The "Shape of Things to Come" for California's Climate and Agriculture

Benjamin Santer

Human-caused climate change is not some future hypothetical event, affecting only remote islands and Arctic villages. It is happening here and now, in our own state. The impacts of 21st-century climate change will be experienced by all Californians and are likely to be pervasive, affecting every sector of California's economy.

Human activities have changed the chemical composition of the atmosphere. Since the Industrial Revolution, atmospheric levels of carbon dioxide (CO_2), a potent heat-trapping greenhouse gas, increased by about 40%. Measurements of lighter and heavier isotopes of carbon reveal that at least three-quarters of this increase is due to human-caused burning of fossil fuels. According to the latest national and international scientific assessments (see "Further Reading"), the rise in atmospheric CO_2 levels has been the dominant cause of the 20th-century warming of the Earth's surface.

CO_2 and carbon isotope measurements are hard scientific facts—as is the link between increasing CO_2 and surface warming. Few climate scientists dispute these basic facts. While there is scientific discussion regarding the amount of warming caused by the 40% increase in CO_2, the existence of a human-caused warming signal is not the subject of serious scientific debate.

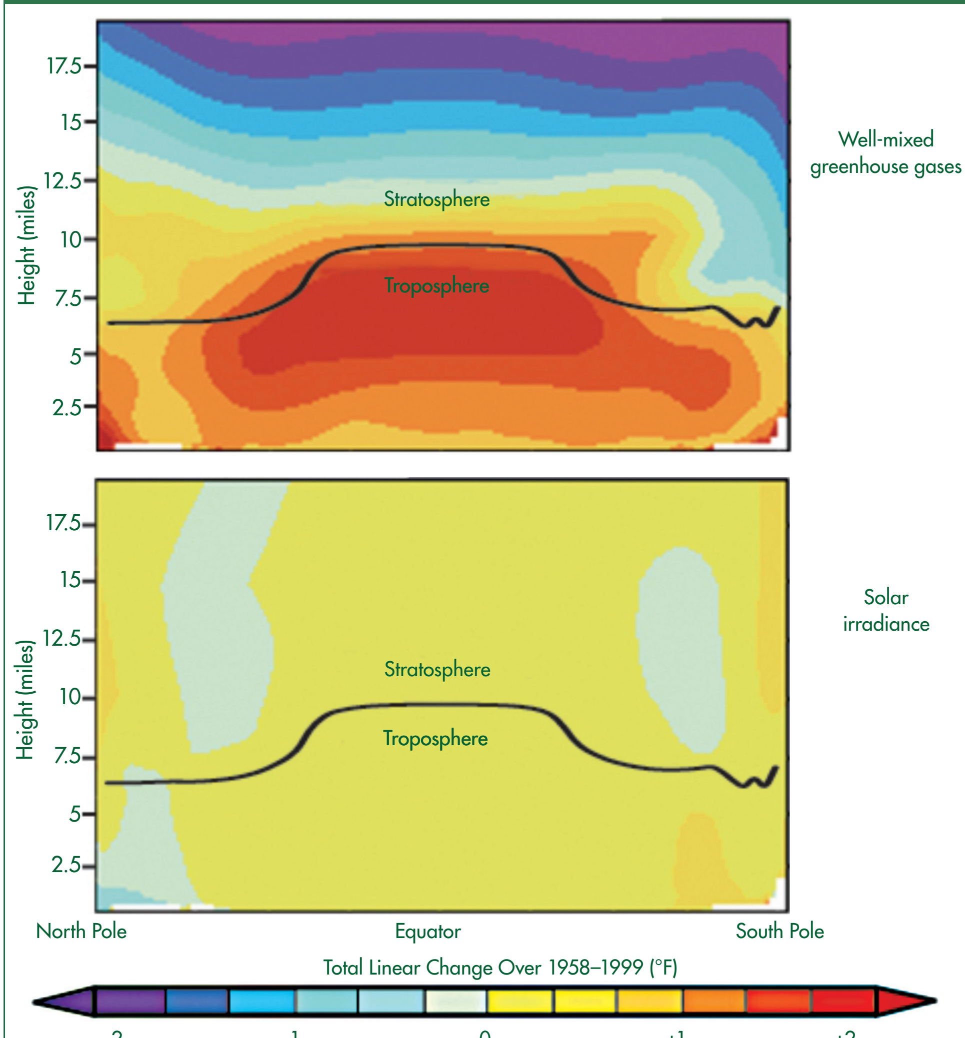
Climate Fingerprinting

The scientific search for this warming signal began in the late 1970s, with the publication of a paper by Klaus Hasselmann describing a statistical method for "fingerprinting" the climate system. Just as no two humans have identical fingerprints, so no two influences on the climate system have identical signatures in climate records. Unique identifiers of different causal factors become much more obvious when scientists probe beyond a single number—such as the global-average temperature of the Earth's surface—and look instead at complex *patterns* of climate change.

The insights that can be gained from studying climate change patterns are clear from Figure 1, which shows trends in atmospheric temperature over 1958 to 1999. Results are from two different simulations performed with a computer model of the climate system. In the first simulation, the model was driven by historical changes in greenhouse gas concentrations (upper panel). The second simulation used estimated 20th-century changes in the Sun's energy output (lower panel). The temperature trends from each simulation were averaged along bands of latitude, and then plotted at 17 different levels in the atmosphere, from close to the Earth's surface to an altitude of nearly 20 miles.

The greenhouse gas fingerprint in Figure 1 (upper panel) has a distinctive pattern of warming of the lower atmosphere and cooling of the upper atmosphere. A similar pattern of "warming

Figure 1. Different Factors That Influence Climate Have Different "Fingerprints"



Source: Modified from Global Climate Change Impacts in the United States, Karl et al., 2006 down low, cooling up high" is found in temperature observations made from satellites and weather balloons. In sharp contrast, the solar fingerprint warms through the full vertical extent of the atmosphere (lower panel of Figure 1) and does not look like the actual observations. The best explanation of the observed temperature changes requires a substantial contribution from human influences (see the 2013 Santer *et al*. paper in "Further Reading").

Fingerprint research was influential in shaping the bottom-line finding of the IPCC's Second Assessment Report in 1995: "the balance of evidence *suggests* a discernible human influence on global climate." This cautious but historic sentence generated strong reactions. One line of criticism was that the fingerprint research contributing to the "discernible human influence" finding relied heavily on studies of surface temperature change. Critics argued that if there really were a human-caused climate signal in observations, it should be identifiable in the oceans, atmosphere, water cycle, and in snow and ice—not just in surface temperature.

Researchers in the relatively new field of climate change detection and attribution (D&A) took this criticism seriously and expanded the search for human effects on climate. D&A researchers demonstrated that human fingerprints on climate were pervasive, and could be identified in rainfall, atmospheric moisture, salinity, ocean heat content, and many other types of observational record. The internal consistency of the D&A evidence was both scientifically compelling and sobering—a wake-up call for humanity.

On the strength of this new evidence, the 2013 IPCC Fifth Assessment Report concluded that: "Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes... It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20^{th} century." The words "extremely likely" had a very specific meaning: the likelihood of this finding being correct was assessed to be 95% or greater.

Fingerprint studies have successfully identified human effects on California's temperature, snowpack depth in mountainous areas of the western United States, and the timing of stream flow from major western river basins. In each one of these cases, the changes in climate are of great practical and economic concern.

In a mere 16 years, the climate science community moved from a cautious "something unusual is happening in the climate system" to "humans are playing a dominant role in the warming of planet Earth." This transition marked a growing awareness that humans are now active participants in the climate system, and no longer simply innocent bystanders.

Detecting Human Effects on California's Climate

While the identification of a human fingerprint in global climate is an important scientific milestone, our personal experience of a changing climate is at the regional and local level. Can we see human signals in the regional-scale climate changes in California? Do such regional signals exist in things that have real social and economic value?

The answer to both of these questions is clearly "yes." Fingerprint studies have successfully identified human effects on California's temperature, snowpack depth in mountainous areas of the western United States, and the timing of stream flow from major western river basins. In each one of these cases, the changes in climate are of great practical and economic concern.

A prime example is the shift towards declining snowpack in the Sierras, and towards earlier spring runoff. As the 2014 U.S. National Climate Assessment noted: "Winter snowpack, which slowly melts and releases water in spring and summer, when both natural ecosystems and people have the greatest needs for water, is key to the Southwest's hydrology and water supplies." The better we understand such changes, the better we can prepare for them.

Implications of Detection Results for Future Climate Change

What does successful detection of human-caused fingerprints tell us about the expected future changes in California's climate? This question is difficult to answer. In almost all D&A studies, the fingerprints identified in observations are estimated with complex computer models of the climate system. Successful simulation of 20^{th}-century climate change is a necessary condition for building confidence in computer model projections of 21^{st}-century climate. But the past is not always prologue to the future, so scientists evaluate the credibility of model projections in many different ways—not just by comparison with historical climate records.

For example, D&A analysts ask whether projections of 21^{st}-century climate change are robust across a range of different climate models. They consider whether the projected changes make physical sense. They evaluate how well the models used for making projections simulate key climate processes—particularly the processes responsible for "spread" in the 21^{st}-century projections. They check whether climate forecasts made 20 to 30 years ago were accurate. Computer models of the climate system are constantly subjected to a variety of different reality checks. They are the best tools we have for attempting to understand 21st-century climate change.

Robust Features of 21st-Century Changes in California's Climate

The current historic drought in California has prompted serious concern about 21st-century changes in rainfall, snowpack, runoff, and atmospheric circulation. What do current state-of-the-art climate models tell us about projected changes in these quantities?

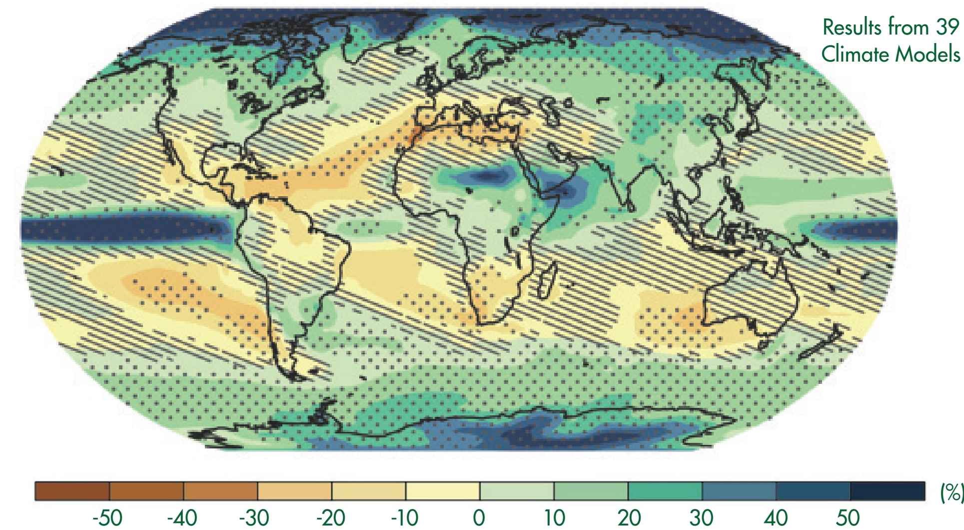
Consider rainfall first. Figure 2, taken from the 2013 IPCC Report, shows the percentage change in annual-average rainfall between the end of the 20th and the 21st century. The results are based on simulations of historical and future climate change performed with 39 different computer models of the climate system. The stippling indicates areas where at least 90% of the models agree on the sign of the rainfall change and where the model average rainfall change is large compared to natural climate variability. Many areas of the globe are stippled. A prominent example is the Arctic, which becomes wetter over the 21st century.

In the diagonally shaded areas, however, the model average rainfall change is of comparable size to natural, decade-to-decade fluctuations in climate. Such is the case over much of California. The results in Figure 2 suggest that for decades to come, the "signal" of human-caused changes in California rainfall may be difficult to discriminate from the large background "noise" of natural climate variability.

Despite this uncertainty in California rainfall projections, there are many things we can be confident about. We know, for example, that the 21st century will be considerably warmer than the 20th century. According to the 2014 U.S. National Climate Assessment, annual-mean surface temperatures over the southwestern U.S. (including California) "are projected to rise by 2.5°F to 5.5°F by 2041–2070, and by 5.5°F to 9.5°F by 2070–2099, under a 'business as usual' emissions scenario."

Figure 2. Can We Reduce Scientific Uncertainties in Projected 21st-Century Rainfall Changes?

Change in Average Precipitation Between the End of the 20th and 21st Centuries



Source: Summary for Policymakers, IPCC Fifth Assessment Report, 2013

Regional warming in response to continued human-caused increases in greenhouse gases is a very robust feature of model simulations. This warming signal drives a reduction in snowpack, which in turn means that more of the runoff from snow-fed river basins is likely to occur earlier in the year.

Another robust feature of model climate change projections relates to the temperature of the lower 4 to 11 miles of the atmosphere (the troposphere). Virtually all model simulations show larger tropospheric warming over the Arctic than at the equator. This preferential warming of the Arctic is also a prominent feature of satellite observations. It is largely due to so-called "feedbacks" involving the shrinking of Arctic snow and ice coverage.

The tropospheric temperature gradient between the equator and the North Pole has a major influence on Northern Hemisphere winds, storm tracks, and the jet stream. Precisely how these large-scale circulation features will respond is unclear, particularly in terms of their effects on regional climate. What is clear, however, is that the atmospheric circulation must react to major changes in its temperature structure. Such circulation responses may well have profound impacts on California's climate in the 21st century.

Human-caused Climate Signals in Agricultural Productivity

Today, D&A studies are not only being performed with changes in the climate itself—D&A analysts are also trying to link agricultural and ecosystem impacts to human-caused climate change. Such work is challenging. It requires accounting for confounding influences unrelated to climate. In agricultural D&A studies, these confounding factors include changes in land use and irrigation, and the development of crop varieties resistant to certain diseases and pests.

Despite these significant scientific challenges, the 2014 U.S. National Climate Assessment concluded that: "There have already been detectable impacts on (agricultural) production due to increasing temperatures." Intuitively, this makes sense. Scientists have successfully detected human-caused changes not only in the average climate, but also in the behavior of extreme temperature and rainfall. Agricultural productivity is very sensitive to the frequency, intensity, and duration of such extremes. It is highly likely, therefore, that agricultural productivity has already "felt" (and will continue to feel) the effects of human-caused changes in extreme events.

Final Words

In the absence of significant efforts to reduce emissions of CO_2 and other greenhouse gases, continuation of the 20th-century status quo—for California's climate, water resources, and agricultural productivity—is the least likely outcome for the 21st century. We are leaving known climate for an uncertain climatic future, and are relying on models, physical intuition, and past observations as our guides in this uncharted climatic territory. It will be a bumpy ride for all of us. But the ride will be a little smoother if we have better scientific understanding of human fingerprints on climate, and can identify robust features of the projected climate changes.

Suggested Citation:

Santer, Benjamin, 2014. "'The Shape of Things to Come' for California's Climate and Agriculture." *ARE Update* 18(1):2-5. University of California Giannini Foundation of Agricultural Economics.

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