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Global Warming: The Settled Versus The Unsettled Science

Executive Summary

- This paper is a primer on the science of climate change to help policymakers distinguish between the generally known and the uncertain or even unknown.

- There are three general areas of scientific agreement on climate change.

    - Atmospheric concentrations of greenhouse gases have risen from 280 parts per million (ppm) to 380 ppm over the last century due in large part to fossil fuel consumption.
    - The Earth's average temperature has risen approximately 1.3 degrees F over the last century.
    - Carbon dioxide, methane, and a few other trace gases exert a warming influence on the climate.

- Beyond these areas of general agreement, there is considerable uncertainty.

- Although rising greenhouse gas concentrations should warm the planet, it is difficult to determine how much of the past warming is due to human activities.

- It is even more difficult to determine whether human activities will have a relatively benign or catastrophic effect on the climate in the future.

- This uncertainty arises due to the complexity of the climate system, which is still beyond the capacity of climate scientists to adequately model.

- Sea level is rising and has been rising since before the industrial revolution. It is unclear whether a recent increase in the rate of sea level rise is a temporary change in natural variability or a long-term trend.

- The link between numbers of and intensity of hurricanes and climate change is tenuous. There is evidence for and against increased storm intensity due to climate change, but there are no clear trends in the number of hurricanes.

Introduction

The science of climate change is often portrayed in the popular press as being settled. Certain aspects of the science are indeed settled, or at least settled for the time being. Scientific judgements in this area – as in all areas of science[1] – are tentative and subject to change. Other aspects of the debate are still riddled with profound uncertainties, even unknowns, that confound our ability to determine the extent to which manmade emissions of greenhouse gases are contributing to warming, and the extent to which the planet may warm in the future.

Distinguishing between what is generally agreed upon, what is uncertain, and what is unknown is essential to policymakers who are being asked to act based on the prevailing science. In February, the United Nations Intergovernmental Panel on Climate Change (IPCC) released its Summary for Policymakers, a summary of an approximately 700-page scientific report that will be released in May. The Summary makes several claims about climate change (which this paper addresses), but policymakers will have to wait until May to learn the underlying science behind the Summary's claims.

A Thumbnail Sketch of the Greenhouse Effect and Climate System

This section provides a description of the greenhouse effect and the climate system, in particular the physical processes that operate within the system and how the rising atmospheric concentrations of greenhouse gases may change those physical processes. This discussion provides the basis for understanding which elements of the science are generally settled and why many important elements are still unsettled. The sections that follow discuss the agreed upon science and the uncertain science.

Greenhouse Effect Necessary to Maintain Life on Earth

The "greenhouse effect" is one of the natural mechanisms that keep the Earth at an appropriate temperature to maintain life. Shortwave radiation (sunlight) passes through the atmosphere and warms the Earth's surface. During the average year, about 340 watts per square meter of solar radiant energy enters the top of the atmosphere in the form of visible light. Clouds and the Earth's surface immediately reflect about 30 percent of that incoming light back to space, reducing the amount of energy absorbed at the surface to about 240 watts per square meter. The energy absorbed at the surface then rises in the form of infrared radiation (heat) and is absorbed again in the atmosphere by water vapor and certain trace gases. It is then reradiated upward and downward. In the absence of an atmosphere, the surface temperature of the Earth would be much colder than it is.[2]

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[1] Even estimates of physical constants, such as the speed of light, have undergone changes. See, Max Henrion and Baruch Fischhoff, "Assessing Uncertainty in Physical Constants," American Journal of Physics, 54(9): 791-798, September 1986.

[2] Richard S. Lindzen and Kerry Emanuel, "The greenhouse effect," *Encyclopedia of Global Change, Environmental Change and Human Society, Volume 1*, Andrew S. Goudie, editor in chief, pp 562-566, Oxford University Press, New York,710 pp.: 2002.

However, the natural greenhouse effect is so powerful that in the absence of other atmospheric processes, the Earth's surface temperature would be much hotter than it is.

The Role of Convection

Convection is a process by which the Earth's surface is cooled. Convection is conceptually simple. It is the movement of air. As will be discussed below, modeling air movements is tremendously difficult. Because the air rapidly decreases in temperature with altitude (the rate at which air cools with altitude is known as the lapse rate) there is a constant overturning of the Earth's atmosphere, in which the high altitude cool air sinks and low altitude warm air rises. At the surface, almost all of the transfer of heat away from the planet occurs due to convection, but, at higher altitudes, radiative heat transfer becomes progressively more important until convective processes cease and the atmosphere is at near radiative equilibrium at a temperature of approximately -18 degrees C (-0.4 degrees F).

It is at this level, between 10 and 12 kilometers above the surface of the Earth, that the amount of energy entering the atmosphere equals the amount of energy leaving it. It is at this altitude, known as the effective emission level, where changes in greenhouse gas concentrations exert the most influence on the temperature of both the atmosphere and the surface. An increase in greenhouse gas concentrations warms the atmosphere at the effective emissions level moving it to a higher altitude. By following the lapse rate back down to the surface, the temperature change at the surface can be calculated. A doubling of atmospheric concentrations of carbon dioxide, all else being equal, should lead to temperature rise of about a 1 degree C (1.8 degrees F) at the surface.[3]

The Role of Water Vapor as a Feedback Mechanism

Not all else is equal, however. There are various feedback mechanisms that either enhance or diminish the warming caused by changes in greenhouse gas concentrations. Many of these mechanisms are poorly understood, and it is likely that some of them are still unknown. One key feedback mechanism is the response of clouds and water vapor to changes in greenhouse gas concentrations. It is generally assumed that the small amount of warming caused by increases in greenhouse gas concentrations would lead to rising concentrations of water vapor in the atmosphere due to accelerated evaporation. Since water vapor is also a greenhouse gas, this enhances the greenhouse effect leading to even greater warming. The IPCC estimates that, as a result of water vapor feedback, a doubling of carbon dioxide concentrations will lead to a warming of between 2 and 4.5 degrees C (3.6 to 8.1 degrees F).[4] It also states, however, that, "Cloud feedbacks [which are tightly related to water vapor] remain the largest source of uncertainty."

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[3]Lindzen and Emanuel, 2002.

[4]An interesting side note is that this estimate of climate sensitivity (the change in temperature due to a doubling of carbon dioxide concentrations) has changed very little over the years. As early as 1979, the range was estimated to be 1.5 to 4.5 degrees C (See, Jule G. Charney, et al., *Carbon Dioxide and Climate: A Scientific Assessment,* National Academy of

Some studies have cast doubt on the size or even the existence of a positive water vapor feedback. One empirical study found that the warming induced by carbon dioxide decreases the ratio of cirrus cloud area (clouds that trap infrared radiation and warm the planet) to cumulus cloud area (clouds that block incoming sunlight and cool the planet) by 17 to 27 percent, allowing more heat to escape the atmosphere. This "negative" feedback may be large enough to fully offset human-induced warming.[5] Another study found that the tropical troposphere, the layer of air between 25,000 and 50,000 feet, is much dryer than has generally been assumed. The tropical troposphere, then, can act as the Earth's exhaust vents for escaping heat allowing the planet to cool.[6]

These findings are still controversial and have been challenged by other scientists.[7] But these scientific debates illustrate the uncertainties that still exist in the science.

Areas of General Scientific Agreement

Scientists generally agree on several points with regard to climate change. First, atmospheric concentrations of carbon dioxide have increased from a pre-industrial level of 280 parts per million to 380 parts per million in 2005.[8] This increase is due primarily to fossil fuel consumption.

Second, globally averaged temperature, measured with ground-based thermometers, has risen by about 0.74 degrees C (±0.18 degrees C) or 1.3 degrees F over the last century.[9]

Third, carbon dioxide, methane, and a few other trace gases are indeed greenhouse gases, and human emissions of these gases contribute to warming. The IPCC Summary says that it has "'high confidence' [meaning at least a 90 percent chance] that

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Sciences, Washington, D.C.: 1979) The current estimate of 2 to 4.5 degrees C only narrows that range slightly. For all the IPCC's talk of improved understanding and better modeling, the range for climate sensitivity has narrowed very little.

[5]Richard S. Lindzen, Ming-Dah Chou, and Arthur Y. Hou, "Does the Earth Have an Adaptive Infrared Iris?, *Bulletin of the American Meteorological Society*, 82:417-32, March 2001.

[6]Roy W. Spencer and William D. Braswell, "How Dry is the Tropical Free Troposphere? Implications for Global Warming Theory, *Bulletin of the American Meteorological Society*, 78:1097-1106.

[7]See, for example, Dennis L. Hartmann and Marc L. Michelsen, 2002: "No evidence for iris," *Bulletin of the American Meteorological Society*, 83: 249-254, February 2002. For the response see, Richard S. Lindzen, Ming-Dah Chou, and Arthur Y. Hou, "Comment on 'No evidence for iris,'" *Bulletin of the American Meteorological Society*, 83: 1345-1348, September 2002.

[8]United Nations Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007: The Physical Science Basis*, Summary for Policymakers, February 2007.

[9]IPCC, 2007.

the globally averaged net effect of human activities since 1750 has been one of warming."[10]

Though scientists agree that human activities have indeed led to some warming, it is unclear how much of the warming observed over the last century can be attributed to those activities and how much is due to natural climate processes. Even more uncertain is how much the Earth is likely to warm in the future.

How Reliable are Climate Models?

The primary basis for projecting future temperature rise are climate models. These models are tremendously complex but still do not adequately replicate important climate processes. The 2007 IPCC Summary refers to "advances in climate change modeling" at several points, but does not discuss the reliability of the models per se. The 2001 IPCC report did address this issue, stating that, "In climate research and modeling, we should recognize that we are dealing with a coupled non-linear chaotic system, and therefore that the long-term prediction of future climate states is not possible."[11] It remains to be seen what the 2007 IPCC report will say on this matter.

The Problem of Turbulence

The key difficulty that scientists run into when attempting to model the climate is the inability to properly model turbulence. The Second Law of Thermodynamics dictates that over time, changes in temperature even out in the physical system. In the climate system, this law dictates the overturning of the atmosphere through convection. The wind blows for the same reason, to even out temperature differences. These large fluid motions in the atmosphere are complex, non-linear, and chaotic and so defy prediction. Scientists know the equations that govern turbulence but, because turbulence is chaotic, they cannot be solved. To deal with this problem, scientists substitute numbers known as parameters, or flux adjustments, to stand in for complex climatic processes. This makes the models tractable, but it significantly reduces their realism and ability to predict the future.

Several scientists have discussed these problems. Hendrik Tennekes, who retired as Director of Research for the Royal Netherlands Meteorological Institute after 30 years in the field, explained, "There exists no sound theoretical framework for climate predictability studies. As a turbulence specialist, I am aware that such a framework would require the development of a statistical-dynamic theory of the general circulation, a theory that deals with the eddy fluxes and the like. But the very thought is anathema to the mainstream of dynamical meteorology."[12]

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[10] IPCC, 2007.

[11] IPCC, 2001.

[12] Hendrik Tennekes, A Skeptical View of Climate Models, January 1, 2007: http:/www.sepp.org/Archive/NewSEPP/Climatemodels-tennekes.htm.

In a study on ocean dynamics, Greg Holloway a scientist at the Institute of Ocean Sciences, makes the same point about dealing with turbulence, "In principle, we suppose that we know a good approximation to the equations of motion on some scale.... In practice we cannot solve for oceans, lakes or most duck ponds on the scales for which these equations apply."[13]

Christopher Essex, is a mathematician at Western Ontario University, who specializes in the underlying mathematics, physics and computation of complex dynamic processes. He had this to say about the problem of turbulence: "Turbulence is a pervasive feature of atmospheric processes, yet analysis from first principles is not possible because the relevant equations cannot be solved directly. The governing system is known to exhibit chaotic behavior, which means in principle that prediction and causal interpretation of past events is not possible. . . . . When you mix the different components of classical physics together on this bubbling boiling turbulent foundation, the result is a disaster for classical forecasting."[14]

Dr. David Orrell, a mathematician who specializes in the prediction of complex systems has explained that, "The track record of any kind of long-distance prediction is really bad, but everyone's still really interested in it. It's sort of a way of picturing the future. But we can't make long-term predictions of the economy, and we can't make long-term predictions of the climate." In fact, he added, "*Scientists cannot even write the equation of a cloud, let alone make a workable model of the climate* (italics added)."[15] Orrell also argues that "the predictions of the recent IPCC Summary are "extremely vague," and says "there is no scientific reason to think the climate is more predictable than the weather."[16]

Predicting Sea Level Rise

Average sea level has risen and fallen naturally for thousands of years. It has been estimated that over the last 20,000 years, sea level has risen about 120 meters. Based on a few long-term tide gauge records, it is thought that the rate of sea level rise was higher in the 20th century than in the 19th century.[17] The IPCC Summary states that average sea level rose 1.8 mm (0.07 inches) per year from 1961 to 2003. From 1993 to

[13] Greg Holloway, "From Classical to Statistical Ocean Dynamics," *Surveys in Geophysics*, 25: 203-219, 2004.

[14] Christopher Essex and Ross McKitrick, Taken by Storm: The Troubled Science, Policy and Politics of Global Warming," A briefing sponsored by the Cooler Heads Coalition, February 27, 2003.

[15] *National Post*, "The Green Fervor: Is Environmentalism the New Religion," February 16, 2007.

[16] *National Post*, February 16, 2007.

[17] United Nations Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

2003, the rate of increase rose to 3.1 mm (0.12 inches) per year. The IPCC Summary acknowledges that it is unclear whether this is a temporary rate increase is due to natural variability or an increase in long-term trends.[18]

Arctic Sea Ice

The concerns over sea level rise are centered on the possibility of large-scale melting of the Earth's polar ice, in particular the ice sheets of Antarctica and Greenland, which could lead to catastrophic sea level rise. There is some evidence that sea-ice extent has diminished in the Arctic; but since Arctic sea-ice is floating, it already fully displaces an equivalent amount of water, so even if it melted completely it would have no effect on sea levels. Moreover, recent research has shown that the Arctic was as warm around the latter part of the 1930s as it has been recently, which suggests that it goes through natural warming and cooling cycles.[19]

Antarctic Ice Sheet

The Antarctic ice sheet, on the other hand, is not floating, but is grounded. Were it to melt significantly, it would cause sea levels to rise and might pose a danger to low-lying island nations and coastal regions. The IPCC Summary estimates that the Antarctic has contributed about 0.14 mm (0.006 inches) per year to sea level rise from 1963 to 2003. But it also states that, "Current global model studies project that the Antarctic ice sheet will remain too cold for widespread surface melting and is expected to gain in mass due to increased snowfall. However, net loss of ice mass could occur if dynamical ice discharge [ice flows and calving of glaciers] dominates the ice sheet mass balance."[20]

There is evidence that currently the Antarctic is cooling and its ice sheet is growing. A study published in *Nature* concluded, "Our spatial analysis of Antarctic meteorological data demonstrates a net cooling on the Antarctic continent between 1966 and 2000, particularly during summer and autumn."[21] A study published in *Science* found "strong evidence for ice-sheet growth (between about 10 and 40 gigatons per year)" in the Antarctic.[22]

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[18]IPCC, 2007.

[19]Igor Polyakov, David Walsh, Igor Dmitrenko, Roger L. Colony, Leonid A. Timokhov. 2003. Arctic Ocean variability derived from historical observations. *Geophysical Research Letters*, 30(6): 31-34, 2003.

[20]IPCC, 2007.

[21]Peter T. Doran, John C. Priscu, W. Berry Lyons, John E. Walsh, Andrew G. Fountain, Diane M. McKnight, Daryl L. Moorhead, Ross A. Virginia, Diana H. Wall, Gary D. Clow, Christian H. Fritsen, Christopher P. McKay, and Andrew N. Parsons, "Antarctic climate cooling and terrestrial ecosystem response," *Nature*, 415: 517-520, 2002.

[22]Joughin, Ian and Slawek Tulaczyk (2002). "Positive Mass Balance of the Ross Ice Streams, West Antarctica," *Science*, 295: 451-452.

Greenland Ice Sheet

The Greenland ice sheet is also grounded and could substantially raise sea level if it were to melt. The IPCC Summary notes that Greenland has contributed about 0.05 mm (0.002 inches) per year to sea level rise. It also states that, "If a negative surface mass balance were sustained for millennia, that would lead to virtually complete elimination of the Greenland ice sheet and a resulting contribution to sea level rise of about 7 meters [23 feet]."[23]

According to one study, the interior of Greenland's ice sheet is growing at a rate of about 6.4 centimeters (2.6 inches) per year at altitudes above 5,000 feet. Below 5,000 feet, the ice sheet is shrinking at a rate of 2 centimeters (1 inch) per year. The net increase is 5.4 centimeters per year.[24] However, other studies have found a net contribution (though tiny) to sea level rise from Greenland.[25]

Also, much like the Arctic, the current warming in Greenland is not unprecedented. According to one study, "Almost all decades between 1915 and 1965 were warmer or at least as warm as the 1995 to 2005 decade…suggesting the current warm Greenland climate is not unprecedented and that similar temperatures were a norm in the first half the 20th century." The study also argues that the rate of warming during the 1920s was 50 percent faster than the rate of warming from 1995 to 2005.[26]

Hurricanes and Climate Change

One of the concerns about climate change that has been raised is a possible increase in the numbers of hurricanes and hurricane intensity and whether or not human activities are contributing to more and more powerful hurricanes. The very active U.S. hurricane season in 2005, which saw the enormous destruction from Katrina and other hurricanes raised fears that such hurricane seasons could become the norm due to global warming. The quiet hurricane season of 2006 has lessened those concerns to some extent. Neither the active hurricane season of 2005 nor the quiet hurricane season of 2006 should be taken at this time as evidence for or against global warming or its link to hurricane activity.[27]

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[23] IPCC, 2007.

[24] Ola M. Johannessen, Kirill Khvorostovsky, Martin W. Miles, and Leonid P. Bobylev, "Recent Ice Sheet Growth in the Interior of Greenland," *Science*, November 11, 2005.

[25] Scott B. Luthcke, H. Jay Zwally, Waleed Abdalati, David D. Rowlands, Richard D. Ray, R. Steven Nerem, Frank G.R. Lemoine, J.J. McCarthy, and D.S. Chinn, "Recent Greenland Ice Mass Loss by Drainage System from Satellite Gravity Observations," *Science*, November 24, 2006.

[26] Chylek, P., M.K. Dubey, and G. Lesins. 2006. Greenland Warming of 1920-1930 and 1995-2005. *Geophysical Research Letters*, *33*, L11707, doi:10.1029/2006GL026510.

[27] See, for example, this Q&A with hurricane expert Kerry Emanual, http://wind.mit.edu/~emanuel/anthro2.htm.

Trends in Hurricane Numbers and Intensity

The IPCC Summary notes that there is evidence for increased hurricane intensity in the North Atlantic, which is correlated with higher sea surface temperatures. It adds this substantial cautionary note, however: that "multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity." It also states that even though there is some evidence of increased intensity, "There is no clear trend in the annual numbers of tropical cyclones."[28]

In November 2006, the World Meteorological Organization (WMO) held a two-week International Workshop on Tropical Cyclones (or hurricanes) where leading hurricane researchers wrote a Statement on Tropical Cyclones and Climate Change. The Statement says that recent research has found "evidence for a substantial increase in the power of tropical cyclones in the West Pacific and Atlantic basins during the last 50 years." It notes, however, that some scientists argue that the trend may not be real, and instead is due to improved monitoring of strong tropical cyclones in recent years.

With regard to changes in hurricane activity, the statement says that the Atlantic basin has the most reliable historical hurricane records. The causes of multi-decadal variability in major hurricane activity in this basin is still being debated. Some scientists argue that Atlantic hurricane activity fluctuates naturally. The Statement notes one study that disputes this, arguing that variability is due to a combination of changes in solar activity, volcanic and manmade aerosols, and greenhouse gases.

Does Human Activity Contribute to Changes in Hurricane Intensity?

The IPCC Summary assesses the likelihood of increases in intense hurricanes as "likely [better than 66 percent chance] in some regions since 1970," and states that the likelihood of a human contribution is "more likely than not," though in the footnote it also notes that the "magnitude of anthropogenic [human] contributions [was] not assessed."

The WMO Statement notes that, "Though there is evidence both for and against the existence of a detectable anthropogenic signal [i.e., human component] in the tropical cyclone climate record to date, no firm conclusion can be made on this point." Part of the difficulty in identifying the human component, if any is, as the IPCC Summary itself notes, that tropical cyclone activity varies naturally over the decades. "This variability makes detecting any long-term trends in tropical cyclone activity difficult," according to the WMO statement. The statement also notes that, "The recent increase in societal impact from tropical cyclones has largely been caused by rising concentrations of population and infrastructure in coastal regions."

[28] IPCC, 2007.

Finally, the Statement notes that, "The scientific debate...is not as to whether global warming can cause a trend in tropical cyclone intensities. The more relevant question is how large a change: a relatively small one several decades into the future or large changes occurring today? Currently, published theory and numerical modeling results suggests the former."[29]

Conclusion

Climate change continues to be a controversial scientific issue. The IPCC process is a major effort to provide a comprehensive overview of the state of climate science, though as is evident even from the Summary – which, due to the necessity for brevity, tends to downplay uncertainties – there are still many difficult obstacles and uncertainties to overcome in determining the influence of human activities on the climate.

There are three areas upon which there is general agreement. The average temperature has risen, atmospheric concentrations of greenhouse gas have risen, and the latter has probably contributed to the former. The important question is whether changes will be relatively benign or catastrophic. This is still an open question. It would be prudent for policymakers to continue to closely monitor the science.

[29] "Statement on Tropical Cyclones and Climate Change," Prepared by participants of the WMO International Workshop on Tropical Cyclones, IWTC-6, San Jose, Costa Rica, November 2006.