

**STATEMENT TO THE
SUBCOMMITTEE ON ENVIRONMENT
COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY
OF THE UNITED STATES HOUSE OF REPRESENTATIVES**

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“Policy Relevant Climate Issues in Context”**

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Judith A. Curry
Georgia Institute of Technology
curryja@eas.gatech.edu

I thank the Chairman, the Ranking Member and members of the Subcommittee for the opportunity to offer testimony today on *Policy Relevant Climate Issues in Context*. I am Chair of the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. I have devoted 30 years to conducting research on topics including climate feedback processes in the Arctic, energy exchange between the ocean and atmosphere, the role of clouds and aerosols in the climate system, and the impact of climate change on the characteristics of tropical cyclones. As President of Climate Forecast Applications Network (CFAN) LLC, I have worked with decision makers on climate impact assessments, assessing and developing meteorological hazard and climate adaptation strategies, and developing subseasonal climate forecasting strategies to support adaptive management.

Prior to 2005, I spent my time comfortably ensconced in the ‘ivory tower’ of academia, debating esoteric scientific issues with colleagues. Publication of a paper on hurricanes and global warming¹ several weeks after Hurricane Katrina exposed me to the rancor associated with the public debate surrounding climate change and the challenges and problems associated with mixing science and politics². For the past several years, I have been promoting dialogue across the full spectrum of beliefs and opinion on the climate debate through my blog, Climate Etc. (judithcurry.com). I have learned about the complex reasons that intelligent, educated and well-informed people disagree on the subject of climate change, as well as tactics used by both sides to try to gain a political advantage in the debate. By engaging with decision makers in both the private and public sector on issues related to weather and seasonal climate variability through my company CFAN, my perspective on uncertainty and confidence in context of prediction, and how to convey this, has utterly and irreversibly changed. I have learned about the complexity of different decisions that depend, at least in part, on weather and climate information. I have learned the importance of careful determination and conveyance of the uncertainty associated with a forecast, and the added challenges associated with predicting extreme events. Confidence in a particular probabilistic forecast is determined by consistency of consecutive forecasts, and historical evaluation of forecast accuracy and errors under similar conditions. I have also learned how different types of decision makers make use of forecast uncertainty and confidence information. I have found that the worst forecast outcome is a forecast issued with a high level of confidence that turns out to be wrong; a close second is missing the possibility of an extreme event.

¹ Webster, P.J., G.J. Holland, J.A. Curry, H.-R. Chang, 2005: Changes in tropical cyclone number, duration and intensity in a warming environment. *Science*. 309 (5742): 1844-1846. <http://webster.eas.gatech.edu/Papers/Webster2005b.pdf>

² Curry, J. A., P. J. Webster and G. J. Holland, 2006: Mixing Politics and Science in Testing the Hypothesis That Greenhouse Warming Is Causing a Global Increase in Hurricane Intensity. *Bull. Amer. Met. Soc.*, 87 (8), 1025-1037. <http://webster.eas.gatech.edu/Papers/Webster2006d.pdf>

For the past three years, I have been working towards understanding the dynamics of uncertainty at the climate science-policy interface. This research³ has led me to question whether these dynamics are operating in a manner that is healthy for either the science or the policy process. The role of scientists should not be to develop political will to act by implicitly or explicitly hiding or simplifying the uncertainties behind a negotiated consensus. Greater openness about scientific uncertainties and ignorance, and more transparency about dissent and disagreement, would provide policymakers with a more complete picture of climate science and its limitations, and ensure that the science community, policymakers, and the public are better equipped to understand, respond and adapt to climate change.

If all other things remain equal, it is clear that adding more carbon dioxide to the atmosphere will warm the planet. However the real difficulty is that nothing remains equal, and reliable prediction of the impact of carbon dioxide on the climate requires that we understand natural climate variability properly. Until we understand natural climate variability better, we cannot reliably infer sensitivity to greenhouse gas forcing or understand its role in influencing extreme weather events. Natural climate variability refers to forcing from the sun, volcanic eruptions and natural internal variability associated with chaotic interactions between the atmosphere and ocean. The most familiar mode of natural internal variability is El Nino/La Nino. On longer multi-decadal time scales, there is a network of atmospheric and oceanic circulation regimes, including the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation. While 20th century climate change is most often explained in terms of external forcing, with natural internal variability providing high frequency ‘noise,’ the role of large multidecadal oscillations is receiving increasing attention. Further complicating this interpretation are new hypotheses whereby the external forcing projects onto the modes of natural internal variability, producing ‘shifts’ in the climate system.⁴

With this context, my testimony focuses on three scientific issues of central relevance to climate policy:

- Interpretation of the IPCC AR4 consensus conclusions on climate sensitivity and attribution of climate change in view of recent research and observations;
- Linkages between climate change and extreme weather; and
- Reasoning about climate uncertainty, including challenges and opportunities related to decision making under uncertainty

Climate sensitivity and attribution of climate change

The Intergovernmental Panel on Climate Change 4th Assessment report (IPCC AR4) published in 2007 made the following key statements in the Summary for Policy Makers⁵:

“Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.” (p. 5)

“Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations” (p. 10)

“For the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES emissions scenarios.” (p. 12)

³ Curry, JA and Webster PJ 2011: Climate science and the uncertainty monster. *Bull Amer Meteorol. Soc.*, 92, 1667-1682. <http://journals.ametsoc.org/doi/pdf/10.1175/2011BAMS3139.1>

⁴ Tsonis, A et al. 2007: A new dynamical mechanism for major climate shifts. *Geophys. Res. Lett.*, 34, L13705. <https://pantherfile.uwm.edu/aatsonis/www/2007GL030288.pdf>

⁵ IPCC AR4 Summary for Policy Makers http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html

The IPCC 5th Assessment Report (AR5) is well underway, and the *Working Group Report on The Physical Science Basis* will be published in September 2013⁶. Recent observations and analyses are illuminating the complexity of the climate system and challenging our understanding of the role of natural variability in contributing to recent climate change. The analysis provided below summarizes some of this recent research and key areas of controversy.

Key observations

As evidence that warming is unequivocal, the IPCC AR4 cites observations of global average air and ocean temperatures, ocean heat content, snow and ice melt, and sea level rise. In assessing this evidence, we need to consider the quality of these data in terms of their maturity as climate data records⁷ and length of the records, so we can interpret appropriately the context of recent variations. To detect a human signal in recent climate change, we need to consider confounding factors associated with each of these data sets in assessing quality for purpose (including background natural variability). In context of these criteria, I focus my analysis here on the global surface temperature data and also sea ice extent data since 1979.

Surface temperature. Figure 1 shows the global average surface temperature anomalies through 2012, from the HadCRUT4 data set⁸ (note: the GISTEMP and NOAA NCDC data sets show similar results).

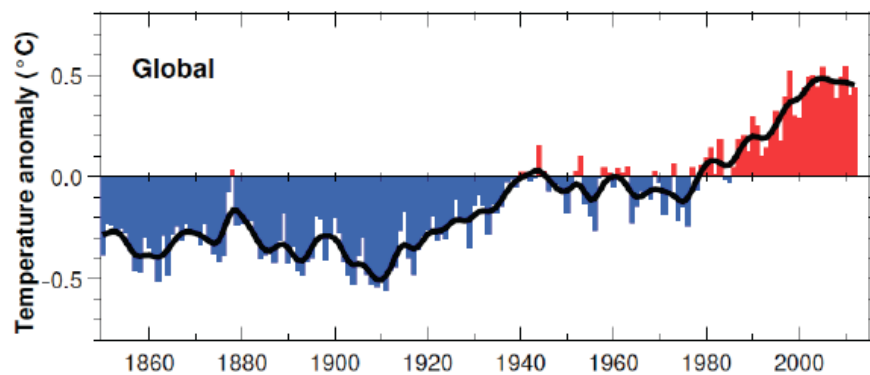


Figure 1. Global average surface temperature anomalies from the HadCRUT4 data set.
<http://www.cru.uea.ac.uk/cru/data/temperature/HadCRUT4.pdf>

Figure 1 shows a long-term increasing trend, and particularly during the last 25 years of the 20th century. However, since 1998 there has been no statistically significant increase in global surface temperature. While many engaged in the public discourse on this topic dismiss the significance of a hiatus in increasing global temperatures because of expected variations associated with natural variability, analyses of climate model simulations find very unlikely a plateau or period of cooling that extends beyond 17 years in the presence of human-induced global warming⁹.

James Hansen has recently written:¹⁰ “*The five-year mean global temperature has been flat for the last decade.*” Hansen interprets this as “*a combination of natural variability and a slow down in the growth*

⁶ <http://www.ipcc.ch/activities/activities.shtml>

⁷ Bates, JJ and JL Privette (2012): A maturity model for assessing the completeness of climate data records. *EOS Trans. of Amer. Geophysical Union*, 93, p. 441. <http://onlinelibrary.wiley.com/doi/10.1029/2012EO440006/abstract>

⁸ <http://www.cru.uea.ac.uk/cru/data/temperature/HadCRUT4.pdf>

⁹ Santer, B. D., et al. (2011), Separating signal and noise in atmospheric temperature changes: The importance of timescale, *J. Geophys. Res.*, 116, D22105, doi:10.1029/2011JD016263.

¹⁰ Hansen, J., M Sato, R. Ruedy, 2013: Global Temperature Update Through 2012. http://www.columbia.edu/~jeh1/mailings/2013/20130115_Temperature2012.pdf

rate of net climate forcing.” Hansen then suggests that “global temperature will rise significantly in the next few years as the tropics moves inevitably to the next El Nino phase.” Others have suggested that the pause could last up to two decades¹¹ or even longer, owing to the transition to the cool phase of the Pacific Decadal Oscillation that is associated with a predominance of La Nina (cool) events.

Sea ice. The other data set that is of particular relevance in interpreting recent climate change is sea ice extent since 1979. While the Antarctic sea ice extent has increased over this period, the Arctic sea ice extent has declined substantially. The apparent paradox of increasing Antarctic sea ice extent in the presence of warming of the Southern Ocean was explained by Liu and Curry¹² who found an enhanced atmospheric hydrological cycle in the Southern Ocean that has resulted in an increase of the Antarctic sea ice for the past three decades through the reduced upward ocean heat transport and increased snowfall.

Figure 2 shows the time series of Arctic sea ice extent since 1979¹³. The most striking feature of this plot is the large decline of sea ice extent since about 2003, with record low values of minimum autumn sea ice extent set first in 2007 and then in 2012.

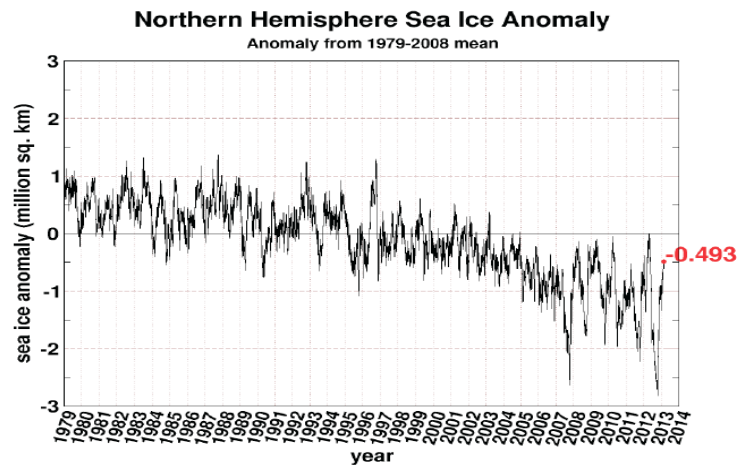


Figure 2. Northern Hemisphere sea ice anomalies
<http://arctic.atmos.uiuc.edu/cryosphere/IMAGES/seaice.anomaly.arctic.png>

It is difficult to untangle the relative roles of human-induced climate change versus natural variability in causing the Arctic sea ice decline. Using climate model simulations from the NCAR CCSM4, Kay et al.¹⁴ inferred that approximately half (56%) of the observed rate of decline from 1979 to 2005 was externally (anthropogenically) forced, with the other half associated with natural internal variability. Stroeve et al.¹⁵ used multiple climate model simulations from CMIP5 to infer that approximately 60% of the observed rate of decline from 1979–2011 is externally forced (compared to 41% determined from the earlier CMIP3 simulations). These simulations suggest an important role for natural variability as well as for human-induced climate change; further clarification of their relative roles awaits improved capabilities of the climate models in simulating natural internal variability, improved historical records of solar variability, and a longer record of sea ice extent.

¹¹ http://www.wmo.int/wcc3/sessionsdb/documents/PS3_Latif.pdf

¹² Liu, J, JA Curry 2010: Accelerated warming in the Southern Ocean and its impacts on the hydrological cycle and sea ice. *PNAS*, 107, 14987-14992. <http://www.pnas.org/content/107/34/14987.full>

¹³ <http://arctic.atmos.uiuc.edu/cryosphere/IMAGES/seaice.anomaly.arctic.png> (downloaded 2/23/13)

¹⁴ Kay, J. E., M. M. Holland, and A. Jahn (2011), Inter-annual to multidecadal Arctic sea ice extent trends in a warming world, *Geophys. Res. Lett.*, 38, L15708, doi:10.1029/2011GL048008.

¹⁵ Stroeve et al. 2012: Trends in Arctic Sea ice from CMIP5, CMIP3 and observations. *J. Geophys. Res.*, 39, L16502. http://www.uib.no/People/ngfhd/EarthClim/Publications/Papers/stroeve_etal_2012.pdf

Climate model - observation comparison

The fifth phase of the Coupled Model Intercomparison Project (CMIP5)¹⁶ has produced a multi-model dataset that includes long-term simulations of twentieth-century climate and projections for the twenty-first century and beyond, as well as an entirely new suite of initialized decadal predictions focusing on recent decades and the future to year 2035. While providing the underlying basis for the forthcoming IPCC AR5, the CMIP5 model output has been made freely available to researchers through a distributed data archive¹⁷. An analysis provided by Ed Hawkins¹⁸ at the University of Reading compares the global average surface temperatures from the HadCRUT4 dataset with 20 models from the CMIP5 simulations (Figure 3).

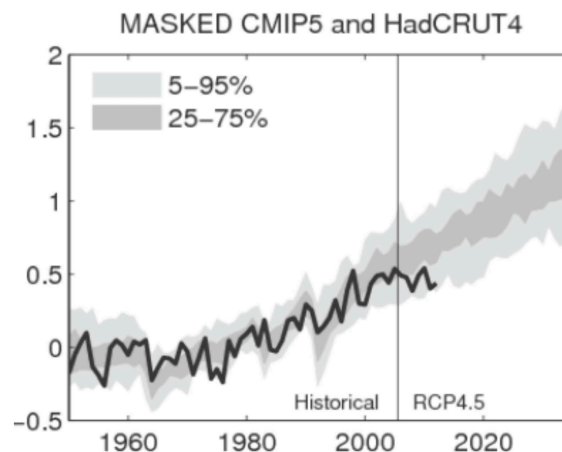


Figure 3. Comparison the global average surface temperatures from the HadCRUT4 dataset with 20 models from the CMIP5 simulations. <http://www.climate-lab-book.ac.uk/2013/updated-comparison-of-simulations-and-observations/>

The comparison in Figure 3 shows that observations particularly since 2005 are on the low end of the envelope that contains 90% of the climate model simulations. Extrapolation of the current flat trend would place the observations outside of the 90% envelope within a few years. While the observations remain within the substantial range of the climate model simulations, the trend in the model simulations is substantially larger than the observed trend over the past 15 years.

When considering possible physical reasons for the plateau since 1998, it is instructive to consider the previous mid-century plateau in global average surface temperature (Figure 1). The IPCC AR4 explained this previous plateau in the following way¹⁹: “the cooling effects of sulphate aerosols may account for some of the lack of observational warming between 1950 and 1970, despite increasing greenhouse gas concentrations.” And “variations in the Atlantic Multi-decadal Oscillation could account for up to 0.2°C peak-to-trough variability in NH mean decadal temperature.”

¹⁶ Taylor, Karl E., Ronald J. Stouffer, Gerald A. Meehl, 2012: An Overview of CMIP5 and the Experiment Design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498. <http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-11-00094.1>

¹⁷ <http://cmip-pcmdi.llnl.gov/cmip5/>

¹⁸ <http://www.climate-lab-book.ac.uk/2013/updated-comparison-of-simulations-and-observations/>

¹⁹ IPCC AR4 Chapter 9, p 686

Recent research on the impact of aerosols on radiative forcing of the climate has demonstrated that the overall cooling from aerosols is less than previously thought owing to a larger role for black carbon aerosols that have a net warming effect on climate²⁰.

With regards to multi-decadal natural internal variability, previous IPCC reports consider this issue primarily in context of detection of an anthropogenic warming signal above the background ‘noise’ of natural variability. The IPCC’s attribution of the late 20th century warming has focused on external radiative forcing, and no explicit estimate of the contribution of natural internal variability to the warming was made. A recent paper by Tung and Zhou²¹ suggests that the anthropogenic global warming trends might have been overestimated by a factor of two in the second half of the 20th century. They argue that a natural multidecadal oscillation of an average period of 70 years with significant amplitude of 0.3–0.4°C is superimposed on the secular warming trend, which accounts for 40% of the observed warming since the mid-20th century. Tung and Zhou identify this oscillation with the Atlantic Multidecadal Oscillation (AMO), although recent research²² suggests a more complex multidecadal signal propagating through a network of synchronized climate indices. Tung and Zhou argue that not taking the AMO into account in predictions of future warming under various forcing scenarios may run the risk of over-estimating the warming for the next two to three decades, when the AMO is likely in its down phase.

The recent research on natural internal variability and black carbon aerosols, combined with ongoing plateau in global average surface temperature, suggests that the AR4 estimates of climate sensitivity to doubling CO₂ may be too high, with implications for the attribution of late 20th century warming and projections of 21st century warming. The IPCC AR4 conclusion on climate sensitivity is stated as:

*“The equilibrium climate sensitivity. . . is likely to be in the range 2°C to 4.5°C with a best estimate of about 3°C and is very unlikely to be less than 1.5°C. Values higher than 4.5°C cannot be excluded. . .”*²³

This estimate of equilibrium climate sensitivity is not easily reconciled with recent forcing estimates and observational data. There is increasing support for values of climate sensitivity around or below 2°C^{24,25,26}. The meta-uncertainty of these estimates remains high owing to inadequacies in the methods used to determine sensitivity from observations and models²⁷. If the climate models are running too ‘hot’ in terms of predicting climate sensitivity that is too high, what are the possible problems with the models that might contribute to this? While the direct forcing from greenhouse gases is well understood, possible problems are associated with the magnitudes of the water vapor feedback and the cloud feedback. The cloud-radiative feedback is one of the most uncertain elements of climate models²⁸; even the sign is uncertain, although most climate models produce a positive cloud-radiative feedback (warming effect).

²⁰ Bond et al. 2013: Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res.* <http://onlinelibrary.wiley.com/doi/10.1002/jgrd.50171/abstract>

²¹ Tung, KK and J Zhou, 2013: Using data to attribute episodes of warming and cooling in instrumental records. *PNAS* <http://www.pnas.org/content/early/2013/01/22/1212471110.abstract>

²² Wyatt, MG and JM Peters 2012: A secularly varying hemispheric climate-signal propagation. *SpringerPlus*, 1:68, doi:10.1186/2193-1801-1-68. <http://www.springerplus.com/content/pdf/2193-1801-1-68.pdf>

²³ IPCC AR4 Summary for Policy Makers, op. cit., p. 12.

²⁴ M. J. Ring, D. Lindner, E. F. Cross and M. E. Schlesinger, “Causes of the Global Warming Observed since the 19th Century,” *Atmospheric and Climate Sciences*, Vol. 2 No. 4, 2012, pp. 401-415. <http://www.scirp.org/journal/PaperInformation.aspx?paperID=24283>

²⁵ Lewis, N. 2013: An objective Bayesian, improved approach for applying optimal fingerprint techniques to estimate climate sensitivity. *J. Climate*, doi: <http://dx.doi.org/10.1175/JCLI-D-12-00473.1>

²⁶ Masters, T. 2013: Observational estimate of climate sensitivity from changes in the rate of ocean heat uptake and comparison to CMIP5 models. *Climate Dynamics*, in press. <http://link.springer.com/article/10.1007/s00382-013-1770-4>

²⁷ Olson, R. et al. 2013: What is the effect of unresolved internal climate variability on climate sensitivity estimates? *J. Geophysical Sciences*, in press. <http://onlinelibrary.wiley.com/doi/10.1002/jgrd.50390/abstract>

²⁸ IPCC AR4 Summary for Policy Makers, op. cit., p 12.

Summary evaluation

The key conclusion of the IPCC AR4 is:

*“Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.”*²⁹

So what is the evidence for, and against, a dominant role in the climate since the mid-20th century of increasing human-induced greenhouse gas concentrations, and what are the major uncertainties? Below is my summary interpretation of the available evidence.

Evidence for:

- Long-term trend of increasing surface temperatures, for more than a century.
- Theoretical support for warming as greenhouse gas concentration increases.
- Long-term trend of increasing ocean heat content³⁰, although the trend for the past 10 years has been small in the upper 700 m of the ocean³¹.
- Decline in Arctic sea ice since 1979, with record autumn minimum in 2012.
- Sea level rise since 1961, although multi-decadal variability and confounding factors such as coastal land use and geologic process hamper interpretation of these data.³²
- Results from climate model simulations.

Evidence against:

- No significant increase in globally averaged temperature for the past 15 years.
- Lack of a consistent and convincing attribution argument for the warming from 1910-1940 and the plateau from the 1940s to the 1970s.
- Growing realization that multidecadal natural internal variability is of higher amplitude than previously accounted for in IPCC attribution analyses.

There are major uncertainties in many of the key observational data sets, particularly prior to 1980. There are also major uncertainties in climate models, particularly with regards to the treatments of clouds, solar indirect effects and the coupled multidecadal oscillations between the ocean and atmosphere. Further, there are meta-uncertainties regarding the methods used to make arguments about attribution of climate change and determine sensitivity to increasing greenhouse gases. And finally, climate models are apparently incapable of simulating emergent phenomena such as abrupt climate change.

In light of these uncertainties, what can we say about the future climate of the 21st century? Most scientists anticipate a decrease in solar forcing in the coming decades, but noting the absence of understanding the solar indirect effects on climate, this is not expected to dominate climate change in the 21st century³³. If the climate shifts hypothesis³⁴ is correct, then the current flat trend in global surface temperatures may continue for another decade or two, with a resumption of warming at some point during mid-century. The amount of warming from greenhouse gases depends both on the amount of greenhouse gases that are emitted as well as the climate sensitivity to the greenhouse gases, both of which are associated with substantial uncertainties.

²⁹ IPCC AR4 Summary for Policy Makers, op. cit., p 10.

³⁰ Balmaseda et al. 2013: Distinctive climate signals in reanalysis of global ocean heat content. *J. Geophys. Res.*, in press. <http://onlinelibrary.wiley.com/doi/10.1002/grl.50382/abstract>

³¹ <http://oceans.pmel.noaa.gov>

³² Gregory et al. 2012: Twentieth-century global mean sea-level rise: is the whole greater than the sum of the parts? *J. Climate*, <http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00319.1>

³³ G. S., M. Lockwood, and P. A. Stott (2012), What influence will future solar activity changes over the 21st century have on projected global near-surface temperature changes? *J. Geophys. Res.*, 117, D05103,

³⁴ Tsonis, A et al. 2007: op. cit.

Climate change and extreme weather

The prospect of increased frequency or severity of extreme weather in a warmer climate is potentially the most serious near term impact of climate change. Metaphors such as climate change ‘loading the dice’ for severe weather or causing ‘weather on steroids’ are frequently used to communicate an elevated probability of extreme weather events as a result of human-caused climate change. Because of their large socioeconomic impacts, weather catastrophes act as focusing events for the public in the politics surrounding the climate change debate. The occurrence of apparently unusual extreme weather events over the past decade has been used as an argument for action to reduce greenhouse gases in the atmosphere. In his recent State of the Union speech, President Obama made the following statement:

*“But for the sake of our children and our future, we must do more to combat climate change. Yes, it’s true that no single event makes a trend . . . Heat waves, droughts, wildfires, and floods – all are now more frequent and intense. We can choose to believe that Superstorm Sandy, and the most severe drought in decades, and the worst wildfires some states have ever seen were all just a freak coincidence. Or we can choose to believe in the overwhelming judgment of science – and act before it’s too late.”*³⁵

Trenberth³⁶ has argued that climate change is affecting all weather now, because the background conditions have changed as a result human-caused global warming. I don’t disagree with this statement; however there is no *prima facie* reason to think that global warming will make most extreme weather events more frequent or more severe. To understand the extent to which anthropogenic global warming might be contributing to individual or collections of extreme events, scientists need to demonstrate that the current extreme weather events are unusual in context of the historical record. Extreme events are by definition rare, and the rarer the event the more difficult it is to identify long-term changes from relatively short data records.

In 2012, the IPCC published a *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX). Key findings from the SREX³⁷ are cited below:

There is evidence from observations gathered since 1950 of change in some extremes. Confidence in observed changes in extremes depends on the quality and quantity of data and the availability of studies analyzing these data, which vary across regions and for different extremes. Assigning ‘low confidence’ in observed changes in a specific extreme on regional or global scales neither implies nor excludes the possibility of changes in this extreme. In many (but not all) regions over the globe with sufficient data, there is medium confidence that the length or number of warm spells or heat waves has increased. There have been statistically significant trends in the number of heavy precipitation events in some regions. It is likely that more of these regions have experienced increases than decreases, although there are strong regional and subregional variations in these trends. There is low confidence in any observed long-term (i.e., 40 years or more) increases in tropical cyclone activity (i.e., intensity, frequency, duration), after accounting for past changes in observing capabilities. There is low confidence in observed trends in small spatial-scale phenomena such as tornadoes and hail because of data inhomogeneities and inadequacies in monitoring systems. There is medium confidence that some regions of the world have experienced more intense and longer droughts, in particular in southern Europe and West Africa, but in some regions droughts have become less frequent, less intense, or shorter, for

³⁵ <http://www.whitehouse.gov/state-of-the-union-2013>

³⁶ Trenberth, KE 2012: Framing the way to relate climate extremes to climate change. *Climatic Change*, 115, 283-290. <http://link.springer.com/article/10.1007%2Fs10584-%C2%AD-012-%C2%AD-0441-%C2%AD-5?LI=true#page-1>

³⁷ IPCC SREX Summary for Policy Makers, http://ipcc-wg2.gov/SREX/images/uploads/SREX-SPMbrochure_FINAL.pdf

example, in central North America and northwestern Australia. There is limited to medium evidence available to assess climate-driven observed changes in the magnitude and frequency of floods at regional scales because the available instrumental records of floods at gauge stations are limited in space and time, and because of confounding effects of changes in land use and engineering. Furthermore, there is low agreement in this evidence, and thus overall low confidence at the global scale regarding even the sign of these changes. It is likely that there has been an increase in extreme coastal high water related to increases in mean sea level.

There is evidence that some extremes have changed as a result of anthropogenic influences, including increases in atmospheric concentrations of greenhouse gases. It is likely that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale. There is medium confidence that anthropogenic influences have contributed to intensification of extreme precipitation at the global scale. It is likely that there has been an anthropogenic influence on increasing extreme coastal high water due to an increase in mean sea level.

While there is limited observational evidence for an increase in the frequency or intensity of most types of extreme weather events, the SREX finds that climate models project increases in frequency and/or intensity of many types of extreme weather events by the end of the 21st century. However, climate models do a poor job of simulating the variability and intensity of rainfall even in the present climate, and also do not resolve tropical cyclones adequately. Further, climate models do not adequately simulate the modes of natural internal variability. *Nature* recently reported:

*At a workshop last week in Oxford, UK, convened by the Attribution of Climate-related Events group — a loose coalition of scientists from both sides of the Atlantic — some speakers questioned whether event attribution was possible at all. It currently rests on a comparison of the probability of an observed weather event in the real world with that of the ‘same’ event in a hypothetical world without global warming. One critic argued that, given the insufficient observational data and the coarse and mathematically far-from-perfect climate models used to generate attribution claims, they are unjustifiably speculative, basically unverifiable and better not made at all . . . Better models are needed before exceptional events can be reliably linked to global warming.*³⁸

Attempts to attribute individual extreme weather events, or collections of extreme weather events, may be fundamentally ill-posed in the context of the complex, chaotic climate system. In addition to the substantial difficulties and problems associated with attributing changes in the average climate to natural variability versus anthropogenic forcing, attribution of extreme weather events is further complicated by their rarity and their dependence on weather regimes and internal multi-decadal oscillations that are simulated poorly by climate models. Given these challenges, why is attribution of extreme events deemed important by climate scientists? The *Nature* summary on the Oxford workshop states:

None of the industry and government experts at the workshop could think of any concrete example in which an attribution [of extreme weather events] might inform business or political decision-making. Especially in poor countries, the losses arising from extreme weather have often as much to do with poverty, poor health and government corruption as with a change in climate. These caveats do not mean that event attribution is a lost cause. But they are a reminder that designers of climate services must think very clearly about how others might want to use the knowledge that climate scientists produce.

³⁸ Nature editorial: Extreme Weather, 2012: *Nature* **489**, 335–336. <http://www.nature.com/news/extreme-weather-1.11428>

Preliminary damage estimates rank Hurricane Sandy as the 2nd costliest Atlantic hurricane, only behind Hurricane Katrina. When Sandy made landfall, it was categorized as a post-tropical cyclone with winds equivalent to a Category 1 hurricane. Sandy's 13 ft storm surge arose from a combination of a very large horizontal extent of the storm plus high tide conditions. Climate scientists and meteorologists continue to argue about what role human-induced climate change might have played in Sandy, but as described above, there is no obvious link to human-caused climate change and attempts at such attribution may be fundamentally an ill-posed problem. Hurricane Sandy, along with Hurricane Katrina and the hurricanes that struck Florida during 2004 and 2005, have focused debate on whether climate change portends more frequent or more severe hurricane impacts. I have provided Congressional testimony twice on the subject of hurricanes and global warming³⁹ and recently wrote an extended assessment report on the topic.⁴⁰

The current elevated hurricane activity in the North Atlantic is associated with the warm phase of the Atlantic Multidecadal Oscillation, which could continue for another decade or two. The recent transition to the cool phase of the Pacific Oscillation is associated with a greater frequency of La Nina events, which are associated with elevated hurricane activity and a preference for Atlantic landfalls (relative to Gulf landfalls).⁴¹ With regards to possible impacts from human-induced climate change, an increase in hurricane intensity has been observed over the past several decades, although it is not easily separated from the large signal from the Atlantic Multidecadal Oscillation. The extension of the tropical Atlantic warm pool eastward towards Africa may be attributable to anthropogenic global warming⁴²; the main impact of this extended warm pool seems to be a tendency for hurricanes to form further east in the Atlantic and recurve northwards, reducing the number of U.S. landfalls.

With regards to the perception (and damage statistics) that severe weather events seem more frequent and more severe over the past decade, there are several factors in play. The first is the increasing vulnerability and exposure associated with increasing concentration of wealth in coastal and other disaster-prone regions. The second factor is natural climate variability. Apart from a possible impact from human-induced climate change, many extreme weather and climate events have documented relationships with natural climate variability, notably El Niño/La Niña, the Atlantic Multidecadal Oscillation (AMO), and Pacific Decadal Oscillation (PDO). We are currently in the warm phase of the AMO and the cool phase of the PDO. The previous analogue for this regime was the 1950s, or more specifically the period from 1946 to 1964. This period was also very active in terms of Atlantic hurricanes,⁴³ especially with regards to U.S. landfalling major hurricanes. Drought in the U.S. is more frequent during the warm phase of the AMO, with drought in the U.S. southwest and Texas being more common during the cool phase of the PDO.⁴⁴ The analogy of the last decade with the previous regime of warm AMO/cool PDO in terms of extreme weather/climate events is imperfect, because global temperatures are about 1°F warmer and Arctic sea ice extent has decreased. The decrease in autumn sea ice has recently been associated with changes in atmospheric circulation patterns and an increase in winter snowfall in North America and Eurasia.⁴⁵

³⁹ <http://curry.eas.gatech.edu/climate/pdf/testimony-curry.pdf>; http://www.eas.gatech.edu/files/Curry_Energy.pdf

⁴⁰ <http://judithcurry.com/2010/09/13/hurricanes-and-global-warming-5-years-post-katrina/>

⁴¹ Kim, H.M., P. J. Webster and J. A. Curry, 2009: Impact of shifting patterns of Pacific Ocean warming on the frequency and tracks of North Atlantic tropical cyclones. *Science*, 325, 77-80.
http://webster.eas.gatech.edu/Papers/KimWebsterCurry_Science_2009.pdf

⁴² Hoyos, C. D. and Webster, P. J., 2011: Evolution of the tropical warm pool: Past, present and future. *Clim. Dyn.* doi: 10.1007/s00382-011-1181-3. http://webster.eas.gatech.edu/Papers/Hoyos_Webster2011.pdf

⁴³ http://www.eas.gatech.edu/files/ins_tampa_09.pdf

⁴⁴ McCabe G J et al. 2004: *PNAS*, 101, 4136-4141.

⁴⁵ Liu, J, JA Curry et al., 2011: Impact of declining Arctic sea ice on winter snowfall. *PNAS*,
<http://curryja.files.wordpress.com/2012/03/pnas.pdf>

Reasoning about climate uncertainty

How to reason about uncertainties in the complex climate system and its model simulations is neither simple nor obvious. Scientific debates involve controversies over the value and importance of particular classes of evidence and disagreement about the appropriate logical framework for assessing the evidence.

The IPCC characterization of uncertainty is based upon a consensus building process that is an exercise in collective judgment in areas of uncertain knowledge. The general reasoning underlying the IPCC's arguments for anthropogenic climate change combines a compilation of evidence with subjective Bayesian reasoning. Given the complexity of the climate problem, expert judgments about uncertainty and confidence levels are made by the IPCC on issues that are dominated by unquantifiable uncertainties. I have argued in a paper entitled *Reasoning About Climate Uncertainty*⁴⁶ that biases can abound when reasoning and making judgments about such a complex problem, through weighting of evidence and excessive reliance on a particular piece of evidence, the presence of cognitive biases in heuristics, failure to account for indeterminacy and ignorance, and logical fallacies and errors including circular reasoning. Further, the consensus building process itself can be a source of bias.

Identifying the most important uncertainties and introducing a more objective assessment of confidence levels requires introducing a more disciplined logic into the climate change assessment process. Improved understanding and characterization of uncertainty and ignorance would promote a better overall understanding of the science and how to best target resources to improve understanding. A concerted effort is needed to identify better ways of exploring and characterizing uncertainty, reasoning about uncertainty, and eliminating bias from the consensus building process itself. There are some encouraging efforts in this direction, including a special issue of the journal *Climatic Change*.⁴⁷ There is also a rapidly growing effort in the area of uncertainty quantification and management with regards to climate models and climate model simulations.

No consensus on consensus

With substantial uncertainties in observations, models and our understanding of processes such as natural variability, along with challenges of reasoning about uncertainty in the complex climate system, there would seem to be plenty of scope for disagreement among scientists. Nevertheless, the IPCC consensus about dangerous anthropogenic climate change is portrayed as nearly total among scientists with expertise and prominence in the field of climate science, and the IPCC consensus has been endorsed by the relevant national and international science academies and scientific societies. I recently authored a paper entitled *Climate Change: No Consensus on Consensus*⁴⁸ that explores the history and consequences of the IPCC's scientific consensus building activities, which provides the basis for my comments here.

To understand the role of scientific consensus in policy making, it is important to understand the policy context for the information on dangerous climate change and the way the political process views uncertainty. The mandate of the IPCC is to provide policy-relevant information to policy makers involved in the UN Framework Convention on Climate Change (UNFCCC). Using the precautionary principle, the UNFCCC established a goal of avoiding dangerous climate change by stabilization of the concentrations

⁴⁶ Curry, JA 2011: Reasoning About Climate Uncertainty. *Climatic Change*, 108, 723-732.
<http://link.springer.com/article/10.1007%2Fs10584-011-0180-z>

⁴⁷ Yohe, G and M. Oppenheimer, 2011: Evaluation, characterization and communication of uncertainty by the intergovernmental panel on climate change – an introductory essay. *Climatic Change*, 108, 629-639.
<http://link.springer.com/article/10.1007%2Fs10584-011-0176-8>

⁴⁸ Curry, JA and PJ Webster 2013: No consensus on consensus. *CAB Reviews*, 8, 001.
<http://judithcurry.com/2012/10/28/climate-change-no-consensus-on-consensus/>

of atmospheric greenhouse gases. The IPCC scientific assessments play a primary role in legitimizing national and international policies aimed at reducing greenhouse gas emissions. The main practical objective of the IPCC has been to assess whether there is sufficient certainty in the science so as to trigger political action to reduce greenhouse gas emissions, and to optimize stabilization targets using climate models. This objective has led to the IPCC assessments being framed around identifying anthropogenic influences on climate, dangerous environmental and socio-economic impacts of climate change, and stabilization of CO₂ concentrations in the atmosphere.

The strategy adopted by the UNFCCC/IPCC is based on the linear model of expertise, whereby more scientific research leads to more reliable knowledge and less uncertainty, and the scientific knowledge then forms the basis for a political consensus leading to meaningful action. In the linear model, the key question is whether scientific knowledge is certain enough to compel action. Given the substantial uncertainties in climate science, the IPCC has arguably adopted a ‘speaking consensus to power’ approach⁴⁹ that attempts to mediate uncertainty and dissent into a consensus. The ‘speaking consensus to power’ strategy acknowledges that available knowledge is inconclusive, and uses consensus as a proxy for truth through a negotiated interpretation of the scientific evidence.

The growing implications of the complexity of the climate change problem and its potential solutions are becoming increasingly apparent, highlighting the inadequacies of the ‘consensus to power’ approach for decision making on the complex issues associated with climate change.

Decision making under ‘deep uncertainty’

My particular interest in the topic of decision making under uncertainty is to understand the dynamics of uncertainty at the climate science-policy interface. I am questioning whether these dynamics are operating in a manner that is healthy for either the science or the policy process, and whether climate science can more usefully support the policy process.

When uncertainty is well characterized and there is confidence in the model structure, classical decision analysis can provide statistically optimal strategies for decision makers. When uncertainty is not well characterized and there is concern about ‘known unknowns’ and ‘unknown unknowns,’ there is increasing danger of getting the wrong answer and optimizing for the wrong target. Given the ‘messy wickedness’ of the climate change problem with irreducible uncertainties and substantial ignorance, reducing the uncertainty isn’t viable, but not acting could be associated with catastrophic impacts. While the precautionary principle states that scientific uncertainty should not preclude preventative measures, greater levels of certainty are usually more conducive to motivating precautionary measures. In this context, making a scientific argument that uncertainty is underestimated and the consensus is overconfident is regarded as making a political statement to sow doubt and so delay action in taking precautionary measures.⁵⁰ If discussing uncertainty and engaging with skeptics is regarded as a political statement or as ‘heresy’⁵¹ then it seems to me that something is wrong with the science-policy interface and the decision-analytic framework that is being used.

In context of decision making, ‘deep uncertainty’⁵² refers to: situations in which the phenomena are still only poorly understood and experts do not know or cannot agree on models that relate key forces that

⁴⁹ Van der Sluijs, J, 2012: Uncertainty and dissent in climate risk assessment: a postnormal perspective. *Nature and Culture*, 7, 174–195

⁵⁰ Oreskes, N. and E.M. Conway (2010) *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming*. Bloomsbury Press, 368 pp.

⁵¹ Climate Heretic: Judith Curry Turns on her Colleagues. *Scientific American*, 10/23/10
<http://www.scientificamerican.com/article.cfm?id=climate-heretic>

⁵² Bammer, G and M Smithson 2008: *Uncertainty and Risk: Multidisciplinary Perspectives*. Taylor & Francis, 382 pp.

shape the future; modeling and subjective judgments are used rather than estimates based upon previous experience of actual events and outcomes; and experts cannot agree on the value of alternative outcomes. The climate change problem arguably meets all three of these criteria.

Rather than choosing an optimal policy based on a scientific consensus, decision makers can design robust and flexible policy strategies that account for uncertainty, ignorance and dissent. Robust strategies formally consider uncertainty, whereby decision makers seek to reduce the range of possible scenarios over which the strategy performs poorly. Flexible strategies are adaptive, and can be quickly adjusted to advancing scientific insights. Under conditions of deep uncertainty, the following options are open to decision makers⁵³:

- Delay in order to gather more information and in the hope of reducing uncertainties
- Enlarge the knowledge base for decisions through broader perspectives
- Invoke the precautionary principle
- Adaptive management
- Build a resilient society.

Each of these strategies incorporates information about uncertainty into the decision making process, albeit in different ways. In the past, the climate policy choices have been framed as a choice between delaying until uncertainties are reduced versus invoking the precautionary principle aimed at emission stabilization targets determined largely by climate models. The other options are receiving increasing attention in policy deliberations. The World Bank has a recent paper entitled *Investment decision making under deep uncertainty – application to climate change*⁵⁴ that summarizes existing decision-making methodologies that are able to deal with the deep uncertainty associated with climate change: cost-benefit analysis under uncertainty, cost-benefit analysis with real options, robust decision making, and Climate Informed Decision Analysis. The World Bank document describes Climate Informed Decision Analysis (CIDA) in the following way:

“Climate Informed Decision Analysis is a method of incorporating climate change information into the decision-making process, by first identifying which sets of climate changes would affect the project and then determining the likelihood of those sets. As a process committed to acceptance of deep uncertainties, CIDA does not attempt to reduce uncertainties or make predictions, but rather determine which decision options are robust to a variety of plausible futures.” (p 24)

The role of climate science in CIDA is to determine the plausibility of relevant groups of climate conditions that would affect the project. This can be accomplished by sensitivity analyses using climate models, analysis of historical and paleo- climate data, and the use of statistical models. The World Bank document describes the use of climate scenarios:

“Climate scenarios can be generated parametrically or stochastically to explore uncertainty in climate variables that affect the system of interest. This allows sampling changes in climate that include but are not constrained by the range of GCM [climate model] projections. The definition of scenarios can be developed as part of a stakeholder-driven, negotiated process, and climate projections can be used in this process. Alternatively, a very wide range of climate alterations can be developed independent of their plausibility and used to identify risks. For scenarios in which the climate consequences exceed coping thresholds, it is then fruitful to evaluate the plausibility of the scenarios. Climate projections, paleo-climate reconstructions, and subjective climate knowledge could all inform such discussions.”

⁵³ *ibid.*

⁵⁴ <http://elibrary.worldbank.org/content/workingpaper/10.1596/1813-9450-6193>

Conclusion

The climate community has worked for more than 20 years to establish a scientific consensus on anthropogenic climate change. The IPCC consensus building process arguably played a useful role in the early synthesis of the scientific knowledge. However, I have argued that the ongoing scientific consensus seeking process has had the unintended consequence of oversimplifying both the problem and its solution, introducing biases into the both the science and related decision making processes. The growing implications of the messy wickedness of the climate change problem are becoming increasingly apparent, highlighting the inadequacies of the ‘consensus to power’ approach for decision making on the complex issues associated with climate change.

The politicization of climate change presents daunting challenges to climate science and scientists. In my assessment, the single most important actions that are needed with regards to climate science – particularly in context of assessments for policymakers – is explicit reflection on uncertainties, ambiguities and areas of ignorance (both known and unknown unknowns) and more openness for dissent. Natural internal variability is a topic of particular importance over which there is considerable disagreement. Disagreement and debate is the soul of the scientific frontier, which is where much of climate science lies. Greater openness about scientific uncertainties and ignorance, and more transparency about dissent and disagreement, would provide policymakers with a more complete picture of climate science and its limitations. When working with policy makers and communicators, scientists should not fall into the trap of acceding to inappropriate demands for certainty; the intrinsic limitations of the knowledge base need to be properly assessed and presented to decision makers. The role of scientists should not be to develop political will to act by hiding or simplifying the uncertainties, either explicitly or implicitly, behind a negotiated consensus.

Increasingly, arguments are being made to abandon the scientific consensus seeking approach⁵⁵ in favor of open debate and discussion of a broad range of policy options that stimulate local and regional solutions to the multifaceted and interrelated issues surrounding climate change. There are frameworks for decision making under deep uncertainty that accept uncertainty and dissent as key elements of the decision making process. Rather than choosing an optimal policy based on a scientific consensus, decision makers can design robust and flexible policy strategies that account for uncertainty, ignorance and dissent. Robust strategies formally consider uncertainty, whereby decision makers seek to reduce the range of possible scenarios over which the strategy performs poorly.

The decision making framework referred to as Climate Informed Decision Analysis has the potential to provide a more useful role for climate scientists and an expanded role for a broader range of different types of climate information. The outcome of CIDA is not a single optimal decision, but a decision matrix that reflects stakeholder concerns and reveals which specific dangers might be associated with specific decisions and supports improved cost-benefit analyses. This decision making framework, along with other frameworks for decision making under deep uncertainty, is more democratic and transparent and avoids the hubris of pretending to know what will happen in the future.

Returning to my experiences with decision makers in using weather and seasonal climate forecasts, I would like to remind that uncertainty about the future climate is a two-edged sword. There are two situations to avoid: i) issuing a highly confident statement about the future that turns out to be wrong; and ii) missing the possibility of an extreme, catastrophic outcome. Avoiding both of these situations requires much deeper and better assessment of uncertainties and areas of ignorance, as well as creating a broader range of future scenarios than is currently provided by climate models.

⁵⁵ Hulme, M., 2013: Lessons from the IPCC: Do Scientific Assessments Need to be Consensual to be Authoritative? <http://www.csap.cam.ac.uk/events/future-directions-scientific-advice-whitehall/>

Short Biography

Judith Curry
Chair and Professor, School of Earth and Atmospheric Sciences
Georgia Institute of Technology
Atlanta, GA 30332-0349
curryja@eas.gatech.edu

Dr. Judith Curry is Professor and Chair of the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology and President of Climate Forecast Applications Network (CFAN). Dr. Curry received a Ph.D. in atmospheric science from the University of Chicago in 1982. Prior to joining the faculty at Georgia Tech, she held faculty positions at the University of Colorado, Penn State University and Purdue University. Dr. Curry's research interests span a variety of topics in climate; current interests include air/sea interactions, climate feedback processes associated with clouds and sea ice, and the climate dynamics of hurricanes. She is a prominent public spokesperson on issues associated with the integrity of climate science, and has recently launched the weblog Climate Etc. judithcurry.com. Dr. Curry currently serves on the NASA Advisory Council Earth Science Subcommittee and the DOE Biological and Environmental Research Advisory Committee, and has recently served on the National Academies Climate Research Committee and the Space Studies Board and the NOAA Climate Working Group. Dr. Curry is a Fellow of the American Meteorological Society, the American Association for the Advancement of Science, and the American Geophysical Union.

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For more information:

<http://curry.eas.gatech.edu/>

<http://www.cfanclimate.com/>

<http://judithcurry.com>