Section I: Climate science overview

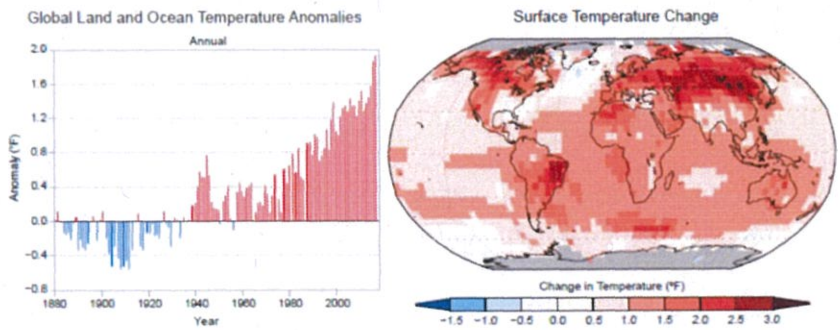
Our overview of climate science is framed through four statements:

1. **The climate is always changing; changes like those of the past half-century are common in the geologic record, driven by powerful natural phenomena**
2. **Human influences on the climate are a small (1%) perturbation to natural energy flows**
3. **It is not possible to tell how much of the modest recent warming can be ascribed to human influences**
4. **There have been no detrimental changes observed in the most salient climate variables and today's projections of future changes are highly uncertain**

We offer supporting evidence for each of these statements drawn almost exclusively from the Climate Science Special Report (CSSR) issued by the US government in November, 2017 or from the Fifth Assessment Report (AR5) issued in 2013-14 by the UN's Intergovernmental Panel on Climate Change or from the refereed primary literature.

1. The climate is always changing; changes like those of the past half-century are common in the geologic record, driven by powerful natural phenomena

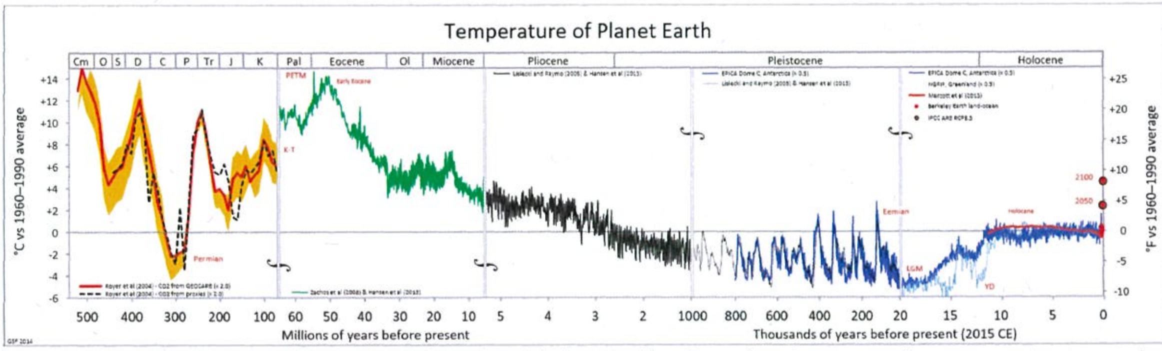
The graph below (CSSR Figure ES.1) shows the globe's warming during the past 130 years as measured directly by surface instruments. The left panel shows changes in the anomaly of the global surface temperature. The annual average temperature anomaly has increased by more than 1.6° F (0.9 C) for the period 1986–2015 relative to 1901–1960. [Red bars show temperatures that were above the 1901–1960 average, and blue bars indicate temperatures below the average.]



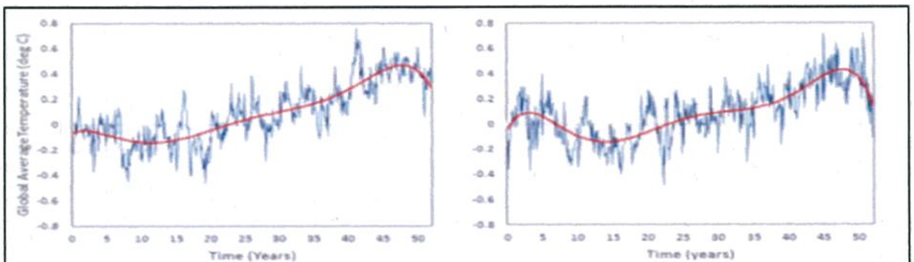
The CSSR's right hand map shows that the warming has been strongest over the land in the Northern Hemisphere and greater toward the pole. As can be found in other CSSR figures, there are other suggestions of modest warming in recent decades, including growing heat in the oceans, rising sea levels, shrinking Artic ice, shrinking glaciers, and a more humid atmosphere.

The story, however, is more complex than might be inferred from the figure. To a scientist looking at the left-hand panel, a few things stand out. First, there are no uncertainty bars, an unfortunately common practice in representations of climate change; it turns out that the uncertainties are 0.2F (0.1C) in recent decades, increasing to about twice that in the earliest parts of the record. Second, much of the seemingly alarming rise in the last few years is due to an El Nino condition, as was also present during the 1998 temperature spike. Finally, the rise in the temperature anomaly is not smooth on the few-decade scale. For example, it was actually decreasing from about 1940-1970. As human influences were significant only after about 1950, the graph suggests that the climate is quite capable of varying significantly on its own.

To buttress that point, consider the longer-term geologic record depicted schematically in the following figure, which shows more directly that the global temperature anomaly has changed dramatically over



the past 500 million years (only 10% of the earth's history!). There has been significant warming over the past 20,000 years (blue line) since the end of the last glaciation and 120,000 years ago there was an interglacial period (the Eemian) when it was the 2C warmer than today and the sea level was 6 meters higher. Over the past million years, there has been a succession of warm and cold periods driven largely by variations in the earth's orbit and orientation, with even larger temperature rises over the past 100 million years. The two red dots on the right show notional projected temperature rises at 2050 and 2100 due to human influences. We discuss the reliability of those projections below.



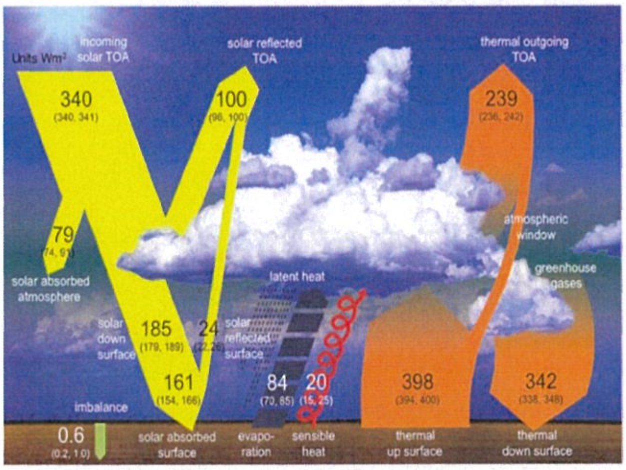
Temperature and time scales for the two time series are identical. One time series has been displaced vertically to give equal means over the 52-year warming period.

(HadCRUT3 Global Average Temperature Data Set)

Even within the instrumental record, the warming of the past four decades is not unusual, as illustrated in the adjacent figure, which compares two 50-year periods, one from the early 20th century where human influences were minimal, and one from the latter 20th century, where they were much stronger. It is difficult to tell them apart, as the rates and magnitudes of warming were comparable. [The left-hand panel is the more recent data showing the 1998 El Nino spike at year 42.]

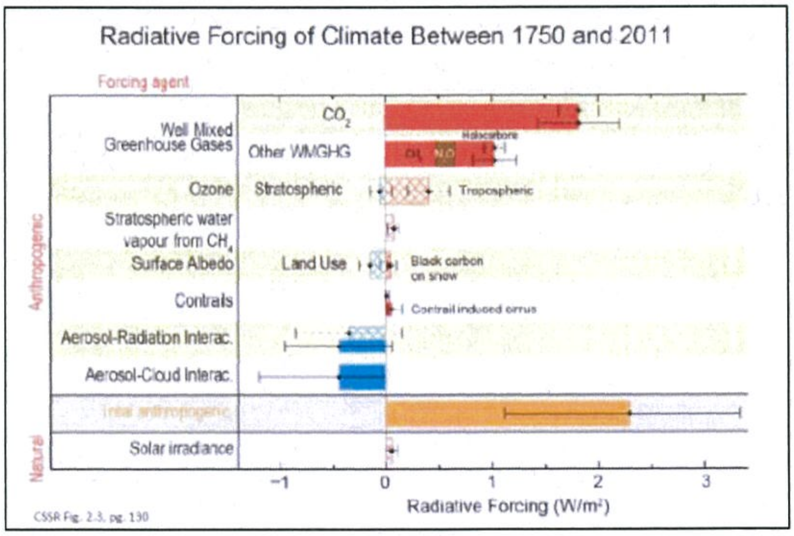
2. Human influences on the climate are a small (1%) perturbation to natural energy flows

To characterize and quantify human influences, we need to look at the energy flows in the climate system, as depicted in the following figure (CSSR Figure 2.1):



The earth's climate system is a giant heat engine, reflecting about 30% of the incoming sunlight, absorbing the rest, and then radiating an almost equal amount back into space as heat, driving the winds, precipitation, and ocean currents in the process. Note that the natural energy flows are measured in 100's of W/m² (Watts per square meter) and, as shown in the lower left-hand corner, there is a claimed net imbalance of 0.6 [0.2, 1.0] W/m² warming the planet.

The chart below (CSSR Figure 2.3) shows how human influences on the climate have grown since 1750. The units are W/m², commensurate with the energy flow graphic above. Carbon dioxide, which is accumulating in the atmosphere largely due to fossil fuel use, exerts the strongest warming influence, although small compared to the natural energy flows. Methane and other well-mixed greenhouse gases (WMGHG) are also important.

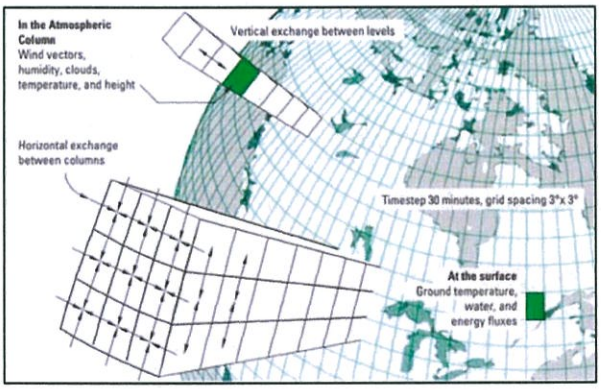


The largest anthropogenic cooling influences are associated with aerosols; they are quite uncertain. Changes in the solar irradiance over the past 250 years are shown to be negligible.

The bottom of the chart above shows that total human influence is currently some 2.3 W/m^2, or less than 1% of the natural energy flows in the system. Isolating and predicting the effects of such a physically small influence in a chaotic, noisy system where we have limited observations is not an easy task. Not only must we have the large parts of the system understood to high precision, but we also have to be sure we've accounted for all of the other phenomena operating at the 1% level.

3. It is not possible to tell how much of the modest recent warming can be ascribed to human influences

General Circulation Models (GCMs) of the climate system are important tools for attributing observed changes in the climate system. Here, the earth is covered with a 3-dimensional grid, typically 100 × 100 km in the atmosphere and 10 × 10 km oceans, with 10-20 vertical layers and up to 30 vertical layers, respectively. The air, water, momentum, and energy are transported through the grid boxes using the basic laws of physics under imposed forcings (e.g., the sun, aerosol loading) with a time step as small as 30 minutes. The results of computer runs extending over centuries are compared with both average and historical climate properties to validate the models.

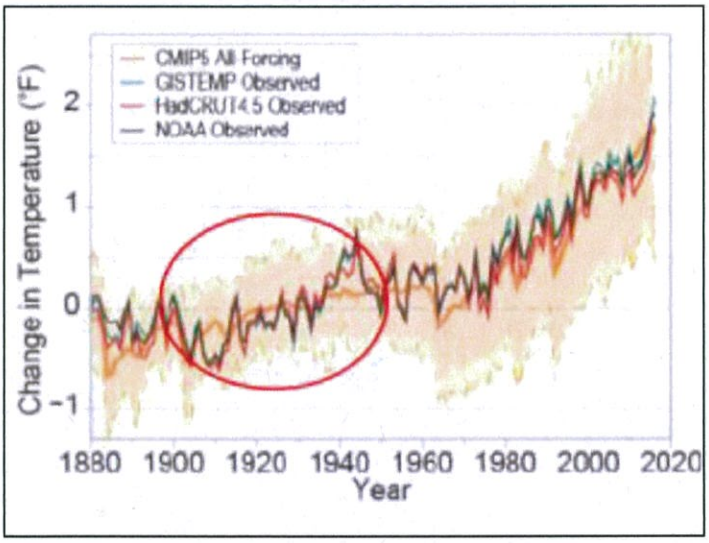


This sounds straightforward in principle, but it is in fact fraught with difficulty. One major challenge is that there are many important weather phenomena that occur on scales far smaller than the grid size (*e.g.,* topography, clouds, storms) and so the modeler must make assumptions about these "sub grid-scale" processes to build a complete model. For example, given the temperature and humidity profiles of the atmosphere in a grid box, "How high, how many, and of what type are the clouds?" While these sub-grid-scale parametrizations can be based upon observations of weather phenomena, there is still considerable judgment in their formulation. So the models are not, as one often hears, "just physics" since the parameters in each must be "tuned" to reproduce aspects of the observed climate.

A second major problem is that there is no unique tuning that reproduces the historical climate data. Since aerosol cooling plays against GHG warming, a model with low aerosol and GHG sensitivities can reproduce the data as well as a model with high sensitivities. As a result, the GHG sensitivity is today uncertain by a factor of three (as it has been for forty years), therefore enlarging the uncertainty in any projection of future climates.

A third problem is that the models must reproduce the natural variabilities of the climate system, which we've seen are comparable to the claimed anthropogenic changes. Climate data clearly show coherent behaviors on multi-annual, multi-decadal, and multi-centennial timescales, at least some of which are due to changes in ocean currents and the interaction between the ocean and the atmosphere. Not knowing the state of the ocean decades or centuries ago makes it difficult to correctly choose the model's starting point. And even if that were possible, there is no guarantee that the model will show the correct variability at the correct times.

Despite these problems, the IPCC pushes on, averaging model results over an indiscriminately assembled "ensemble of opportunity" comprised of some 50 different models from different research groups around the world. These models give results that differ dramatically both from each other and from observations on the scales required to measure the response to human influences. This proliferation of discordant models is further evidence that they are not "just physics".



This figure (CSSR Figure 3.1; red circle added) shows a comparison of observed global mean temperature anomalies from three observational datasets to results from the CMIP5 [Climate Model Intercomparison Project, version 5] model ensemble. The thick orange curve is the CMIP5 ensemble mean across 36 models while the orange shading and outer dashed lines depict the ± 2 standard deviation and absolute ranges of annual anomalies across all individual simulations of the 36 models. All time series are referenced to a 1901–1960 baseline value. Note in particular that while the model mean does a fair job of reproducing the record over the past few decades, it fails entirely during the time from 1910-1940 (red circle) where the data warm at a rate several times the model mean.

Similar data-model comparisons for other climate variables, both global and regional, also show their own problems. Indeed, as the CSSR states (pg 58) in discussing the role of human influences on the climate:

> *Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and particularly regional, scales, and especially for extreme events and our ability to observe these changes at sufficient resolution and to simulate and attribute such changes using climate models.*

4. There have been no detrimental changes observed in the most salient climate variables and today's projections of future changes are highly uncertain

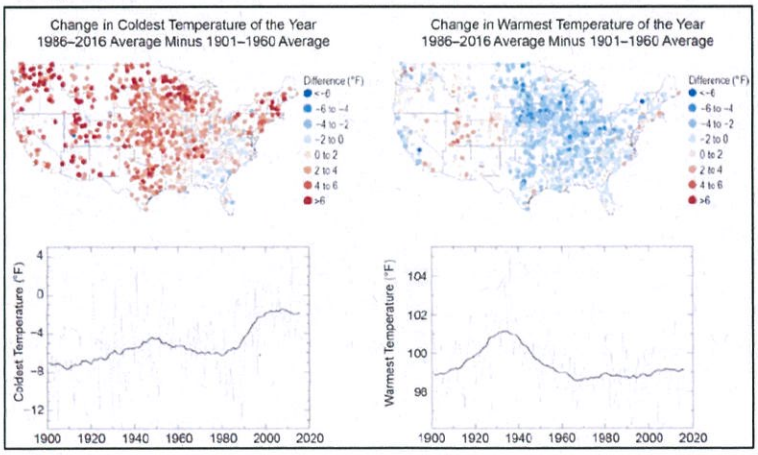
Here is what IPCC says about changes in various weather extremes observed over the past decades. These bullets do not constitute "cherry picking", as each is a modest paraphrase of the text summarizing the discussion in AR5 (WGI, Chapter 2) of a particular weather phenomenon.

- ...since about 1950 it is ***very likely*** that the **numbers of cold days and nights have decreased and the numbers of warm days and nights have increased** ... there is ***medium confidence*** that globally the length and frequency of **warm spells, including heat waves**, has increased since the middle of the 20th century

- ... ***likely*** that since 1951 **increases in the number of heavy precipitation events** in more regions than there have been decreases, but there are strong regional and subregional variations
- ... ***low confidence*** regarding the sign of trend **in** the magnitude and/or frequency of **floods** on a global scale.
- **...** ***low confidence*** in a global-scale trend in **drought or dryness** since the middle of the 20th century,
- **...*****low confidence*** in trends in **small-scale severe weather phenomena** such as hail and thunderstorms
- **...** ***low confidence*** in any **long term (centennial) increases in tropical cyclone activity,** ... ***virtually certain*** **increase** in the frequency and intensity of the **strongest tropical cyclones since the 1970s** in the North Atlantic.
- ... ***low confidence*** in large scale changes in the **intensity of extreme extratropical cyclones** since 1900

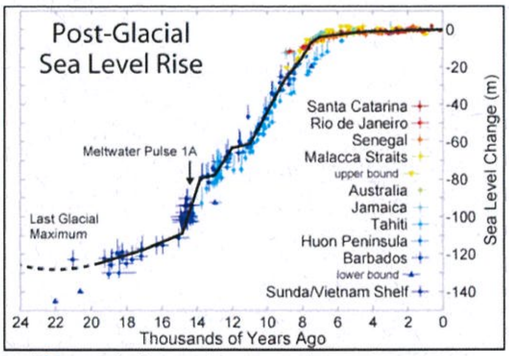
Contrary to the impression from most media reporting and political discussions, the historical data (and the IPCC assessment) do not convey any sense that weather extremes are becoming more common globally.

Heat waves: The most definitive of the IPCC statements on weather extremes concerns temperatures, and even here the story is not so simple. Consider the figure below (CSSR Figure 6.3) documenting temperature extremes in the US. [Even though the contiguous US is only 1.6% of the earth's surface, it is among the most densely instrumented regions and has one of the longest data records.]



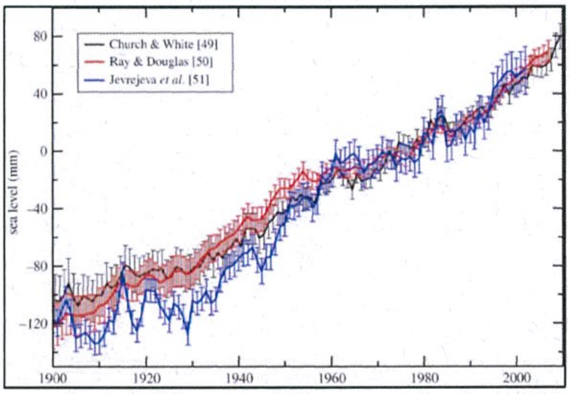
Caption: Observed changes in the coldest and warmest daily temperatures of the year in the contiguous United States. Maps (top) depict changes at stations; changes are the difference between the average for present-day (1986–2016) and the average for the first half of the last century (1901–1960). Time series (bottom) depict the area-weighted average for the contiguous United States. Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network – Daily dataset (Menne *et al.* 2012). (Figure source: NOAA/NCEI).

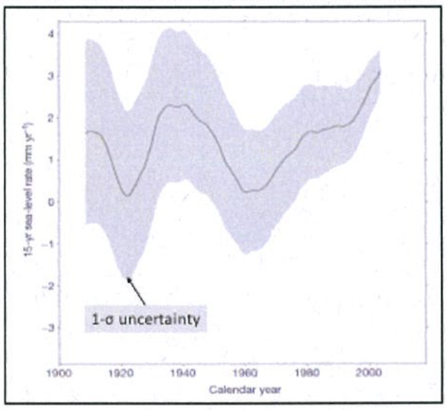
While the coldest temperatures have been rising, the warmest temperatures have not, and have actually gotten cooler over the eastern half of the country. Taken as a whole, the average climate is becoming "milder" across most of the United States. Very recent work attributes the lack of rising temperatures across the eastern half of the country to agricultural intensification: denser plant growth and rising CO_2 levels release more moisture, which both cools the air and increases the amount of rainfall.



Sea level rise: As shown in the adjacent chart, sea levels began rising some 20,000 years ago at the end of the last glacial maximum. They rose some 120 meters until about 7,000 years ago, after which the rate of rise slowed dramatically.

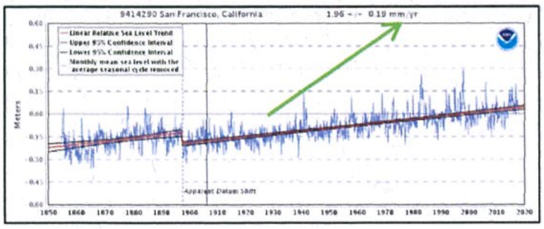
To best assess whether human influences are causing sea level rise to accelerate, we must look at the past century of data, which is available from tide gauges around the globe. Three analyses are shown in the left-hand figure below; these analyses must correct the raw data for the local rising or falling of the coast at each site. The data show that global sea level has risen by some 200 mm since 1900, or an average rate of 1.8 mm/yr, although with considerable decadal-scale variability. Sea level has also been measured by satellite altimetry since 1993; detection of acceleration in that short record remains controversial.



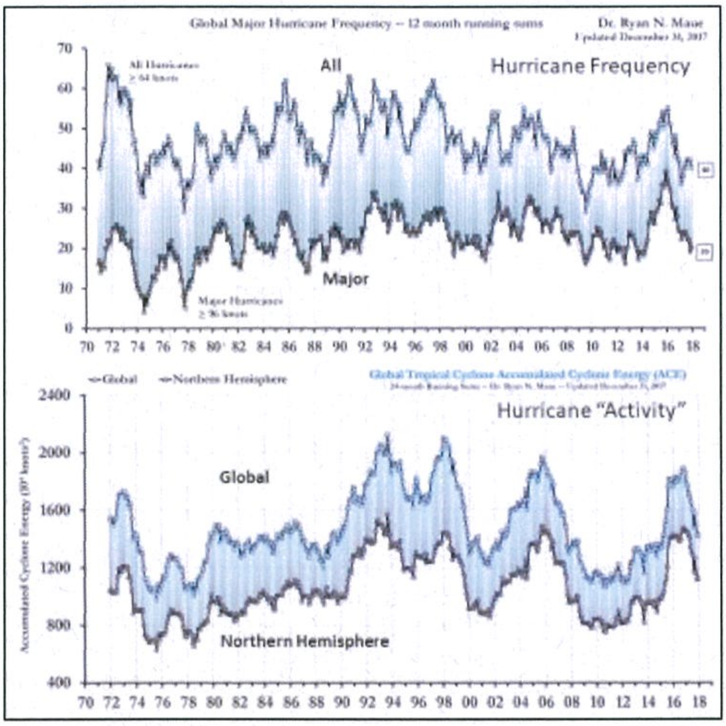


A signature of human impacts on sea level would be an increase in the rate of rise after about 1950, when human influences started to become significant. Such a signature is not evident in the rate over the past century, as shown in the right-hand figure above (adapted from the reference cited by the CSSR); in fact, the acceleration post-1990 is not statistically different from the (presumably natural) acceleration experienced during the 1930s. Given the observed variation prior to 1950 and the steady quadrupling of human influences since 1950, one must conclude there are other important drivers of sea level rise beyond CO_2.

Consensus projections of global sea level rise through 2100 are remarkably discordant with local observations. The figure below shows the NOAA record of monthly mean sea level (corrected for seasonal variation) as measured at the San Francisco station. Apart from obvious shifts due to station movement, the record shows a steady rise at some 2 mm/year. To realize a 1 meter rise by 2100, roughly the mean of IPCC projections, sea level would have to rise *six* times more rapidly (12 mm/yr) averaged over the rest of this century, a slope illustrated by the green arrow.



Tropical cyclones: Another weather phenomenon of concern are the storms termed "hurricanes" in the Atlantic and "typhoons" in the Pacific. The adjacent chart summarizes data on the number and strength of these storms, which include the recent active North Atlantic 2017 season (even so, hurricanes Harvey and Irma were not even among the Top 10 most intense recorded hurricanes). The upper figure shows 12-month running sums of the Global Hurricane Frequency (for all and for major storms). The top time series is the number of global tropical cyclones that reached at least hurricane-force (maximum lifetime wind speed exceeds 64-knots). The bottom time series is the number of global tropical cyclones that reached major hurricane strength (96-knots+).



The lower figure shows the last four decades of 24 month running sums of Global and Northern Hemisphere Accumulated Cyclone Energy (ACE). ACE is a measure of aggregate storm intensity (each storm is weighted by the square of its wind velocity). Note that the year indicated represents the value of ACE through the previous 24-months for the Northern Hemisphere (bottom line/gray boxes) and the entire global (top line/blue boxes). The area in between represents the Southern Hemisphere total ACE.

Despite considerable multi-year variability in these data, there is no clear trend. In fact, NOAA's Geophysical Fluid Dynamics Laboratory posted the following statement in Spring, 2016:

> *"It is premature to conclude that human activities–and particularly greenhouse gas emissions that cause global warming–have already had a detectable impact on Atlantic hurricane or global tropical cyclone activity. ..."*

Overview summary

To summarize this overview, the historical and geological record suggests recent changes in the climate over the past century are within the bounds of natural variability. Human influences on the climate (largely the accumulation of CO_2 from fossil fuel combustion) are a physically small (1%) effect on a complex, chaotic, multicomponent and multiscale system. Unfortunately, the data and our understanding are insufficient to usefully quantify the climate's response to human influences. However, even as human influences have quadrupled since 1950, severe weather phenomena and sea level rise show no significant trends attributable to them. Projections of future climate and weather events rely on models demonstrably unfit for the purpose. As a result, rising levels of CO_2 do not obviously pose an immediate, let alone imminent, threat to the earth's climate.