Manmade CO2:

Effects and Solutions in the Big Picture

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Abstract

The arguments that the rise in CO_2 is natural or mostly natural are dismissed early in this whitepaper, but those arguments and many other non-mainstream arguments are included for completeness. The main focus of the paper is: given the manmade rise in CO_2, what are the effects, what are the current trends in those effects, how we can deal with those effects, and what are the economic costs of weather and any changes in weather. The last section is about solutions, some of which are obvious, some not so obvious, and some that people might view as overly optimistic. But that section also gives the reasons to be optimistic.

The three major effects are the drop in ocean pH, sea level rise, and changes in weather. Ocean pH is dropping with a variety of projected effects and some uncertainty. There is currently a small acceleration in sea level rise, but there has been acceleration and deceleration in the past from natural factors that are still present. Those factors will speed up and slow down a rise that is now mainly manmade.

Global warming has three main weather effects: increased rainfall, hurricanes (which also include rainfall) and heat waves. Other effects are described but are not important or currently declining. Although "heavy" rainfalls are increasing, "extreme" rainfalls of durations of a day or less are not. There is one category of extreme rainfalls that is increasing in frequency: extreme rainfalls lasting more than a day, especially those caused by tropical storms and hurricanes. One example is the brand-new state record for storm total rainfall in Arkansas from hurricane Barry (July 2019). Hurricanes are shown to have a better chance of turning into major hurricanes, even as the number of hurricanes drops. Heat waves in the US are now approaching levels last seen in the 1930's.

Those harmful changes in weather need to be mitigated as demonstrated by the failures, e.g. France in 2003. Various technological solutions and social policies are required to successfully deal with bad weather whether made worse by global warming or not. This includes understanding why wildfires are getting worse lately, from rainfall in California, and a typical drought in Australia, and what to do about it: primarily fuel reduction.

Human output of CO_2 is accelerating, but human progress is also accelerating and that is much more important and consequential. There are amazing rises in agricultural yields, drops in mortality from various weather causes, and a similar drop in economic costs of weather. Many of the worsening weather effects can be mitigated or alleviated. Other effects like hurricane damage are being overcome by economic growth. We will have ever-greater resilience and weather events will be increasingly irrelevant. "Runaway" warming from positive feedback is implausible.

The relentless and unwanted increases in manmade CO_2 will be significantly slowed by cheap and ubiquitous renewable energy in a few decades, especially by energy sources that extract CO_2 from the atmosphere, e.g. hydrocarbon "solar fuels" such as synthetic methane. By the end of the century we will have unimaginable inventions for energy generation and efficiency. We can have a global network of CO_2-neutral energy sources based on large scale solar fuel farming, complemented by sequestration wherever that can be accomplished and funded.

1. First and Second Order Effects

1.1. Manmade CO2

The current rise in CO2 is essentially manmade. There are large natural rises noted in some proxies (Wagner, 1999). If natural rises occurred in the past, couldn't the current CO2 rise be natural? Beyond any issues with the CO2 proxy used in that study, the answer is that the level of CO2 is rising at a rate far beyond any what any known natural process can produce. The ocean probably warmed naturally about 1C in the last 500 years and that would lead to about a 5 to 10 ppm total rise over the ensuing centuries, not the 2.5 ppm rise per year that is currently observed.

Sometimes on the internet, you can find claims that one large volcano produces as much or more "greenhouse gas" as mankind produces. But a very large volcano, Pinatubo, produced 42 Mt of CO2 (Gerlach, 1999) during its eruption, which is about half of one day's worth of current manmade emissions. Pinatubo also produced a lot of water vapor but that water vapor is transient and manmade and volcanic water vapor is trivial compared to the total water cycle, dominated by evaporation. There is no evidence that volcanic activity increased just as the industrial revolution started or that volcanic activity is currently increasing to match the CO2 rise. An apparent volcanic rise is explained in

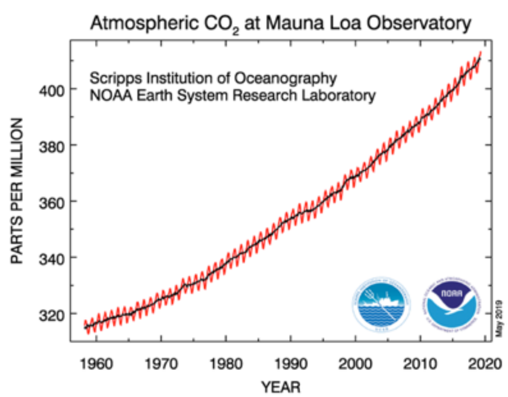


Figure 1 Rise in CO2

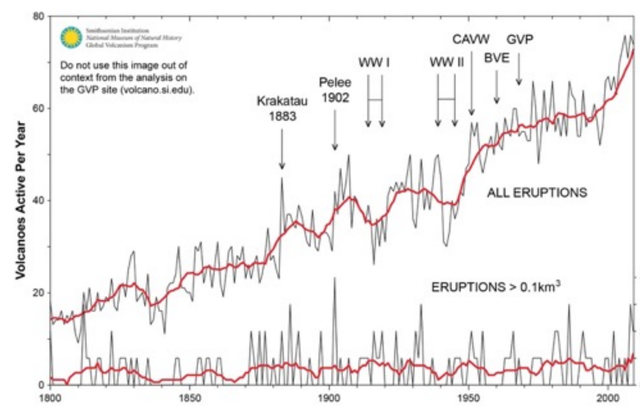


Figure 2 No rise in volcanoes (see explanation)

https://volcano.si.edu/faq/index.cfm?question=historicalactivity The explanation boils down to better observation means that more volcanoes are noticed and recorded.

Thus, the current rise in CO2 is not due to past ocean warming or recent and ongoing volcanic activity. Nor is it due to other known major biosphere changes (excluding known manmade deforestation). The rise must be from manmade from fossil fuel burning, cement making, and deforestation, and the amount of increased CO2 correlates with estimates from the economic data of those activities.

There are a handful of papers suggesting CO2 is mostly of natural origin (Hertzberg, 2016) "*Segalstad's study of the 13C/12C isotope ratios to be shown in Figure 7 confirms that atmospheric CO2 is mainly of oceanic origin and not from fossil fuels*." And "*An issue of critical importance with regard to the IPCC's paradigm is the origin of the recent increases in CO2. Are they natural or caused by fossil fuel combustion? The question has been covered earlier in this paper. The preponderance of evidence suggests* *that human emission is not a significant factor in the increase. Indeed, as shown below, previous IPCC publications, which are no longer available online, calculated human CO2 emissions to be around 4–5% of the global total (Figure 6).*"

These theories, and the particular quantity of "3.4 percent" find their way into internet websites. The "3.4 percent" claim is sometimes attributed to Dr Tim Ball and was publicized by the now-defunct National Center for Policy Analysis around 2007. The NCPA website (defunct and only available at archive.org) even admits the 3.4% figure is misleading: "*Humans contribute approximately 3.4 percent of annual CO2 emissions. However, small increases in annual CO2 emissions, whether from humans or any other source, can lead to a large CO2 accumulation over time because CO2 molecules can remain in the atmosphere for more than a century.*" But on the next page, they use the 3.4% figure to incorrectly conclude that "*Humanity is responsible for about one-quarter of 1 percent of the greenhouse effect.*"

Natural and mostly seasonal CO2 uptake is large and about equal to natural CO2 production, whereas manmade production is about 30 times smaller than the natural flux, but manmade CO2 uptake is essentially zero. The bottom line with very little uncertainty is that the well-documented rise from 280 ppm to over 410 ppm is almost entirely manmade except for the potential minor amount (~5 ppm) mentioned above. Manmade CO2 is approaching 45% (and rising) of total atmospheric CO2.

1.1.1. Eliminating CO2 Starvation

Before mankind started adding CO2 to the atmosphere, the earth was in a unique period of CO2 starvation. This was due mainly to the weathering of newly created mountain ranges like the Himalayas that extracted CO2 from the atmosphere by the very slow process of silicate weathering along with more uncertain carbonate weathering (Liu, 2011). The earth also currently has a geographic layout of landmasses that favors a relatively cold climate with lower CO2 as a result. Note that CO2 extraction by weathering is a very slow process as high as 0.477 Pg C per year (Liu, 2011) compared to current manmade production of carbon of 10 Pg C per year. Weathering may result in recovery from current excess manmade CO2 in as little as 10,000 years (Meissner, 2012). The result of low CO2 on preindustrial earth is that *"the last 6 to 8 Ma of Earth's terrestrial history are different from the entire previous history of Earth."* (Cerling, 1998)

As that latter paper explains, CO2 starvation caused the evolution of new types of plants (C4 plants like many grasses, corn, and sugar cane) that were more efficient at extracting lower concentrations of CO2 from the atmosphere and very large changes in animal life in response to the vegetation changes. CO2 starvation puts the non-C4 plant life at risk.

Another noteworthy effect of CO2 starvation is our current ice age[1] consisting of long glacial periods and short interglacial periods like the current one. It must be noted however that the main reason for the current permanent ice is planetary geography. The isolation of Antarctica makes it an ideal freezer to create and retain ice and help cool the rest of the planet. While it is better to have a bit more CO2 than CO2 starvation, there is

[1] Note that "ice age" is simply defined as a period with large amounts of permanent ice

such a thing as too much of a good thing. CO2 starvation is history and we have rapidly entered a period of increasingly excessive CO2. CO2 starvation is a moot issue.

Exponential Decay. There is a popular claim that CO2 persists in the atmosphere for many thousands of years. That is correct but irrelevant. The ocean absorbs about 3 percent of the "excess" CO2 in the atmosphere each year. Some writeups imply that a larger percentage of annual CO2 is absorbed, e.g. *"This recent relentless rise in CO_2 shows a remarkably constant relationship with fossil-fuel burning, and can be well accounted for based on the simple premise that about 60 percent of fossil-fuel emissions stay in the air* (NASA, 2019)*."* But there is essentially no difference between newly released CO2 and prior excess CO2: it is all absorbed equally.

That roughly three percent (3%) uptake by the ocean is why atmospheric levels will return half-way back to equilibrium in a few decades in an exponential decay. If we were to stop producing CO2 tomorrow, the ocean would keep absorbing a few percent of the "excess" CO2 at an exponentially decaying rate until the excess is about 80% gone in several thousand years. But much more importantly, the excess would be half gone in just a few decades. Excess is defined as the amount above equilibrium, although the equilibrium is shifting higher with more emissions and warming.

Measurements of radioactive carbon isotopes leftover from nuclear testing show how CO2 is absorbed by the ocean (Meijer, 1995). There is an exponential decay:

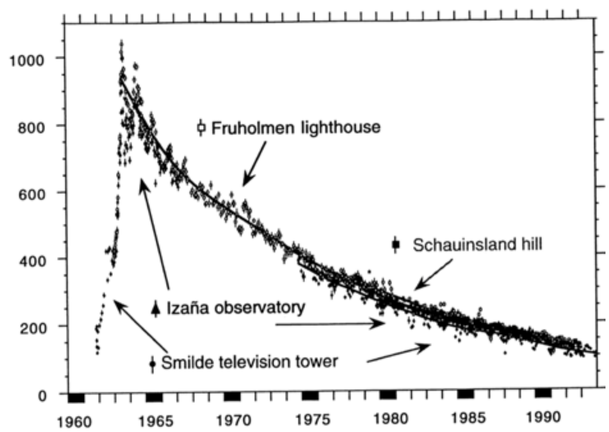


Figure 3 carbon 14 is absorbed by the ocean at creating an exponential decay curve (a negligible amount of C14 also spontaneously decays)

That decay means that there will be an initial rapid drop of CO2 followed by an increasingly slow drop, likely never reaching zero extra (preindustrial levels). But that level was the state of CO2 starvation and we don't want to go back to that. Thus, the thousands or 10's of thousands of years of very slow decay are irrelevant. What is also true is that we are not going to stop producing CO2 in the near future, so the decay rate is moot for the foreseeable future.

1.1.2. Ocean Acidification

As just explained, the ocean steadily absorbs a small percentage of the "excess" CO2 in the atmosphere even as we increase that excess amount. Based on observations, the ocean is absorbing increasing amounts of CO2 albeit with a lot of inter-annual variability (Landschützer, 2014). That ocean uptake is not benign (Doney, 2016).

The pH of the ocean is dropping about 0.02 pH units per decade (D'Olivo, 2015). Note that the pH around shallow coral reefs has a daily variation of up to 1 pH unit (Shaw, 2012). *"The pH of seawater in many coastal environments routinely varies by 1 pH unit from about pH 7.5 to 8.5."* (Hinga, 2002) The manmade pH drop is small in comparison, but inexorable. It is predicted to cause declines in calcification and other harmful effects in the long run. The lower pH has or will have some detrimental effects, for example, decreased diversity in coral reefs (Fabricius, 2011).

If the atmospheric increase were natural, then it would most likely be coming from the ocean, but it is not. The increase in H+ ions, ie. the decrease in pH, means the ocean is increasing in absorption and decreasing in natural production of $CO2$. Ocean acidification means the ocean is absorbing more $CO2$ than it is releasing on average.

Ocean acidification is sometimes referred to as "the other $CO2$ problem" (Doney, 2016). As the paper explains "*since preindustrial times, the average ocean surface water pH has fallen by approximately 0.1 units, from approximately 8.21 to 8.10 (Royal Society 2005), and is expected to decrease a further 0.3–0.4 pH units (Orr et al. 2005) if atmospheric CO2 concentrations reach 800 ppmv*" The drop has resulted in a reduction of the areas of the ocean in which aragonite and calcite (mineral forms of calcium carbonate) are supersaturated. Saturation is a necessary condition for shell and skeleton formation.

Calcium carbonate is formed from $CO2$ in seawater and calcium from shells and skeletons. Calcium carbonate is also used to form shells and skeletons. There is a cycle of calcium carbonate formation and calcification, with solubility varying with "*temperature, salinity, pressure, and the particular mineral phase; aragonite is approximately 50% more soluble than calcite*". In addition there are other inputs like trace metals and other nutrients. Also from (Doney, 2016): "*Saturation states are highest in shallow, warm tropical waters and lowest in cold high-latitude regions and at depth, which reflects the increase in CaCO3 solubility with decreasing temperature and increasing pressure.*"

From (Doney, 2016): "*Interestingly, even though global warming may allow corals to migrate to higher latitudes (Precht & Aronson 2004), the decrease in reef CaCO3 production may restrict reef development to lower latitudes where aragonite saturation levels can support calcium carbonate accumulation (Guinotte et al. 2003, Kleypas et al. 2001).*" That's something of a chicken and egg problem. The effects on coral (and other organisms like plankton that also use calcium carbonate) will vary greatly depending on the amount of dissolved carbonates versus carbonates that sink, precipitate out and fall to the ocean bottom. The general expectation is that surface waters will become undersaturated sooner than deeper waters. But biological effects will vary greatly with both increases and decreases in various life forms as currently observed and anticipated. One result will be changes in the food web and booms in some life forms and decreases in others.

The drop of about 0.1 pH unit since preindustrial times is from 8.2 to 8.1 as noted above. As noted above, a further drop to 7.7 to 7.8 is projected by 2100. Phytoplankton is at the root of the ocean food chain so naturally there is a concern about the effects of the drop in pH on phytoplankton. A study (Chen, 1994) shows a drop in phytoplankton growth rates above pH 8.8 with the study ranging from as low as 7.01 to about 9.3 with the pH artificially adjusted. There was no drop in growth rates for lower pH.

A review of such studies (Hinga, 2002) points out that the natural range of pH in marine environments can be wide enough to affect growth. A manmade drop in pH could shift that range to a lower range of pH depending on the processes that cause the range. The study notes that "It is not possible to manipulate pH without also affecting some of the other components of seawater" requiring a number of different pH control approaches which only approximate the effects in the real world. Figure 22 from (Hinga, 2002) shows the results of a meta-study:

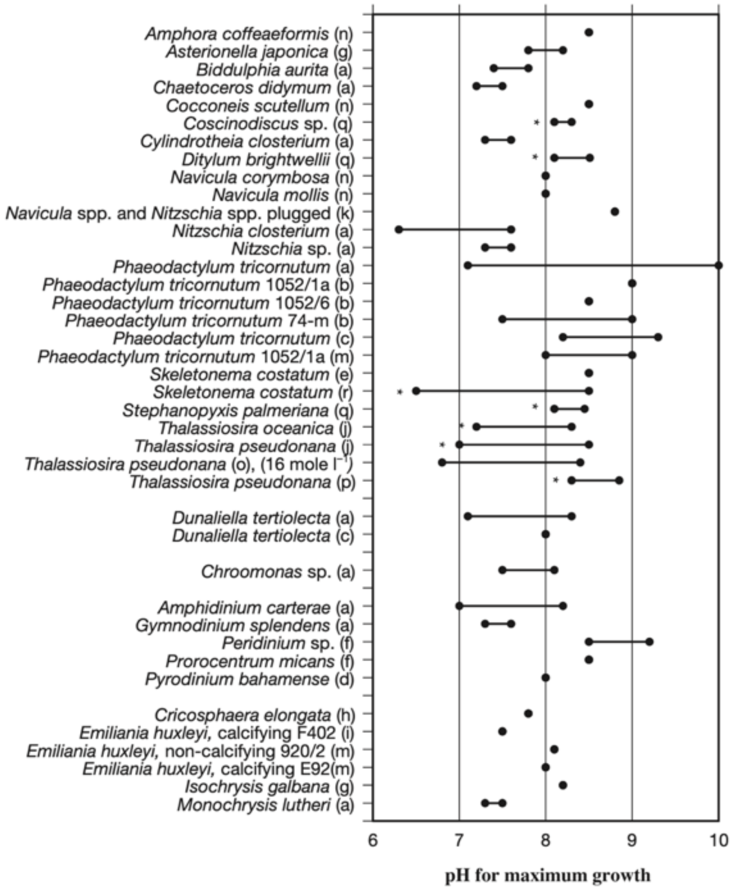


Fig. 22. Maxima in growth, growth rate, substrate uptake, production or photosynthesis/respiration ratio (P/R). Where there was no clear maximum resulting from high values at 2 widely different pH values, the high and low pH values of the broad maximum were plotted and connected. Bars marked with * indicate where the data did not extend to lower values so the range for constant growth may extend to lower values. For the studies by Humphrey (1975), the range bars represent the range of different estimates of maxima from the 3 types of measures he reported (Table 4). Sources are indicated in parentheses: (a) Humphrey (1975); (b) Hayward (1968); (c) Goldman et al. (1982a); (d) is Blackburn & Oshima (1989); (e) Thoresen (1984); (f) Barker (1935); (g) Kahn & Fogg (1958a,b); (h) Swift & Taylor (1966); (i) Paasche (1966); (j) Chen & Durbin (1994); (k) Bacharach & Lucciardi (1932); (m) Johnston (1996): (n) Wang et al. (1998); (o) Pruder (1979); (p) Pruder & Bolton (1979); (q) Goldman (1999); (r) Taraldsvik & Myklestad (2000)

Figure 4 - Maxima in phytoplankton growth rate for a range of pH from (Hinga, 2002)

The results show that there are species with growth rates that are relatively sensitive to changes in pH. There are species that grow in wide ranges of pH. The paper's conclusion is that pH is an important factor but just one of many factors.

Many researchers are starting to examine the combination of the two most salient effects of manmade CO2 which are lower ocean pH and higher ocean temperature. In such studies the temperature increase is often the more important factor.   For example in (Horn, 2016) the researchers find that warming led to higher growth and an earlier peak bloom of phytoplankton while those organisms showed a tolerance to higher CO2 (lower pH). The two factors together had no additive effect on the results.

Finally considering that ocean acidification is a long term problem, and will continue for several centuries, there are studies to consider if lower pH can be mitigated in the far future using geoengineering. One motivation is to engineer the ocean to be a bigger sink for atmospheric CO2, for example by fertilizing ocean surface with iron, thereby using up the dissolved CO2. The result is slightly less low pH in the surface ocean but a lower pH in the deep ocean. Those techniques and some techniques to directly raise pH are listed in (Williamson, 2012).

1.1.3. Greening (CO2 Fertilization)

On land as in the ocean, higher CO2 increases the growth of vegetation. There is often a focus on higher growth of particular plants that are bad for humans or the environment. For example, poison ivy grows better and is more allergenic with increased CO2 (Mohan, 2006). That type of research ignores the fact that beneficial species far exceed non-beneficial species, and CO2 is rarely selective. The only sustainable way to counteract unwanted weeds is to encourage alternatives, for example, Virginia creeper, which benefit just as much from extra CO2 as poison ivy does. In most cases, there is no net positive or negative effect from increased CO2.

I originally thought that the Japanese Stiltgrass smothering parts of my property in Virginia was benefitting from CO2 fertilization. But it turns out it was the extra rain, and instead my invasive Japanese honeysuckle may be benefitting from extra CO2: "*High carbon dioxide levels may negatively affect Nepalese browntop compared to plant species better able to assimilate extra carbon dioxide. In field experiments in Tennessee, Belote and others [19] found that in a wet year, Nepalese browntop produced twice as much biomass under ambient carbon dioxide levels compared to elevated carbon dioxide levels (P=0.07). In a dry year, there was no significant difference in Nepalese browntop biomass between carbon dioxide treatments. In contrast, Japanese honeysuckle, a common nonnative associate of Nepalese browntop, produced 3 times as much biomass under elevated carbon dioxide levels in both wet and dry years*" (Fryer, 2011) I have many native and invasive species which I have to manage. The ecosystem might be speeding up from CO2 fertilization, a longer growing season, more rainfall, and other factors, but the balance in my battle against invasive non-native species or aggressive native species does not change due to more CO2 or changes in the weather.

Most studies show greening as neutral (balance of positive and negative) for the natural environment. The CO2 and weather effects on agriculture are discussed later. As an example of the effect of CO2 fertilization, foliage has increased across many warm, arid environments (Donohue, 2013).

1.1.4. Global Warming

Increasing CO2 causes global warming, and global warming is the main effect of increased CO2. For completeness, I will present an argument against the idea that increasing CO2 causes global warming. There are other more sophisticated arguments against "back-radiation" and the entirety of the greenhouse effect which I will ignore.

Against: Here's a link that claims "Evidence Proves That CO2 Is Not A Greenhouse Gas (Ball, 2018)". Some evidence is presented such as warming preceding rises in CO2 in the ice core record. It is true at least in some cases that rising temperature precedes rising CO2 by 500 to 1000 years. But the page fails to mention that CO2 is an amplifier of warming. The warming starts by various other causes, the warming causes an initial rise in CO2, and the rise in CO2 causes more warming. The positive feedback is evident on most "CO2 lags warming" charts.

Dr. Ball states: "*If both factors caused each other to rise significantly, positive feedback would become exponential. We'd see a runaway greenhouse effect. It hasn't happened.*" That is true. But that just means there is a weak relationship from warming to CO2 production and a weak relationship from CO_2 production to more warming. Neither of those positive feedbacks is strong enough to create runaway warming as noted over the entire history of the earth. The fact of no runaway warming or permanently frozen planet also means that negative feedbacks dominate at the extremes of heat and cold.

Dr. Ball states: "*The assumption that an increase in CO2 causes an increase in temperature was incorrectly claimed in the original science by Arrhenius. He mistakenly attributed the warming caused by water vapour (H2O) to CO2. All the evidence since confirms the error.* ***This means CO2 is not a greenhouse gas.*** *There is a greenhouse effect, and it is due to the water vapour*." The statement in bold (bold in original) implies that CO2 is not a radiatively-active gas, but that is not true.

For: Here's a well-regarded site that explains the effects of increased CO2: the-greenhouse-effect-explained-in-simple-terms/ That page explains that CO2 is a radiatively-active gas and that adding more molecules of those gases increases the opacity of the atmosphere in certain wavelengths. In fact, on average an infrared photon, at a particular wavelength, leaving the earth will be intercepted by a CO2 molecule within 33 meters to 47 meters[2] of the earth's surface. With more CO2 molecules to hit, the mean free path decreases which cause an increase in opacity.

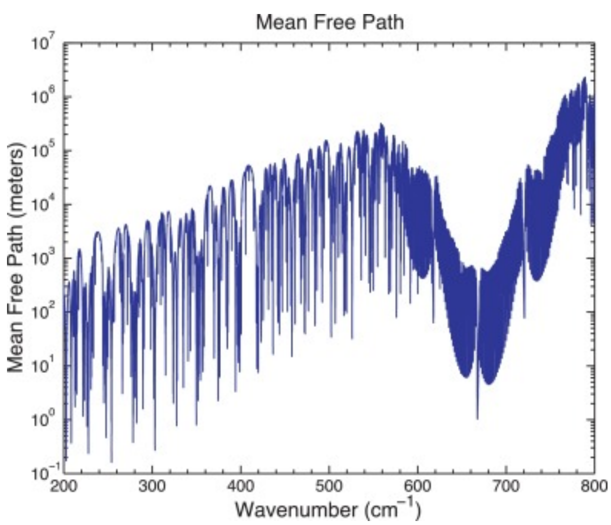


Figure 5 The mean free path varies by wavelength

That interception of IR photons by CO2 molecules warms the atmosphere. That is because the time it takes for the CO2 molecule to conduct the extra heat to the rest of the atmosphere is many orders of magnitude shorter than the time it takes to reemit an IR photon. However, each CO2 molecule absorbs energy from the rest of the atmosphere and emits photons at the same rate as it absorbs photons. Based on those two physical principles there is essentially no doubt that increasing the number of CO2 molecules in the atmosphere will increase the average temperature of all of the air molecules in the troposphere. That is manmade global warming.

The unresolved question in the explanation above is the quantity. The fact that more CO2 molecules produce a warmer atmosphere is a qualitative statement, not quantitative. Also, the warming effect only works when there is a positive lapse rate, that is, the temperature decreases with altitude as is the case in the troposphere. As global warming increases, the lapse rate in the troposphere is expected to decrease and lower the amount of warming produced by each increment of extra CO2. The quantities must be sorted out with climate models but climate models can't predict future weather, only model current

[2] dead link: http://www.globalwarmingskeptics.info/attachment.php?aid=250

weather, modulated by global warming, using parameters that may change with global warming. Without knowing weather feedback there is no way to know future warming except within a range of values derived from varieties of possible prevailing weather.

Could global warming be due to increased solar activity? Solar irradiance reconstructions show a rise in solar irradiation of ~1 W/m2 for the period 1900-1950 (Shapiro, 2011). Divide by 4 since the earth is spherical, multiply by 0.7 since albedo is 0.3 and multiply by 3.7 (per 1C sensitivity) to get 0.05C per 1C of sensitivity. Sensitivity is defined as the amount of global warming for a doubling of CO2 and a doubling of CO2 produces an extra 3.7 Watts per square meter of the earth's surface. The sensitivity is a "high end" long term (century-scale) result, estimated from climate models so it varies depending on climate model parameters. A 2C sensitivity is considered low, 3C is consensus, and 4C is high. That means the long-term warming from increased solar irradiance is roughly 0.1 to 0.2C or 0.15C from 1900 to 1950 using consensus sensitivity. In (Huber, 2011) the authors concluded that using models with maximum possible changes in solar irradiance that *"solar forcing contributed only about 0.07 ◦ C to the warming since 1950"*.

2. Third Order Effects

2.1. Sea Level Rise

Often there will be a claim made that sea level rise is accelerating (Church, 2006) which is true from time to time. The acceleration calculated in that paper requires fitting a quadratic equation to data that has a lot of natural variation. Although sea level has natural fluctuations, there is an upward trend that was natural and is now manmade. There is currently some acceleration but the current peaks are not a lot higher than the peaks in the trend given in the paper.

Using those modern estimates, the rate of sea-level rise for the past 20 years is only slightly higher than 1925-1945. Furthermore, the rate of sea level rise is often adjusted for expansion of the ocean basins. This means the actual, observed rate of sea-level rise is about 0.3mm/yr slower (GIA adjustment, 2011) than the stated rate of 3.1 mm/yr (University of Colorado, 2019). Here is Fig 2 from (Church, 2006):

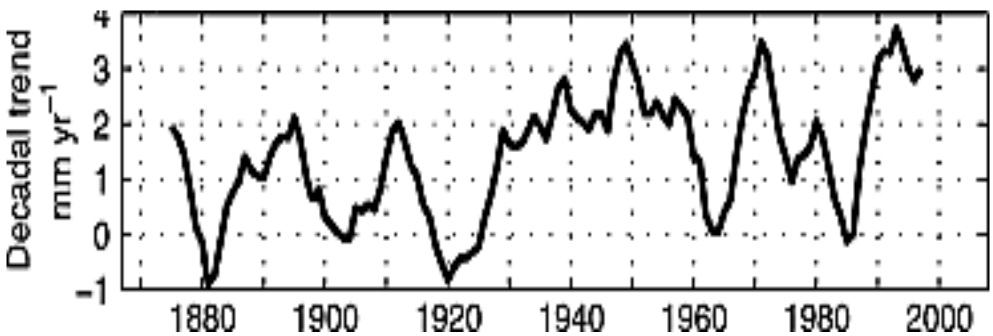


Figure 6 - The rate of sea level rise by the late 1940's is only marginally less than the rate in the 1990's

The explanation for the current acceleration is manmade global warming, but what is the explanation for the acceleration starting in the 1920s? The best complete explanation is manmade warming is causing sea level rise, but the rate of rise varies naturally.

2.1.1. Sea Level Rise from Thermal Expansion

The ocean as a whole has warmed about 0.2C in the past century. Roughly half of that warming was natural. As the ocean warms the water expands and raises the sea level. However, ocean warming is not as simple as observing the atmospheric temperature rise and assuming the ocean will eventually warm the same amount with a long delay. There is both colder and warmer water being mixed down from the surface into the deeper ocean varying by location, season and prevailing weather.

The sea surface temperature (SST) has warmed almost everywhere. But transferring that warmth to the deeper ocean is an uneven process. The Argo buoy network measures ocean temperatures at various depths and shows 15 years of warming depicted and linked below. Much of the recent warming shown in the ocean temperature plot is cyclic warming from the recent super El Nino shown in the Nino 3.4 graph below that. As the current El Nino inevitably fades and La Nina takes over, it will be worth watching what happens to the ocean temperature plot.

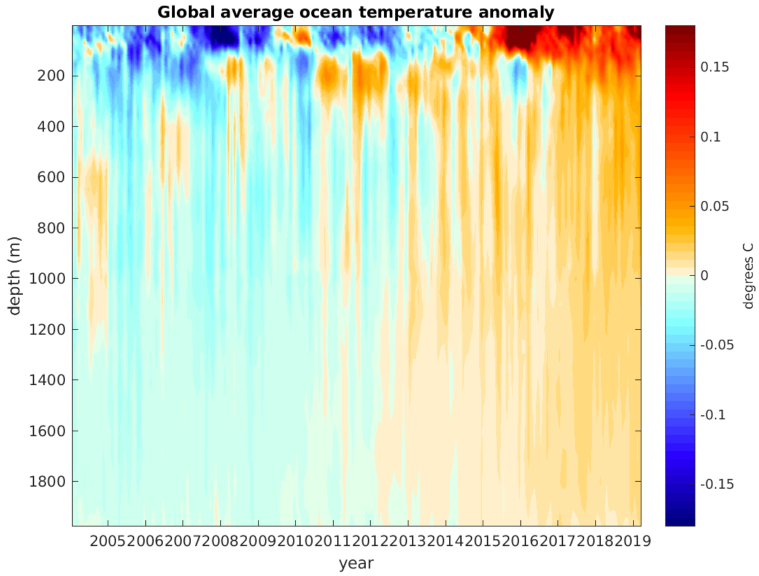


Figure 7 - Average ocean temperature at depths measured by Argo ([source])

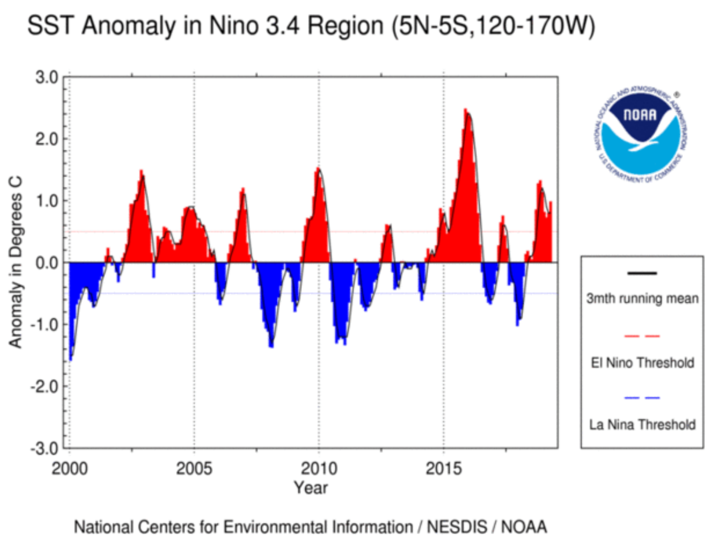


Figure 8 Much of the short-term ocean warming shown above is from the recent El Nino

2.1.2. Sea Level Rise from Greenland Melt

Greenland is much more likely to melt and cause sea level rise than Antarctica since the Arctic is warming much more than the area around Antarctica which is hardly warming at all. There are two somewhat independent processes to consider when discussion Greenland's ice sheet. First is the surface mass balance (SMB) which is the amount of winter snow minus the amount of summer melt. Occasionally it is incorrectly claimed that Greenland's ice is increasing because SMB is positive. That is not correct because there is a second process, calving loss, the flow of ice to the edge where it calves and melts in the ocean. The calving loss is relatively constant at about 500 Gt per year. The amount of SMB gain is highly variable but currently a little over 200 Gt per year on average. That leads to an average net loss of 250-275 Gt per year depending on SMB estimates. From 2002 to 2017 there was a way to measure net loss, that is to measure both SMB change and calving losses, the net result of both processes:

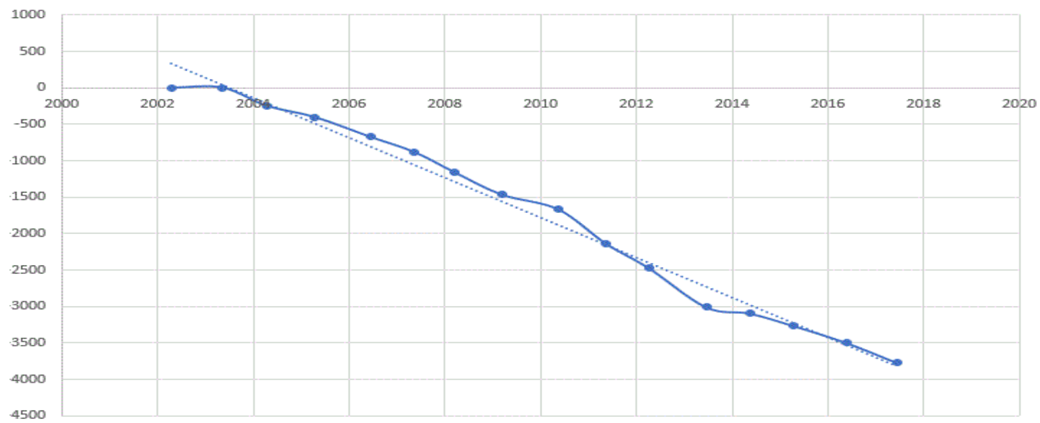


Figure 9 - Linear trend of annual peak ice mass on Greenland

The chart above uses all 15 years of [GRACE]() data from https://climate.nasa.gov/vital-signs/ice-sheets/ and using each year's peak mass, there is an excellent linear fit. The net loss is currently about 275 Gt per year using the slope of that line.

There are claims of accelerating ice loss in Greenland (Bevis, 2019)

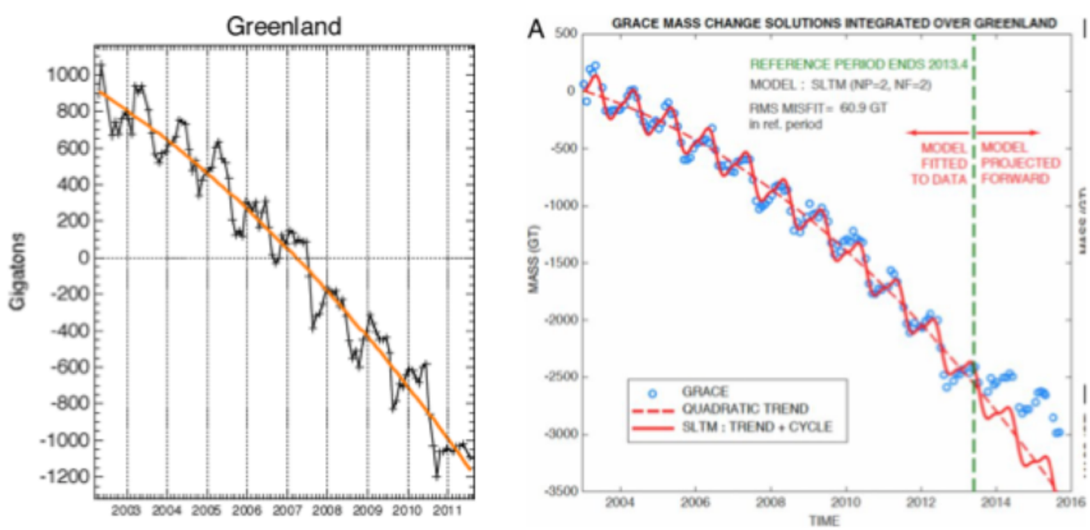


Figure 10 - Skeptical Science (left) and PNAS (Bevis, 2019) (right)

The apparent pause in the acceleration is explained in (Bevis, 2019) as "anomalous". In fact there was no net ice loss in the 2016-17 season: http://sciencenordic.com/how-greenland-ice-sheet-fared-2017 "*Overall, initial figures suggest that Greenland may have gained a small amount of ice over the 2016-17 year. If confirmed, this would mark a one-year blip in the long-term trend of year-on-year declines over recent decades.*" There was almost no loss in 2017-18: http://sciencenordic.com/how-greenland-ice-sheet-fared-2018 "*…it is likely that the relatively high end of season SMB will mean a zero or close-to-zero total mass budget this year, as last year.*" In contrast 2018-2019 had a higher than average loss: "*Overall, melting on the Greenland ice sheet for 2019 was the seventh-highest since 1978, behind 2012, 2010, 2016, 2002, 2007, and 2011*" (NSIDC, 2019). More recently the 2020 melt season started late after late snowstorms, and ended abruptly with a snowstorm. That resulted in another average accumulation, well above 200 Gt, offsetting a cold and dry winter (reflected in a positive NAO index).

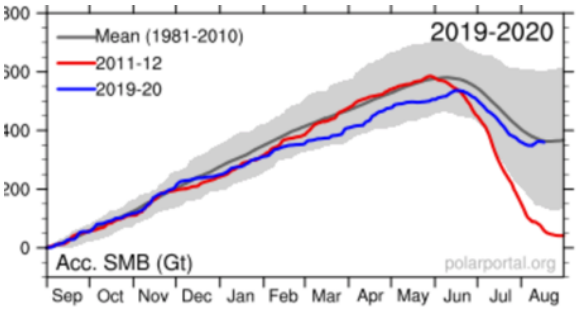


Figure 11 - Accumulated Surface Mass Anomaly http://polarportal.dk/en/greenland/surface-conditions/

Greenland ice loss acceleration ended (potentially temporarily) in 2006 (King, 2018).

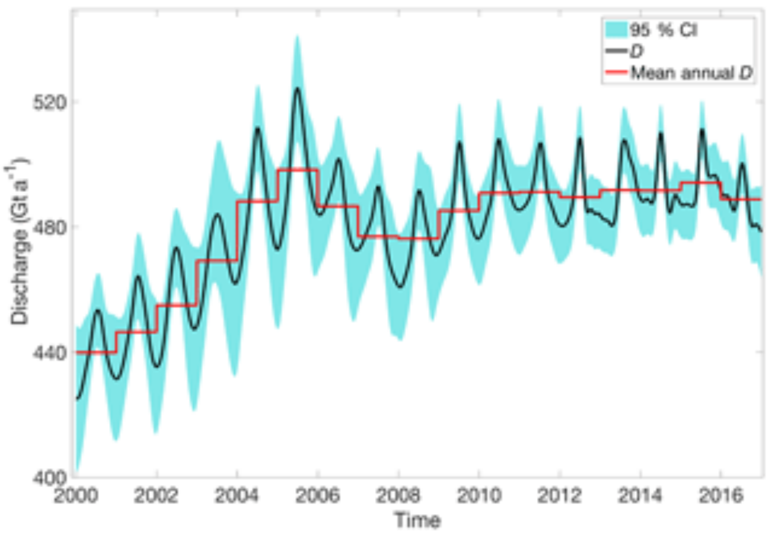


Figure 12 - Greenland ice loss rate (King, 2018)

Greenland warmed rapidly in the 1920's (Wake, 2009) and "*Greenland's glaciers retreated rapidly between 1900 and 1930 as the Little Ice Age lost its grip on the region and temperatures climbed*." (from a press release at https://fallmeeting.agu.org/2014/files/2014/12/2014-Greenland.pdf) The warming was part of the north Atlantic warming of the 1920's and 1930's amounting to 0.5 to 1C (Drinkwater, 2006). The warming and glacier retreat does not necessarily mean there was a large amount of ice mass loss. (Wake, 2009) is only about SMB and does not consider or analyze calving loss.

There is little doubt that net ice loss is more rapid in the past 15 years (using GRACE data) than preceding decades (using other measurements). They discuss this acceleration in (Box, 2012). They describe the period 1961-1990 as balanced with roughly 480 Gt of calving losses balanced by 480 Gt of SMB gain (700 Gt of net snowfall and 220 Gt of runoff (all values per year). They compare that to the increasing SMB losses from 2000 through 2011 and validate and explore causes with a regional climate model. One of the notable trends is increasingly negative NAO, see https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table. The paper is somewhat prescient being written before the record 2012 SMB melt, with essentially zero SMB gain (and at least 500 Gt of calving losses). The NAO was unusually negative in June and July of 2012. Negative NAO is partly an indication of a Greenland block, that is high pressure over Greenland affecting the weather across the north Atlantic and adjacent lands, but inducing warm sunny weather on Greenland. The main focus of the paper is that decreasing albedo, essentially dirty snow on the surface, causes more melt.

The two main questions that need to be answered for Greenland are glacier flow and the weather. As Greenland warms, the outlet glaciers flow more quickly and calve their ice into the ocean faster. That's at least 5,000 years at the current rate (if there is zero SMB gain) or potentially substantial loss in a few centuries if that flow speeds up. In (JOUGHIN, 2010) they confirm that the glacier flow and subsequent calving losses are at least somewhat related to SMB by temperature: "*In Greenland, calving rates often vary seasonally (Sohn and others, 1998), with substantially less calving in winter than in summer, allowing at least some calving fronts to advance over the winter.*" Their measurements comparing 2000-1 and 2005-6 show the majority of outlet glaciers are speeding up. However "*Thus, while outlet glacier dynamics may produce a large contribution to present ice loss, basal topography may limit such retreat to regions near the coast. If this occurs, further ice-sheet loss would be largely controlled by surface mass balance, as is the case now for much of southwestern Greenland.*"

The second question is weather. SMB is currently positive. The one exception was 2012 when SMB was around zero. 2019 came close to 2012 with a long melt season but ended a slightly positive SMB. There is disagreement. NSIDC https://nsidc.org/greenland-today/ shows it as almost identical to 2012. But DMI shows it as positive:

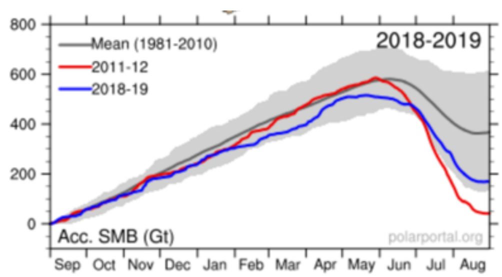


Figure 13 - 2019 Surface Mass Balance at End of Season from http://polarportal.dk/en/greenland/surface-conditions/ (click on date entry and enter 30/08/2019)

In 2016 hurricane Nicole dumped about 10 feet of snow on SE Greenland thanks to a perfect track east of the island. The total snowfall from that storm was about 50Gt. That's a substantial offset (10%) of the total loss from calving. More snow also increases albedo leading to lower losses the following summer.

(Vinther, 2009) describes Holocene thinning episodes in Greenland. From (Vinther, 2009): "*The most significant periods of decrease in elevation coincided with the climatic optimum 7–10 kyr before AD 2000. This suggests that the GIS responds significantly to a* *temperature increase of a few degrees Celsius, even though part of the GIS response in the early Holocene was also associated with ice break-off resulting from rising sea level. The colder climate prevailing during the past two millennia induced a slight increase in elevation of the GIS at these sites.*" The paper mentions regional solar influences as a probable factor for the temperature changes of the past 10,000 years. The conclusion of the paper is that Greenland mass may respond rapidly to a few degrees of warning and cause more sea level rise. But it also seems likely to me that Greenland is more sensitive to solar changes such as the 1 W rise from 1900 to 1950, and the melting in the 1920's, and that some of the current melting is due to solar-based warming.

In summary, Greenland losses vary naturally and the acceleration in losses before 2005 was at least partly natural. A new period of acceleration does not seem likely in the context of predicted slowing solar activity.

2.1.3. Sea Level Rise from Antarctic Melt

Antarctica as a whole is unlikely to contribute to sea level rise significantly if at all. There are older model studies (Huybrecht, 1999) that showed that Antarctic ice gains would balance out losses in Greenland. The predominant factor is that it is too cold to snow in Antarctica as a whole. The average temperature in Antarctica is -50F and it is too cold to snow at -40F (Lachlan-Cope, 1999). The warming of Antarctica has generally been expected to result in more snowfall and net ice gain (Frieler, 2015).

Gain in Antarctica was originally expected to offset loss in Greenland (Alley, 2005) "*For the full range of climate scenarios and model uncertainties, average 21st-century sea-level contributions are –0.6 +/- 0.6 mm/year from Antarctica and 0.5 +/- 0.4 mm/year from Greenland, resulting in a net contribution not significantly different from zero, but with uncertainties larger than the peak rates from outlet glacier acceleration during the past 5 to 10 years.*" More recent papers by the same scientists point out the uncertain prospect of the collapse of the West Antarctic Ice Sheet (WAIS) (Alley, 2011). The prospects for West and East Antarctica are unclear.

As with Greenland, there are GRACE satellite measurements of increased ice loss from the WAIS: Gravity data show that Antarctic ice sheet is melting increasingly faster From that research summary: "*Since 2008, ice loss from West Antarctica's unstable glaciers doubled from an average annual loss of 121 billion tons of ice to twice that by 2014, the researchers found. The ice sheet on East Antarctica, the continent's much larger and overall more stable region, thickened during that same time, but only accumulated half the amount of ice lost from the west*".

The steady increase in the WAIS losses must be considered against sporadic but substantial rises in the EAIS (Lenaerts, 2013). In the anomalous year of 2009 in Queen Maud Land, in the Atlantic sector of East Antarctica, there was an extra 160 Gt of snowfall. The extra snowfall in Queen Maud Land was analyzed with climate models in (Lenaerts, 2013) and found to be increasingly probable toward the end of the 21st century.

After decades of defying predictions of decrease (Parkinson, 1984), Antarctic sea ice suddenly decreased in 2017 and remains below average as of July 2020. It will be interesting to see the consequences of less Antarctic sea ice. Less sea ice means less heat of fusion and warmth that potentially melts the land ice at its margins. Less sea ice means less insulation of water in winter and cooler water reaching the continent. Less sea ice means more snow can land on the continent and stick around rather than landing on the sea ice that melts in the summer. On the other hand, less sea ice means more warming of surface waters during the summer, the strong positive feedback observed in the Arctic. It will be interesting to see how these contrasting forces play out in the colder southern hemisphere.

2.1.4. Local Sea Level Factors

The main effects of sea level rise are increased nuisance flooding in subsiding areas and increased height of storm surges. The global increase is a little over an inch per decade but local factors can increase or decrease that, including increases by multiples. In some cases, the sea level rise is displacing residents. Why would 1.1 inches per decade (the global rate) displace residents? It simply would not. Displacement is due to local conditions and local forces that need to be examined.

In one case the dominant force is claimed to be erosion, for example on some of the Solomon Islands (Albert, 2016). However, the relative sea level rise is three times the global average so part of what is probably being measured is subsidence, gravity changes, and various ocean cycles with some long-term lulls and a current short-term rise (as shown in their fig 6) below. Erosion does not square with the very large short-term fluctuations in the graph.

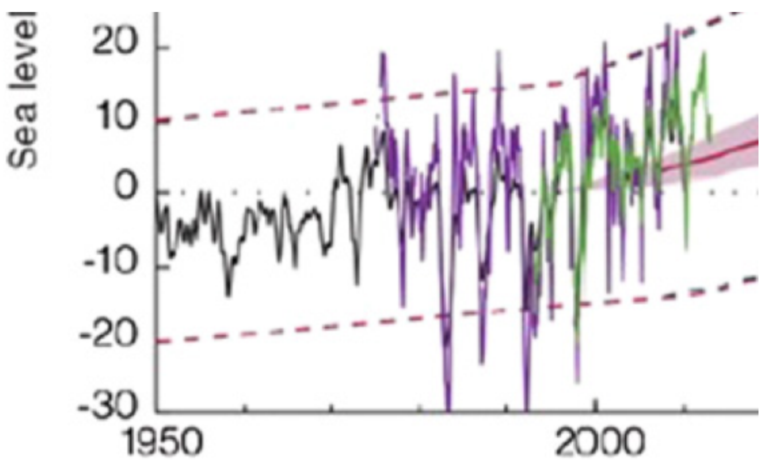


Figure 14 - Sea level in the Solomon Islands from reconstruction (following the approach of Church et al 2004 and Church and White 2011), satellite altimeter (Church and White 2011), tide gauge and projections (truncated) from fig 6 of (Albert, 2016)

As Judith Curry points out in https://curryja.files.wordpress.com/2018/11/special-report-sea-level-rise3.pdf there often is a complex set of factors in regional sea level rise. In my opinion, the paper about the Solomon Islands ought to examine the factors unique to the Solomon Islands when the stated goal is to inform the local communities to aid in adaptation. From (Albert, 2016) *"Residents of Nuatambu described the shoreline recession as incremental over several years, rather than related to a specific storm or wave event as experienced elsewhere in the region (Hoeke et al 2013)."* What caused the recession? What are the local predictions? What can they do about it? That analysis is essential regardless of any coordinated action on global warming that might result in global sea level deceleration in a century or two.

A 2018 study found that land area in Tuvalu grew from 1971 to 2014: https://phys.org/news/2018-02-pacific-nation-bigger.html despite local sea level rise that is double the global average. The study (Kench, 2018) showed that the dominant factors were erosion and accretion, not sea level rise. The result is movement of some islands with erosion on one side and accretion on the other. Their main conclusions are that there is a need to adapt to changes and that there is time (decades) to adapt.

2.2. Extreme Weather

The most important thing to know about extreme weather is that the rarer the event, the less likely that it will display a trend that can then be attributed to global warming. That does not mean that global warming won't be or isn't already a factor in weather. An example of attribution difficulty for rainfall is described in (Barbero, 2017). This statistical truth applies to any weather event but it's sometimes difficult to determine the degree of rarity. For rainfall in particular, the shorter the extreme rainfall duration, the rarer it is. That's because the small-scale weather pattern to obtain extreme record rainfall has to be perfect. Moisture is not the limiting factor; it is moist enough many times in many places every warm season to generate an extreme event. But the rest of the ingredients almost never line up.

One consequence of the statistical difficulty of detecting trends in extreme weather events is that research projects will often focus on events that are not extreme. This is most often done for rainfall as we shall see next. Let me first state that there is ample evidence that heavy rainfalls are getting more common. But the consequence of those is mainly flooding in the usual flood-prone locations.

Finally, a general principle for extreme weather is that for now, in most cases, natural variation exceeds manmade changes.

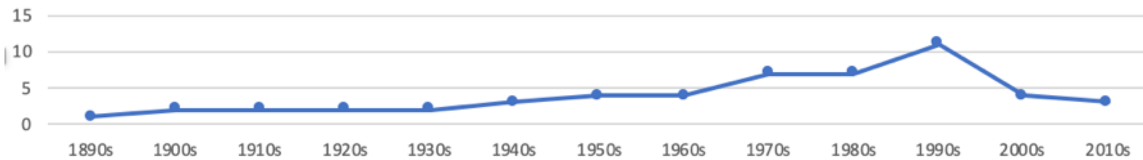
2.2.1. "Extreme" Rainfall

The various claims that "extreme" rainfall is increasing rely on particular definitions of "extreme". Some truly extreme rainfall events are becoming more common in a specific category: long duration events, mostly rainfall of 24 hours or longer, and especially 2 days or longer.

For longer duration events the patterns are less rare, for example, a stalled front. The extra moisture provided by lakes and oceans, warmed by global warming, creates a higher quantity rainfall event. With natural variability, that makes an extreme event more likely. In some cases there is not a particularly large quantity of moisture in the atmosphere at any moment, but it is often refreshed from the source, e.g. blown in from a warmer ocean. Indeed a study of daily and subdaily extremes (Barbero, 2017) concludes that "*changes in the magnitude of subdaily extremes in response to global warming emerge more slowly than those for daily extremes in the climate record.*" In other words, since extreme subdaily events are rare events, it will take more data to tease out a trend.

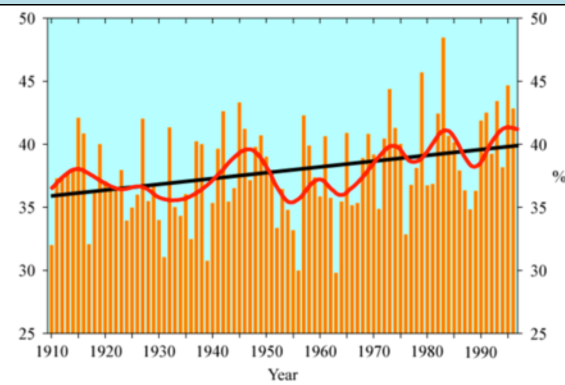
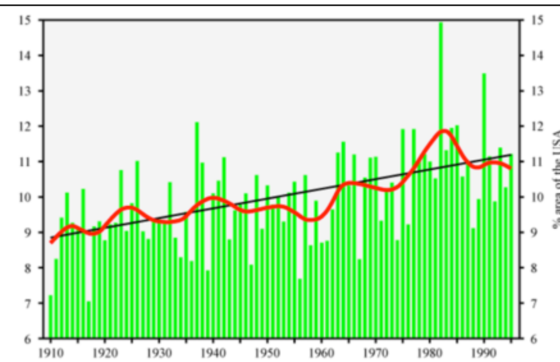
The rainfall records for shorter duration events are almost all decades old. For example 1.23 inches in one minute in 1956, 2.03 inches in five minutes in 1960, etc (see [What is the Most Rain to Ever Fall in One Minute or One Hour?]) The article mentions several rainfall records for an hour or less from the 1940's. With more data from more events, not just the record events, we may start to see a trend.

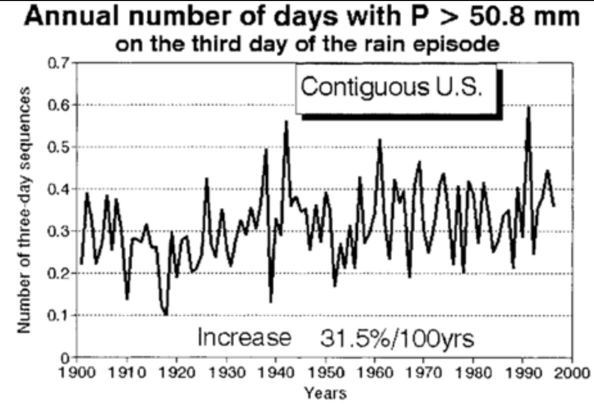
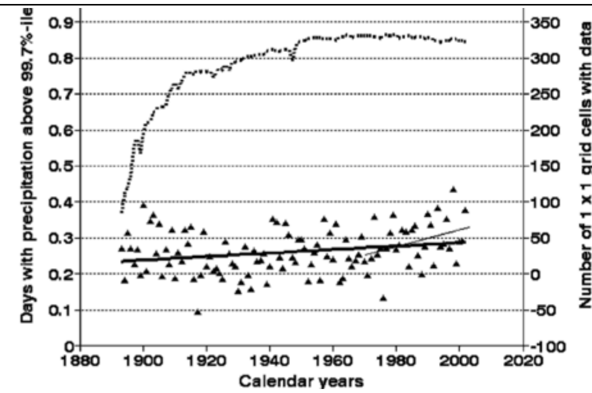
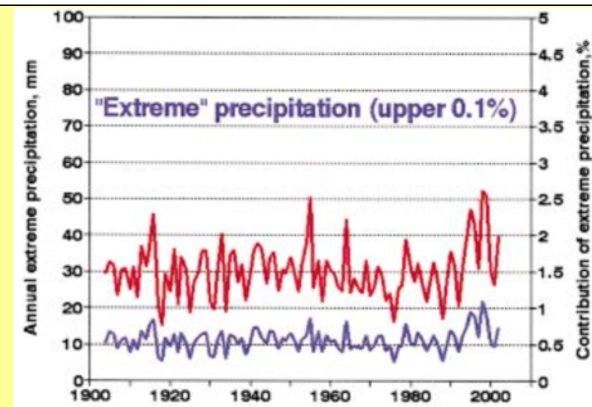
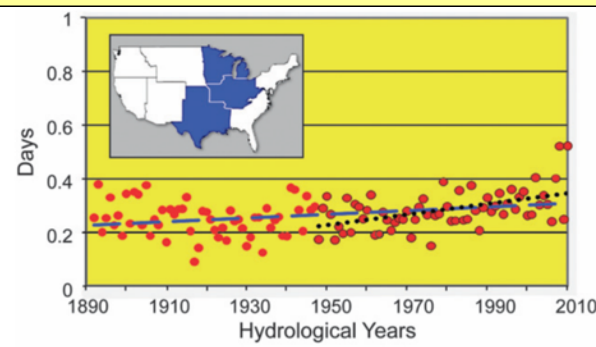
Daily records (24-hour records) are available for each state: (SCEC, 2019). The 24-hour rainfall records by decade are shown below:



The state 24-hour rainfall records appear to have peaked in the 1990s. That peak could be a coincidence of various long-term ocean cycles with a greater peak to come.

In the table below there are many references to "extreme" rainfall events but most refer to heavy but not extreme rainfall. The highlighted entry from (GROISMAN, 2004) has an entry that is genuinely extreme (events with 0.1% likelihood in any year). The cite from 2019 claims that Groiseman reported an increase of 21% per 100 years extreme (upper 0.1%) events. But Groiseman reported that there was no statistical significance to that 21% increase. As is clear from SCEC records shown above as well as detected by Groiseman, there was a spate of truly extreme rainfalls in the 1990's, but fewer since then.

Ref	Extreme Rainfall Definition	Chart
(Karl, 1998)	Percent contribution of the upper 10 percentile of daily precipitation events to the total annual precipitation (United States)	
(Karl, 1998)	Percent of the USA affected by 2 inch/day or more events	

(Groisman, Heavy Precipitation and High Streamflow in the	National variations of the area-averaged annual frequency of the sequence (precipitation, precipitation, and heavy precipitation), where heavy precipitation is daily precipitation total above 50.8 mm (2 in.)	
(GROISMAN, Trends in Intense Precipitation in the	Very heavy precipitation (upper 0.3% of daily rain events with return period of 4 yr) over regions of the central United States	
(GROISMAN, 2004)	Trends in the upper 0.1% precipitation and its contribution to annual totals are insignificant. Groisman reported increases of 14%, 20%, and 21% per 100 years in heavy (upper 5%), very heavy (upper 1%), and extreme (upper 0.1%) events over the contiguous United States during the period 1908–2000. (Joshi, 2019)	
(GROISMAN, 2012)	Annual number of days with very heavy precipitation (defined as an upper 0.3% of daily precipitation events) over regions of the central United States (upper Mississippi, Mid- west, and South; dark blue region in inset panel)	

There is an upward trend in heavy rainfall events in all analyses. A recent popular phrasing is *"very heavy events, defined as the heaviest 1% of all daily events from 1901 to 2012 for each region"* (Walsh, 2014). But those are heavy events, not extreme events.

There is also a possible increase in extreme rainfall events, which may have been an unusual circumstance in the 1990's and/or a new trend. In later sections, we'll examine flood mortality and the trend of the economic impact of flooding.

However, in (GROISMAN, 2012) they state *"Figure 4 shows that during the past 31 yr (compared to the previous 31-yr period), significant increases occurred in the frequency of very heavy and extreme precipitation events in the central United States, with up to 40% increase in the frequency of days and multiday rain events with precipitation totals above 154.9 mm"*. Clearly 6 inches or more in a day is extreme. Following their comparison with figure 5 they state "*Results shown in Figs. 4 and 5 hint that while very heavy and extreme rain days and events became more frequent with time, the processes that control the internal structure of these events (e.g., peak hour rain intensity) do not change.*" Even with a higher frequency of such events, mitigation remains the same.

2.2.2. Flash Floods

During the morning rush hour on July 8th, 2019 a slow-moving complex of thunderstorms moved southeast from Frederick Maryland through the northeast Virginia suburbs of DC and part of DC. It created a flash flood emergency, the highest level of warning by the NWS and a first for the DC area. The Washington Post properly diagnosed and documented the event later that same day https://www.washingtonpost.com/weather/2019/07/08/washington-dc-flash-flood-how-why-area-was-deluged-by-months-worth-rain-an-hour-monday/?utm_term=.5b79a3083cbc starting with these well-supported statements: "*A month's worth of rain deluged the immediate D.C. area early Monday, resulting in one of its most extreme flooding events in years. The record-setting cloudburst unleashed four inches of water in a single hour, way too much for a paved-over, heavily populated urban area to cope with at the height of the morning rush."*

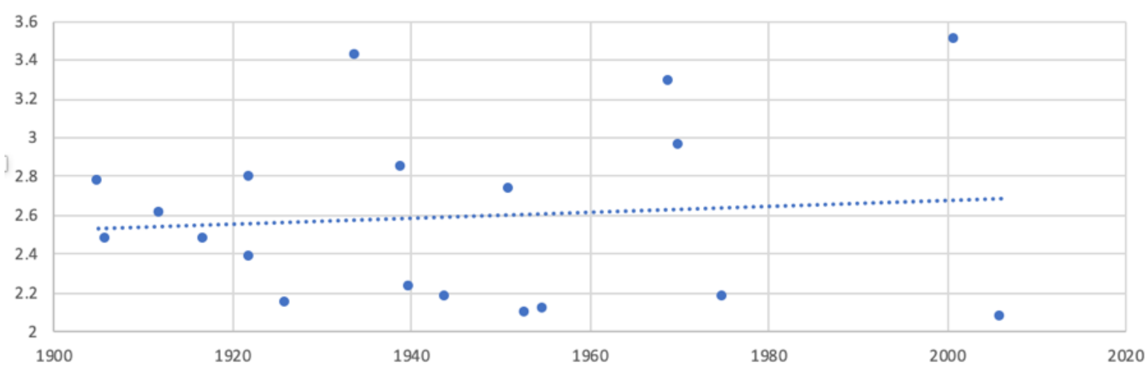
As the authors noted, the severity of the resulting flash flood is undoubtedly worse thanks to decades of population growth and development with very little stormwater mitigation. There are some payments made in DC for stormwater retention. My own stormwater retention efforts in rural Virginia would earn me some handsome annual payments if I made those in DC. Although one can never really have enough retention, it is possible to achieve zero runoff for a few inches of rain on any property with reasonable open space. More rain than the first few inches would run off, but the stormwater impact would be greatly reduced downstream. Rainfall retention helps all the plants on my property, for example, the specimen dawn redwood soaking up water in the 1000-gallon rain garden at the bottom of my driveway, which is my only paved surface. All my extra runoff directly affects the Potomac River in DC since I live on a tributary.

In the July 8th, 2019 event, there was 6.3 inches in Frederick MD, 5.55 in nearby North Potomac, and 5.01 inches in nearby Merrifield and (unofficial) 5 inches Falls Church Virginia. The official readings at Reagan National Airport in Virginia (DCA) were lower. But DCA has had higher totals in every time duration. The DCA totals and historical comparisons were obtained from the sources noted in the table below:

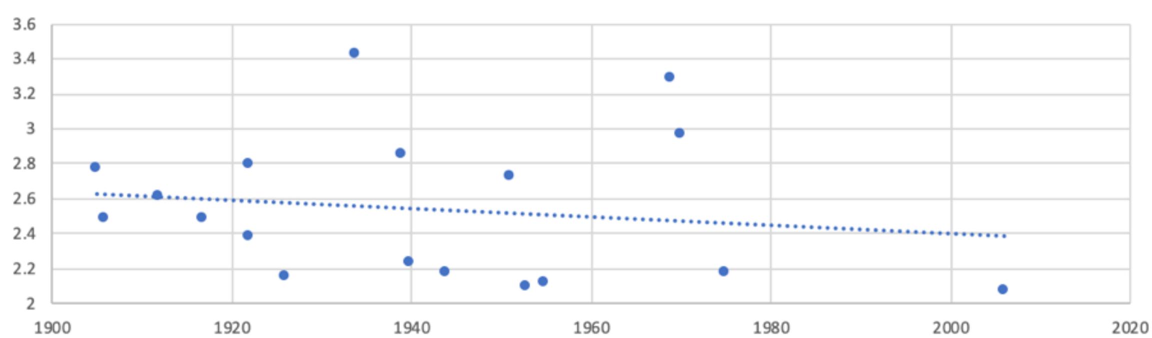
Date	Jul 8 2019	Jul 22 1969	Sep 12 1934	Aug 12 1934	Jul 30 1913
Source	NWS & Wash Post	(Reid, 1975) & (Moody, 2008)			(Moody, 2008)
Highest rainfall in the area	6.3 (1)	7.4 (2)			
Daily record (DCA)	3.44	4.35	4.02		
Two-hour rainfall (DCA)	3.41	4.18			
One-hour rainfall (DCA)	3.3	3.09 (3)	3.42 (4)		
35-minute rainfall (DCA)	2.2				
30-minute rainfall (DCA)		2.53		2.45	
15-minute rainfall	1.0 (5)	1.53 (DCA)			1.51 (M St)

(1) Frederick, MD; (2) Vienna, VA; (3) Data for this event is essentially missing from the Iowa State Mesonet database; (4) Moody and other sources say 3.42, but the Washington Post archives from 9-14-34 say report 3.25 inches in the heaviest hour; (5) calculated using data from link shown in https://pbs.twimg.com/media/D-9mLiaU4AEzkLG.jpg

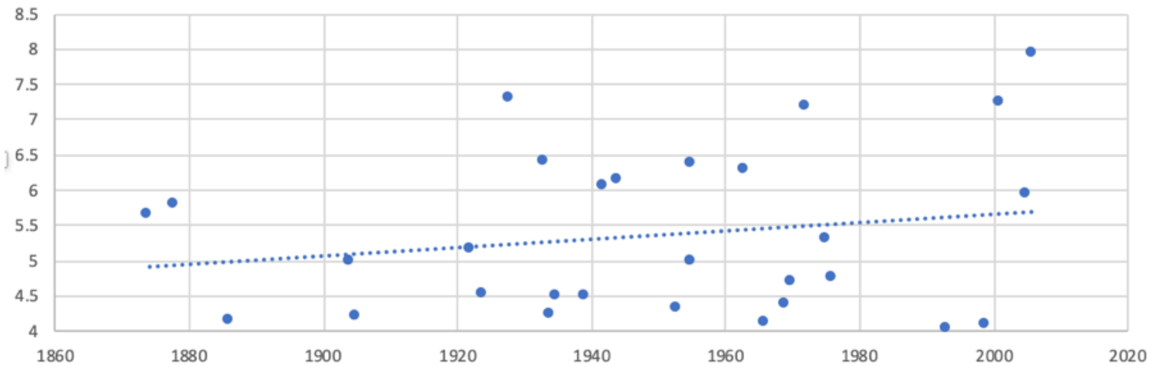
(Moody, 2008) also lists all of the rainfall events with two or more inches in one hour, through 2008. The list includes 3.5 inches in an hour in 2001, but that took place at a gauge in the northern portion of DC, and so is unofficial but it is added below:



With the just that single unofficial 2001 event removed:

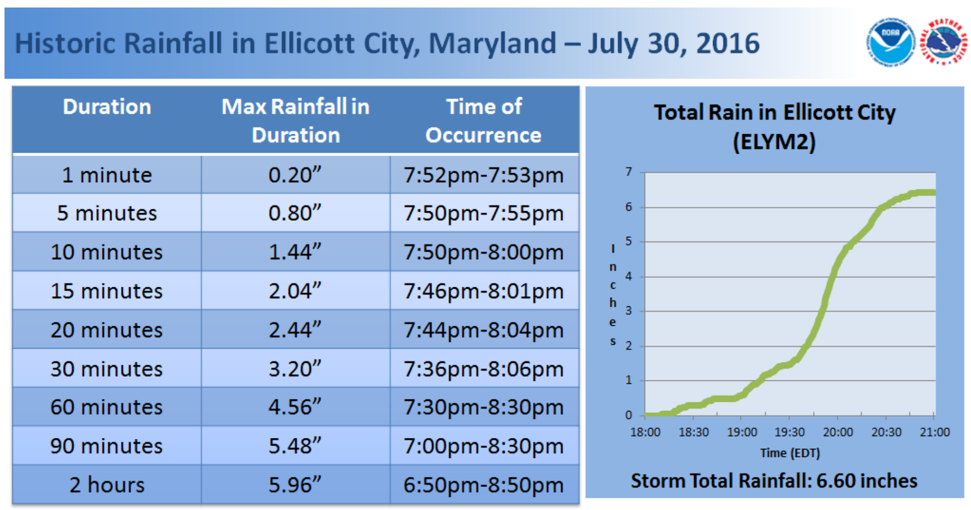


Finally, a chart of all the events with more than 4 inches in 24 hours, also through 2008:



While this dataset is very limited the linear trends show that the longer duration events are increasing in the amount of rain. The one-hour duration events may or may not be increasing although the change in trend by removing a single point shows the data is too sparse to make a determination. As noted above, the longer duration trend comports with (Barbero, 2017), namely the caveat that rarer meteorological events like flash flooding take longer to reveal a trend, and in general, the shorter the duration, the rarer the event.

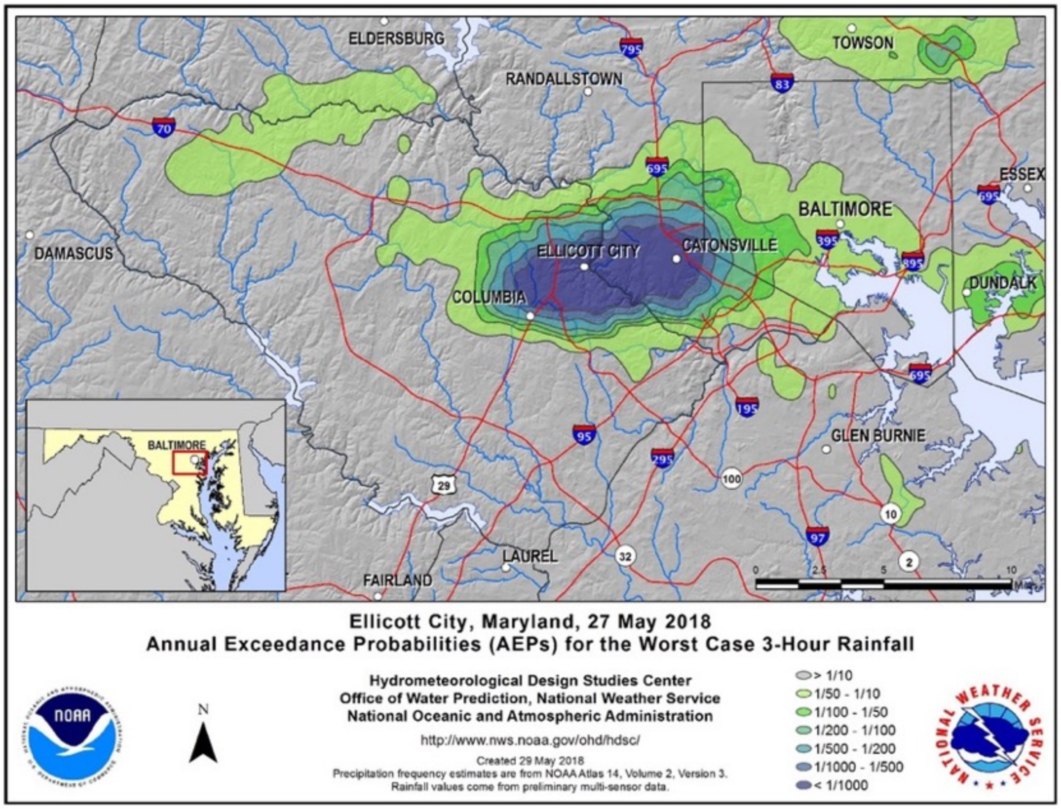
Ellicott City near Baltimore recently suffered two damaging flash floods, first in 2016:



Duration	Max Rainfall in Duration	Time of Occurrence
1 minute	0.20"	7:52pm-7:53pm
5 minutes	0.80"	7:50pm-7:55pm
10 minutes	1.44"	7:50pm-8:00pm
15 minutes	2.04"	7:46pm-8:01pm
20 minutes	2.44"	7:44pm-8:04pm
30 minutes	3.20"	7:36pm-8:06pm
60 minutes	4.56"	7:30pm-8:30pm
90 minutes	5.48"	7:00pm-8:30pm
2 hours	5.96"	6:50pm-8:50pm

Information obtained from the Ellicott City (ELYM2) rain gauge.
This gauge reports in 0.04" increments.

That description is from https://www.weather.gov/lwx/EllicottCityFlood2016 The area affected was relatively small but coincided almost perfectly with the watershed to the west of Ellicott City. The Tiber River is buried under Main St. and when there is too much floodwater for the finite tunnel, the water runs rapidly downhill Main Street causing lots of damage. The lessons from that flood were that development creates more runoff and floodwater channeling cannot be made finite. The lesson was ignored and a larger area got hit in 2018:



As is the nature of these types of thunderstorm events the greatest affected area may be very small but may have particular vulnerability to flash flooding. That includes more urban areas. In Washington, DC one of the city's primary waterways with the same name (Tiber Creek) was buried and turned into a large storm drain (Williams, 1977). The result was seen again on July 8, 2019, when some flatter parts of downtown quickly filled with standing water.

The solution for flash flooding is very simple conceptually: every property needs to retain runoff to the greatest extent possible and the major drainage channels need to be able to overflow as safely as possible. The primary way to do that in a city is to capture floodwater in basins and rain gardens for a day or two allowing it to soak in and run off more slowly. Main drainage channels can be put in or next to parks that are designed to handle the overflow. I have added drainage cheaply although I have done it poorly in the past and it eroded and filled in. This past fall I spent thousands of dollars on professional drainage, not because I have to, but because I want to divert more rainwater to my rain garden and another underfilled, unlined pond relatively high up on the hill that replenishes groundwater. In my experience, it is much easier in the short run to drain excess water than to retain extra water for periods of too little rain. I want to keep my runoff and I believe everyone should retain runoff to the greatest extent possible.

2.2.3. Hurricanes

Hurricanes appear to be getting stronger, on average, thanks to warming oceans in most locations, even as the total number of hurricanes declines. This is the global data which will show the most statistically valid trend. The blue trend line is slightly stronger using the latest data from http://climatlas.com/tropical/

(Maue, 2018)

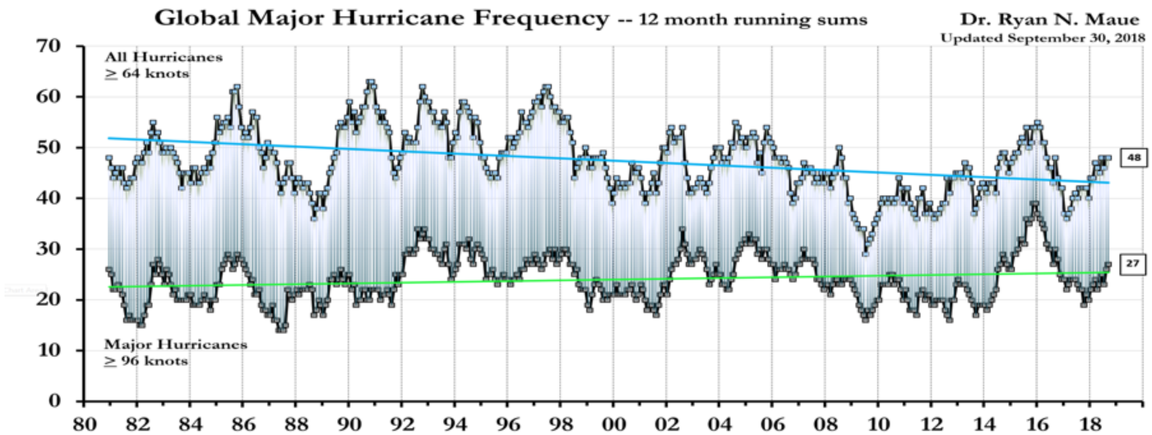


Figure 15- Globally there are fewer hurricanes (blue line) but the percentage of all hurricanes that become major (green line divided by blue line) is increasing

Certainly, major hurricanes are problematic where they hit land. But it is really not feasible to presume that nobody will ever be hit by a major hurricane were it not for global warming. Also, the most catastrophic damage from a major hurricane falls in a relatively small area, for example for Camille: https://sciencepolicy.colorado.edu/about_us/meet_us/roger_pielke/camille/figures/fig7.gif The economic costs of hurricane landfalls will be discussed later but normalized for exposure if the economic cost is relatively flat.

Many natural behaviors of hurricanes are presented as new and unprecedented and caused by global warming, for example, projected increases in synoptic patterns causing "stalling" (Wang, 2018) There is certainly more moisture available thanks to warmer waters and that moisture can fall on land. But the authors also project an increase in the cases of similar patterns to the one that caused Harvey to stall. Although the authors can't quantify the increase in precipitation due to low model resolution, it seems fairly clear that there will be more precipitation. But concurrent with that lack of accuracy in rainfall estimates there is a lack of accuracy in the prediction of the patterns. Blaming some of the increased rainfall on stalling caused by global warming is unsupportable.

Missing from the reports on 60 inches of rain from meandering Hurricane Harvey 2017 was the history of meandering hurricane Flora dropping 100 inches of rain on a location in Cuba in 1963. While hurricane Barry did not exceed the record 24-hour rainfall for Louisiana from tropical depression number two (1962), it set a new storm total record in Arkansas. There may well be more rainfall from these modern storms over an area as a whole causing more flooding. But what is clear from the data is that longer duration extreme rainfall records generally longer than 24 hours are being broken whereas shorter duration extreme rainfall records are not being broken.

In Louisiana there have been a fairly steady number of tropical storms and hurricanes:

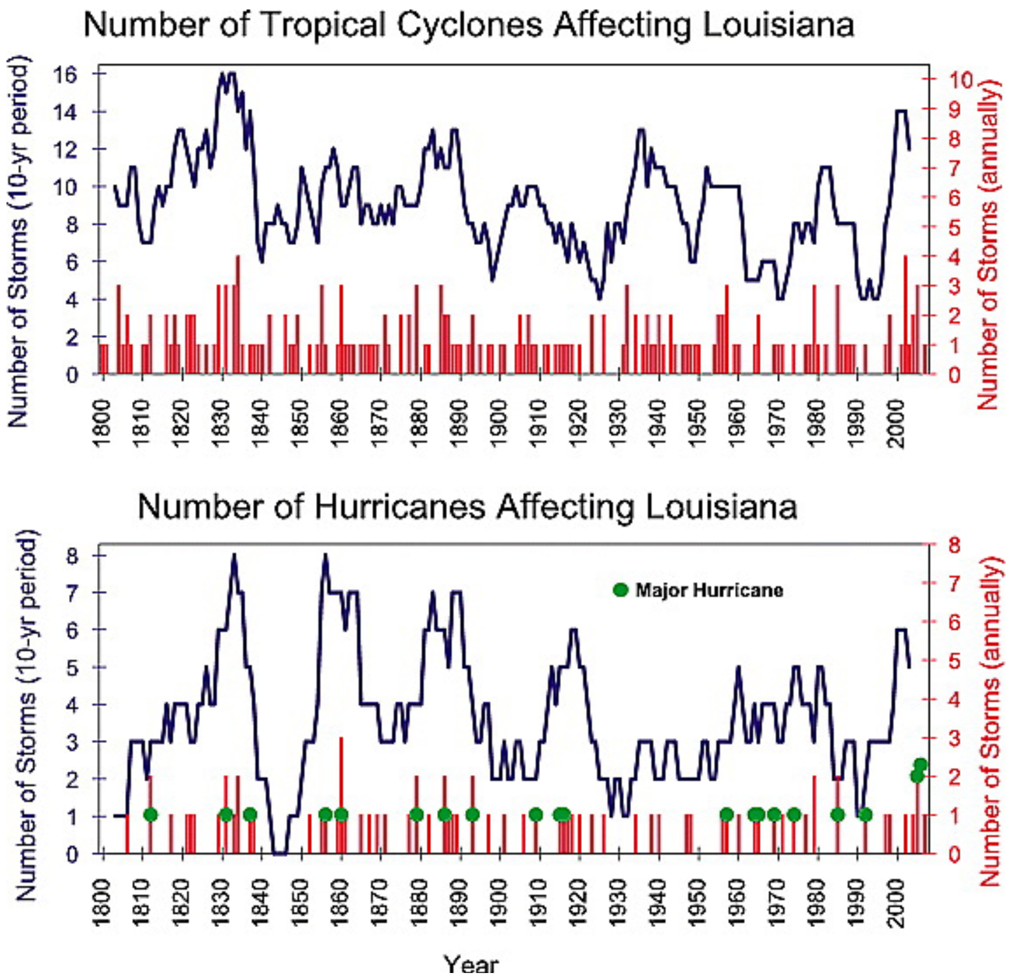


Figure 16 - Louisiana tropical storms and hurricanes from (Mock, 2008)

The data may be exhibiting the same trend as the global data, a higher percentage of hurricanes that turn into major hurricanes. Since Louisiana is a limited area, hurricanes are sporadic and it will be hard to detect a trend.

Hurricane Intensity Measurement

Hurricane intensity measurement is subject to observation biases as observation methods change (mostly improving) over time. Before the 1950's intensity measurements were mainly gathered by happenstance versus during the 1950's when aircraft started being used. Efforts to estimate intensity retroactively for historical storms must by necessity result in underestimates because measurements of the strongest winds and lowest pressure are not available. In rare cases intense storm measurements are available and have established records, only because the weatherman was lucky enough to survive.

Hurricane hunter wind and pressure measurements started in the 1950's but were and are inconsistently applied globally. They are considered to be the most accurate measurements but they also have a bias over time as the hurricane hunters deploy better on-board technology that allows them to locate the strongest convection (and therefore the highest winds). This can also apply to pressure measurements when the lowest pressure is near or in the eyewall.

Wind measurements from aircraft are higher than observed on the ground or ocean surface. For example Dorian passed over buoy 41004 41 NM Southeast of Charleston, SC at 11am EDT on September 5th 2019 as show below:

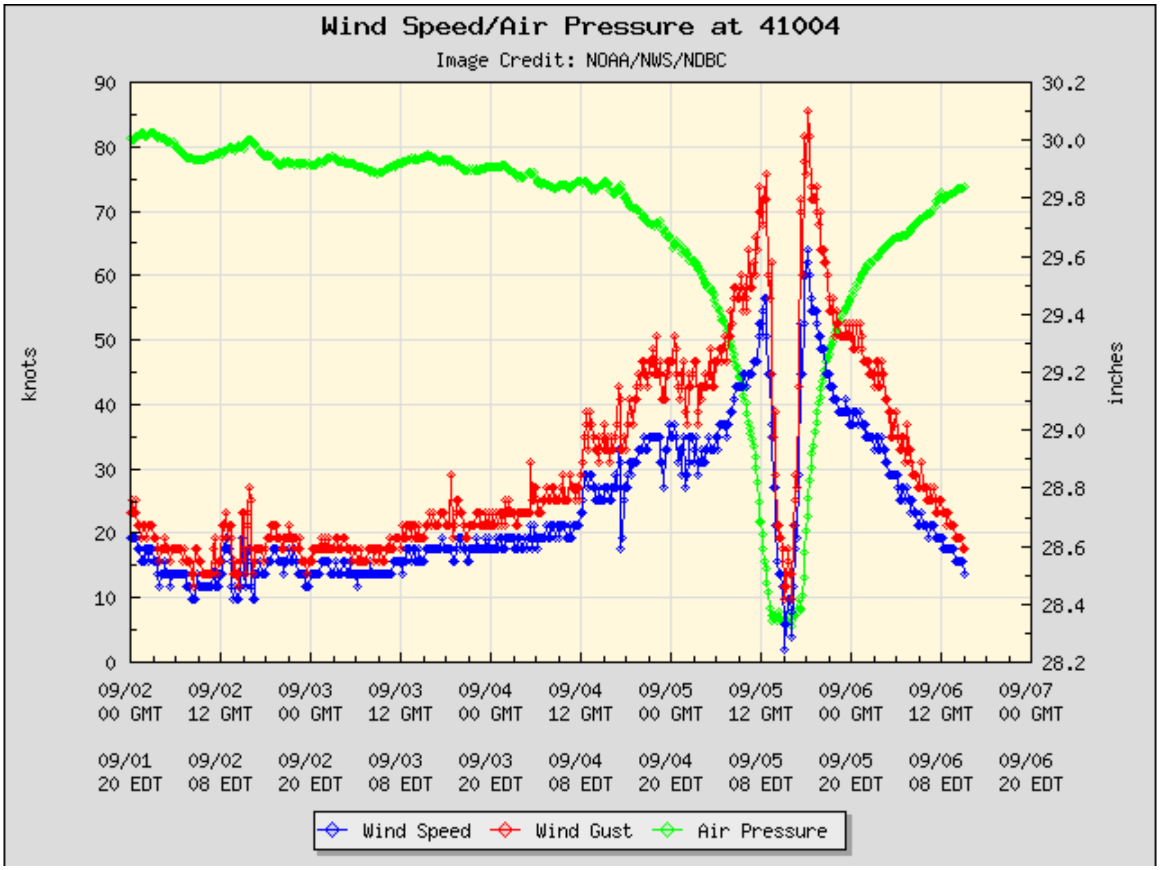


Figure 17 - Wind and pressure measurements as hurricane Dorian passed over bouy 41004

The 11am discussion from the NHC reads "The Hurricane Hunter data indicate that the flight-level and SFMR surface winds have decreased some since 12 h ago, accompanied by a rise in the central pressure. Based on this, the initial intensity is decreased to a possibly generous 95 kt. The central pressure of 958 mb is based partly on data from NOAA buoy 41004, which is currently inside the eye." The wind speed on the bouy peaked at 64 kt with gusts to 96 kt.

The most consistent intensity estimates come from algorithms applied to satellite imagery. The Advanced Dvorak Technique is a set of "equations (that) relate several measured environmental parameters to storm intensity, such as cloud region convective symmetry, cloud region size, and an eye region minus cloud region temperature difference" (Olander, 2007). As the paper points out this technique provides the only hurricane intensity estimates outside of the Atlantic.

A study (Kossin, 2007) used aircraft measurements as ground truth to determine coefficients for an intensity algorithm using normalized satellite imagery. They used the lowest common denominator for satellite imagery, that which was the resolution available in 1983. They found that some of the trends in increasing strength of maximum were inflated or spurious: "*Using a homogeneous record, we were not able to* *corroborate the presence of upward trends in hurricane intensity over the past two decades in any basin other than the Atlantic. Since the Atlantic basin accounts for less than 15% of global hurricane activity, this result poses a challenge to hypotheses that directly relate globally increasing tropical SST to increases in long-term mean global hurricane intensity.*"

The most obvious indication of spurious trends is the increased selectivity of peak strength measurements. The case of Dorian 2019 in the Bahamas is instructive. It was measured as tied in wind velocity and a bit higher barometric pressure than the 1935 hurricane in the Florida Keys, based on the satellite presentation and a wind measurement by aircraft sent to an ideal spot in the eyewall, along with a pressure measurement by a storm chaser. The only reason that the 1935 hurricane is deemed to be the same strength as Dorian is that a trained weather observer happened to be present at landfall, made a minimum pressure measurement, and happened to survive. He almost did not. Had he not survived, the 1935 hurricane would undoubtedly be rated less strong than Dorian.

Although all three hurricanes that hit the Bahamas in 1926 were estimated as category 4, two of the hurricanes had 20 foot surges similar to Dorian, and the result was widespread damage including the destruction of all but two houses in Marsh Harbour, one of the towns most affected by Dorian. As pointed out in the section on economics, it's the economic damage that matters, not the peak strength measured with ideal techniques.

2.2.4. Tornadoes

Violent tornadoes (EF-4 or higher) are declining:

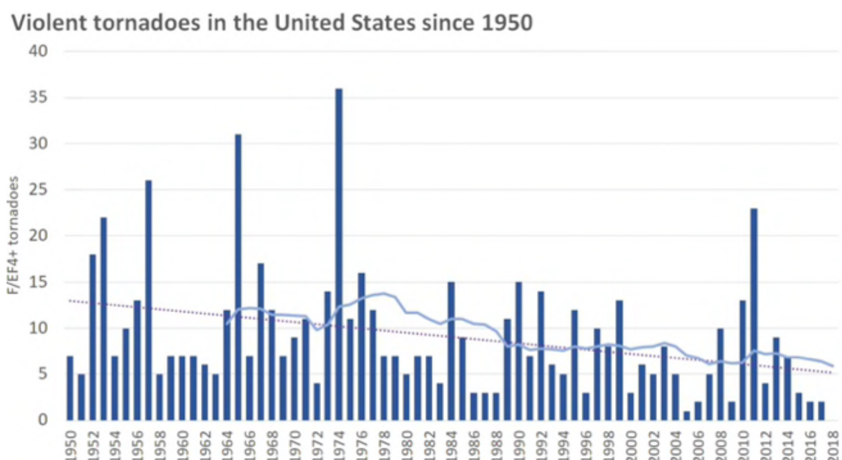


Figure 18 - Annual violent tornado numbers in modern history. The purple dashed line is a linear trend. The blue line is a 15 year average. Data from the Storm Prediction Center (Image and caption from Ian Livingston / Washington Post)

Strong tornadoes (EF-3 or higher) are declining over the long run.

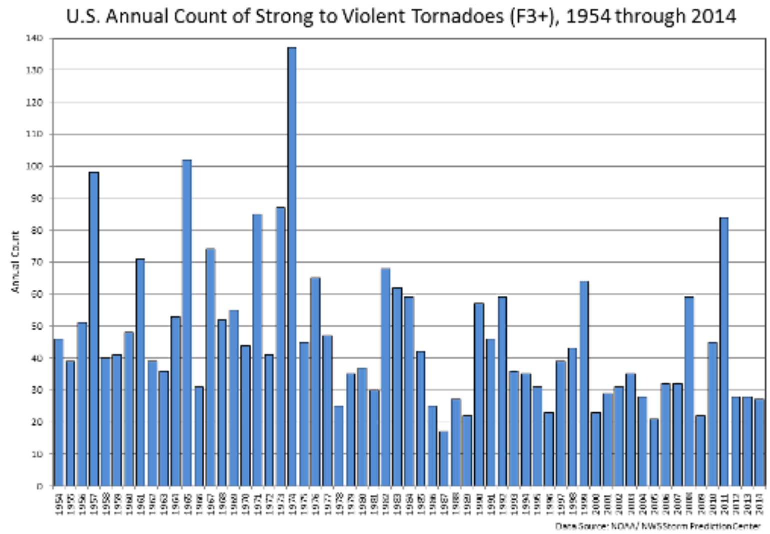


Figure 19 shows a drop in the strongest (EF-3 or higher) tornadoes (downloaded from https://www1.ncdc.noaa.gov/pub/data/cmb/images/tornado/clim/EF3-EF5-t.png)

There is little or no trend for EF-1 or higher tornadoes, however, there is a known problem with the count of EF-2 tornadoes. That count dropped artificially in the mid-1970's due mainly to a tightening of reporting standards. At the same time, the count of EF-1 tornadoes has increased to better detection and reporting. The primary consideration in showing EF-3 or higher is that those are the tornadoes that matter the most and have the most consistent reporting over the years.

2018 was the first year in the record without any EF-4 or EF-5 tornadoes (Livingston, 2018) and had the fewest recorded tornado deaths on record, with just 10 (Rice, 2018). Low fatalities in 2018 were anecdotal but consistent with both the trend towards fewer violent tornadoes and better preparation and warning in many tornado areas.

If heat were the most important factors for tornadoes, then we would see tornadoes peaking in July/August, but instead they peak in May/June:

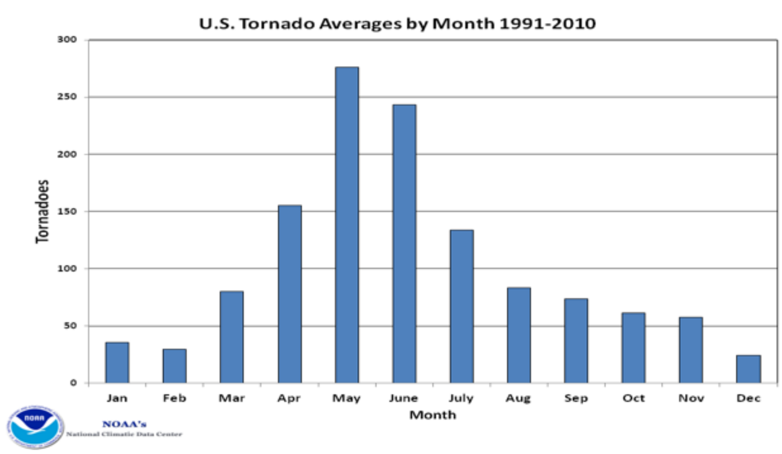


Figure 20 Tornadoes of all strengths peaking in May and June (https://s3.amazonaws.com/bncore/wp-content/uploads/2016/12/tornadoes_bymonth.png)

Tornadoes may also be affected by other factors such as manmade aerosols. See "Why do tornados and hailstorms rest on weekends?" (Rosenfeld, 2011). One potential cause of the decline in strong to violent tornadoes is the rise in Arctic temperatures, more rapid than elsewhere on the planet, leading to a drop in the spring temperature contrast and drop in vertical wind shear (Doswell, 2012). That paper written after the severe and deadly outbreak in 2011, The tornadoes of spring 2011 in the USA: an historical perspective, concludes: "*In our scientific opinion, then, the future regarding changes in tornado outbreak intensity and frequency remains unknown*."

There are claims of "more extreme tornado outbreaks" (Tippett, 2016) "Here, using extreme value analysis, we find that the frequency of U.S. outbreaks with many tornadoes is increasing and that it is increasing faster for more extreme outbreaks." There are similar claims of "more powerful tornadoes" (Elsner, 2019). These are derived from prior work, which uses statistical models to detect increasing "efficiency" of tornado formation (Widen, 2015). This refers to similar numbers of tornadoes being reported on fewer days as shown below:

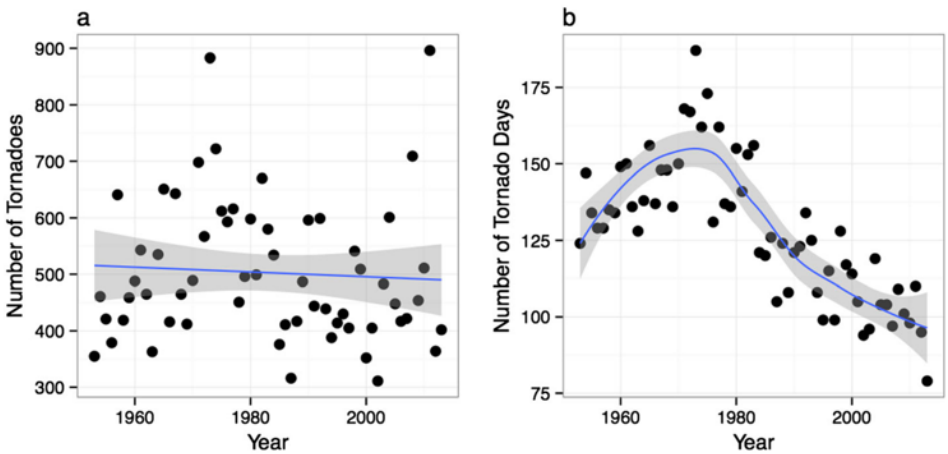


Figure 21 This is figure 2 from (Widen, 2015) showing the decrease in tornado-days

It appears that the latest work (Elsner, 2019) showing increasingly powerful tornadoes is due to a number of analytical factors: upward adjustments for the 2016 El Nino, counting more tornadoes in fewer tornado-days, and using novel energy calculations from path length and width applied to all tornadoes including mostly inconsequential EF-0 tornadoes that were undercounted in the past.

Fewer but Stronger? Similar to the hurricane data, there is a suggestion of fewer storms that may be stronger on average. But it is certainly not as clear as the case of hurricanes. It appears more that the data supports the idea of fewer days with tornadoes, but more tornadoes, not stronger tornadoes, on those days. Even that conclusion must be caveated because of changes in tornado detection.

2.2.5. Jet Stream or Weather Pattern Changes

Claims of changes in the jet stream are an ongoing scientific controversy. One disagreement is over the time period to study. A long term look shows little evidence of change in the jet stream: Arctic warming and our extreme weather: no clear link new study finds "*But a new study finds little evidence to support the idea that the plummeting Arctic sea ice has meaningfully changed our weather patterns. The research, published today in Geophysical Research Letters, says links between declining Arctic sea ice and* *extreme weather are 'an artifact of the methodology' and not real*." The referenced study (Barnes, 2013) shows no jet stream change over the second half of the 20th century.

The contrasting "limited time period" view is that over the era of Arctic Amplification roughly defined as the period starting in 1995, there is "*Increasing AA weakens the poleward temperature gradient—a fundamental driver of zonal winds in upper levels of the atmosphere—which causes zonal winds to decrease, following the thermal wind relationship [18]. A weaker poleward temperature gradient is also a signature of the negative phase of the so-called Arctic oscillation/Northern annular mode (AO/NAM), in which weaker zonal winds are associated with a tendency for a more meridional flow, blocking, and a variety of extreme weather events in much of the extratropics [19]*" (Francis, 2015)

The crux of the issue is whether the alleged 1995 to 2015 drop in AO is a lasting response to Arctic warming, a temporary response to Arctic Amplification, or a coincidence or blip in the (February) data. The main unsupported claim in (Francis, 2015) is the phrase: "*a fundamental driver of zonal winds in upper levels of the atmosphere*". The surface temperature gradient sometimes drives the zonal winds in the upper atmosphere, sometimes the zonal winds drive the surface temperature gradient, and sometimes there is no relationship. This is shown using models (Sun, 2016) and in reality, where natural changes in zonal winds are far higher than any postulated manmade change.

We can help resolve the debate by examining the seasonality of manmade made warming in the Arctic and comparing that seasonality to seasonal changes in AO. Arctic warming from ice loss manifests first in autumn during refreezing. During that season the anomalous refreezing of ice releases extra heat at the surface. During winter the anomalously lower ice cover and some more refreezing creates more anomalous warmth. Those anomalies fade in spring and by summer Arctic temperatures are back to the long-term average. Here are the last three years of Arctic temperature from the Danish Meteorological Institute:

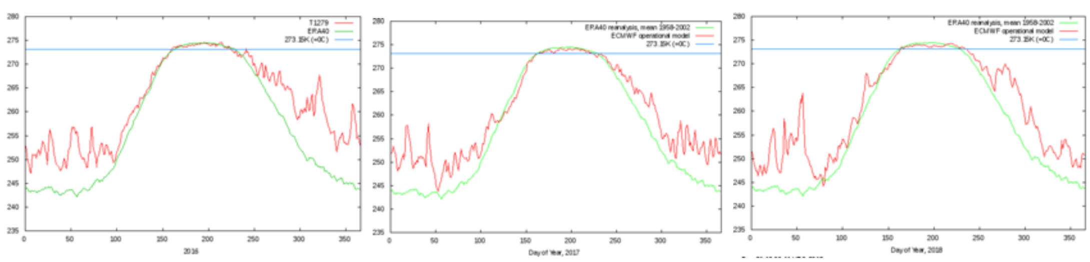


Figure 22 - Last three years of north polar temperature from DMI

The green line is the average for each date using data from 1958 to 2002. Note the significant anomalous warmth in the autumn from heat released by refreezing ice. That's because there is much more open water to refreeze than there was in 1958 through 2002. Winter anomalies can appear larger but there is greater natural variability embedded in those temperature spikes. Nevertheless, the winter anomaly is generally about 5C, which is a significant temperature increase.

Up-to-date AO data is available from AO Tabular format linked here: Climate Prediction Center - AO. Here is the trend using the full and partial datasets:

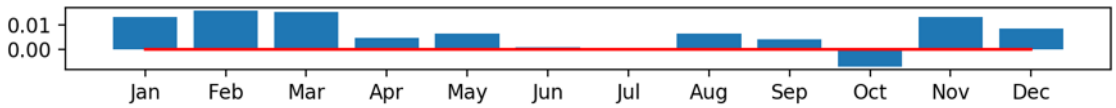
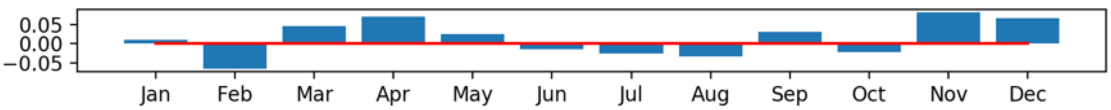


Figure 23 - Monthly linear trends of AO from 1950-2018 above and 1995-2018 below:



Looking at all the data from 1950 to 2018, the October result supports the theory of anomalous warmth from refreezing ice since October is the month with the most open water and below freezing temperatures. However, the October trend is smaller 1995-2018. The winter months 1950-2018 show an increase in AO, meaning a faster and less wavy jet. However, February shows a sharp downward trend 1995-2018 especially compared to the long-term AO increase. The summer months show no change except August which shows a decrease. The complete dataset leads to a conclusion of Arctic warming causing less jet waviness, not more. Looking at just 1995-2015 ignores the need for an explanation of prior jet waviness e.g. in the 1960's. Other than February, the jet is not trending towards more waviness. The anomalous Arctic warmth is just as prevalent in November and December as it is in February, but those months show less jet waviness both in the full data and during 1995-2015.

Another study by Barnes et al (Barnes, 2015) shows the natural variability in the jet over the period of reliable data is much larger than any long-term change. Their conclusion is that "the jury is still out". In more recent work (Screen, 2018) show that SAM (or AAO the southern hemisphere equivalent of AO) has shifted to become more positive not just from greenhouse gases but from ozone depletion causing a poleward shift in the SH stratospheric vortex and tropospheric reflections. For the northern hemisphere, they suggest that southward shifts and wavering or weakening of the polar jet from Arctic ice loss is speculation and that models project increasingly positive NAM (AO) i.e. a faster and less wavy polar jet.

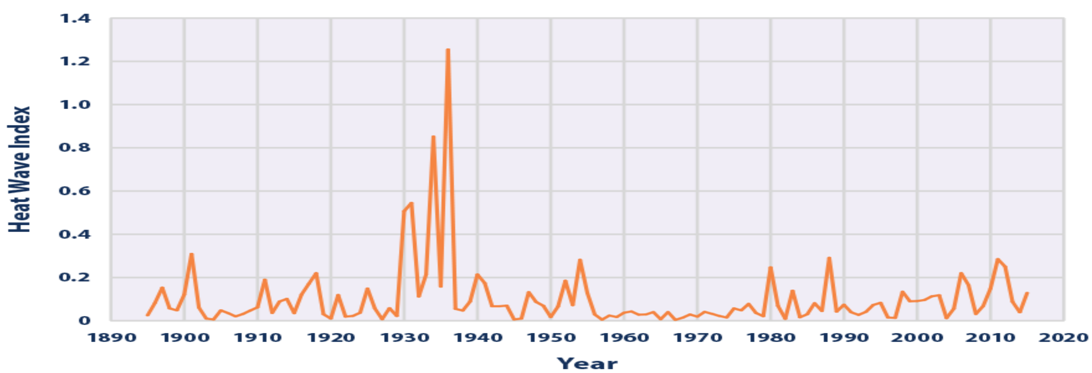
A faster, less wavy polar jet has long been the consensus of climate models even those from Francis et al earlier work where it was shown that a wavy jet was a short-term condition to be followed by a poleward, faster jet in ensuing decades. For example, in (Yin, 2005) the author states: "*The storm tracks are intimately tied to patterns of climate variability, such as the NH and SH annular modes (NAM and SAM). Figures 3g and 3h show that the poleward shift of the storm tracks tends to be accompanied by a reduction in sea level pressure (SLP) over the pole and an increase in SLP at lower latitudes, indicating a shift towards the high index state of the NAM and SAM*". In other words, an increase in the AO index as observed in the full dataset (except October).

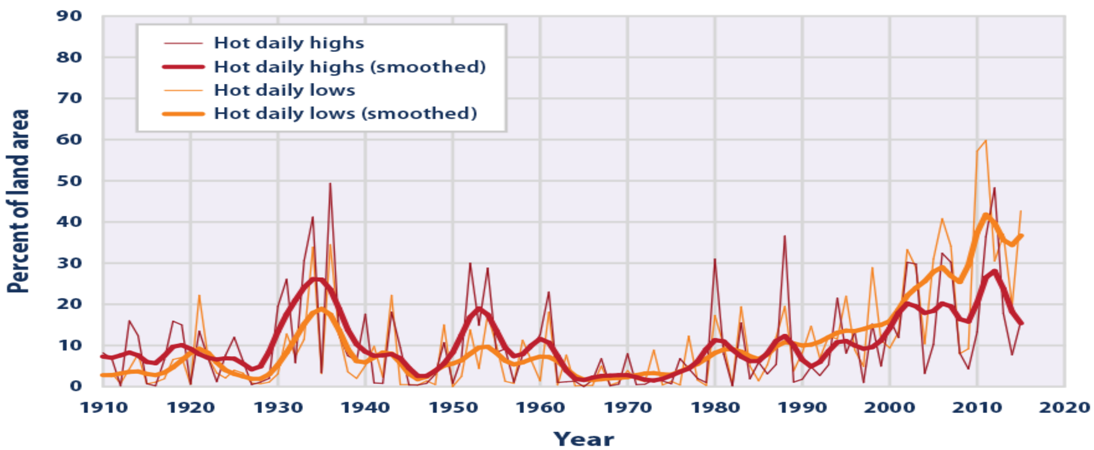
The more recent February jet anomaly is interesting but probably just a coincidence. Basing a theory of "winter" jet changes solely on the change in the month of February over the limited "AA" time period does not strongly support the theory of a wavier jet in winter. The strongest effect from a warmer Arctic should be in late fall and early winter, rather than February.

2.2.6. Heat Waves

Related to the jet stream, an important weather pattern question is will weather patterns create more "blocking patterns" that allow the development of more heat waves? Or will heat waves begin and end as they did before, with added warmth from global warming? Or will naturally-occurring heat waves be strengthened by weather feedback? Out of these three possibilities, I believe the third is most likely. It is quite evident that there is added heat in heat waves as shown by the increase in record high temperatures. The evidence points to more heat waves both in the data, new record 500 mb heights, and in some of the theory, for example, feedback from drier soils (FISCHER, 2007).

This EPA website https://www.epa.gov/climate-indicators/climate-change-indicators-high-and-low-temperatures shows the natural variability of heat waves, the relatively larger increases in warm nighttime low temperatures, and the increase in record highs relative to record lows:





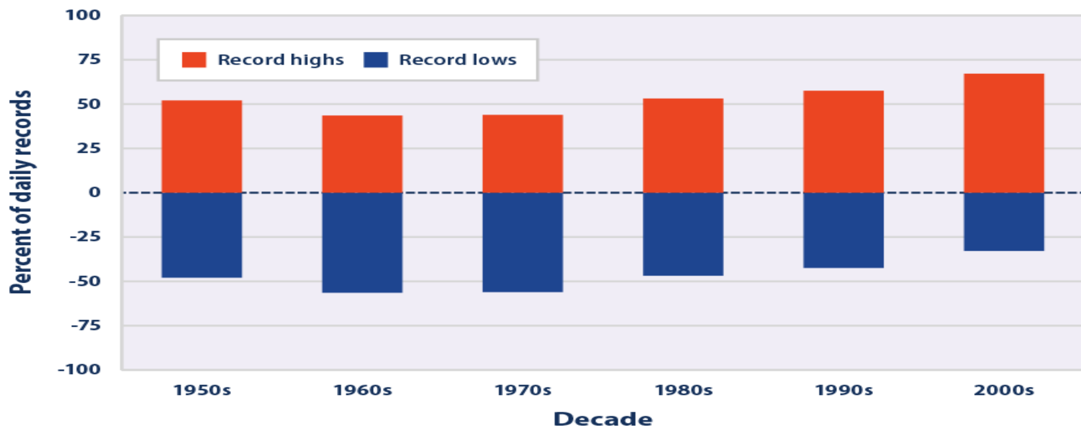


Figure 24 Three figures from the EPA: Indicators of climate change

The third chart unnecessarily omits the 1930's and 40's shown in the first two graphs. The web page provides an incomplete explanation for the 1930's *"The spike in Figure 1 reflects extreme, persistent heat waves in the Great Plains region during a period known as the "Dust Bowl." Poor land use practices and many years of intense drought contributed to these heat waves by depleting soil moisture and reducing the moderating effects of evaporation."* The full explanation is that there were coincidental natural cycles (Schubert, 2004) resulting in a cooler tropical Pacific (La Nina) and warmer Atlantic. Farming practices were a minor drought factor mainly from lack of farming (bare ground) resulting in less transpiration.

Based on record highs, the 1930's had hottest summers recorded in the US (and Canada) https://www.ncdc.noaa.gov/extremes/scec/records Based on those all-time highs and low, 25 states had all-time (summer) highs in the 1930's and 9 states had all-time (winter) lows. Those numbers may not be representative of the rest of the year, but it is clear that the 1930's were a decade of extremes in both seasons.

There are two main causes of the warmer nighttime lows shown in the second chart as well as part of the increase in the ratio of record highs to record lows in the third chart. One cause of warmer nighttime lows is a moister atmosphere *"The enhanced greenhouse effect of water vapor at night may reduce nocturnal cooling and lead to increases in nighttime T, minimum T, or both "* (GAFFEN, 1999).

The second cause of record high minimum temperatures is urbanization. The influence of urbanization is quantified in (Hausfather, 2013). The paper quantifies the effect, describes the "homogenization" process used to remove that effect, and the results of removal: "*According to these classifications, urbanization accounts for 14–21% of the rise in unadjusted minimum temperatures since 1895 and 6–9% since 1960. The USHCN version 2 homogenization process effectively removes this urban signal such that it becomes insignificant during the last 50–80 years*" In other words, a nontrivial portion of the rise in minimum temperatures is due to urbanization. Urbanization also increases maximum temperatures although about 4 times less than the increase of minimums (Hausfather, 2013). But while homogenization is used to correct the temperatures presented on web sites to show the amount of regional or global warming, record high and low temperatures cannot be corrected and are never corrected.

Thus there will be fewer record lows and more record highs due solely to urbanization, especially record high minimums. In (Green, 2007) for example, comparing new record high minimums in the Phoenix heat island to new record high maximums, see link. There is a sharper increase in record-high minimums compared to record-high maximums. As the paper points out *"Rapid urbanization and expansion of the Greater Phoenix metropolitan area has resulted in localized warming, especially with regard to overnight low temperatures, during the past few decades."*

The effect of urbanization on the ratio of records shown above (red versus blue bars) has not been quantified, at least by the authors who produced that chart. Urbanization cannot simply be ignored since it has an effect on heat wave mortality. But heat wave mortality has policy solutions that we will consider in the section on mortality.

There are claims that some recent heat waves are unprecedented: "*One implication of this shift is that the extreme summer climate anomalies in Texas in 2011, in Moscow in 2010, and in France in 2003 almost certainly would not have occurred in the absence of global warming with its resulting shift of the anomaly distribution. In other words, we can say with high confidence that such extreme anomalies would not have occurred in the absence of global warming.*" (Hansen, 2012). Those claims are unsupported. The heat in the European summer of 2003 was likely exceeded by the summer of 1540 (Wetter, 2013) in the low countries. Indeed, the duration of heat in 1947 was comparable to 2003 (Beniston, 2004) (Grütter, 2014).

The European heat wave of July 2019 was unprecedented for at least a century with new national all-time high temperature records set in several European countries. An analysis that attempted to avoid locations with urban heat island issues found that "*Toulouse for June, and Lille-Lesquin, de Bilt, Cambridge, Oxford, Weilerswist- witnessed a historical record both in daily maximum and in 3-day mean temperature (apart from Oxford and Weilerswist-Lommersum where only daily maximum temperatures set a record)"* (Vautard, 2020). So while the country-wide heat records had likely urban influence, there were locations in which the heat was unprecedented in the modern record.

A more supportable claim than Hansen et al is to state that extreme summer climate anomalies such as the ones they list will very likely become more common. That claim is supported by the evidence emerging from natural variability, even if that emergence is slow. The idea of the European 2003 heat wave being part of natural variability was explored in (Chase, 2006). They show that the 2003 heat wave was not unprecedented and its supporting weather patterns are in fact quite common. The caveat that their period of analysis, 1979-2003 is too short to determine any significant trends. With that in mind, the underlying meteorological events, unlike extreme rainfall, may not be very rare and we should more easily be able to detect a trend.

2.2.7. Drought

Drought is intensified in heat waves which are becoming more frequent as discussed above. Balanced against that is a widespread increase in rainfall. The same weather researchers cited above for heavy precipitation also show increases in total precipitation (Groisman, 2004). The precipitation increases are widespread:

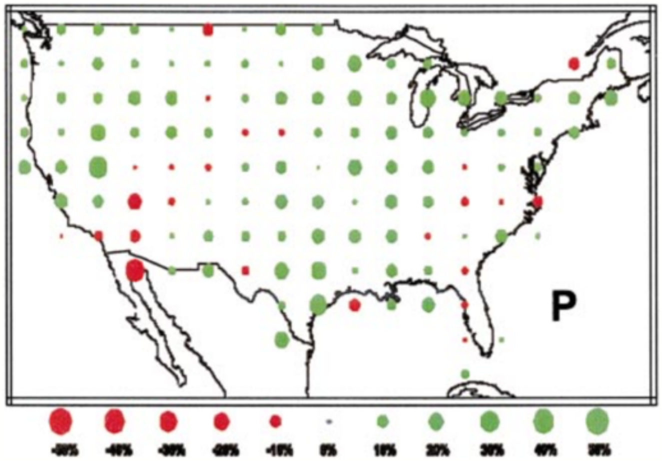


Figure 25 - Linear trends [% (100 yr)□1] of annual precipitation (P; 1900–2002) over the contiguous United States. Individual trends from 1221 USHCN stations (Easterling et al. 1996) from (Groisman, 2004)

There are numerous claims that global warming increases drought: "Drought has also generally increased throughout the 20th century (Dai et al. 2004, Trenberth et al. 2007a), as measured by the Palmer drought severity index (PDSI). Dai et al. (2004) show that very dry land areas across the globe (defined as areas with PDSI less than –3.0) have more than doubled in extent since the 1970s. Drought is generally more widespread during El Niño events, and became very widespread for a year or so after the Mount Pinatubo eruption." (Trenberth, 2011). The increased drought is blamed for instability, unrest, and even mass migration.

Another source of predictions of more extreme precipitation, both positive and negative, comes from models. (Held, 2006) showed "*In contrast, assuming that the lower-tropospheric relative humidity is unchanged and that the flow is unchanged, the poleward vapor transport and the pattern of evaporation minus precipitation (E - P) increases proportionally to the lower-tropospheric vapor, and in this sense wet regions get wetter and dry regions drier*" compared to the slowdown in atmospheric circulation. This effect will be highly localized since varying prevailing patterns will lead to varying responses and models cannot generally predict local changes.

Worldwide drought did not increase from 1982 to 2012. The chart below can be found at https://www.nature.com/articles/sdata20141/figures/5 The chart that ends in 2012 doesn't include the 2016 super El Nino. The higher levels of drought in 1982 and 1998 are likely attributable to the super El Nino in those years.

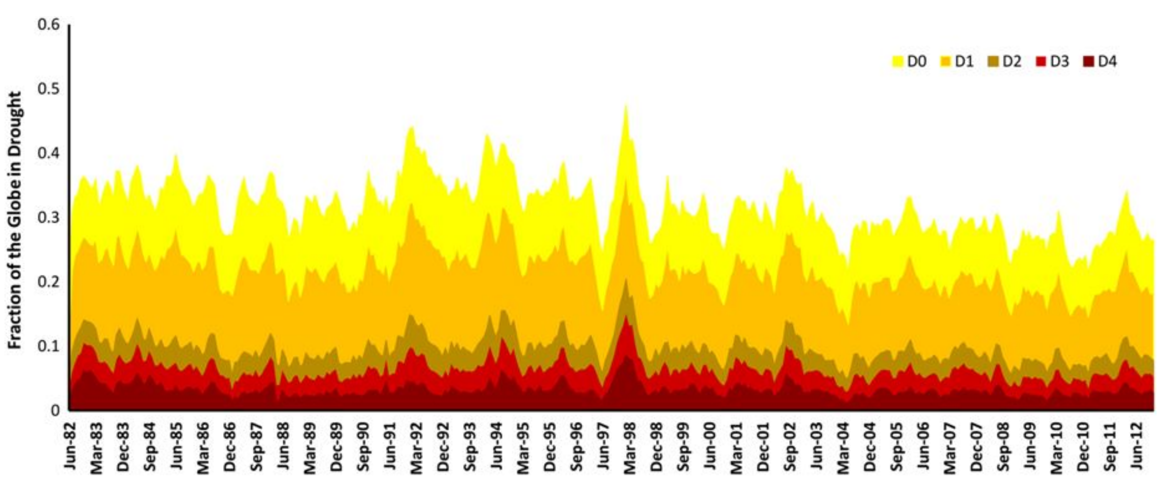


Figure 26 - Worldwide fraction of land area in drought (from https://www.nature.com/articles/sdata20141/figures/5)

PDSI reconstructions using tree rings (COOK, 2014) show decades long "megadroughts" in North America particularly through the Medieval Climate Anomaly also known as the Medieval Warm Period. The southwest US has not seen decades long megadroughts since then. The Cooks and other authors contributed to (Williams, 2015) which determined that the 2014 California drought was record breaking with a manmade warming component while the three-year 2012-2014 drought was not unprecedented although record-breaking in some areas in the period 1901-2014.

In the US as a whole the drought was more severe in the 1930's:

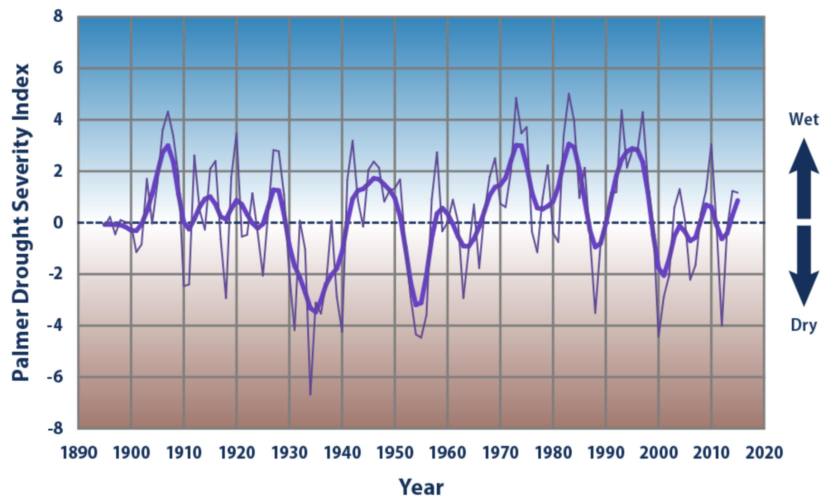


Figure 27 - The most severe drought in the US was in the 1930's (EPA)

The figure above comes from (EPA, 2016). As noted in the heat wave discussion, the 1930's drought is sometimes blamed on poor farming practices creating dust that led to more intense drought *"By reducing the net radiation into the surface beneath the aerosol layer, dust reduces evaporation and thus precipitation [Miller and Tegen, 1998]. There is thus a strong potential for dust forcing to exacerbate drought during the Dust Bowl [e.g., Koven, 2006]."* (Cook, 2008) The effect is a feedback mechanism where reduction in vegetation leads to reduction in transpired moisture. However, the primary cause of the heat waves and drought was the large-scale weather patterns, in particular persistent La Nina (cool tropical Pacific) and a warm Atlantic.

The same patterns are shown to produce severe drought throughout the Holocene (Miao, 2007) The patterns are natural and the dust feedback is a natural part of the pattern. Wide natural variations in drought are a fact of life, and while the intensification of drought from global warming will make things worse, the agricultural effects are temporary as we will see in the agriculture section.

In (Williams, 2020) the authors claim that southwest North America is in an emerging megadrought. The short period of the current drought requires the caveat of "emerging" since the current drought conditions were preceded by a wet period. Otherwise we would have to redefine "megadrought" to be much shorter than any previous definition. The essential claim of the paper is that global warming is enhancing drought by increased evapotranspiration, an increase of 30% in drought severity which they call "anthropogenic drying". They don't explicitly address whether natural variations in precipitation exceed "anthropogenic drying". But that is clear from their figure 1:

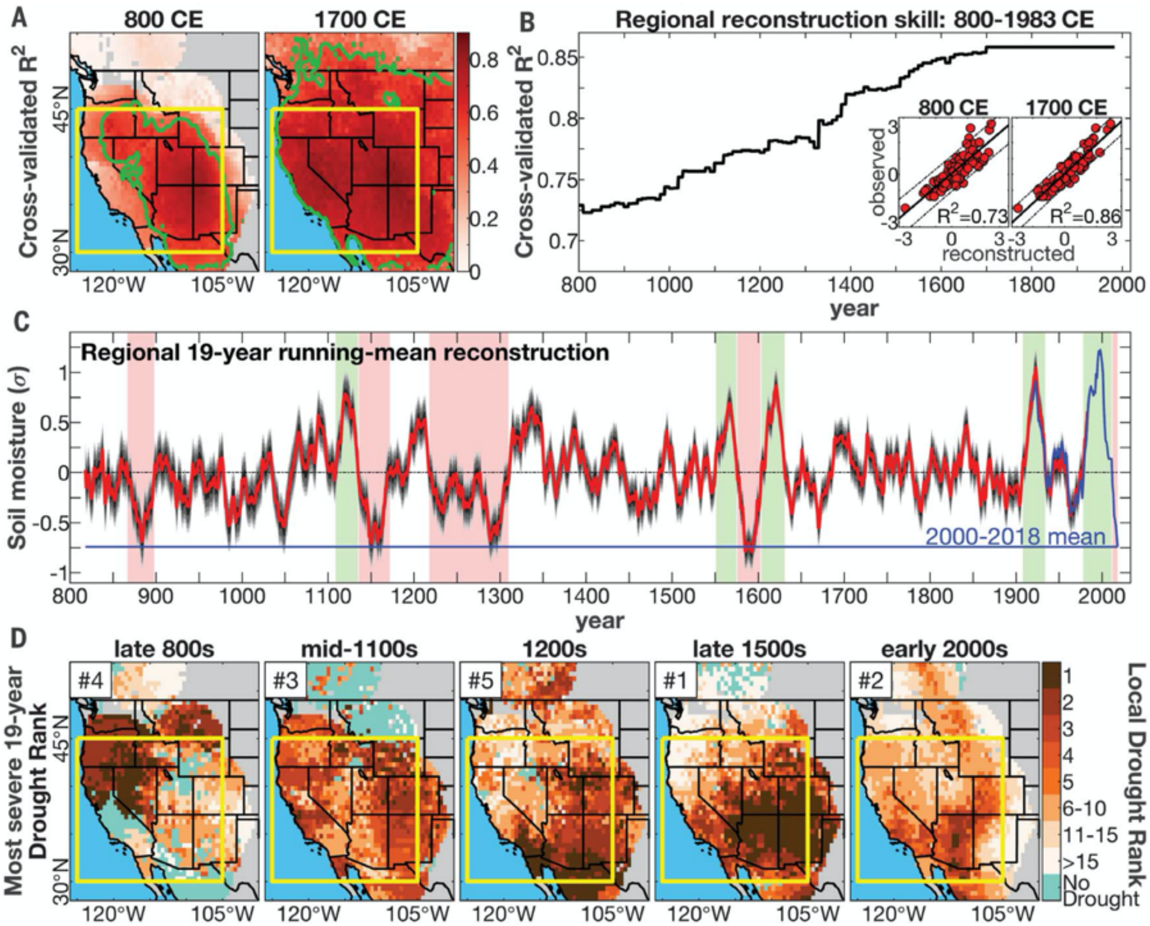


Figure 28 - Fig 1 from (Williams, 2020) showing past and present droughts

The figure shows that drought intensity was greater in all prior cases in some areas. It shows that the metric of areal average soil moisture depends on where one draws the box. Mostly it shows that rainfall variation is much more important than anthropogenic drying.

2.2.8. Extreme Winds

Wind speeds and changes in wind speeds vary greatly by location and season. Wind speeds over the oceans are observed to be increasing (Young, 2011), more so in extreme winds (99th percentile). Over land there is considerably more variation. One study showed decreases in wind speeds over the majority of urban areas studied (Mishra, 2015). Another study states *"There is suggestive evidence of an increase in extreme winds at the annual time scale over parts of the ocean since the early to mid-1980s, but the evidence over land is inconclusive"* (Vose, 2013) In (Vose, 2013) they show primarily decreases in 90th percentile wind speeds (strong, not extreme) over the US, not including Alaska and Hawaii. The (Mishra, 2015) changes in extreme wind speeds in urban areas globally are reproduced below (blue means fewer extreme wind events):

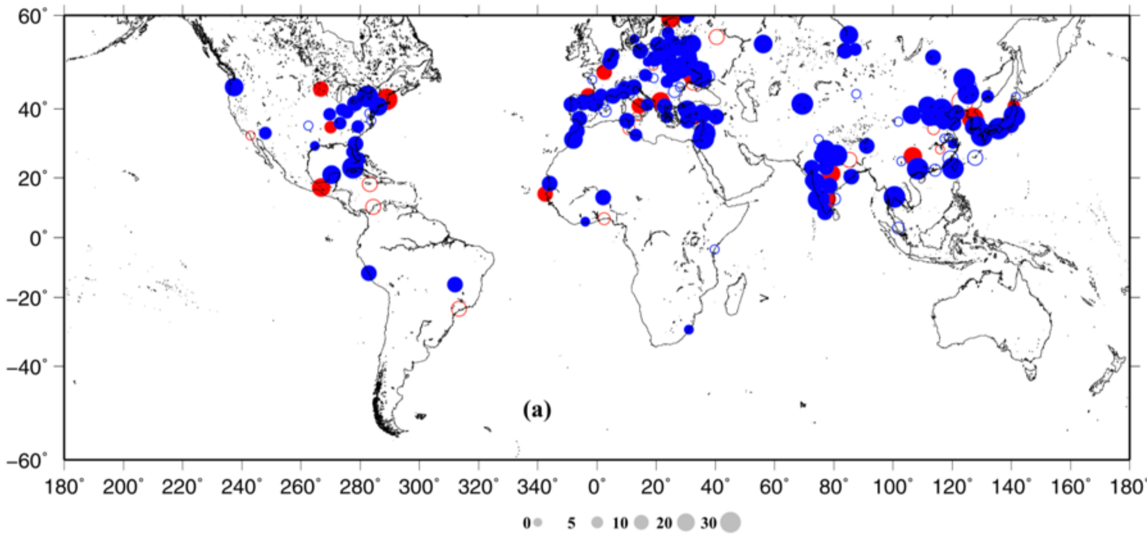


Figure 29 - Changes in frequency (number) of extreme windy days per year (exceeding 99th percentile of the reference period (1973–2012). (Mishra, 2015)

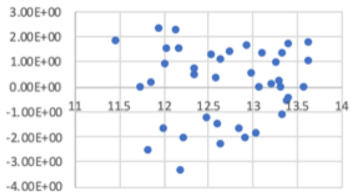
Theory and model results in (Held, 2006) indicate that atmospheric circulation will slow down generally, except for localized tropical storms, contrary to the popular notion that the atmosphere will become more "energetic". However, like all model results, the result is location-dependent, mainly by latitude. They predict a poleward movement of the storm tracks which I would interpret as possibly causing more extreme wind in higher latitudes but less in southern latitudes.

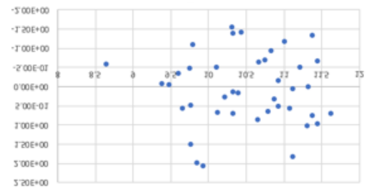
As previously noted in (Guzman-Morales, 2019), Santa Ana winds are expected to decrease in frequency.

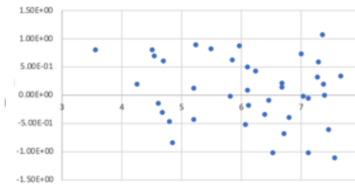
2.2.9. Cold Outbreaks

As a consequence of the controversial changes in the polar jet discussed above, there are claims of stronger or more frequent cold outbreaks. The theory is stated in the introduction to (Kim, 2014): *"Over the past two decades, the Arctic Ocean has warmed significantly in conjunction with conspicuous increase in global surface air temperature (SAT) and rapid decline of Arctic sea-ice1,2. A growing number of studies have found pronounced changes in atmospheric circulation due to Arctic sea ice loss, including changes in the tropospheric jet stream that may lead to cold extremes over Eurasia and North America"* There is a tendency in the popular press to conflate the stratospheric polar vortex with the polar jet at the tropopause. There is certainly a bidirectional relationship between the two although the strength of the relationship in either direction varies as does all weather.

The 1980-2018 scatter plots of AO versus ice extent for December, November, and September show no strong relationship when there is lots of anomalous heat released from refreezing:







However, October, the month with the largest long term drop in AO noted previously, and revisiting that relationship, we see a modest relationship from negative AO to lower ice extent since 1980:

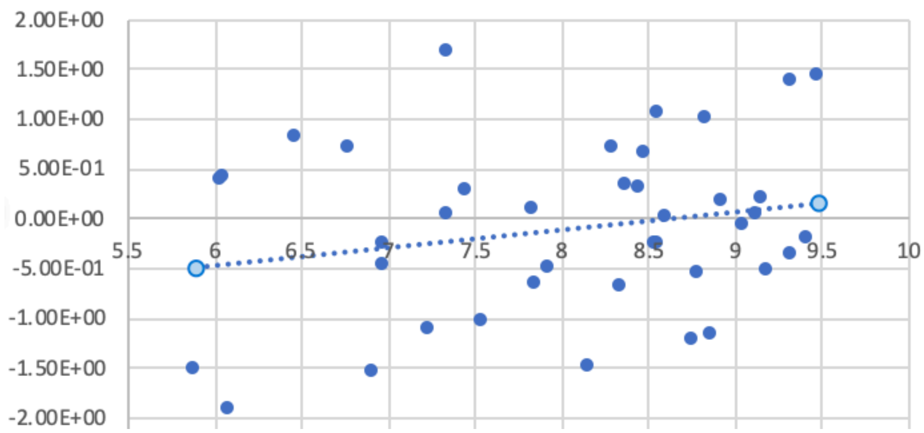


Figure 30 - Linear fit of October AO vs October ice extent from 1980-2018 (Data from CPC and NSIDC)

There is no relationship from February ice extent to February AO, but there could be relationships from fall ice extent to February AO (I will check for that later). One thing is fairly certain: that in a world of global warming, arctic warming. and dropping ice extent, there are fewer and weaker cold outbreaks:

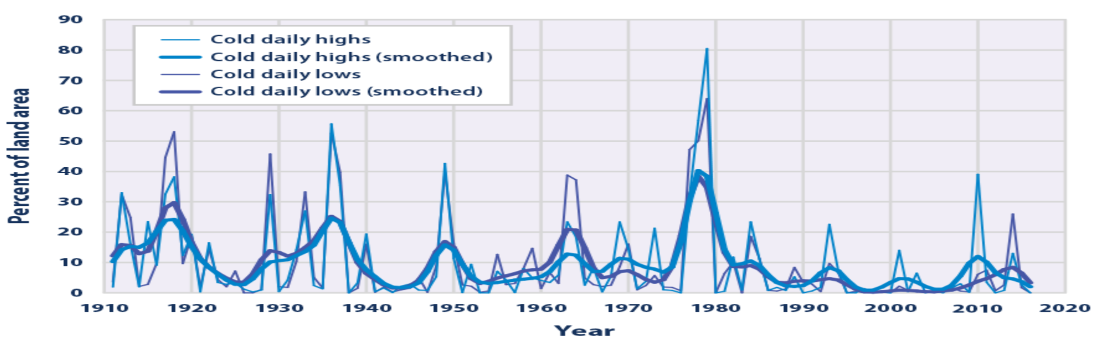


Figure 31 - Graph showing the drop in the area of the contiguous 48 states with unusually cold daily high and low temperatures during the months of December, January, and February. (Source: same EPA Climate Change Indicators website linked and copied above)

That observation makes sense. There is, on average, less cold air available in the Arctic to produce and sustain lower-48 cold outbreaks.

2.2.10. Hail

Early Sunday morning June 30th, 2019, there was an impressive hailstorm in Guadalajara, Mexico's second largest city. The pictures show streets filled with hail several feet thick and some news stories claimed "*Up to five feet of hail fell from the storm early Sunday"* (Fox News). However, an aerial view shows that the thick deposits of hail were washed into the streets as there is a lot less hail on the flat roofs:

Figure 32 - Hail in Guadalajara on July 1st, 2019 from https://www.bbc.com/news/world-latin-america-48821306

The washing effect was pointed out by Daniel Swain on his twitter feed https://twitter.com/Weather_West/status/1145699462590816256 He included a 2003 photo of hail that washed into 15-foot-tall banks in New Mexico. The Washington Post made these same points in their article: https://www.washingtonpost.com/weather/2019/07/02/mexico-hail-storm-was-massive-wasnt-something-new/?utm_term=.61f9035a3860

The incidence of hail in the tropics is documented in (Frisby, 1967). The documented cases in Mexico were mostly at 2000 meters and higher (Guadalajara is at 1566 meters). That documentation does not generally include amounts or effects. The hail in Guadalajara early on July 1, 2019, was small, not "severe" (defined as one inch or larger). Thus figure 1 in (CECIL, 2012) based on (Frisby, 1967) does not quite line up with their paper's climatology although it is closest to July/August.

With a peak of hail in those generally hilly or mountainous tropical locations at peak annual heat (July/August) there is at least a possibility that further warming and moisture will lead to increased hail. Hail reports are driven by population (Martins, 2016) as shown in the scatter plot for rural Brazil:

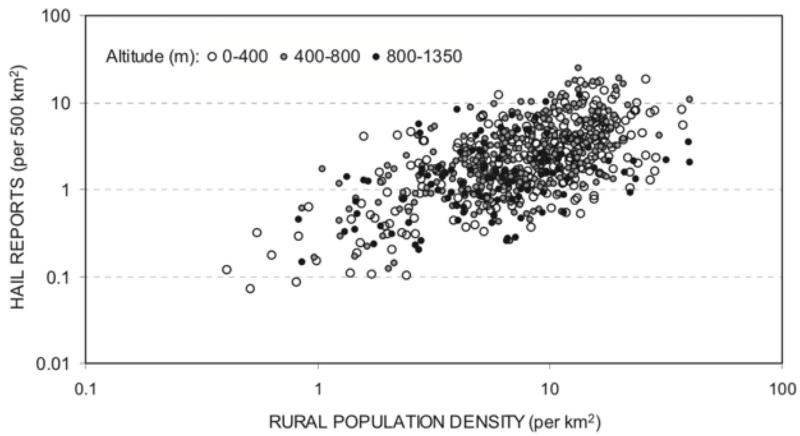


Figure 33 - Scatter plot of hail reports as function of rural population density (Martins, 2016)

This makes it difficult to attribute the observed increase in hail reports (ALLEN, 2015) due to changing types and numbers of observers. *"In view of the limitations of the observed hail dataset, we advocate caution in examining whether the results obtained via analysis reflect real climate signals, or are a result of temporal inhomogeneities. Simple tests involving removal of outliers, and subsampling of climatological periods will likely reveal these limitations, as suggested by Doswell (2007). Authors also should understand that observations may not reveal a climatologically significant signal, but this does not imply the absence of a climatic influence on hail."*

A study using climate models (Brimelow, 2017) projects a "fewer but stronger" type of change for severe hail from (1971–2000) to (2041–2070) depending on location.

2.3. Other Attributions and Predictions

2.3.1. Agriculture

A general understanding of the effects of CO2 and warming on the biosphere can benefit from considering some fundamental principles. First, there are far more beneficial organisms in nature than harmful ones. Second, nature doesn't favor beneficial substitutions and practices but farmers do that for their living. Third, there is no evidence that CO2 increases, global warming or other effects will favor harmful organisms over beneficial ones (or vice versa). More research is needed. For example, in (Mohan, 2006) the authors didn't compare poison ivy with any other plant.

Increases in CO2 are shown to offset some expected negative effects of rainfall and temperature changes (Erda, 2005). The results depend on the crop and many factors that were not studied such as increased nitrogen from increased rainfall and many simple ways that farmers can compensate for what the studies assume are "limiting factors" in agricultural productivity.

With irrigation, high yields (some of the highest of any state) can be obtained in Arizona: https://www.nass.usda.gov/Publications/Todays_Reports/reports/cropan19.pdf Colorado has higher yields for barley and California for cotton. Heat is generally not a problem and, along with elevated CO2, leads to a longer growing season (Reyes-Fox, 2014) The same paper points out that elevated CO2 improves drought tolerance.

However, drought is definitely a problem. The 2012 drought hit hard in Missouri (Hoerling, 2014) and resulted in roughly 50% of the expected yield:

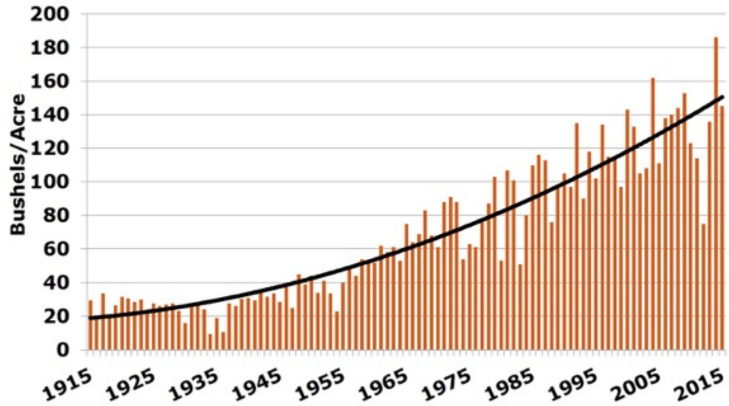


Figure 34 - Missouri corn yield (bushels per acre) from http://crops.missouri.edu/audit/corn.htm

The dip in corn yield from the 2012 drought also shows up nationally:

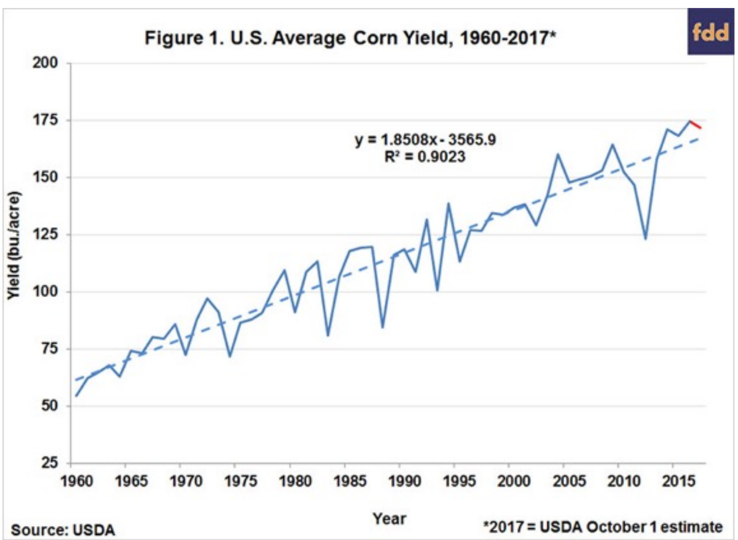


Figure 35 – Corn yields and trend from (Irwin, 2017)

The same article (Irwin, 2017) points out that the normal temperatures and rainfall and especially the cool August in 2017 was beneficial, and that US average soybean yields are rising with a quadratic trend.

An optimistic report indicates that "*An objective drought index that measures the dry and hot conditions adversely affecting crop yields is used in a regression analysis to test whether corn and soybeans have become more drought tolerant. Results indicate that corn yield losses from a drought of a given severity, whether measured in quantity terms or as a percentage of mean yield, have decreased over time*" (Yu, 2009)

A somewhat pessimistic review of agricultural economics in light of climate change (McCarl, 2016) suggests that adaptation for the impending crisis is hampered by market failures and requires intervention by economists. But their evaluation of adaptation potential is fundamentally positive. At the other extreme (Lang, 2010) notes *"Evidence about climate change has been building for decades but its implications for food* *capacities are pressing"* and "*One does not need to be a neo-Malthusian to note the awesome challenge from population growth.*" Global warming is the latest in a long history of fabricated Malthusian crises. While Malthus was concerned about agriculture not keeping up with population growth, his premise is the impossibility of technical progress.

Malthus was wrong in his time because:

- *He assumed that there was a limit to the ability of agriculture to provide subsistence for a growing population. In reality, since 1800, farm mechanization and better fertilizer usage have increased the output per farmer on the order of 400x in developed countries.*
- *He assumed that population would continue to grow at an exponential rate until limited by a resource crisis. In reality, over the last 200 years, a phenomenon called the demographic transition has occurred: as people lived longer and became healthier and wealthier, they voluntarily decided to have fewer children.*

The bullets above are from http://www.senseandsustainability.net/2016/11/08/escaping-the-malthusian-trap-and-the-population-bomb/ Despite the continuing improvements by modern agriculture and demographic transitions (the voluntary reduction of fertility in response to wealth), modern Malthusians insist that famine is just around the corner and Malthus will finally be right. But his prediction has become ever less likely over time because of the constant increase of human wealth and progress, which is the same reason that all other predictions global warming doom are wrong.

On the other end of the rainfall spectrum from drought, a study (Rosenzweig, 2002) shows reduced yields for excess precipitation (fig 1) during the growing season. This was attributed to extreme precipitation events. For the definition of extreme, they appear to refer to (Karl, 1998) which is not extreme as discussed above. More recent studies have looked more broadly at crop production, not just yield (Iizumi, 2015). They stated "*As this review shows, we know little, especially on a global level, about how weather and climate, modulated by farmer decision making and available technology, influence cropping area and intensity*." To which I would add: market forces. In the US the corn supply chart records the 2012 drought impact:

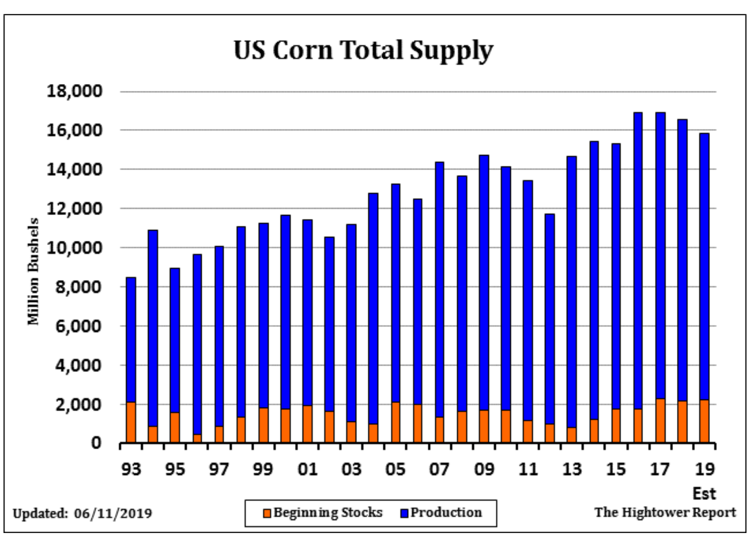


Figure 36 - US Corn supply from https://www.cmegroup.com/trading/agricultural/corn-reports.html

The chart shows that farmers increased production in 2013 to make up the loss. It also shows that with relatively high supply, production falls, also as a result of farmers making decisions. The agricultural market system is not perfect but better than any alternatives especially those proposed by the neo-Malthusians.

The Arbor Day Foundation produced a map of the hardiness zones shown below. Hardiness zones are based solely on the minimum winter temperature in each location since low temperatures freeze plants that are not hardy for those temperatures. As extreme low temperatures have decreased, the zones have shifted north. Growing figs in my zone 6b location, now possibly zone 7, is still difficult. But I get them some years when we are lucky enough to have a mild winter.

Cold climate agriculture such as maple sugaring could be curtailed (Matthews, 2017). The authors do not explain why cold nights and warm days would be reduced instead of just shifted earlier in the year. The dependence of the cold nights on shorter days would not change. It is true however that hot dry weather is not suitable for sugar maples. My own sugar maple tree (a future shade tree) grew much more in our past record rainfall summer than prior dry summers.

Recent studies show reduced nutrition from crops grown in elevated CO_2 (Zhu, 2018). However, the studies measure nutrients as a percentage of dry weight, not factoring in that more crop weight is produced in elevated CO_2. This is already occurring with current levels of CO_2 (Sakai, 2019). The nutrient composition of crops including rice has been and can be improved (Beyer, 2010), which is easier for some nutrients than others but progressing overall. It’s another example of where human progress far exceeds the negatives from human caused changes.

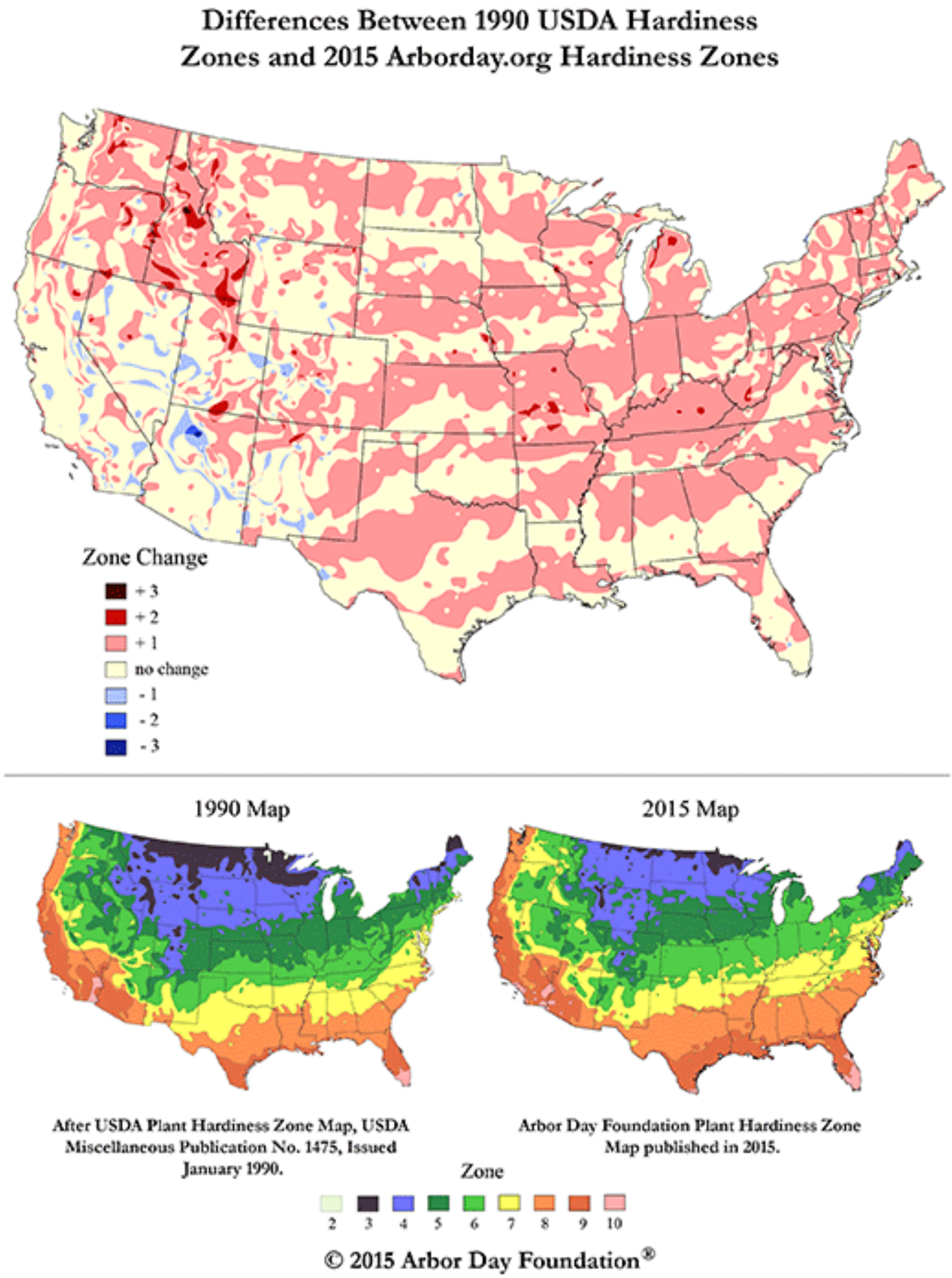


Figure 37 - Hardiness zone shift from https://www.arborday.org/media/map_change.cfm

2.3.2. Human Mortality

In middle and high latitudes mortality is highest in winter (Falagas, 2009). There will be two main effects of global warming on mortality, lower mortality in winter and higher mortality in summer heat waves. The other mortality effects of weather are negligible especially compared to weather mortality prior to the modern era of high resilience, weather forecasting and early warning (and global warming).

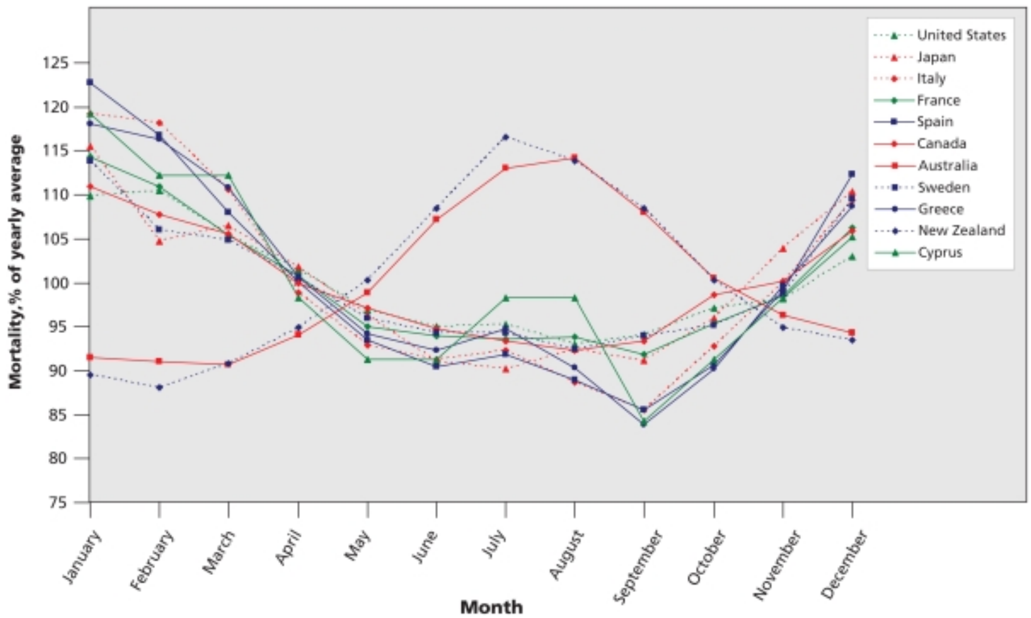
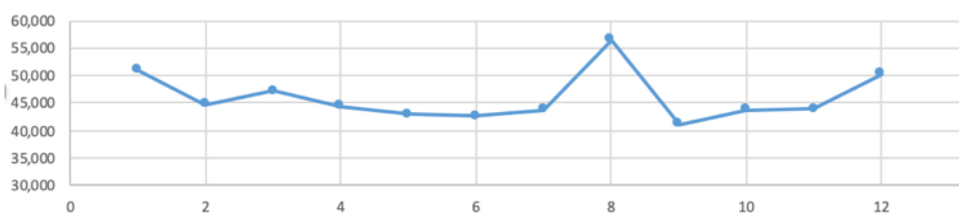
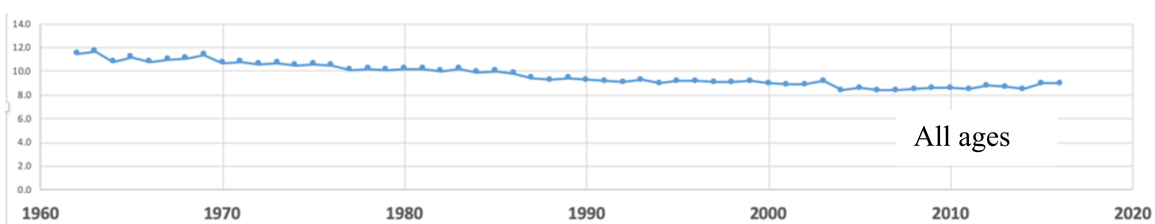


Figure 38 - Monthly percentage variation in mortality compared to yearly average over the last years in European Mediterranean countries and other selected countries worldwide. Caption from (Falagas, 2009)

At first glance, it appears that the effects of heat waves may negate the summer drop in mortality. The French mortality data shows a spike in mortality in August 2003 rising well above any other month of the year:



Additionally, 2003 displaced mortality from 2004 especially among the very old (90+)



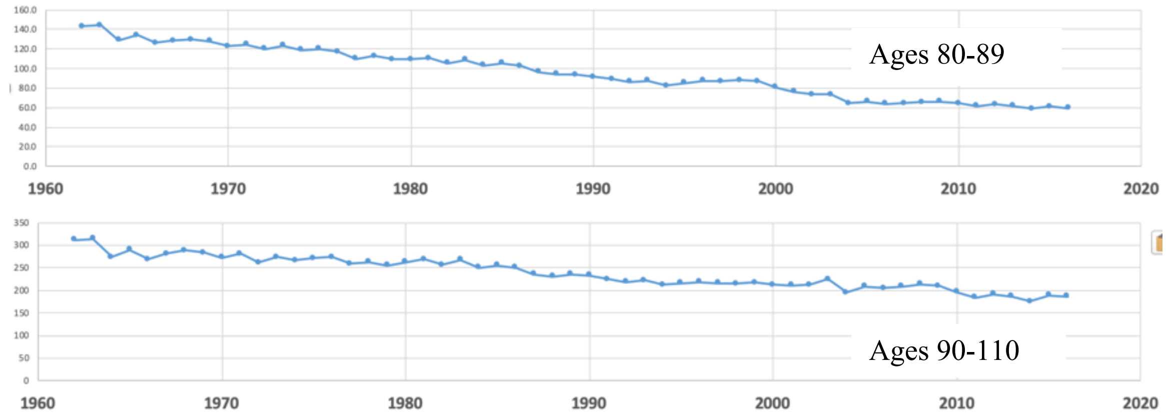


Figure 39 - French mortality data from Institut National d'Etudes Démographiques (INED.FR)

The 2006 heat wave in France may have come soon enough that the displacement effect of the 2003 disaster helped lower the 2006 toll. A study of the 2006 heat wave (Fouillet, 2008) explains some of the potential factors:

- *the French population's increased awareness of the risks related to extreme summer temperatures after the 2003 heat wave;*
- *the set-up of preventive measures with regard to the effects of high temperatures by the health authorities and institutions after the 2003 heat wave;*
- *the set-up and implementation of the heat health watch warning system (HHWWS) by the InVS and Meteo-France as of summer 2004.*

The factors that greatly exacerbated the mortality in France in 2003 are explained in detail in (Lagadec, 2004). The author points out the fact that water, ice, air-conditioned spaces, and emergency services were all readily available but not utilized. Instead the victims were socially isolated, geographically scattered, and essentially ignored. The same occurred in Chicago in 1995 except the victims were mainly both poor and elderly.

In short, social norms and social structures can and must change to address heat wave mortality regardless of their frequency and severity. The first step is to quantify heat waves with indices that better reflect the medical consequences of the heat in different locations. Such a study (Smith, 2013) determined the heat wave trends across the US using 15 indexes. Their work can lead to actionable results, for example, large increases in the max temperature > 35C (H11), can be counteracted with daytime cooling, whereas a relatively high minimum and maximum temperature (H12) requires 24-hour mitigation since people affected won't be able to cool off at night. The next step in this work is to determine the risks and mortality from each type of heat wave and perform the appropriate heat mitigation in each location.

In the US mortality is about 10% higher in winter months than summer months (636,605 deaths in winter, 573,946 in summer) from CDC data: http://www.cdc.gov/nchs/data/dvs/MortFinal2006_WorktableIV_part1.pdf In Canada winter mortality is about 15% higher:

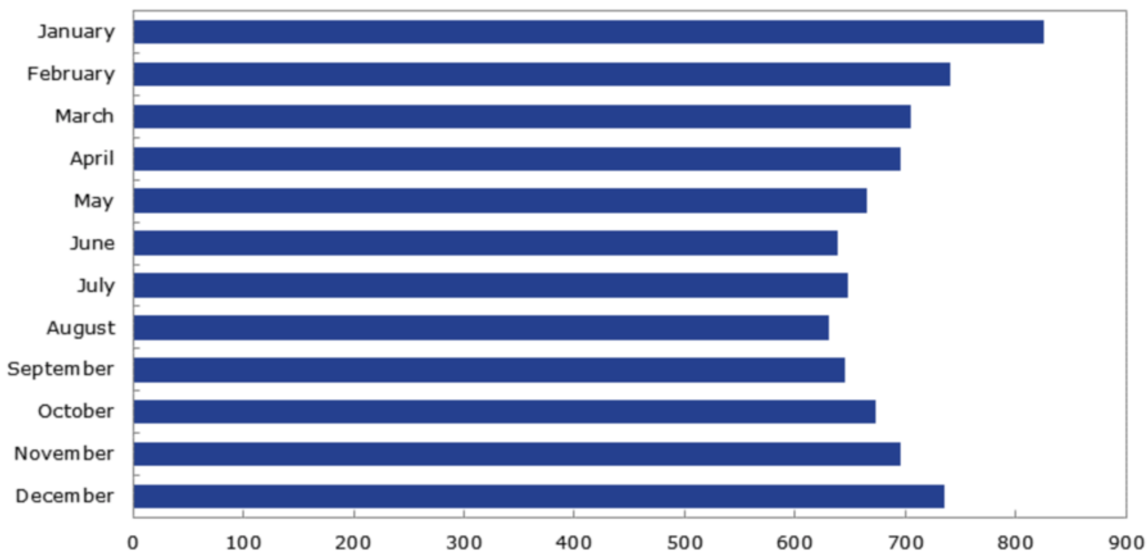


Figure 40 - Average daily deaths by month for 2013 from Statistics Canada

New York City mortality is also about 15% higher in winter (14,764) than in summer (12,774) http://www1.nyc.gov/assets/doh/downloads/pdf/vs/2015sum.pdf

The possibility of less cold winter weather leading to lower mortality was reexamined in (Ebi, 2013). The paper focuses on mortality from cold weather and addresses humidity thusly: "*Recent evidence suggests that seasonal variations in influenza mortality may be associated with absolute humidity, not temperature or with episodes of cold, dry air.*" Absolute humidity is expected to increase with global warming (Held, 2006), suggesting that mortality question deserves another reexamination regarding humidity.

Most other papers focus on cold rather than humidity (Kinney, 2015): "*Since adults in developed countries spend more than 90% of their time indoors, and are largely protected in their daily lives from cold exposure via a range of infrastructure and personal adaptations, humidity may be a more plausible meteorological risk factor for winter season respiratory infections and related cardiovascular mortality. However, seasonal patterns of human exposure to dry air and respiratory viruses remain largely unexplored*." Indoor humidity is at least partly dependent on outdoor humidity.

Influenza is a major winter mortality factor and an inflection point for influenza appears around roughly 0C and about $3 g/m^3$ of humidity in (Jaakkola, 2014). The authors observe "*that a decrease in temperature and AH increased the risk of influenza,*" but for temperature, the risk of influenza was associated with higher temperatures before the decline. They postulate "*Higher temperatures approaching zero degrees may favour transmission and survival of the virus itself, but a decline in temperature and humidity may make the host more susceptible through body cooling and/or drying of the respiratory tract.*" They find that "*very low temperatures and absolute humidity may even reduce the occurrence of influenza infections*."

In Finland, mortality is 14% higher in winter (DJF) than summer (JJA) but March is also high, higher than December as shown below.

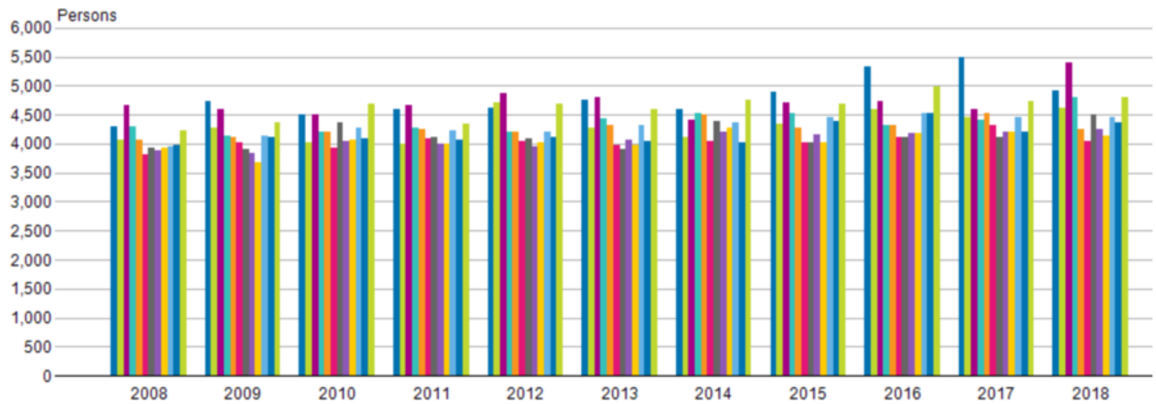


Figure 41 - Finland mortality by month (not normalized for days per month) source Statistics Finland

However, the March causation becomes clearer by comparing average daily mortality to dew point (left axis) showing a close correlation between dry air and mortality:

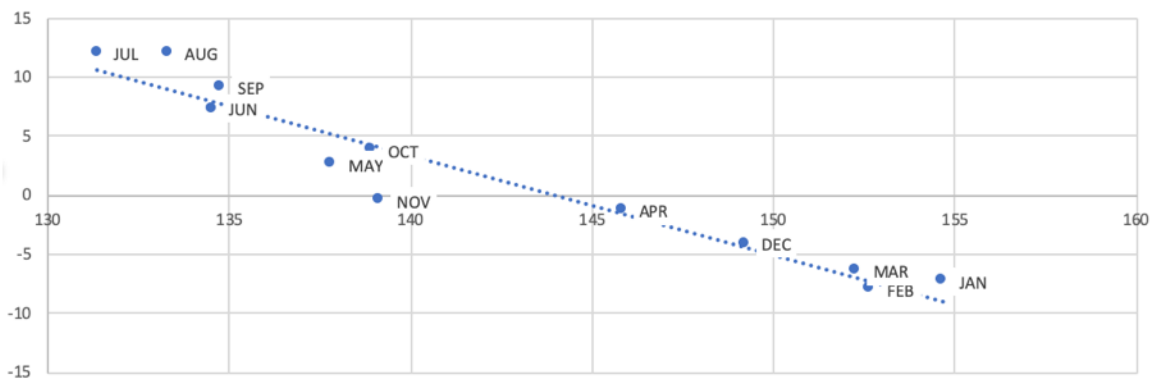


Figure 42 – Average daily mortality versus average monthly dew point, sources Statistics Finland and climatemps.com for Helsinki, Finland

It also appears that the flu virus may have better survival in cold weather: Flu Virus Fortified In Colder Weather The link describes a March 2008 paper: "*The researchers discovered that at temperatures slightly above freezing and below, the virus's lipid covering solidified into a gel. At about 70 degrees Fahrenheit, much of the lipid was still in gel form.*" The paper may help explain why flu transmission is higher in winter.

Specific weather event related mortality. A CDC report (Berko, 2014) states "*During 2006–2010, about 2,000 U.S. residents died each year from weather-related causes of death. About 31% of these deaths were attributed to exposure to excessive natural heat, heat stroke, sun stroke, or all; 63% were attributed to exposure to excessive natural cold, hypothermia, or both; and the remaining 6% were attributed to floods, storms, or lightning.*"

Thanks to better preparation, forecasting, and warnings, killer storms (Cressman, 1969) are mainly in our past. There was a report written a year after Hurricane Maria hit Puerto Rico (University, 2018) https://publichealth.gwu.edu/sites/default/files/downloads/projects/PRstudy/Acertainment of the Estimated Excess Mortality from Hurricane Maria in Puerto Rico.pdf claiming the death toll from Maria to be 2,975 plus or minus about 10%. A death toll from mortality statistics is not comparable to prior storm death tolls which only count storm-related deaths. That number is also based on a population estimate: *We estimated that in mid-September 2017 there were 3,327,917 inhabitants and in mid-February 2018 this number was 3,048,173 inhabitants of Puerto Rico, a total population reduction of approximately 8%. This was factored into the migration "displacement scenario" and compared with the "census scenario."*

The report gives the population data sources as "*Cumulative monthly population displacement after the storm in each month was estimated using Bureau of Transportation Statistics (BTS) data on monthly net domestic migration provided by the Puerto Rico Institute of Statistics and a survey of airline travelers provided by the Puerto Rico Planning Board (Planning Board 2018).*" This 279,744 net out-migration estimate comes primarily from interviews of airline passengers. There is no documented attempt to estimate the errors induced by people who said they were leaving for good but changed their minds and went back to Puerto Rico, the percentages of interviews, or the selection process for interviewees.

Other estimates of net out-migration for the same period vary from 47,652 to 135,000 (Centro, 2018). Without a more scientifically-supported estimate of Puerto Rican net migration for the five months following the hurricane, there is no support for 2,975 or any other specific mortality estimate.

Landslides. A paper shows an increase in "fatal landslides" (Haque, 2019) from 1995 to 2014. While the paper acknowledges the existence of underreporting, it doesn't elaborate on any changes in reporting criteria or mechanisms from 1995 to 2014, specifically for landslides with one or more fatalities. The total fatalities e.g. fig 1 are not normalized for population increase from 5,751,474,416 in 1995 to 7,298,453,033 in 2014.

Floods. The fatalities from US floods are generally dropping thanks to better mitigation and despite increased population:

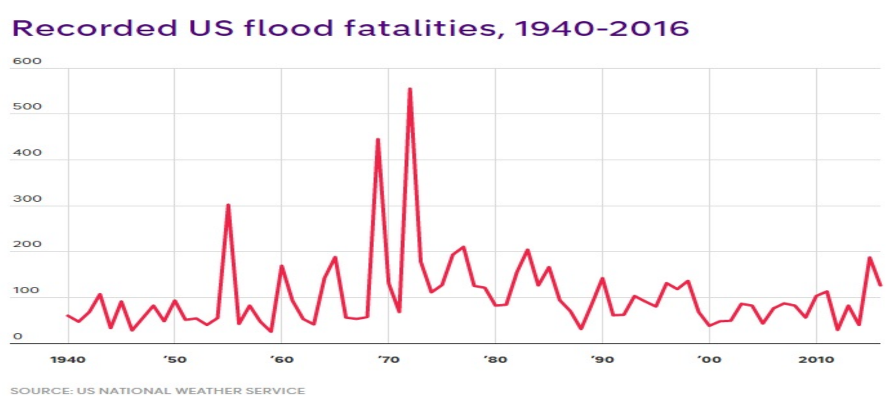


Figure 43 - US flood fatalities from https://www.channel4.com/news/factcheck/2-3-billion-people-affected-by-flooding-disasters-in-20-years (not normalized for population increase)

Global Flood Mortality. The OurWorldInData website contains a large amount of data and graphics for natural disasters at https://ourworldindata.org/natural-disasters One obvious conclusion is that deaths from the graphic is that drought and floods can be mitigated whereas earthquakes are much more difficult to mitigate. Extreme temperature mortality is rising (they don't break down heat and cold). The numbers are not normalized for population.

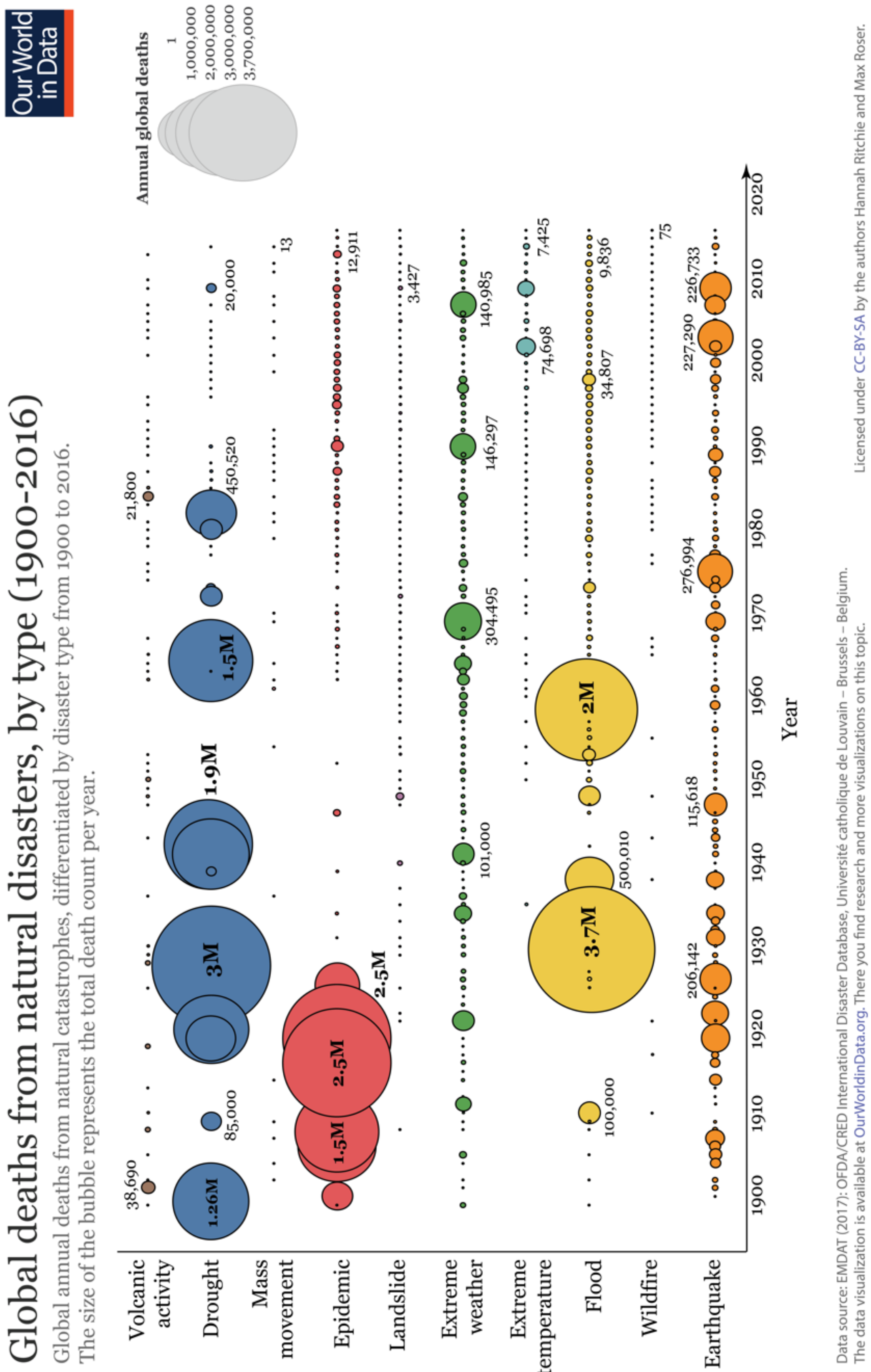


Figure 44 - Global disaster fatalities from https://ourworldindata.org/natural-disasters

Storm Surge Mortality. Extreme storm surges are a good example of a very rare weather event that is showing very slow if any increase despite sea level rise and increased hurricane strength. 2005's Katrina is a recent US outlier at 8.47 meters, a record. The highest surge globally was in Bangladesh in 1876 at 13.7 meters. There are two surges tied for second highest at 12.0 meters in India in 1737 and 1864. The mortality from surges has dropped over time from consistently hundreds of thousands in past centuries (and also 1970) to thousands recently, except for 140,000 deaths in Bangladesh in 1991 (Needham, 2010). That thesis also points out the quadrupling of the US population at risk from 1950 to 2000.

Tropical Diseases. As noted in the same chart, large epidemics can now be mitigated although there appears to be an increase in small epidemics. There are predictions of increases in vector-borne diseases due to the increasing abundance of reservoir species and a longer, more favorable mosquito season (Gage, 2008). However as noted in (Reiter, 2000), "*Discussions of the potential impact of human-induced global warming frequently include malaria, a disease widely perceived as tropical. Articles in the popular and scientific press have predicted that warmer temperatures will result in malaria transmission in Europe and North America (7-12). Such predictions, often based on simple computer models, overlook malaria's history; until recently, malaria was endemic and common in many temperate regions, and major epidemics extended as far north as the Arctic Circle (13).*"

There is a large infrastructure of monitoring and health care keeping such diseases from spreading out of the areas, not all tropical, where they are endemic. They are often detected in incoming travelers, outbreaks are tracked, and if needed, spraying can eliminate any spread through the mosquito vector. In (Carter, 2002) they point out that malaria was likely brought to the Americas by Europeans. It probably reached its global limit around the middle of the 19th century with half of the world's population at risk and 1 in 10 mortality. It became extinct in Europe and North America by the early 1960's.

A similar analysis was done for yellow fever in (Bryant, 2007). Brought from Africa with the slave trade, from the late 1600's YF killed thousands or 10's of thousands annually mostly in the southern US, with the last outbreak in New Orleans in 1905. "*YF is currently classified as a reemerging disease and remains a significant cause of morbidity and mortality, with an estimated 200,000 cases each year and 30,000 deaths [4,5]. Indeed, although a highly effective vaccine is available, epidemiological data suggest an alarming resurgence of virus circulation in West Africa over the last 20 years [6,7]. The failure to implement sustained vaccination programs reflects larger problems of poverty, civil war, and the inaccessibility of rural areas where outbreaks of the disease occur [8]*" (Bryant, 2007).

In short, other than some reservoirs in tropical primates there is nothing particularly "tropical" about these diseases. They don't exist in most developed tropical countries. They spread mainly in the warm season in temperate regions, and in the rainy season in tropical regions. They are better characterized as undeveloped country diseases. YF spreads by Aedes aegypti mosquitoes which were eradicated in large areas in the mid-1900's, see map at http://entnemdept.ufl.edu/creatures/aquatic/aedes_aegypti.htm but remained in many areas like Florida and have reestablished with the ending of the eradication program.

There are predictions of health effects and increased mortality in children from increases in disease vectors, increased malnutrition, heat and extreme weather (Ahdoot, 2015). These predictions are not quantified and are missing the pre-global-warming baselines for heat and weather. The authors do provide baselines for various diseases. But they do not discuss the approximately 3 billion people using dirty fuels for indoor cooking, causing over 2 million childhoods deaths each year (Fullerton, 2008). What is needed is a big picture view of disease and mortality from all causes and an understanding of the best ways to increase the standards of living of all the people on the planet.

2.3.3. Climate Refugees

Central America. There is a claim that "Central America is ground zero for climate change" (Miller, 2018): "*Guatemala, Honduras, and El Salvador lie in the trajectory of the so-called "dry corridor" of Central America that stretches from Southern Mexico to Panama. This epithet is a recently adopted description of the region, to describe the droughts that have risen in intensity and frequency over the last 10 years.*"

However, there is a long history of drought in Central America. In (Stahle, 2016) the authors show numerous major droughts in Mexico and nearby portions of Central America. There is currently a lot of gang violence in those countries and a lot of refugees are fleeing the violence. There is a lack of economic opportunity in those countries and most of Mexico, and the strong economy in the US drawing economic refugees here. There is the same level and severity of drought in the US southwest where the refugees are fleeing to. Additionally, land use changes like deforestation can greatly exacerbate drought as discussed in (Stromberg, 2012). In short, there is lots of evidence that the refugee flow is due to factors other than global warming or the effects of global warming.

Venezuela. The impacts of drought can be exacerbated by social and political conditions, but the main factor is almost always bad policy. For example, over 4 million refugees have fled from Venezuela because of economic stagnation due to socialism. One claim in E&E News was "*A dry winter heading into 2016 led to low water levels at the Guri Dam in Bolívar, the nation's largest hydroelectric facility, and months of power shortages in Caracas and elsewhere.*" (Chemnick, 2019). The article fails to mention the cause of the reduced rainfall was the 2016 Super El Nino.

Similarly reduced rainfall in the 2010 El Nino was a factor in reduced power from the Guri dam. However, the actual cause of the energy crisis was unsustainable reliance (taking into account El Nino) on that single dam for 70% of Venezuela's electricity in 2010 (Calvo, 2018). The root cause of that overreliance was Hugo Chavez freezing electricity prices in 2002 and halting investment in maintenance and production of electricity sources. A motivating factor was reserving oil for export revenues to fund more socialism. Even when investment in electrical generation resumed, corruption reduced the amount energy generated to about 65% of the new capacity (Calvo, 2018).

Syria. Drought made more likely by global warming is claimed to be a contributing factor to the Syrian refugee crisis (Kelley, 2015): "*There is evidence that the 2007−2010 drought contributed to the conflict in Syria. It was the worst drought in the instrumental record, causing widespread crop failure and a mass migration of farming families to urban centers. Century-long observed trends in precipitation, temperature, and sea-level* *pressure, supported by climate model results, strongly suggest that anthropogenic forcing has increased the probability of severe and persistent droughts in this region, and made the occurrence of a 3-year drought as severe as that of 2007−2010 2 to 3 times more likely than by natural variability alone. We conclude that human influences on the climate system are implicated in the current Syrian conflict.*"

Those claims were critiqued in (Selby, 2017). Selby at al point out that the Fertile Crescent region used by Kelley at al in their analysis is huge. As Euan Mearns documented, the agricultural zones in Syria affected by drought did not have exceptional drought:

Figure 3. Drought index (1960-2009)

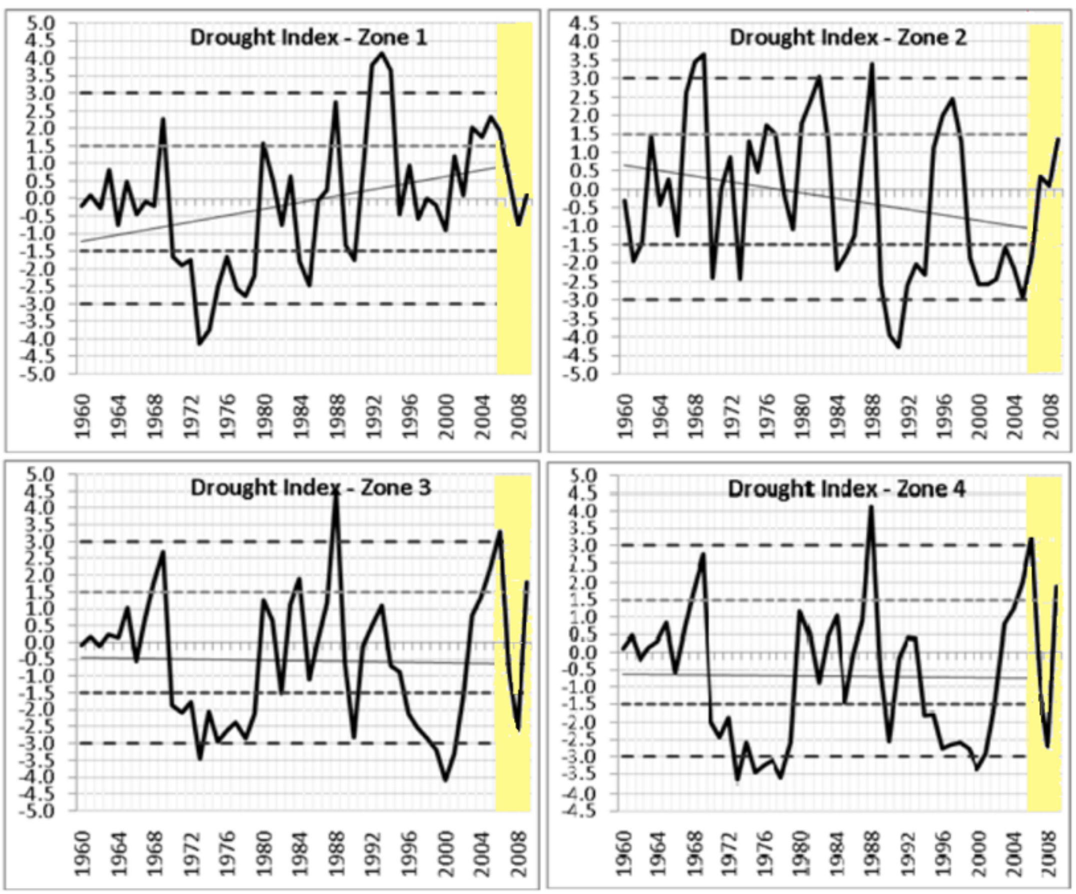


Figure 45 - Drought Index values from Figure 5 of http://euanmears.com/drought-clinate-war-terrorism-and-syria

See the source http://euanmearns.com/drought-climate-war-terrorism-and-syria/ for the derivation of the figure above. (Selby, 2017) points out that the claim of a long-term drying trend in the Fertile Crescent as a whole is unsupported. Some model studies show that warmer means wetter, for example in the Fertile Crescent (EVANS, 2008). The reliability of downscaled models is questionable and we should be skeptical of any such studies. (Selby, 2017) further points out that "*By summer 2009 the UN, using Syrian government figures, was estimating that 40–60,000 families had migrated because of the drought*", which does not support the claim that climate factors caused mass migration. They point out much more important economic factors "*the removal of key subsidies –*

including, in May 2008, the removal of fuel subsidies (which led to an overnight 342% spike in fuel prices) and, in May 2009, the removal of fertilizer subsidies (which led to price increases of 200–450%: De Schutter, 2011: p. 16)." In the big picture, drought was a minor factor in Syrian mass migration in the late 2000's.

2.3.4. Wildfire in California and Australia

California. The western US has a wildfire "deficit" (Marlon, 2012). In year-to-year time scales, fire is controlled by temperature, precipitation, and drought. *"Fire activity in dry shrublands and grasslands is also strongly linked with antecedent precipitation that drives the development of fine fuels necessary for the spread of large fires in these ecosystems…*" Temperature is a factor both on the seasonal time scale but also centennial and longer timescales (Marlon, 2012). California in particular is a "boom and bust" location for rainfall (Dettinger, 2014). This has been true for at least 2000 years (Hughes, 1992).

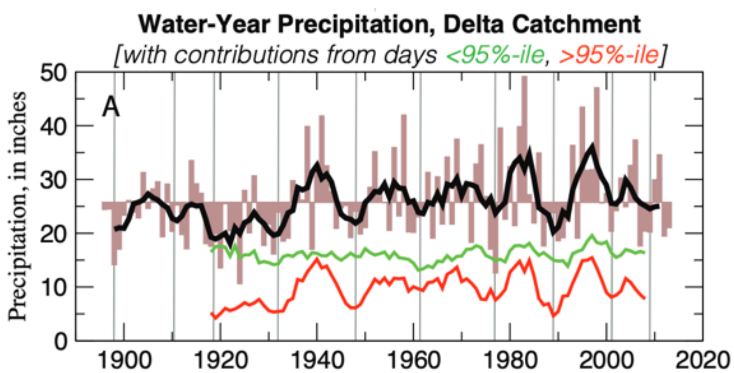


Figure 46 - Precipitation in the California Delta from (Dettinger, 2014)

Following high precipitation rainy seasons, there is an urgent need to clear overgrowth. Clearing is most easily accomplished by natural or prescribed fire although there are alternatives particularly for protecting life and property. After deadly wildfires in California in 2017 and 2018, it is obvious there should have been more clearing. Wildfire is beneficial (Keane, 2010) when it is low or moderate intensity. But in California, there are strict air quality laws drastically limit the amount of natural and prescribed fire on private, state and federal lands. In Butte County the location of the deadly 2018 Camp Fire (153,000 acres) the county only allows 6,000 out of its 1,073,279 acres to be burned at any one time during the relatively short, safe burning season, see 9.12.6 in https://ww3.arb.ca.gov/drdb/but/curhtml/r300.pdf This artificial limitation of both natural and prescribed fire did not allow the excess growth from the high precipitation 2016-17 rainy season to be safely reduced through the most effective means possible. Instead, it was left to burn catastrophically.

Charcoal records in southern California show that there has not been a change in the fire regime despite changes in land use including modern fire suppression (Mensing, 1999). The authors note that large fires follow wet periods and occur when long-term weather patterns support Santa Ana winds throughout the 560-year period. In https://lao.ca.gov/Publications/Report/3798 the authors point out that fires burned an average of 4.5 million acres before 1800. They state that:

"*The VMP treated 17,500 acres with prescribed burns in 2017, somewhat more than the average of approximately 13,000 acres treated per year since 1999. This represents a decrease from about 30,000 acres treated per year from 1982 through 1998. This decrease is due to several factors, including (1) an increase in the amount of planning and documentation required for prescribed burns due to stricter air quality regulations, (2) projects more often being in close proximity to populated areas, and (3) longer fire seasons that can divert CalFire foresters and firefighters who would be available to plan and implement prescribed burn projects*."

The reduction from 4.4 million acres of fire (Stephens, 2007) to 17,500 state plus 250,000 federal acres of thinning and natural and prescribed fire will inevitably result in out-of-control, catastrophic wildfire. The state's new plan for carbon sequestration in forested land recognizes the need for fire: "*Given the forest conditions found in many areas of the state today, it will take substantial, long-term investment in thinning and fuels reduction (including prescribed and managed fire), reforestation, sustainable timber harvest, and other treatments at a large scale to achieve and maintain an ecologically meaningful increase in forest health and resilience.*" See http://resources.ca.gov/wp-content/uploads/2018/05/California-Forest-Carbon-Plan-Final-Draft-for-Public-Release-May-2018.pdf

The new California governor waived some regulations in the spring of 2019 and by the end of 2019 had developed and certified a program for vegetation management on 500,000 acres annually (not including federal land). See https://www.gov.ca.gov/2019/12/31/california-certifies-statewide-programmatic-environmental-impact-review-to-protect-californians-from-catastrophic-wildfires/ The success of the program was real but modest in 2020. "*Between June 2019 and June 2020, Cal Fire burned 27,000 acres in controlled burns, and completed an additional 28,000 acres of fuel reduction projects. Matt Dias, executive director of the California Board of Forestry and Fire Prevention, emphasizes that these numbers do not represent the full extent of fire treatment in California, which involves many other agencies besides Cal Fire.*" https://www.sfweekly.com/news/to-fight-fires-california-must-burn/

In (Kolden, 2019) the author points out that while prescribed fire has health implications from smoke, the contrast between the western and eastern US points to a social difference where prescribed fire is accepted in the southeast US (even legally protected in Florida), but restricted and penalized in the west. The author concludes that without a cultural shift towards the acceptability of prescribed fire in the west, more catastrophic fires are inevitable.

The benefits of prescribed fire in the southeast US are described in (Hahn, 2019): "*Evidence from Coweeta Hydrologic Laboratory and other locations is consistent with the mesophication hypothesis, confirming that long-term fire exclusion shifts forest species dynamics to more mesophytic, fire-intolerant species (Elliott and Vose 2011; Ryan et al. 2013; Elliott et al. 2017). These species channel more water into evapotranspiration, resulting in less groundwater and surface water yield at the watershed scale (Caldwell et al. 2016).*" Without that benefit from prescribed fire or land management with a similar goal, the inevitable out-of-control fires will be worse.

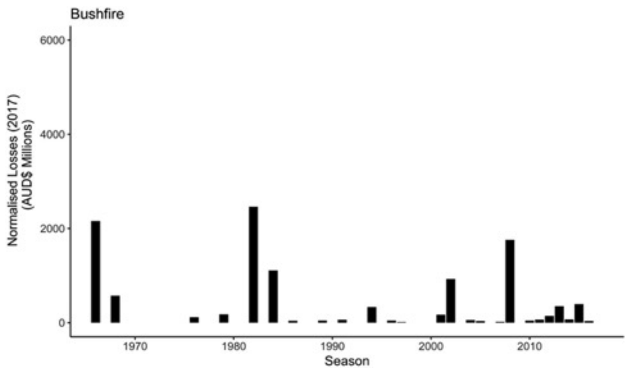
In August 2020 a large amount of lightning sparked many fires in northern California, causing two of the largest fires in modern California history. The reasons for the excessive spread of wildfire was, once again, poor forest management. The problem was described in an article https://www.sfgate.com/bayarea/article/Top-scientist-knew-Big-Basin-was-at-risk-for-a-15514626.php that noted that *"We haven't done a large burn in Big Basin in the last three years because the weather hasn't lined up," Halbert says in the podcast. She brings up other bottlenecks to prescribed burns including permitting issues, staffing, and a short — or nonexistent — window for favorable weather conditions.*" The article references a study (Miller R. , 2020) that restates the obvious, that the California wildfire problem is "sociopolitical". The authors note that prescribed fire in California is being artificially limited by policy and policy perceptions. They note the recommended burn area is about a million acres.

In (Goss, 2020) they note the broadening of the fire season in California and *"We therefore focus primarily on climatic factors that contribute to extreme wildfire conditions during autumn,...*" including increased heat, extended seasonal drought, and increased wind during fire season. Their claim rests on two possibilities, belated winter rains and/or earlier seasonal offshore winds. The most important factor by far is wind as is obvious from their examples of recent fires: *"Both fires ignited during strong and dry 'offshore' downslope wind events, known locally as the Santa Ana winds in Southern California*" Projections for the Santa Ana winds are given in (Guzman-Morales, 2019) about which (Goss, 2020) says: "*Although further research is needed to fully assess changes in the precise timing of cool-season precipitation onset, recent work suggests that projected sub-seasonal shifts in California precipitation ([17, 21–23, 29]; figure S2) have significant potential to interact non-linearly with changes in the seasonality of autumn offshore winds [Guzman-Morales, 2019]."*

Unquestionably an extension of the dry season into the higher wind season would lead to increased fire danger. Models in (Swain, 2018) show November drying (wetter Jan and Feb) in southern California in 2070–2100 and note evidence for a sharper seasonality of rain. Regarding winds, (Guzman-Morales, 2019) is a study using several models all showing a decrease in the frequency of Santa Ana Wind events. The models do not agree on the timing of SAW. About half the models show the winds coming earlier and half later. Also some models show different timing for 2000-2049 vs 2050-2099. There is the potential for "non-linear" interaction but with the variation in the models it is entirely speculative and the overall model conclusion is for a modest decrease in SAW frequency.

Australia. The Australian bushfires that are in the news as of January 2020, have much the same root cause as California: too little fuel treatment. The website Bushfire Front promotes prescribed (fuel reduction) burning as a practical solution to reduce the severity of inevitable bushfires. Their primary focus is western Australia whereas the most severe bushfires are currently in New South Wales and Victoria in southeast Australia, including locations where burns are not common.

The causes of catastrophic fire in Australia are global warming (excessive heat including natural variation), rainfall changes, and inadequate fuel reduction. Each of these factors can be analyzed although quantifying the contribution from each is not possible. However there is no trend in normalized bushfire losses as shown next.



A paper that analyzed all types of Australian natural disasters (McAneney, 2019) contains a chart of normalized insurance losses for bushfires showing no trend. Their analysis of bushfire severity and frequency is limited to 2001 to 2017 using MODIS. They found no trends, but noted p values > 0.05 due to the short record.

Figure 47 - Normalized bushfire losses for Australia from (McAneney, 2019)

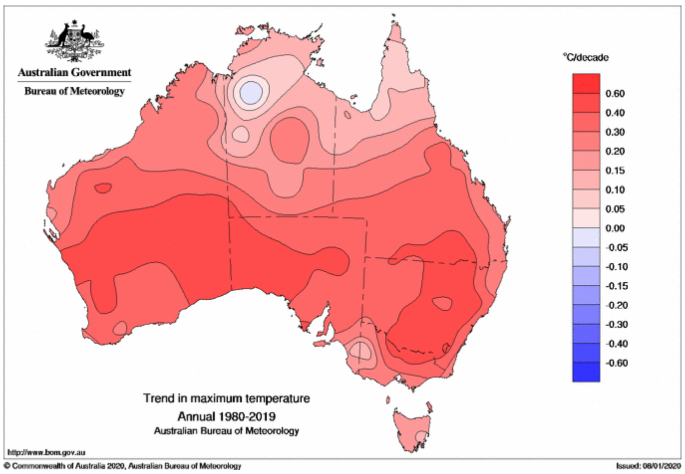


Figure 48 - 1980-2019 maximum temperature trend

There was heat for the 1851 and 1939 fires. In Melbourne in 1851 "The temperature at 11.00 am. was 117° F in the shade. At 1.00 pm. it had fallen to 109° F but by 4.00 pm. it was at 113° F." "BLACK THURSDAY" BUSHFIRES 1851 In 1939 the temperature in Melbourne reached 114 F. Currently there is a trend towards higher temperature throughout Australia, 1980-2019. That trend obviously exacerbates dry season drying.

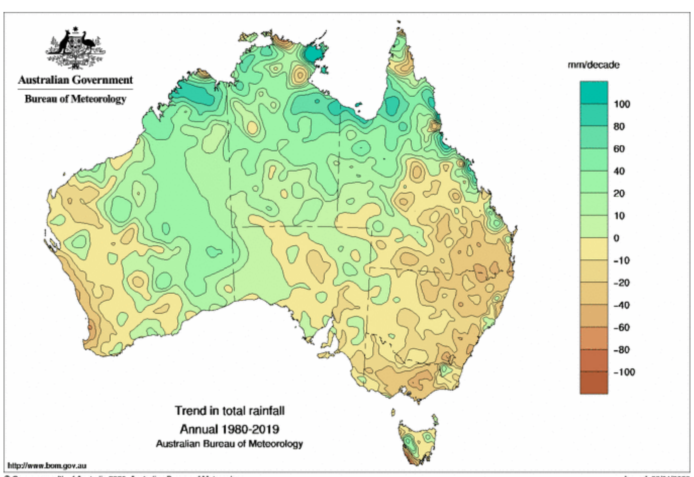


Figure 49 - 1980-2019 rainfall trend

There is also a trend for lower rainfall in many of the locations with bushfires. The temperature trend is explainable by global warming, but the rainfall trend has no explanation other than natural variation. All data is from Climate change – trends and extremes at the Australian BoM.

A report commissioned by the Queensland Government (Burrows, 2019) describes the effects of global warming and mitigation practices for fires along with prevention including prescribed burning. The conclusions of the report were that in all cases, both in Australia and abroad, there was inadequate fuel management. In some cases such as California there was an overuse of fire suppression. However the fuel management conclusions are that in many cases 25% or more of land requires prescribed burning each year.

2.3.5. Extinctions

A claim was made in a publication referenced by (Fulton, 2017) that the **Bramble Cay melomys** (a small rat) was "*the first mammal to be reported extinct due to oceanic inundation associated with human-induced climate change (Gynther et al. 2016)* " The author acknowledges and laments the "*the fact that it is the 30th terrestrial mammal confirmed extinct in Australia since 1788*" The other 29 mammals became extinct essentially as a result of European settlement (Woinarski, 2015). The belated recovery plan developed for the animal identified the threats of sea level rise, nesting turtles disturbing vegetation, and major cyclones (Latch, 2008). See https://www.environment.gov.au/system/files/resources/4fe332f4-f2d3-4d41-ae39-2d3ed467966a/files/bramble-cay-melomys.pdf However, major cyclones have not increased around Australia:

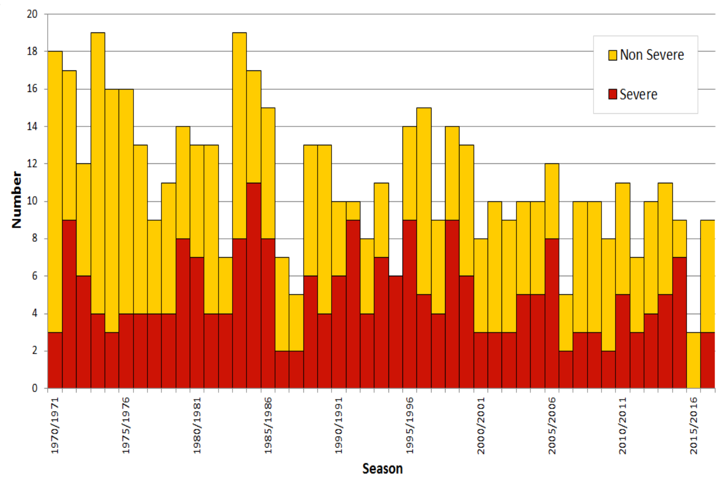


Figure 50 - Graph showing the number of severe and non-severe tropical cyclones from 1970-2017 which have occurred in the Australian region. (from http://www.bom.gov.au/cyclone/climatology/trends.shtml)

Sea level rise at Bramble Cay was about 3 mm /year (1992-2005).

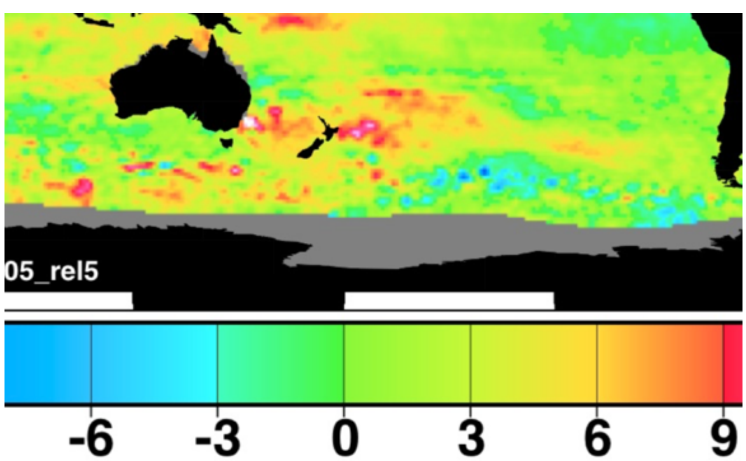


Figure 51 - Sea level rise with IB correction from http://www.bom.gov.au/ntc/IDO60202/IDO60202.2006.pdf

There are several papers documenting that the extinction was from greatly reduced vegetation (food source) *"probably due to ocean inundation resulting from an increased frequency and intensity of weather events producing extreme high water levels and storm* *surges"* (Waller, 2017). The paper mentions the July 2005 storm mentioned in (Latch, 2008). There is no data presented for that winter storm or any trend in such winter storms. My best guess is that female sea turtles hastened the rat extinction, by disturbing the vegetation while burying their eggs 1-2 feet deep in the sand above the high tide line. The green sea turtles at the closest monitoring point, Raine Island, grew at rate of 0.109 from 1976 to 2002 (Mazaris, 2017).

In the mountainous west, the **American pika** is being driven to local extinction (Beever, 2011). However, (Simpson, 2009) examined the potential of the animals avoiding thermal stress in summer at low elevations. That researcher located and documented pika below what was thought to be the lower limit of elevation in the Columbia River Gorge. (Beever, 2011) also located and documented pika to determine an average minimum elevation, adjusted for latitude, where pika are found. That elevation is rising. However, (Beever, 2011) do not appear to have studied populations in the Columbia River Gorge or other low elevation sites in the northern portion of their study range. It seems likely that pika will continue to live further north and won't become extinct. The local extinctions simply reflect the culmination of the interglacial warming following the glacial period.

There have been no local extinctions of **polar bears** from global warming. There are gains at the location with a large reduction in sea ice, Western Hudson Bay. The regulation of hunting, although still about 3.5%, has allowed polar bears to double from the 1970's lows. Simply put, hunting will determine the polar bears' fate, not sea ice. The population with the most decline in sea ice is Southern Hudson Bay (PBSG, 2018)

YEAR	ESTIMATE	LOW	HIGH	MISSING	CULLS	ALLOWED
1986	763	440	1086	90		
1986	641	401	881	90		
2005	673	396	950	0		
2012	860	580	1274	0	58	25
2012	943	658	1350	0	58	25
2016	780	590	1029	0	43 (2014)	20

Having an average of 58 human culls of polar bears (25 allowed per agreement with native tribes and voluntarily dropped to 20) is unsustainable with such a small population estimate with large margins of error. In (Obbard, 2018) they note a deterioration in the condition of the SH population but cannot determine if the population decline from 2012 to 2016 was a one-time event affecting the cubs born in 2015.

2.3.6. Positive Feedbacks (e.g. Albedo, Methane)

Several positive feedbacks are postulated including lower albedo and more methane and CO2, especially in the Arctic. The positive feedbacks, sometimes referred to as "tipping points", are localized (Lenton, 2008). One main conclusion of that paper is that there is no global tipping point and there won't be runaway global warming. Billions of years of earth history without runaway warming should be adequate evidence that it won't happen, and various theoretical discussions point to a possible "moist greenhouse" which is excessively hot but still has oceans (GOLDBLATT, 2012). However, getting to that state requires around 10,000 ppm of CO2.

There is more complexity in local tipping points than there is room to discuss here, see (Lenton, 2008). On the one hand, they expect boreal forests to decline from drought and fire, but on the other they expect more tundra to become forested. The mortality risks to forests may be alleviated, at least partially, by increased humidity and CO2 enrichment (Liu, 2017). The loss of summer sea ice in the Arctic is an example of a localized positive feedback with a modest global impact. A realistic loss of ice, the ice-free summer scenario, is expected to have a global radiative impact of 0.3 W/m2 (Hudson, 2011). A more recent study estimates a global impact of 0.21 W/m2 for the actual loss of Arctic ice through 2011 (Pistone, 2014). For comparison, there is 3.4 W/m2 from the doubling of CO2.

Another local tipping point with global implications mentioned in (Lenton, 2008) is methane hydrates. The global hydrate contribution is currently quite small:

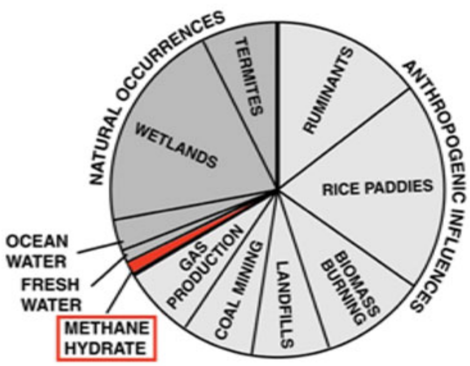


Figure 52 - Methane hydrate global contribution (Ruppel, 2012)

The Arctic methane hydrate melting potential is discussed in (Ruppel, 2012). Their conclusion is that the bulk of Arctic methane hydrates are likely to remain stable. They indicate that 95% of all of earth's gas hydrates are deep enough underwater to remain stable even with thousands of years of ocean warming. Their report is at https://archive.usgs.gov/archive/sites/soundwaves.usgs.gov/2012/06/index.html

Methane from permafrost is also mentioned as a local tipping point in (Lenton, 2008). Papers on the topic ought to include a discussion of the relative prevalence of methane-producing or methane-eating organisms in thawed Arctic soil and why summer concentrations of methane are lower than winter. They should also discuss projections for precipitation and hydrologic changes since methanogens are more prevalent in saturated anaerobic conditions (e.g. at the bottom of ponds) and methanotrophs in drier conditions. The (Lenton, 2008) discussion of permafrost focuses only on biomass and its implications for CO2 rather than methanogens and methanotrophs.

In (Neumann, 2019) the authors show that warmer and wetter Arctic soils produce more methane. Their measurement of methane flux peaked in summer. However, methane concentrations are lowest in summer:

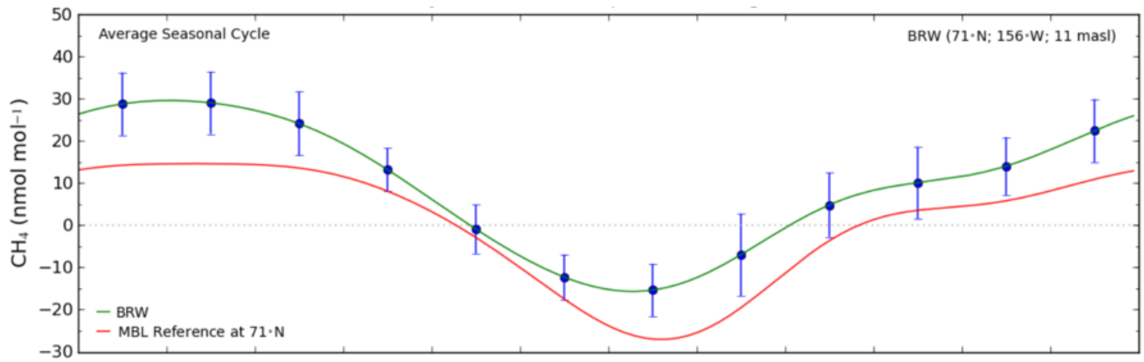


Figure 53 - Barrow methane concentration (annual average) from https://www.esrl.noaa.gov/gmd/webdata/iadv/ccgg/graphs/brw/brw_ch4_sc_obs_00027.png

The resolution to this apparent contradiction may be that the methane flux equals concentration multiplied by wind and higher winds in summer may result in a lower concentration, but I'm not sure.

Deep permafrost is melting very slowly. There is more widespread shallow permafrost that is essentially a relic of the Little Ice Age (Zoltai, 1995). The paper points out that most locations with current permafrost were 2-4 degrees C higher 6,000 years ago than at present. Ground temperatures from Canada still retain a Little Ice Age signal (Beltrami, 1992) demonstrating the slow pace of deep earth warming even in warmer Canadian locations without permafrost. Generally, the geologic methane in permafrost is not a large methane source. Using carbon isotope measurements, (Nakagawa, 2002) determined a maximum of 25% of methane to be "fossil" methane.

A study (Zhuang, 2006) shows a maximum of 54 Pg of carbon emissions per century from high northern latitudes (compared to current manmade emissions of 10 Pg of carbon per year). Furthermore the study shows that higher manmade emissions leads to a little less emission from the high latitudes. Finally, that highest amount of emissions comes from the "no CO2 fertilization" scenario, whereas increased CO2 is expected to increase plant growth in northern latitudes.

A study that cites (Zhuang, 2006) is (Koven, 2011). In that newer paper they examine high latitude sources using a land surface model https://orchidee.ipsl.fr/functionality/ that can model the carbon flux of northern lands, including peat, vegetation and permafrost. Their result shows the northern latitudes "tip" from a carbon sink into a carbon source before 2100 in particular by soil heating from manmade warming and self-heating feedback from microbial decomposition. Contrary to current measurements of less methane in the summer, they see more potential for methanogens than methanotrophs. Their cumulative flux estimates for the year 2100 range up to 100 Pg of CO2 or 27.3 Pg of carbon compared to the annual current annual 10 Pg of manmade carbon.

These are no global tipping points on the time scales we need to concern ourselves with or probably ever. Even if a model "tips" from equilibrium or sink of high latitude carbon to a source of carbon before 2100, the earth as a whole is not reaching a tipping point. A tipping point cannot be defined as a process that can be offset with a relatively small change in manmade actions like rice farming.

For a discussion of the definitions of tipping points, people should read Gavin Schmidt's post: Runaway tipping points of no return. The essay written in 2006 may seem obsolete since it discusses having "only 10 years left". He says: "*While the '10 years' shouldn't be read as an exact timetable, it is surely in the right ballpark. 30 more years of business-as-usual will make it impossible to keep temperatures from rising beyond Eemian levels*". His argument implies that Eemian conditions with sea level 20-30 feet above today's are inevitable. But as discussed above, that kind of rise in sea level is not plausible in the time frames that matter and can be completely mitigated or reversed in longer time frames. Whether temperatures will reach Eemian levels is debatable. It would require about an 8C rise in Greenland for example, see https://www.nbi.ku.dk/english/news/news13/greenland-ice-cores-reveal-warm-climate-of-the-past/

While his conclusion that *"However, it seems more appropriate to view the system as having multiple tipping points and thresholds that range in importance and scale from the smallest ecosystem to the size of the planet."* is essentially true, the planetary scale effects are not part of any feedback loop of warming → something → more warming. All his examples are warming → something → more of that → possible planetary effect not involving warming. His best example is the loss of the Greenland ice sheet. That's not a planetary positive feedback although there are local positive feedbacks involved, mostly ice loss leading to more ice loss. We must distinguish between impossible global tipping points (e.g. earth becomes Venus) and tipping points with global effects (e.g. loss of the Greenland ice sheet). Those effects if they manifest will be easily mitigated in century timescales. It would be interesting to hear his thoughts about methane hydrates.

2.4. Economic Impacts

In Cost Of Disasters Is Falling–Roger Pielke Jr we see a drop in weather disaster costs as a percent of GDP, with some variability:

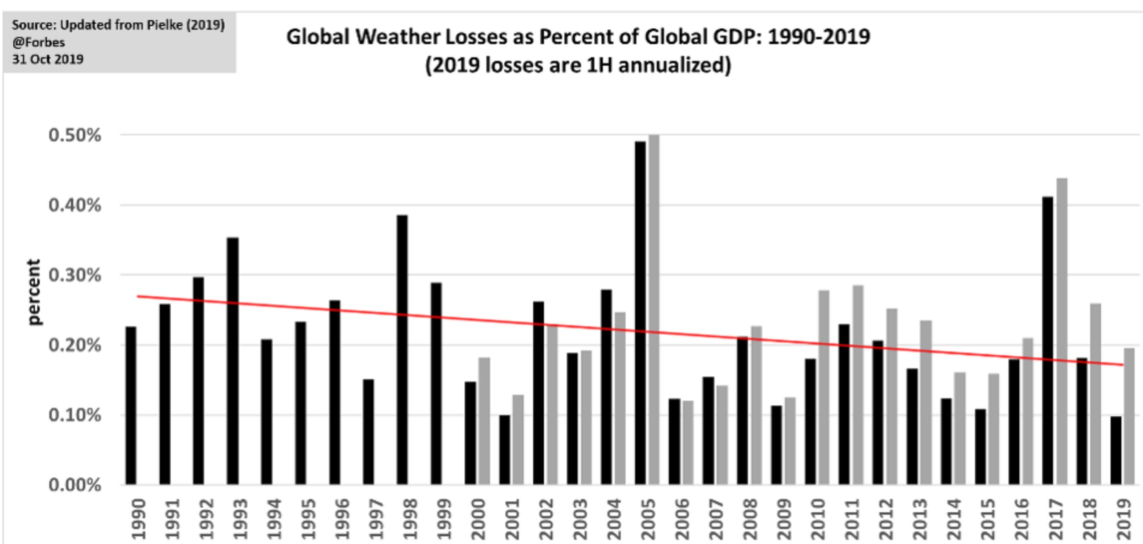


Figure 54 - Global weather and climate-related disaster losses as a percent of global GDP, 1990 to 2019. (R. Pielke Jr.) from "Not a Lot of People Know That" by Paul Homewood

In 2013 Roger Pielke, Jr testified about the economic consequences and trends in weather events (Pielke, 2013). His main conclusions were:

- *Globally, weather-related losses ($) have not increased since 1990 as a proportion of GDP (they have actually decreased by about 25%) and insured catastrophe losses have not increased as a proportion of GDP since 1960.*
- *Hurricane landfalls have not increased in the US in frequency, intensity or normalized damage since at least 1900. The same holds for tropical cyclones globally since at least 1970 (when data allows for a global perspective).*
- *Floods have not increased in the US in frequency or intensity since at least 1950. Flood losses as a percentage of US GDP have dropped by about 75% since 1940.*
- *Tornadoes in the US have not increased in frequency, intensity or normalized damage since 1950, and there is some evidence to suggest that they have actually declined.*
- *Drought has "for the most part, become shorter, less frequent, and cover a smaller portion of the U. S. over the last century." Globally, "there has been little change in drought over the past 60 years."*

Pielke's most-cited work is (Pielke, 2008) in which the authors determine the economic damage from past hurricanes, normalizing for both increases in wealth and increases in population and housing units. This allows a more precise comparison of past and recent hurricanes for which they find no trend in losses. His approach has been adopted by many scientists. Some find increased losses (Miller, 2008) without a significant trend considering the high amount of natural variability. The general conclusion in 2008 was it was too soon to detect a trend.

In a meta-study of normalization methods (Bouwer, 2011) the conclusion is "*The analysis of 22 disaster loss studies shows that economic losses from various weather-related natural hazards, such as storms, tropical cyclones, floods, and small-scale weather events (e.g., wildfires and hailstorms), have increased around the globe. The studies show no trends in losses, corrected for changes (increases) in population and capital at risk, that could be attributed to anthropogenic climate change*." The table in the paper lists various results showing no trend while some showing increasing trends.

A modern version of the hurricane normalization paper includes Hurricane Harvey in 2017 (Weinkle, 2017) which was a "top ten normalized damage" hurricane, the second in this decade after Sandy in 2012. The current decade is the only decade with two hurricanes in the top ten. The authors find no trend in economic damages. They state this is consistent with the finding of no trend in hurricane landfalls from a separate study (Klotzbach, 2018):

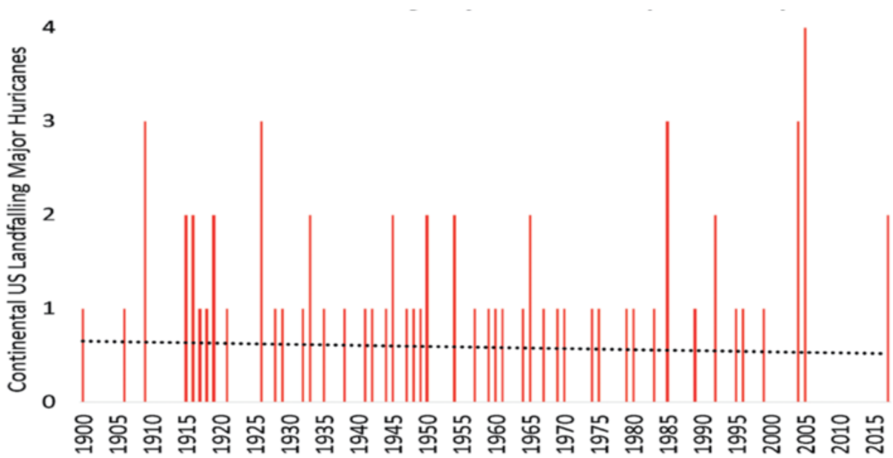


Figure 55 - Continental US landfalling hurricanes 1900-2017 from (Klotzbach, 2018)

Note the peaks in 2004 and 2005, followed by the long (longest ever) gap in major hurricane landfalls from 2005 to 2017. This is evidence of a large variance in the annual probability of catastrophic weather events like major hurricane landfalls which makes it difficult to discern trends over the relatively short time period of more rapid warming from around 1980 to present. As discussed earlier, this is true for many types of rare weather events. The gap may also be evidence for "fewer but stronger".

PREDICTIONS: Although this white paper tries to avoid global warming predictions, there are some simple facts that should be considered. There is 80,000 TW of solar power absorbed by the earth's surface. There is 40,000 TW of latent heat transfer to the upper atmosphere from the water cycle. A typical hurricane releases 600 TW of heat to the upper atmosphere (Landsea, 2014) https://www.aoml.noaa.gov/hrd/tcfaq/D7.html and some portion of that heat is radiated to space around the storm or in higher latitudes. Changes in weather particularly storms may change the energy flux in the future. For example an increase in hurricanes or equivalent concentrated convection could offset some of the energy flux from manmade CO2. A comparison of manmade CO2 to other energy fluxes is shown below:

Source	Power (TW)	Direction	Variability
The sun	80,000	down	about 0.1% over decades
latent heat	40,000	up	depends on average weather
typical hurricane	600	up	-
current manmade CO2	900	down	rising almost 1% per year
560 ppm of CO2 ~2060	2000	down	likely rising 2% per year in 2060
loss of Arctic sea ice	105	down	likely rising to 150 TW

A partial critique of Pielke can be found in (Neumayer, 2011). While they generally agree with Pielke's conclusions, they point out "*Unfortunately, it is impossible to adequately account for measures such as improved early warning systems, better building qualities, heightened flood defences etc. It is therefore impossible to say whether one would see an increasing trend in normalized natural disaster damages in the absence of such measures.*" Their analysis shows a variety of change including increases in the losses from some types of disasters in some locations, including a large difference between developing and developed countries. Developed countries show a much sharper decrease in disaster losses over time than developing countries which supports their theory that mitigation and adaptation help lower losses.

Hurricane Damage. Like other weather-related costs, hurricane damage costs are increasing, but the vast majority of that increase is from the increase in insured value given the large variations in financial exposure (e.g. Miami versus less inhabited Florida coastline). The increase in the amount of property to be damaged and the increase in the value of that property result in an increase in hurricane damage costs.

The (Schinnerer Group, 2019) created an estimator to determine what any past hurricane would cost today. By that measure, the most expensive hurricane of all time is the 1926 Miami hurricane.

Name	Date	R	Current Damage $2019	Base Damage	
Great Miami	Sep 18,1926	1	242,750,000,000	76,000,000	FL
Galveston	Sep 08,1900	2	171,510,000,000	30,000,000	TX
Katrina	Aug 29,2005	3	148,240,000,000	125,000,000,000	LA
Harvey	Aug 25,2017	4	132,690,000,000	125,000,000,000	TX
Galveston	Aug 17,1915	5	121,200,000,000	50,000,000	TX
Andrew	Aug 24,1992	6	87,220,000,000	24,000,000,000	FL
Sandy	Oct 29,2012	7	80,090,000,000	65,000,000,000	NY
#11 in 1944	Oct 19,1944	8	78,840,000,000	63,000,000	FL
Donna	Sep 10,1960	9	73,410,000,000	300,000,000	FL
Okeechobee	Sep 16,1928	10	63,830,000,000	25,000,000	FL

1926 is also interesting because the same hurricane that caused the most economic damage in US history was one of three to greatly damage the Bahamas as noted previously.

Flood Damage. As discussed previously, any increase in flooding rains have been easily mitigated by better flood control and forecasting. We also noted the widespread increases in US precipitation. There is a global increase in rainfall:

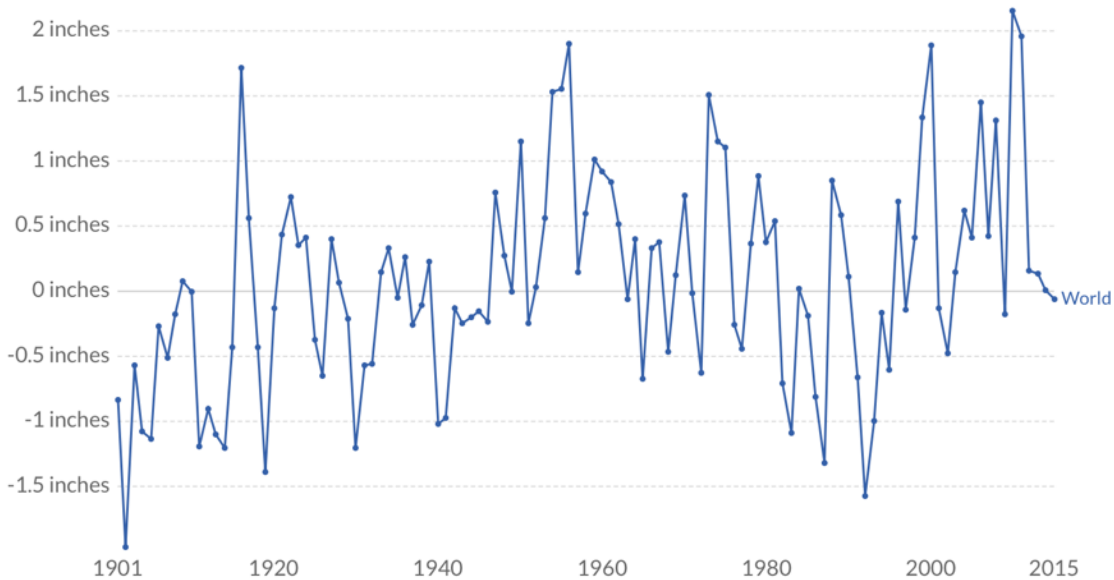


Figure 56 - Global precipitation anomaly from https://ourworldindata.org/natural-disasters

The increase has a lot of natural variation and is very unlikely to be evenly distributed. The result is predicted to be more flooding (Wobus, 2013). But when normalized for exposure, flood damage is generally flat, e.g.: http://rogerpielkejr.blogspot.com/2014/08/new-uk-flood-normalization.html and for the US at http://www.flooddamagedata.org/full_report.html (Pielke, 2002) where flood damage shows a decline compared to wealth.

Storm Surge Damage. The lesson of Sandy and New York City is almost universally unknown. It is that the expenditure of about $6 billion (Padron, 2009) plus a few billion more for the upper east river and smaller areas could have greatly reduced the almost $20 billion in damage from Sandy. The $6 billion price tag included a causeway that could recoup that expenditure over time with tolls. There are many complications in pursuing such a project, the barrier has to keep surges out, but also let flood waters out. It has to constantly allow water circulation. More barriers would be needed like the small one currently protecting Stamford CT. But such barriers are needed regardless of sea level rise and hurricane strength. Surge barriers can be sized for realistic sea level rise over the life of the barrier.

3. Solutions

There is an obvious solution to the rise of CO_2: don't burn fossil fuel. We are transitioning to renewables, but it requires a lot of capital investment that is clearly not available where it matters most, in the developing world. One might reasonably ask why we would reduce our more efficient uses of fossil fuel here in the developed world, or even sequester carbon here, while fossil fuel is still being removed from the ground in increasingly greater quantities in the developing world and used inefficiently.

It is clear to me that to support transition to non-fossil sources, especially in the developing world, we need an alternative to fossil with the same energy density, storage, and transportability characteristics of fossil fuel. That will require investment in R&D and the infrastructure for fuels and electricity in proportions that make sense for the developing world.

Here in the developed world, we can obtain financing for renewables by ensuring the profitability of the renewable energy investment, for example with net metering. That will provide a gradual transition for developed countries, and developed countries must continue research and development. But the largest payoff from a global perspective is funding the R&D that will produce long lasting solutions with several viable solar fuel types with a few decades.

Current renewables are nominally carbon neutral but require fossil fueled maintenance and have a limited lifespan. It is possible to have solutions that are more carbon neutral (efficient extraction and use of ambient CO_2) and carbon negative (extraction of ambient CO_2 with sequestration). One possibility is "solar fuels", producing fuel by extracting carbon from atmosphere, provide the needed energy density, storage and transportability. Those fuels can be used in carbon neutral applications like heating, cooking, or transportation. They can be used in carbon negative applications like electricity production with capture and sequestration of power plant emissions. Those fuels can eventually simply be sequestered when resources are available to do that. We also need innovations to capture and use carbon in solid form. We will need as many incentives as possible to sequester carbon.

Most importantly, we need to address the entire CO_2 problem with a global, free market, and technology progress perspective. A switch to renewables in one location (e.g. offshore wind here in Virginia) is a very expensive way to reduce CO_2 emissions compared to preventing even a single new coal electric plant in the developing world. There are few political or economic incentives for in installing those same renewables in the developing world. Instead, in my opinion, we need a global approach to a technology like solar fuel farming (instead of biofuel) to meet people's immediate energy needs with an eye towards sequestration in the longer term.

Here's what happens when you bypass the free market: *"An irate California Gov. Gavin Newsom signed an emergency proclamation Sunday allowing some energy users and utilities to tap backup energy sources. Newsom acknowledged Monday that the state failed to predict and plan for the energy shortages… In California, the Energy Commission forecasts how much energy the state will need and the PUC focuses on procuring it, the governor said."* https://www.washingtonpost.com/business/california-governor-demands-probe-of-power-blackouts/2020/08/17/40867de6-e0b2-11ea-82d8-5e55d47e90ca_story.html Government control is not the right approach, particularly not government control which bans the production of electricity from available sources even when extra electricity is critical.

Finally, we need to also invest in weather event mitigation whether or not global warming makes weather worse.

3.1. Renewable Energy

Once a fossil fuel electricity plant is built, fossil fuel extraction is very productive when measured by electricity production due to the dense power available from the fuel, the ability to generator on demand, and the transportability of the fuel. As a simple example compare coal mining versus rooftop solar (note that large solar installations would have higher productivity).

Work	Product of an hour of work	Electricity produced in one hour
Coal mining	10 short tons coal (1)	19,270 kWh
Solar installation	5 installed panels	0.228 kWh (2,000 kWh per year) (2)

(1) from https://www.eia.gov/totalenergy/data/annual/showtext.php?t=ptb0707; (2) Based on Virginia where 400 kWh is produced per year per 250W panel

Crucially, the panels keep producing electricity for decades (hundreds of thousands of hours). My oldest large panel is still going strong after 15 years. In contrast, once that hours' worth of coal is burned the miner has to go back to work. Also, the coal miner productivity figure is for surface coal mining. An underground coal miner only produces 1/3 the coal per hour as shown in the EIA link above. In the simplest math, the panels recoup the labor hours in 10 years and only 3 years, 4 months compared to underground coal mining. Obviously, the claims of renewable energy being good for employment is a half-truth. Renewable power creates many manual, low productivity jobs by necessity.

To pay for that labor, renewables require financing: an investment in future power production. A large amount of financing would be needed to produce the same amount of power in the short term. But smaller amounts of financing can be created by guaranteeing that people installing small scale renewables like solar can sell their electricity at the full retail rate that they pay for power. That is called net metering.

Here in Virginia, the law requires net metering for small distributed generation sources: https://www.deq.virginia.gov/Programs/PollutionPrevention/VirginiaInformationSourceforEnergy/DistributedGeneration/NetM/ etering.aspx In the summer a typical rooftop solar system will produce more power than is needed by that homeowner for AC. The extra power is purchased at the retail rate (net metering) and sold at the retail rate to neighboring customers where it mostly coincides with demand on hot sunny days.

There is still a demand for power before and after peak solar. That peak demand power is generally met with natural gas. The Virginia law includes small wind and hydropower which may be able to even out the supply. There is also a need to maintain the grid so everyone should pay a grid maintenance fee even if they are net zero power consumers.

Other countries go further and add fees to their power bills. Those costs mainly fall on residential power customer since business customers with large power demands can create their own cheaper supply if they want to. In my part of Virginia large business customers have the freedom to leave my non-profit wholesale power provider but so far only one has left. ODEC and the state of Virginia recently gave resident coop members the choice of adding community solar to our power mix https://www.odec.com/wp-content/uploads/15Aug18ODEC-Community-Solar-Pilot-Programs.pdf Today, July 13, 2019 I just added one solar block of community solar https://www.myrec.coop/res/save-energy/sunshare.cfm called "cooperative sunshare" to my electric bill which will take effect with my next bill. I will pay for my block using the savings from my demand reduction incentive payment which is described next. I don't want grid-tied solar installed on my roof mainly because I don't want to punch holes in my roof to mount the panels. I have five panels on my roof[3] connected to lead-acid batteries in the crawl space, but those are mounted on free-standing pressure-treated lumber at the crest of the roof. I also don't want to burden my fellow coop ratepayers with my unreliable solar power that they must buy from me at full retail price. The sunshare voluntary plan lets me help to finance the utility-run solar which better suits my needs.

Controlling Demand. In August of 2016 I signed up for the peak demand reduction program: https://www.myrec.coop/res/save-energy/ac-switch-program.cfm. In this program I get a $6 credit in each of the three summer months plus September in exchange for allowing my coop to throttle my air conditioner during peak demand periods. While my AC is mostly off in the summer, and turned on mainly to dehumidify during humid periods, there are numerous times when my thermostat can reach the low 80's AC setting on a sunny, hot afternoon and my AC will turn on. In those cases, my coop can throttle my AC if they need to reduce demand. That throttling does not save much electricity but it saves the coop money and enables a greater use of intermittent renewables. I and fellow ratepayers in this program reduce overall emissions overall by reducing peak demand across our grid.

Germany. Germany is a good example of a large public investment in renewable energy. Their average electric rate is twice what I pay and about 1/3 of the cost of electricity is a long term investment to subsidize the startup costs of renewables. Germany fills their peak summer demand shown below with a combination of wind and solar on top of the base provided by nuclear, biomass and hydro. Coal is throttled. Gas and pumped storage are used to fill the demand when wind and solar don't provide power as shown below:

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[3] Most of my 16 panels are mounted on sheds or on framing just above the ground

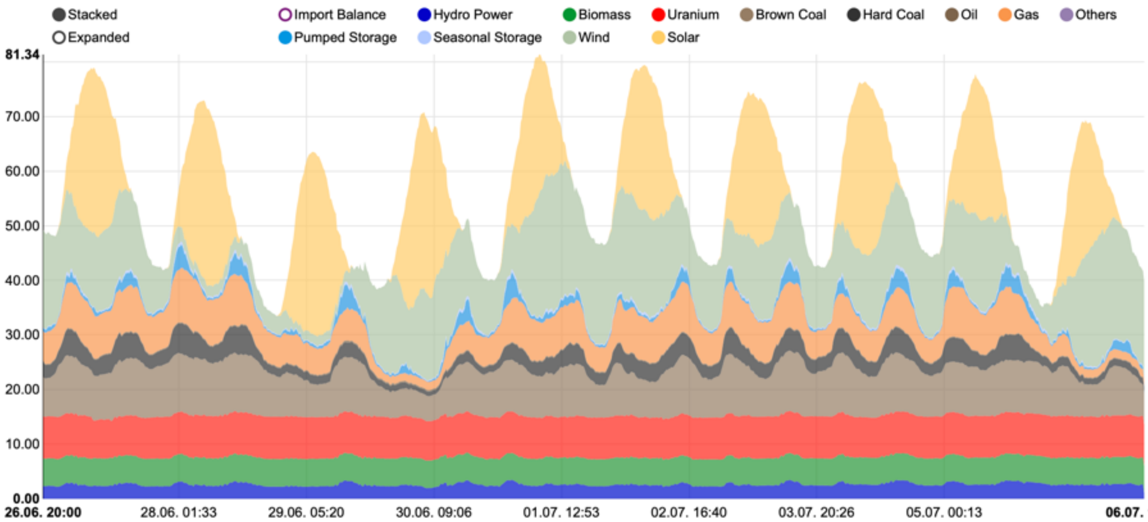

Figure 57 - German energy production from https://www.energy-charts.de/power.htm?source=all-sources

All of Germany's renewables are subsidized with the largest subsidies going to the smallest providers. Germans pay about 30 cents per kWh for electricity:

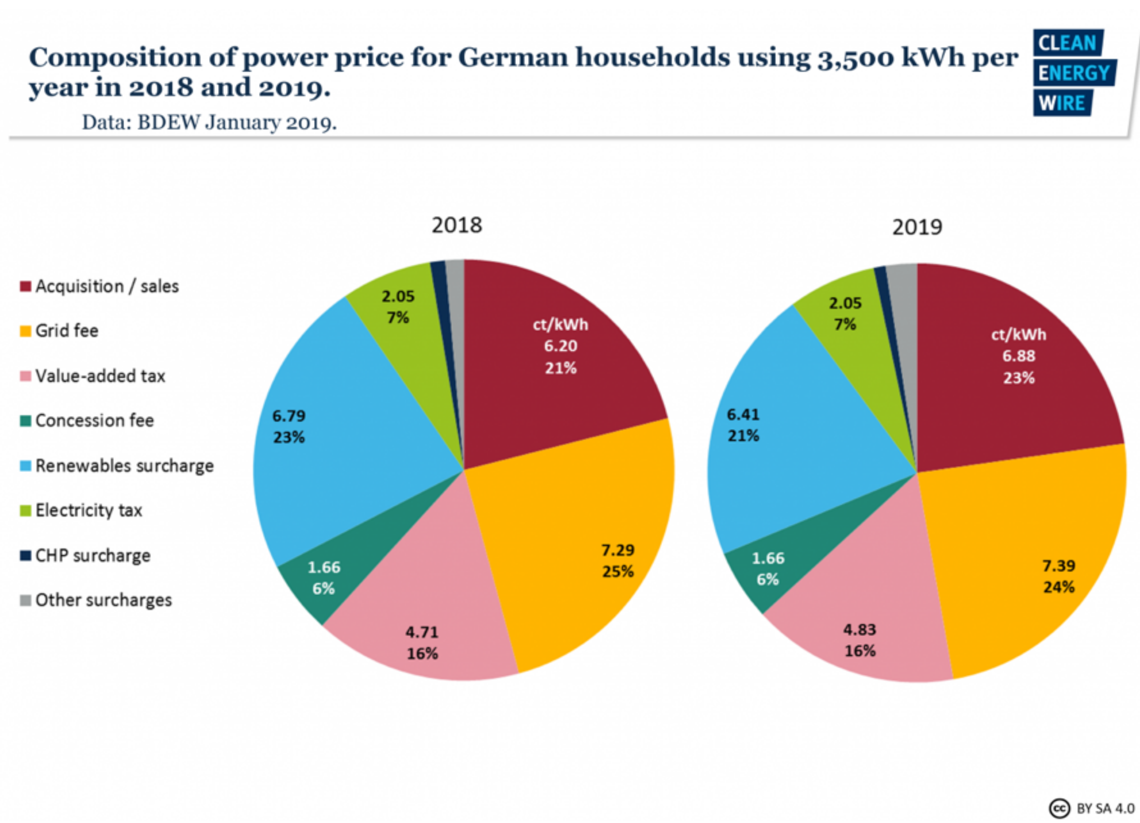

Figure 58 - From https://www.cleanenergywire.org/factsheets/what-german-households-pay-power

I compare their costs to what I pay below, all costs in cents/kWh:

Location	Acquisition	Grid	Renewables	other	Tax/fee	Total	% renewables
Virginia	6.3	7.5	0.2	0	0.8	14.8	6%
Germany	6.38	7.39	6.41	1.5	8.54	30.22	40% (1)
UK (2)	6.38	4.85	3.32	3.56	0.91	19.04	28%

(1) https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts
(40% is up from 35% in 2018 in the first version of this paper. As of August 2020, the first half of 2020 shows 48.7% renewables at that link)
(2) https://www.ofgem.gov.uk/data-portal/breakdown-electricity-bill & $73/month for 4,600 kWh/yr

The rightmost column in the table shows how much power is being produced using renewable sources in each jurisdiction. My 6% number comes from ODEC. My renewable cost of 0.2 cents in the table above includes the cooperative sunshare which I signed up for in August 2019, adding about $1 to my bill each month. I am now up to $5.33 extra a month on my latest bill. To Americans, you have to keep in mind that there is a need for a large investment to increase the share of renewable energy. Somebody has to pay extra for that.

Forcing ratepayers to subsidize startup costs like Germany is one way to do it. In the UK the large renewable suppliers submit sealed bids and the government-owned Low Carbon Contracts Company grants the winning bidder a contract for a 15-year price floor for the renewable. They pay for the contracts using the Interim Rate Levy. It's called Contracts for Difference https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference but it's really just a price floor allowing the renewables developer to recoup their investment. The latest sealed bid may indicate that offshore wind may have very little need for the subsidy. I have not seen a copy of the contract but it apparently contains a price inflator. Also, the Swedish company Vattenfall announced they won the bid for Dutch renewable energy https://group.vattenfall.com/press-and-media/news--press-releases/pressreleases/2019/vattenfall-wins-tender-for-dutch-offshore-wind-power and will be non-subsidized. Part of the reason is that corporate electricity customers have their own backup power. I'm not sure residential power would be non-subsidized, but we will find out in the UK over the next few years.

<u>COST TO OFFSET ONE NEW COAL PLANT</u>

I believe a more realistic price is $100 per MWh for offshore based on the higher maintenance costs and shorter lifespan. Based on that cost and assuming we shut down our coal plants producing a tonne of CO2 per MWh, the cost per tonne of CO2 reduction (assuming offshore wind results in no CO2) is also $100. If we assume India operates a 1,000 MW coal plant for 30 years, that would produce 129 Mt of CO2 for 158 million MWh of electricity at their 60% capacity factor.

To offset that CO2 production we would need to spend $12.9 billion on offshore wind minus the savings of shutting down our own coal plants.

Assuming the coal power we are replacing costs $60/MWh (we have a higher capacity factor), the 129 million MWh would have cost $7.74 billion. We will be spending an extra $5 billion, and only offsetting the CO2 from a single new coal plant.

In addition to Contracts for Differences for actual energy, it's possible to contract for completely virtual renewable energy. In (GEFA, Georgia) there's the claim that "... *it is possible to bring in wind energy via the transmission network from windy areas of the Midwest and Great Plains.*" That claim is completely false. Then they claim that "*...as a result, on January 1, 2016, Georgia Power started receiving energy from the Blue Canyon wind farm in Oklahoma.*" That is also false.

The agreement is explained in an EPA slide presentation. Georgia Power buys generated power from the Blue Canyon company which sells that same power into the wholesale market and sends the proceeds to Georgia Power. There is no transfer of any power from Oklahoma to Georgia, not directly, and not indirectly. While virtual renewable energy purchase agreements may be a helpful market incentive, they have some challenges, mainly additional financial complexity. They are imperfect hedges compared to commodity futures markets because they add regulatory and counterparty risks on top of the price and production risks that are handled by the futures markets.

Solar fuel often referred to as artificial photosynthesis is a carbon neutral solution to energy transmission and storage. Some solar fuels are created using photovoltaic electricity while others are photochemical (Nielander, 2015). Although that paper is general to all fuel types, one of the original solar fuels is hydrogen. While hydrogen is a good fuel, hydrocarbon fuels are preferred for our purposes provided the carbon is extracted from the atmosphere.

No matter the process, very large solar fuel farms will be needed to convert ambient CO2 and water into liquid solar fuel using sunlight as the energy source, although wind or any other electricity source can be used as well with a hydrogen based process. Ultimately solar fuel will be transmitted through pipelines and then used for heating or transportation fuel. The advantage is the energy can be released when and where needed solving the storage problem. That reduces the expense and environmental impact of electric vehicle batteries and allowing renewable home and office heating without the need for electricity which is not available on calm, cold winter nights. More research is needed to improve and scale the technology.

Biofuel has the same storage and distribution advantages as solar fuel. Biofuels are created from plants, which are grown by farmers and then processed into liquid fuels. The farmers and particularly the processors form a powerful political constituency and have succeeded in getting mandated use of biofuel whether they are an overall benefit or not. There's no doubt that economic incentives will improve the efficiency of the growing and processing of biofuels. Also energy return on energy invested is dropping for all types of energy thereby making some biofuels more competitive and sustainable. Obviously more research is warranted.

On the other hand, the mandates and artificial ("green") incentives have created environmental disincentives in some cases. Examples of negative consequences include air pollution, net energy loss, aquifer depletion, rainforest destruction (Reitze, 2015). Advanced biofuels discussed in that paper are defined as producing a portion (e.g. 50% to 60%) of the greenhouse gases produced by the fuels (e.g. gasoline or diesel) they are replacing. The European use of palm-based biodiesel destroys rainforests and is polluting, but fortunately that fuel does not meet the 50% criteria for GHG emission in the US. The case of biofuel is a good argument for small research grants to perform more research instead of large-scale development, as explained next.

3.2. Research and Development

Capitalism will eventually mitigate the harmful effects of CO2, so it is ironic that the unpriced externality of atmospheric CO2 is an imperfection of capitalism. But capitalism funds the R&D needed for solutions, provides economic resilience, and creates higher living standards lead to lower birth rates. But how did R&D produce the solar panel and how will it produce future breakthroughs in renewables, carbon capture, etc?

In 1953 Bell Laboratories invented the silicon solar cell as described in (Perlin, 2004) available at https://www.nrel.gov/docs/fy04osti/33947.pdf leading to a practical cell demonstrated in April 1954. The other inventions leading to the solar cell are described in (APS, 2009) https://www.aps.org/publications/apsnews/200904/physicshistory.cfm which includes a description of the accidental discovery of the P-N junction at Bell Labs in 1940[4]. Russell Shoemaker Ohl's 1939 or 1940 discovery also led to the transistor (Guarnieri, 2017) https://www.research.unipd.it/retrieve/handle/11577/3257397/203442/30 70YearsTransistor.pdf The transistor is the basis of all solid state electronics and computers as described in that article.

The idea of profit-seeking driving innovation was dismissed in (Gertner, 2012) https://www.nytimes.com/2012/02/26/opinion/sunday/innovation-and-the-bell-labs-miracle.html Mr. Gertner, who wrote a book about Bell Labs, describes two "innovations" (using the word as a noun):

"*But what should our pursuit of innovation actually accomplish? By one definition, innovation is an important new product or process, deployed on a large scale and having a significant impact on society and the economy, that can do a job (as Mr. Kelly once put it) "better, or cheaper, or both." Regrettably, we now use the term to describe almost anything. It can describe a smartphone app or a social media tool; or it can describe the transistor or the blueprint for a cellphone system. The differences are immense. One type of innovation creates a handful of jobs and modest revenues; another, the type Mr. Kelly and his colleagues at Bell Labs repeatedly sought, creates millions of jobs and a long-lasting platform for society's wealth and well-being.*"

Mr. Gertner admits innovation needs to be used in its verb form: "*There's no single best way to innovate. Silicon Valley's methods have benefited our country well over the course of several decades. And it would be absurd to return to an era of big monopolies*." He seems to completely ignore that Facebook and Google are big monopolies. He misses the process of innovation in a single sentence: "*But to consider the legacy of Bell Labs is to see that we should not mistake small technological steps for huge technological leaps.*"

But the history of Bell Labs inventions shows that small, creative technological steps are what lead to huge technological leaps. Innovation is simply creative development, usually by small steps, sometimes resulting huge leaps by luck and persistence. Other than the app being software and transistor being hardware, there is no difference between creating an app and creating the transistor. There are many apps that are not innovative just as there were many non-innovative or failed projects at Bell Labs.

Mr. Gertner is unnecessarily harsh on Facebook and Google. Facebook has research laboratories https://research.fb.com/research-areas/ with artificial intelligence and other technology projects including one in which "*Our goals are ambitious, deliver internet connectivity to the more than 3.8 billion people who are not yet online.*" Both

[4] Other sources say 1939

Facebook's and Google's research emphasizes international academic cooperation sharing knowledge with academia. Google research is focused around AI https://ai.google/research but with more of a computer science focus. Much of the value of Google's research is from providing open source tools to software developers who are not academic but practical. They have greatly improved the productivity of tomorrow's innovators and everyone else who uses the tools.

Can the AI being researched by Facebook and Google solve the problem of overproduction of CO_2? No, but it can definitely help. AI enables the smart grid and smart cities allowing people to do more using less energy. Google also ran a project from 2007 to 2011 to lower the cost of renewables described in (Koningstein, 2014). See https://spectrum.ieee.org/energy/renewables/what-it-would-really-take-to-reverse-climate-change The authors appear to have the fatalistic assumption that "*... because CO_2 lingers in the atmosphere for more than a century, reducing emissions means only that less gas is being added to the existing problem*" we cannot reduce CO_2. But roughly 3% of excess CO_2 is absorbed by the ocean each year (but as described earlier we are adding well beyond the rate at which the ocean can keep up). The reduction of CO_2 will require new innovations to take CO_2 from the atmosphere and use it to build things. That kind of carbon capture would benefit from incentives such as charities making the technology free to the developing world. The big monopolies like Microsoft have created the needed amounts of money for their foundations.

The government can greatly help by funding basic research. There is currently research into materials, for example super-insulation; new ways to create and store energy such as solar fuels; and concentrator solar arrays with efficiencies over 50%. Government can provide the grants for the science and the scientists can collaborate with the research institutions. There will always be rent-seeking for boondoggles e.g. (Nader, 1979). See https://nader.org/1979/07/15/mob-psychology-makes-synfuel-boondoggle-hard-to-stop/ That's why government should stick with the basic R&D funded through a small grant process as is done by the NSF instead of competing with or being coopted by the market.

3.3. Mitigation and Resilience

As we see particularly with flash flooding, wildfire, and storm surge, tackling these problems is the same with or without any added effects from global warming. That is because the events are catastrophic regardless of global warming, and they are relatively easy to mitigate, conceptually, although with a cost for each type of mitigation. We need to make renewable energy sources more resilient, for example, the turbines and solar farms that were damaged or destroyed by Hurricane Maria in Puerto Rico.

One alternative is to rely on luck. For example, no major hurricanes hit the Florida panhandle since Opal in 1995 (115mph / 948 mb). Before that was Eloise 1976 (125 mph / 955 mb). Before those was 1917 and 1882 with similar strengths. But then came Michael in 2018 with 160 mph / 919 mb, the third lowest pressure on record for the US (NOAA, 2019). While Michael could have happened without global warming, there's little doubt it was more likely to happen with global warming. There's no question about the increased cost of stronger storms or the increased cost a hurricane-proof structure.

Figure 59 - The elevated house that the owners call the Sand Palace, on 36th Street in Mexico Beach, Fla., came through Hurricane Michael almost unscathed. (picture and caption from https://www.nytimes.com/2018/10/14/us/hurricane-michael-florida-mexico-beach-house.html)

It is quite possible for a hurricane-proof house to be destroyed by other less secure property or other debris, so even that boils down to luck, and the money gone to waste. But that "waste" would happen sooner or later without global warming.

From the evidence presented in this white paper, hurricanes appear to be the worst effect of global warming, although as we saw with Camille the destruction takes place in a relatively small area. There are not many predictions in this paper, as it mainly describes the past and current trends. Here's a prediction for hurricanes (GFDL, 2019) https://www.gfdl.noaa.gov/global-warming-and-hurricanes/ that essentially projects a continuation of the currently observed hurricane trends. It's not a good scenario, but it is manageable. As shown in the beginning of this section, the economic cost of all weather is rather trivial and dropping in general. With advanced technologies and increased resilience it will make little difference if a major hurricane hits a location every 10 years instead of every 100 years.

3.4. Some Ideas for Coming Decades

Indian architects have been designing advanced architecture for decades, such as the PDEC Buildings at Torrent Research Centre, cooled with reasonable comfort (Thomas, 2006) without AC. Their use of AC is not inevitable. But other potential uses of that same electricity include washers, dryers and electric ranges. Electricity is the common factor and it is inevitable. What is needed is a combination of improvements that enable better living without large increases in electricity demand as we have done here in the west. With a more modest demand for electricity India can avoid a large sunk cost in power plants. And with solar fuels they can ultimately bypass the need for fossil.

> To describe the challenge in stopping the rise of CO2, consider giving every household in India an air conditioner powered by coal-burning electric plants. That outcome is likely on our current trajectory. That would add 1.6 Gt of CO2 to the atmosphere per year, or in the table above, increase downward power by an extra 0.44 TW each year (0.44 the first, 0.88 the second year, 1.32 the third year, etc). That inexorably adds to the 900 TW described in the predictions table considering that the CO2 will be increased for several decades of the life of the coal plants.

Three billion people worldwide use indoor cook fires with numerous harmful effects described in a paper (Mobarak, 2012) focusing on rural Bangladesh. Despite the numerous negative effects of the use of traditional indoor biomass cookstoves listed in the paper, South Asians in particular continue to use them. As mentioned in the paper, the Chinese improved the biomass stoves in their country, greatly reducing the health hazards. But there are cooking techniques that don't require electric cooking. The use of solar stoves may be possible with cultural shifts that upgrade wealth and status due to better meals being produced with such stoves. But that transition is very slow and difficult as the paper points out. Ultimately the most promising approach in my view is using solar fuel for clean, carbon-neutral cooking meeting the demand, noted in the paper, for fast cooking.

Solar fuel farming makes sense in the many of the locations where the world's poor are in dire need of increases in living standards. The long term result will be lower birth rates and what this paper shows is that only the long term is important. Solar fuel solves the storage problem so the energy meets demand. Solar fuel solves the energy transport problem with pipelines analogous to electric transmission lines, but also fuel distributed with trucks. Solar fuel produces high heat for rapid, carbon-neutral cooking and heating.

In a previous example we show that spending an extra $5 billion on offshore wind to replace some of our coal generation, would be offset, in terms of CO2 emissions, by a single new coal plant in India. The example assumes we are shutting down extremely inefficient generation here (1 tonne of CO2 per MWh of electricity) and replacing it with CO2-free offshore wind. Those are both idealistic assumptions, the actual CO2 reductions will be less and thus the extra cost will be higher. On the other hand the Indian plants may improve their average efficiency and capacity factor.

From an economics standpoint, it makes very little sense to spend $5 billion on CO2 reduction here while India simply offsets that with one new coal plant. From a political standpoint, it would be very difficult to instead spend that $5 billion on renewables in India that would preempt the building of the coal plant. Technology development is the middle ground that will benefit all of humanity.

The Hydrogen Economy. The hydrogen economy became a popular idea in the 1990's and 2000's due to the factors mentioned above: storage, transportability and high energy density. Hydrogen can be created a variety of ways including coal gasification, methane reforming, electrolysis using nuclear or renewables, and photocatalysis directly from sunlight and water (Sahaym, 2008). The biggest challenge for hydrogen is storage and the paper describes storage using nanomaterials. The paper listed a target of 3 kWh per kg by 2015 with a cost equivalent to $1.50 per gallon of gasoline. By 2012 the Department of Energy had achieved only 1.7 kWh per kg and lowered the final target to 2.5 (Stetson, 2012). The latest targets are listed in Hydrogen Storage (DoE) as 1.5 kWh/kg and the equivalent of $4 per gallon of gasoline.

Because hydrogen gas is so light, it is often promoted as providing 3 times more energy per kg than gasoline, see Hydrogen and Fuel Cells Overview But the energy per mass goal has been lowered over time. The fuel cell and refueling technology is relatively expensive and that cost does not appear to be dropping. I will always promote R&D as the most cost effective approach to reducing CO2 by far, even if only from breakthroughs by serendipity during the research process. But I would also encourage research into alternatives fuels to hydrogen that have a huge added long-term benefit: extraction of ambient CO2 from the atmosphere.

Semiconductor photocatalysis has a long history documented in (Serpone, 2012). As the authors note: "*The seminal short note published in Nature in 1972 by Fujishima and*

Honda3 demonstrated that water could be photolyzed electrochemically at an illuminated TiO_2 and dark Pt electrode combination to yield stoichiometric quantities of H_2 and O_2. What followed soon thereafter was a frenzied series of studies in search of the photocatalytic holy grail to produce H_2 fuel as part of the beginnings of the hydrogen economy, a result of the 1973 oil crisis." They discuss how the field specialized into environmental cleanup by the development of photocatalytic oxidizers to break down a wide variety of pollutants.

The authors focus on their own efforts to prove that catalysis actually takes place which is necessary for a practical implementation of water splitting. They point out the need for higher energy light, e.g. UV and the need for new materials that would use visible light. The point out the lack of better metal oxides, and the common use of water with added sacrificial electron donors and/or acceptors instead of pure water. In short more research is needed, China is doing a lot of it, and they may well discover a breakthrough. The goal is to create an efficient synthesis process that does not require high temperatures or pressures.

Synthetic Methane. An example of the synthesis of methane from ambient CO_2, sunlight and water is described in (Park, 2015). The authors note that the reduction of CO_2 commonly results in the nonselective production of carbon monoxide, formic acid, methanol and methane. While carbon monoxide and hydrogen gas produced by these processes can constitute a fuel ("water gas") it is undesirable due to its toxicity. The authors studied using isopropyl alcohol (isopropanol or IPA) as the electron donor and used a hybrid TiO_2/CdS catalyst. They note that some of the methane arises from CO_2 from oxidation of IPA. Some methane arises from hydrocarbon contaminants. Also the process produces some water gas. The authors did not attempt a practical implementation or provide a cost. Sulfide-based catalysts other than CdS have been proposed and tested including ZnS, SnS_2, CuS, and NiS (Lee, 2017).

Synthetic Methanol. The generation of synthetic methanol can start with hydrogen generation from any of the methods described above, although using fossil would be counterproductive since we want to eliminate the use of fossil. The current low cost of fossil natural gas, below $2.00 per MMBtu as of January 2020, makes synthetic methane or methanol non-competitive. In (Pearson, 2012) the authors describe a process that uses surplus renewable energy to create methanol to use as a transportable storage medium for that renewable energy as shown below:

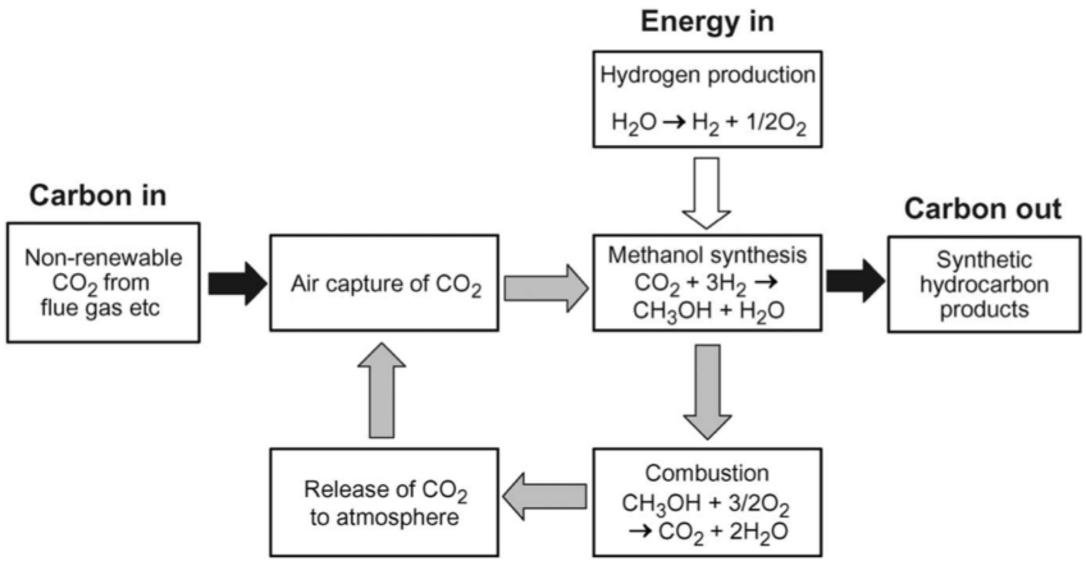

Figure 60 - Cycle for Carbon Neutral Fuel from (Pearson, 2012)

The cost of the process described in the paper is based on the cost of the hydrogen used to hydrogenate ambient CO2. The hydrogen would be generated by electrolysis and used to produce methanol and water as shown in the figure at cost of $7.50 to $9 / GJ for the hydrogen (capital cost only, the electricity assumed to be surplus and free). Assuming everything else is free, the cost for the methanol is roughly the same figure, about $8 per MMBtu or four times the current, historically low cost of fossil natural gas.

Biocatalytic Systems leverage microorganisms to convert CO2, a process that can leverage natural photosynthesis as currently performed in plants, algae and in particular bacteria. In one study available at http://nrs.harvard.edu/urn-3:HUL.InstRepos:27304973 (Liu, 2016) the authors refer to their work described in (Torella, 2015) producing hydrogen gas which they fed to R. eutropha bacteria which produced IPA, the potential electron donor for photocatalytic methane production described earlier. The reduction efficiency is 10% compared to about 1% for plants in natural conditions and 4 to 5% for plants and algae in bioreactors. They remove 180g of CO2 per kWh of electricity.

A coal electric plant will produce almost 1000g of CO2 per kWh of electricity. Clearly it would be more cost effective to replace coal-fired electricity with the solar PV used in that conversion system. In the US the electric power sector emitted 1.74 Gt of CO2 while generating 4 trillion kWh. That equates to 435 g of CO2 per kWh. Even if the CO2 reduction energy efficiency is improved closer to 100% from the current 50% the process will be less effective at reducing CO2 than simply not generating electricity with our current mix of sources. But at that point it will be close and the storage and transportability benefits will be complemented with simple appliances for cooking and heating, especially in the developing world where there are currently no power lines, heat exchangers, electric ranges, etc.

Regardless of advances in technology, the solar input is limited so large farms will be needed for solar fuel. Marginal farms or areas with no current uses can be converted to solar fuel farms. The main infrastructure is tubing and tanks to collect and store the fuel. Modularity will be key to ensuring that the parts of the infrastructure used for fuel collection can remain in place when new conversion cells using new technologies are inserted. That will also make it possible to return and recycle old cells containing hazardous materials like cadmium when the new cells are installed.

Sequestration is a necessary long term step to lower atmospheric CO2 to a level that prevents the worst effects of acidification and warming. At first that level will not be chosen, it will be based on opportunity. By 2100 we will have amazing new energy sources to apply to sequestration and we can determine a suitable target level. Between now and about 2050 we need to focus on research, and transition to renewables where they are cost effective. Between 2050 and 2100 there will be increasing opportunities for sequestration as cheap new energy sources and money/materials become available. The key is to be ready for that with hydrocarbon solar fuel pipelines that serve people's needs now and serve sequestration needs later.

While we do what we can in cost-effective manner to keep fossil fuel in the ground, we need to be investing in the methods to make solar fuel generation affordable to the rest of humanity. The three billion people who currently use indoor cook fires (also used for heating) will benefit and two million of their youngest children won't die every year. Then, in the ensuing decades we can buy their extra fuel and sequester it.

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Changelog

1.2 Fixed errors found in proofreading, added H+ suggestion

1.2.1 Fixed lots of broken links

1.3 Removed reference to Dorf 1959 who quoted Marmar 1948 as global sea level when it was not global. Added the Added more quotes from (GROISMAN, 2012) to point out the 40% rise in 6 inches per day events in the central US. Japanese stilt grass does not benefit from extra CO2.

1.3.1 Added material on ocean acidification, Holocene warming in Greenland, hurricane damage, climate refugees, solar fuel.

1.3.2 Changed calcium to calcium carbonate as limiting factor. Added Australian bushfire section. Updated the melomys extinction to include the July 2005 winter storm theory.

1.4 Added papers on the effect of pH on the growth rates of phytoplankton. Removed the 1930's US hottest decade claim, can't make that claim just based on heat waves. Replaced with state records link. Added coal plant offset example. Changed the focus of the last section to a global approach for carbon capture, reuse, and eventual sequestration.

1.5 Updated Germany renewables. Fixed dead links and removed others. Added latest Greenland data. Edited the 2019 Greenland result, was it slightly positive or close to 2012 (closer to zero)? Added the California government-run electricity screwup. Changed 1.25 inches per decade to 1.1 inches per decade sea level rise, by removing GIA adjustment to state the actual sea level rise on the ground, using latest UColorado estimate. Added Vautard 2020 analysis of the 2019 European heat wave. Added (Zhuang, 2006) and (Koven, 2011) as part of a discussion of high latitude carbon feedback. Added ref to Gavin Schmidt's realclimate post about tipping points. Added (Williams, 2020) in drought section.

1.5.1 Added SFGate article and Nature Sus study. Added the 2019 wind prediction study for Santa Ana winds and 2020 ERL that cited it.

1.5.2 Added references to CalVTP fire management and 2019-2020 progress.

TODO

Discuss Holland-2019