Human Influence on Climate

What are the chances that humans are to blame for climate change? Scientists at MIT weigh the odds that we are.

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In formulating a response to the risk of future human influence on the climate, it is important to understand what has happened in the recent past. Has the climate actually been changing? And if so, how do we know if we are causing it? These two simple questions raise some of the most contentious and complicated topics in the whole climate change debate: the detection and attribution of change. To introduce this complex topic, a look at a more familiar problem may be useful.

Suppose you step onto your bathroom scale some morning and look down to find the number is one pound higher than you expected. You then call out, "Honey, I'm gaining weight. I've been eating too much!" What does it take to reach such a conclusion with any degree of confidence?

First, how do you know your weight is actually higher? You may suspect that the accuracy of your bathroom scale is not that great: you paid only $19.95 for it. You have also observed that readings on your health club scale differ from those at home. So there is error in the measurement itself: you can detect your weight increase only with some error. Thus informed, you might say, "There is a 90 percent probability that my weight is between 0.8 and 1.2 pounds higher than the last time I looked!"

Second, does this measurement indicate a change that might have some underlying cause, like eating too much? Here another complexity enters: your body weight may go up and down by amounts comparable to your observed gain this day regardless of what you eat, in response to changes in temperature and humidity or your psychological state—perhaps your boss is on vacation for the month. If the magnitude of this natural variability is similar to the change you are seeing on the bathroom scale, you should be cautious when saying that you have detected something significant. You have a problem of sorting the "signal" of a significant change in your body, perhaps attributable to food intake, from the "noise" of its natural fluctuations. So a still more accurate statement might be, "There is a 70 percent probability that my weight has gone up between 0.8 and 1.2 pounds for some reason other than natural variability."

The third question that arises is, why the apparent change? Weight gain does have a basis in physiology, and this knowledge may be bolstered by past experience and observation of others. But the relationship cannot be stated precisely because it depends on many factors, such as adjustments in metabolism and amount of physical activity, that are poorly understood.

This gives rise to a fourth question, how accurately have you recorded or recalled your food intake, physical activity level, and other factors that you know affect your weight? With this uncertainty about the relationship of food intake to weight, the most that can be said with scientific accuracy about attribution may be something like, "There is a 90 percent chance that at least one-half of the increase shown on this scale is due to my eating too much." Or, where formal analysis is missing, "Honey, the preponderance of the evidence suggests that I'm eating too much."

To summarize, detection of weight gain and its attribution to increased food intake involves four elements:

- An estimate of the weight change and the potential for error in measuring it,
- Knowledge of the natural variability in your body weight,
- An understanding of the mechanisms by which body weight responds to food intake and other factors, and a model of the relationships, and

■ A record of food intake and understanding of its accuracy.

Detection and Attribution

Now consider the global climate system. We have only imperfect measurements of how climate has changed over past decades, and our understanding of patterns of natural climate variability is limited. Moreover, our models of the interacting chemistry, physics, and biology of the global system are as yet incomplete, and we do not have an accurate inventory of past changes in factors, human and natural, that could have altered the Earth's radiation balance, the so-called radiative forcing.

Detection is the ability to say with confidence that we have seen some trend, and not just the natural variability of climate. This task involves measuring climate variables like temperature, which is like the reading on your bathroom scale, and analysis of the natural variability of the system—analogous to your natural weight fluctuation. Attribution requires showing that any change is associated with human-induced factors and not with some other cause. This additional task requires a model of the climate system and its various influences, like that for human physiology, and also requires estimates of factors affecting the climate system. These include the increasing concentrations of greenhouse gases. It is well known that these concentrations have been rising due to increased human emissions, but our understanding of past changes in this and other factors is far from complete, akin to your less-than-perfect record of food intake.

There are two key steps for detecting change and deciding how much to attribute to human influence during the industrial era. First, we need a temperature record for the globe for this period, roughly the past 150 years.

The record is often separated into four arbitrary periods: 1850 to 1910, 1910 to 1940, 1940 to 1975, and 1975 to 2000. In general the first two periods are cooler than the second two, suggesting a trend over time. If we attempt to simulate what the past 150 years would have been like, taking account of only the natural influences, we find deviations from the average, but no obvious trend. On first look, then, it seems that something other than the natural processes was involved in determining climate over this period.

Now, if we simulate the same historic era, adding into the model known concentrations of greenhouse gases—a warming influence—and estimates of human-produced aerosols such as sulfates—a cooling influence—we find the general pattern of simulated climate fits the estimated historical record much better than if we don't consider these influences, suggesting causation. But is this causal association enough? Is there still some significant chance that the association is coincidental?

Probable Cause

To be confident that the change is real, and to attribute it to human influence, we need to consider several issues. First, is the estimated global temperature record accurate? To create the estimated record, corrections must be included for the urban heat island effect—urban areas tend to generate, absorb, and retain heat, so thermometers there show higher temperatures than in rural areas—and for changes in instrumentation over a century. Data must be estimated for zones that have been poorly monitored, such as over oceans and Siberia. Finally, the record is more sparse the farther back in time one goes, and there is some disagreement between the surface record and satellite measurements of the upper atmosphere, the latter available only for the last couple of decades in any case. Despite these measurement issues, however, climate scientists generally agree that there has been a warming of the globe by about 0.6 degrees Celsius (1.08 Fahrenheit)[1] over the past 150 years,[2] with some uncertainty as to the precise change.

Second, what degree of change might be expected just from natural causes? The climate varies over time as a result of complex interactions among the atmosphere, the oceans, and the terrestrial biosphere, many of which are not captured in even the most complex climate models. These natural processes operate on time scales of a few years, such as El Niño and La Niña; or a few decades, such as Arctic or North Atlantic oscillations. Some, involving deep ocean circulations, have a time scale of several centuries. The temperature record is only a single source of possible global behavior over a century time scale. Any other period of similar length would show different patterns, and perhaps even larger changes caused by the interaction of these natural processes operating at different time scales.

With such system complexity, a record of 150 years is simply not long enough to allow estimation of the variability of the natural system. Imagine trying to understand your own body's natural variation if you had access to a scale for only a few days. The natural variability thus must be estimated from much longer simulations using computer models of the system, with all their shortcomings. These models necessarily must simplify a number of physical, chemical, and biological phenomena, and apply rough approximations for key processes, like the behavior of clouds, where the underlying science is either poorly understood or too difficult to model. Therefore, the model-based estimate of natural variability is uncertain, as is the particular reconstruction of historical surface air temperature. The question whether the observed change is rising out of the "noise" of natural variability can only be stated probabilistically, just as with your observed weight gain.

Lifting Fingerprints

Even if the model-based estimate of climate change were judged to exceed the estimate of natural variability with some high probability, the next question would be, why is it happening? Can the change be attributed to anthropogenic forcings?

To convincingly demonstrate a human cause is a simultaneous two-part process based on the natural science of the system and probability theory. First, it must be possible to reject the hypothesis that some non-human influence, such as solar variation, could have produced the same result. This is done by testing ranges of uncertainty in processes and parameters that are used in modeling these influences. Second, it must be shown that the modeled effects of human factors are consistent with the observed change, revealing the so-called human "fingerprint." Here, one must deal with the final factor above: uncertainty in human emissions.

The historical concentrations of greenhouse gases such as carbon dioxide, methane, and nitrous oxides are well known, but there is large uncertainty in the estimated concentrations of other substances, importantly sulfur oxide from coal-fired powerplants that produces cooling aerosols. In addition, the overall effect of these aerosols on the radiation balance remains uncertain. So models that produce a climate response to past anthropogenic climate forcing—very close to the observed rise in surface temperature—may only reflect a lucky choice of estimates of the level of inputs and modeled effects. For example, a different estimate of the aerosol loading, even one well within the range of uncertainty, could produce a very different simulated pattern of climate change.

Modeling Uncertainty

So how can we decide how much of the observed change in surface air temperature to attribute to anthropogenic forcings? One useful way to illuminate the question is to capture the influence of the main uncertain processes in our analysis of the climate system in a set of uncertain model parameters. Then, using statistical methods and an estimate of the natural variability of the system, we can rule out those combinations of parameters that do not reproduce the historical record. What is left after ruling out the unlikely combinations is a map of the likelihood that different levels of temperature change would have been observed over the period, given the estimated human forcing. This result can then be used to say, with some level of probability, that a particular fraction of the observed change has been due to human influence.

This type of study has been constructed using the climate component of the MIT Integrated Global System Model (IGSM),[3] which was designed to analyze uncertainty in three key climate processes.

One uncertainty is climate sensitivity, which depends on all the feedbacks in the atmosphere that modify the effects of the direct radiative greenhouse gases. The second is a measure of the effect of ocean processes, which determine both the rate of heat storage in the deep ocean and the rate of ocean uptake of carbon dioxide. And the third reflects the strength of the cooling influence of aerosols. The historical period can be simulated many times, assuming ranges of values for these uncertain parameters. By systematically adjusting these inputs and comparing the model response with observations, standard statistical methods can be used to identify a set of simulations, corresponding to particular sets of model parameters, that are consistent with the observations. This procedure allows us to quantify climate-change statements with a specific degree of confidence, akin to saying "there is a 90 percent chance that at least one-half of the increase shown on this scale is due to my over-eating."

Assumptions and Analysis

Before we illustrate how these calculations can be applied to the climate issue, let's summarize some underlying assumptions:

- Our estimate of the long-term natural variability of climate is based on simulation results from the HadCM2 climate model, developed by the Hadley Centre for Climate Prediction and Research in the United Kingdom.[4] Verifying that such an estimate is correct remains a difficult problem.
- We apply the temperature record as if there were no measurement errors or sampling errors, when in fact there are.
- This example does not include the possible effects of the change of solar irradiance over the analysis period, nor do we include the well-known cooling effect of aerosols from volcanic eruptions.
- We assume that the anthropogenic forcings other than aerosols, particularly the greenhouse gas forcings, are accurately known.

Now consider the observed global warming between two averaging periods, 1946 to 1955, and 1986 to 1995. Over these two periods, the historical record shows a global warming of 0.33 degrees Celsius. How much of this change should we think is due to human emissions? Using the ocean-atmosphere component of the MIT IGSM, and an estimate of anthropogenic climate forcings over this period, we have simulated the climate change over the period for many combinations of parameters for climate sensitivity, ocean processes, and aerosol forcing. Given the assumptions above, we can identify those parameter combinations that are consistent with the historical record.[5]

Assume, for example, that for a particular set of parameter values—most likely a high sensitivity and strong aerosol cooling combined with weak ocean heat uptake—the computed change is 0.60 degrees Celsius. Now, if we add the system's natural variability to this estimate, leading to changes greater and smaller than 0.60 degrees, will the estimated range encompass the observed 0.33 degrees Celsius? This is a question that can only be answered in probabilistic terms. Based on a statistical analysis, we might be able to say that there is a 95 percent probability that this 0.60 degree warming, with the parameter combination that leads to it, is too large to be consistent with the observed record.

To extract a statement about attribution from this analysis, we look to the lower end of the uncertainty range. We can select the level of temperature change, and associated parameter combinations, for which there is a 10 percent chance that the number should be excluded as being too low to be consistent with observations. From our results, we calculate that there is only a 10 percent probability that the modeled effect of the human influences on climate is less than 0.10 degrees Celsius over the 40-year period. Put another way, there is a 90 percent probability that at least 0.10 degrees Celsius, or approximately 30 percent of the observed 0.33 degrees Celsius warming, can be attributed to the anthropogenic forcings applied to the climate model. Because of natural variations on decadal and longer time scales, this statement will vary depending on the period of record chosen.

Margin of Error

So what are we led to conclude from this result? How are the four elements of the detection and attribution issue combined? First, we have used the climate model to define the relationship between radiative climate forcings and temperature changes. Second, the strength of this response is varied systematically by alternative settings of the model parameters, and results are chosen to be acceptable or unacceptable when compared with the observations. Third, the natural variability, as estimated by the HadCM2 climate model, is directly included in these comparisons to determine the confidence regions. Finally, the errors in the observations are assumed to be small when compared with the natural variability of the climate system.

Each of these steps involves uncertain assumptions. Also, we have not included the possible effects of a change in solar energy reaching Earth, nor have we included the well-known cooling effect of dust particles from volcanic eruptions. Each of the effects contributes to natural variability of climate and could decrease the fraction of warming explained by our simulations by widening the range of model parameters or changing the modeled temperatures. Additionally, the HadCM2 estimate of natural variability has a level of uncertainty, which has not been determined.

When combined, these uncertainties will alter our conclusions, and most of the components that are inadequately modeled tend to reduce the fraction of the observed warming that can be attributed to human influence with any particular level of confidence. Further, if this method were applied to models other than the MIT IGSM, somewhat different results might be obtained, reflecting the structural uncertainty among models, in contrast to the parameter uncertainty in the MIT model explored here.

Precision Impossible

These difficulties in detection and attribution, and the number of variables that must be fed into any model of climate change, lead scientists trying to summarize the available knowledge to resort to statements such as, "the preponderance of the evidence indicates that" or "it is likely that a significant or substantial portion, or most, of the observed warming is attributable to human influence." The words "preponderance" or "significant" or "substantial" or "most" can take on implicit probabilistic significance among scientists who spend many hours debating them. But the meaning of these phrases also can vary dramatically, even among technical experts in the same field.[6] Moreover, such statements are open to almost unlimited interpretation by lay people who have only the final text of some assessment or, worse, a summary of it, to go by.

Our calculations illustrate one way to make these statements more precise. We hope that this analysis of what lies behind these words may help avoid the too frequent leap to one of two extreme positions: that because of the uncertainty, we know nothing, or that scientists have "proven" that we are responsible for temperature changes of the recent past.■

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NOTES

1. One degree Celsius equals 1.8 degrees Fahrenheit.

2. National Research Council, *Reconciling Observations of Global Temperature Change* (Washington, DC: National Academy Press, 2000).

3. C.E. Forest et al., "Quantifying Uncertainties in Climate System Properties with the Use of Recent Climate Observations," *Science* 295 (2002), pp. 113-117; A. Sokolov, and P. Stone, "A Flexible Climate Model for Use in Integrated Assessments," *Climate Dynamics* 14 (1998), pp. 291–303; R. Prinn et al., "Integrated Global System Model for Climate Policy Assessment: Feedbacks and Sensitivity Studies," *Climatic Change* 41(3/4) (1997), pp 469–546.

4. T.C. Johns et al., "The Second Hadley Centre Coupled Ocean–Atmosphere GCM: Model Description, Spinup and Validation," *Climate Dynamics* 13 (1997), pp. 103–134.

5. Note that for each setting of the three uncertain parameters—for example, sensitivity at level A, ocean heat uptake at level B, and aerosol forcing at level C—the model produces an estimate of temperature change between 1946-55 and 1986-95.

6. M.G. Morgan, "Uncertainty Analysis in Risk Assessment," *Human and Ecological Risk Assessment* 4(1) (1998), pp. 25.