Excerpt from

Climate change caused by human activities is happening and it already has major consequences.

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The climate varies on multiple timescales, but now humans are the main agents of change and are likely to remain so for the next few centuries. It is generally understood that human-induced climate change causes global warming, but what is not adequately appreciated are the direct influences on heavy rainfalls, drought, and storms, at great cost to society and the environment. Although the climate change effects are modest, perhaps 5 to 15% for these events, once thresholds are crossed, things break and damage increases nonlinearly. These aspects are not properly factored into costs of climate change, and preparation for expected effects is woefully inadequate, exacerbating damage.

3. The climate is changing

Human activities have led to the release of carbon dioxide and other heat-trapping "greenhouse" gases in sufficient quantity to change the composition of the atmosphere, resulting in an accumulation of heat in the Earth's system, commonly referred to as "global warming". The Earth's climate has responded through higher temperatures in the atmosphere, land and ocean, ice melting, rising sea level, and increases in extreme weather events (heat waves, wildfires, heavy rains and flooding). The calendar year 2016 is by far the warmest on record for the global mean surface temperatures (GMSTs). It easily beat out 2015, which in turn beat out the previous record holder 2014. Meanwhile, 2017 is now ranked third (or second, depending on dataset). There is no doubt whatsoever that the planet is warming and it has major consequences for other aspects of climate. However, there is also considerable natural variability manifested in the GMST record; the biggest fluctuations from year to year are associated with El Niño events. Decadal variations led to a pause in warming from 2000 to 2013. A major El Niño from 2015-16 somewhat inflated the GMST values, and 2017 values dropped slightly, as a result.

4. How global warming affects extreme events

As well as the overall heating of the planet mainly from human changes in the atmospheric composition, which leads to general temperature increases in the atmosphere and oceans, and melting ice, there are substantial impacts on extreme events. Indeed, the biggest impacts of climate change on society and the environment arise from changes in extremes. These are realized through the daily weather systems, which naturally produce tremendous variability on all time scales and over many different spatial scales. Hence just by chance, extreme values of temperatures, precipitation, or wind, and so forth, occur from vigorous weather systems. With global warming, some of these extremes are pushed higher and beyond previous values, creating new records. Moreover, global warming often pushes values over various thresholds used for design purposes: whether for heat, rain, wind, or sea level, and accordingly things break. This also means that the events and the new records are episodic. There is not a continuous level of high values, rather the values fluctuate substantially as they have always done with natural weather patterns. It also means that in one month records are broken at one location, while in the next month records break somewhere else, and then somewhere else again. The fact that the extremes occur in different places over time, means that the public often does not connect them to climate change, and their accumulated effects have been greatly underestimated by many. It also means that because of the natural climate variability from year to year, it is often difficult to conclusively detect the climate change influences – an issue of signal-to-noise, as discussed later.

4a. Heat waves

The most obvious expectation is for an increase in short-duration heat waves and their impacts as overall temperatures rise. Often these result in temperature rises beyond anything previously experienced in recorded history, and this has been borne out in many studies[1 2], see also IPCC reports[1] and other assessments[2]. Heat waves nearly always occur in association with a strong slow-moving anticyclone. The major European heat wave in the summer of 2003[3], was one of the first to be well documented both in terms of its detection as extremely unusual, and attribution to anthropogenic climate change using climate models. There were major consequences in terms of wildfires, and loss of life. A more recent example is the extreme Russian heat wave of 2010, again with widespread wildfires, smoke, agricultural losses, and loss of life. Some confusion and debate has occurred in the scientific literature about this event over the cause and rarity of the weather situation, versus the role of human-induced warming[4]. As discussed in the next section on attribution, this confusion arises because the weather events (strong anticyclones) tend to occur naturally; while it is the global warming that pushes what would have been an extreme event anyway into one that goes well outside previous bounds and causes major strife.

High temperatures can result in detrimental health, economic, and social impacts[16]. The European 2003 and the Russian 2010 heat waves caused, respectively, almost 70,000 and 55,000 deaths[5], while an average of 658 deaths were reported annually during 1999-2009 in the United States alone due to excessive heat[6]. Extreme high temperatures may cause human casualties in large cities and have profound impacts on farms due to reduced crop productivity and adverse effects on animals, including mortality. Temperature extremes stress infrastructure, transportation, water supply, and electricity demand; severely affect ecosystems and forests, and increase wildfire activity. Heat strokes—the most lethal condition of hyperthermia—can be caused by exposure to high ambient environmental temperatures[7]. More frequent, more intense, and longer lasting heat waves are robustly projected in the 21[st] Century as a result of human-induced global warming.

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[1] Meehl, G. A., and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* 305, 994–997.

[2] Papalexiou, S. M., A. AghaKouchak, K. E. Trenberth and E. Foufoula-Georgiou, 2018: Global, Regional, and Megacity Trends in the Highest Temperature of the Year: Diagnostics and Evidence for Accelerating Trends, *Earth's Future*, 6, 71-79, doi: 10.1002/2017EF000709

[3] Ciais, P. *et al.,* 2005: Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* **437,** 529–533.

[4] Dole , R. *et al.* 2011: Was there a basis for anticipating the 2010 Russian heat wave? *Geophys. Res. Lett*., **38**, L06702.

Otto, F. E. L., Massey, N., van Oldenborgh, G. J., Jones, R. G. & Allen, M. R. 2012: Reconciling two approaches to attribution of the 2010 Russian heat wave. *Geophys. Res. Lett*. **39**, L04702.

Trenberth, K. E., and J. T. Fasullo, 2012: Climate extremes and climate change: The Russian Heat Wave and other Climate Extremes of 2010. *J. Geophys. Res.*, **117**, D17103, doi: 10.1029/2012JD018020.

[5] Robine, J.-M. *et al.,* 2008: Death toll exceeded 70,000 in Europe during the summer of 2003. *C. R. Biol.* **331,** 171–178.

[6] Anderson, B. G. and M. L. Bell, 2009: Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. *Epidemiology (Cambridge, Mass.)* **20,** 205.

Bobb, J. F., R. D. Peng, M. L. Bell and F. Dominici, 2014: Heat-related mortality and adaptation to heat in the United States. *Environmental Health Perspectives (Online)* **122,** 811.

Kochanek, K. D., J. Xu, S. L. Murphy, A. M. Miniño and H.-C. Kung, 2011: Deaths: final data for 2009. *Natl Vital Stat Rep* **60,** 1–116.

[7] Smoyer-Tomic, K. E., R. Kuhn, and A. Hudson, 2003: Heat wave hazards: An overview of heat wave impacts in Canada. *Natural Hazards* **28,** 465–486.

4b. Drought and wildfire

In the United States, and indeed in mid-latitude continental areas around the world, there is a strong negative correlation between monthly-mean temperatures and precipitation in the summer half year, as there is year-round in the tropics. Heat waves, especially ones of longer duration, often occur in association with drought (see Dai[8] for a general discussion). The anticyclonic conditions that persist in a drought situation make for dry settled weather, with little or no precipitation. Under these circumstances, the land and vegetation dry out, and the modest extra heat from global warming exacerbates the dry conditions. Evaporative cooling ceases as plants wilt, wildfire risk increases, and the heat intensifies. That in turn increases the atmospheric demand for moisture, further drying out the vegetation in a vicious cycle.

The warmest year on record for the United States as a whole was 2012 when there was a widespread drought in association with persistent anticyclonic conditions over much of the country. Extreme drought was estimated to cover 39% of the country at its peak in September 2012, rivaling the Dust Bowl years in the early 1930s. According to the Sept. 4, 2012 drought monitor, 64% of the country was in moderate to extreme drought. Wildfires became endemic in many places, and firefighting costs soared[9]. As a result of these events and the agricultural and livestock losses, the net cost has been estimated as over $75B, although a partial accounting by NOAA lists it as $32B. *Wildfire Today* reports the fire-fighting costs alone in 2012 were $2B.

Perhaps the best example of how climate change can lead to an increase in drought conditions is in the American West, particularly California[10]. A record-setting drought began in 2012 and persisted until 2016 in spite of the big El Niño event (which favors more storms coming into the West Coast). It included the lowest annual precipitation on record, the highest annual temperature, as well as the most extreme drought indicators ever recorded in California. Along with widespread water shortages, the drought brought prolonged and costly wildfires. Indeed, wildfires were rampant throughout the West, especially in the summer of 2015, with wildfires widespread in Alaska, western Canada, Washington, Oregon and California. In May 2016, a major wildfire broke out in Fort McMurray, Alberta following 5 to 8 months of prolonged (El Niño related) drought. Major wildfires continued again in August 2016 and July 2017 in California, and the consensus has become that the wildfire season in California is now almost continuous. In early 2017, in association with unusually high sea temperatures in the subtropical North Pacific, the drought in California was abated with heavy rains and snows, leading to flooding in many areas. This was a boon in terms of snowpack to the Sierra Nevadas and Rocky Mountains.

Certain bugs and diseases flourish under these warmer and dryer conditions, such as the bark beetle, which is decimating forests across the West. Increased carbon dioxide is not good for plants!

4c. Storms and precipitation

Perhaps less obvious, but even more dangerous than heat, are the effects of a warming planet on the water cycle in which the oceans play a key role. The atmosphere holds about 4% more moisture per 1°F (or 7% per 1°C) increase in temperature, which leads to increased water vapor in the atmosphere, and this provides the biggest influence on precipitation[14]. It is undisputed that water vapor is a powerful greenhouse gas, and hence this amplifies the original warming substantially. In addition, sea surface temperatures have

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[8] Dai, A., 2011: Drought under global warming: a review. *Wiley Interdisciplinary Reviews: Climate Change*, **2**: 45–65. doi:10.1002/wcc.81

[9] Allen, C. D. *et al.,* 2010: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest ecology and management* **259,** 660–684.

Abatzogloua, J. T., and A. P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *PNAS* 113, 11770-11775. doi/10.1073/pnas.1607171113

[10] Williams, A. P., et al., 2014: Causes and implications of extreme atmospheric moisture demand during the record-breaking 2011 wildfire season in the southwest United States, *J. Applied Meteor. Climatol*, **53**(12), 2671-2684, doi:10.1175/JAMC-D-14-0053.1.

Diffenbaugh, N. S., D. L. Swain and D. Touma, 2015: Anthropogenic warming has increased drought risk in California. *Proc. Natl Acad. Sci USA* **112,** 3931–3936. doi/10.1073/pnas.1422385112

Worland, J., 2015: How the California drought is increasing the potential for devastating wildfires, *Time*. http://time.com/3849320/california-drought-wildfires/.

warmed by more than 1°F since the 1970s, and over the oceans this has led to 5 to 10% more water vapor in the atmosphere[11].

Storms, whether individual thunderstorms, extratropical rain or snow storms, or tropical cyclones and hurricanes, supplied by increased moisture, produce more intense precipitation events, even in places where total precipitation is decreasing[14]. The increased moisture and related latent heat release can intensify storms and perhaps double the original change so that the precipitation increases 5 to 20%. The effect on the storm depends on where the precipitation and released heat occurs relative to the storm center. For hurricanes, the effect is direct and the result can be doubled or more. For extratropical storms the effects are more complicated and the effect is a factor of 1 to 2 and varies from storm to storm.

Nevertheless, it leads to much stronger and more intense rains, and snows, and it increases risk of flooding that exceeds previous bounds for extreme weather events. At the same time, dry spells in between such events also increase. Indeed, in places where it is not raining, the extra heat dries things out, exacerbating heat waves as the evaporative cooling is lost. Hence, droughts set in quicker and become more intense, increasing risk of wildfire[12]. This is especially a dangerous problem in the U.S. West, as noted above.

Examples are discussed in more detail below. However, in Colorado, the unprecedented widespread flooding along the Front Range in September 2013 is a case in point. The moisture sources came from very warm ocean regions to the south (the Gulf of Mexico and especially from west of Mexico) that undoubtedly had a global warming component[13]. More recently, widespread flooding occurred in Missouri (Nov-Dec 2015), in Houston in April 2016, in Louisiana in August 2016, and in the Carolinas from hurricane Matthew in October 2016. The major winter storm "Jonas" that "bombed" Washington D.C. with several feet of snow in January 2016 is another example of such an extreme event. Meanwhile torrential rains, flooding, mud slides, and loss of life occurred in South America: in northern Chile in late February 2017, in Peru in March, and Colombia in early April in association with a coastal El Niño that led to very high sea temperatures off the Pacific coast in combination with global warming.

Without climate change, these events would have been properly labeled as "1000-year events". However, because of climate change and its effects on the environment, they are no longer 1 in 1000-year events, and instead, they are now more likely 1 in 50-year or 100-year events. They are still uncommon, but not unlikely.

4d. Tropical Storms and Hurricanes

Tropical storms and hurricanes/typhoons mostly occur in the deep tropics in summer in association with high sea surface temperatures (SSTs) over 27°C. In turn these reflect high ocean heat content (OHC) below the surface and it is this heat energy that is transferred into the atmosphere through evaporation, moistening the atmosphere, while evaporative cooling occurs in the ocean. The fuel for tropical storms and hurricanes comes from the release of the latent heat in heavy rainfall as the moisture is gathered into the storm and condensed[14][15].

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[11] Trenberth, K. E., J. Fasullo, and L. Smith, 2005: Trends and variability in column-integrated water vapor. *Clim. Dyn.,* **24***,* 741-758.

[12] Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam, 2006: Warming and earlier spring increase Western U.S. forest wildfire activity. *Science,* **313**, 940–943.

[13] Trenberth, K. E., J. T. Fasullo, and T. G. Shepherd, 2015: Attribution of climate extreme events. *Nat. Clim. Change,* **5**, 725-730, doi: 10.1038/NCLIMATE2657.

[14] Trenberth, K. E., 2007: Warmer oceans, stronger hurricanes. *Scientific American*, July, 2007, 45–51.

[15] Trenberth, K. E., C. A. Davis and J. Fasullo, 2007: Water and energy budgets of hurricanes: Case studies of Ivan and Katrina. *J. Geophys. Res.*, **112**, D23106, doi:10.1029/2006JD008303.

Trenberth, K. E., and J. Fasullo, 2007: Water and energy budgets of hurricanes and implications for climate change. *J. Geophys. Res.*, **112**, D23107, doi:10.1029/2006JD008304.

Trenberth, K. E., and J. Fasullo, 2008: Energy budgets of Atlantic hurricanes and changes from 1970. *Geochem., Geophys., Geosyst.*, **9**, Q09V08, doi:10.1029/2007GC001847.

One harmful aspect of hurricanes is the fierce winds that cause destruction to people's homes and other buildings and infrastructure. However, hurricanes are also responsible for huge storm surges in coastal regions that can be very damaging and are expected to become much worse due to both stronger winds and higher sea levels. The most widespread damage, though, is actually the flooding from torrential rains that can extend hundreds of miles from the coast.

One major source of variability in tropical SSTs is the El Niño phenomenon that produces a warming in the central and eastern Pacific with a corresponding shift in tropical storm activity into that region at the expense of other regions[28]. Hurricanes become more frequent in the eastern North Pacific but decrease in the Atlantic, for example. Indeed, there is always a competition throughout the tropics for where the main activity occurs, and high SSTs are the main factor. Once activity is underway in one region of the tropics, it tends to suppress activity elsewhere by creating a large overturning circulation in the atmosphere that creates subsiding stable air elsewhere and wind-shear in in-between regions (where the low-level winds and upper level winds in the troposphere at jet stream level are indifferent directions and/or speeds), and this tends to blow a developing vortex apart. Accordingly, tropical storms are clustered and cannot occur everywhere at once.

In general, climate warming invigorates tropical storm activity by adding energy to the storms, but it can be manifested in several ways. With climate change, it is expected that hurricanes will contain heavier rains and become more intense, longer lasting, and possibly larger in size, but fewer in number, as one big storm essentially replaces the effects of several smaller weaker storms in terms of the heat energy pulled out of the ocean. Owing to the large natural climate variability from year-to-year and unreliable records prior to the satellite era (~1980), it is difficult to clearly detect climate change influences on tropical storm activity. "Detection" relies on a climate signal that is larger than the noise of natural variability, confounded also in this case by unreliable data. So, it is not that there is no signal, but rather that the noise is large. Indeed, there is very compelling evidence that there is a climate signal to increased tropical storm activity.

Examples of increased activity are the record-breaking exceptionally large number and strength of storms in the Atlantic in 2005, super storm Sandy on the East Coast in 2012, the strongest land-falling typhoon on record: Haiyan in 2013 that went through the Philippines, and the very strong storms recorded in several regions in 2015 and 2016 (strongest in the southern Hemisphere – Winston in 2016 that went through Fiji). Then in 2017 it was the Atlantic's turn, with Harvey, Irma and Maria creating devastation in Texas, Florida and the Caribbean Islands, and Puerto Rico. The year 2015 is the most active year globally for hurricanes/typhoons ever. The latter is in part because it was an El Niño year, but it highlights the fact that high sea surface temperatures from whatever reason produce bigger and stronger storms. At the same time, there are quiet years, that highlight the large variability.

Costs of flooding for a number of events have been assigned and hurricanes Katrina, Rita and Wilma in 2005 cost over $180 billion (2011 prices). The recent Atlantic hurricanes in 2017 are estimated to have damages of over $230 billion.

4e. Snowfall and snow cover

In winter over the northern hemisphere land, the snow season is getting shorter at each end as more precipitation arrives as rain. Generally, the biggest snowfall occurs with temperatures just below freezing, and hence in mid-winter, the prospects, as observed, are for bigger snowfalls and larger snow pack from November through January. With climate change, it is no longer "too cold to snow" very often. In contrast, snow pack is observed to be much reduced across the northern hemisphere from March through August 1966 to 2014. Due to global warming, snow melt starts sooner, runoff occurs sooner in the spring, and the risk of drought and water shortages are greater in summer, along with wildfire, and insect pest infestations.

7. Conclusions

There are increasing numbers of billion-dollar disasters in the U.S. and around the world. In the U.S. in the past 20 years through 2016 there had been on average over $42 billion in weather-related disaster costs, according to NOAA. Figure 5 shows overall monetary losses worldwide from Munich Re for 1980 through

2016 along with the contributions from weather and climate-related events in billions of US $. Now 2017 adds another spike to the plot of over $300 billion from the hurricanes and wildfires. A lot of this depends on where the disaster happens and how much infrastructure is present, and it does not measure the human factors, strife and loss of life, especially in developing countries.

Extreme weather has always happened, but now thresholds are being crossed, records broken, and so at least a portion of these losses can be ascribed to climate change. There is no precise tool for how much should be ascribed to human influences. On the one hand, records can be broken even without climate change. At the very least, the storm, precipitation and weather-related events are amplified by water vapor increases of 5 to 10% since 1970, and these lead to 5 to 20% increases in precipitation intensity, or more. But it is not appropriate to then assign only 5 to 20% of the cost of the disaster to human-induced climate change because the damage is highly nonlinear.

It is generally accurate to say that extreme events, which break records and cross thresholds, would not have happened without global warming, because otherwise the event would have been well within previous experience. Thus, thresholds are crossed and records are broken because of anthropogenic climate change. Moreover, every event is different. Events occur in different places and evolve very differently, whether floods, wildfires, or heat waves, but they all have one aspect in common, they would not have been as severe without the human influence. In light of this, one could argue that the whole cost might be assigned to climate change. Certainly, a very good case can be made that damages due to climate change are likely already well over $10B per year.

Hence the increased ocean temperatures and the increased water vapor in the atmosphere have led to changes in extremes, which have huge impacts on society and on ecosystems and the environment. Thus, climate extremes exacerbated by human-induced climate change already pose a serious risk of harm to people's lives, personal security, and property in new ways. The causes of the global warming are clear and future projections are for more of the same but with increasing magnitude. What are extreme and unusual events now, boosted by the right kind of circumstances (weather system), will become commonplace in a decade or two. Without immediate reductions in fossil fuel emissions, farming may become difficult unless major evolution occurs (different crops), and by mid-century many trees and ecosystems will no longer be viable where they currently stand.

The atmosphere is global; we share these problems with other nations, although when considering cumulative emissions, the U.S. has been the biggest contributor by far. As scientists, we can lay out the facts and evidence, and the prospects, but fully addressing climate change requires government leadership. The costs of the increased frequency and destructiveness of extreme weather events are not borne by those who cause the problem. There is still time to manage the problem and avoid the worst possible outcomes, and there can be major economic advantages as well greater energy efficiency when transitioning off fossil fuels. It does not have to cost more if done in the right way. Swift action to reduce emissions and transition off of fossil fuels can slow and eventually stop further damage to the climate system and water cycle. The need is to swiftly decarbonize the U.S. energy system, as an essential step to protect children and future generations from the real dangers posed by human-induced climate change.

This is a global problem. We are all together on this spaceship Earth. What the U.S. government does with our national energy system and emissions matters immensely to our ability to preserve a livable climate for our posterity.