Water and the Environment
Pontifical Academy of Sciences, *Scripta Varia* 108, Vatican City 2007
www.pas.va/content/dam/accademia/pdf/sv108/sv108-imam.pdf

WATER DISTRIBUTION AND AVAILABILITY AN OVERVIEW OF CLIMATE CHANGE IMPACTS ON WATER RESOURCES

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1. INTRODUCTION

Water resources management, distribution, and utilization were major beneficiaries of 20th century advances in civil engineering. As seen in Figure 1 (see over), which illustrates the number of large dams built during the past century, the core element of water resources development and management strategies for many nations has been the reliance on infrastructures to store and transport an ever increasing amount of surface water resources. In addition to hydroelectric power, these engineering solutions provided protection against floods and droughts and played a key role in attenuating the impacts of climate and weather variability on life and properties. Improved efficiency of ground water extraction and water treatment facilities, were also important elements of water resources development strategies.

Towards the end of the century, environmental degradation, along with increasing evidence of climate change, caused a shift in focus from structural solutions to non structural options. As many dams reached or exceeded their operational life, weighing the adverse ecological and environmental impacts of excessive streamflow regulation became an important factor in modern water resources management strategies. As a result, by the 1990s, several small dams were de-commissioned and/or removed for the purpose of river restoration. For example, to restore the salmon habitat in the Loire River Basin (France), the St. Etienne de Vigan, Barrage Mobile de Blois, and Maison Rouge dams were removed in 1998, 1998, and 2005, respectively. Five hundred small dams were decommissioned in the United States for various environmental, ecologic, and safety purposes. In parallel,

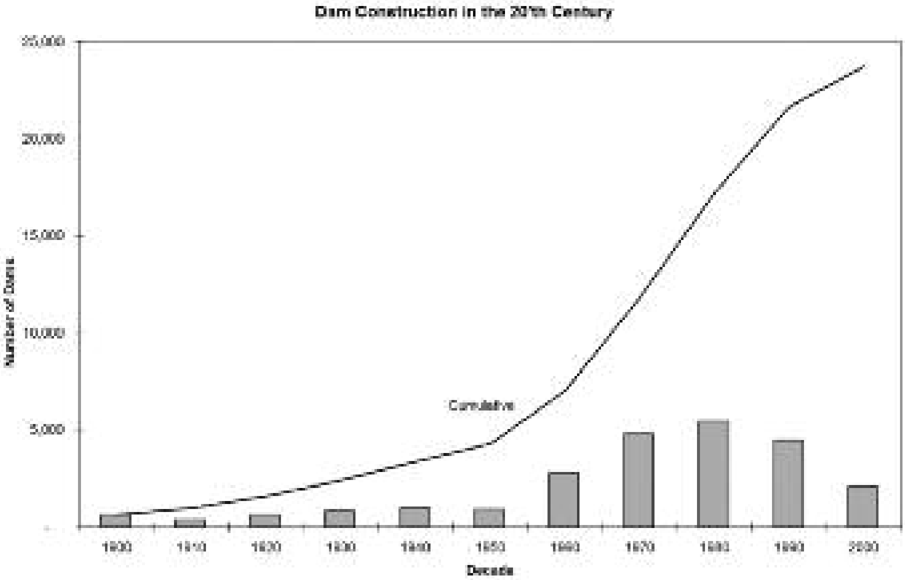

Figure 1. Patterns of large dam construction during the 20th Century.

the calls for conjunctive management of surface and ground water within integrated water resources management strategies gained recognition as the impacts of over-extraction of ground water on the structural integrity of overlying strata and on nearby streams were becoming more evident.

Decommissioning a few dams may address some local environmental issues. However, it does not address the overarching challenge of water availability, which is now recognized as a high priority development issue for the 21st century. In this regard, the Ministerial Declaration of The Hague on Water Security in the 21st Century has identified seven pertinent key challenges as: (1) meeting basic needs, (2) securing the food supply, (3) protecting ecosystems, (4) sharing water resources, (5) managing risks, (6) valuing water, and (7) governing water wisely. To meet these challenges, the declaration advocated integrated water resources management, which takes into account social, economical, environmental, and ecological aspects of water resources management. Addressing these challenges demands political commitment, both at national and international levels to develop and implement sound and sustainable integrated water resources management policies and practices. Such commitment becomes more necessary when taking into account the relationships between the three key stresses facing sustainable water resources management, which are: (a) limited fresh water supply, (b) population growth, and (c) climate change. It can be argued that quantifying the first two stresses requires that we improve our ability to understand, quantify, and predict the potential impacts of the latter, which is climate change, on various hydrologic responses.

2. Observed Hydrologic Impacts of Climate Change

Motivating the growing interest in climate change is the well documented increase in the average global temperature since 1880 (0.3°C to 0.6°C), with 0.2 to 0.3°C increase observed during the more reliable period of record (after 1960). Changes in mean global temperature have also been measured through satellite observations, which have confirmed that warming is evident in both sea surface temperature (Cane *et al*., 1997) and land-based surface air temperatures. In a recent study, Smith *et al*. (2005) treated uncertainties due to scarcity of reliable meteorological observations during the earlier part of temperature records and confirmed the above mentioned trends in global temperature (Figure 2a, see over). While an analysis of the causes of global warming is beyond the scope of this paper, the fundamentals of its potential impacts on the hydrologic cycle result from the well-known Clausius-Clapeyron law, which states that the increased temperature will result in an increase the atmosphere's moisture holding capacity. This increases the total amount of water in the atmosphere, which can affect the intensity of storms. It will also change the atmospheric moisture recycling ratio, with potential effects on drought frequency (Figure 2b, see over). The effect of higher temperature on atmospheric moisture content has been confirmed by various studies, most of which indicate that despite uncertainties in measurements, evidence obtained from satellite and radio-sound observations point to statistically significant upward trends in atmospheric moisture of several percents/decade (Ross and Elliott, 1996, 2001; Trenberth *et al*., 2003; IPCC, 2001). This is consistent with observations of the increased mean global temperature. From a hydrologic and water resources perspective, recent, long-term, and paleo-climatic records must be examined to determine if 1) precipitation characteristics have changed due to increased temperature,

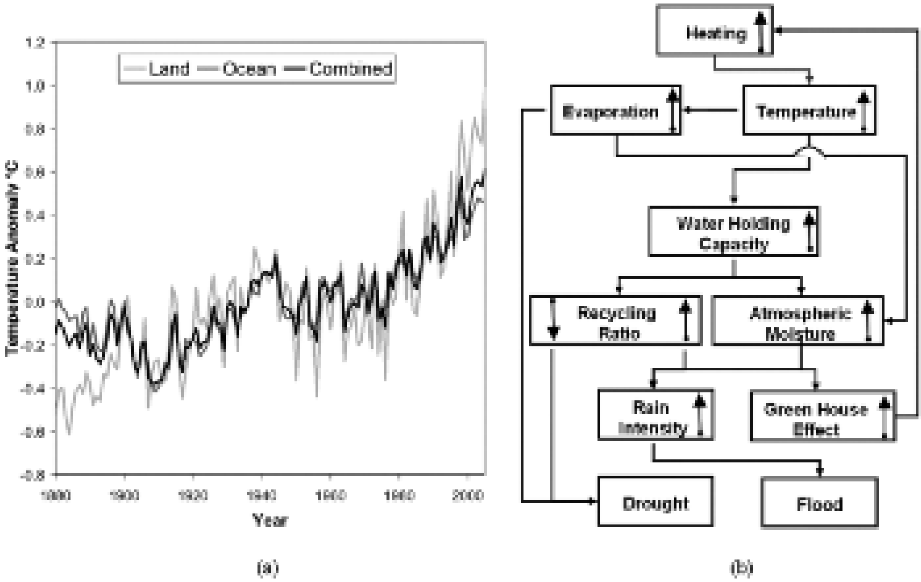

Figure 2. a) Trends in global temperature over land, ocean and combined. b) schematics of possible consequences of increased atmospheric temperature on the hydrologic cycle (revised after Trenbreth, personal communication).

2) droughts and/or floods are becoming more frequent, 3) the severity of droughts/floods is increasing in specific areas, 4) the timing and magnitude of snow-accumulation and snow-melt onset is changing, and 5) changes are taking place in regional vegetation cover. Needless to say, the global coverage of many state-variables over the longest possible time series is needed to understand the natural variability of the hydrological cycle so that deviations from the norm, such as a genuine progressive amplification of the cycle, can be detected with confidence.

a. *Precipitation*

At the global scale, the effects of changes in atmospheric moisture on precipitation have been confirmed by several studies. In general, a statistically significant increase of 2% in the average precipitation has been observed during the 20th century (IPCC, 2001). However, available records indicate large spatial and temporal variability in precipitation response to increased temperature. The northern hemisphere's mid and high latitudes show a marked increase, and the sub-tropical regions, particularly in western Africa show a decrease in precipitation. Changes in seasonal and inter-annual variability of precipitation patterns over some regions are consistent with stronger ocean circulation indices such as ENSO in South America, and the North Atlantic Oscillation in Europe.

b. *Severe Floods*

Concerns about the potential impacts of climate change on the hydrologic cycle have risen in recent years due to the rising catastrophic impacts of major floods in several countries. As seen in Figure 3 (see page 215), which maps severe floods since 1985, floods affect nearly all regions of the world. The underlying data indicates an upward trend in the number of severe floods since 1985 (Brakenridge, 2005). The question of whether climate change has altered the frequency of severe floods is rather complicated and it cannot be discerned for any individual flood. Most studies acknowledge that higher risk of human and economic losses due to large floods can be attributed to socio-economic factors such as expanding development in flood prone areas and over-reliance on flood protection infrastructure (Pielke and Downton, 2000; Kundzewicz *et al.*, 2005). Naturally, when discussing floods, changes in the total annual precipitation are less important than changes in other characteristics of precipitation including intensity, duration, and the number of consecutive days of heavy precipitation. The sparse network of hourly precipitation gauges on a global scale hinders assessing trends of these characteristics and, therefore, in isolating the climatic signal in recent severe floods. In the United States, where the density of a good quality precipitation network allows such analysis, the number of days with precipitation exceeding 50.8 mm (2 inch threshold for heavy rain) was found to be increasing (Karl and Night, 1998). However, measurable trends in extreme floods consistent with the above trends in heavy precipitation are lacking, even when the record indicates a general upward trend in annual streamflow such as reported by Lins (1999). Pielke and Downton (2001) proposed a framework for addressing this apparent paradox. Their framework argues for contextually defining heavy precipitation and for considering several precipitation characteristics in conducting trend analysis. A similar study by Small *et al.* (2006) over the eastern

US identified increases in the fall but not the spring precipitation as the main reason for lack of a climatic signal in extreme flood records and for the observed trends in low-flow series.

c. *Droughts*

Another aspect of the hydrologic impact of climate change is drought. This is a particularly critical issue in arid/semi-arid regions because even minor changes in climate regimes are likely to have significant incremental impacts on the availability of water resources. Prolonged droughts can be devastating as they evolve over multi-year duration. Many have questioned whether the increased severity, extent, and duration of recent drought episodes are related to increased temperatures and the consequent increase in evaporation rates over the past 50 years. In recent years, severe droughts in the southwestern US caused significant losses and contributed to widespread forest fire episodes. The longer historical perspective of major drought events during the past century shows that droughts were more common than expected from recent observations. The reconstructed climate record for the El Malpais area in the west-central region of New Mexico (Grissino-Mayer, 1996) shows that when the area's severe drought, which occurred in the 1950s, is compared to other droughts in the past 300 years, it seems typical. When the same event is considered at longer time scales, it seems fairly minor in comparison with multi-decade drought events that have occurred over the past 2000 years. Clearly, historical context of droughts and other extreme hydrologic events must be considered in climate impact assessment studies.

d. *Snow Cover*

Seasonal flow regimes of many of the world's major rivers are snowmelt dominated. Potential impacts of climate change on snow cover extent and timing will therefore affects water supplies across many regions, particularly in the springtime over the northern hemisphere. Satellite data show a 10% decrease in the annual snow cover extent (Robinson, 1999) with much of the decline occurring in the spring snow cover extent. Similar results are seen with respect to snow depth. On the other hand, snow fall observations indicate a statistically significant increase in the winter snowfall in North America and some areas in Russia consistent with the abovementioned observed increases in precipitation (IPCC, 2001).

3. Hydrologic Modeling and Climate Impact Assessment

As seen above, observational evidence increasingly points to possible climate induced changes in the hydrologic cycle. Consequently, interest in assessing the potential future impacts of climate change on various aspects of the hydrologic cycle and their consequences to water resource has been increasing even before the publication of the IPCC 2001 report. In general, predicting the impacts of climate change on the hydrologic cycle first requires the ability to model the long-term climate change for the entire planet under various scenarios. The Earth's climate system is complex and difficult to understand and predict. The new generation of coupled land-ocean-atmosphere models, which are also known as Global Circulation Models (GCMs) do resolve the physical processes occurring within these compartments and at their interfaces, albeit at coarse spatial resolutions (2.5°). Results from these models are subsequently downscaled to hydrologically relevant spatial and temporal scales in order to conduct detailed hydrologic studies using appropriate hydrologic models. Downscaling GCM output is generally based on one of three approaches. The first approach directly forces hydrologic models using the output from a given climate model or ensemble of models under different scenarios. In this approach, the GCM output mainly provides the range of possible changes in long-term mean precipitation and temperature, which are introduced into hydrologic models in a manner similar to 'brute force sensitivity analysis' to determine the expected range of changes in hydrologic responses. For example, Nash (1991) conducted a detailed assessment of climate change impacts on water resources in the Colorado River basin using a two step approach. The first step consisted of applying several GCM derived, scenario-based deviations of long-term mean precipitation [-20% to +20%] and temperature [+2°C to +6°C] to historical precipitation and temperature, and then introducing the latter into the National Weather Service River Forecast System (NWSRFS) hydrologic model. In the second step, the NWSRFS output (i.e., streamflow) was introduced into the U.S. Bureau of Reclamation's Colorado River Simulation System (CRSS), which incorporates management rules and reservoir simulation to track the impacts of climate change scenarios on long-term water availability in key reservoirs within the system. The results indicated a potential range of change in water storage (-61%, +38%), power generation (-57% to +39%), and salinity (+15% to -15%).

The sensitivity analysis approach may provide information regarding the range of possible changes. However, it does not account for special variability of precipitation and temperature, especially at hydrologically-relevant local scales in the assessment of local impacts. A second approach utilizes statistical relationships derived from past observations to downscale climate model output into hydrologically relevant resolutions prior to hydrologic simulations (Wood, 2002a, 2002b; Coulibaly *et al.*, 2005). To a large extent, the statistical approach is based on an important development in hydrologic forecasting, particularly with respect to probabilistic forecasting using Ensemble Forecasts. In climate predictions, ensemble traces are generated using multiple models as well as multiple scenarios (Murphy, 2004). For regional weather forecasts, ensemble traces are generally generated by the model's initial conditions as well as through the utilization of multiple models (Legg *et al.*, 2004; Muller *et al.*, 2005). Similarly, operational probabilistic hydrologic forecasts are gaining wider recognition as the most viable forecasts for risk-based decision making. In most cases, probabilistic hydrologic forecasts are issued by fixing the model's initial conditions and then forcing the model using input traces of historical observation for the duration of the forecasting window (Bradley *et al.*, 2004). For climate impact assessment studies, output from climate mode are used to generate stochastic weather traces based on observations, which are then used to derive hydrologic models. The advantage of this approach is in its ability to spatially downscale model output to a gauge or a network of gauges scale, and thus to maintain coherence with commonly used hydrologic models. For example, Sharif and Burn (2006) used a modified Kernel Nearest Neighbor K-NN (Lall *et al.*, 1996; Lall and Sharma, 1996) to resample historical weather observations conditioned by potential climate scenarios. They argued that K-NN provides superior performance to commonly used autoregressive models by maintaining the spatial structure of precipitation events and the correlation between and among variables. Priarie *et al.*, (2006) argued that a significant advantage of the K-NN framework is that it enables the addition of new conditioning variables such as large scale atmospheric circulations and/or climate change scenarios to generate weather sequences that retain some of the spatial characteristics of observations (Clarke *et al.*, 2004; Wilks, 2002; Gangopadhyay and Clark, 2004; Yates *et al.*, 2003).

The third approach utilizes numerical weather prediction models to perform the dynamical downscaling (Benestad, 2001, 2002) and force hydrologic and water resources models. The extensive data requirement of the latter approach reduces its wide use in assessing the effects of climate model and scenario uncertainty on uncertainties in projected hydrologic impacts of future climate (Quinn *et al.*, 2001) as well as those uncertainties associated with hydrologic models' parameters (Wilby, 2005). For example, Cayan *et al.* (2006), argued that the downscaling of a 150-year transient climate scenario simulation over the state of California to hydrologically relevant resolutions will require months-to-years of computer time. More recent hydrologically-based climate impact assessment studies covered, among other topics, large flood risk at regional and continental scales (Milly *et al.*, 2002; King, 2005; Kundzewicz *et al.*, 2005; Lehner *et al.*, 2006), regional/large basin water supply (Barnett *et al.*, 2005; Koster *et al*, 2005), hydrologic modeling in small watershed (Quinn et. al, 2001; Menzel *et al.*, 2006), downscaling of climate model output (Dibike *et al.*, 2005), and snow cover extent and characteristics (Dankers *et al.*, 2005; Stuart *et al.*, 2004; Dettinger *et al.*, 2004; Barnett *et al.*, 2005). To address uncertainties associated with different predictions arising from different climate models, probabilistic distribution of precipitation and temperature generated using ensemble runs of weather forecasting models (Wood *et al.*, 2005) have been used to force the hydrologic models, and the probability distribution of the hydrologic variables are then used to assess risks associated with climate change (Georgakakos, 2003).

Needless to say, the complexity of the earth climate system along with differences in model formulations of such complexities lead to remarkable differences between the GCM's projections of future climate (Figure 4, see page 216). As seen in the figure, which is obtained from the IPCC 2001 report, there is a great deal of uncertainty in model predictions of future climates. However, it is evident that all of the models agree in their future predictions of increased temperature as a result of the continuing increase in green house gasses in the atmosphere. The uncertainties in precipitation predictions are larger, but they consistently show an increasing mean value. Greater uncertainties would be expected at the local scales, and more significantly in predicting changes in the precipitation characteristics (intensity, solid-liquid, event duration, recurrence) at an event scale (Trenberth *et al.*, 2003). Such uncertainties necessitate cautiousness in approaching climate assessment impact studies. The ensemble framework, described above, not only provides the means to address uncertainties in climate predictions from a hydrologic modeling perspective, but also the framework to obtain modeling results in a manner consistent with decision theory. The upcoming IPCC's fourth report

'Climate Change 2007', is currently undergoing revisions and comments by IPCC member states. This report will rely on a new generation of climate models, improved emission and development scenarios, and higher resolution model output to reach much of its finding regarding possible future climates. While the improved spatial resolution will facilitate an improved utility of climate model output in regional and sub-regional hydrologic studies, much remains to be desired in terms of model uncertainty before the output of these models can be used effectively to determine possible hydrologic impacts at local scale. International efforts and significant investments may be required to reach that goal. Arguably, further research and data-collection activities are needed in order to quantify the impact of the intensification of the hydrologic cycle on the magnitude, direction, and frequency of floods, droughts, and other weather hazards which impact water resources management and to extend the lead time of hydrologically-relevant weather forecasts in a manner that support operational management. Furthermore thorough analyses of existing water resources systems, their operational procedures, and their resiliency are necessary to determine the type and level of operational flexibility (Dracup, 2001) that may be required in the future.

In the meantime, water resources managers must ensure that existing and planned water resources systems infrastructure are only elements of integrated strategies that provide for resiliency and adaptability, while at the same time account for environmental, ecological, and socio-economic concerns.

Acknowledgments

The authors would like to acknowledge support for this research from NASA, NOAA, NWS, GEWEX, and NSF STC for 'Sustainability of Semi-Arid Hydrology and Riparian Areas' (SAHRA). The second author also wishes to express his appreciation for the support of the Pontifical Academy of Sciences in organizing and sponsoring this workshop.

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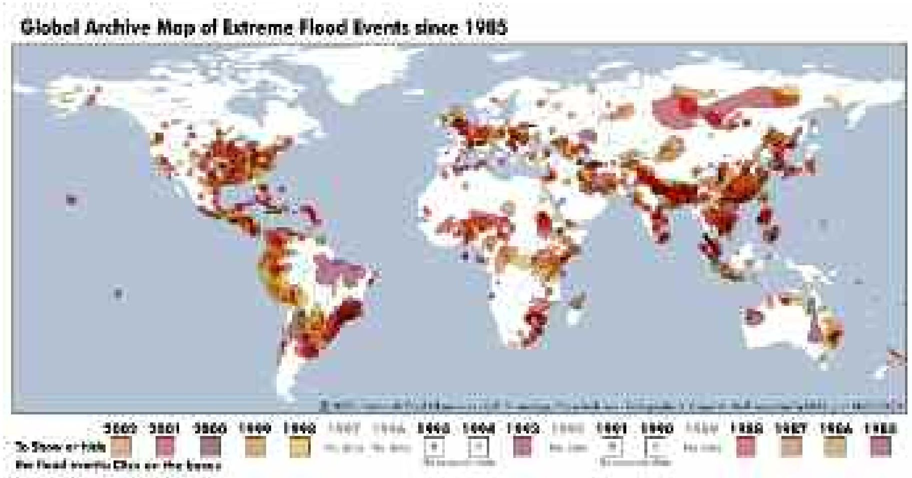

Figure 3. Dartmouth flood observatory mapping of severe floods since 1985. constructed using online application at http://www.dartmouth.edu/~floods/. (Brakenridge *et al.*, 2003).

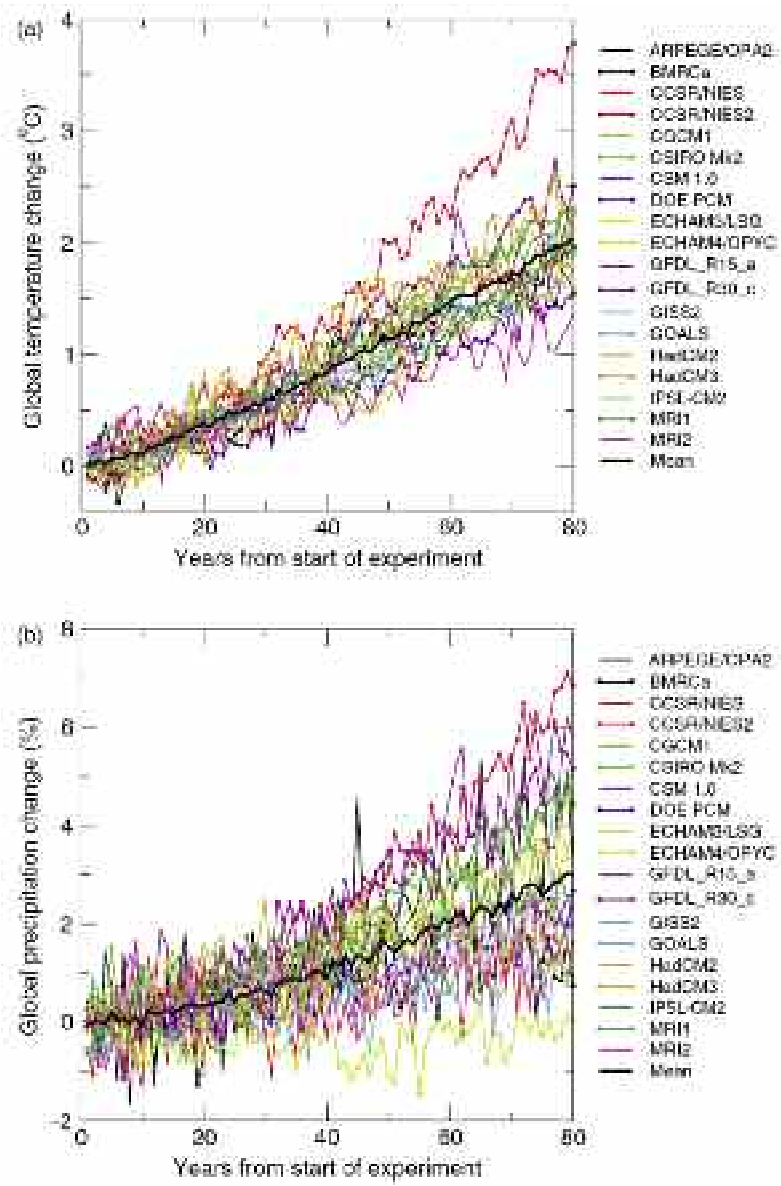

Figure 4. Future climate predictions of temperature (upper panel) and precipitation (lower panel). Notice the wide range of uncertainty in both variables among models and scenarios. (After IPCC, 2001).