Chapter 1: Climate Science and Climate Change
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INTRODUCTION

This is the second edition of a book assembled by the same editors in 1995. The first edition was one of the earliest attempts at regional assessments of the impact of climate change – in our case the application was to the Texas Region. There has been significant progress in climate research since then, and by the present publication we are responding to many requests to revise and update the book. Our aim then and now is to provide an objective assessment of the impacts of climate change on the Texas Region. Our target audience is the well-educated layman, especially those in a policymaking role whether governmental or private. Our object is not to scare but rather to let our readers know what the current thinking is in the field so that they can plan for changes that are likely to occur.

Separate chapters deal with different aspects of the problem and are written by experts in the various fields being treated in that chapter. The chapter authors come from a number of different institutions in and outside of Texas, and it was our intention to not be representing any particular point of view in the book. The book contains very little original research, but rather it represents to the best of our ability the state of the art of the science at this time as drawn from the published literature on the subject.

The current chapter deals with the science of climate change, including the question of whether it even is a scientific undertaking, its foundations, paradigm changes in its history and how we go about assessing the state of the art of climate science and the potential impacts of climate change. Finally, some results are presented along with a few implications for the future climate of the Texas Region.

MODERN CLIMATE SCIENCE

Climate science as we know it took a dramatic turn in the 1970s. Before that climatology consisted of the collection and classification of data taken from conventional sources from all over the world on all the possible time scales such as annual, monthly and even daily tabulations of the summary statistics of weather at particular locations. Often the statistics were averaged over regions, even to continental scale. Climatology books and courses provided diagrams and maps that helped classify different climates depending on factors such as soil type, temperature and moisture availability. The diagrams and maps were accompanied by qualitative discussions of the climate of a particular region in the context of its topography, geography, latitude, seasonality, etc. Some quantitative measurements were also being conducted in such areas as surface energy balances between radiation heating, conduction of heat into the atmosphere and the latent heat exchanges from evaporation. For the most part global and regional climate were regarded as stable, and such concepts as ‘drought of record’ were valuable planning tools. Some primitive models of global climate were finding their way into the literature such as those of Budyko (1968) and Sellers (1969).
Numerical models for forecasting weather have been around since the 1950s when the first operational digital forecasts were carried out at the Institute for Advanced Study in Princeton, New Jersey. As the computers became more powerful and the codes evolved, they were gradually adopted as one of the tools used by the Weather Bureaus around the world to forecast weather, although the human forecaster still did most of the work. The discipline imposed by forecasts and having to face the music day-in-day-out, caused the gradual evolution of the weather models until their utility was undeniable in the early 1970s. It was a natural step to adapt these models to address the problem of climate simulation.

Unlike econometric and other models that are sometimes based on balancing flows of quantities but with liberal helpings of regression coefficients, weather forecast models are physical models depending on the laws of fluid mechanics, electromagnetic radiation and thermodynamics. The physics provides strong constraints on the model solutions. A weather model forecast is analogous to computing the trajectory of an ideal projectile based upon Newton’s laws of motion. If the projectile’s initial position and velocity are known, the parabolic trajectory is determined as is shown in every high school physics book. Picture for example a dot where the projectile is computed to land. A small random error in the initial position or velocity will lead to a small error in the location of the final dot on the earth’s surface. If we repeat this procedure over and over with a different error each time we will obtain a swarm of dots at the end point. The longer the trajectory the larger the spread of dots as the trajectories diverge more with time of flight.

The weather forecast is similar to the single trajectory computation except we must follow the millions of air parcels simultaneously along their paths. The problem is further complicated because the parcels encounter different forces along the way, not least of which are the forces exerted on one from the others. So instead of the back-of-the-envelope calculation of the single projectile’s end point, we have to compute those of millions of air parcels from their original positions (pressure distribution) and velocities (winds) on a rotating sphere with non-uniform temperatures (buoyancies). The planet is heated more near the equator than at its poles and this causes a planetary convection of air called the general circulation. Also heat is released as moist parcels form droplets that make up clouds and this gives them additional buoyancy jolts (formation of the droplets releases large quantities of heat – opposite to the evaporation that cools our skin). Despite all these complications the computations go pretty much like the single projectile case, except that we must keep track of millions of parcels and this requires very large and fast computers. In a modern global forecast model, the inevitable errors in initial location and velocities lead to growing errors that become intolerable after a few days. But the erroneous evolution of the simulated weather beyond a few days still looks like real weather (the statistics of temperature, storm passages, etc., look similar to what actually happens). The forecast fails to predict correctly the weather on a particular day at a particular location. Nevertheless, we still have the progression of midlatitude storms from west to east, the seasonal cycle looks remarkably faithful, etc.
What would ‘climate change’ look like in our projectile model? An analogy to climate change is the shift of some external parameter such as the gravitational acceleration (nominally $g = 9.81$ meters/second$^2$). If we do this (say, change it to 12 meters/second$^2$), our (initial error-induced) swarm of end points will now occupy an elliptical pattern on the surface but now somewhat closer to the initial projection point. The entire pattern shifts and its shape might change as well.

When we run our weather model as a climate simulator we often want to know how the climate changes as we change some parameter in the model such as the concentration of some gas in the atmosphere or perhaps the solar brightness. We are interested in the new summaries of weather statistics (climate). This is a simplified explanation of the way climate simulations are conducted. If the change in the acceleration of gravity for the toy projectile model is small the swarms will overlap, but even small changes might be detected if enough data are collected, and such small changes of the statistics could be important. Changing one of the external parameters such as the gravitational acceleration in the toy model to a different value is similar to a change in climate induced by say a change in the sun’s brightness or any of the other possible parameters that might cause a change in the weather statistics (climate).

Climate models are more complicated than ordinary weather forecasting models since they need to include more processes that are not very important in the weather forecast. This is because even slow, tiny changes in say the solar brightness will cause the statistics to shift to new values. The main new features that must be included are comprehensive treatments of details of radiation passing through the atmosphere (e.g., absorbing, scattering, emitting, etc.), water vapor transport, cloud physics and ground surface properties. Moreover, the long term changes in the ocean play a big role in climate change but hardly any in short term weather forecasts.

The success of weather forecasting led to a worldwide data collection and assimilation system. These observations from ground and balloon based systems could be
archived after use in the forecast initialization and made available for climatological research. Another breakthrough occurred in the mid-1970s: the Earth-orbiting-satellite observing systems. In the beginning these observations were intended mainly for initializing weather forecasts, but it was quickly noted that these orbiting observatories could collect vital climate data as well. Such elusive observations as cloud cover, sea ice cover and area averages of precipitation (especially over the oceans) are now routinely observable on a global basis. The satellite data can be used to check the climate model simulations of the present climate. Now data routinely collected by ships passing over the world oceans reveal not just the surface parameters but those below as well. All of these observations are being collected and sorted into useful data sets for global climate research. The synergy of modeling and global observing systems has continued through the decades since the mid-seventies.

So what is the climate change that has been the cause of all the concern? Even the simplest global climate model, which balances the rate of visible sunlight being absorbed by our planet and the rate of energy emitted from Earth to space, predicts a higher surface temperature if the planet has an atmosphere with some opacity in the infrared portions of the electromagnetic spectrum. In fact, our planet would scarcely be warm enough for habitation by our species if there were no ‘greenhouse’ effect (mostly due to water vapor which is a greenhouse gas). This kind of energy rate balance model is a ‘back of the envelope calculation’, and it has been known for a century, at least qualitatively. A paper published by Gilbert Plass (1956) estimated that doubling the carbon dioxide in the atmosphere would increase the planet’s temperature by about 2.5°C (4.5°F), a change very close to the currently accepted value (Plass later spent the rest of his career as a professor of physics at Texas A&M University). Plass left this research area because he thought that in order to improve on his theory there would need to be more accurate measurements of the absorptivity of greenhouse gases to infrared radiation. Now 50 years later this task has been essentially completed.

The problem is that we are increasing the infrared opacity of our atmosphere by its accumulation of gases that are fully absorbing in some ranges of wavelength in the infrared. Rough computations with simple models can give us approximate answers for climate change due to changes in greenhouse gases (plus or minus 75 percent), but a proper treatment of the feedbacks in the system requires much more comprehensive models. Moreover, estimations of global average temperature are not enough to help decision-makers. Changes in precipitation and the regional peculiarities of the warming cannot be computed with the simple energy balance models. To solve these problems we must turn to the giant comprehensive climate models that have grown out of weather forecast models – those that push the world’s largest and fastest computers to their choking points.

The space-time dense data sets compiled over the last three decades close many gaps in our understanding of climate change, both natural and those forced by external parameter changes. We not only have comprehensive estimates of the history of the atmospheric and oceanic temperatures and the winds, currents, etc., but also of the agents that force climate to change such as the opacity of the atmosphere following a volcanic eruption, long records of the brightness of the sun taken from satellites outside the atmosphere, the concentration of the greenhouse gases, the properties and composition of tiny particles afloat in the air, and changes in pH of the oceans, to mention just a few.
These measurements of the cause and effect over the last three decades allow us to separate ‘natural variability’ cleanly from the trends that are forced in the climate system. As we go back further in time the comprehensiveness and accuracy of the data degrade so it is more difficult to draw the same rigorous inferences. However, even with these limitations, the evolution of climate over geologic time scales down to the present is beginning to fit a consistent paradigm of climate change and its causes.

MODELS AND DATA

Although we may accept the paradigm that we can use the laws of physics implemented via very sophisticated numerical analysis on the world’s best computers to simulate climate, there are always problems in the implementation. The implementation is accomplished by casting the problem onto a grid, or a similar construct, covering the planet. Presumably the finer the grid the more faithfully are the equations from physics represented in the simulation. The coarseness of the grid spacing is a major limitation of the approach, and steady improvements in this area have been made (see Fig. 1.2). Even so, clouds and precipitation patterns, particularly in the tropics, are much smaller than today’s model boxes. Rather than have the model simulate 110-km-wide thunderstorms, the cumulative effect of the various thunderstorms that would occur within an individual grid box need to be specified. These fudge factors are adjustable parameters that inevitably enter the model making. Such fudge factors will never exactly mimic the behavior of the real processes that they replace. Reducing the errors that arise from this approximation is among the most challenging problems in the field and is the subject of continual study.

As with the models, there are inevitable problems with the data. We would love to have data on temperature, precipitation, pressure, cloudiness, humidity, etc., over a global range, mapped at fine resolution in both the horizontal and vertical dimensions. We would love to have centuries of it. But we cannot go back in history and make additional observations. The records are often not long enough and are not at fine enough spatial scale. Instead, we must get by with what we have, and check our model simulations of past and current climate against the available data. In some cases we need to adjust those pesky parameters a bit to nudge the simulation to better fit the (also approximate) facts. Besides the global coverage of data, we need to augment our observational picture with field programs that help us understand individual processes such as cloud formation, soil drying, etc. These programs are very labor-intensive, often requiring multiple aircraft, delicate instruments, etc., and of course they are limited to small regions of the planet. Field programs are essential for understanding the small-scale (tens of miles) processes and for serving as ‘ground truth’ for the satellites.

Aside from these concerns there is the need to analyze the data and the output of the models. This analysis and testing form a large part of the climate change enterprise.
IS CLIMATE SCIENCE REALLY SCIENCE?

This is a question that arises from time to time especially among climate change skeptics. In other words is climate science something like astrology? That is to say is the theory so qualitative, flexible and tentative that it can accommodate (explain away) any conceivable new seemingly contradictory data within its framework? Successful
scientific theories should run some kind of risk or they quickly become as uninteresting as armchair prattle. Philosopher Karl Popper would say the theory should be falsifiable—it should make predictions that if proven invalid falsify the theory. Most philosophers of science now believe that such a strict criterion in modern science is too stringent (Worrell 2003) because of the many assumptions that must underlie both the observations and the reduction of the theory to a specific test. This certainly appears to be the case in climate science where the implementation of the laws of physics on a finite numerical grid and the derivation and interpretation of such data as those retrieved from instruments on satellites all involve many assumptions and approximations that are not always easy to justify.

Some people believe concerns about global warming are politically driven or even that they are the product of a sect of environmentalists analogous to a religious movement. While there has been political passion (e.g., a former Vice President being a visible and outspoken advocate of climate change concerns), the scientific consensus is hard to deny. At last, partisan political bickering about anthropogenic climate change is subsiding. There has also been a false impression that many scientists are opposed to the theory. But objective surveys over scientists who have recently published in mainline journals on the subject show overwhelming support for the proposition that human activities are responsible for the recent warming (personal communication, 2008, Professor Arnold Vedlitz, Bush School, Texas A&M University).

The philosopher and science historian Thomas Kuhn (1970) in his influential book The Structure of Scientific Revolutions describes the way science frameworks change course from time to time. Typically science moves along at a steady pace following a certain paradigm or way of thinking until the current theory or way of describing things breaks down or comes up against an array of observations or internal contradictions. At this point some of its former adherents begin to cast about for a new way of approaching the problem. At other times the paradigm might give in to stagnation. For example, there might be no new data available for generating new problems to solve, and scientists must have problems to solve; otherwise, they move to a new area where there are interesting things to do. The 1970s presented such a barrier for climate science. Rapid advances in technology described earlier awakened climate research from a state of stagnation. The original climate models were not invented to address global warming, but rather they were concerned with explaining past climates (for which new data were being analyzed and interpreted for such phenomena as the continental glaciations). As climate models and the accompanying tech-heavy data advanced (e.g., ocean floor drilling), so did climate science. We moved into a phase that Kuhn would refer to as normal science. This is a period of slow but steady advance, because there are lots of scientific questions arising that can be addressed in the new framework. The framework was successful in answering those questions and science hungered for more. Science and scientists have continued along these lines, answering question after question, puzzle after puzzle. The list of questions answered and understood through climate modeling would fill a book far thicker than the present one. This program will continue until another impasse is reached. There is no such impediment even vaguely in sight at the present time. While the relevant laws of physics are pretty well understood there is lots of work to be done in implementing (approximating) those laws on computers. Likewise, there are many challenges in understanding and expanding the observational database, but this process is
healthy and moving forward. So climate science fits the usual criteria of a newly emerging field in the scientific enterprise. There is no reason to think we are on the wrong path.

It is not always easy to separate the scientific findings (so-called ‘positive statements’), from other statements that have to do with value judgments (so-called ‘normative statements’); these latter include finger pointing, what ought to be done, who is to blame, who pays, etc. (Dessler and Parson 2006). The normative issues are truly important but they have little to do with the positive statements. If we can keep these two categories separated we will make much greater progress in dealing with our problem.

**A FEW QUESTIONS OFTEN POSED BY SKEPTICS**

At seminars or with call-in questions about climate change, several questions from laymen or engineer/scientists from different disciplines repeatedly come up. A few, with answers, follow:

1. Since water vapor is the strongest greenhouse gas and it is naturally occurring, why do climate scientists always pick on carbon dioxide and the other anthropogenically produced greenhouse gases? **Answer:** Water vapor is indeed a very strong greenhouse gas, so much so that without water vapor (and perhaps clouds) in the atmosphere the planet would be about 60 deg. F colder than it is. In addition, water vapor amount increases as the climate warms. Hence, it is a very powerful positive feedback mechanism, roughly doubling the response that we would expect normally from doubling CO₂ (expected to be about 1.0°C or 1.8°F). Climate models are nearly unanimous on this point. But because atmospheric water vapor amount is so directly connected to global temperatures, there is nothing practical we can do to substantially alter the amount of water vapor, other than keeping global temperatures in check by other means.

2. The concentration of carbon dioxide is only 380 parts per million (it makes up only 0.038 percent of the molecules in the atmosphere) whereas there’s about 100 times more water vapor. How can adding a few more molecules of CO₂ matter? **Answer:** The air is pretty cold and dry where the emission of infrared radiation to space takes place. The number of CO₂ molecules is as much as a third that of H₂O at that altitude (about 10km or 6 miles). So the two are comparable. Each absorbs and emits in its own characteristic band in the infrared and in important bands they do not overlap. Hence, the emissions and absorptions of these two gases both matter a great deal.

3. During the major glacial advances in the last million years the temperature swings appear to lead the CO₂ swings by a few hundred years. How could CO₂ be the cause? **Answer:** The consensus among climate scientists is that CO₂ and methane are positive but very slow feedbacks in the climate system. It is the changes in the orbital elements of the Earth’s motion about the sun that trigger the glaciations (Milankovitch Effect). Once the glaciers begin to grow from this trigger the concentrations of several important greenhouse gases are drawn down and the glaciers grow even more. Model studies show that the orbital element changes alone cannot account for the size of the resulting glaciers. The greenhouse gas
feedback seems to be an essential component in the process. The origin of the feedback must lie in the biogeochemical parts of the system. While these are not yet known in detail, the explanation is very plausible. So, carbon dioxide and methane are not the original cause but rather a very important feedback mechanism that amplifies the response to the orbital trigger (sometimes referred to as a pace-maker).

4. Earth has undergone large climate changes long before human influences. Who or what caused those? Answer: On geological time scales, the processes of mountain building (lots of volcanism and CO₂ buildup) and subsequent erosion of rocks (acid rain from the CO₂) on the mountainsides can modulate the CO₂ concentration drastically. This is undoubtedly the origin of much of the past greenhouse effects on the planet.

5. What about the Medieval Warm Period (centered around 1000 AD) when Greenland was colonized (and possible actually green), but abandoned in the 1300s. Wasn’t that warmer than the present? Answer: While we cannot be certain of the existence or nonexistence of a Medieval Warm Period, it appears that it did exist in the Northern Hemisphere (but less likely in the Southern Hemisphere). However, current studies indicate that it was not warmer than at the present. Greenland might have had less ice cover at that time, and it might be so again in the next century or so.

6. Climate models do not get the trend right in the upper troposphere according to satellite data. Doesn’t this discredit the theory? Answer: This problem has been around for a few decades. Improvements in the models have helped resolve it, but more importantly, the early interpretation of the satellite data has been shown to underestimate the warming in the upper troposphere. The bias was extremely hard to find and took many years to unravel. Further examination of weather balloon observations has found additional errors, and it’s looking like the models have been right all along.

7. How about the sun? Doesn’t it change its brightness from time to time? Answer: The sun’s irradiance does vary about 0.1 percent with the eleven-year sun spot cycle. But measurements with satellites taken outside the Earth’s atmosphere show that it is very unlikely that a trend exists over the last 30 years, just exactly when the planetary warming has been the most rapid. We cannot say as much about earlier periods in Earth history, but some evidence suggests that the brightness has changed over millennial time scales. Because of the relatively small magnitude of its variations and the timing of the recent warming, the sun seems to be playing at most a minor role in recent climate change.

8. Question from a spectroscopist: Since the spectral lines of CO₂ and the other greenhouse gases are discrete, once the concentration is large enough that the absorption lines are saturated they no longer have an effect. How then can increasing the concentration further raise the temperature? Answer: Let’s translate this to the real greenhouse (in the back yard) problem. The greenhouse glass already absorbs 100 percent of the infrared. So what if we double its thickness? Well, nothing happens to the temperature at the ground underneath is correct. Getting back to the atmospheric problem, some of the sharp spectral lines do saturate, but when CO₂ is doubled, the infrared radiation to space is now emitted
from a higher level in the atmosphere where the temperature is lower. This means that its total emission to space is reduced. Since the amount of incoming solar radiation is unaltered by the doubling, the planet’s temperature now must increase about one degree C to maintain balance.

THE ASSESSMENT PROCESS

As the science of climate change progresses with literally a cast of thousands of scientists grinding away, there is the need to periodically assess the state of the art. This is for both the engineering aspect (societal needs) as well as the scientific one in which the investigator seeks answers to deeper questions. Other issues arise such as anomalies (special cases where the data and modeling do not agree, as with the satellite data in the last section). These need to be delineated and strategies developed to reconcile them within the climate science paradigm. So far this approach has been successful, as there are no serious outstanding anomalies at this time. These periodic inspections are called climate assessments. They come in a variety of forms. For example, the National Academy of Sciences (NAS) frequently assembles committees to look into scientific questions and assess the status of various fields of medicine, engineering and even climate. Numerous NAS committees have taken on portions of this task over the last three decades. Besides these rigorous assessments, the professional societies to which climate scientists affiliate themselves often issue statements on matters of public interest that reflect the thinking inside the community of scholars in that particular field. For example, the American Geophysical Union (about 35,000 members) and the American Meteorological Society (about 11,000 members) have issued very strong statements.

In the case of climate science we look not only to the assessments mentioned above, but to the Intergovernmental Panel on Climate Change (IPCC), under the auspices of the United Nations. It was charged with providing periodic assessments of climate science with special attention to possible climate change and its impacts on society. The first assessment report (FAR) of the IPCC was published in 1990, followed by another every five or six years. The latest (Assessment Report Four; AR4) was published in 2007 (IPCC 2007). Much of the rest of this chapter is a summary of the AR4.

It is important to understand the IPCC process. Each report consists of the findings of three working groups: Working Group I assesses the current status of the science, Working Group II considers impacts of climate change given the findings of Working Group I, and Working Group III examines what steps might be taken to mitigate climate change. Each working group report consists of 10 or so chapters of approximately 100 double column pages. Each of the chapters has several lead authors and 20 or so co-authors. In assembling information for the chapters numerous workshops and open forums are held. As the report is cast into draft form it is sent out to anonymous referees for comment. Also the draft report is made available on the web. AR4 received some 30,000 comments and every one was addressed in some form. Ultimately there is a reading and review of the report summaries by the political representatives of the 120 countries involved, followed by unanimous approval.
Figure 1.3. Bar graph of the different forcings contributing to global warming since 1750 AD (in Watts per meter squared. The ‘I-bars’ represent uncertainty ranges in the estimates. Adapted from AR4).
The Working Group I AR4 reviews all aspects of the status of the science of climate change research with chapters on past climates, natural variability, current observations, climate models and future climate projections. Selected conclusions from the report may be summarized as follows:

1. The concentration of CO₂ has been increasing and is now higher than it has been in many thousands of years. The bulk of the increase over the last century can be attributed to the burning of fossil fuels, certain industrial processes and land use changes.
2. Understanding of climate change has improved over the last five years and it can now be stated with a very high level of confidence that human activity has been a primary influence in the warming (see Fig. 1.3).
3. Warming of the Earth is unequivocal from a variety of observations (see Fig. 1.4).
4. Research on past climates suggests that the present warmth exceeds that of the last thousand years, and the last time it was warmer was during the previous interglacial, 125,000 years ago, when sea level was four to six meters (13-20 feet) higher.
5. In a stronger statement than that of the previous report, the AR4 states that the warming is very likely to be due to human activities.
6. For the next few decades we can expect a warming of about 0.2°C (0.4°F) per decade.

Here we focus on the projections. Such a projection necessarily depends on the future record of emissions of greenhouse gases and other changes in climate drivers (e.g., land use). The IPCC has developed a suite of alternative future societal behaviors for input into climate simulation models, and some of these are briefly described in the AR4 Summary for Policymakers. Figure 1.5 shows AR4 results from simulations under various scenarios. Of these the A1 scenario leads to the most warming. It is a future with “very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies.” The results for a few other scenarios are shown in Fig. 1.5. Even if carbon dioxide levels are artificially held fixed at 2000AD levels, there is still some warming due to the thermal inertia of the system (not shown).
Figure 1.4. Graphs of past (a) global average temperatures in degrees Celsius (shown as departures from the 1961-2000 average), and (b) global average sea level (in mm, shown as departures from the 1961-2000 average). The vertical width of the gray swatches represent uncertainty ranges. Adapted from AR4.
Figure 1.5. Global average temperature projections for different scenarios (A2, A1B, B1) of greenhouse gas emissions for the past and current centuries. A2 (solid curve) is a near ‘business as usual’ scenario with others employing smaller emissions. A brief definition of the scenarios is given in the AR4 Summary for Policymakers. The range of uncertainty for the climate simulations is about plus/minus 0.5 deg. C and the uncertainty in the emission scenarios is another plus/minus 1 deg. C. (Adapted and simplified from AR4)

Figure 1.6 shows the change in precipitation averaged over 2090-2099 compared to the 1980-1999 average as simulated by about 20 climate models. Note that the subtropics in both hemispheres show a decrease in precipitation. There exists now a number of papers based upon both models and data from the recent decades indicating that the storm tracks in winter will recede slightly towards the poles in each hemisphere under forced climate change (data based: Archer and Caldeira 2008; Seidel and Randel 2007; model based: Yin 2005; Kushnir et al. 2000; Bengtsson et al. 2006). In particular, one study (Seager et al. 2007) focuses on the US Southwest (land areas from 95W (about I-35) to the West Coast and from South Texas to Kansas). This paper makes use of the same simulation models as AR4 and examines the changes in precipitation and evaporation over the region. They find that the region will become drier toward the end of the century with the normal climate comparable to the drought of the 1950s (see the schematic in Fig. 1.7). This suggests that use of the drought of the 1950s (the so-called ‘drought of record’) may not be appropriate for future water resource planning, since the study implies that large drought (and wet period) swings above and below the current ‘drought of record’ will be common.
Figure 1.6. Simulations of December-January-February precipitation changes for the end of the century compared to the present (using results from about 20 climate models). June-July-August conditions are similar. Note the band of dryer (cross-hatched) conditions in the subtropics in both hemispheres, part of which overlaps West Texas. White areas indicate that less than 66 percent of the models agree on the sign of the change. (Adapted from AR4)

Figure 1.7 Schematic adapted from Seager et al. (2007) of simulations of precipitation and evaporation changes from 21 AR4 models averaged over land areas in the US Southwestern box of all land between 125W and 95W and between 25N and 40N. The curves are smoothed estimates from the original paper. Large fluctuations of decadal length drought and wet cycles are to be superimposed on these ‘mean’ curves.
Much interannual variability of precipitation and temperature in the Texas Region is accounted for by persistent sea surface temperature distributions in the Pacific. For example, it has been well known for many years that the El Nino/La Nina (often referred to as ‘ENSO’ for the El Nino/Southern Oscillation) cycle in the Pacific modulates winter rain in Texas. Winters are usually wet and cool during El Ninos and dry and mild during La Ninas. Excellent tutorials on ENSO can be found at www.cpc.noaa.gov and www.pmel.noaa.gov. There is evidence that other sea surface temperature changes in the Pacific can lead to curious changes in the storm tracks crossing the US mainland. For example, model studies (Schubert et al. 2004) indicate that sea surface temperature anomalies played a role in the droughts of the Dust Bowl (1930s). Persistent anomalies in the Pacific sea surface temperatures are part of the natural variability of the climate. Such anomalies as ENSO recur every 2-5 years, but no two are exactly alike. Other anomalies, such as those linked to the decadal length droughts of the last century, come and go with less regularity. Some might be attributable to sea surface anomalies, but others might originate with a confluence of otherwise benign circumstances leading to a ‘perfect storm’ situation.

Texas and the Southeastern part of the US tended to cool over much of the last century until the last few decades (see Chapter 2) when even this region began to fall into line with the global trend. Climate model evidence suggests (Robinson et al. 2002) a linkage of this cooling to the increasing sea surface temperatures in the Tropical Pacific. The modeling studies cited in this and the last paragraph do not use actively coupled ocean models, but rather they specify sea surface temperatures in a variety of numerical experiments to unravel cause and effect relationships. During periods of El Nino Atlantic Hurricanes tend to be suppressed, further influencing the climate of Texas.

Figure 1.8 shows the present mean annual distribution of tropical precipitation. The schematic diagram on the left shows the Hadley Cell with rising air at the Equator and sinking air at about 30 degrees N and S. The data on the right agree with this idealized picture with heavy rain along or near the Equator and dry conditions in the Subtropics. Note that the major world deserts occur in these (white) zones.
Figure 1.8. The mean annual distribution of present precipitation (right panel) from the Tropical Rainfall Measuring Mission (satellite). Air rises along the equator giving rise to heavy precipitation and it tends to sink in the latitude bands around 20 to 30N leading to dry descending air, giving rise to most of the world’s deserts (a circulation known as the Hadley Cell). The map of satellite data indicates a band of heavy precipitation encircling the globe near the Equator with very dry conditions (white areas) in the subtropics. (Data available from the TRMM website.)

Figure 1.9 shows the seasonal march of precipitation in the Continental US and in Tropical areas nearby. Note the west-east gradient in precipitation across the Texas Region. There is heavy rain in the east and dry conditions in the west. This is undoubtedly due to the availability of moist air from the Gulf of Mexico in the east and the lack of moisture in air descending from the west. Other familiar features are also apparent in the diagrams: The heavy winter rain in the Pacific Northwest, the Southwest Monsoon coming up the western coast of Mexico in summer, the intensification and northward migration of the equatorial rains in the Northern Hemisphere summer. The rainfall in Texas shows a sharp west-to-east gradient in January through May, but the pattern breaks down during summer as localized convective storms tend to dominate the precipitation throughout the high plains. What happens to this picture as the globe warms?
Figure 1.9. The seasonal cycle of rainfall rate for North and Central America. Note the sharp west-east gradient of rain rate in the Texas region and the way it changes over the course of the year.

**IMPLICATIONS FOR THE US**

Virtually all of the projections from different scenarios indicate warming for the continental US, much of it slightly more than for the global average. In the western and central portions of the continental US (see Fig. 1.10) the changes are centered on 4.0°C (7.2°F) (since 1950) for the end of the century, with model differences of about plus/minus 1.0°C (1.8°F). Similar changes are projected for the Eastern Continental US, with even larger changes in temperature expected for most of Canada (not shown here). From this we can conclude that the Continental US will be about 4.0°C warmer than it was in 1950.

Precipitation changes are shown in Fig. 1.11. The upper panel shows changes in the mean December-January-February precipitation. This map suggests that northern portions of the continent will experience more rain while southern portions of the US will receive less. This is a pattern consistent with the idea of the storm tracks receding towards the North Pole and the accompanying expansion of the sinking branch of the Hadley Cell also expanding toward the north. The lower panel shows summer results, which suggests that the sinking branch of the Hadley Cell now extends roughly to the Canadian border with diminished rain throughout the Continental US.
Figure 1.10. Results from simulations of about 20 climate models for Western North America (WNA) and Central North America (CNA) (regions are indicated by the green boxes in the maps). The solid black curve is the data and the red swath covering it is the range of simulations (90 percent fall within), while the orange swath indicates the same range of the projections. The vertical colored lines on the right indicate the range derived from three different scenarios. Adapted from Fig. 11.11 of AR4 Working Group I.

ENERGY, WATER AND CLIMATE CHANGE

According to the simulations from the AR4 (Figs. 1.10 and 1.11) we find that mean annual temperatures for Texas are projected to rise about 4.0°C (7.2°F) plus or minus 1.0°C (1.8°F) from the last two decades of the 20th Century to the last two of the 21st. Most of Texas is likely to experience much higher air conditioning bills. Since heating bills are much less than cooling bills, the savings in winter are not likely to balance the increased expense in summer.

Estimating future precipitation is more problematic. The GCM results of Fig. 1.11 suggest that virtually all of Texas will get less precipitation in both winter and summer. The decrease might be as much as 5 to 15 percent especially in West Texas in winter. According to the model projections, the rain in summer might not be diminished as much, perhaps due to the Southwest Monsoon as the convection creeps up the west coast of Mexico in summer (see Fig. 1.9). However, as discussed in the following chapter, there is large variability among the model projections for both winter and summer.
The next chapter also notes that over the past century precipitation increased in East Texas but was unchanged in the West. Why, then, do models predict drying? Are they missing such important fine-scale features as low-level jets that efficiently convey moisture northward from the Gulf of Mexico? This moisture in turn feeds the storms so common to the East Texas area. The mechanisms for precipitation are complex in this interesting region and the lack of spatial resolution in our current models might mislead.

Obviously, water resources, energy and food prices, population increases, threats to ecological habitats and climate change interact in complex ways. If Texas gets less precipitation and higher temperatures, we can expect more evaporation and less runoff into rivers and less recharge of aquifers. For example, if Texas is drier with prolonged droughts on top of the drier normals, we can expect interruptions by power plants using stream-derived water as a coolant. West Texas may find itself shifting from an agricultural economy because of inadequate supply of low cost water to a wind energy economy.
Climate science really emerged as a thriving enterprise in the 1970s with the sudden increase in the scientific attention to the problem. The new awareness was rooted in the sudden prospect for attacking and solving many interesting problems in past and future climates for both Earth and the planets. This stimulated the collection, quality controlling and archiving of global data sets. The speed and capacity of large digital computers and the adaptation of weather forecasting models to the climate problem enabled new problems to be attacked in climate research. Other technological advances such as instrumented research aircraft and ships enabled exciting new field programs to check and improve models. Scientists were attracted from neighboring fields, blending their expertise with that of meteorologists and oceanographers. The result has been an explosion of research on past and future climates. The climate science paradigm is being pursued at fever pitch. The state of the art of climate science is regularly assessed by many scientific organizations; the Intergovernmental Panel on Climate Change provides the comprehensive assessments every five or so years.

There are many conclusions in climate science that appear to be robust. These include the general warming of the planet (1.5-4.5°C, or 3-8°F, during the coming century) mainly driven by the increasing concentrations of greenhouse gases. There is (and will continue to be) more warming at the poles than elsewhere and the global hydrological cycle is very likely to intensify between a few and seven percent per degree (Celsius) of warming. If no catastrophic melting occurs on Greenland and/or Antarctica, we can expect Sea Level to rise one to two feet. All the ice on Greenland represents about 18 feet of sea level rise and the same for the West Antarctic ice sheet. The melting of these is unlikely to happen during this century, but there is a small probability of it. Because of the potential consequences, it cannot be taken lightly.

The forecasting of future climate details for a region as small as Texas is still problematic. This is even more difficult for Texas because of its unique location bordering to its south the contrasting surfaces of arid Mexico and the warm waters of the Gulf of Mexico, these conditions being combined with the prevailing winds across Texas coming from the south most months of the year. Texas is also located at a latitude such that winter weather (cold/warm fronts and rainy passages) crosses most months of the year – these so-called storm tracks are subject to some change as global warming proceeds. Storm tracks are likely to recede northwards with global warming, making the passage of fronts across Texas less frequent in spring and fall. Texas is also situated next to New Mexico and Arizona both of which experience a summer monsoon creeping up the west coast of Mexico. West Texas could benefit from the summer monsoon, if it strengthens. Texas winters are also strongly influenced by the El Nino/La Nina cycle. Typically El Nino brings wet winters to Texas. Hurricanes and tropical storms impinge on Texas Coasts. The frequency and/or intensity of both El Ninos and Tropical Storms might change with global warming. The occurrences and interactions of all these factors make for a precarious forecast for precipitation. There can be legitimate differences of opinion: this author opts for more rain in the eastern part of the state and less in the west, but confesses that strictly speaking the jury is still out.

What about ‘downscaling’? This is the process of taking the projection of a global model with coarse grid (e.g., Figure 1.2) and using either a statistical regression scheme
to extrapolate to smaller scales, or actually embedding a finer scale model within the
coarser model grid. In either case we run into the problem of choosing which coarse scale
model to use for the input. If we feed poor coarse scale information to a fine scale model,
there may be very little information added. But if topography or some other factors are
important there could be genuine value in the ‘downscale’. The efficacy of downscaling
is still an open question in climate modeling and the focus of current research.

What can we expect in the future for climate research? The most formidable
problems are connected with convection (bursts of rising air, e.g., localized tropical
precipitation phenomena) because important features of these are usually far smaller than
our grid lattices. Great efforts are being expended along these lines. The range of
uncertainty is mainly due to our lack of quantitative understanding of the feedbacks in the
problem. It may be many years before these are cleared up. But I expect serious progress
on the frequency and/or intensity of tropical storms and the El Nino cycle in the next
decade. Other consequences of the warming will also be better understood, including
impacts on the ice sheets of Greenland and Antarctica and the hydrological cycle. There
is a good chance that we can clarify the situation on future precipitation in Texas in the
next decade as increased computer power allows model grids to become denser.

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