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BEFORE THE

COMMITTEE ON OVERSIGHT AND REFORM.

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Mr. Chairman, and members of the Committee. My name is Michael Mann. I am Distinguished Professor of Atmospheric Science at Penn State University, and Director of the Penn State Earth System Science Center. My research involves the use of climate models, the analysis of empirical climate data, and developing methods for comparing observations and model predictions. The primary focus of my research is understanding the long-term behavior of Earth's climate system, and determining the roles of various potential agents of climate change, both natural and human.

I have served as organizing committee chair for the National Academy of Sciences *Frontiers of Science*, and as the co-author or advisor for several National Academy of Sciences reports related to climate change. I have served as editor for the *Journal of Climate* of the American Meteorological Society and have served as a member of numerous other international and U.S. scientific working groups, panels and steering committees. I was awarded the Hans Oeschger Medal of the European Geophysical Union in 2012 and received the Friend of the Planet Award from the National Center for Science Education in 2014. I received the Stephen H. Schneider Award for Outstanding Climate Science Communication in 2017, the Award for Public Engagement with Science from the American Association for the Advancement of Science in 2018 and the Climate Communication Prize of the American Geophysical Union in 2018. In 2019 I received the Tyler Prize for Environmental Achievement. I am a Fellow of the American Geophysical Union, the American Meteorological Society, the Geological Society of America, the American Association for the Advancement of Science, and the Committee for Skeptical Inquiry. I am also a co-founder of the award-winning science website RealClimate.org.

I have authored or co-authored more than 200 publications, and four books including *Dire Predictions: Understanding Climate Change*, *The Hockey Stick and the Climate Wars* and *The Madhouse Effect: How Climate Change Denial Is Threatening Our Planet, Destroying Our Politics, and Driving Us Crazy* with *Washington Post* editorial cartoonist Tom Toles, and the children's book, *The Tantrum that Saved the World.*

I am perhaps best known for my paleoclimate research two decades ago that produced the iconic "hockey stick" curve demonstrating the unprecedented nature of human-caused planetary warming. My research in recent years, however, has focused on the increased coastal risk from sea level rise combined with intensified hurricanes, and the impacts of climate change on extreme summer weather events.

I would like to talk about the substantial progress that has been made in these areas in recent years. Let me first talk about hurricanes. The sometimes fractious debate about whether we'll see more or fewer storms in a warmer world is somewhat misplaced. What matters is that there *is* an emerging consensus we'll see stronger and worse flood-producing storms—and in fact we're seeing them already.

Hurricanes get their energy from warm ocean waters, and the oceans are warming due to the human-caused build-up of heat-trapping gases in the atmosphere primarily from the burning of coal, oil, and gas. The strongest hurricanes have gotten stronger because of global warming. Over the past two years we have witnessed the most intense hurricanes on record for the globe, both hemispheres, the Pacific, and the open Atlantic. With a recent post-season upgrade in status, Michael—my namesake—is now established as the latest land-falling category five hurricane in U.S. history, having devastated regions of the Florida panhandle when it made landfall last October.

We also know that warmer air holds more moisture, and the amount of water vapor in the atmosphere has increased, due to human-induced global warming. We've measured this increase and it has been unequivocally attributed to human-caused warming. That extra moisture causes heavier rainfall, which has also been observed and attributed to our influence on climate. We know that rainfall rates in hurricanes are expected to increase in a warmer world, and now we're living that reality.

And global warming also means higher sea levels, because ocean water expands as it warms, and land-based ice in the mountains and at the poles melts. Sea level rise is accelerating, and storm surge from hurricanes rides on top of higher seas to infiltrate further into our coastal cities. Our own work has shown, for example, that the combination of sea level rise and larger, more intense hurricanes, has increased the likelihood of a Superstorm Sandy-like storm surge (measured at 13 ft at Battery Park NYC) from a roughly 500 year event (an event we wouldn't expect to happen more often than once in a thousand years) to a 25 year event. If we continue with business-as-usual burning of fossil fuels, we estimate that is will be a ~5 year event by mid-century. By next century, we estimate that flood height will be *permanently* exceeded, due primarily to sea level rise.

Heavier rain and higher sea levels can combine to cause compound flooding in major hurricanes, as the deluges cause flooding that must drain to the sea but can't do so as quickly because of storm surge. We saw this effect in play in the catastrophic flooding from August/September 2017 hurricane Harvey and August/September 2017 hurricane Florence.

There are scientific linkages we're still trying to work out. The record flooding from Harvey and Florence, like 2011 Hurricane Irene before it that (which caused catastrophic flooding in my own state of Pennsylvania) resulted from a combination of factors. Very warm ocean temperatures meant more moisture in the atmosphere to produce heavy rainfall. The storms were also very slow moving, nearly stationary at times. The slower the storm moves, the more rainfall that accumulates in any one location and the more flooding you get. Cutting-edge climate science suggests that such stalled weather patterns could result from a slowed jet stream, itself a consequence—through principles of atmospheric science—of the accelerated warming of the Arctic. Consistent with this proposition, one recent study in the journal *Nature* concluded that hurricanes are indeed moving more slowly upon making landfall. The fact that climate changes in far-off regions like the North Pole can have very real impacts on extreme weather faced here in the lower 48 are a reminder that surprises may be in store—and not welcome ones—when it comes to the unfolding impacts of climate change.

Florence and Harvey both underwent rapid intensification into strong category 4 hurricanes over very warm western Atlantic waters. Past studies indicate a roughly 7% increase in the peak wind speed of a cat 4 or cat 5 storm for each 1C warming of ocean surface temperatures. In the case of Florence, an early autumn ocean "heat wave" brought sea surface temperatures in the western Atlantic to bathtub-level warmth. Just as summer heat waves on land are greatly increased in frequency and intensity by even modest overall warming, so too are these ocean heat waves becoming more frequent and more extreme as the oceans continue warm.

Roughly 1.5C warmer-than-normal waters in the subtropical Atlantic where Florence intensified (and keep in mind that "normal" as modernly defined by NOAA as the average during the 1981-2010 period is itself already about 1C warmer than pre-industrial times prior to advent of human-caused greenhouse warming) corresponds to a roughly 11% increase in peak winds. Since the destructive potential of a storm goes as the cube of the wind speed, that that 11% increase in wind speed corresponds to a 37% increase in destructive potential. That's not a subtle effect. We've seen it in the form of record-strength hurricanes, like Irma, which cut a swath of devastation through the Caribbean in September 2017. Similarly intense cat 5 storm Maria which devastated Puerto Rico, causing massive loss of access to electricity and drinking water for months, constituted the greatest loss of life for American citizens from any natural (if we can call it that) disaster.

In the case of Florence, the winds decreased substantially as the storm approached landfall, but as a strong, very slowly-moving landfalling hurricane pounding structures with near 100 mile per hour winds for hours on end, Florence did considerable damage as it skirted the long Carolina coastline, taking down trees and powerlines and rendering large areas without electricity.

The greater threat in this case, however, was the *storm surge*. Though the storm weakened as it approached the coast, the storm surge was built up over of a period of several days, including the several days during which it existed as a cat 4 or strong cat 3 storm. That means the catastrophic ~10-foot storm surge from Cape Hatteras to Myrtle Beach was baked in well in advance of the landfall of the storm.

That storm surge was superimposed on roughly 1 foot of sea level rise that has occurred along the southeastern U.S. coast, mostly due to climate change (there's a small contribution owing to the geological subsidence of the coast). The coastal town of New Bern was particularly hard hit by Florence. The historic downtown area was flooded by the 10 foot storm surge and 200 people required rescue. It is seemingly prescient that I gave a lecture in New Bern just a year earlier, during the prior storm season, warning about the coastal threat from climate change. I gave that lecture in a church that would later be flooded by Florence's storm surge.

Last but not least, we have the threat of *inland flooding*. Warmer oceans mean more moisture in the atmosphere. It's one of the simplest relationships in all of meteorology; for each 1C of warming, there is about 7% more moisture in the air. That means those 1.5C above normal ocean temperatures have given the storm about 10% more moisture. All other things being equal, that implies about 10% more rainfall.

The science of attributing aspects of these extreme events to climate change has developed substantially in recent years. These "attribution" studies compare the results of climate models with and without human-caused greenhouse gas increases to assess the impact that climate change may have had in impacting a particular weather event. In the case of Florence, the record rainfall in North Carolina was, according to one attribution study, increased by as much as 50% by warming oceans. If anything, these sorts of studies are likely to underestimate the impact of climate change because the models don't do a good job capturing the physical processes that are leading to stalled summer weather patterns.

This issue is particularly important in the case of mid-latitude summer weather extremes, i.e. floods, heat waves, drought and wildfires like those we've witnessed in North America (and Europe and elsewhere) during the past few years. So I will now shift to a discussion of the impacts of climate change on this other family of extreme weather events.

As I wrote in the *Washington Post* last fall, it's not rocket science. A warmer ocean, as discussed earlier in the context of tropical storms and hurricanes, evaporates more moisture into the atmosphere — so you get worse flooding from coastal storms like

Hurricanes Harvey and Florence. Warmer soils evaporate more moisture into the atmosphere—so you get worse droughts (think California, and Syria). Global warming shifts the extreme upper tail of the "bell curve" toward higher temperatures, so you get more frequent and intense heat waves (think summer 2018 just about anywhere in the Northern Hemisphere). Combine heat and drought, you get worse wildfires (again, think California).

Climate scientists have become increasingly comfortable talking about these connections. Much like medical science has developed key diagnostic tools, we have developed sophisticated tools to diagnose the impact climate change is having on extreme weather events. One of these tools, "extreme event attribution," can be thought of as climate science's version of an x-ray. In this case, a climate model is run both with and without the human effect on climate. One then compares how often a particular extreme event happens in both the "with" and "without" cases. If it occurs sufficiently more often (i.e. beyond the "noise") in the former case, a study can "attribute" and quantify how climate change affected the extremeness of the event.

The scorching European heat wave last summer, according to one such study, was made more than *twice as likely* by global warming. The record rainfall in North Carolina from hurricane Florence was, according to another study, increased by as much as 50% by warming oceans.

The climate models used in these sorts of studies represent remarkable achievements in the world of science. But no tool is perfect. In our medical analogy, some injuries — like soft tissue damage — are too subtle to be detected by an x-ray. So medical professionals developed even more sophisticated tools, like the MRI. Similarly, some climate change impacts on extreme weather are too subtle to be captured by current generation climate models.

In a study my co-authors and I recently published in the journal *Science Advances*, we identified a key factor behind the rise in extreme summer weather events like the ones that played out in summer 2018 that—as we demonstrate in our study—is *not* captured by current generation climate models. Using an alternative approach based on a combination of models and real-world observations, we showed that climate change is causing the summer jet stream to behave increasingly oddly. The characteristic continental-scale meanders of the jet stream (its “waviness”) as it travels from west to east are becoming more pronounced and are tending to remain locked in place for longer stretches of time.

Under these circumstances -- when for example a deep high-pressure “ridge” gets stuck over California or Europe -- we usually see extreme heat, drought, and wildfire. And typically there’s a deep low-pressure “trough” downstream, stuck over, say, the eastern U.S. or Japan, yielding excessive rainfall and flooding. That’s exactly what happened in summer 2018. The spate of extreme floods, droughts, heatwaves and wildfires we experienced were a consequence of such jet stream behavior.

Our recent study shows that climate change is making that behavior more common, giving us the disastrous European heat wave of 2003 (during which more than 30,000 people perished), the devastating 2011 Texas drought (during which ranchers lost 25% of their cattle), the 2016 Alberta wildfire (the worst North American wildfire in history) and yes, the extreme summer of 2018. Indeed, we are off to a similar start in spring/summer 2019. The extreme flooding and tornado outbreaks we’ve seen over the past month are associated with this same mechanism—the resonant amplification of planetary waves.

Just as climate models almost certainly *underestimate* the impact climate change has already had on such weather extremes, projections from these models also likely underestimate future increases in these types of events. Our study indicates that we can expect many more summers like 2018 – or worse.

Climate change deniers love to point to scientific uncertainty as justification for inaction on climate. But as we have just seen, if anything, the model projections are likely underestimating the impact climate change is having on extreme weather events. Yes there is uncertainty to be found here. But it is *not* our friend. It is in fact reason for even more concerted action. We already know that projections historically have underestimated the rates of ice sheet collapse and sea level rise. Now it appears they are also underestimating the odds of extreme weather as well. The consequences of doing nothing grow by the day.

Some headlines reported that Florence is a warning of what is to come. But in reality, it is a warning of what *has already arrived*. Far worse is to come if we don't get serious, in a hurry, about acting on climate. We must transition away from fossil fuels toward renewable energy even more rapidly, and we must elect politicians who will support such efforts.

The impacts of climate change are no longer subtle. We are seeing them play out before us here and now. And they will only get worse if we fail to act. Which leads us, inevitably, to a discussion of policy—and indeed politics. Previous administrations focused on adaptation to climate change, with an eye to what the planet would look like in the future. But events like Harvey, and Irma, show that we are not even adapted to our current climate (which has already changed due to our influence).

The Trump administration, however, seems determined to lead us backward. Over the past two years we have witnessed a dismantling of the policies put in place by the Obama administration to (a) incentivize the necessary move from climate change-producing fossil fuels toward clean energy, (b) increase resilience to climate change impacts through sensible regulations on coastal development, and (c) continue to fund basic climate research that can inform our assessments of risk and adaptive strategies. Ironically, just 10 days before Harvey struck, President Trump rescinded flood protection standards put in place by the Obama administration that would take sea level rise and other climate change impacts into account in coastal development plans.

At a time when climate change damages are escalating, we need sensible policy in Washington to protect the citizens of this country, both by reducing future climate change and preparing for its impacts.