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Madam Chair, Ranking Member Lukas, and Members of the Committee, thank you for inviting me to participate in this morning's hearing on extreme weather. I am Adam Sobel, a professor and atmospheric scientist at Columbia University's Lamont-Doherty Earth Observatory and School of Engineering.

Introduction

In this testimony I will cover three topics:

- A brief overview of the relationship of different extreme weather events to climate change;
- In the case of hurricanes in particular, some of the complexities of their relationship to climate, the sources of uncertainty, and the challenges this poses for communicating and acting on our understanding of the risks they pose; and
- Recommendations for future research, with an emphasis on an expanded view of what the insurance industry calls "catastrophe modeling".

My testimony is based on the peer-reviewed literature, including reports from the Intergovernmental Panel on Climate Change, the National Climate Assessments, and others, as well as being informed by my own research and that of my colleagues at Columbia. I was one of the authors of a 2016 National Academy of Sciences Report *Attribution of Extreme Weather Events in the Context of Climate Change,* which also informs my views.

How extreme weather is affected by climate change: An overview

Extreme weather is changing as a consequence of human-induced climate change. How it is changing, how quickly, and how well we can detect those changes varies across different kinds of extreme weather events. In my view, there are multiple answers to the question "how are extreme weather events changing"?

Let us first establish some basic concepts. Weather is the instantaneous state of the atmosphere and its evolution over short time scales – days, say. Climate, to take the simplest definition, is the average of the weather over long periods of time. The climate is strongly influenced by external factors, some of which are predictable and act over long periods of time: the position of the earth in its orbit around the sun, the slow circulation of the oceans, and the concentrations of greenhouse gases in the atmosphere. While these factors may control the climate, the internal chaotic dynamics of the atmosphere still give the weather much freedom to fluctuate about that climate. So every weather event, including an extreme one, has many proximate causes, and most of those causes are natural. (Chaos theory teaches us, in fact, that we cannot trace these paths of causality very far back in time in the atmosphere.) So it is never accurate to say that climate change "caused" a single weather event without further qualification. But a change in climate can still change the *probability* that a given type of weather event will occur, or the severity of events in a given class when they do occur. (Event attribution studies, such as described in the 2016 National Academy report, assess those changes in probability or severity for individual events, and investigate to what extent – always much less than 100% - climate change can be held responsible for a given event.) We need to understand those causal links in order to know how to best respond to the reality of human-induced climate change.

Our understanding rests on three distinct sources: observations of the events; numerical models that allow us to simulate and predict them in the context of the larger climate within which they occur; and "theory". By theory, I mean our well-grounded and tested understanding of the first principles that govern the events and their relationship to climate, principles that can be expressed without resorting to numerical models. When observations, models and theory yield similar answers about how some type of event is related to climate, we become more confident in our understanding of the relationship. If one or more of the three is inadequate, or they are inconsistent with one another, we are much less confident.

Heat waves are the best example of a case where observations, models, and theory converge. Observations show heat waves increasing in frequency and intensity in most parts of the world; we understand well how heat waves are related to the climate in which they occur; and because climate models predict that they should be increasing in frequency and intensity. At this point in history, when a heat wave occurs, one can almost say with confidence that global warming made it *more likely*, *more intense* or *both*, even without doing a formal attribution study.

To take the other extreme, we know relatively little about how tornadoes are changing. The observations do show some changes in statistics of tornado occurrence – especially, increasing tendency for them to be bunched into large outbreaks, rather than spaced out more in smaller clusters. But the observations themselves are imperfect; and beyond that, we do not have the necessary theoretical understanding of how tornadoes are related to climate to be able to say with confidence that these changes are caused by warming, and climate models at this point provide only weak guidance.

Most kinds of extreme weather fall in between these extremes of understanding and ignorance.

We have good confidence that heavy rain events are increasing in many parts of the world: again observations, theory and models are all broadly consistent. Droughts and wildfires are both to some degree influenced directly by temperature, so we have good confidence that global warming increases either the frequency or intensity of these events under some conditions, although other factors that influence them may sometimes be more important.

In the case of wildfires such as those that have devastated the American west in recent years, warming and drying are the primary causes. Pre-historical evidence stored in tree rings and charcoal buried in lakes tell us that for thousands of years, periods of warming have coincided with periods of increased wildfire activity in this region. While fire is very complex and affected by much more than just climate, the data from recent decades indicate the same thing today as in the past: the hot years are the years with the most wildfire, and as temperatures have increased, burned areas have increased in step. It is entirely possible that on-the-ground human factors such as land management and accidental ignitions have set the stage for an especially potent fire response to warming in some areas, but the relationship between annual burned areas and temperature has nonetheless been strong and stable over the past few decades. We should plan for continued increases in western U.S. wildfire activity due to continued warming.

We have relatively little understanding of how winter storms are changing, except we know that warming makes some storms produce rain when they would have produced snow in the past (though when it remains cold enough to snow, warming can under some conditions increase the amount of snow).

In-depth example: Hurricanes

Of all types of extreme weather, hurricanes do the most damage. Hurricane Dorian's absolute devastation of the Bahamas is fresh in our minds; the U.S. was fortunate to escape major impacts from Dorian, but was not so fortunate with Hurricanes Michael and Florence last year, or Hurricanes Harvey, Irma, or Maria in 2017. Hurricanes are also the focus of my own research, and the issues around interpreting their relationship to climate are to some extent representative of those with other kinds of events. Hurricanes illustrate some broader issues around communicating and acting on our scientific understanding of the risk, as well as for their own intrinsic importance.

What we know about changes in hurricanes

What do we know about how hurricanes are changing with climate? We can give the most precise answer if we break it down into different aspects.

The most certain way in which hurricane risk is increasing due to climate is that, because of sea level rise, coastal flooding due to hurricane storm surge is becoming worse. Storm surge occurs when the winds from a storm push the ocean onto the land. The total flooding is determined by the surge (the part produced by the wind), the tide, and the background average sea level. As sea level has risen – about a foot in New York City, for example, of which about eight inches is related to climate - for any given combination of storm and tides, the flooding is exacerbated by that amount. There is no doubt about this. The flooding Hurricane Sandy produced, for example, was due to nine feet of storm surge plus a high tide that was five feet above low tide. So the eight inches of additional water due to sea level rise was a small fraction of that, but still a significant one. There is no question this number will increase in the future; sea level rise projections are uncertain in magnitude, but certain in sign: sea level will only go up, not down.

Also the rain hurricanes produce is increasing. Rain-driven flooding from storms like Harvey and Florence is becoming exacerbated, perhaps somewhere between five and twenty percent per degree Celsius (or per 1.8 degrees Fahrenheit) of warming.

In the case of Harvey – and also Dorian in the Bahamas, though its damage was more due to wind and surge than rain – the disaster was made much worse by the slow forward motion of the storm, so that it stayed in one place for a long time. Several recent studies show that storms on average have been slowing down, and suggest that this is a consequence of climate change. These are relatively new findings, not fully understood or digested by the scientific community yet, so this conclusion is particularly uncertain. But the studies are of high quality, and their implications are very serious, so they should be taken into consideration as part of our overall assessment of risk.

Another fairly certain consequence of warming is that hurricane winds are strengthening. Again there is support for this conclusion from observations, theory, and numerical models. The evidence is particularly strong for the north Atlantic – the source of the hurricanes that threaten the United States. The magnitude of the increases in intensity we can attribute to warming is not clear; it may only be a few percent, but even that is significant. The strongest storms do by far the most damage, and increases in intensity at the high end mean more category four and five storms. Because damage is proportional to wind speed cubed, or perhaps even a higher power, we see that for a given small percentage increase in wind, the damage increase is three or more times greater.

In contrast, some aspects of changes in hurricanes are almost entirely uncertain. In particular, we can say very little about how hurricane frequency – the total number of storms that occur each year – will change with warming. Because all other aspects of changes in hurricanes only matter if, where and when a hurricane occurs in the first place, this uncertainty about hurricane frequency limits our ability to assess overall hurricane risk in a changing climate.

We do not have a good understanding of what controls the overall number of tropical cyclones (tropical storm intensity and higher) on the earth presently, which is around 90 per year for the whole earth, around 11 for the Atlantic. Additionally, and we do not have any physical theory for how this should change as climate does. The observations lack any clear indication, mostly showing large fluctuations year to year and decade to decade that make it difficult to discern clear trends. Until recently, numerical simulations tended to show that hurricane frequency should decline with warming, but in the last few years simulations with a couple of the best models have instead produced increases. This produces a large uncertainty in our overall assessment of hurricane risk; if each storm on average produces stronger winds, heavier rains, and worse coastal flooding, but the total number of storms were to decrease enough, the total hazard - the probability of an event of a given magnitude at any given location – might still stay constant, or even decrease. But if the number of storms increases along with the intensities of their wind and rains, then we are in even bigger trouble.

With hurricanes we have the following complex situation: Some aspects are certainly becoming worse with warming; others are likely becoming worse, but with some uncertainty; and other aspects are very uncertain, such that changes in the overall hazard are also uncertain. This situation is broadly representative of other kinds of extreme weather events. The degree of uncertainty varies, but is usually substantial. Yet it would be a grave mistake to interpret this uncertainty as license to ignore the problem and postpone action on climate. There are at least two reasons for this.

Uncertainty is not our friend

Uncertainty about how the risk is changing means we have to accept some possibility of the worst outcome, namely that the risk is increasing at the upper bound of plausible scientific estimates. This is sometimes known as the "precautionary principle", and it is consistent with how human beings rationally deal with other kinds of risks in life, particularly when the worst outcomes would be truly serious.

Much of the uncertainty in our understanding of changes in extreme weather is due to the fact that our observational record is short while natural variability is large, so that it is difficult to separate the contribution of human influence from that natural variability. The climate fluctuates naturally from year to year, decade to decade, and even century to century. The gradual trends due to human-induced climate change are superimposed on these large fluctuations. With extreme events, the fluctuations are even larger because the events are - by definition – rare, so that the statistics are less conclusive.

To understand this, just flip a coin some number of times, and calculate the fraction of the time it comes up heads. Repeat with different numbers of coin flips, and notice that the more flips you have, the closer your average generally gets to 0.5. When we look at extreme events compared to regular weather, it's like having fewer coin flips. Now to understand the role of climate change, try to imagine that we are trying to determine whether the coin is fair, or whether the probability of heads has become, say, slightly greater than 0.5, though it was 0.5 in the past. This will be more difficult the fewer flips we have; that example is similar to the situation with hurricanes, since there are few of them compared to days with normal weather.

Further, climate scientists traditionally apply criteria for detecting and attributing trends that are very conservative: they are designed to minimize the risk of a so-called type 1 error (claim of a change when none is actually present, or "false alarm") but in doing so they maximize the probability of type 2 errors (failure to detect a change when one actually is present).

NOAA makes the public statement, as is currently visible on one of its web pages maintained at the Geophysical Fluid Dynamics Laboratory: "In the Atlantic, it is premature to conclude with high confidence that human activities–and particularly greenhouse gas emissions that cause global warming–have already had a detectable impact on hurricane activity." A few sentences later: ""Human activities may have already caused other changes in tropical cyclone activity that are not yet detectable due to the small magnitude of these changes compared to estimated natural variability, or due to observational limitations."

What NOAA is trying to say, in my view, is "there are changes, but we cannot show at 95% confidence that those changes could not have occurred in the absence of human-induced climate change". That may be true, but I would argue that that is not the right question to ask. We know that human-induced climate change is present. The right question is: what is our best estimate of what the changes are, with what confidence? How wide is the range of possibilities that are reasonably consistent with the data, and what is the worst-case scenario?

The most important thing to understand here is: when it comes to disaster risk, uncertainty is not our friend.

When faced with risks we can't assess precisely, but where we have some evidence that they may be increasing, choosing to ignore that evidence because of uncertainty is not prudent. Imagine you want to cross a highway. There are few cars on this highway, but they drive fast, and you can't see around a sharp corner. You don't know the probability that a car is coming, and none have come by for a for a while. Do you assume it's fine and walk across? Or, if there were an action you could take that would reduce your risk, even at some cost – say, walking to somewhere with a better view in both directions, even if it makes you late to where you need to be – wouldn't you do it?

Or, we can make the analogy a little closer using another risk that is hard to quantify: terrorism.

Imagine that a U.S. intelligence agency has some evidence that some bad people somewhere in the world may be planning an attack. The evidence is inconclusive, but strong enough to warrant concern. These bad people are having a meeting somewhere, and it is suspected that their agenda at that meeting is to plan the attack. U.S. agents are not present at the meeting, but have managed to plant a microphone in the room, connected to a transmitter so that they can hear the sound in the room at their offices in the U.S. But the room is noisy and the bad people are speaking quietly, so it is impossible to make out what they are saying, and thus impossible to be sure if they are really planning the attack or not. Would we want the U.S. agents to interpret this uncertainty as meaning everything is fine and no action needs to be taken? Or would we want them to take whatever measures they have at their disposal to prevent the attack, given whatever incomplete information they do have? In this analogy, the possible terrorist attack represents the possibility that hurricane frequency is increasing - along with hurricane wind intensity, rain, and coastal flooding – representing the greatest possible increase in risk. The "noise" is natural variability.

In this example, I think most of us would want to take action and the same is true, in my view, with respect to extreme weather and climate.

Changes in the future will be greater than in the past or present

In addition to taking inappropriate comfort from uncertainty, another fallacy is to assess the human influence on extreme weather risk using only data from the present, while ignoring *the likely greater increases in the future*.

Human-induced climate change has already caused changes in some kinds of extreme weather events. Attribution studies are now done in real time to assess to what extent any given event that just happened may have been influenced by global warming. These studies are important in helping the public to understand the links between climate and extreme weather, because they capture attention during the teachable moments right after major disasters.

But by focusing attention on the present, when the warming is less than it will be in the future, they can actually give the impression that climate change is less serious than it is, once we accept some responsibility to future generations. With many kinds of events – including hurricanes – event attribution studies give inconclusive results, because of the large natural variability and short, imperfect historical records (and sometimes also because numerical models are not quite good enough to do such studies). If an attribution study gives inconclusive results, as some do, that might leave the impression that climate is not changing that kind of event, and that this is one less reason for action now. Perhaps it would make more sense to wait until we see clearer indications of human influence in extreme events, and then take action. The problem here is that there is a long lag between action and result when it comes to greenhouse gas emissions. We need action now if we hope to reduce the impacts of climate change in the future.

The greenhouse gases already emitted by human activity have committed us to some additional warming beyond what has already been realized, due to the time it takes for the ocean to warm. We are almost certainly committed to additional warming beyond that due to the commitment baked into our current economic and energy systems – that is, absent much stronger and more immediate commitments to decarbonization than currently appear likely, greenhouse gas emissions will continue at sufficient rates to drive further warming for some time. If the climate were a ship, it would be a very large aircraft carrier or ocean liner – it can't be turned around quickly. As further warming proceeds, the changes in extreme weather will continue to grow.

We cannot wait until all the uncertainties have resolved themselves. To take the case of hurricanes, by the time we know with precision how much hurricane risk increases with each degree of warming, the risk will have increased quite a lot – that is how we will be sure, because only then will the data show it conclusively – and by then we will have baked in yet much more warming, warming that we could have avoided with earlier action.

Future Research Challenges

There are several different areas where additional research on extreme weather is urgently needed.

Short-term forecasts directly save lives and property. Weather forecasts, including those for extreme weather, have continuously improved from decade to decade since the mid-20th century. The three-day hurricane track forecast today, for example, is as good as the one-day forecast was 30 years ago --- and two extra days of warning makes an enormous difference in emergency managers' abilities to save lives and property. This increase in forecast skill is an amazing success story of science and technology, even if the public doesn't always recognize it, and it has been largely driven by federal investment in research – much of which was authorized by this Committee. Such improvements will continue as long as the government sustains its support of the research into the observations, numerical models, data assimilation, and high-performance computing that form the backbone of the modern weather, water and climate enterprise --- and the Congress continues to exercise constructive oversight on weather and climate research as it has done via the Weather Research and Forecasting Innovation Act of 2017.

On the longer time scale, an exciting development of the last decade or so has been the emergence of some skill in numerical models on the "subseasonal to seasonal" time scale – especially the subseasonal, meaning roughly 2-4 weeks ahead. This new capability is making it possible to produce forecasts of some phenomena on that time scale. But these forecasts remain mostly experimental and have only a very small amount of skill. The challenges are not just to figure out what can be usefully predicted and to make the predictions better, but also to figure out *how to communicate and use forecasts when they are only slightly better than no forecast at all.* You can make money if you bet on such a forecast over a long time, but much of the time it will still be wrong. Under what circumstances is such a forecast useful, and how can one make sure users understand its limitations and do not develop unrealistic expectations that are sure to be disappointed? For example, there might be moves that could be taken to begin pre-positioning people or materials well in advance of a wildfire or hurricane that appears possible in two weeks, due to a subseasonal forecast, such that the response to a disaster later will be more effective, but that are sufficiently inexpensive that there will be little regret if the event does not materialize.

For more accurate detection and attribution of changes in extreme weather events due to human-induced climate change several things are needed. First, as in all climate research, *the observational network must be sustained over time*, or better, strengthened, so that we can maintain the long-term records that are necessary to document climate change, including its manifestation in extreme events. Second, *climate models need to be continuously improved* -- the US should maintain and build on its strength in climate modeling. Third, and perhaps least appreciated but equally important, *fundamental understanding of the relationship between climate and extreme weather events must be improved*. This is essential to our confidence in our interpretations of the observations and the models. In the case of hurricanes, we lack a plausible candidate theory that might explain the number of hurricanes on the planet each year and how that should change. This makes us totally reliant on numerical models which, though rapidly improving, are still not adequate to answer the question on their own. The Federal agencies that support climate research should more explicitly prioritize work whose goal is to achieve such basic understanding, as much as it prioritizes work whose goals are to improve models or observations.

Perhaps most urgently needed, though, in my view, is *research that quantifies the risks from extreme weather, and their changes as the climate warms, in terms of their impacts on human society: economic losses, fatalities and human health impacts, harm to ecosystems, etc*.

For most of the past decade, I have been interacting closely with colleagues in the insurance industry. They use tools called "*catastrophe models*" to assess the risks from extreme weather events. These industry catastrophe models are designed to solve the problem that most disaster losses come from a few large events, those events are rare, and often modern recorded history has no analog. Before Hurricane Sandy, the last comparable event in New York City occurred in 1821. There were neither good measurements, nor did the city have anywhere near its size or population in 2012. Understandably, the impacts were not comparable. How could one have assessed the risk, pre-Sandy, lacking good, recent historical analogs? Catastrophe models generate large numbers of synthetic events – virtual storms, say, that are realistic, but fill such gaps in history. The models calculate not only the storms' geophysical dimensions but also the impacts they would have on buildings and infrastructure. Essentially, catastrophe models produce synthetic histories from which more representative estimates of risk can be produced.

Such catastrophe models have served the insurance industry well until now, but they have significant limitations in the new environment we face today, where climate change is an established fact and the industry, along with most of the rest of the private and public sector, needs to understand how extreme weather risk is changing. Because of the way catastrophe models have been developed, based closely on historical data, they implicitly assume that the present and near future will be similar to the past, and thus do not adequately capture climate change. The most influential and widely used models are also proprietary, meaning the details of their construction and output are not subject to open scientific debate and peer review. Finally, they are designed to be used in places and for assets where the insurance industry has significant exposure, but tend to be less accurate or nonexistent elsewhere. Thus for calculating property damage risk due to hurricanes in the U.S. they may be pretty good, while they basically can't be used to calculate human health risks from hurricanes in Mozambique, for example.

Some public, academic and nonprofit catastrophe models do exist, but these largely share the weaknesses of the private sector ones, or have even more severe limitations in some respects. The science of climate-aware catastrophe modeling is in its infancy. Yet with the rapidly increasing pressure for climate-related financial disclosure in the private sector, and for increased resilience and adaptation to extreme weather risk at the state, local and federal level in the public sector, there is a rapidly growing need to overcome these limitations.

It is time for the Federal science agencies to invest in a set of open-source tools to assess changing extreme weather risk in a way that is practically useful for real decisions, accounts for climate change, and whose methodologies and assumptions can be debated openly, in the peer-reviewed literature and elsewhere. This will highlight their strengths, weaknesses, and appropriate uses – including the best way to quantify the uncertainties, which will be even larger when climate change is accurately integrated into models and forecasts. They would be available for the insurance industry, and the rest of the private sector, to use (alongside the existing proprietary models, which should and would remain in place) but also be available for use by the governments, such as to inform cost-benefit calculations for building physical flood defenses or any other measure being designed to increase resilience.

The private sector would benefit greatly from the existence of such tools, but for them to be trusted it is important that no company or other private interest "own" them, thus the funding needs to come from the government, or perhaps a public-private partnership. A federal research program in such a direction could be guided, for example, by a steering group with representatives from the private sector, government, and academia.

Concluding Remarks

Thank you for the opportunity to participate in today's hearing. I also want to thank this Committee and your colleagues on both sides of the aisle and both sides of the Capitol for your steadfast support for the Nation's research enterprise. I suspect you have many difficult decisions to make on where to allocate the public's resources. Your support for research and education has helped this Nation maintain its competitive edge and allowed science to contribute to the nation's national, economic and environmental security. I would be pleased to answer any questions or provide additional follow up information that may be useful to the Committee.