthetic” scenarios attempt to “bracket the uncertainty”. They are were constructed based on 5 key criteria⁸⁰;

1. **Consistency** with global projections that estimate planetary warming to be in the range of 1.4°C to 5.8°C by 2100.
2. **Physical Plausibility** and strict adherence to physical laws. Changes need to be physically consistent across the globe and among different climate variables.
3. **Applicability** in impact assessments. Variables and scale considered (time and space) should allow for impact assessment; daily to annual mean values about changes in temperature, precipitation, solar radiation, humidity and wind speed is provided for a specific site, at a specific day. This becomes an issue when “downscaling” to finer resolutions RCM’s.
4. **Representativity**. Scenarios should be representative of the potential range of future regional climate change.

⁷⁴ Northern Britain was used as Spatial Analogue for Iceland to investigate future grass growth (Bergthsson et al., 1988).

⁷⁵ Carter et al., 1994.

⁷⁶ Environment Canada, 2009.

⁷⁷ IPCC, 2001.

⁷⁸ IPCC, 2007-b

⁷⁹ Schneider and Kuntz-Duriseti, 2002.

⁸⁰ Environment Canada, 2009.

5. **Accessibility.** Scenarios should be straightforward to obtain, interpret and apply in impacts assessments.

All the models development depended heavily on future emissions of greenhouse gases and aerosols, and therefore on population demographics, economic growth, energy use. The IPCC developed alternative “images of the future, or alternative futures” that that are “neither predictions nor forecasts⁸¹”.

Those “GCM-Derived Scenarios”, now the most common scenario type encountered⁸², were coordinated by the IPCC until its 25th session (Mauritius, 26-28 April 2006), when it was decided to leave the task of scenario development to the research community, in the run-up to a possible 5th Assessment Report (AR5). There are now 40 different emissions scenarios classified into 4 “families”; A1, A2, B1 and B2.

Each scenario family explores “alternative development pathways” without including “additional climate policies above current ones”⁸³. Each storyline making different assumptions about economic growth, demographic changes, and the pace of productivity increase through the introduction of efficient technologies, depending on whether the world moves towards an “inspiration economy” or continues in the current “perspiration” framework.

Within those families, 6 scenarios were selected as illustrative, or “marker scenarios”; A1FI, A1B, A1T, A2, B1 and B2. To each scenario there is some corresponding baseline data, organized into 9 major world regions: Africa, Australasia, Europe, Latin America, Middle East/Arid Asia, North America, Small Island States, Temperate Asia, and Tropical Asia. By the time of IPCC TAR, most global climate modelling groups had completed climate change simulations for A2 and B2. Most of them used mainly A2, A1B and B1 for IPCC AR4. The outputs from those scenarios are often compared to those from a “business-as-usual” scenario, the IS92.

⁸¹ Nakicenovic et al, 2000.

⁸² Environment Canada, 2009.

⁸³ IPCC, Climate Change 2007: Synthesis Report, p. 44.

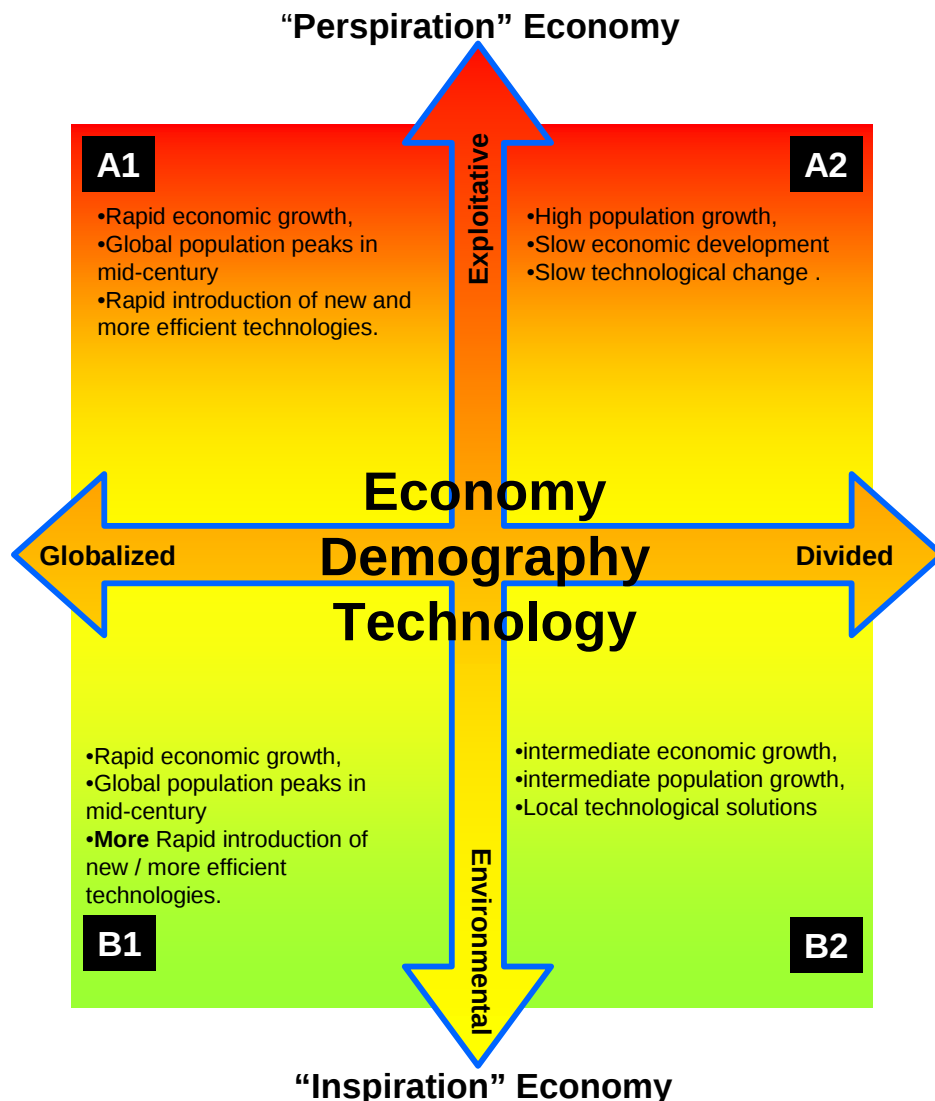


Figure 14. The IPCC’s Main Scenario Families.

Scenario Data: Air

In considering the effect of atmospheric constituents, the IPCC focused on Carbon Dioxide (CO₂), Ozone (O₃), sulphur and nitrogen compounds, as well as Smoke and other particulate matter.

The IPCC focused on CO₂ because it is the most important GHG under current conditions, accounting for approximately 63% of radiative forcing⁸⁴. It is also easier to study; because it is well mixed in the atmosphere, observations from a single site can be adequate for most impact studies. Because plants breathe CO₂, its concentration affects both the growth and water use of many plants. However, the relationship is not strictly linear, as plants stop growing beyond a certain threshold level. The quantity of CO₂ released in the atmosphere is estimated based on the emission scenarios and models of plant growth, then “fixed” in models for a given time period.

⁸⁴ Hoffman et al., 2006.

Ozone is found in either the Stratosphere or the Troposphere. When evaluating Stratospheric Ozone, the IPCC is focusing on depletion, and the resulting increase cancer-inducing ultraviolet radiation. This aspect of the IPCC work is important for countries at mid to high latitudes, especially during the spring and early summer when levels of stratospheric ozone are generally at a minimum. In the Arab World, Tropospheric Ozone appears to be becoming a growing concern, not least because recently accelerating urbanization is increasing concentrations for this gas that is toxic for a wide range of living organisms.

The same applies for the other pollutants considered by the IPCC; compounds of **sulphur and nitrogen**, as well as smoke and other **particulate matter**. However, there appear to be few systematic studies of the concentration of those pollutants in Arab urban centers. Unlike CO₂, the distribution of those pollutants varies across regions, and it is therefore not clear how closely the IPCC “Emission Scenarios” apply in the Arab world. In the case of sulphur and nitrogen compounds, their role in either “acid rain” or regional cooling may play an important role in regulating local climates. In the case of smoke and other particulate matter in the atmosphere, aside from their role in visibility and human health, they can affect cloud formation and precipitation. In semi-arid regions such as the Arab World, the lack of data of those parameters is an issue.

Scenario Data: Water

Under all scenarios, freshwater availability is set to be affected in either quality or quantity.

Under all scenarios considered by the IPCC, sea levels are set to rise. In the Arab world, this will cause further **seawater intrusions in coastal aquifers** that are already overtaxed by a growing population.

Most studies of vulnerability to sea-level rise use the mean sea-level at a single date, and those employing the IPCC Common Methodology use the 1990 level. However, there is little research on coastal vulnerability in the Arab world, especially on the Gulf Area where much investment was made in resorts. Closer assessment of coastal vulnerability will require baseline tide gauge and wave height observations to reflect tidal variations in combination with the effects of weather such as severe storms, the frequency of which is set to increase under most IPCC scenarios.

Another effect on water availability is water quantity. This is unclear from the current scenarios, because “a critical assumption of the standard assessment paradigm is that the **probability of extreme events** such as droughts⁸⁵” will remain either unchanged or within the bounds of the expected climate changes. This assumption may not be valid because it appears that changes in daily temperature variations can significantly affect the vulnerability to global warming of climate extreme-sensitive environments⁸⁶ such as the Arab Region. It is uncertain how Climatic variability might change as the climatic mean changes, but variability in precipitation is expected to increase⁸⁷.

Under all IPCC scenarios, water stress is expected to increase in the Arab world, affecting an additional 80 to 100 million people⁸⁸ by 2025. Many aquifers are already been depleted, as withdrawal rates are far exceeding recharges. Human intervention can worsen these effects; in North-Eastern Syria, 160 villages had to be evacuated as overpumping depleted aquifers already undersupplied because of drought. The lack of “fine” data may prove to be an issue for long term estimates of local climate because the selection of appropriate baseline period for model comparison depends largely on a good understanding of the likely causes of fluctuations.

⁸⁵ Schneider and Kuntz-Duriseti, 2002.

⁸⁶ Mearns et al., 1984.

⁸⁷ IPCC, 2001; IPCC, 2007.

⁸⁸ Cervigni, R.; Kremer, A.; Liverani, A. et al., 2007.

Scenario Data: Land

Data on land cover and use has been compiled for the IPCC by remote sensing (satellite imagery, aerial photographs) as well as ground surveys and national statistics, covering a time period that generally extended from 1970 onward. Most remote sensing data was gathered through the “Land Use and Land Cover Change Programme” (LUCC) of the “International Geosphere-Biosphere Programme” (IGBP) and the “International Human Dimensions Programme” (IHDP) on Global Environmental Change.

Under all IPCC scenarios, Agriculture yields are expected to decrease in the Arab world, especially in the case rain-fed cultivation. In value terms, output is expected to decrease by “21% by 2080, with peaks of almost 40% decrease in countries like Morocco and Algeria⁸⁹”.

V.B.3 From GCM-Derived Scenarios to High-Resolution Scenarios

Although GCM’s provide an accurate representation of the global climate, their simulation of current regional climate remains inaccurate⁹⁰ because of the “finer” scales involved. This is caused by uncertainty, which can either “explode” or “cascade”.

An “Uncertainty Explosion”

In Climate change impact assessments, “there are a number of sources of uncertainty [...] which contribute to uncertainty in the final assessment”. On the global scale, “uncertainty accumulates throughout the process of climate change prediction and impact assessment”, as the uncertainties grow across the “causal chain” that links different climate processes.

Since IPCC TAR, this issue has been currently better managed in GCM’s. A consensus has emerged among scientists, as to probability estimates for a number of factors such as the increase in global mean temperature for a doubling of CO₂, in spite of a there is a wide divergence of opinion on extreme outcomes (negligible or highly serious⁹¹).

Note:

Estimates of the economic impact of extreme climate change made by **natural scientists** tends to be **e 20 to 30 times higher** than **conventional economists** (Nordhaus, 1993; Roughgarden and Schneider, 1999).

However, they both agree that the shape of the “damage curves” is “right skewed”, meaning that **severe climate damage** (“Nasty Surprises”) is expected to be **much more likely** than that of any **moderate benefits** (“Pleasant Surprises”). While “most knowledgeable experts from a variety of fields admit to a wide range of plausible outcomes”, extremely pessimistic or optimistic projections are considered to be the two least likely outcomes (Schneider and Kuntz-Duriseti, 2002).

, which may indicate that all four IPCC AR4’s scenario families are generally considered optimistic (Roughgarden and Schneider, 1999).

However, a problem remains when moving to the finer resolutions of the regional scale.

A “Cascade of Uncertainty”

The various scenarios that are valid on the global scale cannot represent the full range of potential climate changes in a region. In many documented cases, the “application of high resolution scenarios produced from” and RCM produced changes “that were significantly different from the changes calculated from a coarser resolution GCM scenario⁹²”. This was particularly the case when investigating such fine processes as crop yields or river flow.

⁸⁹ Cervigni, R.; Kremer, A.; Liverani, A. et al., 2007.

⁹⁰ Giorgi et al., 2001.

⁹¹ Schneider and Kuntz-Duriseti, 2002.

⁹² Mearns et al., 2003.

When considering the regional scale, it is therefore necessary to develop specific scenarios that describe the range of climate changes in a given region. One way of achieving this is to “downscale”. However, downscaling is very difficult to implement in practice because of differences in the sources of uncertainty. At the regional scale, these uncertainties form an ever more intricate “cascade” in which each parameter is related to the other in multiple manners.

In this cascade, “at each step, and at each sub-component of each step, alternative approaches or estimates are available which then have the potential to yield a range of valid results as inputs for the next step”. As a result, when using “coarse” resolution climate change results from GCM’s to obtain high resolution results from RCM’s, new uncertainties are introduced “as different regional models (or statistical downscaling methods) can yield different results even when conditioned by the same GCM⁹³”.

For this reason, at the present state of knowledge, there are no reliable methods to translate global patterns into local information. One leading effort in this field is the initiative for “Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects” (PRUDENCE).

V.C HIGH-RESOLUTION SCENARIOS FOR THE ARAB WORLD

In considering scenarios for the Arab World, one has to be mindful of developments that followed the publication of the IPCC report.

V.C.1 Temporal Analogues

The long history of human settlement in the region means that there is a wealth of historic record that date back to ancient times. Egypt, in particular, has extensive records on the Nile’s year-on-year fluctuations, which can be correlated with its many existing economic records. There are also more recent records that, much as in Europe, reflect daily seasonal information across the Arab World; this was done as part of ancient monastic traditions, Ottoman tax collection efforts...

In addition, such historic climate records can easily be supplemented by detailed “palaeoclimate” data obtained from archaeological and geologic investigations. Such investigations have allowed researchers to develop a good understanding of the Jordan Basins’ evolution over the past 10,000 year, as it evolved from a glacial “Lake Lisan” to the current river system that we see today.

However, RCM’s may require “finer” data than what is available so far, in addition to more “formal” representation of measurement units. This will require a large effort to create incentives for researchers to make the information available.

V.C.2 The Need for Specific RCM-Derived Scenarios

IPCC scenarios result in an estimate of global emissions that varies between 1.7% and 3.4%. However, the growth rate of global emissions had exceeded 2.5% in the period between 2000 to 2005, much higher than its 1% per year average during the 1990’s⁹⁴. The growth rate appears to have accelerated further until the onset of the 2008 world recession, exceeding 3% in the period between 2000 and 2008. Such growth spurs exceeded most scenarios, suggesting that the IPCC’s may have been too optimistic

In the same period, energy consumption in the Arab world had also been accelerating, as the hot and humid climate requirement for extensive use of indoor air conditioning led to “comparatively high rates of electricity consumption, and corresponding rates of carbon dioxide emissions⁹⁵”. While the Arab contribution to GHG emissions had been among the lowest over the course of the 20th Century (about 4.5% of the world’s total by 2000), air quality has been worsening recently at an accelerating pace. In the

⁹³ Mearns et al., 2003.

⁹⁴ Raupach et al., 2007.

⁹⁵ UN-ESCWA, 2007.

economic boom period that extended from 1990 to 2004, emissions had increased by +88%, or “3 times faster than the world's average”⁹⁶.

A further concern is that this rate of increase may have local effects that are not reflected by the various IPCC scenarios. Indeed, actions taken in the short term may have serious long-term and potentially irreversible consequences, as weak short-term climate policies build into the long-term future unexpected, major changes in climatic conditions⁹⁷.

As a result, it may be more realistic to take into account the worse case IPCC scenarios when considering the Arab World. Indeed, the consensus among preliminary assessments of the of the Arab world's vulnerability to climate change⁹⁸ appears to be that it will exacerbate the region's endemic water scarcity. Diminished freshwater resources will lead to decreasing agriculture yields and worsening water and air quality. This will expose the Arab world to large economic and social impacts that the best way to prepare for is by developing region-specific scenarios for use in validating RCM's.

V.D MITIGATION AND ADAPTATION

In considering adaptation or mitigation strategies, policy makers cannot solely focus on addressing current issues. Strategies need to be developed to fit the conditions of the future as it is likely to be, by relying on constantly revised forecasts. The IPCC AR4 has reinforced the certainty that the world needed to both mitigate and adapt for climate change, by both reducing such “Anthropogenic Forcings” as GHG emissions and preparing for the impacts of climate change.

While there is often a debate on “mitigation versus adaptation”, it is likely to be an artificial debate; akin to a car driver comparing the benefits of the taking the foot off the accelerator versus applying the brake as road conditions change ahead of them. By itself, mitigation will not be sufficient to address the climate change challenge. Aside from obvious issues related to policy definition, coordination, and implementation, there are systemic issues related to climate “inertia”⁹⁹. As this slows down the system's responses to Forcings, the effect of mitigation measures may take a long time to be clear. Adaptation measures will therefore be essential; even if their foot is off the accelerator, the driver will need to apply the brake to negotiate the changed road conditions ahead.

Such an approach is particularly needed in the Arab world, an already “hot” region where average temperatures are above 20°C, and where most people already live on the edge of water scarcity. The Arab strategy therefore has little option by to focus on “fitting” human life to a warmer environment through adaptation. However, in order to do so successfully, policy makers need a proper determination of vulnerability.

V.D.1 Vulnerability

Vulnerability can be approached in either of two approaches; “scenario-led”, or “vulnerability-first”.

The first approach is valid when considering a “punctual” crisis in which the issue is still poorly characterized. The focus then becomes one of adaptation to marginal impacts in the context of short-term responses. However, such an approach is ill-adapted to climate change; not only is it a longer-term crisis, but it is also a complex challenge.

The second approach is more adapted to the context in which the crisis is both complex and highly variable. By focusing on the impact of adverse events, policy makers can concentrate on the necessary mix of adaptive measures and mitigation policies with a sustainable development focus.

⁹⁶ Cervigni, R.; Kremer, A.; Liverani, A. et al., 2007.

⁹⁷ Mearns et al., 1984; Schneider and Thompson, 2000.

⁹⁸ Dasgupta et al., 2007; Cervigni, R.; Kremer, A.; Liverani, A. et al., 2007.

⁹⁹ Trenberth, 1992.

This focus leads to a definition of vulnerability that defines how well a community is able to cope with adverse effects of climate change. It is function of the type, magnitude, and rate of climate variation to which that community's systems are exposed. Vulnerability can therefore be represented as a "Vector"¹⁰⁰; a plot of the impact versus time of a given threat for each given sector or group considered.

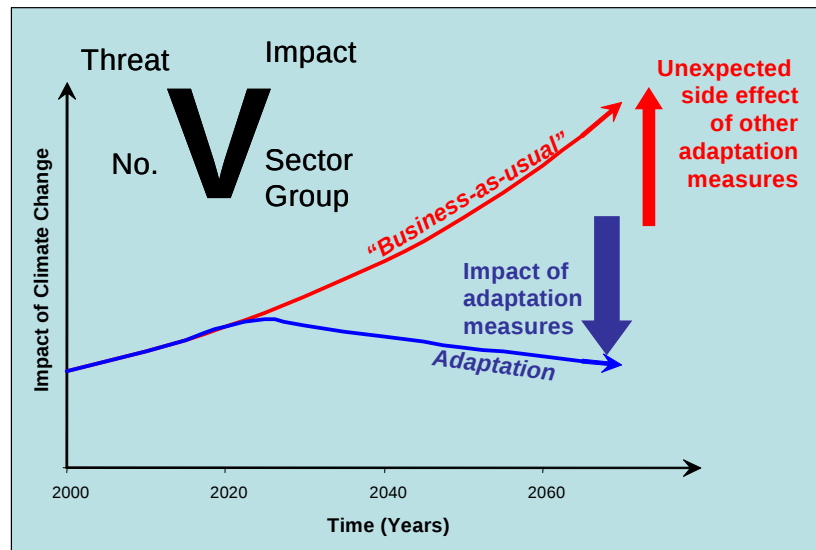


Figure 15. Vulnerability Vector

Vulnerability will also differ across groups (region) or sectors. In part because of their different faculties of adaptability, not all regions will cope in the same manner for a given climate impact. In the same manner, various sectors will cope differently depending on how the weather affects their activity. For this reason, any evaluation of Adaptability of Resilience will have to be region specific and may need to be sector specific.

V.D.2 Adaptability and Resilience

Adaptability has two components; it is not merely a community's ability "to adjust to climate change to moderate potential damages" or "cope with the consequences", but also its ability "to take advantage of opportunities"¹⁰¹. Such communities are defined as resilient, as they can do relatively better than others thanks to a comparatively better ability to "to resist, absorb, and recover from the effects of hazards in a timely and efficient manner, preserving or restoring its essential basic structures, functions and identity"¹⁰².

In the context of climate change, there were various broad list of indicators developed, but it appears that practitioners did not find them useful. A better approach was to develop "specific, time-bound and measurable" parameters that would serve as "adaptation targets" (i.e. number of vulnerable people). This would make "adaptation strategies concrete" as it would allow more effective "piloting" of targets "on the basis of an integrated approach involving systemic appraisal and longitudinal studies"¹⁰³.

In the context of the Arab world, Resilience could be evaluated as a function of 6 key elements; "Overall Policy", "Early Warning", "Preparedness", "Adaptation", "Mitigation", and "Knowledge".

¹⁰⁰ Tellam, 2008.

¹⁰¹ IPCC Working Group 2, 2001. Third Assessment Report, Annex B: Glossary of Terms.

¹⁰² UNISDR, 2009. Terminology: Basic terms of disaster risk reduction and IISD et al, 2007. Community-based Risk Screening – Adaptation and Livelihoods (CRiSTAL) User's Manual, Version 3.0.

¹⁰³ Tellam, 2008

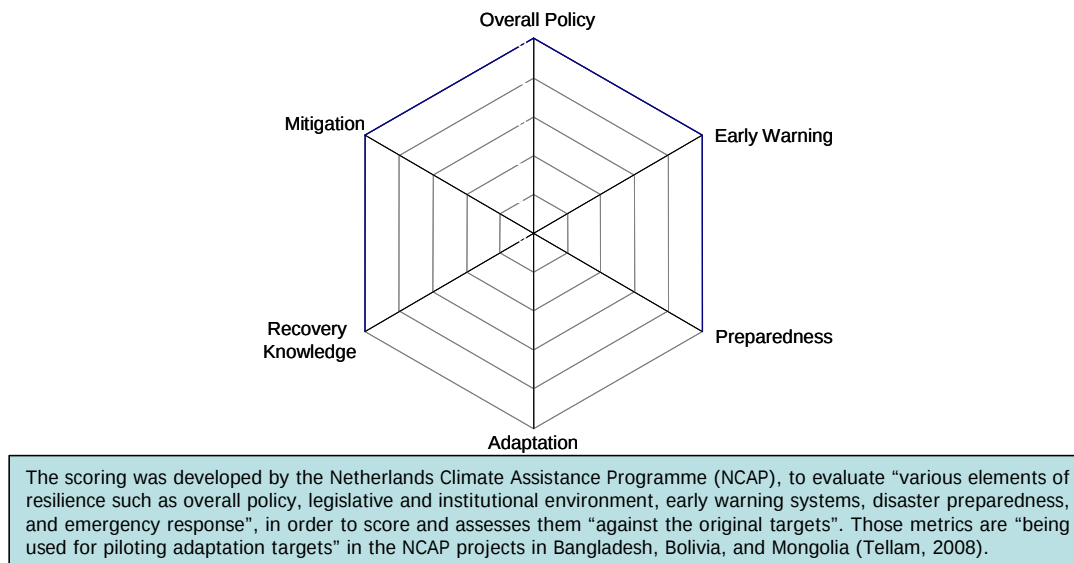


Figure 16. Adaptability/Resilience Matrix.

The term “Overall Policy” is often confusing as it is used interchangeably to mean different concepts of “action” or “impact. In this context of adaptation to climate change, the term is used here to mean “action”; the aim is to see how much policy making is actively working to address the issues. As an example, the Overall Policy score would be low when climate change issue is “owned” by Environment Ministries, with little or no input or action by the other departments affected by it.

Early Warning is an important tool of any strategy to confront the climate change challenge. It is here that the implementation of RCM’s for the Arab world plays an important role, as it will not only allow for a proper characterization of the challenge, but it would help prioritize the actions that need to be implemented.

Adaptability and Resilience are defined by both knowledge and infrastructure. The “**knowledge**”, in this context, is people with the necessary “background and knowledge resources to address actions and measures in the field¹⁰⁴”. The “**infrastructure**” would then be the equipment and amenities necessary for those people to carry out their tasks. The lack of either Adaptability or Resilience indicates a climate change “Hot Spot”.

Each of the metrics considered can be quantified in one three key methods; financial, development-related, or based on broad sectoral indicators¹⁰⁵.

Financial metrics would simply be the amount of money allocated for adaptation either by the country, or through foreign “Official Development Assistance” (ODA). However those targets would need constant review and revision because they would need to be determined based on available information on available cost, which is itself very limited, based on various and complex assumptions.

As an alternative to financial metrics, **Development-related metrics** are simply based on concrete and measurable economic development targets. This would allow continuous evaluation without the need for hard-to-verify assumptions on future costs and discount rates. However, this approach may not apply to “mature” economies or regions, where development is not as much an issue as continued sustainability.

The third option is more focused on developing regions, and depends on setting specific indicators focused on **vulnerable sectors of the economy**, selected to reflect linkages with climate change. Such indicators can be simply taken from either the 48 indicators that measure progress towards meeting the

¹⁰⁴ Prasad et al., 2009.

¹⁰⁵ Levina, 2007.

United Nations' 2009 "Millennium Development Goals" (MDG), or the other 96 that have been developed to measure sustainable development¹⁰⁶. Some of these indicators are relevant for use as adaptation metrics¹⁰⁷, provided they prove to be uncorrelated in the Arab context.

¹⁰⁶ UN, 2009.

¹⁰⁷ http://wikiadapt.org/index.php?title=Designing_Metrics_for_Adaptation

Table 5. Typical Sectoral Indicators.

Indicator Target	Description
adaptive capacity	Proportion of population living on less than \$1 (PPP) per day Net enrolment ratio in primary education Literacy rate of 15-24 year-olds % Of National Budget Dedicated To Carrying Out Vulnerability Assessments
Result-oriented	Prevalence of underweight children under-five years of age Share of preserved coastal wetlands Human and economic loss due to hydro-meteorological disasters % of land lost due to sea level rise % of population living on flood planes
process-oriented	Availability of national climate change impacts and vulnerability assessments Availability of national adaptation strategies with identified adaptation priority actions National reports integrating adaptation into sectoral policies and planning Amount of funding directed for community adaptation projects

VI. CONCLUSION AND RECOMMENDATIONS

As the Arab world faces the climate change challenge, it needs to adopt an integrated managerial-technical strategy. The strategy cannot be fixed, and necessarily needs to evolve as the nature of the challenge changes and our knowledge develops. The optimal framework Strategy should be build around 6 key elements.

1. **Defining Current Knowledge Domain.** It is simple fact that uncertainties will remain concerning data and forecasts on climate change. The “Precautionary Principle” here should be followed; “when a reasonable degree of doubt exists over the consequences of human action, there are, perhaps, sound reasons for taking a conservative approach”¹⁰⁸. In the case of the Arab region, effort should be made to improve knowledge about epiphenomena such as ENSO/ITCZ because of their large effect on some key regions in the Arab World.
2. **Scenario Building.** The configuration of the Arab World and West Asia are very different from other regions, with very specific climate zones and different development patterns. Many regions in the Arab World are already “on the brink” with limited resources, scarce water supply, and rapidly expanding populations. Rather than simply “scaling down” global models or “adapting” other regional models, the Arab World needs region-specific scenarios for climate change that should be varied and often revised in order to reflect its hard-to-predict development patterns.
3. **Investigating “Climate Surprises”.** As climate change accelerates, it will **very likely** have an impact on the Arab World and West Asia that is disproportionately larger than the rest of the world. The region’s prevailing arid to semi-arid climate makes it uniquely vulnerable to extreme events, even if those were limited in duration and location. In contrast with global modeling efforts on which the IPCC, regional climate scenarios for the Arab World should also reflect the side-effect of “climate surprises” such as faster-than expected rate of sea level rise.
4. **Model Development.** Regional Climate Models should take into account the unique configuration of the Arab World:
 - The large role played by such elements as the deserts of West Asia and North Africa, which have a proportionally large effect on radiative forcing than other regions,
 - Changing topography:
 - In deserts, where the movement of dunes affects surface wind patterns and
 - In the built environment, mostly due to excavations in freshwater-rich areas and their effect on surface albedo, wind patterns, and groundwater flow,
 - In resource-extraction areas, to factor in the effect of ground subsidence,
 - The relatively recent and expanding concentration of population around urban centres, which are not only altering surface albedo and wind patterns by fortifying a “heat Island” effect, but also modifying cloud formation,
 - The interaction between groundwater flow, over-pumping, and seawater intrusion that is very specific to many coastal regions of the Arab World,
 - Land Degradation, particularly the interaction between temperature, precipitation and changes in forest cover. Deforestation is a long-term regional pattern that needs to be better understood now that rapidly growing populations are putting ever more pressures on the region’s ecosystem,

¹⁰⁸ Owen and Pickering, 1997.

5. **Result Interpretation. The results of the RCM models should be investigated** in an open, shared, peer-reviewed framework in which various integrated RCM models are used.
- On the technical front, this effort should be build on standardized databases of long term historic regional trends, similar to DEMETER or PCMDI. The technical focus should be on encouraging local organizations and universities to develop, modify, and implement climate change models in order to facilitate technology transfer/trickle-down:
 - o Web coordination and comparison among various models,
 - o Data storage available for online retrieval,
 - o Possible “open-source” online collaborations can be also investigated.
 - The socio-economic impacts of climate change should also be factored in, because of the potential for any feedback effects. This will involve cross-disciplinary effort that needs to be coordinated.
6. **Vulnerability Assessments.** The focus here is to provide policy makers with a “road map”; while no one can ever be certain of the **absolute likelihood** of any specific event, the **relative likelihood** of different climate events and their **expected impact** can be determined. This can help develop a regularly updated “policy road map” that can help policy makers define **cross-border cooperation**, and prioritize actions aimed at either mitigating climate change or adapting by building up resilience by targeting the risks that were considered most likely at the time.

The final outcome of this endeavour would be a simple to understand matrix and plot that scores the vulnerability of countries based on the IPCC’s “degrees of doubt” (Table 4Table 4) to various climate change impacts, as well as “scoring” of sustainability.

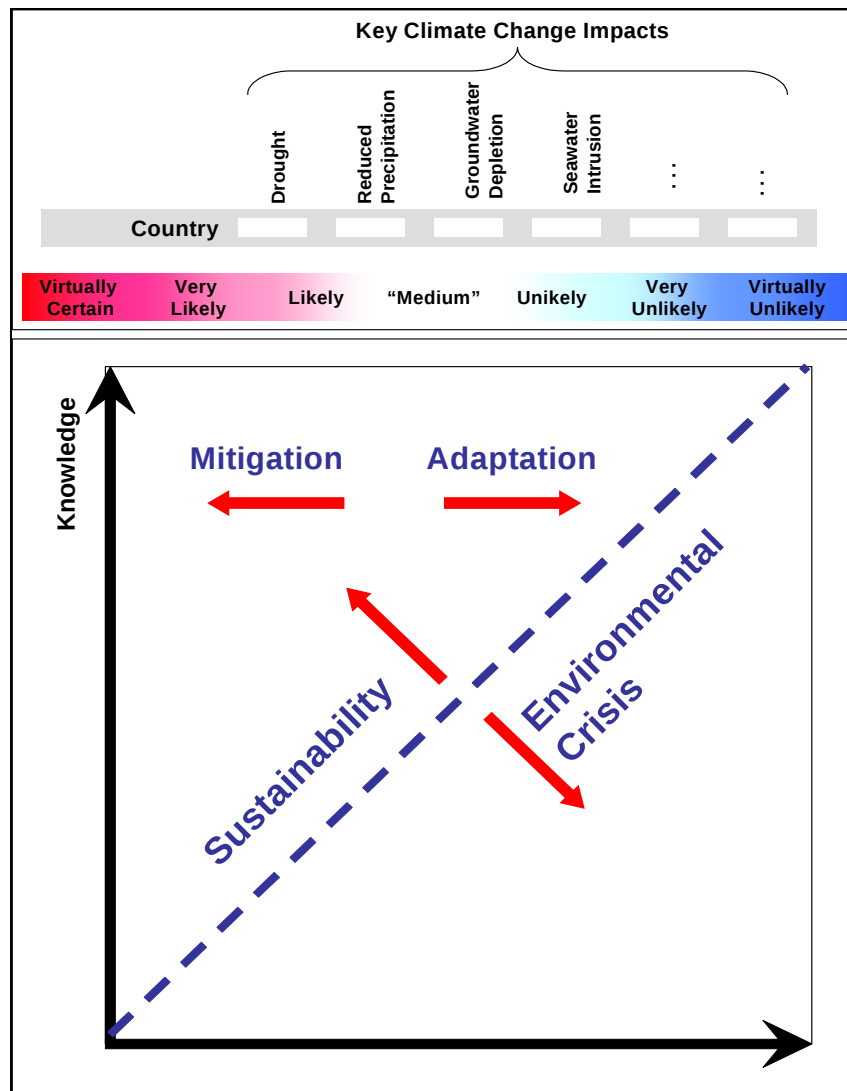


Figure 17. Proposed Matrix for Presenting Impact of Climate Change on the Arab World¹⁰⁹.

¹⁰⁹ Adapted from Bar Yam, 1997; Nasr, 2009.

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