# **Climate Change Science for Mesoamerican Decision Makers**

# **A Practical Manual**



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Cover Image: Preliminary results from a Regional Climate Model (RCM) climate change scenario show regions of both increased and decreased precipitation over Mesoamerica. Possible impacts from climate change in this region include both increased droughts and increased flooding.

[Photo credits: flooding - http://www.mercycorps.org/countries/guatemala/10825; drought - http://www.redorbit.com/news/science/1789646/drought\_caused\_by\_el\_nino\_wreaks\_havoc\_across\_latin\_america/index.html]

# **EXECUTIVE SUMMARY**

The Mesoamerican region is already suffering the effects of climate change. Furthermore, the region's limited capacity to adapt, largely a product of its socio-economic context, makes it highly vulnerable. Therefore, it is of utmost importance to help support these countries as they attempt to understand and deal with the effects of climate change. Information provided by state-of-the-art climate models adds considerable value to the planning and policy development process. However, results from climate models are not always easy to understand for decision makers who need to deal with the impacts of climate change, but are not necessarily familiar with its science and interpretation of results from climate models. The goal of this report is to address these difficulties.

The *weather* is the fluctuating state of the atmosphere around us, while climate is the statistical description of weather. Variability on time scales of a few years to a few decades is usually referred to as *climatic variability*. Variability on time scales longer than a few decades is usually referred to as *climatic change*. Greenhouse gases occur naturally and pre-industrial concentrations are responsible for keeping the Earth's average temperature nearly 30°C higher than if no greenhouses gases were present (*i.e.*, the *natural greenhouse effect*). Higher concentrations of GHGs due to human activities lead to even higher temperatures. It is this *enhanced greenhouse effect* that is the subject of concern today. Projections of future emissions of GHGs are based on assumptions of economic development, population growth, alternative energy development, and technological change. No one emission scenario is 'correct', or even has the greatest likelihood of occurrence.

*Weather and climate models* are used to predict weather in the near future and to study how the climate system responds to various types of changes, or *forcings*. Global climate models cannot reproduce the recent, observed warming without including anthropogenic forcings (particularly GHG emissions). As it becomes increasingly clear that humaninduced climate change is occurring, the IPCC emphasizes that focus is shifting from basic global climate science into understanding and coping with the impacts of climate change. Results at the global scale are useful for indicating the general nature and largescale patterns of climate change, but not very robust at the local or regional scale (typically 10-20 km). The latter requires use of *regional climate models*.

A climate change *impact* means: A specific change in a system caused by exposure to climate change. A vulnerability means: The degree to which a natural or human system is susceptible to, or unable to cope with, adverse effects of a climate change impact. The assessment of key vulnerabilities involves substantial *scientific uncertainties* as well as value judgments. A key point for Mesoamerica: Low-latitude, less developed regions are likely at greater risk! This does not mean that climate changes are largest in low-latitudes, indeed observations and models both indicate that the largest changes will occur in high latitudes. It is the nature of the human systems that put this region at greater risk. Finally, global warming due to GHG increases is by no means the only important agent of climate change. Factors such as land use changes can also be important locally.

# **INTRODUCTION**

The Mesoamerican region (the group of countries from Mexico to Colombia) is already suffering the effects of climate change. Furthermore, the region's limited capacity to adapt, largely a product of its socio-economic context, makes it highly vulnerable to climate change. Therefore, it is of utmost importance to help support these countries as they attempt to understand and deal with, through adaptation and mitigation, the effects of climate change. One way of contributing to this effort is providing the region with adequate tools to assess vulnerability to, and anticipated impacts of, climate change. Nowadays, information provided by state-of-the-art high-resolution climate system models adds considerable value to the planning and policy development process. However, results from climate models are not always available in a format practical and easy to understand for decision makers who need to deal with the impacts of climate change, but are not necessarily familiar with its science and interpretation of results from climate models. The goal of this report is to address these difficulties.

This report starts with a basic climate primer defining what we mean by weather, climate, climate variability and climate change as precisely as is possible. The mechanisms by which increases in greenhouse gases can cause climate change are discussed. This leads into a description of climate models and why they are required, followed by a discussion of why both global and regional climate models are necessary to produce appropriate climate change scenarios. Focus then turns to using the model output in assessing likely impacts and vulnerabilities. This includes model verification using observations, quantification of model probabilities and uncertainties, identification of key vulnerabilities as well as adaptation potentials, and, finally, developing response strategies. The report concludes with a summary of likely climate changes confronting Mesoamerica in coming decades and the possible consequences of those changes.

# **CLIMATE AND CLIMATE CHANGE**

# What Do We Mean By 'Weather', 'Climate', 'Climate Variability' and 'Climate Change'?

The first step in addressing climate change issues is to define as precisely as possible what is meant by 'weather', 'climate', 'climate variability', and 'climate change'. Weather and climate are different entities and the distinction is often misunderstood. The **weather** is the fluctuating state of the atmosphere around us, while climate is the statistical description of weather. More formally, the Intergovernmental Panel on Climate Change<sup>1</sup> (IPCC) defines climate thusly:

<sup>&</sup>lt;sup>1</sup> The IPCC is a scientific body organized by the United Nations Environmental Programe (UNEP) and the World Meteorological Organization (WMO) to study and assess climate change and is open to representatives from all their member countries (for additional information on the IPCC's role and mission, see http://www.ipcc.ch/organization/organization.htm).

Climate in a narrow sense is usually defined as the "average weather", or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

More colloquially, "climate is what you expect, weather is what you get." The exact boundaries of what is climate and what is weather are not well defined and depend on the application. Climate is typically defined in terms of 30-year means and, although year-toyear variations about these means are expected, it is assumed that the magnitude of these variations is not changing during the averaging period. On the shortest time scales, as noted above, we enter the realm of weather, while variability on time scales of a few years to a few decades (*i.e.*, shorter than a 30-year climatic averaging period) is usually referred to as *climatic variability*. Variability on time scales longer than a few decades (longer than a standard climatic averaging period) is usually referred to as *climatic change*.

#### **Basic climate change science**

The Earth's climate system (Figure 1) is comprised of five major components: the atmosphere, the hydrosphere (oceans, lakes, rivers, etc.), the cryosphere (ice sheets, glaciers and sea ice), the *biosphere* (vegetation and soils) and the *lithosphere* (volcanoes, orography, weathering). These components interact through numerous physical processes (primarily exchanges of heat, matter, and momentum between components) to produce the Earth's climate. A change in any of these components can result in changes in other components through these interactions. Changes to the components are caused by changes in forcings, or external factors, that may be either positive (lead to warming) or negative (lead to cooling). Climate forcings can be classified as natural or anthropogenic (i.e., human-induced). Examples of natural forcings include solar variability and volcanic eruptions, while anthropogenic forcings include greenhouse gas (GHG) emissions, aerosol production and land-use changes. Moreover, through various feedbacks, the initial change may grow (positive feedbacks) or be reduced (negative feedbacks). Changes in natural forcings have always occurred and continue today, having produced climate change and variability throughout Earth's history; only recently have anthropogenic forcings become large enough to significantly affect the climate system.

Nearly all the energy driving the climate system comes from the Sun but, while solar output varies over time and has led to climate changes during Earth's geologic history, changes in solar radiation cannot account for the warming observed over the past 30 years during which accurate measurements of solar output have been made. In the absence of solar forcing, arguably the largest climate forcing is due to changes in atmospheric composition, particularly of greenhouse gases and aerosols. Greenhouse gases occur naturally and pre-industrial concentrations are responsible for keeping the Earth's average temperature nearly 30°C higher than if no greenhouses gases were present (*i.e.*, the *natural greenhouse effect*). Higher concentrations of GHGs due to

human activities – in the absence of any feedbacks – would undoubtedly lead to higher temperatures. It is this *enhanced greenhouse effect* that is the subject of concern today. While the basic effect is atmospheric warming, this in turn leads to other effects such as changes in precipitation patterns, glacier and ice sheet melting, and sea level rises.



Figure 1: Schematic view of the components of the climate system, their processes and interactions (from IPCC AR4 WG-I, FAQ 1.2, Figure 1).

### **Climate Change Scenarios**

Projections of future emissions of GHGs are based on assumptions of economic development, population growth, alternative energy development, and technological change. Based on different combinations of assumptions, the IPCC has developed 40 separate GHG emission scenarios (Figure 2), organized into 4 scenario families (A1, A2, B1 and B2). Scenario family A1 is further divided into 3 scenario groups (A1FI, A1B and A1T), based on their assumptions about the world's mix of fossil fuel use and alternative energy sources. Each of these groups contains more than one scenario, although one member from each group was chosen as 'illustrative'. These emission scenarios can be used to estimate future GHG concentrations in the atmosphere, which can then be used to develop projections of future climate change. Which emissions scenario to choose for planning purposes depends on the problem at hand, as well as the potential impacts and vulnerabilities to be expected. Many times the 'A' families (especially the A2 'business as usual' scenario) are considered, as they should lead to the

largest climate changes, and hence greatest stress on natural and human systems. Consideration of weak or strong stabilizations (the 'B' families), on the other hand, may be appropriate if a range of possible adaptation needs and strategies is being investigated. It is important to remember that no one emission scenario is 'correct', or even has the greatest likelihood of occurrence. Indeed, policy decisions being made now and in the future can strongly influence ('mitigate') the GHG emissions that will actually occur in coming decades.



Figure 2: Total global annual CO2 emissions from all sources (energy, industry, and land-use change) from 1990 to 2100 (in gigatonnes of carbon (GtC/yr)) for the families and six scenario groups. The 40 SRES scenarios are presented by the four families (A1, A2, B1, and B2) and six scenario groups: a) the fossil-intensive A1FI (comprising the high-coal and high-oil-and gas scenarios), the predominantly non-fossil fuel A1T, the balanced A1B; b) A2; c) B1; and d) B2. Each colored emission band shows the range of harmonized and non-harmonized scenarios within each group. For each of the six scenario groups an illustrative scenario is provided, including the four illustrative marker scenarios (A1, A2, B1, B2, solid lines) and two illustrative scenarios for A1FI and A1T (dashed lines) (from IPCC SRES, Figure 3).

## **MODELING CLIMATE CHANGE**

#### Why Do We Need Climate Models?

Humanity is in the process of conducting a climate change experiment by means of increasing atmospheric GHG concentrations and other changes to the climate system. Unfortunately, it is an uncontrolled experiment – that is, we have only one Earth on which to experiment and we cannot know what the climate would be in the absence of the anthropogenic forcings we have applied to the system. Moreover, we cannot know the outcome of this experiment until it is completed and, by then, any changes that have occurred may be quite large and possibly irreversible. The complexity of the climate

system also precludes the use of laboratory-based experimentation. To address these issues, mathematical models – implemented on high-performance computers – provide a tool that can be used to conduct numerous numerical experiments on the likely effects of anthropogenic forcings.

### What IS a Climate Model?

In order to simulate climate, we have to calculate the effects of all the key processes operating in the *climate system*. Many of these key processes are described in Figure 1. Our knowledge about these processes can be represented in mathematical terms, but the complexity of the system means that the calculation of their effects can, in practice, only be performed using a computer. The mathematical formulation is therefore implemented in a computer program, which we refer to as a *climate model*. It is also important to realize that these climate models are very similar to the models used for weather prediction and forecasting. Current climate models are also widely considered to do a credible job at simulating the observed present-day climate, suggesting that we have a high degree of understanding about how the climate system works.

Weather and climate models are the equations of fluid motion, physics, and chemistry, applied to the atmosphere. Because the atmosphere is highly variable in space and time, these systems of equations must be solved at a great number of points within the atmosphere (both horizontally and vertically) to predict the changing state of the atmosphere through time (*i.e.*, the weather). If these simulations are conducted over an extended time period, the average state and intrinsic variability of the system (*i.e.*, the climate) can be estimated. Because of the large number of equations that must be solved at a great many points over an extended time, these models are implemented as computer programs that must be run on high-performance computers. These *weather and climate models* are used to predict weather in the near future and to study how the climate system responds to various types of changes, or *forcings* (*e.g.*, changes in solar output, increases in greenhouse gas concentration, or alterations of the land surface). Once these models have been tested and verified for present-day climate, they can be used to simulate past and future climate change.

In order to simulate future climate change, we must represent possible or expected changes in climate forcing – both natural and anthropogenic (human-induced). Some natural forcings – such as changes in solar output – have reasonably well understood physical mechanisms and can be incorporated into projections of the future climate state; other natural forcings – such as volcanic injections of gases and particles into the atmosphere – are less predictable. Human forcings fall between these extremes – neither highly predictable nor essentially random. These human forcings, including emissions of greenhouse gases, have many underlying controls, such as population growth, economic development, and technology. In order to account for these factors, we must develop *scenarios* of how greenhouse gas concentrations will change over time. Once these scenarios are constructed, they may be used as input to climate models to project how the climate system will change in response. The IPCC has developed a number of greenhouse gas emission scenarios based on different underlying assumptions about economic and

technological development over the next century that were used to project atmospheric greenhouse gas concentrations for use in climate models.

Because we do not have a second Earth on which to run climate experiments, nor do we have time to await the results of our current "experiments" on our own Earth, climate models, in conjunction with greenhouse gas scenarios, are our best tool for understanding how the Earth's climate system will respond to anthropogenic forcing.

#### General Circulation Model

The General Circulation Model (GCM) is a sophisticated numerical model that attempts to simulate all relevant parts and processes of the climate system. These are sometimes also called 'Global Climate Models', though many much simpler climate models could also be referred to as such. The GCM is not in actuality a true climate model; rather it is a model that simulates daily weather patterns, which are then statistically aggregated to obtain climatic states, in exactly the same manner by which we use daily weather observations to obtain actual climatic states. In fact, the GCM at its core is very similar to the models used for weather forecasting. There are both atmospheric GCMs (AGCMs) and ocean GCMs (OGCMs). An AGCM and an OGCM can be coupled together to form an atmosphere-ocean (or fully) coupled general circulation model (AOGCM). Because climate change involves interactions between the atmosphere and the ocean, use of the AOGCM has become standard. A recent trend in GCMs is to extend them to become Earth System Models that include such things as submodels for atmospheric chemistry or a carbon cycle model, or interactive (dynamical) vegetation, but these are still very much in a developmental stage.

#### Regional Climate Model

As it becomes increasingly clear that humaninduced climate change is occurring, the IPCC emphasizes that focus is shifting from basic global climate science into understanding and coping with the impacts of climate change. A fundamental aspect of this shift is the need to produce accurate and precise information on climate change at local and regional scales. IPCC and other current projections of climate change rely on global models of climate which, due to demanding computational resources on even the most powerful supercomputers, must be run at a coarse horizontal resolution (approximately 150 km for many of the models used in IPCC 4<sup>th</sup> Assessment Report (AR4). As stressed by IPCC, results at the global scale are useful for indicating the general nature and large-scale patterns of climate change, but not very robust at the local or regional scale (typically 10-20 km). This is for two key reasons: i) global models can only

#### Generating Regional Climate Change Scenarios – Steps to Follow

The following steps are involved in developing regional climate change scenarios under global warming due to increases in greenhouse gases (GHG):

- Identify the greenhouse gas 'emission' scenario (*e.g.*, business as usual; stabilization, commitment) for which you wish to estimate the regional climate change.
- Identify the global climate model(s) to be used - ensure that runs with output twice or more daily are available.
- Make your own global model runs if necessary, BUT always use what's already available if you can!!
- Make RCM control runs forced with observations (re-analyses) to validate that the model does a reasonable job of simulating the present-day climate.
- 5) Make RCM climate change runs forced by the GCM.

explicitly resolve those physical processes operating over several hundred kilometers or larger; and ii) especially over land, spatial surface heterogeneities can be very large and occur on small spatial scales (*e.g.*, regions of complex topography; differing land use patterns, etc). These spatial heterogeneities can have a profound influence on regional climate, but obviously it can be difficult or even impossible to realistically represent them at the coarse resolution of the global models (Figure 3). Yet it is precisely at the smaller 10-20 km scale that most of the impacts from climate change will occur, and need to be understood and dealt with. A key question as we explore the use of climate models is how best to 'downscale' the results of coarse global models to individual regions – and specific localities within those regions – in a manner that produces results that are physically accurate and hence meaningful.



Figure 3: The effect of increasing model resolution on the land/ocean geography and terrain height resolved by climate models. Grid spacing depicted is typical of: a) GCM (144 km), b) low-resolution RCM (48 km), c) medium-resolution RCM (12 km), and d) high-resolution RCM (4 km).

Regional climate models (RCMs) are essentially nothing other than versions of GCMs run over a limited area (or domain), rather than for the entire globe. These models are used to address the horizontal scale limitations of the global GCM; the latter has a horizontal resolution of 100-300 km while the RCM can be run at a horizontal resolution of 10-50 km. Essentially they can be used to *physically downscale* global model results to the regional – and even local – scale. Depending on the domain size and resolution, RCM simulations can also be computationally demanding, which has limited the length of many experiments to date. Figure 3 shows the effects on topography and coastlines from the coarse resolution of a GCM to the highest resolution RCM.

While it may be interesting to have explicit predictions of climate change for your own neighborhood, such predictions are useful only if they provide meaningful input for methodologies, such as decision support systems (DSS), by which the impacts of climate change on the entire range of human and natural systems can be assessed. The use of climate change predictions for impacts studies represents a transition from *basic science* (understanding the physics by which climate change takes place) to *applied science* (assessing the practical consequences of these changes on other natural and human systems). Such assessment is an essential precursor to development of strategies for adaptation and/or mitigation. This transition has been notoriously difficult to accomplish, and the resultant gap between basic and applied science has often been colloquially referred to as the 'valley of death'. Providing a bridge across this valley of death is the primary objective that must be accomplished.

# MODEL VERIFICATION AND UNCERTAINTY

Simulating climate change, even at the high-resolution regional scale is one thing; understanding model strengths and weaknesses so as to manage the uncertainty of climate models for the decision making process is also essential to the decision-making process. The most basic question of any model: How well does it do what we want it to? This tells us how much confidence we can have in the model results; how well we understand the problem at hand; and what in the model most needs to be improved. While easily said, *HOW* to do this is more difficult - what model output(s) do we want to verify, what observations will we use, and how will we quantify the results? Two key aspects are readily apparent. One involves the *global-scale:* How well does the global climate model (used to provide large-scale forcing) simulate the observed climate? The other is *regional-scale:* Does the regional climate model improve the simulations beyond what is provided by the global models?

As an example at the global scale, Figure 4 shows that global climate models cannot reproduce the recent, observed warming without including anthropogenic forcings (particularly GHG emissions). The models all agree on direction of change, although they differ in magnitude of projected change. Furthermore, as noted above, the global models are generally considered adequate at simulating the present-day climate.



Figure 4: Comparison between global mean surface temperature anomalies (°C) from observations (black) and AOGCM simulations forced with (a) both anthropogenic and natural forcings and (b) natural forcings only. All data are shown as global mean temperature anomalies relative to the period 1901 to 1950, as observed (black, Hadley Centre/Climatic Research Unit gridded surface temperature data set and, in (a) as obtained from 58 simulations produced by 14 models with both anthropogenic and natural forcings. The multimodel ensemble mean is shown as a thick red curve and individual simulations are shown as thin yellow curves. Vertical grey lines indicate the timing of major volcanic events. Those simulations that ended before 2005 were extended to 2005 by using the first few years of the IPCC Special Report on Emission Scenarios (SRES) A1B scenario simulations that continued from the respective 20th-century simulations, where available. The simulated global mean temperature anomalies in (b) are from 19 simulations produced by five models with natural forcings only. The multi-model ensemble mean is shown as a thick blue curve and individual simulations (no more than  $0.2^{\circ}$ C per century). Each simulation was sampled so that coverage corresponds to that of the observations (from IPCC, AR4, WG-I, Figure 9.5).

As an example at the regional scale, Figure 5 shows time series for surface temperature for Cali, Colombia and Mexico City, Mexico. Shown are observations, as well as a series of runs with the WRF regional climate model. Two key features are seen: 1) the model simulation depends on horizontal resolution, with the highest resolution performing the best. 2) The high resolution 12 and 4 km model results agree quite well with the observations.

### **Quantifying Uncertainty: Issues**

Although the IPCC concludes that 'most sources of uncertainty at regional scales are similar to those at the global scale', they note two important exceptions: 1) inhomogeneity in land use cover and land use changes; 2) forcing due to atmospheric aerosols. These exceptions are crucial for Mesoamerica because climate change due to land use changes such as urbanization and deforestation can be 'huge' and if, for example, deforestation is accomplished via burning, then this is a major source for aerosols, that can also have significant impacts on regional climate, most likely through cooling and drying.



Figure 5: Time series of temperature (°C) for the first 80 days of 1991 as simulated by WRF at 48, 12, and 4 km resolution and compared to station observations for Mexico City, Mexico and Cali, Colombia. The legend indicates the actual elevation of each station, as well as the elevation and distance from the station of the nearest WRF grid point.

Obviously, we want to use real observations to validate as best we can the ability of our models to simulate the present-day climate. Comparing model results to observations can only take us so far – how do we evaluate the robustness of future climate change simulations? Two key aspects: 1) What are the uncertainties? How do they manifest and propagate from the global to regional scale? 2) Can we estimate probabilities of occurrence? How robust are these probability density functions (PDFs)?

#### **Constructing and Evaluating Probabilities**

No single model can be considered 'the best' at simulating climate change – a multimodel approach must be used. This leads to the possibility of probabilistic assessments of climate projections from diverse models. However, a significant problem immediately arises – model bias. None of the models simulate perfectly the present-day climate, the difference between the observed and simulated climate represents *model bias*. It is possible to estimate this bias for the present-day climate by quantifying the model uncertainty as described above. For most models the bias is small and the reasons for it fairly well-known, although the biases do differ between models. The problem: there is no guarantee that the model biases for future climate change simulations are the same as that for the present-day climate. Until these biases are minimized, corrected for, or at least understood, it is difficult to assign robust probabilities to the likelihood of occurrence of modeled climate change predictions. Several approaches have been used to date, of which two are particularly illustrative: 1) assume that the present-day biases are representative of future biases; and 2) use prior expert knowledge to constrain the biases. All of the approaches suggest that warming will take place and all have similar qualitative patterns, but they do differ in their probabilistic assessment of the amount of warming. For example, approach 1 assigns somewhat less warming to the highest probability of occurrence than does approach 2. On the other hand, the probability of extreme warming (greater than 5°C), though still quite low, is higher in approach 1. Not surprisingly, this is a very active area of current research. IPCC strongly suggests that expert judgment, on the part of climate scientists, policymakers, and stakeholders will play a key role. To quote the IPCC (WG1, Ch. 10, p.811),

A preferred method [for estimating probabilities] cannot yet be recommended, but the assumptions and limitations underlying the various approaches, and the sensitivity of the results to them, should be communicated to users.

## **VULNERABILITY AND IMPACT ASSESSMENT**

#### **Vulnerability Assessments and Regional Impacts**

A climate change *impact* can be defined as: A specific change in a system caused by exposure to climate change. A vulnerability to a climate change impact can be defined as: The degree to which a natural or human system is susceptible to, or unable to cope with, adverse effects of a climate change impact. The system involved can be natural or human socio-economic, or a hybrid of the two. The change can be either beneficial or harmful (not *ALL* effects of climate change are necessarily bad!) Therefore, understanding possible vulnerabilities can be complicated, and not necessarily obvious. Crucially, a wide range of vulnerabilities occurs across both natural and human systems. The IPCC has identified seven criteria for identifying key vulnerabilities: 1) *Magnitude of impacts;* 2) *Timing of impacts;* 3) *Persistence and reversibility of impacts;* 4) *Likelihood (estimates of uncertainty) of impacts and vulnerabilities and confidence in those estimates;* 5) *Potential for adaptation;* 6) *Distributional aspects of impacts and vulnerabilities - equity issues;* 7) *Importance of the system(s) at risk.* Furthermore, it is possible to identify the following categories of vulnerability: Global social systems; regional systems; global biological systems; geophysical systems; extreme events.

It is critical to note that the assessment of key vulnerabilities involves substantial *scientific uncertainties* as well as *value judgments*. Furthermore, given the complexity of issues, including non-climate considerations, a *traceable account* of all relevant assumptions must be maintained to *achieve transparency*. In addition, it must be remembered that 1) vulnerability to climate change differs considerably across socio-economic groups, raising questions of 'equity', and 2) no single metric for climate impacts can provide a commonly accepted basis for climate policy decision-making.

A key point for Mesoamerica: *Low-latitude, less developed regions are likely at greater risk!!* This *does not* mean that climate changes are likely to be largest in low-latitudes, indeed observational evidence and model results both strongly indicate that the largest changes will occur in high latitudes. It is the nature of the human systems that put this

region at greater risk – the developing countries of the low latitudes, in general, and Mesoamerica, in particular, have economic and social structures that may make them more susceptible or vulnerable to climate change impacts.

### **Response Strategies for Key Vulnerabilities**

Once vulnerabilities are identified, how can they be dealt with? It is important to understand that the ultimate need is *risk management*. A first consideration involves *adaptation* - that is, can you figure out a way to deal or cope with the change. In general, for social systems, considerable possibility exists for adaptation, but the economic costs are (at best) poorly known and unequally distributed. For biological and geophysical systems, there is much less potential for adaptation. Adaptation in general becomes more difficult the larger and/or faster the change.

If it is not possible or feasible to adapt to a change, the other alternative is to attempt to stop the change from happening, that is, *mitigation*. Mitigation in this case would involve substantial and immediate reductions in GHG emissions. This must be done at the global level as GHG are well-mixed in the atmosphere. That is, no matter where they are emitted, GHG affect the entire globe. It is not clear if the world's nations have the capability, much less the will to do so (indeed, as of this writing, scientific experts and policy makers are convening in Copenhagen to negotiate these issues). Furthermore, IPCC and even more recent studies suggest that tipping points<sup>2</sup> may already have been reached in some systems, even at current levels of GHG concentration. Once a tipping point is reached, mitigation is generally no longer an option, therefore the only choice is to adapt.

### **Uncertainties in Assessment of Response Strategies**

It is not sufficient to just consider uncertainties in the climate model outputs. Importantly, uncertainties also occur in the assessment of appropriate response strategies. These include:

- *Natural randomness.* Variability occurs in *all* natural systems, not just those involved with climate. These diverse variabilities need to be assessed, but it is frequently unclear how to do so.
- *Lack of scientific knowledge.* This includes both the physical science of the natural systems, and the social science of the human systems.
- *Social choice ('reflexive uncertainty').* How will individual humans, and in aggregate their social systems, respond to climate change, and especially to the uncertainty surrounding it?
- *Value diversity.* Different segments of a given society may well have different sets of values, based on such factors as economic standing; or differing religious and/or political beliefs.

 $<sup>^{2}</sup>$  A tipping point refers to a threshold that once a human or natural system crosses, it is difficult or impossible to return to the original state. For example, once forest is removed from a region, it may not be able to return.

Some of these are easy to categorize probabilistically, others are more difficult, and in many cases judgment calls, or degree of belief, are essential components.

### **Competing Agents of Change**

Global warming due to GHG increases is by no means the only important agent of climate change! Especially, factors such as land use changes can be important locally. For example, our prior work for Central America suggests that deforestation in Mesoamerica can have regional impacts on climate that are as large *or larger* than those due to GHG increases. Furthermore, the effects of deforestation tend to *exacerbate* those due to GHGs. Other agents, such as increases in atmospheric aerosols, may help induce cooling that can tend to *ameliorate* the effects of GHGs, though in many cases these aerosols represent pollutants that may cause other harmful effects.

# CLIMATE CHANGE IMPLICATIONS FOR THE MESOAMERICA REGION

Figure 6 shows temperature and precipitation changes over Central and South America from the IPCC MMD-A1B<sup>3</sup> simulations using 21 global climate models. Based on analyses from these models, the IPCC AR4 (WG-I Ch. 11) summarizes for Mesoamerica: *All of Central and South America is very likely to warm during this century. The annual mean warming is likely to be larger than the global mean warming. Annual precipitation is likely to decrease in most of Central America, with the relatively dry boreal spring becoming drier. A caveat at the local scale is that changes in atmospheric circulation may induce large local variability in precipitation changes in mountainous areas.* 

Furthermore, they note that:

Systematic errors in simulating current mean tropical climate and its variability (Section 8.6) and the large intermodal differences in future changes in El Niño amplitude preclude a conclusive assessment of the regional changes over large areas of Central and South America. Most MMD models are poor at reproducing the regional precipitation patterns in their control experiments and have a small signal to-noise ratio. As with all landmasses, the feedbacks from land use and land cover change are not well accommodated, and lend some degree of uncertainty. Over Central America, tropical cyclones may become an additional source of uncertainty for regional scenarios of climate change, since the summer precipitation over this region may be affected by systematic changes in hurricane tracks and intensity.

<sup>&</sup>lt;sup>3</sup> A key feature of IPCC is the collection of a comprehensive set of model output, referred to here as 'The Multi-Model Data set (MMD). This has allowed hundreds of researchers to scrutinize the models from a variety of perspectives



Figure 6: Temperature and precipitation changes over Central and South America from the MMD-A1B simulations. Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation (from IPCC, AR4, WG-I, Figure 11.15).

#### Regional Model Results

A set of regional climate change scenarios for Mesoamerica is currently being implemented using the Weather Research and Forecasting (WRF) regional model. A domain at 12 km spatial resolution includes all of Mesoamerica (plus Peru and Jamaica). Portions of central Mexico and Colombia are covered by separate 4 km domains embedded within the 12 km domain. The domains are all shown in Figures 7 and 10. Large-scale forcing is provided by an IPCC A2 ('business as usual') global climate model scenario for 2050-2052, along with a 'present-day' control for 2000-2002.

As of this writing (January 2010), these model simulations are currently underway with the first year of each completed. We show some preliminary plots here; these will be updated on a regular basis via <u>http://weather.unl.edu/RCM/reports/impacts/</u>. It is essential to keep in mind that just one year is currently shown. Any climate change must compete with short timescale 'natural' climate variability, which can be quite large year-to-year. Nonetheless, general trends are already clear, and as the runs progress (and the website is



Figure 7:(left) monthly mean temperature (°C) for February 2050 and (right) the difference between the February monthly mean temperatures for 2050 minus 2000, for the WRF 12 km domain. The boxes indicate the locations of the 4 km domains for Mexico and Colombia.

updated) the effects of interannual variability will begin to cancel out, leaving the longerterm climate change signal more obvious.

Figure 7 shows surface temperatures for the basic 12 km 'Mesoamerica' domain for February 2050, and the difference between February 2050 and February 2000. The plot for 2050 shows a realistic distribution of surface temperatures, with latitudinal and altitudinal controls clearly evident. Compared to 2000, a general warming is seen, largest (about 5°C) in northern Mexico (and the southern U.S.). The mountainous areas of central Mexico, Guatemala, Costa Rica, and Colombia show little change, or even a slight cooling. The cooling is almost certainly a function of interannual variability, but the clear implication is that temperature changes in these regions are likely smaller than elsewhere. The rest of Mesoamerica shows a general warming of 1-2°C.

Figure 8 shows surface temperatures for the very high-resolution 4 km 'Mexico' domain for February 2050, and the difference between February 2050 and February 2000. Figure 9 shows surface temperatures for the very high-resolution4 km 'Colombia' domain for February 2050, and the difference between February 2050 and February 2000. In both cases, the basic results are like those of the 12 km case, but it is clear that the topography is much better resolved. The lack of warming in the high elevations is clearly highlighted.

Figure 10 shows precipitation (rainfall plus any snowfall) for the 12 km domain for February 2050, and the difference between February 2050 and February 2000. Obvious on the plot for 2050 are the effects of mountains, as well as the low-relief Isthmus of Tehuantepec. Compared to 2000, northern Mexico shows increased precipitation, as do



Figure 8: (left) monthly mean temperature (°C) for February 2050 and (right) the difference between the February monthly mean temperatures for 2050 minus 2000, for the WRF 4 km Mexico domain.



Figure 9: (left) monthly mean temperature (°C) for February 2050 and (right) the difference between the February monthly mean temperatures for 2050 minus 2000, for the WRF 4 km Colombia domain.

the mountainous regions of Colombia. Though outside the region of immediate interest, Ecuador and northern Peru show very large decreases. Southern Mexico and Central America show a mixed response; some regions have increased precipitation, while in others it decreases. This is in contradiction with global studies, which suggest a general decrease, but cannot adequately resolve the steep, complex topography. Clearly, these topographic controls on precipitation are at least as important as for temperature. Figures 11 and 12 show the above effects even more clearly for central Mexico and Colombia.



Figure 10: (left) monthly total precipitation (mm) for February 2050 and (right) the difference between the February monthly total precipitation for 2050 minus 2000, for the WRF 12 km domain. The boxes indicate the locations of the 4 km domains for Mexico and Colombia.

## SUMMARY AND FUTURE STEPS

The Mesoamerican region is already suffering the effects of climate change. Furthermore, the region's limited capacity to adapt, largely a product of its socio-economic context, makes it highly vulnerable. Therefore, it is of utmost importance to help support these countries as they attempt to understand and deal with the effects of climate change. Information provided by state-of-the-art climate models adds considerable value to the planning and policy development process. However, results from climate models are not always easy to understand for decision makers who need to deal with the impacts of climate change, but are not necessarily familiar with its science and interpretation of results from climate models. This report has addressed those needs.

Climate is defined as the statistics of weather; variability on short time scales of a few decades or less is referred to as climate variability, while variability on time scales longer than a few decades is referred as climate change. Because we cannot perform laboratory



Figure 11: (left) monthly total precipitation (mm) for February 2050 and (right) the difference between the February monthly total precipitation for 2050 minus 2000, for the WRF 4 km Mexico domain.



Figure 12: (left) monthly total precipitation (mm) for February 2050 and (right) the difference between the February monthly total precipitation for 2050 minus 2000, for the WRF 4 km Colombia domain.

experiments, climate models are required to make predictions of future climate change, especially due to enhanced greenhouse gas emissions. The global climate models adequately simulate the present-day climate, but have too coarse a horizontal resolution for impacts studies at the regional scale. To perform the latter, regional climate models are required, especially where strong topographic controls on climate exist.

A climate change impact refers to a change in a natural or human system due to exposure to climate change; this impact may be either detrimental or beneficial. If a system will suffer adverse effects due to exposure, it is said to be vulnerable. The ultimate need is *risk management*. A first consideration involves *adaptation* - that is, can you figure out a way to deal or cope with the change. A key point for Mesoamerica: *Low-latitude, less developed regions are likely at greater risk!* This *does not* mean that climate changes are likely to be largest in low latitudes, rather it is the nature of the human systems that put the developing countries of this region at greater risk. Furthermore, GHG increases are not the only potential climate change issue facing Mesoamerica – other regional effects due to deforestation and aerosols may also be important.

We have identified two key further steps that should be undertaken as soon as feasible:

- 1) Continue to develop regional climate change scenarios. In addition to the ones currently underway, planning should begin now for the IPCC Fifth Assessment Report (AR5) global scenarios projected to be released in 2012.
- 2) Develop pilot programs in which climate modeling scientists, stakeholders (*i.e.*, those affected by climate change impacts) and decision-makers have in-depth discussion on how to use climate model results to determine vulnerability and then develop appropriate adaptation strategies.