



Global Fingerprints of Greenhouse Warming A Summary of Recent Scientific Research

In the past two years the science attributing global warming to human enhancement of the greenhouse effect has progressed dramatically. New measurements show that climate change and its impacts have occurred globally, rather than regionally, which is readily explained by global warming, and not by natural regional variations. Many changes that have been predicted by models are now occurring, and the observed pattern of change points to the enhanced greenhouse effect. Hence, there has been much progress in identifying fingerprints of climate change driven by greenhouse gases. Fingerprints are changes that show a certain pattern that is unique to a specific climate-change driver.

1. Attribution of global warming to the enhanced greenhouse effect. Scientists have tested alternate hypotheses of natural vs. anthropogenic (human-caused) forces to explain how climate has changed over the past century or more. Two recent studies illustrate the state of this science, but represent only a small fraction of the studies that have produced comparable results.

Physical simulation of 20th-Century surface warming. A study (Meehl et al. 2004. *Journal of Climate* 17:3721-3727) by scientists at the National Center for Atmospheric Research examined the contributions of a variety of natural (solar, volcanoes) and anthropogenic (GHG, ozone, sulfate aerosols) driving factors in changing global surface temperature, comparing results from models, with and without the various hypothesized driving factors, with observed changes over the 20th Century. A graph of global surface temperature over the past century shows a crooked line that can be thought of as a *fingerprint*. Any climate driver fed into a model must match this fingerprint to qualify as a likely cause of observed warming. Potential drivers that do not improve the match to the fingerprint are deemed unlikely to be significant to the observed changes. This is a type of experimental hypothesis testing, which requires many samples. Since there is only one planet Earth, models provide simulated earths for comparison. The objective of the study was to determine which drivers, or combinations of them, allowed the model results to match the fingerprint of actual surface warming. The best fit of the model output to the observed data was produced when all of the driving factors were included, indicating that both natural and anthropogenic factors were involved. But different factors contributed differently over time. Anthropogenic factors were relatively unimportant during the first few decades of the 20th Century, but changes in solar energy and volcanic activity were. During the last half of the 20th Century, the largest contribution to the fingerprint by far was from anthropogenic greenhouse gases. These and many other results directly contradict skeptical claims that models fail to mimic observed changes.

Physical simulation of heat penetration into the ocean. Scientists at Scripps Institution of Oceanography, Lawrence Livermore National Lab, the UK's Hadley Center, and NCAR published a study showing six oceans (N. Atlantic, S. Atlantic, N. Indian, S. Indian, N. Pacific, S. Pacific) are warming simultaneously as a result of enhanced greenhouse warming (Barnett et al. *Science* 309:284-287). Natural temperature variations occur at different times, and often in direct opposite patterns, in different oceans. This type of change is called *internal variability*, and it results simply from transporting heat from one place to another,

but it adds no new heat. A big challenge for assigning a cause to temperature changes is distinguishing internal variability from *external forcing*, which adds new heat to the system. This study demonstrates that the six oceans that circle the globe, straddling the equator, have been warming simultaneously for at least the past 40 years, which requires external forcing. The data show that the oceans have been warming from the surface downward and that heat penetration with depth varies from ocean to ocean, providing a fingerprint that drivers in a model must match. Modeling of internal variability alone did not produce temperature profiles that matched this fingerprint, whereas combining internal variability with the effects of greenhouse gases did. Using a different approach from the study by Meehl et al. (described above), scientists again found that observed patterns of climate change could only be mimicked by including anthropogenic greenhouse gases as a climate driver.

Physical simulation of the increasing height of the tropopause. The tropopause is a region of the atmosphere that separates the lower atmosphere (troposphere) from the upper atmosphere (stratosphere). Its height is determined by physical conditions, including the temperature of the troposphere below and the stratosphere above. Factors that either warm the troposphere or cool the stratosphere increase the tropopause height, whereas those that cool the troposphere or warm the stratosphere decrease tropopause height. Scientists from the US, UK, and Germany teamed up to test whether they could simulate observed changes in the height of the tropopause based on changes in natural climate drivers (solar radiation and volcanic particles) and/or anthropogenic drivers (decreases in the stratospheric ozone layer and greenhouse gases in the troposphere) (Santer et al. 2003. *Science* 301:479-483; Santer et al. 2004. *Journal of Geophysical Research* 109:D21104). Observations revealed a 620-foot increase in tropopause height between 1979 and 2001. The scientists obtained a similar increase in the simulated tropopause height when their model included both anthropogenic greenhouse gases and stratospheric ozone depletion (from man-made chemicals). About 40% of the effect was from greenhouse gases and 60% from ozone depletion. Including natural variability of solar input and volcanic emissions in the model had little effect on this outcome, suggesting that enhanced greenhouse warming and depletion of the stratospheric ozone layer were the main causes of global tropospheric height increase. Because of the Montreal Protocol, ozone-depleting chemicals will decline in the future. However, the model predicted that tropopause elevation would continue in the future, because anthropogenic greenhouse gases will continue to rise. This prediction gives scientists an indicator for monitoring future climate change.

2. Linking major climate change impacts with global warming. In recent years, several important impacts have been observed that are readily explained by human-induced global warming. In some cases, global warming plus regional variability combine to produce impacts, but natural variability alone cannot explain the observations.

Global ice cover – In recent years glaciologists and oceanographers have been surprised by the unprecedented rates of change in global ice cover, both for Arctic sea ice and land-based glaciers and ice sheets.

Greenland: The second largest land-based ice sheet, with enough water to raise the global sea level by 6 meters if melted, covers the Greenland continent. Fifteen years ago, glaciologists believed that the Greenland ice sheet was in balance (i.e. not losing or gaining ice). Over the past decade, glaciologists documented rapid melting around the coasts of Greenland and adjusted their estimates to reflect a net loss of ice due to melting. In February 2006, new satellite-based measurements of ice flow were published, revealing that Greenland is losing ice even more rapidly than realized as a result of ice flowing into the sea at high rates. This work doubled the estimated rate of ice loss from Greenland and its contribution to the rate of global sea level rise (Rignot et al. 2006. Science 311:986-990).

Antarctic ice sheet. Western Antarctica is losing ice rapidly. Until recently, East Antarctica was thought to be gaining ice, but now is thought to be just in balance, such that future warming could quickly shift it to net ice loss. Overall, Antarctica appears to have lost about 450 km³ of ice, roughly the volume of Lake Erie, in the past three years (Velicogna. 2006. Science Online, March 2). Because these results are from the GRACE satellites launched in 2002, we do not know how long Antarctica has been losing ice. Antarctica holds enough ice to raise sea level by 70 m if melted.

Arctic sea ice: Arctic sea ice is being lost at an unprecedented rate, reaching a record low area during summer 2005. Some scientists estimate that by the end of the 21st Century the Arctic Ocean will be completely free of ice during the summer, a condition that probably has not existed for at least a million years (Overpeck et al. 2005. EOS 86:309-312). This loss of ice has important implications for global climate change and for Arctic ecosystems and wildlife (Arctic Climate Impact Assessment. 2005. Cambridge Univ. Press, New York).

Mountain glaciers. For several decades, glaciologists have documented a continuing worldwide loss of mountain glaciers, which continue to dwindle at an accelerating rate (Dyurgerov. 2006. AAAS Symposium, St. Louis; Dyurgerov, 2005. INSAAR Occasional Paper No. 58, Univ. of Colorado). Billions of people around the world depend solely on glaciers for their water supply. In Central Asia, mountain glaciers are retreating rapidly and may be virtually gone within decades, creating a billion environmental refugees (V. Aizen, 2006. AAAS Symposium, St. Louis).

The global trend. There is a clear pattern of globally distributed loss of ice indicative of global greenhouse warming, and not isolated regional losses of ice resulting from natural regional variability, as some skeptics claim. While some regions of the globe may presently be in a phase of natural warming, in addition to enhanced greenhouse warming, other regions are in natural cooling phases that will also reverse at some point. Hence, the overall loss of ice is a fingerprint of global warming.

Hurricanes – In 2005, two independent studies found that hurricanes were becoming more intense worldwide (Emanuel, 2005. Nature 436:686-688; Webster et al. 2005. Science 309:1844-1846). All oceans where tropical cyclones develop showed this change in recent decades. Immediately, skeptics responded that this upswing resulted from natural variability, rather than from greenhouse warming. However, they overlooked the well-established knowledge that natural cycles do not occur in sync

across the various basins. In fact, they tend to vary in opposite phases, for instance, in the North Atlantic and North Pacific basins. The existence of a trend of intensification in all six of the tropical cyclone-producing ocean basins thus represents a fingerprint of global warming, consistent with the enhanced greenhouse effect and not with natural variability alone.

Species changes – Two recent studies have documented apparent connections between changes in species and anthropogenic climate change. One study (Root et al. 2005. Proceedings of the National Academy of Sciences 102:7465-7469) found that 130 species, including many different plants and animals, have responded to earlier spring temperatures between 1970 and 2000 with such changes as the timing of flowering or migration. The strength of this study was that it linked these changes statistically to a climate model, demonstrating that the relationship between the timing of spring biological events was well correlated with greenhouse gas-driven climate change but not with natural variability alone. The species were located throughout Europe, North America, and Asia, thus representing a large portion of the Northern Hemisphere and not a particular region. Hence, the same type of response occurred regardless of differences in regional climate variability. The correlation with greenhouse gas-driven climate change demonstrates that this global response can be explained by enhanced greenhouse warming but not by natural climate variability alone.

A second study (Pounds et al. 2006. Nature 439:161-167) linked widespread mass amphibian extinctions in the tropics to the timing of climate change events associated with sea-surface and atmospheric temperatures. Warm years, which have become more frequent over time, are followed closely by extinctions in proportion to the degree of warming. Also, the majority of recorded extinctions are associated with warm years. Although extinction rates correlate with the large-scale warming trend, they do not correlate with local variability associated with regional El Nino events, once again demonstrating that a global trend, rather than regional variability, is the more likely explanation for the impact. The authors explained this relationship as a function of disease outbreaks fostered by the observed warming and moistening trend in tropical mountain environments as a result of climate change. The disease-causing organisms, a type of fungus called chytrids, have moved up the mountainsides as the climate has become warmer and wetter. So not only do we see species extinctions as a result of human-induced climate change, but also the migration of disease-causing organisms to new habitats.

Compiled by Jay Gulledge, PhD
Senior Research Fellow on Science and Impacts
Pew Center on Global Climate Change