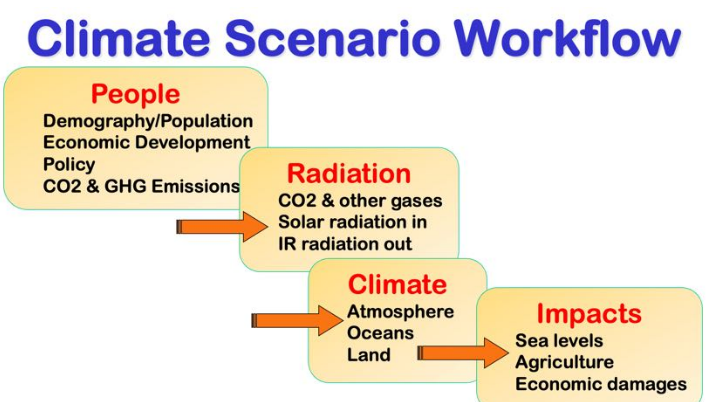
8. Future Climate Change

Climate has changed more in the past century than in many thousands of years previously, and changes are accelerating. As we've seen, it's pretty straightforward to estimate changes in global mean surface temperature using well understood climate forcing and sensitivity. Actually planning for climate change and enacting rational policy to avoid catastrophic costs requires more information than just equilibrium warming. We use climate and Earth System Models to project changes in many variables besides temperature: rainfall, winds, storms, sea level, snowpack, agricultural productivity and so forth. Furthermore climate projection with models allows climate scientists to project changes with some degree of spatial and decadal detail.

8.1. Climate Projection Workflow

Projecting future climate requires projecting change sin climate forcing: mostly this means estimating future concentrations of greenhouse gases like CO_2, CH_4, and N_2O. Estimating the future trajectories of GHGs requires detailed assumptions about emissions, but of course future emissions depend mostly on social and economic decisions that haven't happened yet. Indeed many of the people who will determine future emissions haven't yet been born!



Rather than try to actually predict future emissions, climate projections are made using emission scenarios. Think of these as stories. Social scientists (economists, demographers, policy and technology analysts) develop self-consistent storylines about future changes in national populations, economic development, trade, and technological progress. These stories are structured and organized around emissions outcomes, and then the resulting GHG emissions are used as input to Earth system models to produce scenarios of future climate consistent with the emission scenarios.

Earth system models use detailed calculations of atmospheric transport and radiative transfer to turn emission scenarios into time histories of future climate forcing. These in turn lead to global calculations of the world's weather several times every hour for centuries, and to projections of changes in the oceans, soil moisture, plant growth, river flow and so forth. Ultimately the scenario of physical climate resulting from a given emission scenario is then interpreted by social scientists who analyze impacts to economic and social systems such as agricultural production, migration, and economic damages resulting from climate change.

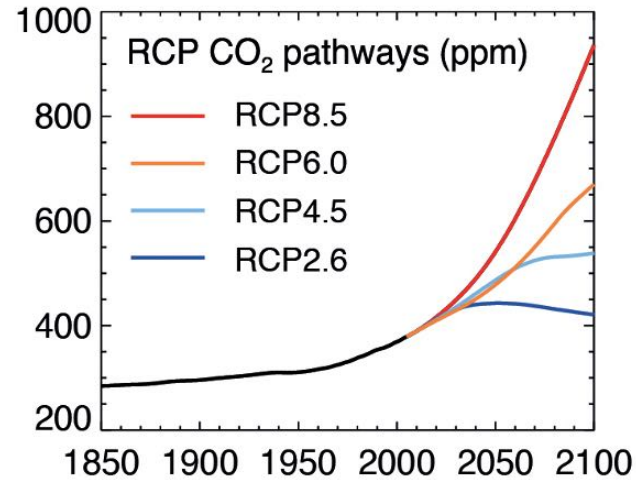


Figure 8-1: Projected future CO2 levels under Representative Concentration Pathways assessed by IPCC AR5

Emission, GHG, climate, and impact scenarios analyzed by the IPCC 5th Assessment were called Representative Concentration Pathways (RCPs). They were numbered according to simulated climate forcing (W m^{-2}) in the year 2100 relative to preindustrial conditions (Fig 8-1). You can think of the RCPs as telling "what if" stories. If GHG emissions are unchecked, CO_2 will rise to nearly 950 ppm and radiative forcing of climate will be 8.5 W m^{-2} in 2100. This is scenario is named RCP8.5. By contrast a scenario in which the nations of the world work together effectively to rapidly eliminate fossil fuel combustion, CO_2 levels in 2100 will be about the same as today, and radiative forcing will be only 2.6 W m^{-2} relative to preindustrial conditions. This is called RCP2.6. Two intermediate scenarios were also summarized: RCP4.5 in which CO_2 remains below 500 ppm with 4.5 W m^{-2} of forcing and RCP6.0 with CO_2 around 660 and 6.0 W m^{-2} of radiative forcing in 2100.

Emissions of CO_2 under the four RCPs considered in IPCC AR5 are shown in Fig 8-2 along with historical emissions up to the time of the assessment report in 213. The units are petagrams (10^{15} grams) of carbon per year (PgC/yr), which is the same as gigatons (billions of tons) of carbon per year (GtC/yr). Current global emissions are about 10 GtC/yr.

Many social scientists use a related unit to measure emissions: GtCO2 per year. Each GtC of fuel burned reacts with oxygen in the air to create about 3.7 GtCO2, so current global fossil fuel emissions of 10 GtC/yr are also frequently written as 37 GtCO2/yr.

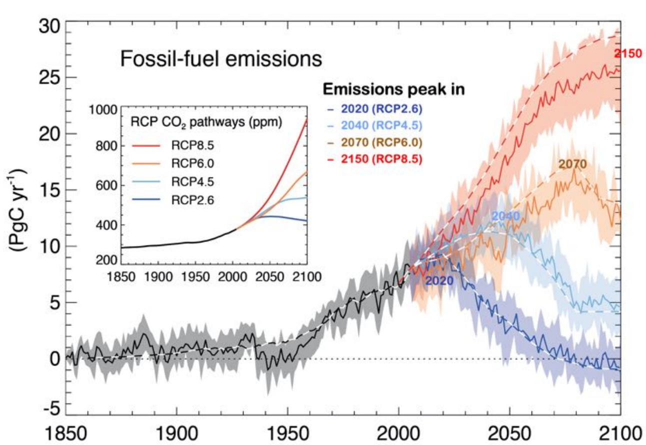


Figure 8-2: Fossil fuel emission scenarios for four RCPs considered by IPCC AR5

In the most optimistic scenario (RCP2.6), global CO_2 emissions would peak by 2020 and fall rapidly after that (Fig 8-2). In RCP4.5, emissions peak about 2040. Under RCP6.0, emissions peak around 2070. Under the highest emission scenario, emissions reach 25 GtC/yr by 2100 but don't actually peak until 2150.

It's important to understand that emission and climate scenarios are not predictions, in the sense that nobody can predict what future people will decide to do. We call the scenarios projections, meaning that *if* people decide to emit this much CO_2, *then* these consequences are likely to occur. None of the scenarios is considered to be more or less likely than the others. There is no "official best guess" for how much CO_2 future societies will actually emit. Nevertheless, many people express skepticism that actual emissions can fall as fast as envisioned in RCP2.6. At the same time some economists are very skeptical that there are enough coal reserves in the world to actually reach the extremely high levels of emissions projected under RCP8.5, especially in the 22nd Century.

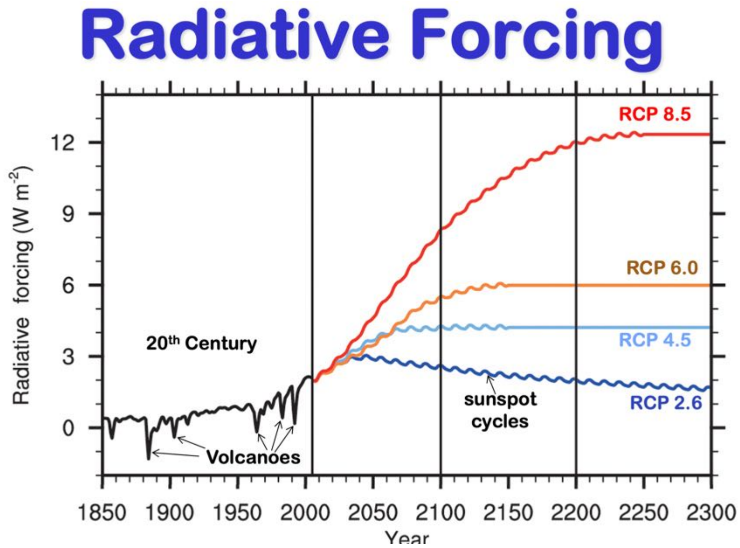


Figure 8-3: Radiative forcing resulting from GHG emissions in four RCPs considered by IPCC AR5

Projected radiative forcing of climate for each of the RCPs is shown in Fig 8-3 all the way out to the year 2300, along with historical values in the 20th Century. Under RCP2.6, radiative forcing peaks a few decades from now and slowly declines. Under RCP 8.5, radiative forcing continues to rise for almost 200 years from now, reaching a staggering 12 W m^{-2}. Recall from Module 5 that the radiative forcing associated with deglaciation following the Last Glacial Maximum was about 6.5 W m^{-2}. That last great global warming took 100 centuries and rewrote the face of the Earth. Sea levels rose 400 feet and both coastlines and vegetation zones were radically reshaped. Under RCP8.5, we are on the verge of climate forcing nearly twice that strong but 50 times faster!

In the most recent IPCC Assessment (AR6), climate scenarios are no longer called Representative Concentration Pathways (RCPs) but are instead referred to as Shared Socioeconomic Pathways (SSPs, Table 8-1). They are very similar to RCPs in practice but each SSP has two numbers in its name. The first number is now the approximate amount of global mean warming (in Celsius) projected by 2100, and the second carries the radiative forcing just as the RCPs (but without the decimal point. An additional scenario (SSP1-19) was considered in IPCC AR6 in which emissions fall even faster than SSP1-26.

Table 8-1: Comparison of scenario names in IPCC AR5 vs IPCC AR6

Scenario Name		Conditions in 2100	
in AR5	in AR6	~ Warming (ºC)	Forcing (W m^{-2})
RCP2.6	SSP1-26	1	2.6
RCP4.5	SSP2-45	2	4.5
RCP6.0	SSP3-70	3	7.0
RCP8.5	SSP5-85	5	8.5

8.2. Warming

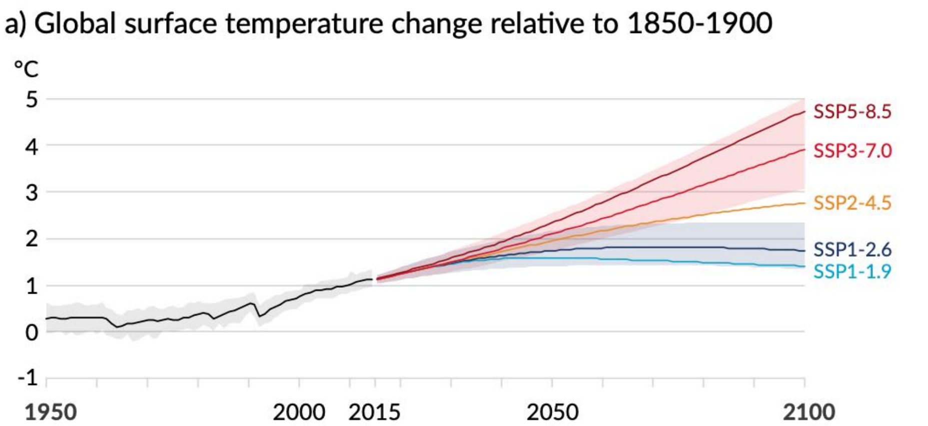


Figure 8-5: Global warming projections for five GHG emission scenarios in IPCC AR6 (2022)

Global average warming relative to late 19th Century is indicated for five different emission scenarios in Fig 8-4. The range of possible future warming is enormous, with the low emission scenarios essentially stabilizing global temperature near today's conditions and the high emission scenarios branching into a radically different world from today. The spread in projected global mean warming among dozens of participating Earth system models is shown as a colored band for SSP1-26 and SSP5-85. These uncertainty bands are large, but the biggest source of uncertainty in future climate change is the "scenario uncertainty" (the different pathways themselves). In other words, the biggest source of uncertainty in our future is the decisions we and our successors make regarding GHG emissions. Note that the names of the scenarios don't

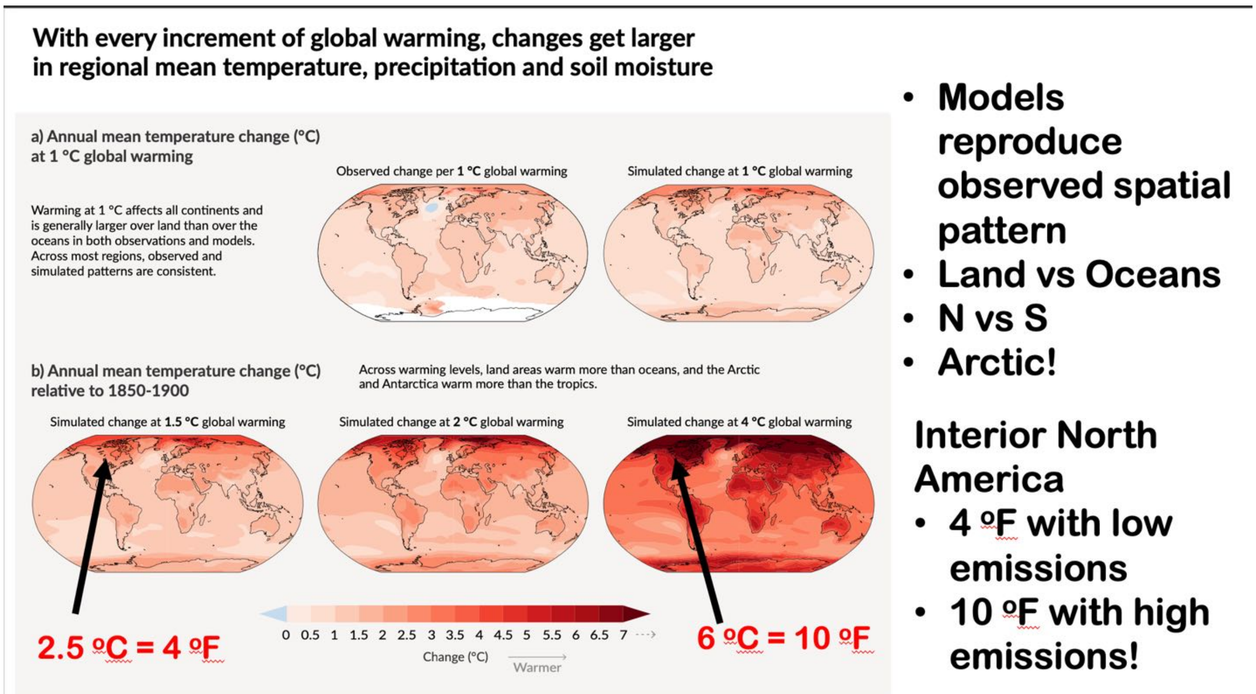
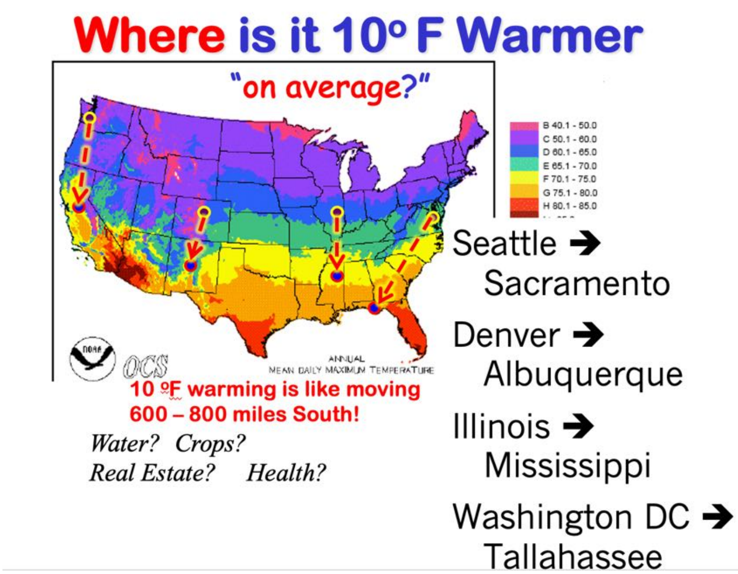


Figure 8-4: Spatial patterns of global warming in observations and with different levels of global warming (IPCC AR6, 2022)



exactly correspond to the global warming in 2100. For example, SSP3-7.0 warms about 4 ºC and SSP2-45 warms almost 3 ºC.

Projected spatial patterns of warming from Earth system models show marked differences in different regions (Fig 8-5). As we saw in Module 7, warming is more intense over land because much of the heat added to the ocean surface is used to evaporate water rather than change the air temperature. The Northern Hemisphere warms more than the Southern Hemisphere because of the very unequal distribution of land. The Arctic warms more than anywhere else. These spatial patterns of warming in the observations are very well reproduced in the models (top panels in Fig 8-5). These spatial patterns persist as global warming intensifies in the higher emission scenarios, but the patterns are amplified (lower panels of Fig 8-5).

Because of our northern continental location, the interior of North America is both observed and projected to warm about 50% more than the global mean (2.5 ºC when global warming is 1.5 ºC, 6 ºC when global warming is 4 ºC). On the Fahrenheit scale commonly used in the United States, this means projected warming of about 4 ºF under SSP1-19 and about 10 ºC under SSP3-70.

Even 10 ºF of warming may not sound like much but consider how far you'd have to move to find average high temperatures 10 ºF warmer than where you live. In much the United States, this would require moving 600 to 800 miles south. An Illinois farmer suddenly transported to Mississippi would need to grow different crops and use different equipment.

8.3. Sea Ice

The Arctic is an ocean surrounded by land and the Antarctic is land surrounded by ocean. Arctic sea ice at the end of summer has already shrunk by about half since the mid-20th Century, exposing open water about the size of India to absorb summer sunlight and add heat to the Arctic atmosphere.

Under the lowest emission scenarios, Arctic sea ice is expected to stabilize in the next few decades (Fig 8-6). Under all other scenarios, the late summer Arctic Ocean is projected to be practically ice-free by the

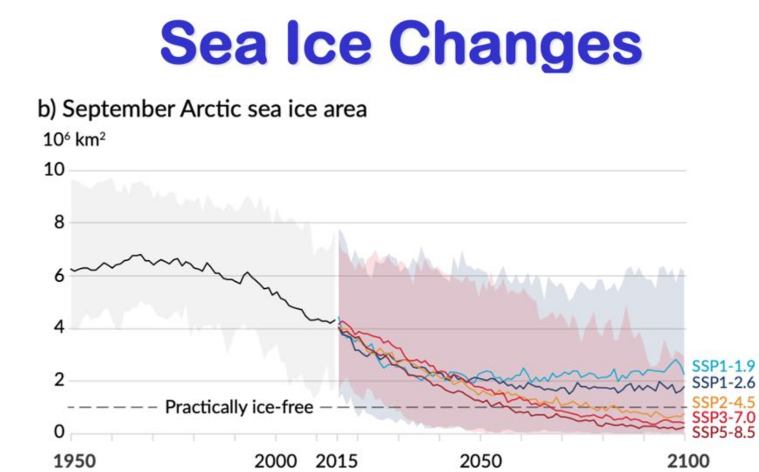


Figure 8-6: Changes in September sea ice in the Arctic Ocean as observed and projected under SSP scenarios (IPCC AR6, 2022)

2070s. This would have profound effects on fish, wildlife, cloudiness, shipping, erosion, and all other aspects of life in the far north.

8.4. Changes in Precipitation, Drought, and Water Stress

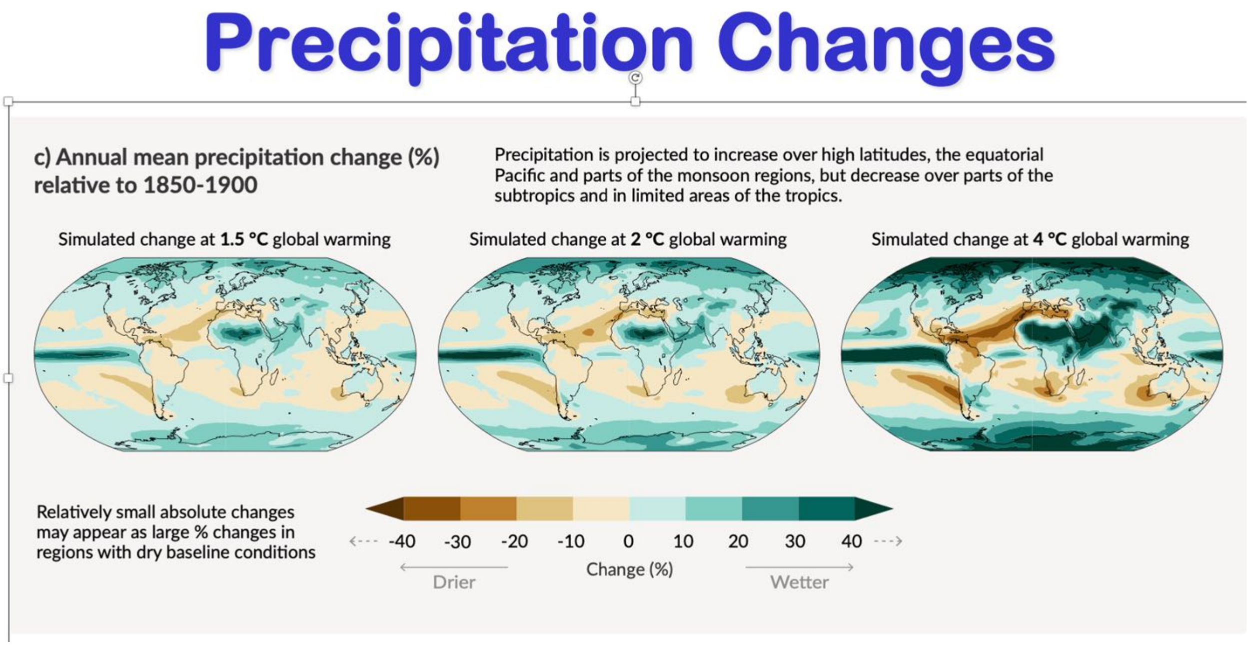
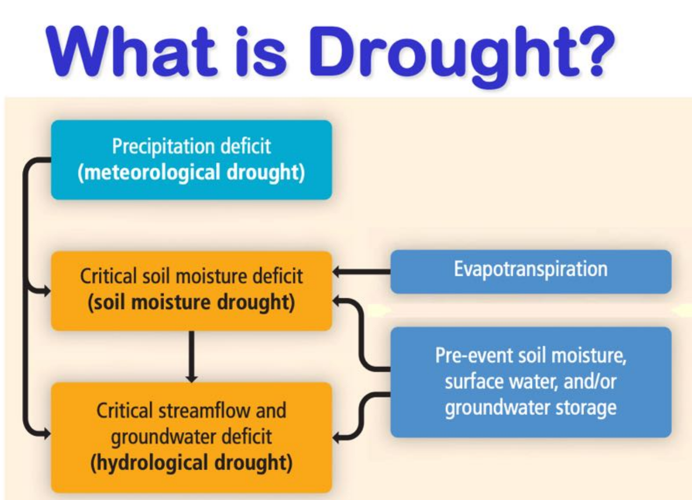


Figure 8-7: Geographic patterns of projected changes in precipitation

Overall, *global precipitation must increase in a warmer climate* because increases in evaporation from the oceans lead to extra water vapor to be rained out of the atmosphere. But spatial patterns of observed and projected precipitation are complicated (Fig 8-7). Like temperature, the geographic patterns of precipitation change in a warming world are pretty robust but become amplified as warming increases.



Precipitation is projected to increase over the high latitudes, the tropical Pacific, and the monsoon regions of India and Africa. Conversely, precipitation is projected to decrease over much of the subtropics where many arid regions are located. This pattern has been called “the wet get wetter and the dry get drier (WWDD).” Notable exceptions to the WWDD patterns are the Sahara Desert and the Amazon Rainforest. The maps in Fig 8-7 are expressed in percent changes to the current climate. Since little rain falls in the Sahara the large percentage changes depicted there are still small amounts of rainfall. But drying of the Amazon could be catastrophic for forests and feed back to cause huge changes elsewhere too.

Among the most serious impacts of warming climate is drought and water stress. Drought is commonly imagined as a shortage of rainfall. But drought is also affected by water losses through evaporation and transpiration (evaporation through plants). Evaporative demand increases exponentially with air temperature (about 7% per ºC), so a warming climate dries out soil and plants even if precipitation remains constant.

Anybody who has watered a lawn or garden knows that more water is required in hot than in cool weather. This also applies to farms, pastures, and forests. The flow of water in rivers and water storage in reservoirs and wells depends not only on precipitation but also on temperature ad evapotranspiration losses.

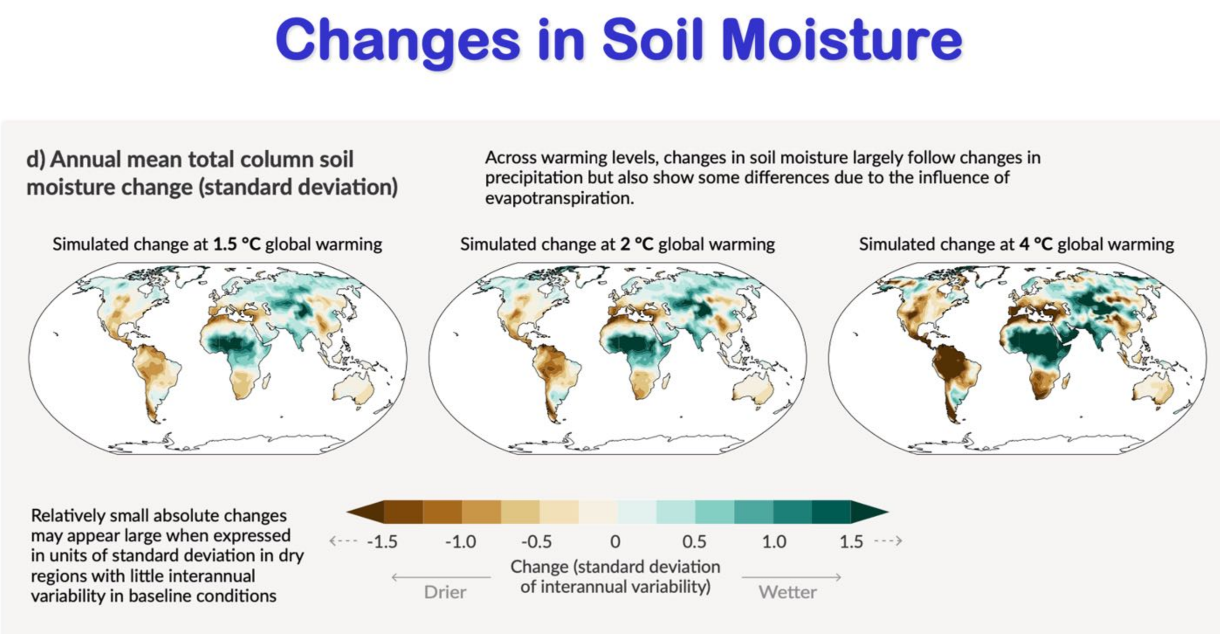
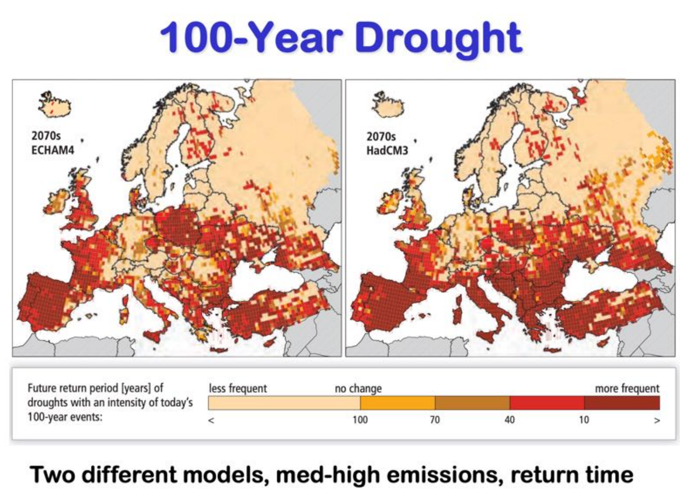


Figure 8-8: Projected geographic patterns of changes in soil moisture. IPCC AR6 (2022)

Projected changes in soil moisture under a warming climate are more extensive and severe than changes in precipitation (Fig 8-8). These changes include the effect of the increased evaporative demand of warm air. Whereas most of North America is projected to experience increased precipitation, soil moisture deficits are projected over huge areas. Soil moisture deficits are projected to become more extreme with increased warming and to cover huge areas of the world. The Amazon rainforest, southern Africa, western North America, east Asia, and the Mediterranean

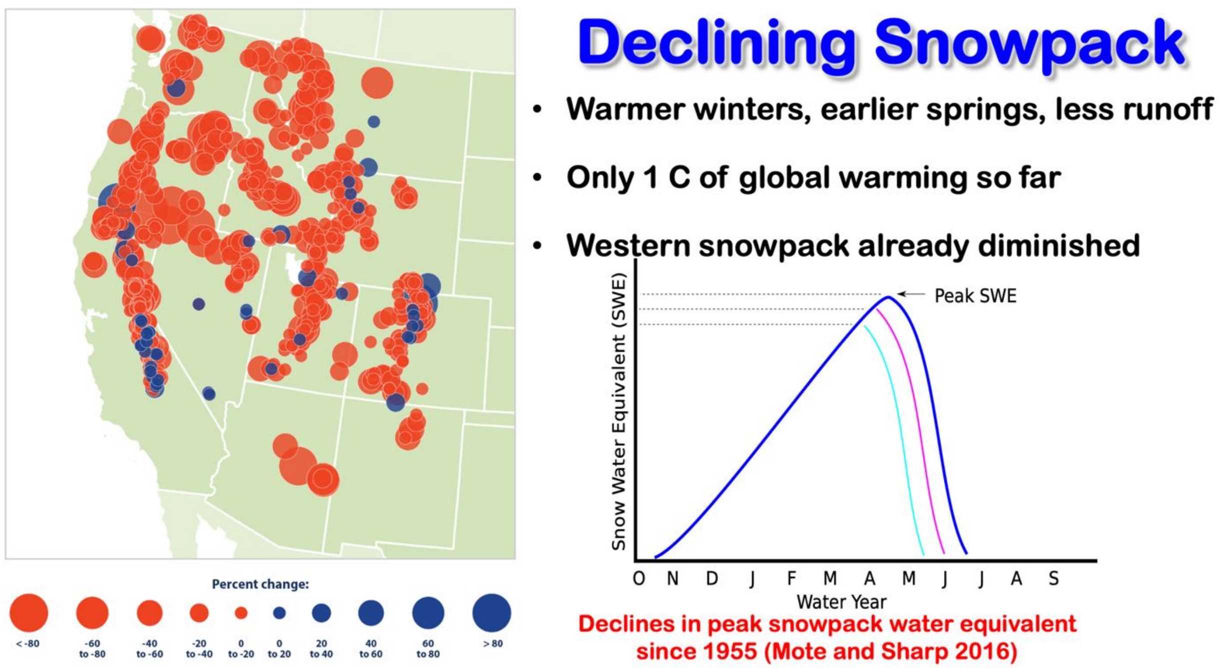


region are projected to be especially hard-hit. By the 2070s under a moderately high emissions scenario, southern Europe is projected to experience droughts equivalent to today's "worst drought of the century" more than once per decade.

8.5. Mountain Snowpack

Like continental ice sheets, mountain snowpack accumulates slowly and melts quickly. It takes all winter to build a snowpack at the rate water can be transported from the oceans and deposited in the high country. But the rate of melting is limited only by the delivery of heat and sunlight in high summer.

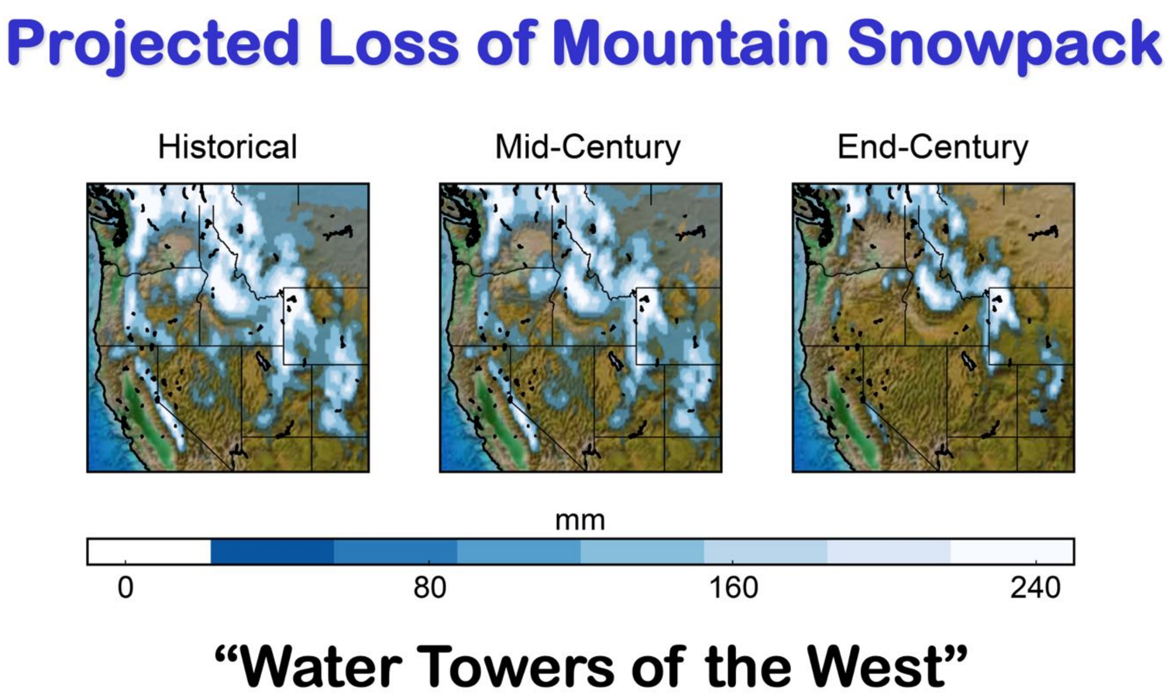
As climate warms, snow accumulation starts later and melting begins earlier, leaving fewer weeks to build winter snowpack. Warm dry spells in winter cause snowpack losses due to



melting or evaporation, and rain-on-snow events can severely erode stored water.

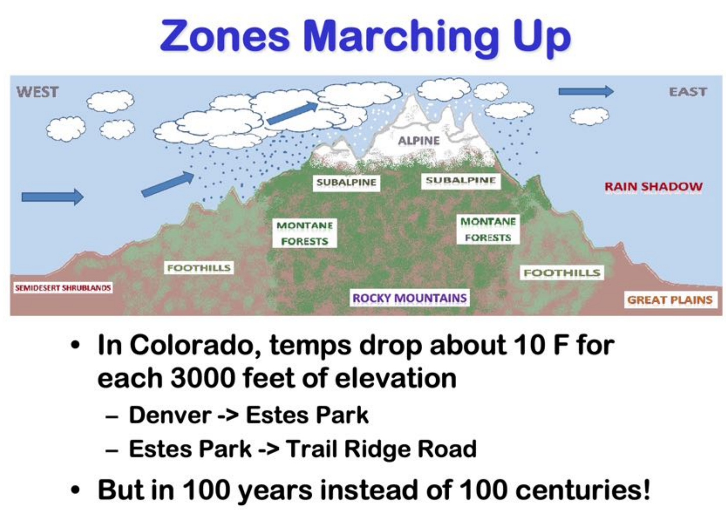
The United States Department of Agriculture maintains more than 800 mountain stations across the western US at which snow water equivalent has been measured every day for decades. Most show significant declines in peak spring snowpack water with only the small amount of warming to date. Hundreds of stations have already lost half of their peak spring snowpack.

Projections of mountain snowpack show severe losses developing in the American Southwest and progressing northward through the Rocky Mountains throughout this century. Meltwater from mountain snows is the primary source of water for forests, pastures, rivers, reservoirs, and cities across the intermountain west.



8.6. Wildfire and Landscape Conversion

In complex, mountainous terrain the average temperature drops about 6 ºC for every 1000 meters of elevation. In US units this translates to about 10 ºF per 3000 vertical feet. As we’ve seen above, 10 ºF of projected warming in the interior USA can be expected for moderately high emissions (SSP3-70). This corresponds to average temperatures climbing about 3000 vertical feet up the mountain landscape.



During the last great global warming that began at the end of the last Ice Age, temperatures warmed about 10 ºF over 100 centuries. Forests slowly migrated up the mountains and alpine tundra was nearly eliminated in all but the highest ranges. Vegetation zones can change only slowly as individual trees grow and die and seed new generations.

Modern global warming may be comparable in magnitude to warming during post-Ice Age deglaciation, but in one or two centuries rather than 100 centuries! There is no time for forests and grasslands to migrate up the mountains. Instead, climate is projected to race ahead of the vegetation zones, stranding forests in climates that are much too warm and dry to sustain trees.

The result of very rapid warming of forest landscapes is wildfire.

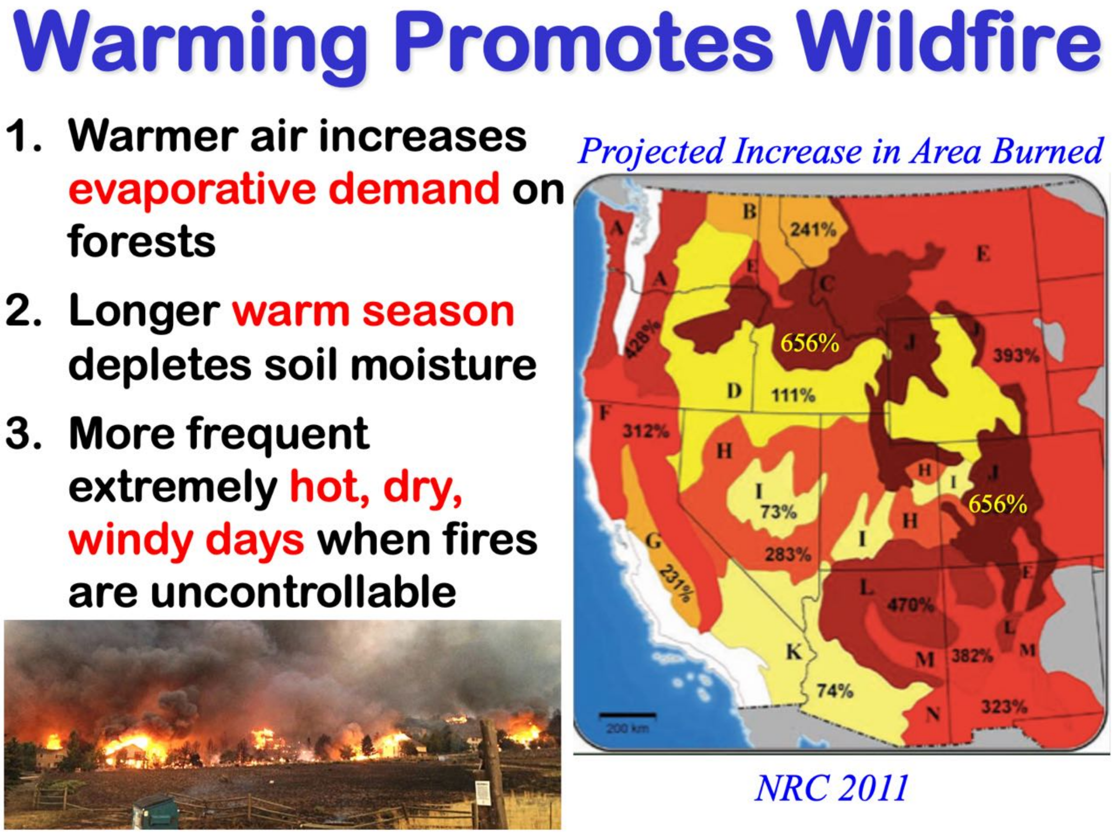
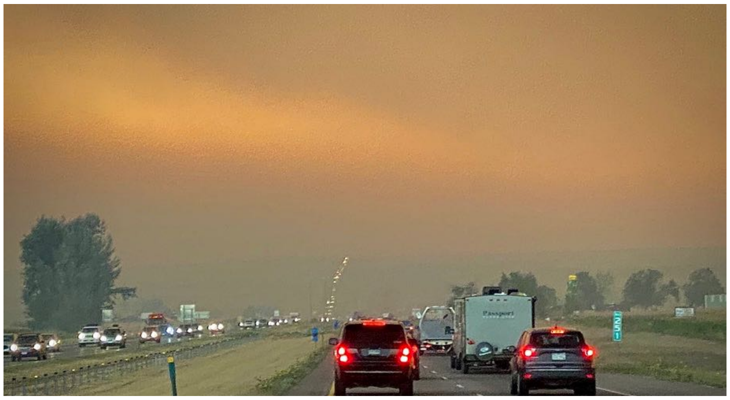


Figure 8-9: Impacts of warming on wildfire in the US Intermountain West

Most forests in the intermountain west consume more water through transpiration during the summer than they receive as summer rainfall. This works because they make up the difference in fall, winter, and spring when transpiration is minimal. High elevation forests accumulate most of their annual precipitation in huge snowpacks that store a meter of more of water consisting of many months' worth of precipitation. In late spring and early summer snow melts rapidly and completely saturates soil moisture storage, which represents the reservoir from which trees draw water when rainfall is insufficient during hot summer months.

In the warmer climates of the future, transpiration is projected to increase exponentially with rising summer temperature, so that the daily draw on soil moisture reserves will increase. The spring snowmelt already exceeds soil moisture storage capacity (leading to the infamous "mud season" during spring runoff), so increased summer transpiration inevitably produces water stress in late summer and early fall when soils can't supply evaporative demand. During this



Traffic on Interstate 25 in Northern Colorado at 2 PM on September 6, 2020

time, forests become vulnerable to wildfire as fuel dries out, and the fire season will get more severe as trees use the stored winter water more rapidly in a warmer climate.

As explained in the previous section, warming also “eats into” the snow accumulation season from both ends (fall and spring), so that spring runoff comes earlier and earlier with increased temperatures. Peak runoff in the Colorado Rockies already occurs three weeks earlier than it did in 1980, and the region has only felt about 1 °C of warming. Shortening the snow accumulation season and reducing peak snowpack water inevitably lengthens the season during which trees draw from the stored spring soil moisture reservoir. This leads to more and more weeks of fire vulnerability due to extremely dry fuels and drought-stressed trees in late summer.

Moreover, the frequency of occurrence of extremely hot, dry and windy days that promote extreme fire behavior is dramatically higher during warmer summers. These are the days in which wildfires become uncontrollable and fires advance by many miles. Firefighters are forced to withdraw, residents evacuate, and hundreds or even thousands of homes burn. Millions of people are exposed to unhealthy levels of smoke from wildfires as it spreads across the region.

In a landmark report, the National Research Council (2011) projected that the annual area burned by wildfire across the intermountain western USA would increase exponentially with warming. Especially vulnerable are forests across the Rocky Mountains in which annual burned area is projected to increase more than 600% per degree Celsius of warming. Given that high-emission scenarios project warming in excess of 6 °C for the region, this implies increases of more than 36x in wildfire area. Given that a century or more is required to regrow mature forests following stand-replacing fire, this suggests a total loss of these forests in the 21st Century under high-emission scenarios.

My back yard at noon on September 7, 2020

8.7. Rising Sea Levels

Just as the impacts of global warming some regions is tied to a *shortage of water* to meet demand, many other regions are projected to be impacted by *too much water*.

Global sea levels rise through two separate mechanisms:

1) Thermal expansion causes ocean water to occupy more volume;
2) Melting of glaciers and ice sheets *on land* adds water to the oceans.

It's important to note that *melting sea ice does not contribute directly to rising sea levels*, because the water in icebergs and pack ice is *already* in the ocean. In fact the volume of water displaced by floating ice is precisely the same as the volume of meltwater that results when ice melts. (This is why your glass of iced tea does not overflow when it's left on the picnic table).

Sea levels have already risen about 25 cm (10 inches), mostly due to thermal expansion of seawater. Ice sheets in Greenland and Antarctica have begun to melt and this has added water to the oceans, but this process is extremely slow. Only very recently has melting land ice caught up to thermal expansion in raising sea level. Projecting future changes in continental ice sheets is very difficult, and these projections are the main source of uncertainty in future sea level rise. Once started, the disintegration of continental ice sheets can accelerate and may last for many thousands of years as occurred at the end of the Last Ice Age (Fig 8-10).

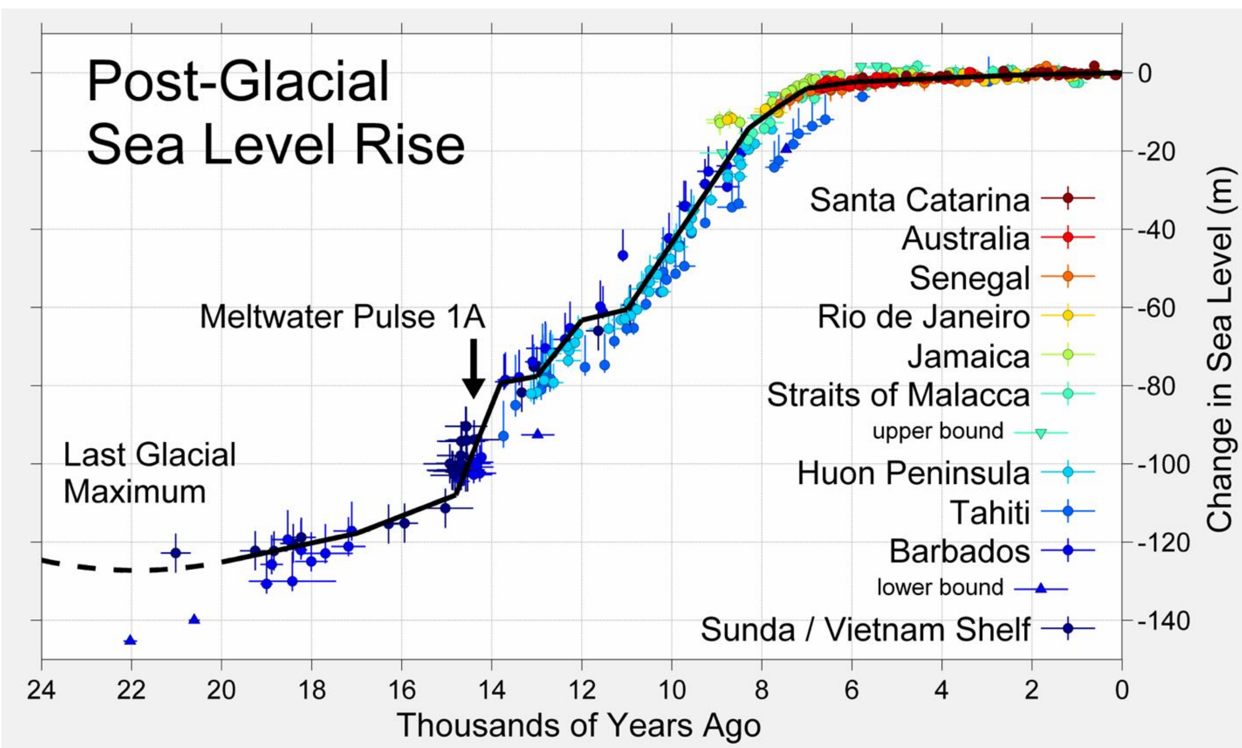
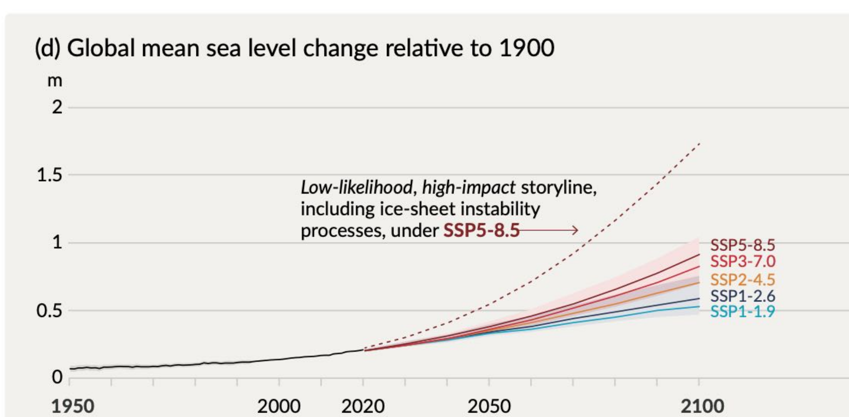


Figure 8-10: Global changes in sea level during the last great global warming following the last Glacial Maximum 18,000 years ago. Oceans rose about 120 meters (400 feet) in 10,000 years as ice sheets in North America and wester Eurasia collapsed and melted.

During the last great global warming, melting of continental ice sheets took dozens of centuries with a similar amount of warming as projected for SSP5-8.5, so it's hard to imagine modern ice sheets to collapse in a matter of decades. As a caution, modern warming is dozens of times faster than deglaciation. During the most rapid collapse of ice sheets around 14,000 years ago (Meltwater pulse 1A, Fig 8-10), global sea levels rose 30 m (100 feet) in just 400 years. That's 30 inches per decade for 40 decades in a row! The level of social, economic, and political catastrophe such a rapid encroachment of the sea would impose on today's world is unfathomable.

Global sea levels are projected to rise by 0.5 to 1.0 meter in the 21st Century relative to 19th Century conditions, depending on emission scenario (Fig 8-11). Note that even under low emission scenarios in which warming stops, projected sea levels continue to rise. IPCC also considered a low-likelihood, high-impact scenario in which sea level rise accelerates, leading to catastrophic flooding over the coming decades.

Once continental ice sheets begin to melt, positive climate feedbacks tend to accelerate sea level rise. Even under the lowest emission scenarios, IPCC AR6 projects that global sea level will increase by up to 10 feet over the next 200 years. Under high emission scenarios, seas are projected to rise 2 to 7 m and even 15 m is possible (Fig 8-11).



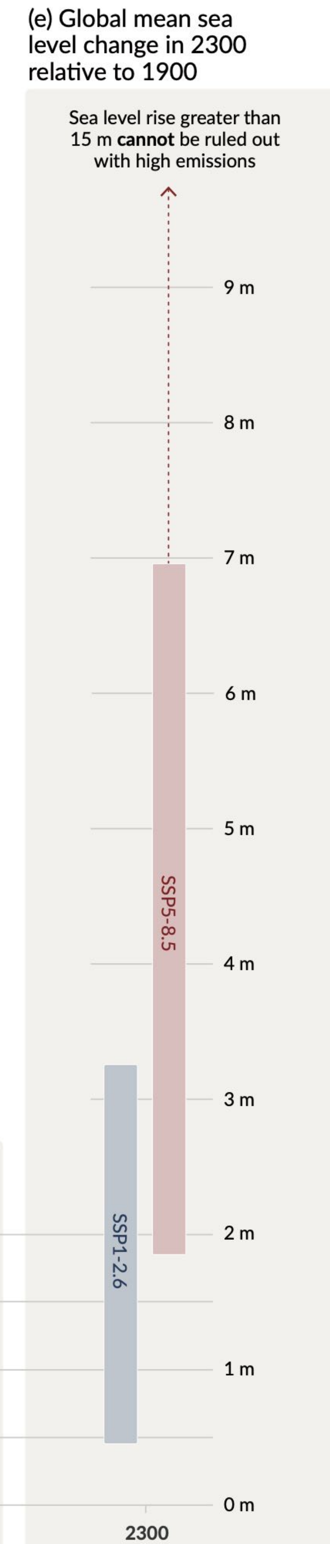


Figure 8-11: Sea level projections for various emission scenarios during the 21st Century (left) and in 2300 (right). IPCC AR6 Summary for Policymakers (2022).

8.7.1 Coastal Flooding

Changes in sea level are not projected to be uniform. Changes in local and regional sea level differ from changes in global average sea level because of rising and falling of land levels (coastal subsidence) as well as inherent "lumpiness" in the surface of the oceans due to thermal expansion, winds, and currents. Sea levels along the coast of the United States are projected to rise between zero and six feet by 2100 (Fig 8-12).

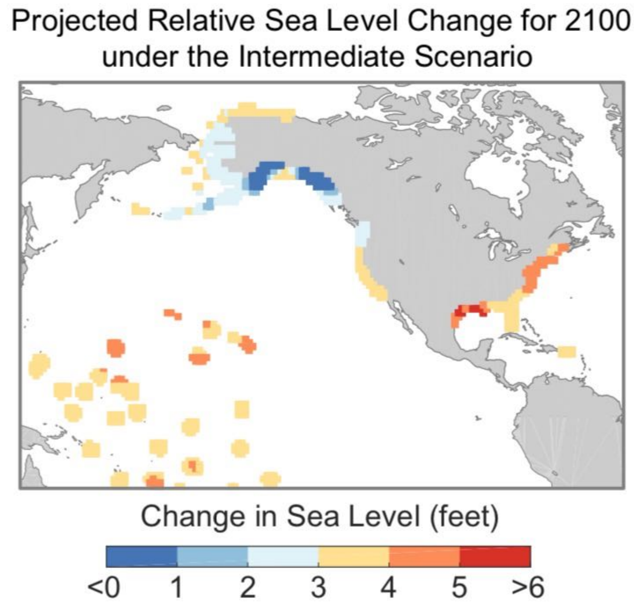
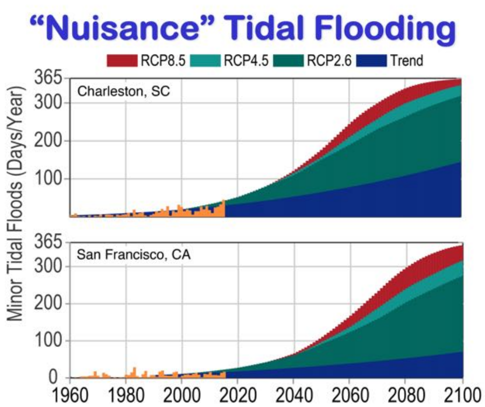


Figure 8-12: Projected sea level rise in North America. US 4th National Climate Assessment (2017)

We have seen in Module 6 that a rise in mean temperatures produces a dramatic increase in the frequency of extreme temperatures due to the shape of the "bell curve." Similarly, an increase in mean sea level produces dramatic increases in the frequency of coastal flooding. Even under low emission scenarios, the US National Climate Assessment projects that tidal flooding (floods arising just from high tides without any storm) will occur nearly every day in Charleston SC and San Francisco CA. These projected changes are three to five times the frequency that would be expected by just extrapolating historical trends, because the mean sea level is projected to rise several feet.



8.7.2 Storm Surge Flooding

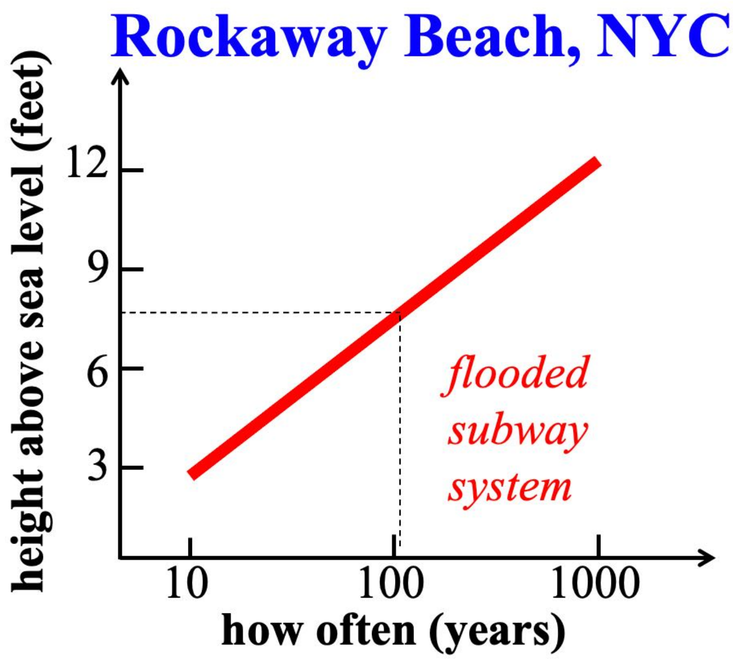
Storm surge is a dome of high water that is pushed ashore by winds during strong storms at sea. Storm surge temporarily raises mean sea level and is overtopped by both high tides and waves generated by the storm. In combination with flooding from heavy rainfall, storm surge flooding accounts for most deaths and property damage in big coastal storms like hurricanes.

Statistical analysis of historical coastal floods typically show a nearly linear increase in the depth of floodwaters vs the logarithm of the "return time" (Fig 8-13). For example, historical flooding at Rockaway Beach, NY shows that floodwaters are typically 3 feet deep about once a decade, 8 feet deep about once per century, and about 12 feet deep once per millennium. The slope of this line reflects the historical behavior of storms, the shape of coastline, and the depth of the near-shore sea bottom. Most coastal locations have similar statistics although the slope of the line can vary.

The trouble with sea level rise is that the line shifts up!

Even without any change in the frequency or behavior of storms, adding 3 feet to the coastal flood to account for a rising baseline means that floods of a given depth happen much more frequently.

In the case of Rockaway Beach, the once-in-a-century storm surge that flooded the New York City subway system with seawater during Hurricane Sandy in 2011 would become a once-per-decade event.



Damage from Hurricane Sandy to house in Brooklyn, NY. October 30, 2012. Image credit Proud Novice. CC-BY-SA-3.0

It's critical to understand that like the behavior of extreme heat waves for a shifting bell curve of temperature, this projection of increasingly damaging floods has nothing to do with future storminess or intensity. Rather, it's simply a function of the underlying statistical frequency of historical storms if floods start from a higher baseline.

Enormous areas of the United States coastline are already at risk of storm surge flooding, and projections indicate that the frequency of damaging floods is likely to increase tenfold or more in this century due to rising sea levels. The heavily populated Atlantic coast of the US Northeast is especially vulnerable. The Gulf Coast is also highly vulnerable because global sea level rise is exacerbated by coastal subsidence and because so many shipping ports and oil and gas infrastructure are located at very low-lying points along this coast.