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.

Keywords: climate change, extreme weather, mitigation, adaptation, global warming

1. Introduction

There are many facts related to climate (see below) to demonstrate conclusively that the problem of human-induced climate change is real. The observational evidence combined with physical understanding based on well-established physical principles makes this abundantly clear. Former U.S. Senator Patrick Daniel Moynahan famously said "*You are entitled to your own opinion but not your own facts*". The observations and data – the facts – are of mixed quality and duration, but together tell a compelling story that leave no doubt about the human role in climate change. Changes in some phenomena, such as hurricanes and tornadoes, are confounded by the way observations are made (e.g., the role of satellites) and shortness of reliable records. But the absence of evidence is not evidence of absence of important changes, and our physical understanding and climate modeling can fill the gaps. However, the facts are not enough. The role of scientists is to lay out the facts, evidence, prospects and consequences, but the decisions on what to do about them resides in the realm of politics and should involve all of society.

The Intergovernmental Panel on Climate Change[1], U.S. national assessments[2], reports from the National Academy of Sciences[3], and many other scientific organizations have proclaimed that "global warming is unequivocal" and it is mainly caused by human activities. Yet the public is not alarmed. Many politicians either do not believe in global warming or discount it. But it is not a matter of belief. From the scientific standpoint, by the time the problems associated with climate change are so blatant, it will be far too late to do anything about it. Already the costs are substantial every year – from tens to hundreds of billions of dollars – from drought, wild fires, floods, heat waves, storm surges, hurricanes and strife. The climate events that cause the damage are isolated events, regional in nature, and affect but few at a time. The public does not see an integrated view. A major report comes out and it is a headline for at most one day. But the problem continues, and in fact gets worse every day. Yet it is no longer news because it remains the same problem, although the problem has not been solved. It is easy for the public to set it aside.

Climate change is inherently an inter-generational problem. What kind of a planet are we leaving our grandchildren? It is also a problem of equity among nations. Small island states and developing countries have not contributed much to the problem but are affected by it[4]. Costs of climate change and air pollution are often not borne by those who cause these problems. There are substantial uncertainties associated with exactly what form and where climate change effects will be felt, but the risks are growing. A normal way society deals with risk is by assessing possible impacts, building resilience, preparing for possible adverse outcomes, and taking out insurance. The precautionary principle should come into play. But society is not doing enough to mitigate the problem or plan for the consequences. This aspect is discussed more specifically for the recent Atlantic hurricanes of the summer of 2017.

2. The climate system

The climate system consists of the atmosphere, oceans, land and cryosphere. The atmosphere is the most volatile component while both atmosphere and oceans are fluids and combine to produce the predominant patterns of variability in weather and the water cycle. We live on land, where availability of water depends on rainfall, snow-melt, lakes and rivers, while ice is important where it occurs. Weather and climate extremes happen all of the time, even in an unchanging climate. Yet these extremes are becoming more frequent and more severe, and the primary driver is human-induced climate change[5]. Indeed, the main way in which climate change is already affecting, and is likely to continue to affect, human societies around the world, is through changes in extreme weather events. Here a summary is provided of the way

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[1] IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Intergovernmental Panel on Climate Change [Field, C.B., et al. (eds.)]. Cambridge University Press, Cambridge, UK, 582 pp.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Cambridge Univ. Press.1535pp

[2] USGCRP 2017: *Climate Science Special Report: Fourth National Climate Assessment*, Vol. I (Wuebbles, D. J., et al. (eds.)). U.S. Global Change Research Program, Washington, DC, USA, 470 pp. https://doi.org/10.7930/J0J964J6

[3] National Academies of Sciences, Engineering, and Medicine 2016. *Attribution of extreme weather vents in the context of climate change.* Washington, DC: The National Academies Press. doi: 978-0-309-38094-2. https://doi.org/10.17226/21852

[4] "Achieving Justice and Human Rights in an Era of Climate Disruption." https://www.ibanet.org/PresidentialTaskForceClimateChangeJustice2014Report.aspx

[5] Rahmstorf, S., and D. Coumou, 2011: Increase of extreme events in a warming world, *Proc. Natl Acad. Sci*. USA **108**, 17905–17909.

to think about the relationship between our oceans and atmosphere, weather and climate change. It is evident that climate change is increasing many extremes, with major consequences for human society and the environment.

Activities on Earth are adjusted to our current climate, which has been relatively stable throughout the past 2,000 years, coinciding with much of the development of human civilization. Natural changes in the past have occurred from small variations in the sun and effects of volcanic eruptions, and on geological time scales from changes in the Earth's orbit around the sun. Now changes in atmospheric composition from human activities, primarily the burning of fossil fuels and deforestation, are the main cause of anthropogenic climate change by enhancing the greenhouse effect (Fig. 1). Globally, on a day-to-day basis, the effects from these human activities are responsible for only about 1% of the flow of natural energy through the climate system. However, because anthropogenic global warming is always heating the planet, excess energy accumulates, and those cumulative effects create a much bigger impact. The net energy imbalance of the planet is close to 1 W m^{-2}, for all 510×10^{12} m^2 of the planet, and so the net heating amount is 0.5 PetaWatts[6]. For comparison, the total world's energy consumption in 2015 is estimated as 575 quadrillion (10^{15}) British thermal units[7], which is 0.02 PW. In the first place, this demonstrates that the direct human influence is small and cannot compete with the sun. In the second place, the main way humans have an effect is by interfering with the natural flow of energy through the climate system. However, because of the "concrete jungle" and a lot of space heating concentrated in cities, there are important local "urban heat island" effects.

Because this heating is always in the same direction, while it is not large enough to be important at any instant, it accumulates. Over 92% of it accumulates in the ocean, which was the warmest ever on record for the globe down to 2000m depth in 2017 ever (Fig. 2). On land, the effects are mitigated in general by water through evaporative cooling, and it is mainly in drought where the accumulated effects mount, exacerbate the drought and greatly increase the risk of wildfire. For instance, over 1 month (720 hours) without rain, the accumulated energy of a 1 W m^{-2} energy imbalance is equivalent to the full power of a small microwave oven (720 W) running in every square meter for 1 hour. No wonder things catch on fire!

Importantly, all weather events are now occurring in an environment which has changed in significant ways, as compared to 50 years ago. The main way this is manifested, the "memory" of these changes, is through the accumulated warming of the oceans and the loss of Arctic sea ice. Owing to anthropogenic global warming, sea surface temperatures have warmed by over 1°F since the 1970s, and over the oceans this has led to 5 to 10% more water vapor in the atmosphere. The warmer and moister atmosphere in turn has likely led to at least a 5 to 20% effect on storms that is greatly exaggerated for extreme weather events. When climate change's increased effect on storms is compounded with natural variations, such as an El Niño event, the effects are much larger, and more destructive.

Up until recently, scientists claimed we could not attribute any single weather event to global warming (climate change) even though the event was consistent with expectations. The reason scientists were reluctant to attribute a single event to global warming is that weather events cannot be predicted more than about 2 weeks in advance, at best, see Section 5 for details. But climate change clearly increases the odds of such events occurring. In reality, ***all*** weather-related events have both natural and anthropogenic components in this era of climate change. When anthropogenic climate change and natural climate patterns work synergistically, thresholds are crossed, records are broken and it can be said that such extreme events would have been very unlikely to occur without global warming. If business-as-usual greenhouse gas emissions continue, the security and lives of young people and future generations will be increasingly threatened by ever more extreme weather events than those already being experienced.

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[6] Trenberth, K. E., J. T. Fasullo, and J. Kiehl, 2009: Earth's global energy budget. *Bull. Amer. Meteor. Soc.*, **90**, 311-323. doi:10.1175/2008BAMS2634.1.

[7] U.S. Energy Information Administration, https://www.eia.gov/outlooks/ieo/

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) (Fig. 1). It easily beat out 2015, which in turn beat out the previous record holder 2014. Meanwhile, 2017 is now ranked third (Fig. 1) (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[8]. A major El Niño from 2015-16 somewhat inflated the GMST values, and 2017 values dropped slightly, as a result.

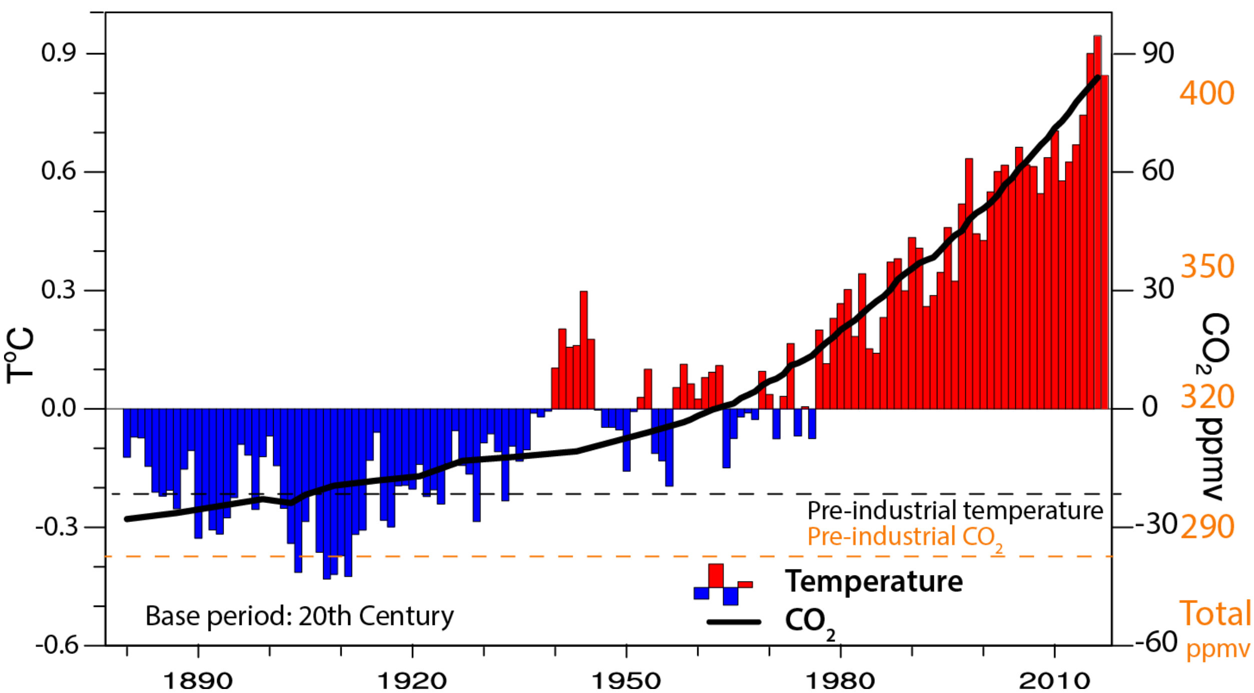

Fig. 1. Global mean annual surface temperatures °C (from NOAA) relative to the Twentieth Century average, along with the carbon dioxide concentrations (values at right) in parts per million by volume (ppmv) (from NOAA) based on the Mauna Loa record after 1958 and ice core bubbles of air prior to then. Estimates of the pre-industrial values for each are also given (Updated from Trenberth and Fasullo[9]).

[8] Trenberth, K. E., and J. T. Fasullo, 2013: An apparent hiatus in global warming? *Earth's Future*. **1**, 19-32. Doi: 10.002/2013EF000165.

Trenberth, K. E., J. T. Fasullo, G. Branstator, and A. S. Phillips 2014: Seasonal aspects of the recent pause in surface warming. *Nature Climate Change*, **4**, 911-916, doi:10.1038/NCLIMATE2341.http://rdcu.be/o7wB

Trenberth, K. E., 2015: Has there been a hiatus? *Science*, **349**, 691-692. doi:10.1126/science.aac9225.

[9] Trenberth, K. E., and J. T. Fasullo, 2013: An apparent hiatus in global warming? *Earth's Future*. **1**, 19-32. Doi: 10.002/2013EF000165.

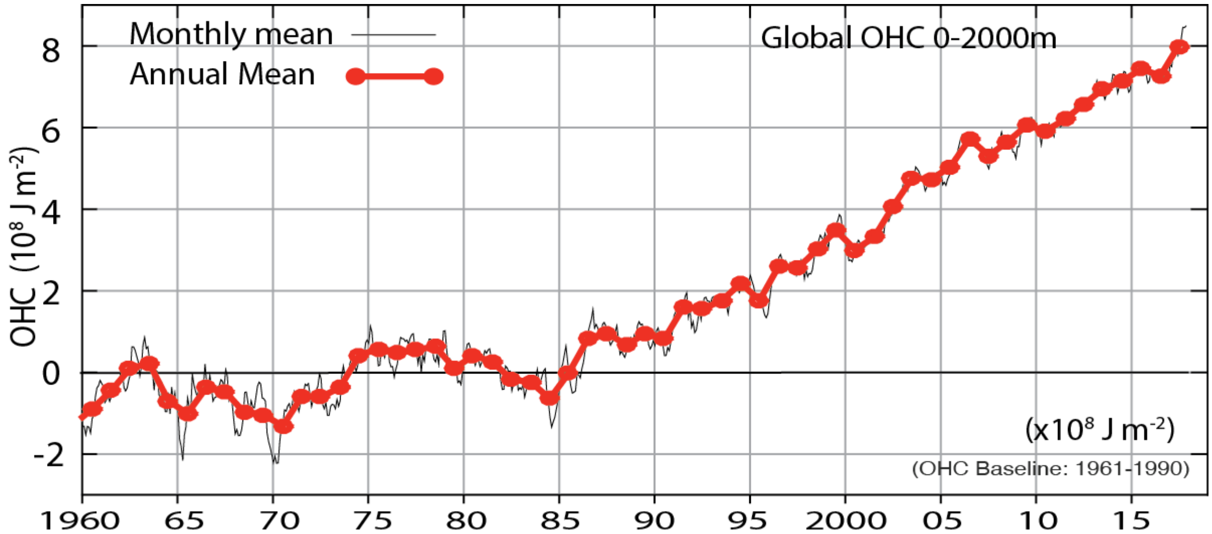

Fig. 2. Global ocean heat content for the top 2000m of the ocean, relative to the mean for 1961-2010 in 10^8 Joules per square meter, (updated from Cheng et al.[10]).

The overall warming is caused by human activities, mostly through the changes in composition of the atmosphere through burning of fossil fuels (e.g., industry, electricity generation, driving cars, flying airplanes, space heating, etc.), and deforestation. Carbon dioxide concentrations in the atmosphere have increased by well over 40% since pre-industrial times (see Fig. 1) and a key reason is that carbon dioxide has a lifetime of centuries. Air pollution in the form of aerosol particulates also play an important role, but because they are washed out by rainfall, their average lifetime is of order a week. Hence their effects are not global but rather regional, and their production has to continue for their effects to be present. Their effects are also complex because some reflect the sun and cause cooling, some (carbonaceous) are dark and absorb the sun's rays, and many become involved in clouds and affect the brightness, lifetime and disposition of clouds; in general, they cause a cooling effect. In contrast, even if we stopped emitting carbon dioxide into the atmosphere today, the elevated concentrations already established would persist for some time, thus underscoring the need for urgent reductions in carbon dioxide emissions. Hence, changes in atmospheric composition, and particularly the increase in carbon dioxide concentrations, enhance the greenhouse effect, although with important regional effects from aerosol particulates. That global warming is driven primarily from the rise in carbon dioxide can be readily demonstrated by using comprehensive climate models, which enables us to also make projections into the future[1].

Most of the energy imbalance as excess heat, over 90%, ends up in the ocean[11]. Hence, the oceans are warmer, Arctic sea ice is melting, and land glaciers and ice sheets, such as Greenland, are also melting. The largest temperature rises are occurring in the Arctic, where bright reflective snow and ice are melting to reveal dark ocean and land. This darkened surface reflects less sunshine, compounding the warming that is causing the melting in the first instance. The combination of a warmer ocean that expands, and extra melt-water in the oceans means that sea level is rising at a rate of well over a foot per century (Fig. 3).

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[10] Cheng, L., K. Trenberth, J. Fasullo, T. Boyer, J. Abraham, and J. Zhu, 2017: Improved estimates of ocean heat content from 1960-2015. *Sci. Adv.* **3**, 3, e1601545, Doi:10.1126/sciadv.1601545. http://advances.sciencemag.org/content/3/3/e1601545

[11] von Schuckmann, K., M. D. Palmer, K. E. Trenberth, A. Cazenave, D. Chambers, N. Champollion, J. Hansen, S. A. Josey, N. Loeb, P.-P. Mathieu, B. Meyssignac, and M. Wild, 2016: Earth's energy imbalance: An imperative for monitoring. *Nature Climate Change*, **6**, doi:10.1038/NCLIM-15030445C, 138-144.

Figures 2 and 3 shows that OHC and sea level are clearly rising as the planet warms, and the noise level of natural variability is a lot less than for GMST[12] (Fig. 1).

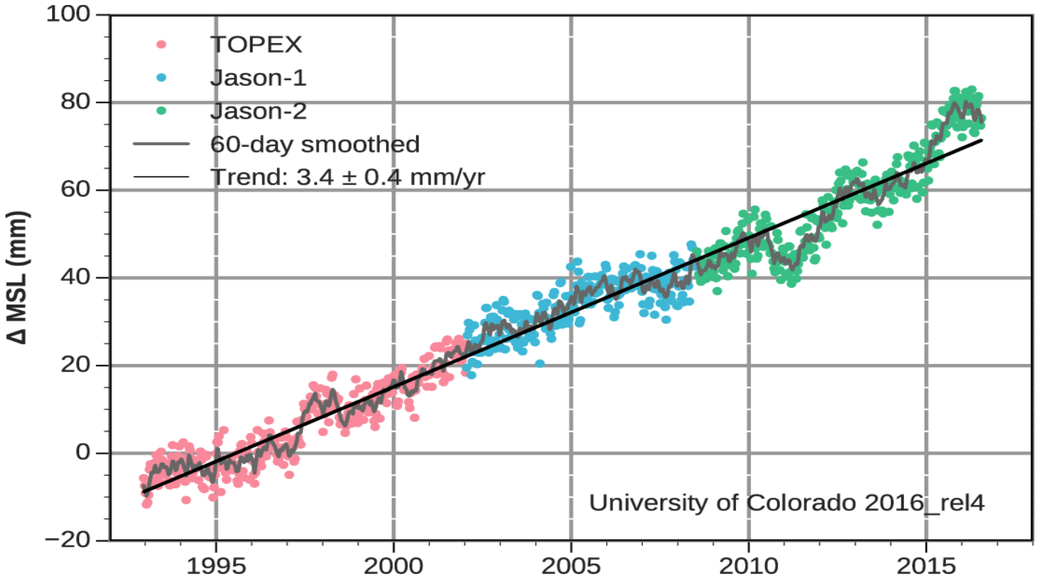

Fig. 3. Global sea level rise based upon altimeter measurements from space since late 1992, with the annual cycle removed (adapted and updated from Nerem, et al.[13]).

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

[12] Cheng, L., K. E. Trenberth, J. Fasullo, J. Abraham, T. Boyer, K. von Schuckmann, J. Zhu, 2018: Taking the pulse of the planet. *Eos*, doi: 10.1029/2017EO081839

[13] Nerem, R. S., D. Chambers, C. Choe, and G. T. Mitchum. Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions. *Marine Geodesy* 33, no. 1 supp 1 (2010): 435. http://sealevel.colorado.edu/

from year to year, it is often difficult to conclusively detect the climate change influences – an issue of signal-to-noise, as discussed later.

The conceptual framework for how extremes change with climate change is given in Fig. 4[14].

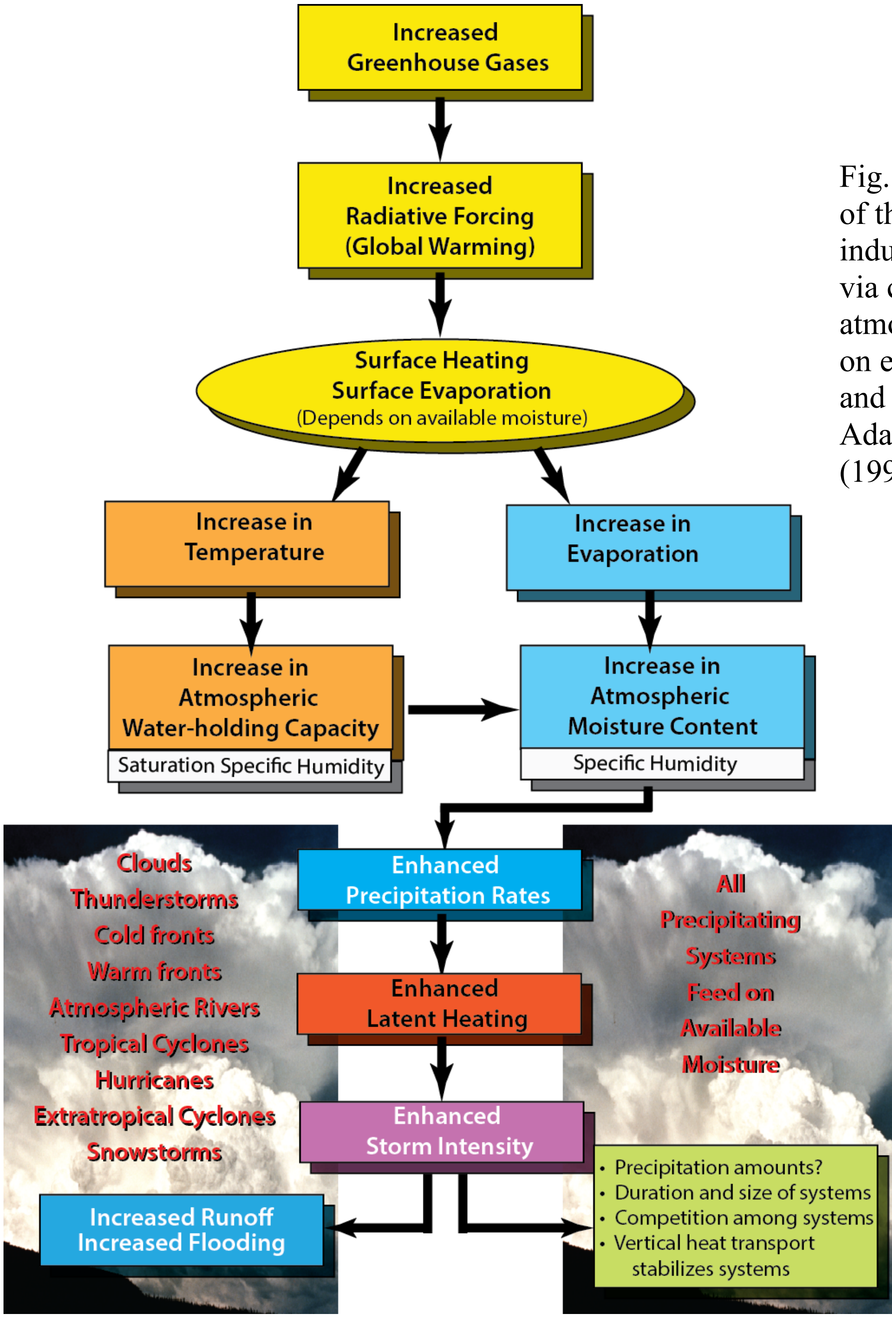

Fig. 4. A summary figure of the effect of human-induced climate change via changes in atmospheric composition on extremes of storms and precipitation. Adapted from Trenberth (1998)[14].

[14] Trenberth, K. E., 1998: Atmospheric moisture residence times and cycling: Implications for rainfall rates with climate change. *Climatic Change*, **39**, 667–694.

Trenberth, K. E., 1999: Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change*, **42**, 327–339.

Trenberth, K. E., A. Dai, R. M. Rasmussen and D. B. Parsons, 2003: The changing character of precipitation. *Bull. Amer. Meteor. Soc.*, **84**, 1205–1217.

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[15 16], 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[17], 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[18]. 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[19], while an average of 658 deaths were reported annually during 1999-2009 in the United States alone due to excessive heat[20]. 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

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Trenberth, K. E., 2011: Changes in precipitation with climate change. *Climate Research, **47**, 123-138.* doi:10.3354/cr00953.

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

[16] 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

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

[18] 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.

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

[20] 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.

temperatures[21]. More frequent, more intense, and longer lasting heat waves are robustly projected in the 21st Century as a result of human-induced global warming.

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[22] 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[23]. 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[24]. 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

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[21] 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.

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

[23] 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

[24] 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/.

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 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[25].

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[26]. 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[27]. 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.

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

[26] 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.

[27] 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.

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[28][29].

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

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

[29] 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.

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[30] 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[30].

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.

5. Attribution

Scientists are working to attribute causes to weather and climate events, which is often challenging. Owing to the chaotic nature of the atmospheric circulation (often depicted by the flap of a butterfly's wings changing the future weather), the detailed day-to-day weather cannot be forecast more than about two weeks into the future. Many repeated computer runs with small perturbations in initial states (forming ensembles) are used to bring out the robust features in future predictions versus those that depend on unknown details. This is done even for 2-week weather forecasts and is essential for climate simulations and predictions. In dealing with climate predictions, then, the goal is not to predict the detailed evolution but the general patterns of weather, such as those that occur from one season to the next. Hence the reason scientists are reluctant to *attribute* a single event to global warming is that weather events cannot be predicted more than about 2 weeks, but climate change may change the odds of such events occurring.

In the past, the traditional way of approaching attribution tried to deal with all aspects of the problem. But the changes in weather phenomena and weather systems, where they go, and so forth have infinite variety (called weather) and any climate change signal is small (except in the case of the ozone hole). This has confounded the results[31]. In particular, the conventional approach to attribution of climate events is to characterize the event and ask (i) whether the likelihood or strength of such events has changed in the observational record, and (ii) whether this change is consistent with the anthropogenic influence as found in one or more climate models. This approach has had considerable success with extremes that are strongly governed by thermodynamic aspects of climate change, especially those related to temperature, each finding providing another independent line of evidence that anthropogenic climate change is affecting climate extremes. But the traditional approach requires many climate model runs with and without climate change present to sort out how unusual the weather event was and how the odds were changed by climate change. Because of the infinite natural variety of weather and the often-uncertain nature of the human influences, such changes are mostly very small and lost in the noise. The huge computational demand precludes the near real-time commentary required by the media.

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[30] Michel-Kerjan, E., and H. Kunreuther 2011: Redesigning flood insurance. *Science*, **333**, 408-409.
NOAA 2017: Billion dollar weather and climate disasters. https://www.ncdc.noaa.gov/billions/events/US/1980-2017

[31] Hoerling, M. *et al.,* 2014: Northeast Colorado extreme rains interpreted in a climate change context. *Bull. Am. Meteorol. Soc*. **95**, S15–S18.

Hence the conventional approach is severely challenged when evaluating climate extremes that are strongly governed by atmospheric circulation, including local aspects of precipitation. It is inherently conservative and prone to false negatives, which underestimate the true likelihood of the human influence. This is all the more reason why the new "conditional" approach[32] provides more insight and illumination as to what is going on and the role of climate change. Instead it is more useful to regard the extreme circulation regime or weather event as being secondary – it is the means whereby the event happens – and focus on the effects of the well-established changes in the environment from global warming on the impacts of the particular event. Hence, it is better to examine whether known changes in the climate system's thermodynamic state (i.e. temperature related) affected the impact of the particular event. Because the water-holding capacity of the atmosphere depends strongly on temperature – it increases 7% per °C – there is also a direct relationship with humidity and precipitation. In other words, given the change in atmospheric circulation that brought about the event, how did climate change alter its impacts?

Therefore, a fruitful and robust approach to climate extreme-event attribution is to regard the circulation regime or weather event as a conditional state (whose change in likelihood is not assessed) and ask whether the impact of the particular event was affected by known changes in the climate system's thermodynamic state (for example sea level, sea surface temperature or atmospheric moisture content), concerning which there is a reasonably high level of confidence.

The National Academy of Sciences[33] in March 2016, presented both approaches as two aspects of the same spectrum, virtually without comment. But the message was that the strongly conditioned approach is completely acceptable, and moreover that the traditional approach will be limited by adequacy of the modeling tools available. Nevertheless, the large traditional attribution community has been hostile to the new approach[34] and have evidently been threatened by it.

The consequences of climate change are that things dry out quicker (stronger longer droughts) –as the atmosphere demands more evaporative moisture - and the extra moisture means heavier rains and greater risk of flooding elsewhere, so that ironically, the risk of both extremes of the hydrological cycle are substantially increased. This is confusing to many people, but of course the floods and droughts occur at different times or even different years, and different places at the same time. Those studies that have sought to understand this through changes in the weather patterns have generally failed and concluded that natural variability rules. But, as explained above, the weather patterns occur in a different environment, one that is warmer and moister and thus one where the atmosphere demands more moisture and causes drying where it is not raining, but one that provides much more moisture to storms with resulting much heavier rains, or even snows, where it is precipitating.

Of course, there are some observed changes in weather patterns, most notably in the southern hemisphere in association with the ozone hole, and small changes elsewhere are projected in the future. In addition, some changes have apparently occurred in association with decadal variability (e.g., related to

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[32] Trenberth, K. E., 2011: Changes in precipitation with climate change. *Climate Research, **47**, 123-138.* doi:10.3354/cr00953.

Trenberth, K. E. 2012: Framing the way to relate climate extremes to climate change. *Climatic Change,* **115**, 283-290, Doi: 10.1007/s10584-012-0441-5.

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.

[33] National Academies of Sciences, Engineering, and Medicine 2016. *Attribution of extreme weather vents in the context of climate change.* Washington, DC: The National Academies Press. doi: 978-0-309-38094-2. https://doi.org/10.17226/21852

[34] Lloyd, E. A. and Oreskes, N. 2018: Climate Change Attribution: When is it appropriate to accept new methods? *Earth's Future*. doi:10.1002/2017EF000665 (in press)

the pause in the rise of GMST from 2000 to 2013; Fig. 1) to further confound results, but the signal is not that of climate change. This confusion has been apparent in IPCC reports and national assessments. Below we provide some examples where the thermodynamic aspects are emphasized to bring out the human influence.

6. Examples

Super Typhoon Haiyan/Yolanda, November 2013: the strongest recorded storm ever to reach land. The ocean heat content (OHC) and sea level in the Philippine's region had both increased a great deal since 1993 and especially since 1998. Consequently, as Typhoon Haiyan approached the Philippines, it was riding on very high sea surface temperatures (SSTs) with very deep support through the high OHC. The strong winds and resulting ocean mixing did not cause as much cooling as would normally be experienced, helping the storm to maintain its tremendous strength. Moreover, the storm surge was undoubtedly exacerbated considerably by the sea levels, which were some 30 cm (1 foot) above 1993 values. Although natural variability played an important role, increased OHC from the Earth's energy imbalance (climate change) made the typhoon more severe[27].

Super storm Sandy. Super storm Sandy struck the Northeast in late October 2012 and devastated the Jersey Shore and parts of New York City, including flooding the subway and tunnels to Brooklyn and New Jersey, and 233 lives were lost. Munich Re puts the cost of the storm surge at US $68.4B although other estimates are higher. Because the storm was very well predicted a week ahead of time by sophisticated numerical weather prediction models, it was possible to run many computer-based forecasts with observed SSTs versus those with climatological conditions, that showed almost no effects on the track of the storm, but large and significant effects for intensity, wind strength and size[35]. Hence Sandy was undoubtedly larger and stronger as a result of climate change, and the storm surge was much greater owing to high sea levels and stronger winds. It is quite likely that the subways and tunnels in and around New York would not have flooded without the warming-induced increases in sea level and in storm intensity and size[27].

This is an excellent example of thresholds being crossed with highly nonlinear consequences. Relatively small increases in water from the climate change component caused billions of dollars in damage.[36]

California drought, 2013-16. One study of the recent California drought that focused on atmospheric circulation effects found no significant trends in winter precipitation in recent decades while another pointed out the critical role of the record high annual mean temperatures in combination with record low annual precipitation for 2013, which led to increased evapotranspiration and more intense drought. Another study[37] suggested between 8 and 27% of the warming contributing to the drought was anthropogenic, but even this is likely an underestimate as it used inadequate models and did not account for the changing snowpack. The combination of the weather pattern and climate change had impacts on water shortages, vegetation and agriculture, and increased wildfire risk. The odds of this combination of events have increased with human-induced climate change and anthropogenic warming causing increased

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[35] Magnusson, L. *et al.* 2014: Evaluation of medium-range forecasts for hurricane Sandy. *Mon. Weather Rev.* **142,** 1962–1981.

[36] For example, on 14 Nov. 2012 the New York Times editorial "*Money to rebuild after Sandy*" reported that "New York, New Jersey and Connecticut — the states hit hardest by Hurricane Sandy — will need tens of billions of federal dollars to repair bridges, tunnels, subway and commuter rail lines, rebuild schools, power stations and homes, and pay off staggering amounts of overtime" and noted the request from Mr. Cuomo (the Governor) for $30B.

[37] 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.

risk of drought and heat waves[38]. Again, several studies are consistent with the view that the atmospheric circulation changes are not the dominant factor, as they arise mostly from natural reasons, while climate change greatly increases heat and drying under favorable conditions and thus increases the impacts.

Colorado Floods, September 2013: In Colorado, the unprecedented heavy rains (over 9 inches in 24 hours, over 17 inches in several locations from 9 to 15 September) led to widespread flooding along the Front Range caused widespread devastation, with 345 homes lost and over 550 more damaged. The unusual tropical moisture sources came from very warm ocean regions to the south (the Gulf of Mexico and especially from west of Mexico), where twin hurricanes Manuel and Ingrid formed as soon as the moisture flow to the north was cut off and the double strike in Mexico led to 192 deaths and nearly $6B in damage[27]. The exceptionally high SSTs in the absence of an El Niño undoubtedly had a global warming component.

Southeast flooding in 2016 from both Louisiana floods (August) and hurricane Matthew (October). In both cases, record high values of atmospheric moisture were measured (by instrumented radio-sonde balloons) in association with very high SSTs in the Gulf of Mexico and in the subtropical North Atlantic. The moisture was transported into the region of the flooding by the storms and resulted in unprecedented rains and flooding. By one estimate, climate change increased the chance of the 3-day torrential rains in south Louisiana by over 40 percent[39]. The impacts were profound.

Summer 2017 Atlantic hurricanes. Prior to the beginning of northern summer of 2017, ocean heat content was the highest on record both globally and in the Gulf of Mexico, but the latter sharply decreased with hurricane Harvey via ocean evaporative cooling. The lost ocean heat was realized in the atmosphere as moisture, and then as latent heat in record-breaking heavy rainfalls. Accordingly, record high ocean heat values not only increased the fuel to sustain and intensify Harvey, but also increased its flooding rains on land. Harvey could not have produced anything like as much rain without human-induced climate change. Moreover, proactive planning for the consequences of human-caused climate change is not happening in many vulnerable areas, making the disasters much worse. Planning for such supercharged hurricanes (adaptation) by increasing resilience (e.g., better building codes, flood protection, etc.) and preparing for contingencies (such as evacuation routes, power cuts, and so forth) is essential but not adequate in many areas, including Texas, Florida and Puerto Rico where Harvey, Irma and Maria took their toll[30].

These events highlight that it is the combination of natural variability (weather, El Niño etc.) and climate change; when they go in the same direction records are broken. Hence there are more extreme climate events of all sorts. The result is huge both in terms of economic loss and human suffering.

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[30]. Figure 5 shows overall monetary losses worldwide from Munich Re for

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[38] Williams, A. P., R. Seager, J. T. Abatzoglou, B. I. Cook, J. E. Smerdon, and E. R. Cook, 2015: Contribution of anthropogenic warming to California drought during 2012–2014, *Geophys. Res. Lett.*, **42**, 6819–6828, doi:10.1002/2015GL064924.

[39] van der Wiel, K., et al., 2017: Rapid attribution of the August 2016 1 flood-inducing extreme precipitation in south Louisiana to climate change. *Hydrol. Earth Syst. Sci.*, **21**, 897-921, https://doi.org/10.5194/hess-21-897-2017. http://www.noaa.gov/media-release/climate-change-increased-chances-of-record-rains-in-louisiana-by-at-least-40-percent

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[40]. 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

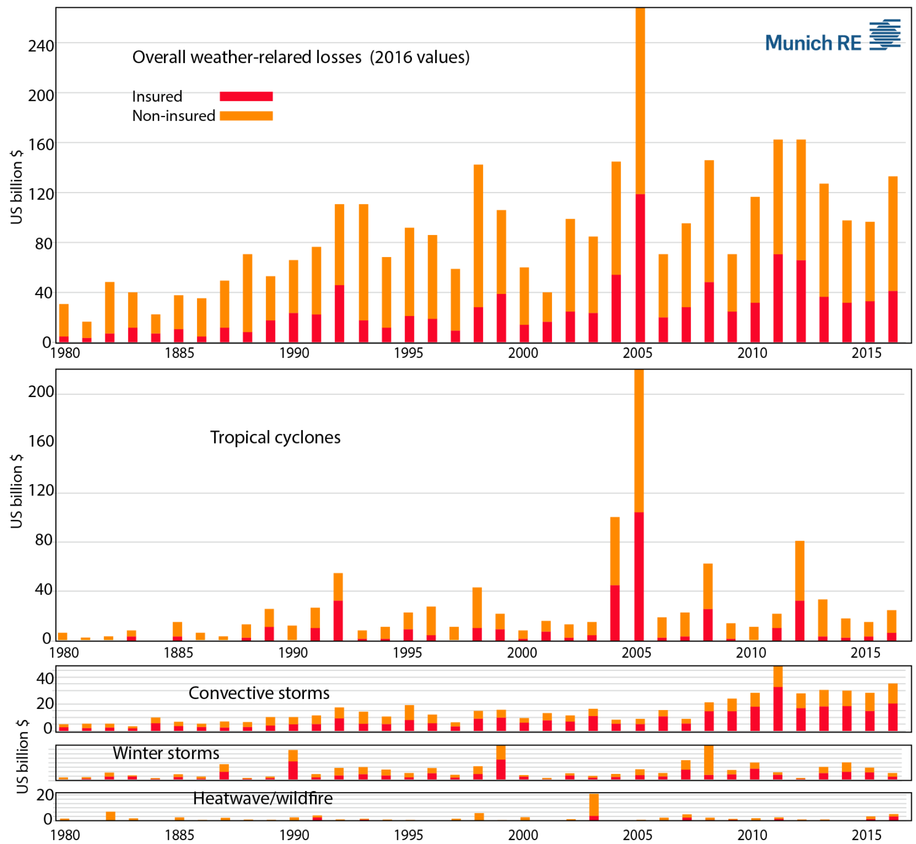

Fig. 5. Estimates of insured (dark bar) and total (grey bar) losses from various weather-related phenomena world-wide in billions of US $ for 1980 through 2016. Based upon data from Munich Re. (downloaded 26 February 2018)

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.

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[40] National Academies of Sciences, Engineering, and Medicine 2017. *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24651.

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.