6 Recent Climate Change

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Earth’s climate has changed really fast in the past couple of centuries!

Staring around the year 1800, industrialization swept the world. First in England, then the rest of Europe and the United States began building factories and railroads. Global trade linked the emerging industrial powers via a huge increase in transoceanic shipping. All of this industrial activity was powered by combustion of fossil fuels: first and foremost coal, later oil and gas.

Burning carbon (reacting it with oxygen from the air) liberates stored energy and produces carbon dioxide (CO_2). Carbon dioxide isn’t as strong of a greenhouse gas as water vapor, but it builds up in the atmosphere over the long term.

At this writing, CO_2 has risen about 50% above its preindustrial concentration, to about 420 parts per million (ppm) and global average surface air temperature has increased by about 1.3 ºC. Water vapor in the atmosphere has increased associated with the warming as expected, providing strong positive climate feedback. Ice and snow have declined sharply, and global mean sea level has risen about one foot.

These changes have reversed 8000 years of cooling (since the warm postglacial climate optimum) in 100 years and Earth’s climate is now as warm as it’s been since at least the previous interglacial interval 125,000 years ago. The concentration of atmospheric CO_2 is higher than it’s been since before the Pleistocene Ice Ages began millions of years ago.

By the late 19th Century scientists understood that the buildup of CO_2 from burning coal would warm the climate. In 1965, the Lyndon B. Johnson administration reported to the US Congress that global warming was underway as aa result of burning fossil fuels.

6.1 Intergovernmental Panel on Climate Change (IPCC)

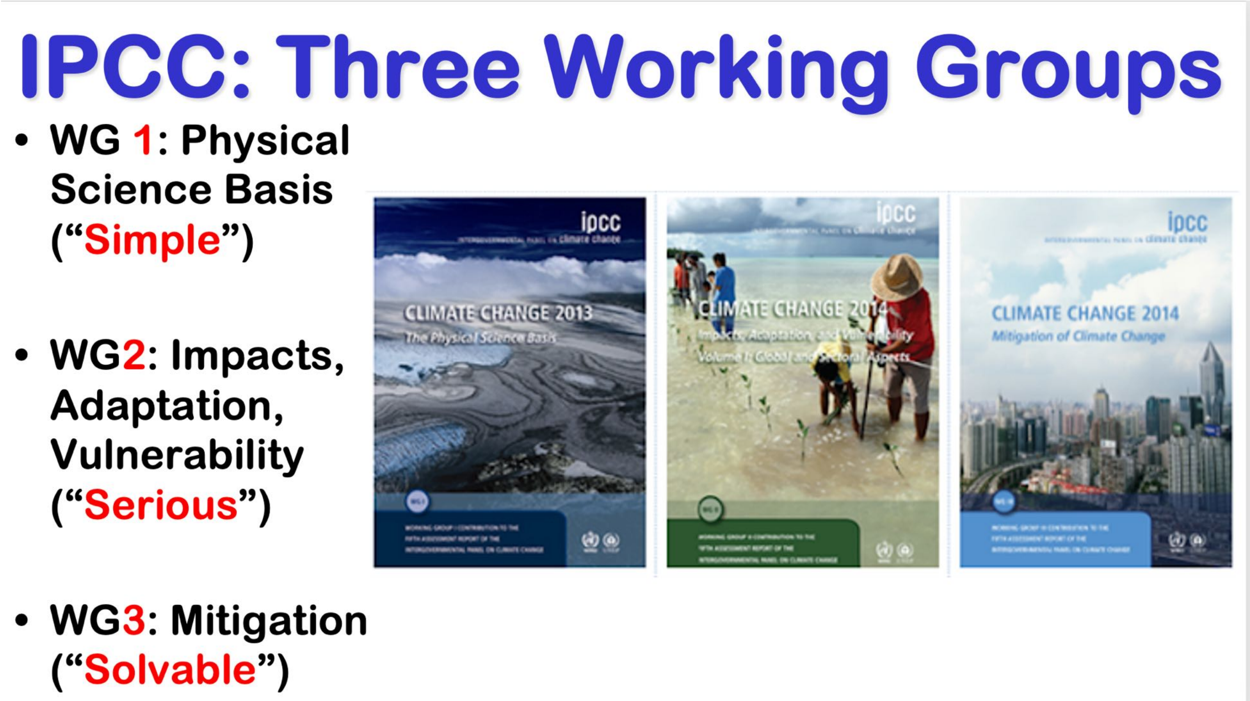
Beginning in the 1980s, the governments of the world recognized the threat of global warming and organized an international structure to monitor and assess it. This became the Intergovernmental Panel on Climate Change (IPCC).

6.1.1 History and Organization

The World Meteorological Organization and the United Nations Environment Program constituted the IPCC in 1988 to assess scientific research on climate change and make periodic reports to national governments. IPCC doesn’t actually conduct scientific research. Rather, it compiles large groups of experts to assess published studies and writes comprehensive reports every 6 to 9 years.

Assessment Reports of the IPCC are organized into three Working Groups. Working Group 1 assesses the Physical Science Basis of climate change. Working Group 2 assesses Impacts and Vulnerability. Working Group 3 assesses measures that can be taken to mitigate (prevent) and adapt to climate change. In a broad sense, the IPCC Working Groups assess the Three S's of Climate Change as we're doing in this course. Working Group 1 writes about the first S ("Simple"). Working Group 2 writes about the second S ("Serious"). Working Group 3 deals with the third S ("Solvable").

The IPCC First Assessment Report (FAR) was published in 1990, and the Fifth Assessment Report (AR5) was published in 2013-14. The Sixth Assessment Report (AR6) was published in 2021-22 and is the basis for a lot of the material in this course.



IPCC: Three Working Groups

- **WG 1: Physical Science Basis ("Simple")**
- **WG2: Impacts, Adaptation, Vulnerability ("Serious")**
- **WG3: Mitigation ("Solvable")**

Each group's assessment occupies a separate volume of nearly 1000 pages about 2 inches thick. Each is summarized in a Technical Summary (TS) and a Summary for Policymakers (SPM). There is also an overall synthesis document representing the high-level conclusions for all three groups.

IPCC Synthesis Reports represent a truly ***authoritative*** international scientific consensus of the natural and social science of climate change. They are well-organized, impeccably documented and referenced, and can serve as valuable reference works. But there are some serious downsides to using them as primary learning materials:

1) They are unavoidably ***dated***. The assessments review literature that was published at least a few years before the reports are released. Newer publications have to wait for the next assessment cycle (typically 6 to 9 years).
2) They are inherently ***conservative*** with respect to drawing conclusions due to the fact that they are the work product of thousands of scientists who may disagree about details.
3) They are really ***hard to read!*** They are written in a technical and bureaucratic style that reflects the "writing and editing by committee" process and the intended audience of government officials.

The SPM and Synthesis documents are subject to word-by-word review of hundreds of representatives of national governments, which tends to dilute the messaging and soften conclusions.

6.1.2 Summary of the IPCC Sixth Assessment Report (AR6)

Working Group 1 (Natural Science Background) concludes that:

- Changes are “widespread, rapid, intensifying, unprecedented”
- Without immediate rapid emission reductions, 1.5 C will be out of reach
- Indisputable human impact on extreme climate events: heat waves, heavy rainfall, droughts
- Affects every region – changes will increase

Working Group 2 (Impacts, Adaptation, and Vulnerability) concludes that:

- Evidence is unequivocal: climate change is a threat to human well-bring and the health of the planet
- Impacts are magnified in cities where more than half the world’s population lives
- Simultaneous extreme events compound risks
- There are limits to climate adaptation. Above 1.5 ºC it will be difficult for some countries to adapt to the lack of fresh water. Above 2 ºC production of many staple crops will be challenging

Working Group 3 (Mitigation of Climate Change) concludes that:

- Annual GHG emissions are the highest in history; We are not on track to limit warming to 1.5 ºC
- Clean energy is now less expensive than fossil fuels in much fo the world
- Limiting warming to 1.5 ºC requires reducing CO_2 emissions 43% and methane emissions 34% by 2030, with net zero emissions by 2050s
- Limiting warming to 2 ºC requires reducing global CO_2 emissions 27% by 2030 and achieving net zero emissions by 2070s
- There are options available now to cut GHG emissions in half by 2030
- Without immediate and deep emission reduction in all sectors, 1.5 ºC is beyond reach

6.2 US National Climate Assessment

In addition to periodic reviews by IPCC, there is also a US National Climate Assessment (NCA) with a similar mandate: to review the best published climate science and issue periodic summary reports. The US NCA is addressed to agencies of the US Government, and drills down to US regions with specific analyses. Unlike IPCC Ars, the US NCA is written much more for a nontechnical public audience and is therefore much easier to read.

The Fourth Assessment (NCA 4) was published in 2017-18 and is used to develop a lot of content for this course. One of the key advantages for a US audience is the plain-language analysis of the impact of climate change on US regions, with temperatures in Fahrenheit, rainfall in inches, and sea-level changes in feet.

In this course we will emphasize regional changes in extreme rainfall from NCA 4.

6.3 Changes in Mean Climate

Routine measurement and recording of daily high and low temperature began in the US and Europe in the mid-19th Century, and by 1880 station coverage had increased enough for modern reconstructions of global trends. This is not an easy task and requires spatial patterns derived form modern data to be extrapolated back to earlier times when station density was sparse, especially in less developed countries. Sea surface temperature (SST) has long been measured by bucket sampling from ships and recorded in logs. After World War II sea temperatures were measured in engine coolant intake water.

Global temperatures rose a few tenths of a degree Celsius in the first decades of the 20th Century and then flattened from about 1940 to 1980 before rising rapidly ever since (Figure 6-1). The flattening of the trend in the middle of the 20th Century is not completely understood but may reflect the influence of reflective air pollution and perhaps the change in sampling methods for SST measurements. There is substantial year-to-year variability in the temperature timeseries, much of which can be explained by El Nino and the Southern Oscillation (ENSO). Since temperatures began rising more quickly in the 1930s, the trend has been about 0.18 ºC per decade. Overall global average warming since the beginning of the record is about 1.3 ºC.

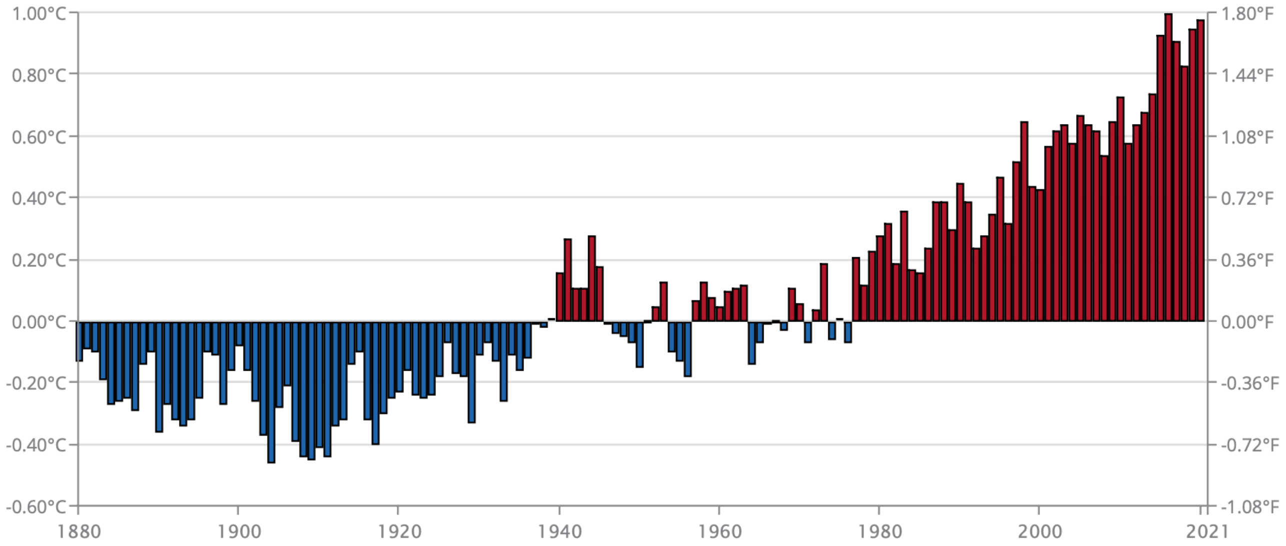
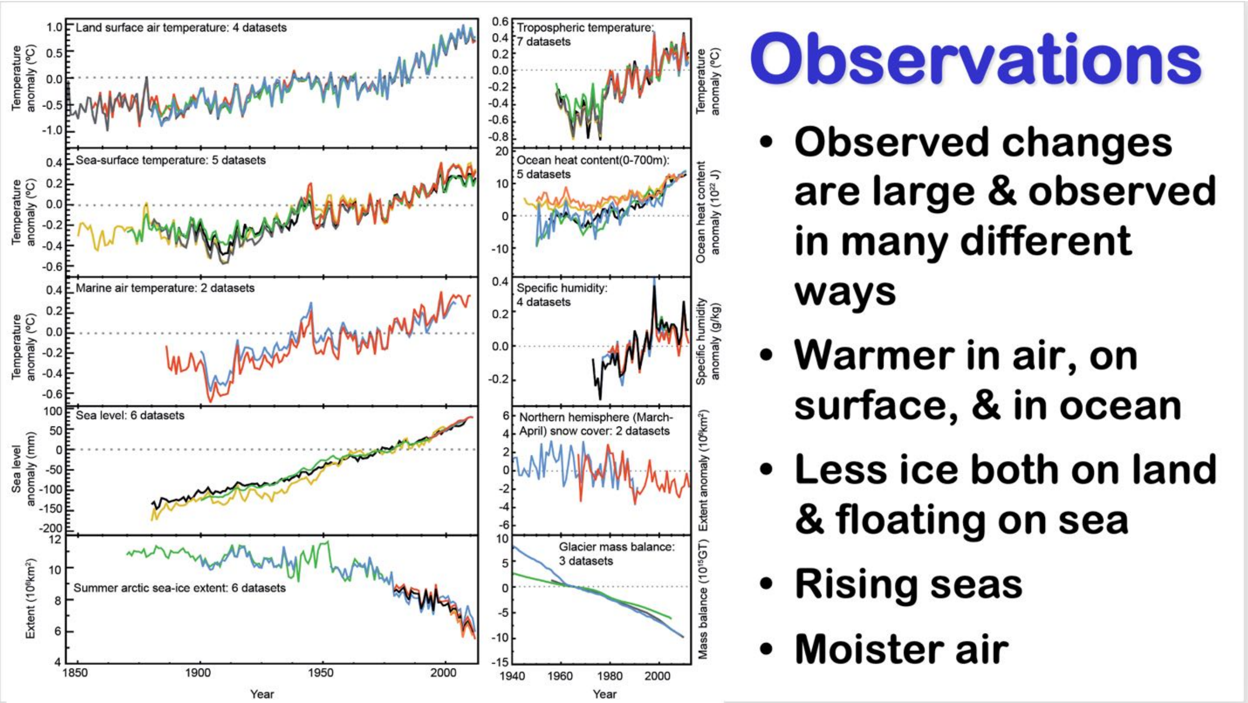


Figure 6-1: Changes in global average surface air temperature since 1880. US National Oceanic and Atmospheric Administration (NOAA). Reprinted from Schmittner (2022)



Observations

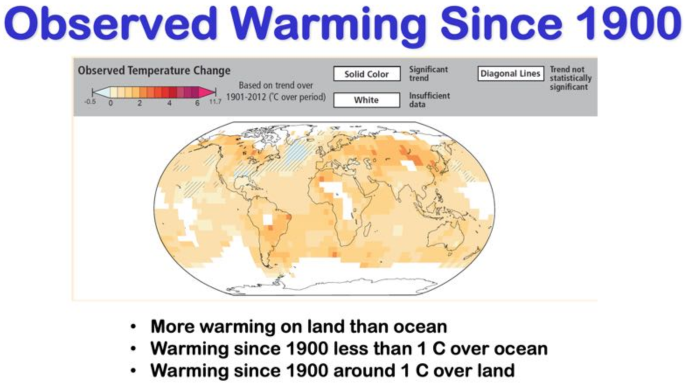
- Observed changes are large & observed in many different ways
- Warmer in air, on surface, & in ocean
- Less ice both on land & floating on sea
- Rising seas
- Moister air

Figure 6-2: Global changes in a wide range of variables observed via multiple data sets since 1850. IPCC AR5 (2013)

As climate has warmed, many other variables besides temperature have changed too. Figure 6-2 summarizes concurrent warming of air temperature over land, sea-surface (water) temperature, and air temperature over the ocean. Each plot at top left includes several different reconstructions by different groups of authors using various methods, yet the patterns are very similar, with a leveling out of warming trends during the mid-20th Century followed by rapid warming since about 1980. Warming on land is faster and more pronounced than in and over the oceans, probably because so much added heat energy at the sea surface is used to evaporate water. Sea levels have risen since the late 19th Century as measured by tide gauges and later by satellite altimetry. Summer sea ice cover in the Arctic has declined by more than half since the mid-20th Century.

On the right side of Fig 6-2, data sets are summarized that weren't possible to measure until later in the 20th Century. These include warming of the air aloft (measured by instruments on weather balloons), the stored heat content of the deep oceans (measured by robotic sounders), and atmospheric water vapor (specific humidity, measured from satellites). Snow cover extent over the entire northern hemisphere and the mass balance of glaciers are also shown.

All these observations depict a rapidly warming world. They are self-consistent, with rising temperatures producing more atmospheric water vapor, rising seas with more internal heat content, and decreasing snow, sea ice, and land ice. Both the consistency across man studies with different data and methods, and the consistency across variables gives us confidence that we are seeing profound changes in the functioning of the climate system.


Observed Warming Since 1900

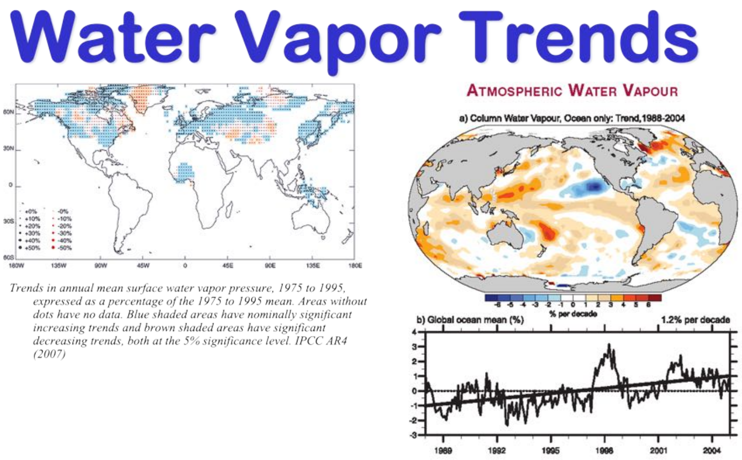
- More warming on land than ocean
- Warming since 1900 less than 1 C over ocean
- Warming since 1900 around 1 C over land

Figure 6-3: Spatial patterns of observed warming since 1900. IPCC AR5 (2013)

Figure 6-3 shows a map of the total surface warming since 1900. Some regions are blank because there isn't enough data from 120 years ago to establish the 100-year total. The global average increase is about 1 ºC over these 12 decades, but warming isn't uniform across the world.

Land areas have warmed more than the ocean surface due to evaporative cooling of seawater. The deep interiors of continents (especially North America and Asia) have warmed more than other continental areas. There has been weak cooling of the North Atlantic Ocean, possibly due to melting of land ice in Greenland which flood the region with buoyant fresh water.

6.3.1 Water Vapor


Water Vapor Trends

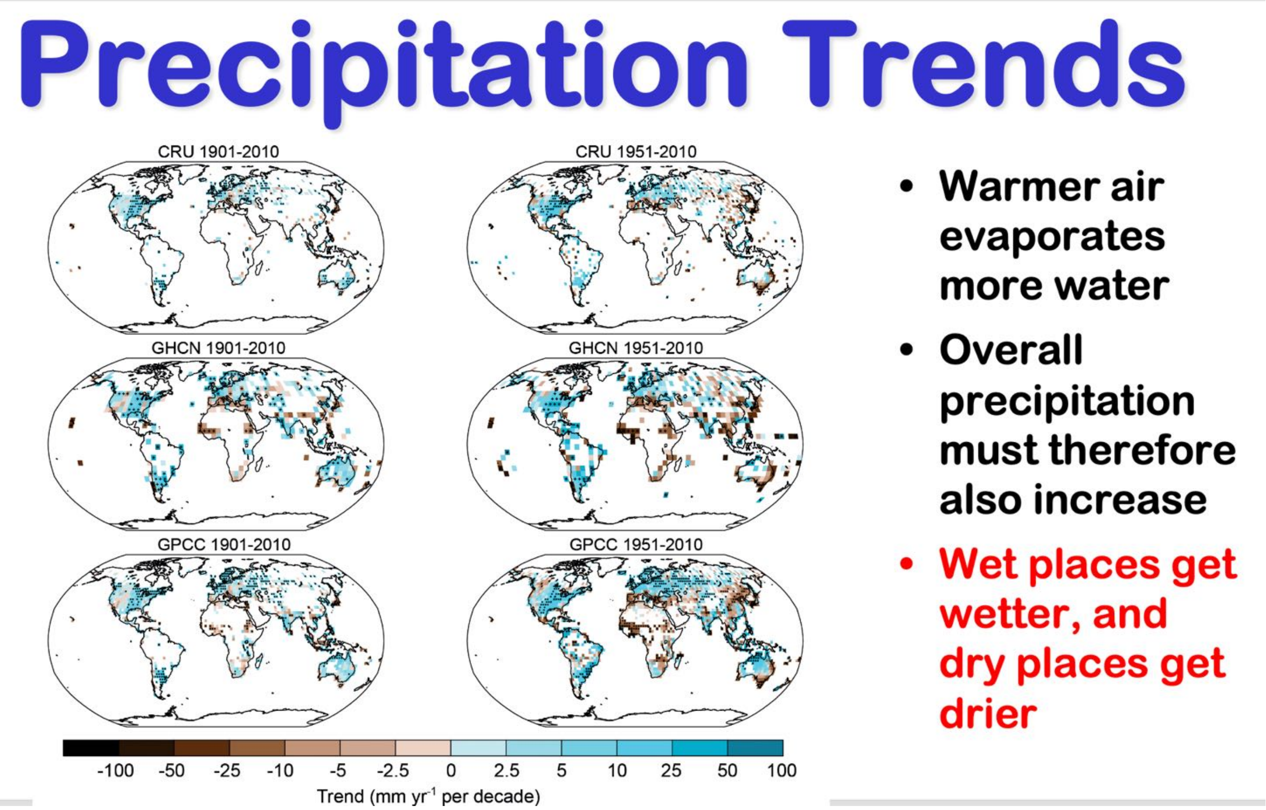
Trends in annual mean surface water vapor pressure, 1975 to 1995, expressed as a percentage of the 1975 to 1995 mean. Areas without dots have no data. Blue shaded areas have nominally significant increasing trends and brown shaded areas have significant decreasing trends, both at the 5% significance level. IPCC AR4 (2007)

Figure 6-4: Global and spatial trends in atmospheric water vapor. IPCC AR4 (2007)

In the global mean, atmospheric water vapor has increased by about 1% per decade since the advent of the modern satellite record in the 1980s (Fig 6-4). Spatial patterns are a bit complicated by atmospheric circulation, with some regions moistening much faster and some areas more slowly than the global mean. Higher concentrations of water vapor are supported by greater evaporation in the warmer climate. More importantly, they are sustained by the higher temperatures in the atmosphere and contribute substantially to warming via the strong water vapor feedback.

6.3.2 Precipitation

As global evaporation increases, global precipitation must also increase. Reliable precipitation records on land are available from around 1900, but estmiates of ocean precipitation only became available in the satellite era. Most regions have in fact experienced rising precipitation as climate has warmed (Fig 6-5), and the trend is accelerating. Spatial patterns show substantial regional differences. Precipitation has incrased most in wetter regions (North America and northern Eurasia) whereas precipitation has decreased in some of the driest regions



Precipitation Trends

- **Warmer air evaporates more water**
- **Overall precipitation must therefore also increase**
- **Wet places get wetter, and dry places get drier**

Figure 6-5: Changes in precipitation over land since 1901 (left column) and since 1951 (right column) for three different data sets. IPCC AR4 (2007)

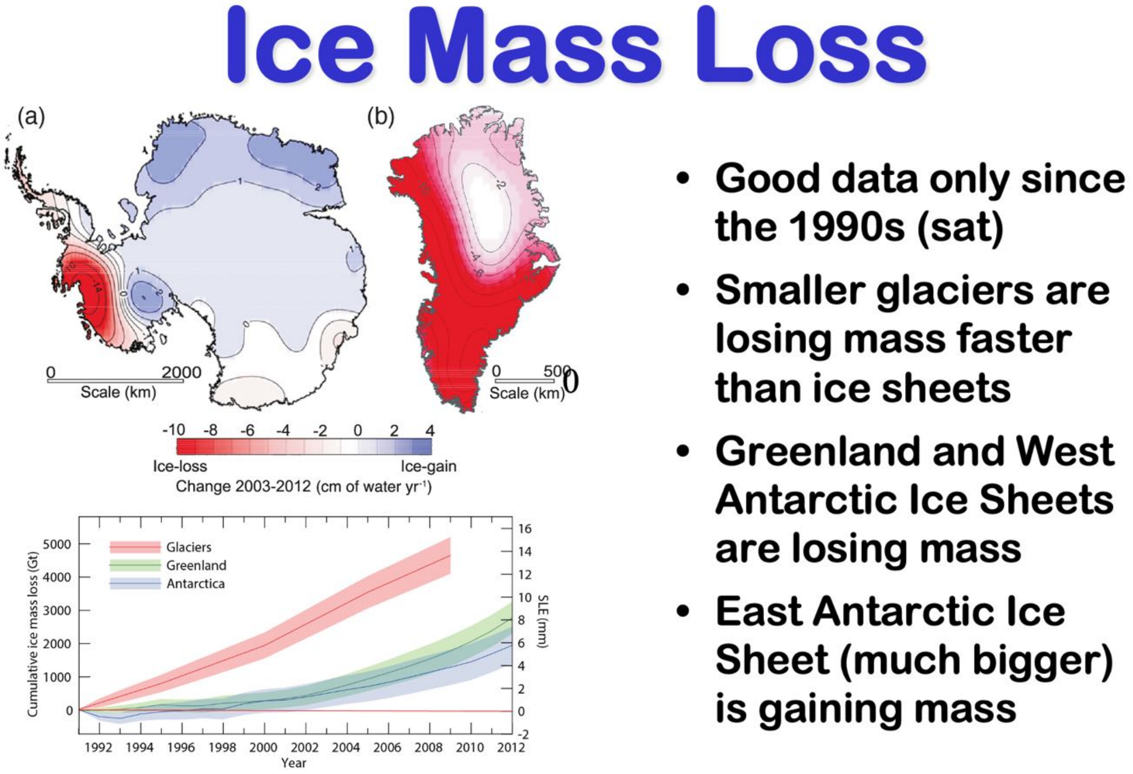
(North Africa and the Middle East, Central Asia). These patterns are robust across multiple data sets and different averaging periods.

6.3.3 Ice Sheets and Mountain Glaciers

Satellite altimetry involves firing a laser at the surface from an orbiting spacecraft and timing the return pulse to measure the height of the surface. Since the 1990s, it has been possible to track the changing height of continental ice sheets in Greenland and Antarctica to monitor changes in total ice volume.

These data show rapid rates of ice loss over the warmest parts of both ice sheets (southern Greenland and West Antarctica) with large areas losing more than 10 cm of ice per year (Fig 6-6). The coldest regions of the ice sheets (northeast Greenland and East Antarctica are stable or perhaps accumulating a little bit of ice as precipitation (snowfall) increases.

Smaller mountain glaciers have lost even more volume than the large ice sheets. The contribution of melting land ice to rising sea levels has been modest so far (about 3.5 cm from 1992 - 2012), with about half of that total coming from mountain glaciers. Most sea level rise up to now has been caused by thermal expansion of the oceans as they warm, but the contribution from melting ice on land is accelerating.



Ice Mass Loss

- **Good data only since the 1990s (sat)**
- **Smaller glaciers are losing mass faster than ice sheets**
- **Greenland and West Antarctic Ice Sheets are losing mass**
- **East Antarctic Ice Sheet (much bigger) is gaining mass**

Figure 6-6: Changes in volume of the two large continental ice sheets since the advent of satellite altimetry. IPCC AR5 (2013).

6.3.4 Sea Ice

Melting sea ice does not contribute to rising sea levels. Sea ice floats on the ocean, displacing the same amount of water that the melted ice would occupy, with only about 10% (the tip of the iceberg) protruding above the water surface. Just as your drink doesn't overflow when the ice cubes melt, changes in sea ice will not contribute to rising seas.

Melting sea ice is very important for regional and global climate however. The albedo of sea ice is typically greater than 60%, and when it melts the dark ocean underneath is exposed to the Sun with a typical albedo less than 10%. This is the positive ice-albedo climate feedback. Also the surface air temperature over sea ice in the Arctic winter can be as cold as -40 ºC. By contrast open water is never colder than the freezing point (about -2 ºC for salty sea water). So melting sea ice leads to much greater solar heat absorption in Arctic summer and much warmer surface temperatures in Arctic winter (at least until the surface refreezes).

Since the advent of modern satellite monitoring, the sea ice cover has declined by about half in the Arctic, but much more slowly or not at all in the Antarctic (Fig 6-7). The Antarctic is much colder and changes in wind over the Southern Ocean may be responsible for regenerating Antarctic sea ice.

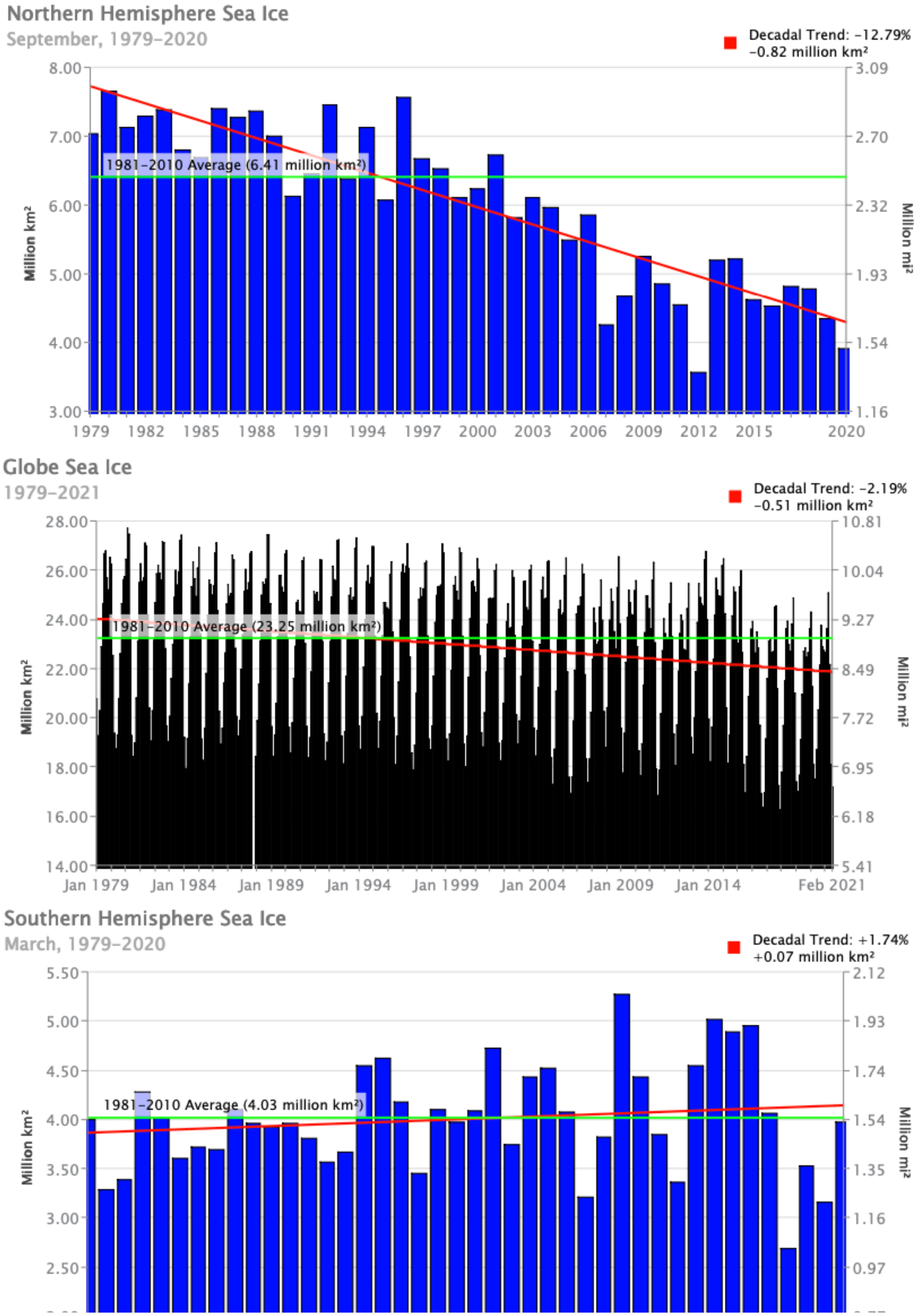


Figure 6-7: Changes in sea ice cover since 1979. Reprinted from Schmittner (2021)

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6.4 Changes in Variability and Extremes

While changes in average temperature, precipitation, sea level and other climate variables is important, the impact of changes in extreme values may be much greater. You might not notice a change in the annual mean temperature in Colorado, but you'd certainly notice a summertime heat wave with daily highs above 110 ºF! Similarly, a slow change of 10% in annual precipitation. Might escape your attention, but a single weekend rain of 10 inches might be catastrophic. Statistics tells us that changes in extreme values march hand-in-hand with changes in mean quantities.

6.4.1 The Bell Curve

Many variables in nature (and also in society) follow what statisticians call the "Normal Distribution." This is technically named a Gaussian Distribution and is often called a "bell curve" in ordinary language, because it looks kind of like a nicely symmetrical bell.

The bell curve is a measure of variability. It's a graph of the frequency of different values of a variable. In plain English, the bell curve says "values near the average happen a lot, and the farther you get above or below the average, the less frequently those values will occur."

A common example of bell curves from everyday life is the distribution of people's height. Suppose the average woman is 167 cm (about five and a half feet) tall, and that the overall distribution of women's heights follows a normal distribution with a standard deviation of 10 cm (about 4 inches). Then if we were to measure the heights of a random sample of 1000 women the distribution of their heights would be as shown below (Fig 6-8).

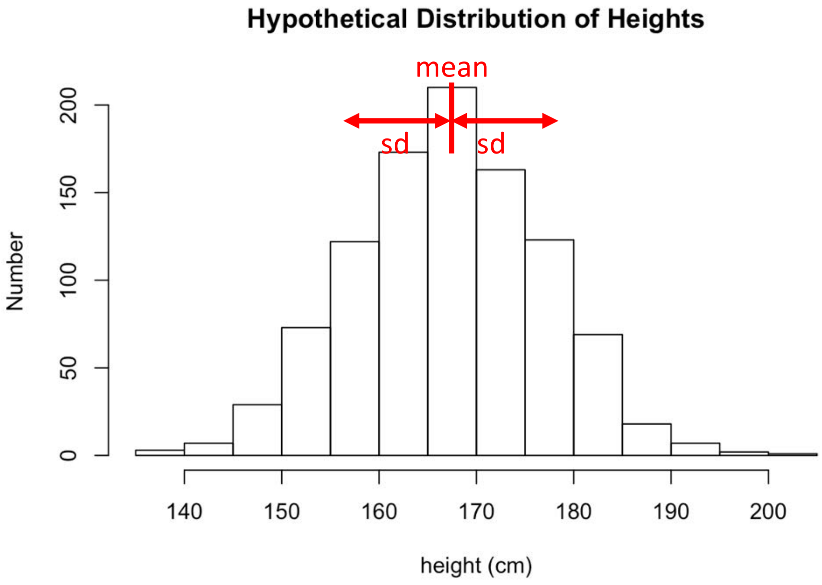
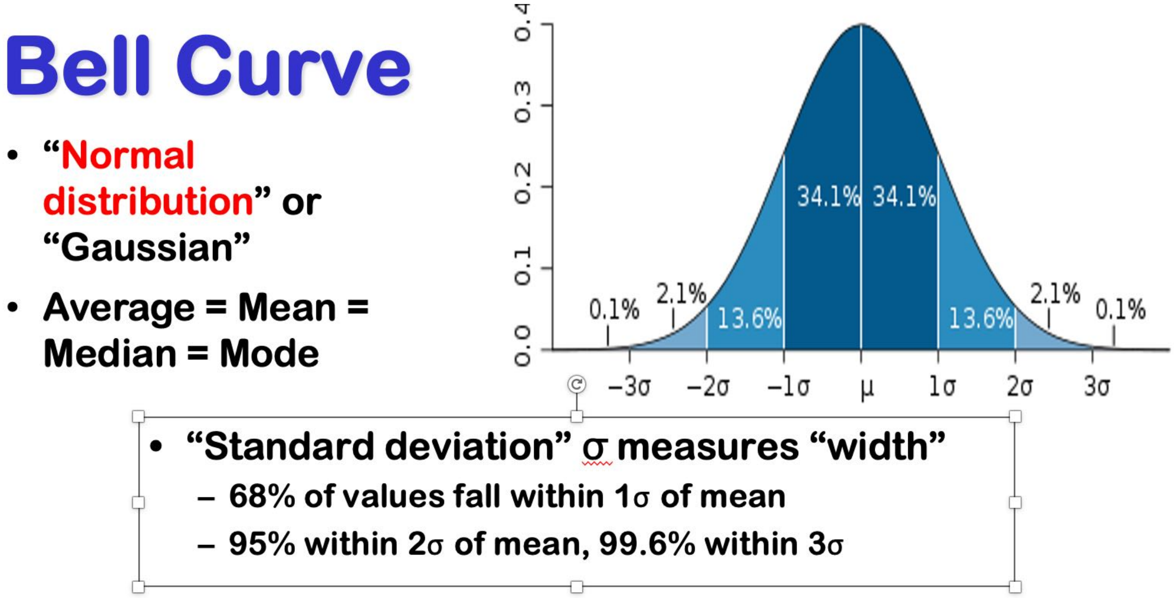


Figure 6-8: Normal distribution of a sample of 1000 heights with a mean of 167 cm and a standard deviation of 10 cm

The most common value of a normally-distributed variable is the mean, and the standard deviation measures the amount of variation around this central tendency. In this example of 1000 measurements of height, the most common height is 167 cm. Sixty-eight percent of the women have heights within 10 cm (1 standard deviation) of the mean – that is, about 2/3 of women in this sample are between 157 and 177 cm tall.

In general, we can define a bell curve or normal distribution as one in which the average is the most common value, and the frequency of values drops off steeply at first as we get away from the average and then more and more slowly. For a normally distributed variable, the three common measures of the average (mean, median, and mode) are equal and the frequency of values is symmetrical about this central value. We commonly abbreviate the mean using the Greek letter μ and use the Greek letter σ to indicate the standard deviation. The standard deviation measures the width (or scatter) around the mean.



Bell Curve

- “Normal distribution” or “Gaussian”
- Average = Mean = Median = Mode

- “Standard deviation” σ measures “width”
  - 68% of values fall within 1σ of mean
  - 95% within 2σ of mean, 99.6% within 3σ

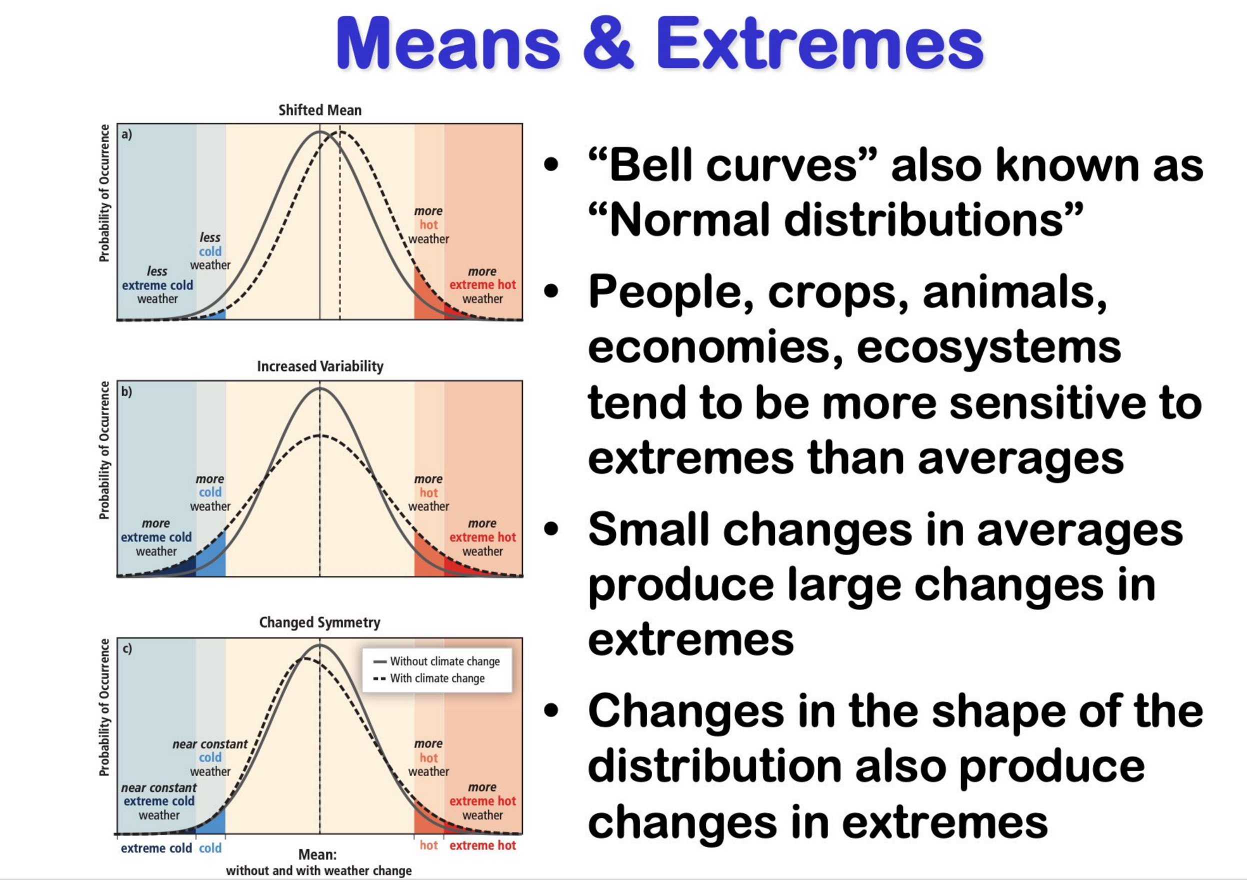
Temperature typically follows a normal distribution. If the mean high temperature at a particular station in July is 89 ºF and the standard deviation is 4 ºF, then daily highs in July will fall between 85 ºF (89 ºF – 4 ºF) and 93 ºF (89 ºF + 4 ºF) on about 68% of July days. It will be quite rare for temperatures to exceed μ + 2σ = 97 ºF – in fact we can expect temperatures to exceed that value on only about 2.2% of July days. Similarly, high temperatures would fall below μ - 2σ = 81 ºF on just 2.2% of July days. Temperatures above μ + 3σ = 101 ºF would be exceedingly rare, occurring on just 0.1% of July days.

Some climate variables do NOT follow bell curves. Notably precipitation can’t be normally distributed because there’s no such thing as negative precipitation, and the most common value for most locations is zero, which is certainly not the average! The statistics of precipitation are complicated and won’t be discussed in detail here.

6.4.2 Mean Warming Has a Huge Effect on Extreme Temperatures

Think about what happens to the distribution of temperature when climate warms (Fig 6-9).

If temperature follows a bell curve and we simply add a few degrees to all the temperatures, then the bell curve doesn’t change shape, but it shifts to the right (top panel of Fig 6-9). In this case the frequency of hot days (temperature above μ + 1σ) increases and the frequency of cool days (μ – 1σ) decreases. The frequency of *extremely* hot temperatures that were previously very rare (μ + 2σ occurring less than 2% of the time) increases dramatically. The incidence of



Means & Extremes

- **“Bell curves” also known as “Normal distributions”**
- **People, crops, animals, economies, ecosystems tend to be more sensitive to extremes than averages**
- **Small changes in averages produce large changes in extremes**
- **Changes in the shape of the distribution also produce changes in extremes**

Figure 6-9: Three possible changes to temperature distribution with a shift in the mean (top panel), an increase in the standard deviation (middle panel), and an increase in both the mean and standard deviation (bottom panel). IPCC AR5 (2013)

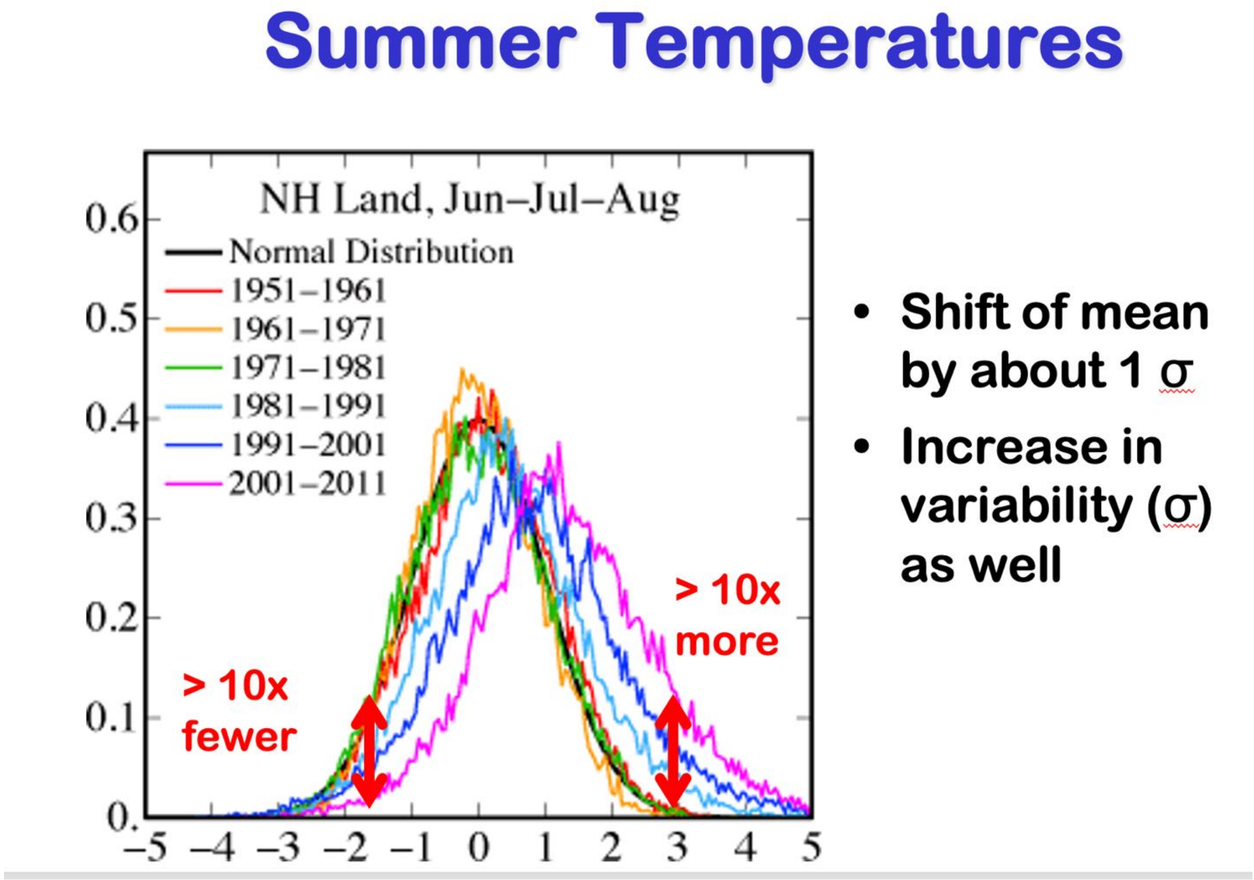
extremely hot weather increases by a much larger percentage than the frequency of days that are merely hot. Similarly there is a dramatic drop in days that were previously extremely cold (temperature less than $(\mu - 2\sigma)$).

Alternatively, what if instead of simple warming, the ***weather becomes more variable*** (middle panel of Fig 6-9)? This might indicate a shift in the patterns of winds and fronts that bring different air masses to a region over a period of months, for example. Statistically, an increase in variability is represented by a change in σ rather than μ. Graphically, the ***bell curve gets wider*** rather than shifting to the right. In this case we’d expect ***both warm and cold days to happen more often*** as the bell curve swells into the hot and cold weather that was previously rare. Increases in unusually warm and unusually cold weather would be symmetrical.

Finally, consider what happens if both the mean (μ) and variability (σ) increase (bottom panel of Fig 6-9). It ***doesn’t take much average warming in this case to produce dramatic increases in the occurrence of extremely hot weather***. The reduction in extreme cold is less dramatic than for a simple shift in the mean, but the increases in extreme heat are more pronounced. There is in fact some evidence that ***variability is increasing as climate warms***, as we’ll see below.

6.4.3 Observed Changes in Temperature Distributions

An important advantage of working with normal distributions is that we can combine changes across many locations whose mean climate is very different. Figure 6-10 below shows the distribution of summer temperatures across every location on the Northern Hemisphere continents over 60 years (from 1951-2011). At each location, the average (m) temperature was computed and then the variations were divided by the standard deviation (s) to produce a bell—curve-like distribution and then these distributions were combined across all land points across the entire Northern Hemisphere. One bell-like curve was computed for every decade (1951-1961, 1961-1971, etc.) and then the decades were overlain on the figure.



Summer Temperatures

- **Shift of mean by about 1 σ**
- **Increase in variability (σ) as well**

Figure 6-10: Distributions of summer temperatures across all land in the Northern Hemisphere by decade from 1951-2010. The x-axis is the deviation from average temperature in units of standard deviation (s) and the y-axis is the frequency of those temperatures. Hansen et al (2012) (https://www.giss.nasa.gov/research/briefs/2012_hansen_17/)

For the first few decades (1950s in red through 1970s in green), the distributions (bell curves) are essentially identical and pretty much overlap the heavy black line that indicates a normal distribution. Beginning around 1980, the decadal curves begin marching steadily toward the right and also broadening. This indicates that actual summer temperatures are behaving like the bottom panel in Fig 6-9, with increases in both mean (μ) and variability (σ). By the first decade of the 21st Century, the average summer land temperature had increased about one standard deviation compared to conditions in the 1950s-1970s. In other words, the mean (μ) of the bell curve had shifted to the right by (1σ). As a result, temperatures that had previously occurred only on the hottest 0.1% of days (μ + 3σ in the 1970s) now occur 10 times more frequently than they did 40 years ago!

The bottom line here is that even the small amount of warming we've experienced since 1980 has produced a 10-fold increase in extreme summer heat. This is not some kind of mysterious weather weirdness – it's simply a property of the normal distribution in statistics. Many many weather phenomena are affected by this property. This is fundamentally the reason that climate scientists talk about the increase in extreme weather than accompanies even small amounts of global warming.

6.4.4 The European Heat Wave of 2003

Heat Wave Statistics

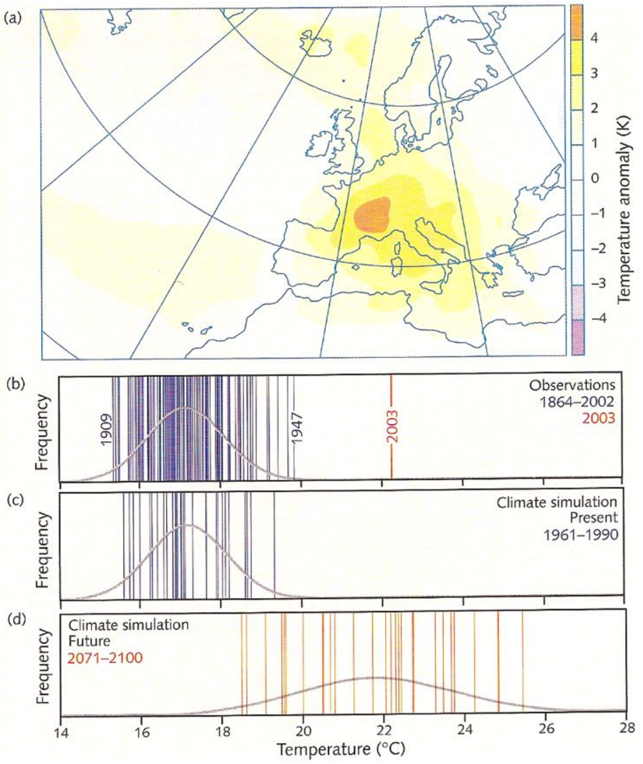


Figure 7.19 Characteristics of the summer 2003 heatwave in Europe. (a) June, July, August (JJA) temperature anomaly with respect to 1961–90; (b) to (d) JJA temperatures for Switzerland; (b) observed during 1864–2003; (c) simulated with a regional model for the period 1961–90; (d) simulated for 2071–2100 under the SRES A2 scenario. The vertical bars in (b) to (d) represent mean summer surface temperature for each year of the time period considered; the fitted Gaussian distribution is indicated in black.

Figure 6-11: Summertime temperature statistics in western Europe since 1864, showing the extreme deviation (5s) of the heat wave of 2003. The bottom panel shows projected distribution of summer temperature for 2071-2100, by which time the temperatures of 2003 will be normal. IPCC AR4 (2007)

As an example of the remarkable impact of extreme heat, consider the statistics of summertime temperatures in western Europe since modern recordkeeping began in 1864 (Fig 6-11).

The map shows the distribution of temperature anomalies (actual minus average) for the summer of 2003, with a bullseye over southern France of about 5 K (9 ºF) above average. About 72,000 people died as a result of this incredible heat wave (Wikipedia).

The distributions below the map show average summer temperatures for every year since 1864 (top panel); simulations of 30 summers from 1961-1990 with a climate model (middle panel), and simulations of the last 30 years of the 21st Century with the same climate model (bottom panel). The 2003 heat wave is shown in the top panel in orange – an incredible 4s above the mean, which should be expected occur about once in 10,000 years. The bottom panel shows that such extreme heat will in fact occur in most years by the end of this century under a high CO_2 emissions scenario.

6.4.5 Actual Changes in Temperature Extremes in the United States

Figure 6-12 compares the occurrence of record high and record low temperatures in the contiguous United States (excludes Alaska and Hawaii) since 1930. In a stable climate, the occurrence of record highs and record lows would be equal. In other words, their ratio would be 1-to-1 (one record high for every record low). For a few decades in the mid-20th Century (roughly 1950-1980), record low temperatures exceeded record highs by 50% or more with twice as many record lows as highs (2:1) in a handful of years.

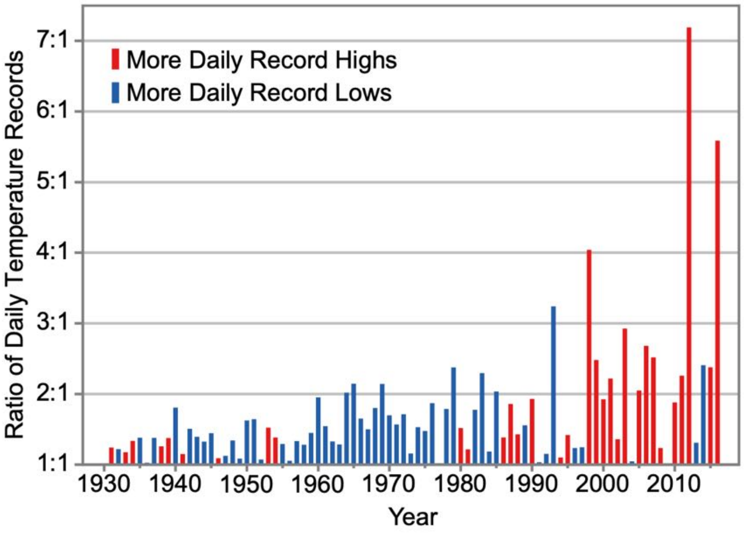


Figure 6.5. Observed changes in the occurrence of record-setting daily temperatures in the contiguous United States. Red bars indicate a year with more daily record highs than daily record lows, while blue bars indicate a year with more record lows than highs. The height of the bar indicates the ratio of record highs to lows (red) or of record lows to highs (blue). For example, a ratio of 2:1 for a blue bar means that there were twice as many record daily lows as daily record highs that year. Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset.[16] (Figure source: NOAA/NCEI).

Figure 6-12: Changes in record high and low temperatures in the conttiguous US since 1930. US National Climate Assessment (NCA4, 2017)

After 1980, the occurrence of record high temperatures skyrocketed and the occurrence of record lows dropped. In the 21st Century, record highs in the US have occurred 3 to 6 times more often than record lows. This is a direct consequence of the shift of the normal temperature distribution to the right, with an explosion of values at the extreme hot "tail."

6.4.6 Changes in Extreme Precipitation in the US

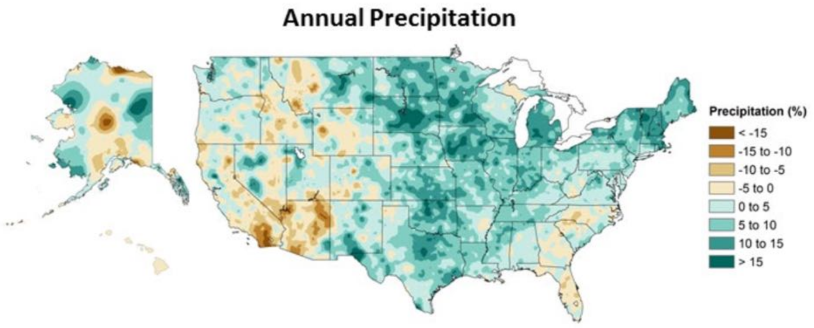


Figure 6-13: Percent change in US annual precipitation: 1986-2015 minus 1901-1960. US NCA4 (2017)

Since the first half of the 20th Century, annual precipitation has increased over much of the United States (Fig 6-13). There is some indication of the expected "wet gets wetter, dry gets drier" pattern projected by climate models, with increases in the north and central plains and decreases in the desert southwest. It's easy to imagine this as a map of "winners and losers" with improved farming conditions in the Midwest and severe droughts in California and Arizona. But in fact many of the areas in which precipitation is increasing are not water limited so don't benefit from the extra moisture.

Recall that unlike temperature, rainfall does NOT follow a normal distribution (bell curve). Rather, the most frequent value for daily precipitation is zero and the distribution tails off quickly toward extremely heavy rainfall. In many regions rainfall is good because of course water is required to grow crops and natural vegetation and is needed for cities and industry. But the very heaviest rainfall is not good – it causes flooding.

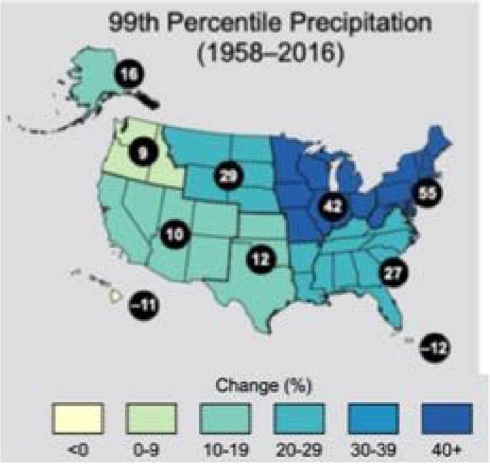


Figure 6-14: Change in very heavy precipitation in the United States. NCA4 (2017)

The occurrence of the very heaviest rainfall (that which occurs on the 1% wettest days) is increasing rapidly across most of the United States (Fig 6-14). Extreme rainfall now happens 42% more often across the upper Midwest and 55% more often across the densely populated northeast.

Even in the desert southwest where total precipitation has decreased (Fig 6-13), the frequency of very heavy rainfall has increased (Fig 6-14). How is this possible?

As climate has warmed, evaporation from the oceans has increased and the atmosphere carries more water vapor on average. Extreme rainfall requires special meteorological conditions: strong updrafts dramatically cool the air and condense out most of the water as rain. Perhaps such storms are increasing in frequency. But even if "storminess" remains constant the updrafts have more water vapor in the air to work with. A storm of the same intensity will naturally produce more rainfall if there's more water vapor available to condense.

What appears to be happening across much of the world is that dry periods are interspersed with extremely heavy precipitation. We've seen the "wet gets wetter, dry gets drier" pattern across space (on maps). This analysis shows that “wet gets wetter, dry gets drier” also applies in time. Even if the total rainfall decreases, more of the annual total arrives in a few extreme events. Unfortunately, extreme rainfall does very little good for farming or urban water supply. Rather, extreme events are associated with destructive floods and don’t replenish supply nearly as well as slow steady rain,