A Four Corners Climate Primer

Howard P. Hanson, Ph.D.

The environmental future of the U.S. Southwest, from the high alpine tundra to the mesas of the Colorado Plateau to the Sonoran Desert, depends to a large extent on how climate change manifests itself there and how the population responds and adapts to that change. Education is critical in this response and adaptation.

Around the turn of the century, I wrote a series of essays, in the form of web pages, about the climate of the Southwest—the Four Corners Region—for high-school students to use as source material for term papers. If the thankful comments I received are any indication, that seems to have been a success.

These essays are presented here reformatted into a single (rather long) document, updated as appropriate to include new perspectives. The narrative is still written for about the same audience (in particular, it's devoid of mathematics, and it's non-technical), but it is now stitched together into a more coherent whole.

It is perhaps worth emphasizing at the outset that the perspective discussed here, and especially its conclusions, have been thoroughly validated by the past twenty years of research by climate scientists world-wide. Indeed, in many respects what is presented here represents a very conservative view of the situation.

Global Climate Basics

Although it is too strong to state that all of the critical environmental issues facing the Southwest are related to the climate, a case can be made that climate is central to many of them. Moreover, evolution of the climate over the next several decades, both the global climate and its manifestation regionally, could well involve new stresses on already stressed ecosystems in the Four Corners region. In particular, the accumulation in the atmosphere of carbon dioxide (CO_2) from fossil fuel burning and other sources is changing the climate to which we and the world around us have become adapted. Therefore, it seems useful to provide a background discussion of the Earth's climate, how the climate of the Four Corners fits into the global picture, and what we may be in for down the road. My intention here is to provide only an outline of the complex system of processes that controls the climate and its variability.

Radiation—the driver

First, it is important to introduce, and to de-mystify, the term "radiation," because this is what controls the global climate at the most fundamental level. Not "ionizing" radiation, the kind associated with nuclear reactions or radioactive isotopes or x-ray machines, but radiation from the Sun and from the Earth itself: sunlight and Earth's radiant heat.

This discussion is not meant to be comprehensive, and the subject of quantum physics is too far afield to dig into here. Suffice it to say, therefore, that it is a fundamental property of matter that it emits energy in the form of electromagnetic radiation if its temperature is greater than absolute zero.

We are all familiar with the temperature at which water freezes, 0°C (or 32°F). Absolute zero—the temperature at which matter ceases to emit radiation—is measured with a different temperature scale, so that 0°K (Kelvin) is about -273°C (or about -460°F). Anything warmer than this emits some radiation.

Further, the peak wavelength of the spectrum of radiation emitted, as well as the energy involved, decreases with the temperature of the matter doing the emitting—hotter objects emit shorter wavelengths of radiation, and more of it. Much of the radiation emitted by our Sun, the surface of which, at several thousand degrees Kelvin, is pretty hot, is in the visible part of the electromagnetic spectrum. The spectrum of colors in a rainbow, or as seen using a prism, represents much of the Sun's emitted energy. At the other extreme, even the sparsely distributed gas molecules in deep space emit radiation—not much, but it's there, very faint and at very long wavelengths. A couple of guys at Bell Labs got a Nobel Prize some time back for measuring it.

Because the Sun is hotter than the Earth, its radiation (solar radiation) has shorter wavelengths (yellow is shorter than red is shorter than infrared) than the Earth's radiation (terrestrial radiation, in the infrared part of the spectrum). These two kinds of radiation interact very differently with the molecules of air in the atmosphere, and with clouds.

Conceptually, Earth's climate is pretty simple. The Sun emits solar radiation, some of which hits the Earth. The Earth absorbs a fraction of this and heats up. It heats up to the point that the terrestrial radiation emitted by the Earth just balances the amount of energy it's absorbing from the Sun. If something changes, the balance may take a while to achieve—the oceans, for example, store a lot of heat and would take some time to cool down, should the Sun get dimmer. But it's this balance—the Sun heats up the Earth and the Earth emits its own radiation to cool off—that the climate always tends toward.

In the simplest calculation, using the relevant formulas from math and physics along with satellite observations of how much sunlight the Earth absorbs, it's possible to calculate what the temperature of the Earth should be. The satellites tell us that the Earth absorbs about 70% of the sunlight that it intercepts. This, combined with the fact that it is the disk of the Earth that is doing the intercepting of solar radiation while it is the entire (nearly spherical) Earth's surface doing the emitting of terrestrial radiation, suggests that the Earth's averaged surface temperature should be -18°C or so (which is just about 0°F).

Needless to say, this is nonsense. Even taking into account the cold polar regions, this is far, far too cold—observations of the Earth's averaged surface temperature tell us that it's more like 14°C (or 59°F—a slightly warm wine-cellar temperature).

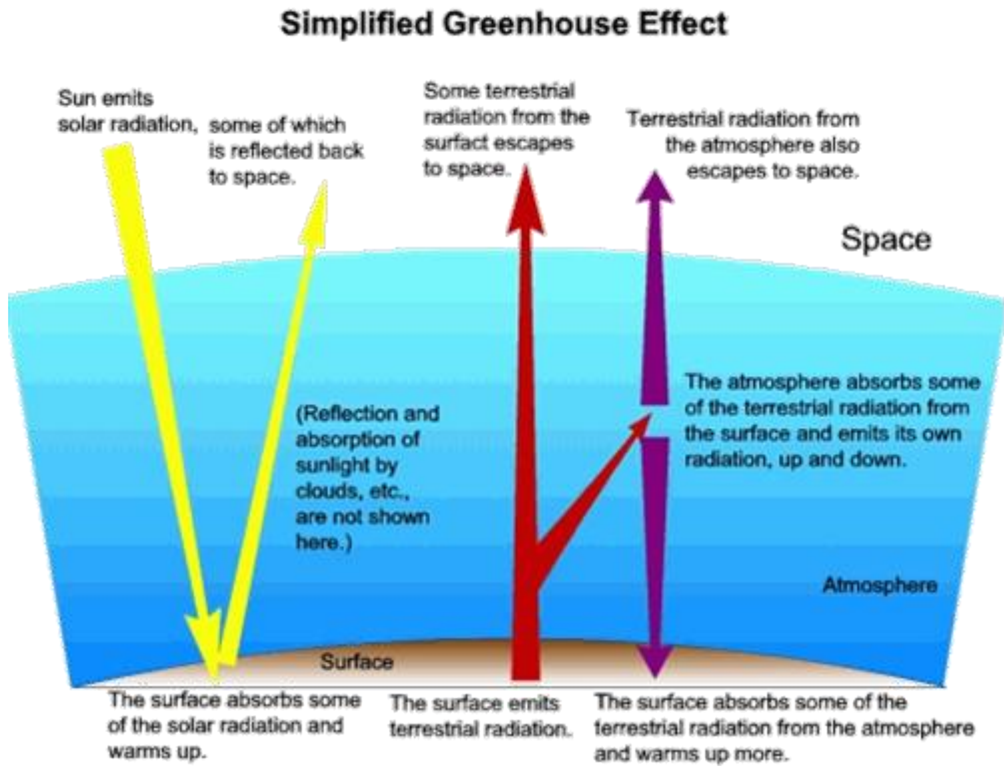

Figure 1: Schematic diagram of Earth's Greenhouse Effect. The downward purple arrow is the additional heating of the Earth's surface by infrared radiation from greenhouse gasses in the atmosphere.

The problem with this simple calculation is that it ignores the Earth's atmosphere. Except for clouds, the atmosphere is almost transparent to solar radiation, but is only semi-transparent to terrestrial radiation. Thus (ignoring clouds for the moment), sunlight passes through the atmosphere and warms the Earth's surface, which radiates its heat away. Some of this heat is absorbed by the atmosphere and some passes through to space (red arrows in Figure 1). The part that's absorbed by the atmosphere heats the atmosphere up, so the atmosphere radiates its own heat away, but in both directions, up and down, as depicted schematically by the purple arrows in Figure 1. So now the Earth's surface is absorbing radiation (that is, it's receiving energy in the form of radiation) from both the Sun and the atmosphere, and it maintains the 14°C averaged surface temperature as a result. This phenomenon—the extra heating of the Earth's surface by the atmosphere—is part of what we call the Greenhouse Effect. It seems obvious that, should there be additional gasses in the atmosphere that absorb more infrared radiation, the whole system will warm up. That is, an enhanced Greenhouse Effect will lead to Global Warming.

Of course, describing the Earth's climate with one "Magic Number"—14°C—misses a lot. Nonetheless, a considerable amount of effort has gone into trying to understand how this "Magic Number" might change with the increase of the strength of the Greenhouse Effect due to increased amounts of CO_2 in the atmosphere. This effort is understood in scientific circles to relate to providing a baseline from which more detailed work can grow. Still, the rate of surface temperature increases due to atmospheric CO_2 increases as estimated over 50 years ago has remained remarkably stable despite significant advances in how it is calculated. Early climate scientists deserve a lot of credit for their work.

Hot equator, cold poles

Perhaps the most obvious feature of Earth's climate that the "Magic Number" approach misses is spatial variations, in particular the substantial difference between the climates of the tropics and the polar regions. The Earth is nearly spherical, and the angle of the incoming sunlight is more oblique in the polar regions (that is, the Sun is lower in the sky—all day long—in the polar regions). So there is less sunlight absorbed in the Arctic and in Antarctica. So it's colder. Because it's colder, there is snow and ice on the ground, which makes the ground whiter than the tropical rain forests, and this tends to reflect sunlight, meaning that even less sunlight is absorbed and it is even colder. The percentage of sunlight reflected, instead of being absorbed by the Earth, is called the albedo. Snow and ice have high albedos, sometimes as high as 75%.

As with this example of snow and ice in the polar regions, the albedo is linked to the climate itself. This is why, in the simple calculation that gave the wrong answer above, we had to use satellite observations of the fraction of absorbed sunlight. To calculate that would require knowing what the climate is doing, and even so it would be extremely complicated. Computer models of climate have become increasingly sophisticated, and complicated, in their attempts to include all of these relevant processes. It is these complicated feedback loops—in this case, cold temperatures making snow, which reflects sunlight, which makes it colder—that make the behavior of the climate both so complex and so interesting to study.

The fact that the tropics absorb much more sunlight than the polar regions, and so are much hotter, leads to another important factor in climate: the winds. In a global sense, the winds are simply nature's way of trying to adjust the temperature to be even. Molecular diffusion (the process that makes the handle of a cast iron skillet hot even though it's not over the flame) isn't fast enough, and so the air starts moving around. Moving air is wind. Of course, once the air starts moving, lots of other factors come into play, such as the Earth's rotation and gravity and the characteristics of the surface (from fields to forests to mountains).

The humidity is also an important part of this, because water vapor in the atmosphere can condense when it's moved around, making clouds. When water condenses, it releases energy in the form of heat, and this can create even more motion—another feedback loop. This is more easily understood if we first discuss a second feature of how the atmosphere varies spatially.

Up

Everyone knows that warm air rises. This is why hot-air balloons fly, why candle flames look the way they do, and why thunderstorms work. But if this is so, why do people drive up to the mountains in the summer to cool off? Well, everyone also knows that the temperature of the atmosphere is lower the higher up you measure it. So what happened to all that rising hot air?

Simply put, it expands and cools off. If you compress air, it heats up, and if you do something to let it expand, it cools off. Pumping up a bicycle tire with a hand pump, and then feeling the base of the pump where the air goes into the tube (or valve) will prove that compression heats. (Yes, there's friction heating, too; but mostly, the hot bicycle pump is because of compressing the air.) And, if you don't mind the extra work, you can prove the expansion cooling part by letting the air out of the tire and feeling how it's cooler than the ambient air—although to really prove this, you need a thermometer, because the expanding air will be moving and that makes it feel cooler, too.

Anyway, the atmospheric pressure is simply the weight of the column of air above where the pressure is being measured. At sea level, a one-inch square column of air weighs a bit less than 15 pounds. The surface pressure decreases with elevation (meaning height of the ground above some reference, usually what's called Global Mean Sea Level). This is because there's less air above where you are the higher up you go. So, as air rises, it expands, and when it expands, it cools off. Near the surface, below bases of clouds, the free atmosphere cools at a rate of about 10°C per kilometer of altitude (or about 5.5°F per thousand feet). Higher up, where clouds are condensing and releasing heat, the cooling rate is only about two-thirds of this. Of course, if you drive up into the mountains, you're not in the free atmosphere—you're stuck to the surface instead—so it doesn't cool off quite this quickly.

Given the region's mountains, elevation is one of the most important factors when considering the climate of the Southwest. Not only does it control the temperature, it is the primary reason there is any water at all.

Water

Find yourself a world map somewhere and trace the latitude (37°N) of the Arizona/Utah and New Mexico/Colorado state lines around the world. Except for the maritime longitudes—the Atlantic and Pacific Oceans, and the Mediterranean Sea—and except for a few areas such as the US east of the Mississippi, the Himalayas of north of India, and Eastern China, this is a pretty dry latitude circle: it includes not only the US Southwest but also the Middle East, Iran, Afghanistan, and the deserts of Tibet. Moreover, the maritime longitudes are quite dry as well: the classification "Mediterranean Climate" describes a mild, dry region (such as Spain), so it is no accident that the Four Corners states are arid.

But the Southwest is not completely arid (officially, it's classified as "semi-arid"). As noted in the previous section, elevation is a strong influence on the Southwest's water resources, because the precipitation—both rainfall and snow—tends to be strongly linked to mountains. This is not only because it's colder up there, but also because when air flows over a mountain, it gets lifted up, cooled, and the water vapor can then condense into clouds and make precipitation. The popular explanation for this is that warmer air can "hold" more water vapor than cooler air. This is not a precise description of the phenomenon, let alone an explanation of it, but it is sufficient for our purposes here.

(This makes two popular descriptions of processes in atmospheric science that are misnomers. The "Greenhouse Effect" really isn't; and warm air does not "hold" more water vapor than cool air. I can't fix this stuff, but I'll try to be honest about it.)

Water, in its three phases, plays a variety of roles in the climate. As noted above, snow and ice (the solid phase) affect the amount of sunlight the Earth absorbs. The vapor phase functions to redistribute water from its origins in surface evaporation, especially from the ocean surface, across the planet. When water vapor condenses, it releases the heat that caused it to evaporate in the first place and affects the atmospheric circulation and, as rain and snow, provides liquid water resources for life itself. This complex behavior makes water by far the most important substance in the climate system, and the fact that it is essential for life emphasizes this importance.

Another role played by water vapor is another complicated feedback process in the climate system. Like CO_2, water vapor contributes to Earth's Greenhouse Effect. As a natural greenhouse gas, water vapor in the atmosphere will change as the climate changes, in all probability. If atmospheric water vapor increases as the climate warms up, it will cause the climate to warm up even more.

And clouds are water, in liquid drops and ice crystals. Clouds have their own Greenhouse Effect; and, like snow on the ground, they also reflect sunlight. Because of these competing effects on climate, they deserve their nickname as the “wild cards” of the climate system.

With this background, it’s possible to illustrate some aspects of the Four Corners Climate with examples.

Regional Climate: The Four Corners

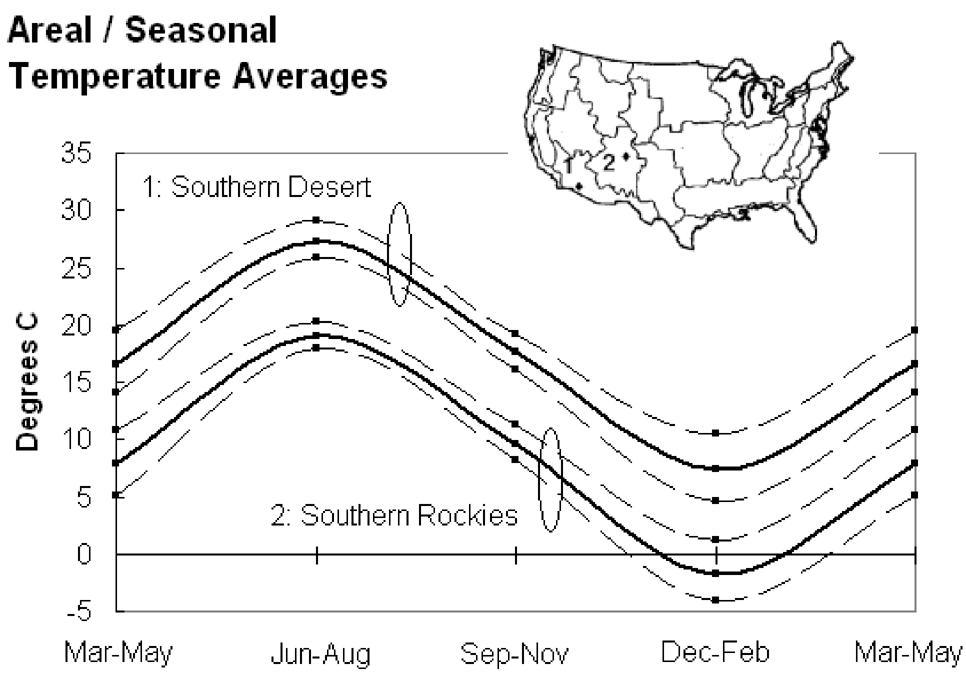

Figure 2: Temperature averages for over 85 years for two sub-regions in the Southwest.

Desert and mountains

The equator-to-pole spatial variations discussed in above still do not describe Earth's climate very well, because they say nothing about the seasons. Just as climate variations in space are relevant to the Southwest, so are changes in time. These are most easily described with graphs, in which time runs from left-to-right and the climatic quantity that's under discussion runs up and down. Figure 2 is an example of such a time-series plot. This graph shows temperatures averaged over two sub-regions of the Southwest; these sub-regions are shown on the inset map. The Southern Rocky Mountain sub-region, which includes the mountains of Colorado, Southern Wyoming, Northern New Mexico, and Utah, is representative, in a general way, of the higher elevation parts of the Southwest. The Southern Desert sub-region, which includes southern New Mexico, much of Arizona, and the Mojave Desert in California east of the coastal range, represents the lower elevations. Each set of temperatures on Figure 2 shows the averaged high and low temperatures (dashed) and the average of those two (solid) in each sub-region for the four seasons shown on the horizontal axis at the bottom. The temperatures are shown in degrees Celsius; for reference, 0°C is freezing and 25°C is 77°F. The temperature differences between the two sub-regions illustrate the range of climate over the Southwest. An easy way to think of these variations is to note that summer in the mountains is about the same temperature as spring and fall in the desert; and winter in the desert is about the same as spring and fall in the mountains. Note also that the range of extremes—the spread between the dashed curves—is largest in winter and spring. This reflects the weather systems that bring snow to parts of the Southwest in these seasons.

Temperature Extremes

The sub-region/seasonal averages in Figure 2 smooth out the temperature variations considerably, because the temperatures over these large areas are averaged together and the years from 1901-1986 are averaged together. One way to examine the spatial variations in greater detail is to look at temperatures from two locations. An example of this is shown in Figure 3. The two time-series plots shown give temperatures averaged over a number of years for Yuma, Arizona (top), and Gunnison, Colorado. These two cities were chosen as extreme representatives of the two sub-regions in Figure 2; their locations are noted with dots on the map inset in Figure 2. Although Gunnison is farther north, that is, farther from the equator, than Yuma, the climatic differences are due more to its higher elevation than to the north-south distance.

The plot for each city has five temperature time series on it. The middle one is the averaged temperature for each day of the year; that is, the January 1st temperature in the middle plot is the average temperature for all the January firsts averaged together. The two plots just above and below this average temperature are the averaged high and low temperatures for the date in question. The two outside plots are the extreme high and low temperatures for the date; that is, these are the "record" temperatures for the date. The years included in these averages are noted; they represent all of the data available in the Historical Climate Data Set used for these plots.

Between these two graphs and among all the plots on them, there is a lot of information in Figure 3. Some things are pretty obvious: it's considerably hotter in Yuma than in Gunnison, year 'round; the winters in Gunnison can get pretty rough—the record low temperature looks to be somewhere around -45°C (almost 50° below zero Fahrenheit!). And summer in Yuma is no picnic, with record highs over

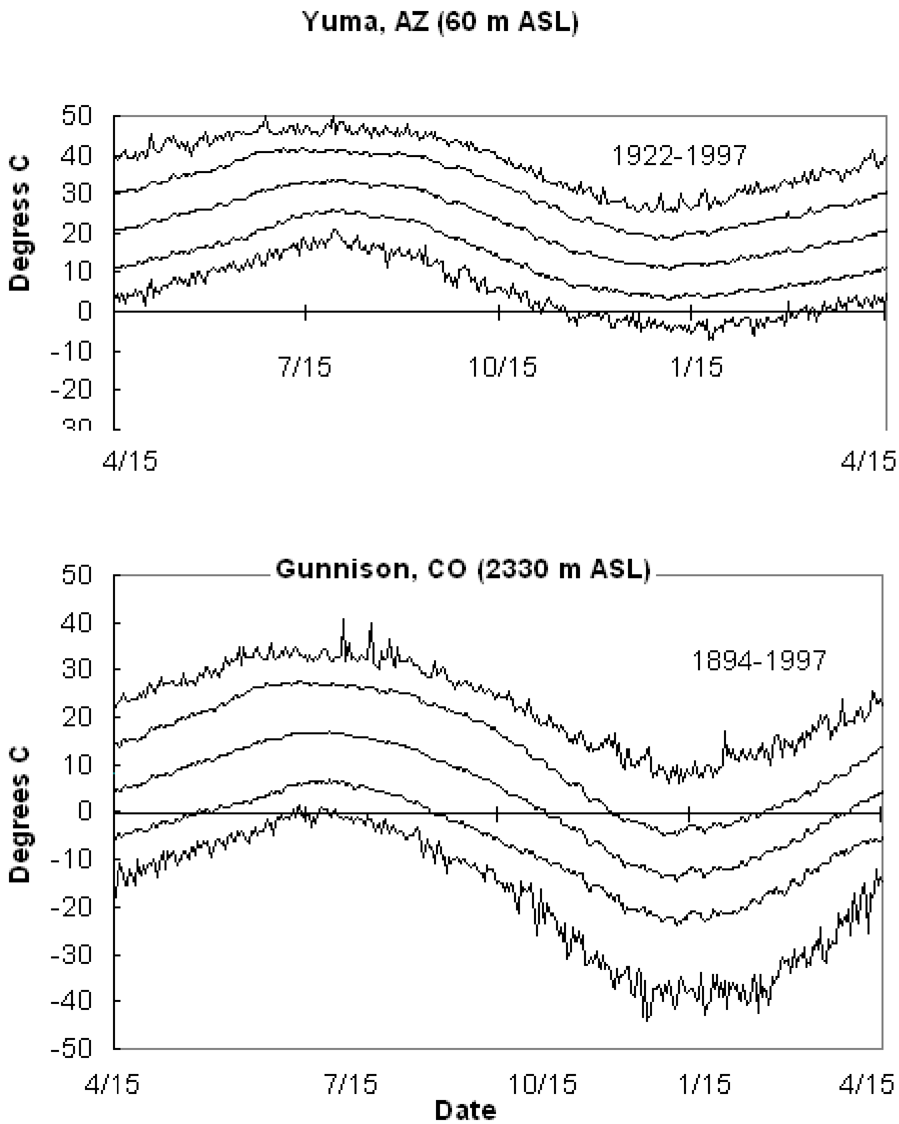

Figure 3: Yuma, AZ and Gunnison.CO averaged temperatures including extreme.

100°F (about 38°C) for over four months of the year. On average, each city has an *annual cycle*—that is, the summer-winter change in average temperature—of about 20-25°C (or as much as 45°F). The daily temperature range, which, on average, is the difference between the average high temperature and the average low temperature, is nearly this large.

What about Global Warming? To assess the effect of Global Warming on the temperatures in the Southwest, we need to turn to the most sophisticated climate models. The calculation discussed above in which we (erroneously) found the Earth's average temperature to be 0°F represented the use of an extremely simple climate model. Of course, the best climate models in use today are far, far more complicated, and accurate, than this one was. Even though they aren't perfect, they do quite a good job of calculating Earth's present climate. They also include as many of the climatic feedback loops as scientists can figure out ways to include, such as the one about cold temperatures, snow, and the reflection of sunlight noted above, as well as feedbacks involving the oceans, cloud processes, and on and on.

If you set up one of these models to calculate what the temperature changes in the Southwest will be as the CO_2 in the atmosphere increases, you find that the temperatures tend to warm up. By the end of the this century, the models suggest that the temperature increases could be as much as 4°C (assuming that the CO_2 content of the atmosphere continues to rise, and that nothing strange—such as an increase in the number of volcanic eruptions—happens). The models also suggest that the wintertime temperatures could rise more than the summertime temperatures (much to the relief of people in both Yuma and Gunnison, one might imagine). This means that the plots in Figure 2 or 3 would not simply slide upward in a uniform way—their shapes would change somewhat as well.

Now, compared to the annual and daily ranges of some 20°C, 4°C (just over 7°F) isn't a huge temperature change by any means. Further, different climate models give different answers, some suggesting hardly any average change at all. However, there is more to consider than simply this comparison. First, changing the shapes of the curves in Figure 3 could change such things as the length of the growing season. This would affect both agriculture and the sustainability of natural ecosystems. Second, the strength of extreme events could be affected. That is, a small increase in average summer temperature could translate into new record high temperatures on some days. The two 50°C (over 120°F!) record highs in Yuma could become relatively commonplace. This would affect both the type of ecosystems that could survive as well as people's health. Consequently, even small average changes are reason to study the problem more.

Temperature, of course, is only part of the story. In the Southwest water is always a concern as well.

Precipitation

It has already been noted that the Southwest is a semi-arid region, and this is reflected in the precipitation records at the two cities. Figure 4 shows the daily precipitation averages over the period of record (left column of panels) and the extreme precipitation events (right column) for Yuma and Gunnison. The bottom row shows the contribution of snowfall to the Gunnison precipitation (there is no snow in the precipitation record for Yuma, at least in this dataset).

In the daily averages (left column of panels), the heavy lines show 31-day running averages, included here to smooth out the day-to-day variations. These represent "monthly" averages, at least for the 15th of each month. That is, the first point at the left ends of the heavy lines is the monthly average for April.

As with the temperature records in Figure 3, these precipitation time-series plots contain a large amount of information. One thing that is obvious is that neither of these cities receives very much in the way of water—there are 25.4 millimeters in an inch, and so the daily averaged precipitation in both

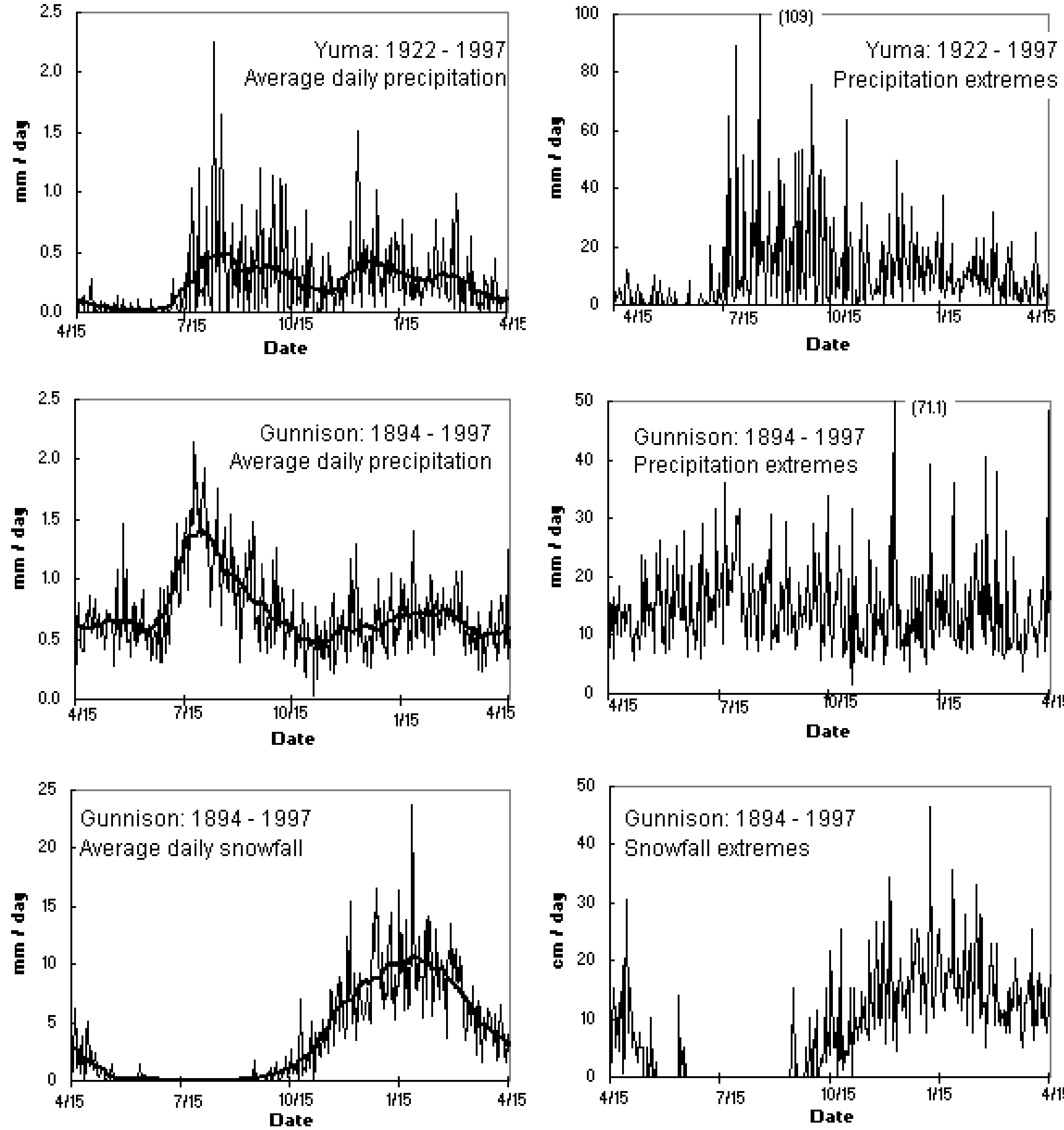

Figure 4: Precipitation records for Yuma and Gunnison.

locations is always well below a tenth of an inch per day. Several other points are worth emphasizing here.

- The records for both cities exhibit two peaks in the annual precipitation, a several-month period of enhanced precipitation from about July to October and another from about October to April. These peaks are most obvious in the smoothed data (heavy lines). In the Southwest generally, these two peaks can be called the summer "rainy season" associated with the Southwest

Monsoon, and the winter rainy season, associated with storms coming off the Pacific Ocean. The Southwest Monsoon is an extremely important climatological feature of the region that provides badly needed summertime rainfall, particularly in the southern deserts. Even though there is significant snowfall in Gunnison, the summer rainy season provides more water to the region: note the higher summertime peak.

- Although there is no snow in Yuma, there is still the secondary rainy season due to winter storms. In Gunnison, the secondary enhanced period of precipitation in the winter and spring is due to snowfall. This is true generally in the mountains of the Southwest (for example, the area of sub-region 1 in Figure 2 above), and the spring runoff from the melting snowpack is also quite important to the Southwest's water resources. Not only is the amount of water important, but the delay associated with the snowfall's remaining on the ground for weeks to months exerts a strong influence on water resources. The changing climate's effect on this delay is important to the future of the Southwest.
- The day-to-day variations in the daily averages, combined with the scale changes from the left column to the right in Figure 4, suggest that extreme precipitation events play a strong role in the averaged rainfall. For example, consider the extreme event of 109 mm (over 4 inches—no doubt from a large thunderstorm) at Yuma on about August 1. If it never rained on any of the other August firsts (or whatever date this is) in the 76-year record, the daily average for this date would be 1.4 mm/day. It appears that most of the "daily averaged" precipitation for this day of the year may be due to this one event.
- Although this particular event is the most extreme of the entire 76-year record, other large rainfall events at Yuma are also evident in the upper right-hand panel of Figure 4. Undoubtedly, much of the "daily averaged" precipitation for Yuma shown in the upper left-hand panel is associated with these large events. The same is likely true for Gunnison as well.

The point here is that extreme precipitation events, like record high and low temperatures, will be affected by climate change, but we do not yet know how. Will there be more 4-inch thunderstorm events in Yuma? How will the Southwest Monsoon—which is just lots of thunderstorms day after day for several months—be affected by global warming? Will there be less or more snow in the mountains? And when will it melt?

Answering these questions is the focus of ongoing scientific research, and this work is critical to the future of the Four Corners region.

Four Corners Water (and Lack Thereof)

Almost everything environmental in the Southwest concerns water in some way. Whether it is the availability of water or its quality, no single issue captures as much attention in regional environmental circles. And to say that water is a political issue understates the situation as much as saying that summers in the southwestern deserts are warm.

The cliché is that, in Colorado, "Water flows uphill toward money," and this applies to the other Four Corners states as well. One basis for this cynicism is the extraordinarily complex system of water law in the various states, a topic far too difficult to tackle here.

However, one generality that is common to the various political jurisdictions of the region is the notion of water rights, and the principle of seniority, a concept based in the precept “first in use, first in right.” Basically, this means that people who laid claim to water resources first have the most senior right of use. In most jurisdictions, there is an additional requirement that right of use be exercised in a “beneficial” manner. It is the legal interpretation of “beneficial” that is controversial. In addition, the question of Native American water rights (they were here first, after all) complicates water law even further.

Because of this complexity, and because of the scarcity of water, the challenge of water resources is the one that overwhelms all other environmental challenges facing the Four Corners states.

The problems posed in meeting this challenge depend on your point of view. First and foremost is the fact that this is a semi-arid region, so there is simply not enough water to do everything that we want to do. Our society’s aspirations depend on abundant fresh water supplies, and the scarcity of water thwarts those aspirations and challenges our management of water resources. Of course, it may be argued that we need to adapt our aspirations to match the available resources. But this approach, as sensible as it may sound, merely presents a different set of problems to be solved.

Historically, water has always been a challenge for human society in this region. The early development of irrigation systems—New Mexico’s traditional acequias—allowed agriculture to flourish by bringing mountain water to the lowland desert where it was needed. Reservoirs, long before the Bureau of Reclamation’s mega-projects, were built to retain runoff from summertime thunderstorms and from springtime snowmelt. And early societies adapted to the regional conditions by treating water as a precious resource not to be wasted.

With the development of water projects on vast scales—the two river basins of the southwest are now essentially elaborate plumbing systems, controlled from headwaters to the oceans—society has developed a slightly different view of water resources. Golf courses in the desert, open-air fountains, warm-water lakes, and large-scale flood irrigation techniques are all profligate in their usage of water. In particular, they all lead to huge amounts of waste, in the form of evaporation. Water that could be put to another use simply wafts away in the atmosphere.

It is not possible here to present a comprehensive overview of water resources in the southwest. Entire books, including technical textbooks and more popular narratives such as Marc Reisner’s *Cadillac Desert: The American West and Its Disappearing Water* [1993, Penguin USA, ISBN: 0140178244, 528 pp.] are devoted to the topic. Some of the background material for the discussion here is included on other pages (e.g., the regional overview).

This commentary is concerned with two topics, the water cycle of the Four Corners region and how our society has chosen to allocate water resources.

The Water Cycle

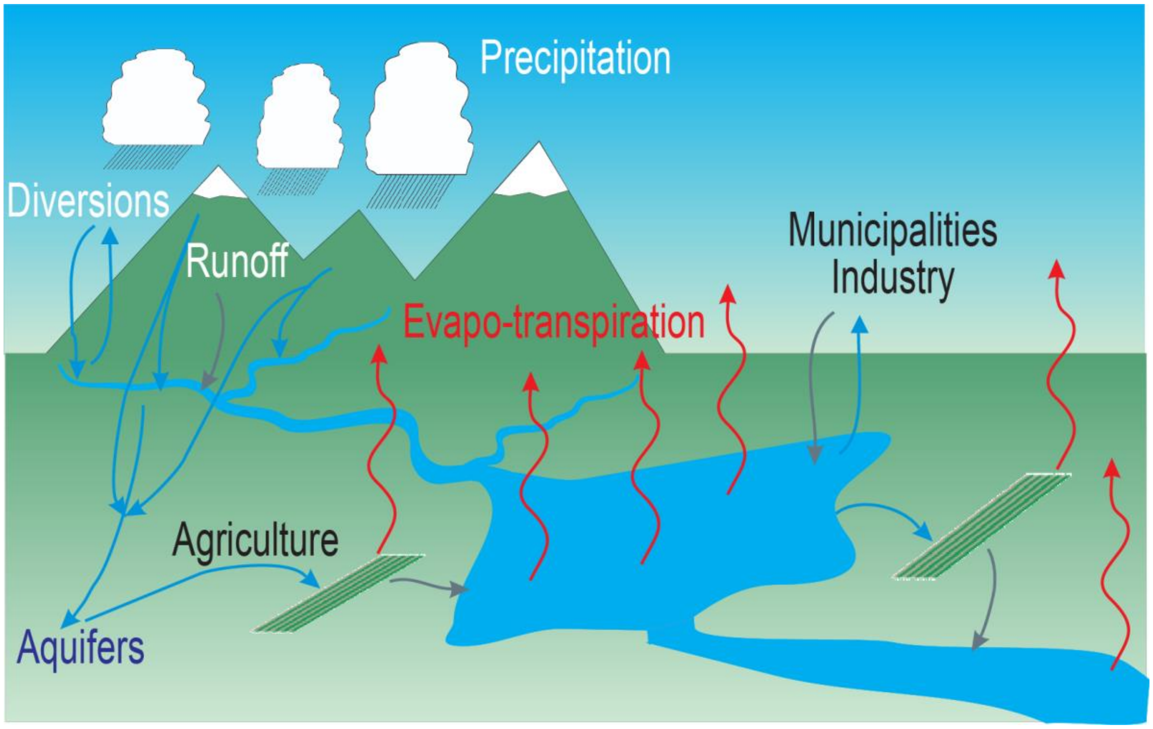

Figure 5. Schematic diagram of the water cycle.

In a discussion of water, political boundaries become arbitrary. A more useful approach is to consider the water cycle within river basins. This was recognized more than a century ago by John Wesley Powell. In the Southwest, the Colorado River and the Rio Grande basins are of primary interest.

Figure 5 shows a schematic representation of the water cycle. All of the water that is naturally available in a basin falls as precipitation; for the two southwest river systems, this occurs as mountain snow in the winter and, in the desert, as rainfall during the winter and during the summer monsoon season.

The water on the ground, whether liquid or solid, either stays put (creating a lake), runs off, soaks in, or evaporates. (Snow can sublime—that is, turn directly to water vapor—but it has to melt before the water can soak in or run off.) The runoff eventually collects in rivers; along the way, some of it also soaks in or evaporates. And evaporation is also complex, because water that soaks into the soil can be taken up by plants and then transpired, which augments surface evaporation. The net result of plant transpiration and surface evaporation is called evapo-transpiration. Finally, the water that soaks in can flow underground and either re-surface (in a spring) or contribute to aquifer recharge.

In Figure 5, there are several places where society enters the picture. The first of these, the "diversions" on the left, represents inter-basin water transfers, part of the plumbing system referred to above. For example, the Rio Grande system receives water from the Colorado system via the San Juan-

Chama diversion; and the Colorado system also contributes water to the Platte system to serve the cities of the Colorado Front Range. (Note that both of these water transfers move water across the Continental Divide.) Other societal usage in Figure 1 removes water from the system and returns (some of) it; this represents agricultural, municipal, and industrial water usage.

With a conceptual diagram such as Figure 5, it is possible to quantify the behavior of the water cycle in a basin given precipitation amounts and other parameters affecting the movement of water through the river system. Parts of the problem, particularly representing the surface and sub-surface process, are highly complicated, but scientists are making progress on computer simulations of the water cycle.

Allocations

As noted above, water law is a topic far too arcane and complex to even attempt to understand unless that's what you do for a living. To complicate matters further, the Four Corners states of Colorado, New Mexico, Arizona, and Utah have different laws concerning water. There are, however, two common principles, seniority of rights and the requirement of beneficial use discussed previously. Traditionally, beneficial use has been associated with agriculture (or ranching), municipalities, or businesses. Consequently, it is not possible to establish water rights for the purpose of just letting the river flow. This has become controversial in recent years, because it is increasingly recognized that the riverine ecosystem, and the riparian community along it, need a certain amount of water to survive. The existence of endangered species within these communities has brought this controversy to the public's attention.

With increasing numbers of people coming to appreciate the benefits of the rural environment, appreciation of rivers and streams is on the increase. This means that the definition of "beneficial use" is evolving. Maintaining minimum stream flow sufficient to support a trout population, for example, is becoming part of the definition. Such changes will allow special interest groups to purchase and use senior rights for purposes other than traditional agricultural or industrial water needs.

Water Resources: Quantity and Quality

To the extent that water is scarce, it is valuable. Providing enough water to meet society's demands means some combination of finding more or making the best use of what we have. The second of these implies that we should work hard to avoid wasting water.

The schematic diagram of the water cycle in Figure 5 suggests that the main "waste" of water is due to evapo-transpiration. Other pathways provide water for use either locally or downstream (after the societal uses return it to the river, for example), or by pumping aquifers. Therefore, minimizing evapo-transpiration is a way to conserve water resources. Drip irrigation, rather than sprinklers, is one way to do this.

Finally, it is worth emphasizing that water quantity is only half the story. Water *quality* is the other half. Some indications of water quality issues are included in Figure 5. Generally these issues are associated with societal use or with historical problems such as mine tailings. For example, the Alamosa River in southern Colorado and the Red River of northern New Mexico are both contaminated with heavy metals from nearby mining activities. Agriculture is also problematic, because the water returned to the river after irrigation can be highly saline. This is a problem especially in the lower reaches of the Colorado River.

Certain Uncertainty

Understanding climate and climate change is an endeavor that has consumed the entire careers of a large number of scientists (including me), and there are still unanswered questions. Some of these questions will be answered as more and more people become climate scientists and study them. Others may never be answered.

But perhaps the most difficult concept to grasp is that some climate- and weather-related questions are simply impossible to answer with certainty. Here's one: *Will it be raining at noon at my house on this day a year from now?*

Now, depending on where your house is, it may be possible to give a pretty good answer. If you live in the Sahara Desert, an answer of "no" is probably going to be right. And if you live in Indonesia, and "now" is the rainy season, "yes" is a pretty good answer. But these are just the easy cases, and they use climatology for their answers. That is, we know from the behavior of the climate that it doesn't rain in the Sahara Desert and that it does in Indonesia in the rainy season. What this implies is that answers based on climatology have some probability of being right. In these two examples, the probability of no rain in the Sahara Desert a year from now is probably 99% or better. And the probability of rain in Indonesia (assuming that a year from now is the rainy season) is probably 90% or better. But at noon? Well, maybe the Indonesia probability goes down to 75% or maybe as low as 50%.

What this says is that there is uncertainty in the answer to this question. And, in these examples, the uncertainty is due to the fact that we're using the climate as our guide.

There are other possible guides as well. For example, if we're asking about rain tomorrow, we could use a weather forecast for guidance. Weather forecasts (at least 24-hour ones) don't use climatology; instead, they use computer models. A computer model of the weather takes the physical principles that govern how the atmosphere works (such as Newton's Laws), puts them in a form that a computer can solve, and uses the weather now to forecast the weather at some time in the future. And these weather models are actually pretty good—much better than climatology, for tomorrow's weather.

So, with the guidance of a computer-generated weather forecast, we might find out that there is a 50% probability, or maybe higher or lower, of rain at noon at your house tomorrow. What this means is the following: If this particular forecast (the 50% probability forecast) is made 100 times, the forecast is correct if it rains 50 of those times. If we knew in advance which 50 times it was for sure going to rain, we would be able to make 100% probability forecasts on those times and 0% probability forecast on the other ones.

Now, this doesn't sound like we know much about forecasting. However, forecasts like this aren't made for particular locations (like your house) or for precise times (like noon). They're made for larger areas (such as your town) and for time periods (such as "early afternoon"). Still, the probability of rain is often forecast as 50%, and this simply speaks to how hard this is to do.

So far, we've discussed climatological forecasts and computer-generated weather forecasts. There is another way to do weather forecasting, called persistence. A persistence forecast says, quite simply, that the weather is going to be doing what it's doing right now. Needless to say, if you want to forecast the weather 10 seconds from now, or even 10 minutes from now, persistence is a good way to do it. This is because the weather generally takes longer than this to change. (Not always, of course. How about 5 minutes before sunset?)

So what forecasting method is best? It depends on the time of year and where you are, but, in general, persistence works well for very short-term forecasts, computers work well for the 1-10 day forecasts (although 6-10 days can be a real stretch), and, after that, a climatological forecast is about the best that can be done, except for special things.

What if you use a computer weather forecasting model to try to find out if it's going to rain at your house on this day next year? This goes back to the issue of questions that are impossible to answer. Naturally, if you turn the computer on and let it find an answer, it will give you one. But, even though it is an official computer forecast with pretty pictures and everything else, it won't mean anything. And this gets to the heart of uncertainty.

If you live near a little stream, there's an experiment you can do. If you don't, you can just think about this and probably understand it anyway.

Find a section of the stream that's straight but that has some rocks in it that make the water swirl around. Now, find a stick and break it into little pieces, maybe 1/2" long. Carefully drop a piece of stick exactly behind one of the rocks and watch where it goes. After it's downstream, do it again with another piece of stick, and make sure you drop it as close as you can to where you dropped the first one. Chances are that this second piece doesn't go exactly where the first one went. And, if you keep putting sticks at exactly the same place, you are likely to see lots and lots of different paths that the pieces take as they float downstream.

It shouldn't surprise you to see that these different paths get more and more different the farther downstream the sticks get, and as the stream gets faster, with more rocks and more swirls.

Now, the stream is a fluid, and the swirls are turbulence, so this system is what scientists call a turbulent fluid. And it is a fundamental property of turbulent fluids that they are not completely predictable. As time passes—the farther in the future the prediction is—the less and less predictable they become.

The atmosphere and the oceans are also turbulent fluids, and so they are also not completely predictable. This is why the computer model can't give a meaningful answer to the question of whether it's going to rain at your house on this day next year. And this is why weather forecasts will always be uncertain.

But what about climate forecasts? The climatological forecasting technique mentioned above works (pretty well) for the climate we have now, if you do it with probabilities. But what if the climate changes?

First, it's important to understand that climate models are based on weather forecasting models, but they're more complex because they need to include the oceans and other parts of the Earth system that are relevant to climate. And, if the climate model is any good, it will predict the climate, both the present climate and changed ones. It can't predict specific weather events (like rain at your house), but it can predict the overall behavior of the climate and its statistics.

But not, however, with complete certainty. Quantifying uncertainty—that is, putting numbers to it in a meaningful way—in climate forecasts is one of the big challenges facing climate scientists today.

Ecosystems and Biodiversity

The atmosphere and oceans behave according to well-established scientific principles, such as Newton's Laws and the Laws of Thermodynamics, yet certainty in predictions is not possible. Because a full set of analogous "laws" has yet to be fully understood, or even described, in ecological systems, the uncertainty involved with predicting the future of those systems when they are subject to changes in what drives them is huge. Yet, because climate is one strong driver of those systems, and because climate is changing, such uncertain predictions are unavoidable. And because other factors than climate are also affecting ecosystems' behavior and because human society depends on this behavior for its very existence, improving such predictions is a high priority. One aspect of this concerns biodiversity.

The term "biodiversity," which biologist and author E.O. Wilson coined as a contraction of "biological diversity," has come to be a sort of mantra for environmentalists. It is tossed about freely whenever there appears a threat on someone's environmental horizon, often without concern for its real meaning or importance. Like using garlic to ward off vampires, using "biodiversity" to ward off developers is the tactic of choice these days.

This tactic is unfortunate, because it desensitizes both the public and the policy-makers to how critical biodiversity is to our society and, indeed, to our planet itself. The discussion here presents a very brief overview of biodiversity, with emphasis on its relevance to the US Southwest, and how it dovetails with other topics discussed on these pages. Though a bit dated, a useful reference for this discussion is *Biodiversity: Connecting with the Tapestry of Life*, which is available online.

Biodiversity in its most comprehensive sense describes simply the wide variety of life on Earth. Scientists always work hard to develop precision, however, and so this comprehensive definition has been refined by breaking it into three levels. While these levels are tightly interlinked, they provide a clearer context for the discussion.

Ecosystem biodiversity refers to the variety of ecosystems on our planet. Although the precise definition of "ecosystem" is not entirely clear, it is obvious that tropical rain forests differ from deserts; that coral reefs differ from the arctic tundra. Each of these ecosystems—and it is equally important to emphasize that there is variety in an individual category, e.g., not all deserts are alike—includes its own unique variety of plant and animal species and interactions among them.

Species biodiversity, then, is the next level of diversity, because it occurs within an ecosystem. (Animals or plants are said to belong to the same species if they can reproduce with each other.) The interactions among the various species in an ecosystem, combined with the climatological and geological characteristics of the geographic area, determine the characteristics of that ecosystem.

Finally, within species, there is *genetic* biodiversity. Of course, this exists across species as well, which is the reason for species diversity. But the genetic diversity within an individual species is critical to the long-term health of that species. This is well-known to zoo-keepers concerned with the long-term survival of endangered species such as the snow leopard. It is genetic diversity that helps a species to adapt to a changing environment.

Each level of biodiversity plays a critical role in the next level up. Within species, genetic diversity is critical to the long-term health of that species. Within ecosystems, species diversity is critical to the viability of that ecosystem, especially as its climatological and geological conditions evolve. And, for our planet, the diversity of ecosystems fills every niche that offers nutrients for life to exist, from the hot ocean-floor vents to the arctic sea-ice and from the bottom of Death Valley to the rocks atop the Himalaya Mountains.

Here in the Four Corners region, biodiversity is every bit as important as it is anywhere else, if more subtle. Desert ecosystems, because of their harsh conditions and relatively low availability of nutrients, support fewer species than do, say, tropical rainforests. But each species within a desert ecosystem has an important role to play in its overall maintenance. For example, butterflies and moths are critical to pollinating the cacti, and the cacti provide food for these (and other) insects as well as shelter for birds. The birds eat the insects, keeping their numbers in check so they don't decimate the plants.

Biodiversity is also an important component of the overall health of forest ecosystems. This is brought into sharp relief when considering wildfires. In historical times, before fire suppression, the occasional low-intensity ground fire in ponderosa forests would clear underbrush, resulting in a forest consisting of large, widely spaced trees with grasses and fast-growing woody shrubs in between. The variety of food sources supported a variety of animal species. In contrast, the pine forests of today are almost monocultures consisting of far too many closely spaced small trees that shade the ground and prevent any significant growth of grasses or other ground plants. This eliminates the food source for insects and mice, etc., that would otherwise live there, creating a monoculture of stunted pines with very little animal life.

Professor Wilson called biodiversity "the very stuff of life." To the extent that life is important, biodiversity is fundamental to its existence. Why is life important? Well, I, for one, like to eat, and rocks just don't do it for me. We need lichens to break the rocks down into dirt, microbes and fungi to process the dirt into soil, plants to grow in it, and animals to eat the plants. Then we can think about dinner. And it is the diversity of life—biodiversity—that makes dinner interesting and healthful.

Conclusion

Although the implications of the discussion above point toward a clear answer, the question "Is global warming happening?" was nowhere addressed directly.

Often, this question is personalized, as in "Do you believe in global warming?" In my view, asking the question that way makes it ill-posed from a scientific perspective. It may be the case that there are people who think of climate as some sort of religion that requires faith—which is what "belief" is about, after all—but that's not how science works.

From a scientific perspective, it's not a matter of belief, but rather of the weight of the evidence. So the question becomes: "Does the evidence support the hypothesis that global warming is happening, and, if so, with what level of certainty?"

Suppose we create a scale of probability for uncertainty (0-50%) and certainty (50-100%), in which 0% is utterly uncertain, 100% is fully certain, and 50% is a toss-up.

When I first wrote this primer around the turn of the century, my answer to this more well-posed version of the question would have been “Yes, with a fair level of certainty, say 75%.” Now, after two more decades of intensive research by, literally, thousands of scientists, that answer has become “Yes, with very high certainty, better than 99%. It’s happening for sure.” (How much warming there will be beyond what has already occurred will depend on humanity’s future greenhouse emissions, however, and those are highly uncertain.)

More than a half-century ago, an early climate modeling study published in one of the more carefully peer-reviewed scientific journals—indeed, the leading atmospheric science journal of then and now—made two predictions: that a doubling of atmospheric CO_2 would eventually raise the Earth’s surface temperature by about 2.5°C, and that, associated with this surface temperature increase, the upper atmospheric temperature would decrease. (This turns out to be a fundamental consequence of an enhanced Greenhouse Effect.) A few years after that, two other papers, presenting results from completely different models, predicted that higher atmospheric CO_2 levels would heat the polar regions more quickly than the equatorial regions, due largely to the positive feedback effect of snow and ice (polar regions warm, snow melts and the surface is less white so more sunlight is absorbed, and it warms up more, more snow melts...).

The temperature increase, in the early model, was an equilibrium value—with no oceans or other slow climate-system components, the time scale for the change was not a part of that study. But in the decades since, direct measurements have shown that both the atmospheric CO_2 and the global temperature have increased in a fashion consistent with this result, given the existence of those slow components in the real world. And, meanwhile, the temperature measurements have also shown that the upper atmosphere has cooled and that the polar regions are warming faster than the equatorial regions. Predictions made five decades ago are being verified, and ever more strongly verified as time goes on.

Further, these are only three of many such correct predictions made about global warming over the past several decades. Still, fine-tuning our understanding of the effects of global warming on specific regions is yet a work in progress, and translating that into the future of the ecosystems of those regions is in its infancy.