Clearway

CLIMATE SCENARIO ANALYSIS

A REPORT BY

Climatrends

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Climate Scenario Analysis – Clearway Energy Group

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Paul Douglas is a Penn State meteorologist with over 45 years of television and radio experience. A serial entrepreneur, Douglas is Founder and Chief Meteorologist at Praedictix, providing weather services, consulting and briefings for media and corporate interests. Developers and engineers create unique streams of weather data, imagery and API's for corporations via AerisWeather. The latest science and models are leveraged to provide insight for corporations factoring climate trends into investment, resilience and sustainability via ClimaTrends. Douglas is a member of the Climate Science Rapid Response Team. In 2017 he co-authored a book on climate, focused on matters of faith and science: "Caring for Creation, the Evangelical's Guide to Climate Change and a Healthy Environment". Featured in NOVA's "Decoding the Weather Machine", Douglas has spent the last 25 years connecting the dots between climate volatility and weather disruption. Today ClimaTrends provides company-specific climate scenario analysis and TCFD financial risk disclosures for businesses determined to stay ahead of a rapidly changing climate.

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Susie has worked with Paul Douglas for over a decade as a meteorologist and general manager. Susie has trained as a forensic weather consultant and continues to serve as the lead consulting meteorologist at Praedictix. Susie has served as a weather expert in dozens of cases across the country over the last 5 years writing forensic weather analyses and presenting her work in court. Her expertise in reporting and analysis allows her to construct in-depth research on the impact of climate change on businesses and presents it in a way that is digestible and relevant. Susie grew up in Costa Rica and is bilingual (English/Spanish). She is a cum laude graduate of the University of Miami (2005) and holds a Bachelor of Science in Meteorology & Mathematics. She is currently a Certified Broadcast Meteorologist (CBM) and is on the CBM reviewing panel for the American Meteorological Society. Susie is currently working on completing the American Meteorological Society's Certified Consulting Meteorologist program.

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Josh Prigge is a sustainability consultant, college professor and public speaker with over a decade of experience managing sustainability programs and initiatives for large organizations. Prigge is the founder and CEO of Sustridge, a Las Vegas-based sustainability consulting firm with a single mission: to help organizations of all sizes become sustainability leaders. Josh also produces and hosts the popular podcast, Sustainable Nation, interviewing global leaders in sustainability every week. Prior to founding Sustridge in 2017, Prigge worked as the Director of Regenerative Development at Fetzer wine company, Sustainability Coordinator at Hawai'i Pacific University and served as President of the Sustainability Association of Hawai`i.

Josh Prigge's work has been featured in publications such as Forbes.com, The Guardian, The Huffington Post and Triple Pundit, and he has presented at numerous sustainability conferences and events around the world including the UN COP21 Paris Climate Conference, Sustainable Brands Conference, Ceres Conference, and B Corp Champions Retreat among many others. In 2017, Josh was recognized as a top fifty sustainability leader in the business sector by receiving the Environmental Leader 50 award, followed by an E+E 100 award in 2019.

Prigge received a Master of Arts in Global Leadership and Sustainable Development and a Master of Business Administration from Hawai'i Pacific University, as well as certified training in Global Reporting Initiative (GRI) sustainability reporting, LEED Green Associate accreditation, TRUE Zero Waste Advisor accreditation and Building Operator Certification (BOC) for energy efficiency in commercial buildings.

EXECUTIVE SUMMARY

This report communicates the results of a climate scenario analysis conducted for Clearway Energy Group, looking at three different future climate scenarios and the associated physical and transitional risks associated with each. The three 2050 scenarios include a Sustainable Futures Scenario (less than 1.5 degree global temperature increase), a 2-Degree Scenario (2 degree global temperature increase) and a Current Policies Scenario (business as usual resulting in 3 degree or higher increase in global temperature). Each of these future scenarios paints a different picture of the world in 2050 and allows Clearway Energy Group to assess their current strategy against each of them.

Scenario Name	Temperature Rise Expected	GHG Trajectory	WEO Scenario
Sustainable Future Scenario	.3 – 1.7	RCP 2.6	Sustainable Development Scenario
2 Degrees Scenario	1.1 – 2.6	RCP 4.5	Stated Policies Scenario
Current Policies Scenario	2.6 – 4.8	RCP 8.5	Current Policies Scenario

For each scenario and expected temperature rise, we identify reputable sources that project future physical and transitional changes associated with those temperature increases. For the physical impacts we pull data from the Intergovernmental Panel on Climate Change (IPCC) reports that have produced future impacts of various greenhouse gas (GHG) emissions trajectories known as Representative Concentration Pathways (RCP). For the transitional impacts, we source information from the International Energy Agency's World Energy Outlook 2019 report, which has created future energy scenarios around expected temperature increases.

Physical risks represent natural climate and weather impacts that may be present in the future as a result of an increase or decrease in global temperatures such as extreme weather, sea level rise, flooding, precipitation, wind strength, extreme heat and other climate impacts. Transitional risks are other risks associated with an increase or decrease in global temperatures such as changes in energy use, changes in technology, changes in consumer behavior and changes in policies that might be needed to achieve the associated temperature increase or decrease.

The news for renewable energy is generally good, with a few caveats. A trend toward less cloud cover should be a net positive for the solar industry this century. But a wildcard remains with a potential for more dust, especially in the southwestern USA, where drier soils may spawn more dust storms. Wind speeds have been increasing since 2010, and that trend should continue beyond 2030. But the longer-term trend still calls for a gradual easing of winds during the latter half of the 21st century.

A warmer climate is flavoring all weather now. There is more water in the atmosphere to fuel garden-variety thunderstorms, as well as the most violent hurricanes. This is no longer theory; the thumbprints of a warmer, more volatile climate are becoming harder to dismiss and deny with every passing year. Confidence levels are high that flooding events will become more frequent and severe, especially over northern tier states, from The Dakotas to New England. 1 in 1000-year floods are already popping up with alarming frequency, with more flooding in areas that aren't even in the flood plain, well away from rivers and streams.

Even if we could somehow stop all greenhouse gas emissions from the burning of fossil fuels, magically slow the rate of deforestation and implement best practices that release less CO2 from farmland into the atmosphere, previous and current emissions mean we will likely have continued warming of at least a couple degrees Fahrenheit into mid-century. This is the tip of the (melting) iceberg.

The extended outlook calls for maximum resilience: new methods, materials and best practices that enable business-as-usual, no matter how extreme weather patterns become. Cities, corporations and a small and growing army of people, many of them young and worried for their future, are already demanding change. With new technologies, an almost inevitable price on carbon and less skepticism from elected leaders, a worst-case (RCP 8.5) scenario may be avoided.

The only constant is change, diligence and informed, methodical preparation for what comes next.

Paul Douglas
ClimaTrends
Founder, Meteorologist, and Climate Analyst

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KEY TAKEAWAYS

Summary of Trends Seen Across Scenarios

General climate impacts:
- Extreme heat waves are hotter, lasting longer: HIGH confidence.
- Droughts are becoming more severe over time: HIGH confidence.
- Floods are more prevalent, setting more records with heavier rainfall totals: HIGH confidence.
- Wildfires are burning longer and hotter, affecting a greater percentage of land: HIGH confidence.
- Tornado Alley may be shifting over time: LOW — MODERATE confidence.
- Hail frequency and intensity is being impacted by a warming world: LOW confidence.

Wind Production: Generally, a slow increase in wind speed and wind gusts is expected to continue in the short to medium-term. Long-term, mean wind increases are projected for the southern US (Texas to California) with potential declines in the eastern US.
- Summer to bring increase in wind for southern U.S.
- Fall morning wind speed projections: decrease in eastern US, northern Plains, and Pacific Northwest. Increase for Texas and California.
- Confidence beyond 2040-2050 are low to moderate.

Solar Irradiance: Generally, long-term outlook suggests greater variability with potential increases & decreases of up to 10% by 2060.
- Winter: Increase for southern U.S. with decreases from Upper Midwest to the Great Lakes and New England.
- Spring: Increase in west coast and parts of New England with decreases in the central U.S.
- Summer: Increase for most of the country—greatest in PNW, Upper Midwest/Great Lakes into New England.

Precipitation: Fewer days with precipitation overall, but when it does rain (or snow) precipitation intensities and amounts will increase. An "all-or-nothing" weather pattern.

Extreme Heat: More than 95% of the land surface of the contiguous United States has warmed since 1986.
- Warming is greatest and most widespread in winter.
- Daily extreme temperatures are projected to increase substantially in the contiguous United States, particularly under the higher scenario (RCP8.5).
  - Frequency of heat waves most jarring in the southern U.S.: 20–30 more days per year with a maximum over 90°F (32°C).

Dust Trends: The frequency of dust storms in the southwest USA has more than doubled since the 1990s — from 20 per year to 48 in the 2000s — and will likely continue to increase.

Wildfire Trends: Fire weather seasons have lengthened across 11.4 million square miles—about the size of Africa, and 25.3 percent of the Earth's vegetated surface—resulting in an 18.7 percent increase in global mean fire weather season length.

Severe Weather: Scientists predict an increase in thunderstorms with straight-line winds, with more derechos (long-lasting, violent windstorms that cover hundreds of miles before dissipating).
- A warmer, wetter world should increase hail frequency and size across parts of the United States.

Hurricanes: We may not see an increase in the total number of hurricanes that form every year, but the hurricanes that do form will be bigger, wetter, windier.

Potential Business Implications of Climate Trends

Extreme Heat

Solar – Where inverters are in enclosures, protecting them from extreme temperatures, they are more resilient to temperature changes than those that are exposed.

Exposed inverters are more susceptible to temperature derating due to high temperatures. CEG will want to assess where exposed inverters are operating in areas expected to have extreme heat.

Solar Modules – Modules are not as susceptible to temperature increase as inverters, so solar modules should not be impacted by extreme heat.

Wind Turbine Generators – Different WTG have various susceptibility to temperature derating. Extreme heat can reduce production of turbines. In WTGs liquid cooled system vs. air cooled system have better performance in areas of extreme heat.

Electronics in WTG are generally only rated to about 104°F. High temperatures may cause exceedance of their ratings and production issues.

Generators and gearboxes can experience deratings due to component failures, which can occur more often from temperature extremes. CEG's maintenance cycle may need to increase as more maintenance is needed to address issues due to component failure.

Transformers and Generators – Transformers are fairly resilient to temperature increases.

Labor (operators and technicians) – CEG is already dealing with hot temperatures at their facilities in the Sonora and Mojave deserts. Working more shifts at night may need to be looked at in the future as temperatures increase in these and other areas. Working at night could potentially cause other safety and security issues as well. CEG could also look into workers starting their work day earlier (4am or 5am) to avoid heat extremes.

Increased Precipitation

Solar Modules – Precipitation intensity favors solar because intense rain helps wash the panels, especially if the rain events are more spread out. More panel efficiency may be seen due to cleaner panels. Roads are dirt in many areas so increases in precipitation will decrease accessibility to solar fields.

Wind Turbines – Mobility of employees and workers onsite will decrease from increased precipitation. Roads are dirt in many areas so increases in precipitation will decrease accessibility to WTG.

Equipment – Water intrusion in equipment could possibly be a small issue to keep an eye on. Increasing periodic maintenance activities to maintain seals and gaps in equipment will become more important. Transformers and WTG water intrusion should not be an issue.

Wind Speeds

Wind Turbines – Higher wind gusts could be problematic as some equipment in WTG are vulnerable to damage from high wind gusts. Production could ultimately decrease from heavy gusts causing equipment damage. Increase in average wind over time is good, but not more frequent gusty winds.

Hail

Wind Turbines – According to CEG Operations and Maintenance (O&M) staff, recent hailstorms had minimal impact the on wind turbine generators. "We have inspected the turbines and much to our surprise we haven't found any visual damage since the recent hailstorm. No one was on site when the storm passed thru but golf ball to baseball size hail was reported in the area. Between 5 and 10 years ago we had a similar storm, the turbines did fine but the hail beat out the protective clear cover on several of our FAA lights and dented a few of the cups on some anemometers. Other than that, the turbines have held up very well."

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Winter Weather In Massachusetts

Turbine Blades – Ice builds up on turbine blades and can lead to ice throw, which can be a safety issue and decrease performance of turbines. New WTG models installed at new facilities or during existing facility repowering have software programs to detect ice and shake off the ice before it builds up. This is a new technology that may be advantageous in the future as ice becomes more of an issue.

Solar – CEG has not had difficulty dealing with ice on solar at this point. According to O&M staff, there seems to be a benefit from having trackers in cold weather climate. The trackers allow for snow shedding by tilting to one side to eliminate the buildup of snow. This is far more efficient than the manual method of driving to affected sites and clearing the snow manually. There doesn't seem to be any noted issues with ice on other solar system equipment as most of the main tracker components are enclosed.

Nebraska Droughts

Equipment – Droughts affect panels, cooling systems and filters by contributing to more dirt and debris in the air (currently a problem in Oklahoma). Dust can get in all electronics causing shorts, get in and foul cooling systems, cover panels resulting in lower output and require more cleaning. Nebraska and surrounding locations are generally farmland, so dust can be an issue that may need to be addressed due to increase in droughts.

Safety Concerns – Increased ice and snow around plants will lead to safety concerns for employees and less accessibility to equipment, more slipping and vehicle accidents would be expected.

Wildfires in Southwest

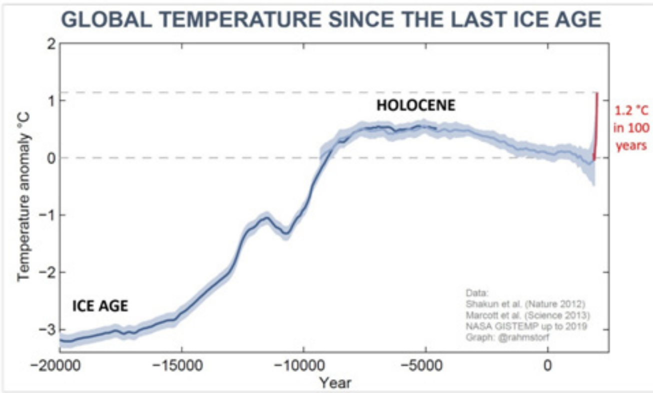
Employee Safety – The safety of employees and workers being the most critical issue to be concerned for with regards to wildfires. These safety concerns involve direct impacts from the fire, but also secondary impacts from smoke inhalation. Fire preparedness programs are currently conducted at the CEG facilities and more training efforts may be prioritized as the threat increases. Employees will likely need to conduct more visual inspections of the surrounding area to identify fires when climbing turbines.

Equipment – Wildfires can cause physical damage to facilities with solar facilities being more vulnerable to fire damage. Wind turbine generator equipment is fairly protected from wildfires due to vegetation normally being cleared from base of each WTG and the protective nature of the tower structures.

At solar facilities fire can damage cabling and solar modules. In addition, smoke in the air from wildfires shades solar panels which decreases production.

1 PHYSICAL RISK ANALYSIS: A MACRO VIEW

Author: Paul Douglas

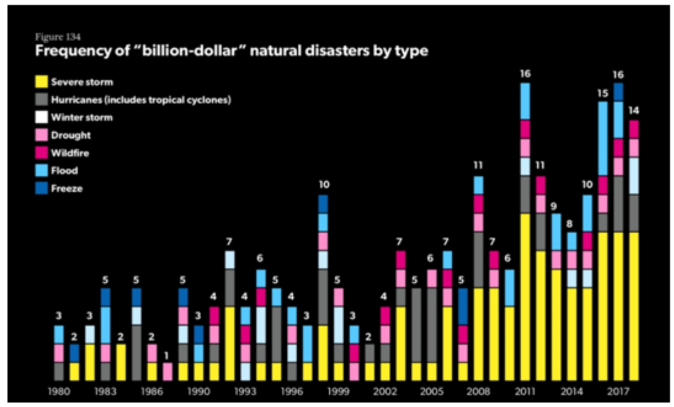


Source: Stefan Rahmstorf. Data courtesy of Shakun, Marcott et al. and NASA GISTEMP

Earth is warming, at a rate faster than any time in the planet's geological history. There have been warmer periods in the past, but scientists confirm the spike in temperature since the mid-1900s is historically unique. The 2F increase in global temperature since 18801 may not seem like much, but climate scientists confirm it took only a 5F worldwide temperature drop to trigger the last age approximately 20,000 years ago. Temperatures are rising much faster at northern latitudes: a 3-4F increase from Maine to Minnesota – as much as 5-8F warmer from Alaska into the Arctic. The uneven nature of the warming may be impacting the configuration and speed of the jet stream steering winds aloft, impacting the movement of weather systems. By some estimates, upper air wind speeds have diminished by up to 12% resulting in a slowing of storms, especially during the warm season. This slowing of weather patterns, coupled with a roughly 8% increase in water vapor overhead (a warmer atmosphere can hold more water), is a recipe for more flooding, which is what data shows across the country and worldwide.

There have always been floods, droughts, storms and wildfires. A warmer climate doesn't trigger these calamities. However, there is a large and growing body of evidence that a warming atmosphere and oceans is making weather events that occur naturally more severe: hotter, longer heatwaves, drier droughts, wetter floods and more severe, long-lasting fires. In essence, we are turning up the volume of the weather. What would have been a bad, 1 in 50-year flood is now a biblical, 1 in 1000-year deluge. Across much of the planet the number of days of debilitating heat and humidity is on the rise. This is a slow-motion transformation on a global scale.

Since 1965, over a trillion metric tons (a trillion hot air balloons) of greenhouse gases have been released through the burning of fossil fuels, adding to the natural chemical blanket of CO2 and methane that warms the planet. We are, in essence, turning up the thermostat, and then sitting back and observing the symptoms of a warmer, more volatile planet.



Source: USA Facts[1]

With climate change we have transitioned from theory to reality. The symptoms of a warmer, wetter world are showing up all around us. Billion-dollar weather disasters are on the rise. Insurance companies report that weather-related losses have tripled since the 1980s, from an average of $10 billion to nearly $50 billion every year. Major disaster declarations are spiking upward. Between 1990 and 1999 there were an average of six emergency declarations in the U.S. annually. From 2000 to 2009 that number jumped up to an average of fifteen major disaster declarations every year.

[1]https://annualreport.usafacts.org/articles/27-transportation-infrastructure-energy-naturalHyper-disasters-experiencing-fire-severe-storm-declarations-hurricanes-remain-dea?utm_source=EM&utm_medium=email&utm_campaign=fireandrain

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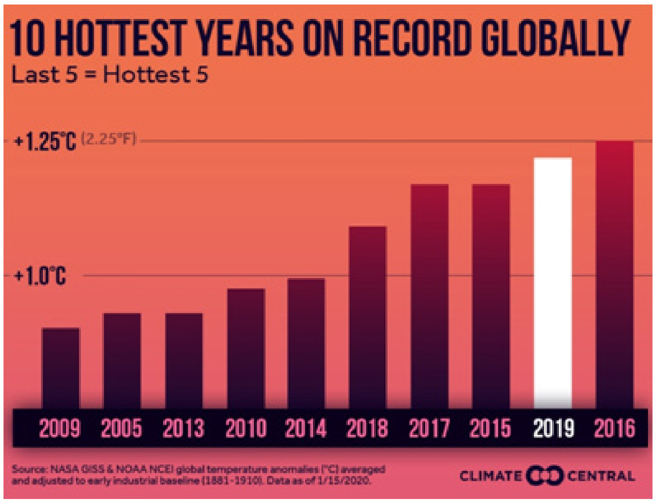


Source: NOAA and Climate Central

Globally, the 10 hottest years on record have occurred since 2005. The first 15 years of the 21st century was among the top-twenty warmest years on record. Experts say the odds of this happening without man-made emissions are 1.5 quadrillion to 1 (a quadrillion is a million billion).

Connecting the dots – tying extreme events to a rapidly warming climate – is known as attribution. A warmer, wetter climate is flavoring all weather now – but confidence levels vary, based on the type of weather phenomena. Here is a summary of how climate scientists and meteorologists view the current state of the science, which continues to evolve over time:

Extreme heatwaves are hotter, lasting longer: high confidence

Droughts are becoming more severe over time: high confidence

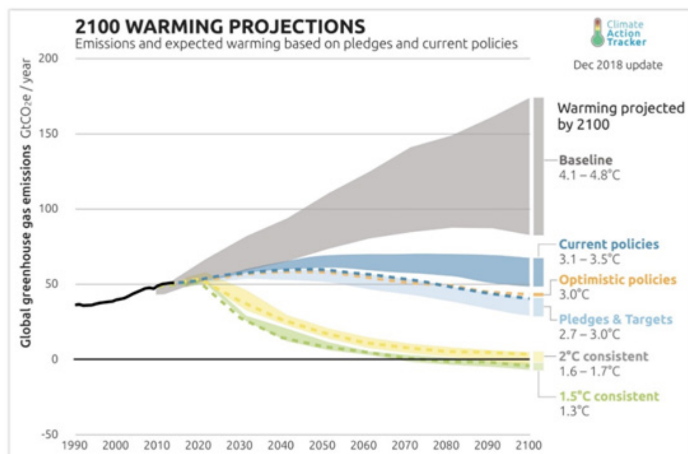
Floods are more prevalent, setting more records with heavier rainfall totals: high confidence

Wildfires are burning longer and hotter, affecting a greater percentage of land: high confidence

Hurricanes are often more intense, dropping heavier rainfall amounts: moderate confidence

Tornado Alley may be shifting over time: low to moderate confidence

Hail frequency and intensity is being impacted by a warming world: low confidence

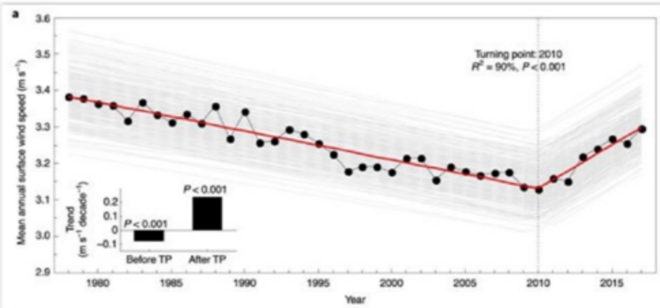


2100 Warming Projections. Source: Climatetracker.org[2]

Climate scientists we worked with for this report insist there is enough *significant additional warming already in the pipeline* – the result of past and current emissions (CO2 in the atmosphere takes roughly a century to decay) – for a *fairly predictable rate of additional warming* through roughly 2050. What happens during the latter half of the 21st century will depend on evolving government policies, and how quickly we transition to economies dominated by clean, renewable energy – from transportation to utilities and agriculture. There is emerging consensus that, based on current policy and trends, an additional 3°C, or over 5°F of additional man-made warming, is quite possible by the year 2100.

[2] https://climateactiontracker.org/global/temperatures/

Wind Speed Trends

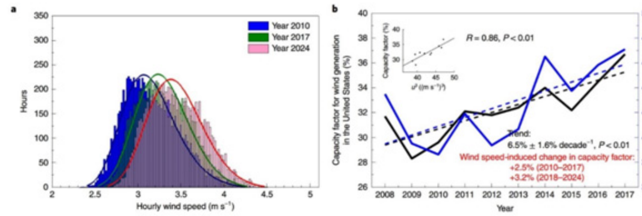


Global mean annual wind speed during 1978–2017 (black dots and line). The piecewise linear regression model indicates a statistically significant turning point (TP) in 2010. Source: Nature Climate Change[3]

For decades, wind speeds have been gradually slowing across the planet. And then something peculiar and scientifically material happened, on a global scale - in 2010. Wind speeds leveled off and started to increase. In fact, average wind speeds have increased from 7 mph to 7.4 mph. The increase in wind speed is global and doesn't depend on the season.

Why? Earlier scientific theories pointed to a concept of global stilling, a reduction in wind speed triggered by more buildings and other man-made obstructions to wind. This theory was tenuous at best, and never proven. Current theories suggest that natural climate cycles, or oscillations, are responsible for the decadal increases and decreases in wind speed. The long-term warming signal will continue, but within that global trend regional temperature swings are driving the observed increase in wind speeds, and may continue through 2030, possibly longer. The bigger the contrast in temperature, the stronger winds must blow to keep the atmosphere in a state of equilibrium. So, temperature extremes dialing up stronger winds are responsible for the uptick in winds since 2010, not a warming climate.

Most climate models suggest a gradual slow-down of winds by the latter half of the 21st century as the warming signal overtakes these regional drivers. The short to medium-term news for the wind industry is promising. According to at least one expert: "*Almost half of the increase of recent capacity factor is related to changes in wind speed – approximately half from technological improvements.*"



*(Left) Frequency distribution of global mean hourly wind speed in 2010 and 2017, and the year 2024 assuming the same increasing rate as that during 2010–2017. The density curves from the respective generalized extreme value distributions are also provided (lines). (Right) Time series of the overall capacity factor for wind generation in the United States (black line) and the cube of the regional-average wind speed (blue line) from 2008 to 2017. Source: Zhenzhong Zeng et al: "**A reversal in global terrestrial stilling and its implications for wind energy production.**" Nature Climate Change[4]*

A few notes about the latest December 2019 Nature study into current and future wind trends. The increase in wind is not merely wind gusts, but also mean wind speeds. Due to regional weather cycles, a slow increase in wind speed should continue for the next decade or more. "Our findings are therefore good news for the power industry for the near future", the December 2019 research concluded.

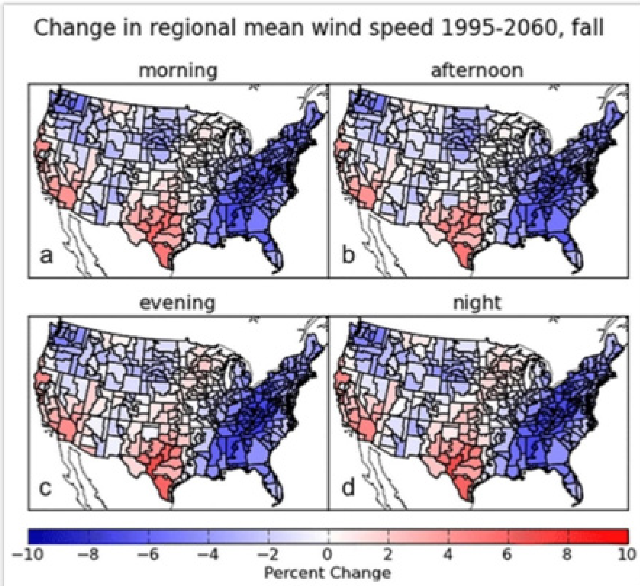
Since 2010, mean wind speed increases of .24 meters/second per decade have been observed. As always, past and current trends carry more weight than a climate model, no matter how reliable. And those trends, based on actual global observations, suggest the reversal in wind speed will continue through a 2030 timeframe. As always, confidence levels are highest in the short-term, which for climate prediction implies the next 5-20 years. As we stated earlier, based on past and current CO2, methane and other greenhouse gas emissions, the temperature increases through roughly 2050 are essentially baked in.

Geopolitical energy disruption, manifested in a potentially accelerated move away from fossil fuels, will determine whether emissions (and temperatures) level off, or even fall during the latter half of the 21st century. Changes in political policy on a country by country basis are impossible to predict, but as prices of clean, renewable fuels continue to fall, as liability risk continues to grow for fossil fuel interests and a new generation of younger voters come of age, signs point to a cleaner, renewable-centric power supply.

[3]https://www.nature.com/articles/s41558-019-0622-6.epdf?referrer_access_token=M6reg8ZReLlTkSlBIZglotRgN0jAjWel9jnR3ZoTv0Np_qIwZCHfm_lhD8LnO7btJtZ7BXucTzTyYCKiDlAFYmK8RuhjUu35bqeR3z3_smjm5brrUMjApsilkk-FM9Zsmz-7fCJ4jCHXYvriTSHkVTeaUU5ilikm8fyZ5QFE8Pswhf_euoEy3wuJMI-0gB699M2H7PL1dXh-9Mq6LBnElJUMU52Ldh29Hx_A5KMMlRvajyzm23tdMObFMcBBF83i-LtY7FeOUsMcqqaEielyDHQ%3D%3D&tracking_referrer=www.scientificamerican.com

[4]https://www.nature.com/articles/s41558-019-0622-6.epdf?referrer_access_token=M6reg8ZReLlTkSlBIZglotRgN0jAjWel9jnR3ZoTv0Np_qIwZCHfm_lhD8LnO7btJtZ7BXucTzTyYCKiDlAFYmK8RuhjUu35bqeR3z3_smjm5brrUMjApsilkk-FM9Zsmz-7fCJ4jCHXYvriTSHkVTeaUU5ilikm8fyZ5QFE8Pswhf_euoEy3wuJMI-0gB699M2H7PL1dXh-9Mq6LBnElJUMU52Ldh29Hx_A5KMMlRvajyzm23tdMObFMcBBF83i-LtY7FeOUsMcqqaEielyDHQ%3D%3D&tracking_referrer=www.scientificamerican.com

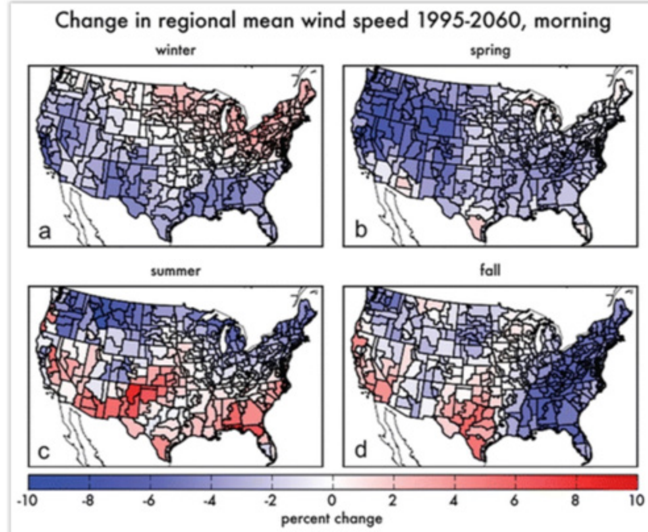
How quickly this transformation comes to pass, and whether countries like China and India will invest the resources necessary – is still very much up in the air.



Change in regional, fall mean wind speed 1995-2060: (a) morning, (b) afternoon, (c) evening, and (d) night. Source: Sue Ellen Haupt: "A Method to Assess the Wind and Solar Resource and to Quantify Interannual Variability over the United States under Current and Projected Future Climate." American Meteorological Society[5]

Diurnal Wind Changes During Autumn. The short-range outlook into 2030 or 2035 suggests a continued increase in mean wind speeds, due to natural temperature and wind cycles unrelated to the larger background warming. But at some point, possibly beyond 2035 or 2040, the warming signal may dominate these natural, regional cycles, resulting in a slowing of wind speeds for much of the USA. Climate scientists say the wind energy industry should plan on more ups and downs as we approach mid-century; greater variability on a longer time frame. The choice of turbine capacity, rotor and tower should be optimized not only for the higher mean wind speeds of the recent past and near future, but potential declines toward the end of turbine lifespans.

Overall, long range climate models show a general, long-term mean wind increase over the southern USA, especially Texas to California, but potential declines in wind speeds for much of the eastern USA – with smaller reductions in wind speed over the northern USA.



Projected future changes in hub-height wind speed from current morning (0600–1300 CST) hours for each season: (a) winter, (b) spring, (c) summer, and (d) fall. Source: Sue Ellen Haupt, American Meteorological Society[6]

Seasonal Wind Changes During Morning Hours. The maps above show increases and decreases in mean wind speeds from climate models, focusing on morning hours for each season by mid-century. There is a general drop in wind speed over time for most of the USA, but with a few notable exceptions.

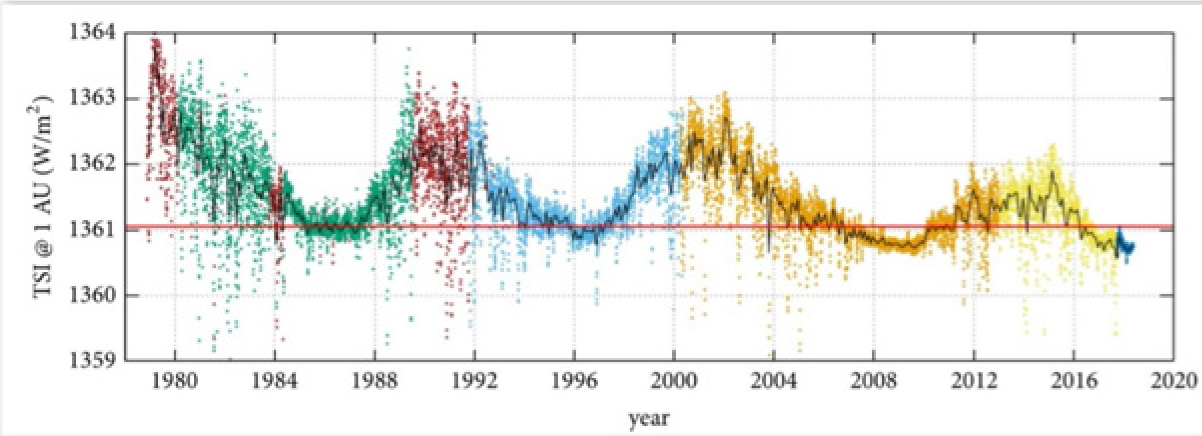
Winter months in the future show a slight (3-5%) increase in mean wind speed from the Upper Mississippi River Valley and Great Lakes into New England, thanks to persistent jet stream winds overhead. By spring, climate models show a general decrease in morning wind speeds, especially over the Rocky Mountain states and far western USA. Somewhat counter intuitively, summer is predicted to bring an increase in wind speeds for much of the southern USA, as warming creates a stronger, southern storm track. Mid Century mornings during the fall months show a significant decrease in wind speeds for the eastern USA, northern Plains and Pacific Northwest, with increases in wind for Texas and California - perhaps the biggest winners in net wind speed changes looking out to 2060. Confidence levels beyond 2040-2050 are low to moderate, and at least one climate scientist we interviewed had an interesting prediction:

"Effects of improved manufacturing, better durability and efficiency will be much more impactful than any slight changes to the actual wind or solar energy."

–Dr. John Abraham, Professor of Thermal Sciences, University of St. Thomas

[5] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-15-0011.1
[6] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-15-0011.1

Solar Irradiance Trends



Satellite total solar irradiance (TSI) composite since 1978. Source: Hindawi[7]

Changes in the amount of sunlight reaching the Earth are not responsible for the warming we are measuring all around us. In fact, solar irradiance has been holding steady, even falling slightly since 1980. From a long-term, geological perspective we should be slowly sliding into another cold phase or even an Ice Age, but temperatures continue to spike upward in response to the rapid accumulation of greenhouse gases in the atmosphere and oceans.

The cyclical pattern in solar radiation above is the result of a natural sunspot cycle, which averages 11 years. Climate scientists explain that any future changes in solar capacity are largely a function of expected changes in cloud cover. One of many challenges: how will a warmer (wetter) climate impact the seasonal position of the jet stream and future storm tracks, which will impact future cloud cover?

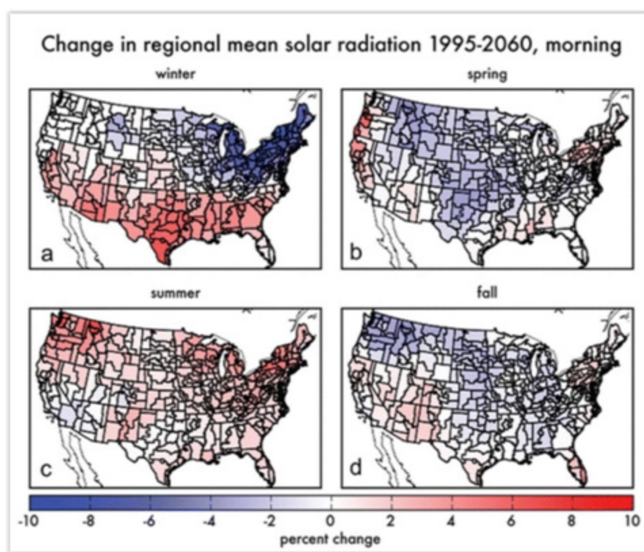
The primary paper we base these findings on is from NCAR, published in 2016. A warming climate will produce seasonal shifts in expected cloud cover and solar irradiance. Climate scientists estimate potential increases/decreases of up to 10% by the year 2060.

Winter is expected to bring significant increases in solar radiation for the southern USA, with net decreases from the Upper Midwest into the Great Lakes and New England. Generally warmer winters will translate into more open water on the Great Lakes, creating longer-lasting lake-effect clouds and less sunlight during the winter season.

Spring may bring increases in solar radiation to the west coast of the USA and portions of New England, with a net decrease for much of the central states. Springs are already trending wetter for much of the nation, a pattern that may accelerate by mid-century.

Summers show net gains in solar radiation for the entire country; the greatest gains for the Pacific Northwest, and from the Upper Midwest and Great Lakes into New England. In general, climate models show fewer days of clouds and rain during the warm season, but when it does rain, the intensity and amounts are forecast to be higher – a trend we're already seeing in the data.

By mid-century, the autumn months show net increases in solar radiation for the southwest, south Texas and Florida, with slight decreases for the Plains and Mid-South.



Projected future changes in morning solar irradiance for each of the four seasons: (a) winter, (b) spring, (c) summer, and (d) fall. Source: Sue Ellen Haupt, American Meteorological Society[8]

[7] https://www.hindawi.com/journals/aa/2019/1214896/
[8] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-15-0011.1

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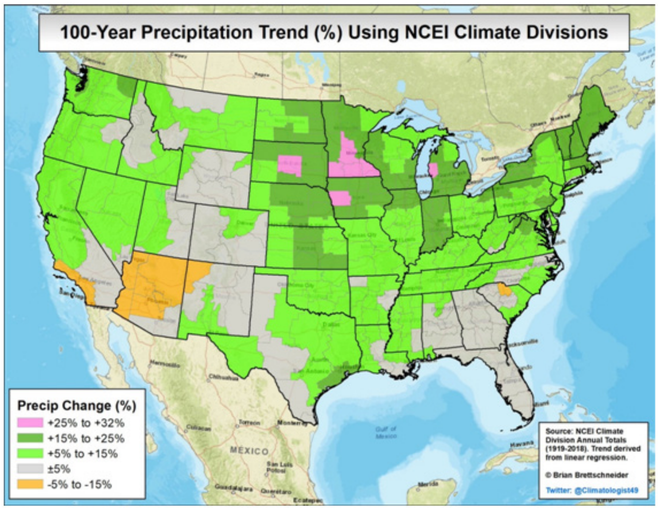
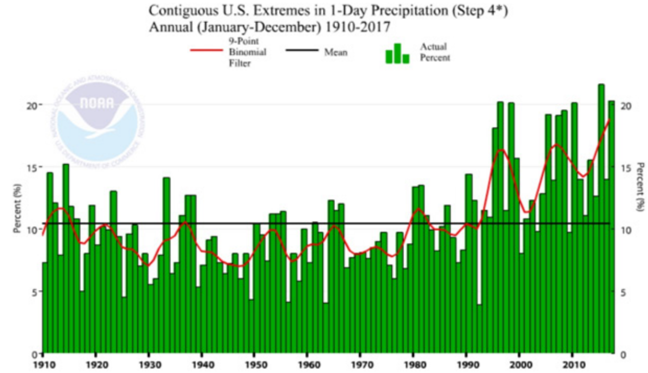
Precipitation Trends



Precipitation trends from 1919-2019. Source: NOAA NCEI and Brian Brettschneider.

It's an axiom that deserves repeating: actual observations trump weather or climate models. Connecting the dots over time can isolate significant trends that impact operations. Half a century ago climate scientists predicted wet areas would trend wetter, and dry areas would become drier. That is precisely what we are seeing in the data.

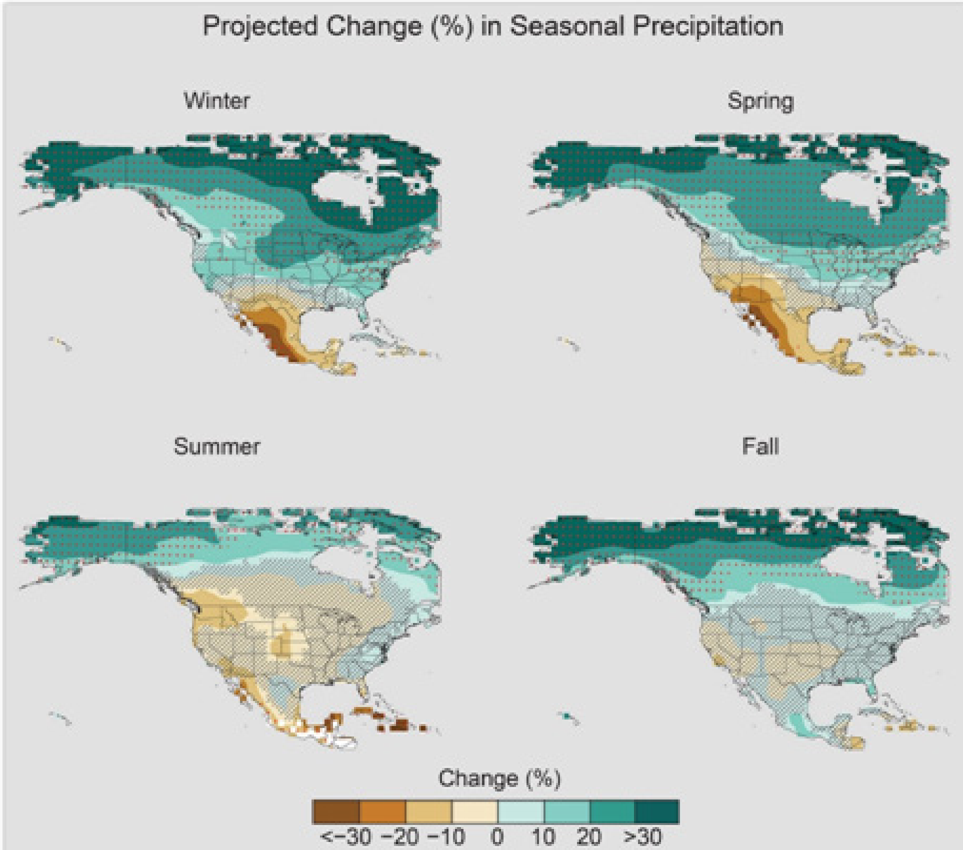
The map above shows observed precipitation trends from 1919 to 2018. The greatest increase in precipitation has taken place over the Northern Plains and Upper Mississippi Valley; an increase of 25-32% over a century. The most significant increases in precipitation are taking place from the Plains and Midwest into the Great Lakes and New England. Springs, specifically, are trending much wetter over time, and summer thunderstorms are dropping more rainfall, thanks to a roughly 8% increase in water vapor overhead. Only Arizona, northwest New Mexico and southern California have experienced a decrease in rainfall over the last 100 years.



Percentage of the contiguous US impacted by extreme1-day precipitation. Source: NOAA NCDC.

The graphic above is one (of many) that convinced me that what we are experiencing is not a "natural cycle". Data from NOAA's National Climatic Data Center shows the percentage of the USA experiencing extreme precipitation events since 1910. It's worth pointing out that nature never moves in a straight line, but step back and look at the big picture over time and trends emerge. The percentage of the USA experiencing precipitation extremes has risen from an average of 7-10% from the 1930s to the 1970s – to closer to 15-20% since 2000. The reason is quite clear: warmer air can hold more water vapor; more fuel available for storms.

This is a recurring theme with climate change: fewer events, but the events that do take place are becoming more extreme over time. Climate scientists predict a warmer atmosphere may produce fewer days with precipitation overall, but when it does rain (or snow) precipitation intensities and amounts will increase. We can expect more whiplash, more of an "all-or-nothing" weather pattern, characterized by big swings and extremes.



Projected change (%) in total seasonal precipitation from CMIP5 simulations for 2070–2099. The values are weighted multimodal means and expressed as the percent change relative to the 1976–2005 average. These are results for the higher scenario (RCP8.5). Source: National Climate Assessment

The latter half of the 21st century should see precipitation increases for much of the USA in the winter and spring months, and a slight decrease in precipitation during the summer months. Fall may see a slight increase in amounts over northern tier states of the nation. According to the latest National Climate Assessment *"This pattern of projected precipitation change arises because of changes in locally available water vapor and weather system shifts."*[9]

Less snow during the winter months, and a northward shift in the rain–snow transition zone in the central and eastern United States was observed in longer-term climate models. Under the higher scenario (RCP8.5) the number of extreme events (exceeding a 5-year return period) increases by two to three times the historical average in every region by the end of the 21st century, with the largest increases in the Northeast. Data suggests that increased water vapor resulting from higher temperatures will be the primary cause of the increases.

The West Coast is not immune. According to NCA4: *"Atmospheric rivers (ARs), especially along the West Coast of the United States, are projected to increase in number and water vapor transport and experience landfall at lower latitudes by the end of the 21st century."* With the exception of the southwestern states, the forecast calls for wetter patterns across the USA.

[9] *https://science2017.globalchange.gov/chapter/executive-summary/*

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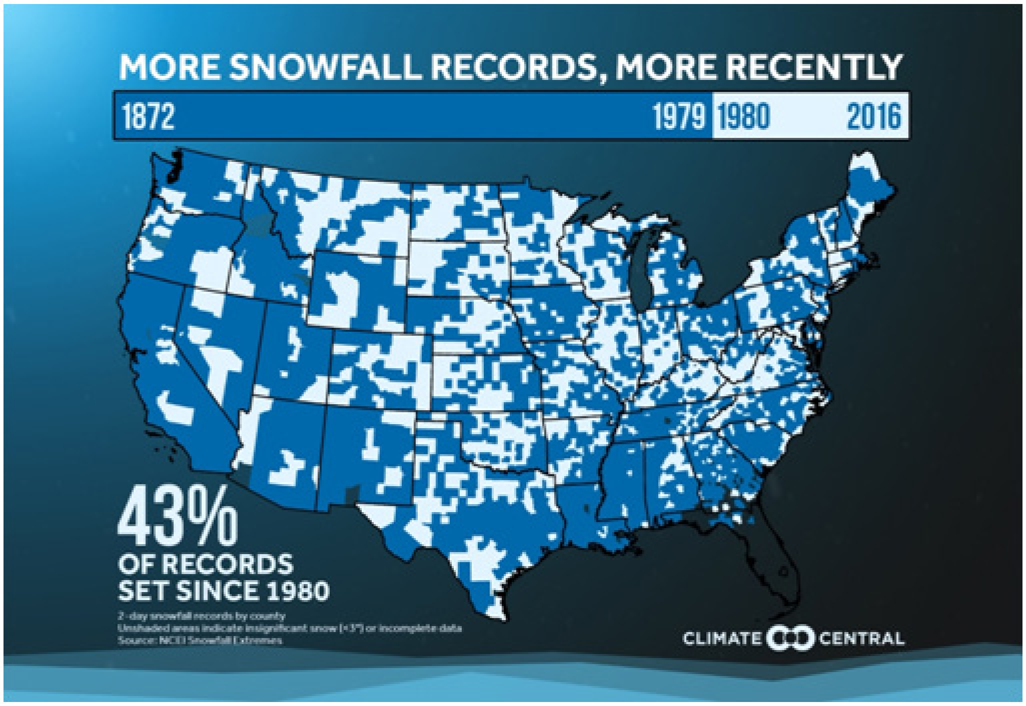
Winter Storm Trends



Snowfall records. Source: Climate Central.

NOAA data shows that the frequency of extreme snowstorms in the eastern two-thirds of the contiguous United States has increased over the past century. Approximately twice as many extreme U.S. snow storms occurred in the latter half of the 20th century than the first.[10] East coast "Nor'easters" have been influenced by warmer Gulf Stream waters, increasing moisture inflow into these massive storms, often resulting in heavier amounts. According to the latest National Climate Assessment, the frequency of large snowfall years has decreased in the southern United States and Pacific Northwest and increased in the northern United States. Analysis of storm tracks indicates that there has been an increase in winter storm frequency and intensity since 1950, with a slight shift in tracks toward the poles.

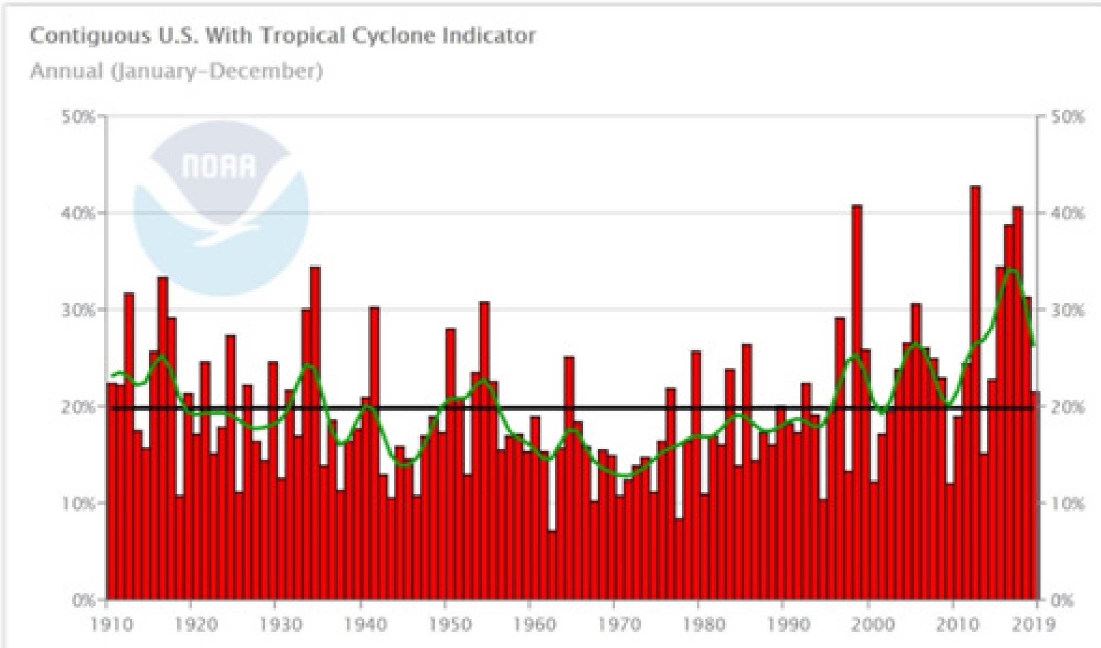
With a few exceptions, notably the east coast, snow is on the ground for less of the winter across the USA, with maximum snow depth occurring one week earlier than it did in the 1960s. Warming winters means less ice on the Great Lakes – open water fosters the formation of "lake-effect" snows downwind, with heavy squalls and extreme accumulations.

A study at NCAR, the National Center for Atmospheric Research, predicted that smaller snowstorms, those dropping just a few inches, will be few and far between by the end of the century. Total snowfall will become less as more precipitation falls as rain, because of the warming influence of greenhouse gases on the atmosphere. But the devastating Nor'easters will stay the course as the planet heats up.

Winters are already trending shorter with a smaller window where temperatures are cold enough for all snow. We may experience fewer storms in the future, but the availability of more moisture aloft will fuel the storms that do form, creating extreme snowfall amounts, *especially within a few hundred miles of the Mid Atlantic and New England coastline*. Snow is on a slow fade, but many storms, especially Nor'easters, will still pack a wallop.

[10] *https://www.ncdc.noaa.gov/news/climate-change-and-extreme-snow-us*

Extreme Weather Events



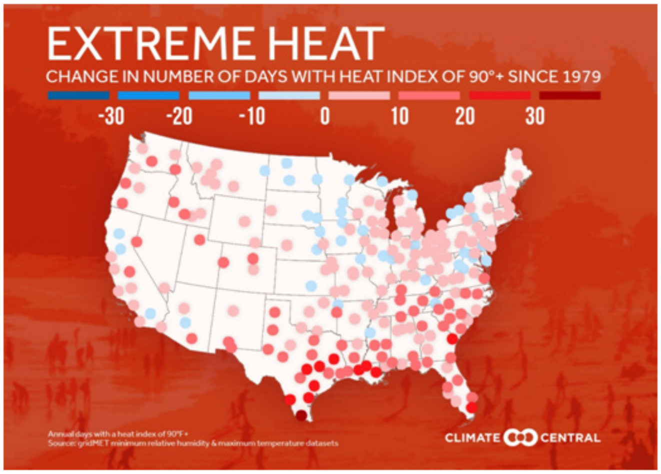
Climate Extreme Index showing percentage of USA over time impacted by severe flood or severe drought. Source: NOAA National Centers for Environmental Information.[11]

The graphic above shows the percentage of the USA experiencing either severe flood or severe drought. From the 1940s to 1980s that number was 15-20%. Since 2000 the percentage of the nation enduring precipitation extremes has risen from 20 to 30%. A warmer climate is *turning up the volume* on events that would have occurred naturally. Stating the obvious: *climate resilience* will become increasingly paramount: new methods and materials that leave facilities and supply chains more flood-proof, drought-tolerant and heat-resistant.

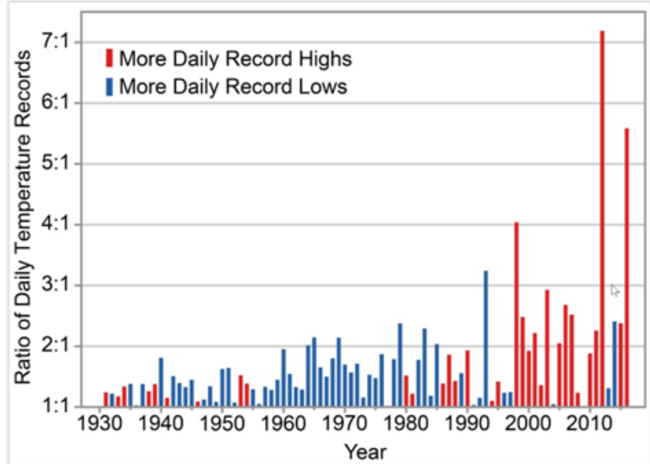
NOAA now includes tropical activity in the Climate Extreme Index: *"The revised CEI now includes an experimental tropical system component and is calculated for multiple seasons. The newest indicator documents trends in tropical system activity based on the wind velocity of landfalling tropical storms and hurricanes."*

[11] *https://www.ncdc.noaa.gov/extremes/cei/*

Extreme Heat Trends



Extreme Heat: Change in number of days with a heat index of 90°+ since 1979. Source: Climate Central.



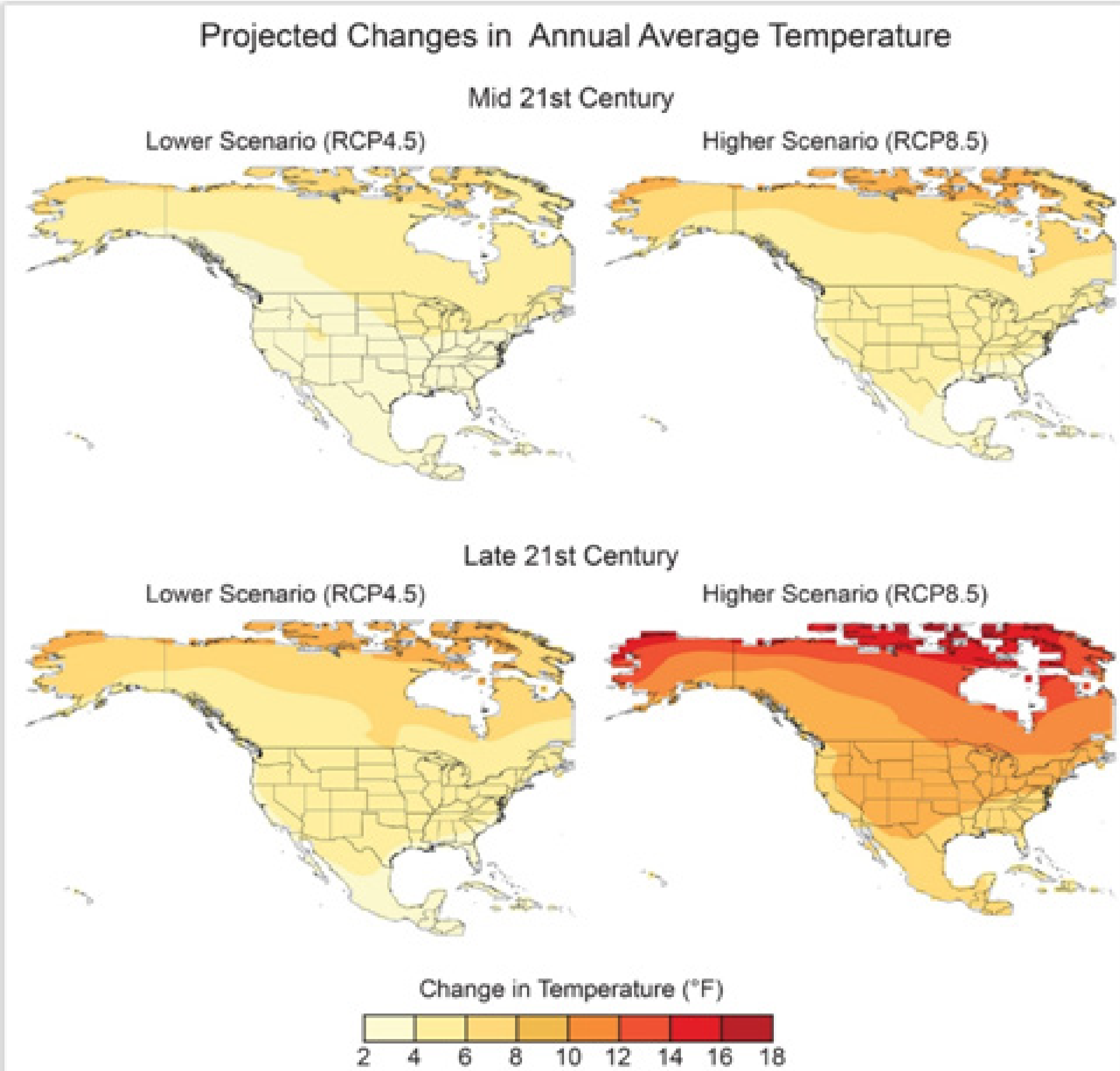
Observed changes in the occurrence of record-setting daily temperatures in the contiguous United States. Red bars indicate a year with more daily record highs than daily record lows, while blue bars indicate a year with more record lows than highs. The height of the bar indicates the ratio of record highs to lows (red) or of record lows to highs (blue). Source: National Climate Assessment 4.

More than 95% of the land surface of the contiguous United States has warmed since 1986, with very slight cooling for parts of the Southeast and Southern Great Plains. Warming was greatest and most widespread in winter, with increases of over 1.5°F (0.8°C) in most areas. The increase in days with a Heat Index of 90+ since 1979 (map above) is a function of warming temperatures and higher dew points. Warmer air can hold more water vapor, and dew points are rising, resulting in consistently higher heat indices east of the Rocky Mountains. According to the latest National Climate Assessment, cold extremes have become less severe over the past century. The frequency of intense cold waves (4-day, 1-in-5 year events) peaked in the 1980s and then reached record-low levels in the 2000s.

Confidence levels are high among climate scientists that a warming atmosphere and oceans are priming the pump, favoring more hot weather extremes, worldwide. Extreme heat poses the greatest risk to human health (and business risk) from the southwestern USA into the southern and eastern states.

If no warming was taking place you would expect the ratio of record highs to record lows to be close to 1:1. Since 2000 the ratio is closer to 2:1 – twice as many record highs as record lows. Recent summers have seen that ratio jump as high as 5:1 and even 7:1 as the warming signal grows louder.

The latest National Climate Assessment 4, released in 2017, states: *“The frequency and intensity of extreme heat and heavy precipitation events are increasing in most continental regions of the world (very high confidence). These trends are consistent with expected physical responses to a warming climate.”*



Projected changes in annual average temperature. Source: Global Change.

Statistically significant warming is projected for most of the USA this century, with the greatest warming over far northern latitudes and Alaska. Warming is least in Hawaii and the Caribbean, due to the moderating effect of oceans. Daily extreme temperatures are projected to increase substantially in the contiguous United States, particularly under the higher scenario (RCP8.5). For instance, the coldest and warmest daily temperatures of the year are expected to increase at least 5°F (2.8°C) in most areas by mid-century, rising to 10°F (5.5°C) or more by late-century.

Increasing background warmth by a few degrees dramatically increases the potential for record/extreme heat in the years ahead. According to the latest National Climate Assessment, the frequency of heat waves (6-day periods with a maximum temperature above the 90th percentile) will increase in all regions, particularly the Southeast, Southwest, and Alaska.[12] The changes will be jarring, especially for the southern USA. Climate model simulations predict about *20–30 more days per year with a maximum over 90°F* (32°C) in most areas by mid-century under RCP8.5, with increases of 40–50 days in much of the Southeast, according to NCA4.[13]

The temperature increase will not be uniform, but increasing background warmth loads the dice in favor of more record, and in some cases dangerous, heat waves in the years to come.

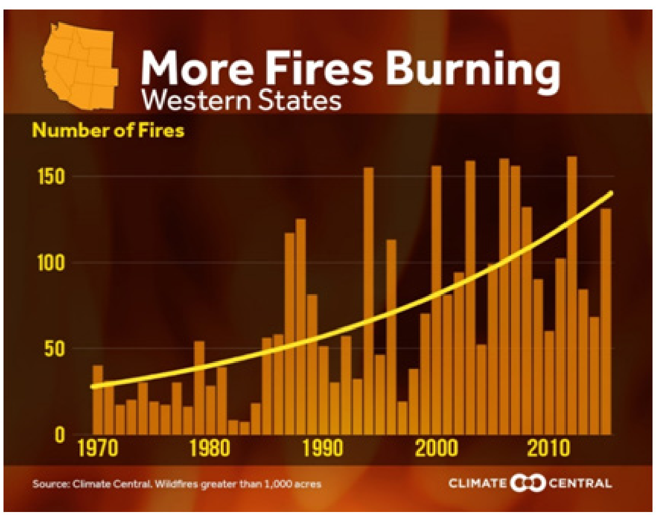
[12] *https://science2017.globalchange.gov/chapter/6/*
[13] *https://science2017.globalchange.gov/chapter/executive-summary/*

Dust Trends

The frequency of dust storms in the southwest USA has more than doubled since the 1990s — from 20 per year to 48 in the 2000s — and will likely continue to increase, according to one study. This is probably not a result of warming, at least not yet. What's going on? Studies suggest a combination of warmer sea surface temperatures in the North Pacific during the 2000s than during the 1990s, along with colder waters off the California coast. This allowed for cooler and drier northerly winds from the North Pacific into the southwestern U.S., helping to *dry the soil*.[14]

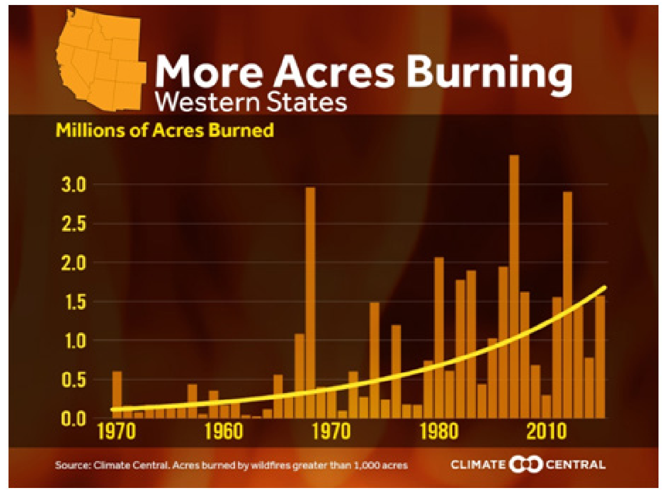
Dust clouds and the aerosol particles they contain have major impacts on climate in other ways, such as the blocking of sunlight headed for Earth. But this field of research is young and complex, and the science is lacking, adding uncertainty to future climate models.[15] Dust storms are projected to be lower in the Great Plains of the United States; an *increase in precipitation* stimulates plant growth, which caps the soil. Perhaps a small silver lining in a warmer (wetter) world.

Wildfire Trends



Number of wildfires. Source: Climate Central

The western United States is experiencing bigger, hotter, longer-lasting fires, and the most likely culprit is a rapidly warming/drying climate. More than half the US Western states have experienced their largest wildfire on record since 2000. From 1980 to 2010, there was a fourfold increase in the number of large and long-duration forest fires in the American West; the length of the fire season expanded by 2.5 months; and the size of wildfires increased several-fold.[16] A global analysis of daily fire weather trends from 1979 to 2013 shows that fire weather seasons have lengthened across 11.4 million square miles—about the size of Africa, and 25.3 percent of the Earth's vegetated surface—resulting in an 18.7 percent increase in global mean fire weather season length.



Number of acres burned. Source: Climate Central

Recent years have been nothing less than apocalyptic, especially in California. The past decade has seen half of the state's 10 largest wildfires and seven of its 10 most destructive fires, including last year's Camp Fire, the state's deadliest wildfire ever. Since 1972, California's annual burned area has increased more than fivefold. Since the early 1970s, summers in Northern California have warmed by 2.5°F (1.8°C) on average. That may not sound like much, but heat has an exponential relationship with forest fire. The additional heat speeds up evaporation, dries the soil and vegetation faster, creating more fuel for mega-fires to burn.

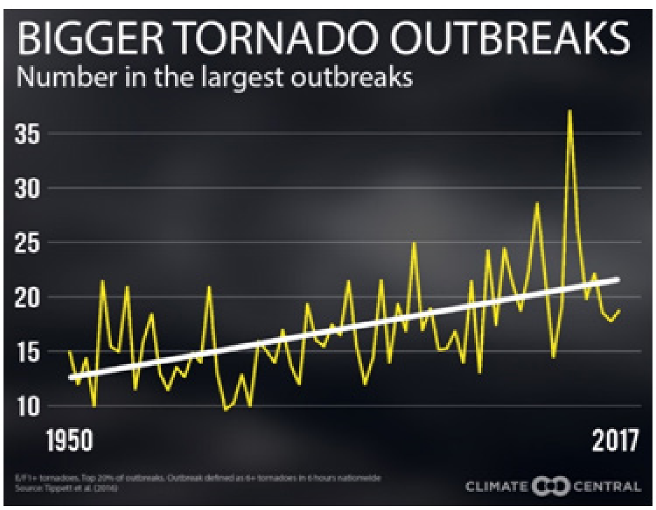
At least one study showed that human-caused climate change contributed to an additional 16,400 square miles (the size of upper peninsula Michigan) of forest fire area across the western USA from 1984 to 2015. This nearly doubles the area expected without global warming. Wetter trends for most of the USA east of the Rocky Mountains may help to inoculate much of the nation from severe wildfires, but conditions will, in all probability, continue to worsen for western states, especially California, in the years to come.

[14] https://www.noaa.gov/media-release/spike-in-southwest-dust-storms-driven-by-ocean-changes
[15] https://e360.yale.edu/features/climate-connection-unraveling-the-surprising-ecology-of-dust
[16] https://www.climatesignals.org/climate-signals/wildfire-risk-increase

Severe Weather Trends

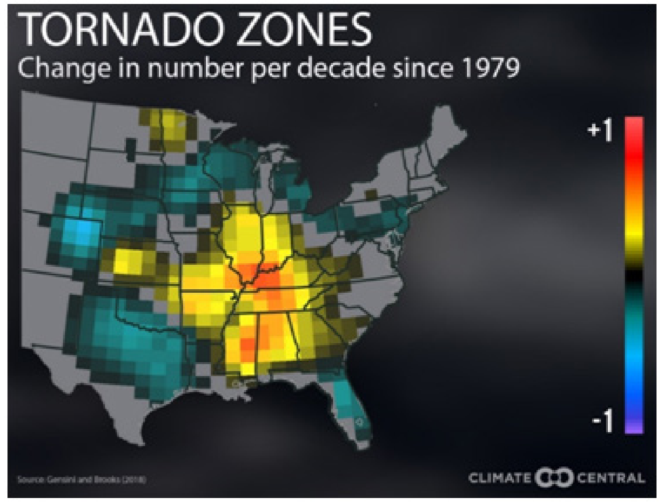
According to the most recent National Climate Assessment, tornado and severe thunderstorm events cause significant loss of life and property: more than one-third of the $1 billion weather disasters in the United States during the past 25 years were due to such events, and, relative to other extreme weather, the damages from convective weather hazards have undergone *the largest increase since 1980*.[17] America's climate is already warmer and wetter, and the availability of more water vapor is likely to fuel heavier rains (high confidence). The outlook for severe thunderstorms is more difficult to model and anticipate. Some climate scientists predict an increase in thunderstorms with straight-line winds, with more derechos (long-lasting, violent windstorms that cover hundreds of miles before dissipating). Confidence levels are low regarding specifics, including any possible uptick in lightning from (more) severe thunderstorms flaring up during the warm season.

Tornadoes



Number of large outbreaks since 1950. Source: Climate Central

With the advent of Doppler Radar and professional storm spotters, tornado observations have become much more reliable since 1950. Data shows no observable increase in either the intensity or frequency of tornadoes across the United States. However, data does suggest that the largest tornado outbreaks or clusters are producing more tornadoes. The swarms of multiple tornadoes are trending more violent over time, with more communities impacted on the big tornado days.



Change in the number of tornado zones per decade since 1979.
Source: Climate Central

One trend that does jump out in the data sets is a possible shift in Tornado Alley over time. In recent years some of the deadliest, most damaging tornadoes have struck from Indiana and Illinois southward to Mississippi and Alabama. Whether this is climate-related is unclear, but more Americans are being impacted in areas not accustomed to large and violent tornadoes, increasing risk from Chicago and St. Louis southward to Memphis, Nashville and Atlanta.

[17] *https://science2017.globalchange.gov/chapter/9/*

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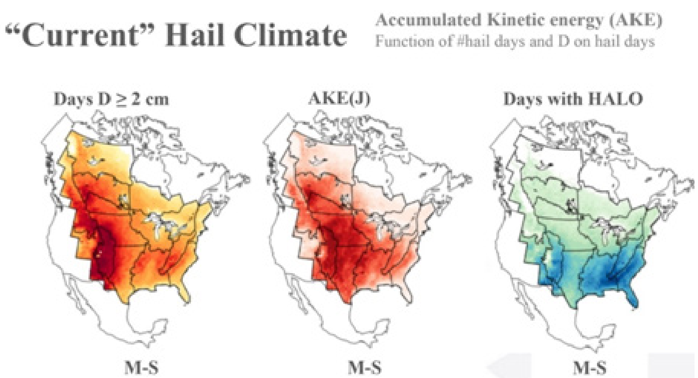
Hail

Hail and wind-related losses from severe thunderstorms are, in fact, trending upward, according to data from reinsurance companies like Munich Re. But multiple factors may be responsible for these trends, including expanding cities, dubious observations, untrained storm chasers, rising building costs, even unscrupulous roofing contractors filing false claims. Pinning any apparent increase in hail frequency and cost entirely on a warming world may be, at best, simplistic. New technology and more trained weather spotters (looking for hail) may be responsible for the uptick in hail reports since 2000. Expanding population centers in areas that have a high, natural climatological frequency of hail is costing the insurance industry billions of dollars a year, heightening concern.



"The Changing Hail Threat Over North America in Response to Anthropogenic Climate Change." Julian Brimelow, William Burrows and John Hanesiak, Meteorological Service Canada. "HALO" stands for "hail aloft only"; days when the model produced hail in the thunderstorm, but it melted before reaching the surface. Climate models show less hail for the southeastern USA, but potentially more hail for the Great Plains and US/Canadian Rockies. Source: Nature[18]

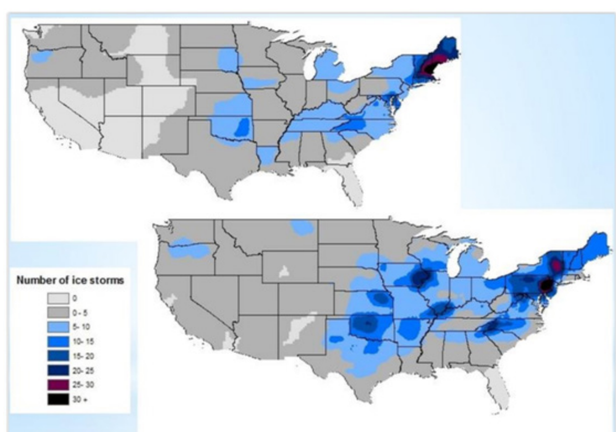
"Observationally, there isn't a lot of evidence at this stage that a warming signal is affecting frequency or size of hail" according to John Allen, Assistant Professor of Meteorology at Central Michigan University. But there is emerging consensus that a warmer, wetter world will increase hail frequency for some regions. Dr. Julian Brimelow, a climate scientist specializing in hail, sees a *possible increase in the number of large summer hail events over the foothills of the northern Rockies and Canadian Prairies*. Warming may reduce hail frequency over southeastern states, where smaller hail will be more prone to melting before reaching the ground.

"There are places where there will be more frequent large hail" Dr. Michael Tippett concludes. Dr. Noah Diffenbaugh has a similar long-range hail outlook. *"We find an increase in severe thunderstorm days overall east of the Rockies with increasing GHG concentrations."* Brimelow at Environment Canada concurs. His efforts are extending beyond coarse, severe storm environmental conditions, using regional climate models to drive a cloud and hail model to delineate supercell initiation. His prediction: *"Moving forward, it does look like that potential for large hail in certain regions and certain times of the year is very likely to increase."*

A warmer, wetter world should increase hail frequency and size across parts of the United States, Canada and the planet in the years to come. Complacency feels premature.

Icing Trends

Recent climate studies suggest an increase in ice storm events for much of the US, as winter temperatures warm over time, and more precipitation falls as sleet or freezing rain vs. snow. Minnesota has already experienced a 4X increase in severe midwinter icing events since 2000, so this signal is already emerging and strengthening. A 2015 study on climate change and ice storms concluded: *"As temperatures increase, we find a poleward shift and a shift toward winter. Furthermore, southern locations experience fewer ice storms at all times of the year, while northern areas experience fewer in the spring and fall and more in the winter."* Climate models suggest regional variations in ice storm potential as warming continues in the 21st century. *"Researchers estimate an increased frequency of ice storm events throughout much of the winter across eastern Canada and in the U.S. west of the Appalachian Mountains as far south as Tennessee."*[19]



Total number of documented ice storms across the US between the winters of 1966-1977 (top) and 1998-2011 (bottom). The Northeast experienced the highest frequency during both periods, with a westward shift evident. Source: Southern Climate[20]

Although attribution, the link between a warming climate and frequency/intensity of ice storms, is not fully understood and confidence levels are low to moderate, warming winters will – in all probability – produce more ice and considerably less snow by the middle of the 21st century.

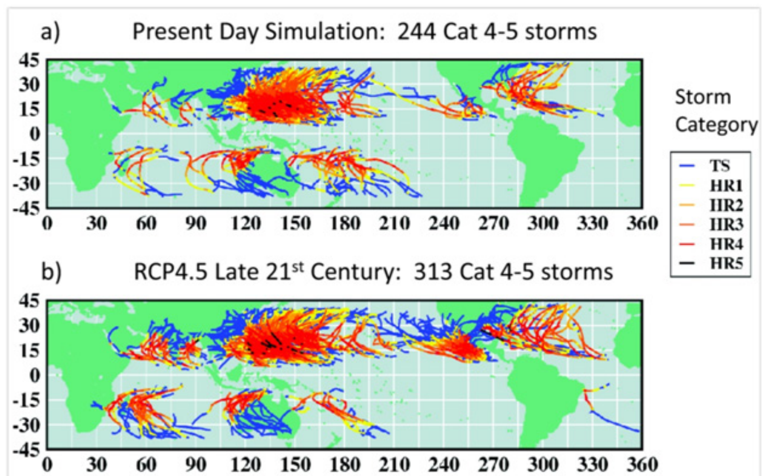
[18] https://media.nature.com/original/nature-assets/nclimate/journal/v7/n7/extref/nclimate3321-s1.pdf
[19] https://link.springer.com/article/10.1007/s10584-015-1460-9
[20] http://www.southernclimate.org/documents/Ice_Storm_Frequency.pdf

Hurricane Trends

Hurricanes are a natural part of Earth's climate system, "automatic pressure relief valves" that transport excess heat from the tropics to northern latitudes. But research suggests an increase in intense hurricane activity in the North Atlantic since the 1970s. There has been little change in the frequency of hurricanes globally, but 93% of the additional warming from man-made greenhouse gases like CO2 and methane is going into the world's oceans. Hurricanes get their strength from warm ocean water: the warmer (and deeper) the layer of warm water in excess of 82°F, the greater the potential for rapid intensification. Warmer temperatures translate into more water vapor overhead, more fuel capable of increasing rainfall amounts from landfalling hurricanes. Climate models project an increase in the average precipitation rate of hurricanes as a result of global warming. Hurricane Harvey dumped over 60" of rain east of Houston in 2017. Researchers have concluded that a repeat of rainfall that intense is predicted to happen only once every 9,000 years. A majority of the rain was caused by Harvey's extremely slow movement, another possible symptom of a slowing jet stream due to uneven warming during the warm season. Harvey may have been a glimpse of super-sized, super-wet hurricanes to come.

Climate scientists predict stronger hurricane wind speeds and heavier rainfall amounts as the planet continues to warm. The projected increase in intense hurricanes is very substantial—a doubling or more in the frequency of category 4 and 5 storms by the end of the century, due mainly to the availability of warmer ocean water. Recent hurricanes, including Michael, Irma and Maria, intensified explosively after passing over eddies of unusually warm ocean water. Examining the hurricane record in the Atlantic basin from 1986 to 2015, a recent study found rapid intensification increased 4.4 mph per decade. The study's authors attribute most of the gains to a shift into the warmer phase of the Atlantic Multidecadal Oscillation, a natural cycle. Rising seas will magnify the impact of the storm surge, allowing water to push farther inland. Some climate studies predict hurricanes with wind speeds well in excess of Category 5 strength, suggesting that the current Saffir-Simpson hurricane rating scale may have to be extended to deal with much stronger hurricanes in the 21st century.

Like other weather phenomena, we may not see an increase in the total number of hurricanes that form every year. In fact, there may be fewer hurricanes forming in a warmer environment. But the hurricanes that do form will be bigger, wetter, windier - capable of inflicting more damage and loss of life. About 40 percent of the US population—about 123 million people—lives in coastal counties, at risk of hurricanes. People living well inland away from the coast shouldn't be complacent. Major hurricane strikes in the future will be traumatic and expensive, impacting state and federal budgets, supply chains and the mood of the nation. Over time the combination of stronger hurricanes and rising seas will force a slow retreat from some coastal regions, especially where land subsidence is accelerating coastal flooding. Again, we are running a slow-motion experiment, but the outlines of future hurricane climate risk are becoming clearer over time.



A 2019 GFDL study made the following key findings for a warmer world: fewer tropical cyclones globally in a warmer late-twenty-first-century climate, but also an increase in average cyclone intensity, the number and occurrence days of very intense category 4 and 5 storms in most basins and in tropical cyclone precipitation rates. Existing studies suggest a tropical cyclone wind speed increase of about 1-10% and a tropical cyclone precipitation rate increase of about 10-15% for a moderate (2°C) global warming scenario.

A familiar theme emerges amid the various climate model scenarios: potentially fewer hurricanes overall, but the storms that do form will be turbocharged; much more likely to reach Category 4-5 strength, capable of catastrophic damage.

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Building Resilience

Low-tech solutions are already gaining credibility in the struggle for climate resilience. Farmers, increasingly, are planting cover crops – practicing "no-till" farming on their land. Planting rye grass, crimson clover, oats, oil-seed radishes, or cereal rye can help to improve soil quality, leaving farms less vulnerable to flash flooding and subsequent soil erosion, lowering risk to wind and solar facilities.

New methods, materials and processes will be required to lower overall operational risk and maximize safety for staff and vendors, literally out in the field. Best practices will continue to evolve over time as a combination of effective traditions and new technological breakthroughs allow us to handle whatever Mother Nature throws at us.

How Will Facilities Be Impacted?

Climate models uniformly predict a warmer, wetter, more volatile atmosphere, capable of making extremes that would have occurred naturally even more extreme. There may be fewer days of rain, but the rain will fall harder, resulting in more flooding—a trend that is already emerging in the data.

Implications for facilities:

- More weather extremes capable of transportation disruptions, impacting everything from staffing to supply chains.
- Flash flooding and river flooding will continue to increase. Siting facilities in areas not within the 500-year floodplain is critical. But flash flooding will occur well away from rivers and streams – effective drainage and rapid recovery will become increasingly mission-critical to ensure fewer weather-related closures.
- More days with dangerously high temperatures and heat indexes. The roughly 8% increase in water vapor triggered by warming is resulting in consistently higher dew points. More water in the air results in a higher heat index, increasing the potential for heat stress and potentially deadly heat stroke.
- More mid-winter icing events as temperatures continue to warm, especially northern US.
- New invasive species; potential for disease transmission increases in a warmer, wetter world.
- *Tipping points:* we don't yet have all the answers. We don't know what we don't know. Melting permafrost and little or no arctic ice by mid-century may impact jet stream winds and weather patterns in ways the climate models can't anticipate today. Vigilance and flexibility will be required to maximize profitability as weather becomes more volatile.

Climatrends

2 PHYSICAL RISK ANALYSIS: LOCAL CLIMATES

At the request of Clearway Energy Group, we have run a climate scenario analysis analyzing three different future scenarios for the following five locations/regions through, generally, the year 2050. The following provides a brief summary of the reasoning behind the region selection:

Eastern Massachusetts

- Selected due to the large interest in the regional market. State incentive programs make Massachusetts a premier community solar state. Clearway has dozens of Community Solar projects operating in the state with just under half of all Community Solar projects in development and construction based in Massachusetts.

Kern County, California

- Selected as this area is a focal spot for wind and solar development. Surrounding counties make up some of the biggest wind and solar counties in California. Currently, Clearway has several projects in development, under construction, and operating in Kern County.

Petersburg, Nebraska

- Selected due to Clearway's existing operating projects and a desire to understand the impact of climate change on production and resources in Middle America.

Sterling City, Texas

- Selected due to Texas remaining a primary market for both utility scale wind and solar. Existing operating projects, potential repower opportunities, and new wind/solar development and construction activity makes this an important region for Clearway.

Southeast Minnesota

- Selected as this region is suitable for future utility and DG solar and utility wind sites. The region is currently home to dozens of Clearway operating community solar projects and is also proximate to operating utility wind projects.

In order to understand the impact of climate change on a local or regional level, ClimaTrends turned to the Coupled Model Intercomparison Project 5 (CMIP5) model used by leading climate experts. The CMIP5 is a standard experimental framework that facilitates the assessment of the strengths and weaknesses of climate models. The CMIP5 data accessed provide projections of future climate change at an approximate 250 km resolution.

As discussed earlier in this report, this analysis will be reviewing various weather parameters under three emissions scenarios. Human effort to curb greenhouse gas emissions is a big factor in calculating the longer-term impacts of climate change.

The physical risks for each location will be discussed in terms of three emissions scenarios:

1. Sustainable Future Scenario (RCP 2.6): Major emissions reduction efforts would result in a drastic reduction in GHG emissions by 2050 with emissions dropping to near 0 by 2080.
2. 2 Degrees Scenario (RCP 4.5): moderate emissions reduction efforts would result in a reduction of GHG emissions after 2050.
3. Current Policies Scenario (RCP 8.5): often considered "business as usual" with little to no active effort to reduce GHG emissions.

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EASTERN MASSACHUSETTS

Key Takeaways:

- *Temperature* – Models suggest a temperature rise of at least 0.8°C and 0.9°C by 2035 and 2050 respectively is “baked in” regardless of scenario.
- *Extreme Heat* – The # of dangerous heat events are projected to rise with extreme temperatures and higher humidity.
- *Precipitation* – The Northeast has experienced the largest increase in precipitation in the United States. More overall precipitation and more intense precipitations events are projected to occur.
- *Winter Weather* – A shift towards rainier and icier winters with a significant decrease in snow.
- *Radiation* – Research suggests an increase in solar radiation during in Summer and a decrease in winter.

Extreme Temperatures

Generally, the Northeast has seen significant warming for over a century with temperatures increasing by almost 2°F between 1895 and 2011. Weather station records in the Northeast indicate warming at a rate of nearly 0.26°C (0.5°F) per decade since 1970 with winter temperatures rising at an even faster rate of over 0.7°C (1.3°F).[21] Massachusetts is among the top 10 fastest warming states in the country, based on annual average temperatures since 1970.[22]

In our analysis of the CMIP5 data in Eastern Massachusetts, we can confirm a significant rise in temperatures regardless of the emissions scenario selected. The data suggest a “baked-in” 0.8°C (1.4°F) temperature increase by 2035 and 0.9°C (1.6°F) by 2050 under a Sustainable Future Scenario—regardless of how much we reduce current emissions, the region’s temperature is projected to rise by nearly 1°C. Under a Current Policies Scenario, the increase is significantly higher with a temperature rise of 1.2°C (2.1°F) by 2035 and 2.1°C (3.8°F) by 2050.

PROJECTED TEMPERATURE RISE			
YEAR	RCP 2.6	RCP 4.5	RCP 8.5
2035	0.8°C	1.0°C	1.2°C
2050	0.9°C	1.4°C	2.1°C

Table 1: Raw CMIP5 model data for Eastern Massachusettsunder three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

Summer heat is a significant concern when it comes to the impact of climate change. According to the City of Boston’s *“Climate Ready Boston”* report[23], Boston’s average summer temperature of 69°F (1981-2010) may increase to as high as 76°F by 2050 in a Current Policies Scenario.

Additionally, an average of 11 days per year over 90 degrees occurs in Boston (from data between 1971 and 2000). In a Current Policies Scenario, there may be as many as 40 by 2030 in contrast with an increase to around 20 by 2030 in a Sustainable Future Scenario. By 2050, the number of “90° days” could reach as high as 90 in a Current Policies Scenario (Figure 1).

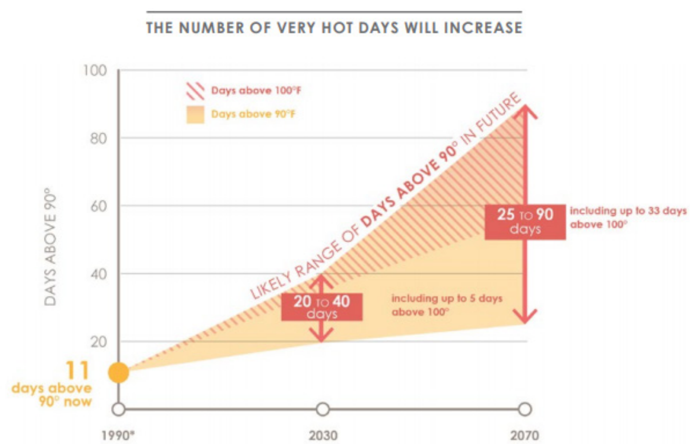

Figure 1: Baseline represents historical average from 1971 - 2000. Upper values from Current Policies Scenario. Lower values from Sustainable Future Scenario. (Source: Climate Ready Boston, Rossi et al. 2015)

Heat is a significant concern for Eastern Massachusetts as the number of dangerous heat events are projected to rise. According to States at Risk, the state currently observes between 0 and 2 days at or above 100°F. In a Sustainable Future Scenario, this could increase to 3 days by 2100. The data is far more concerning in a Current Policies Scenario, where up to 28 “100° days” will be possible by 2100. Further exacerbating the heat is the projected rise in dew points. Increasing greenhouse gas emissions and a warming atmosphere will increase evaporation.[24] In turn, this will increase water vapor in the air, raising humidity. Higher dew points will create far more dangerous weather conditions on extremely hot days with heat indices that could easily reach unsafe levels.

[21]https://www.mass.gov/files/documents/2017/11/29/ch%202.pdf
[22]https://statesatrisk.org/massachusetts
[23]https://www.boston.gov/sites/default/files/file/2019/12/02_20161206_executivesummary_digital.pdf
[24]https://www.climatecentral.org/gallery/graphics/summers-getting-muggier-as-dewpoint-temp-rises

Extreme Precipitation

The large increase in precipitation that we've seen in the Northeast as a region is impressive. The increase is greater in this part of the United States than any other region in the country. According to Climate Ready Boston, there has been a 70% increase in the amount of accumulated precipitation between 1958 and 2010.

While overall precipitation has, historically, increased in recent decades, it is important to note that the natural variability and the complex nature of precipitation events muddies the water with regards to climate change. Recent research, however, does suggest an increase in overall precipitation for Massachusetts in a warming climate. The raw CMIP5 total annual precipitation also returns an increase in all scenarios (Table 2). Moreover, a very strong climate signal exists when analyzing extreme precipitation parameters—this is the case for much of the country. For Eastern Massachusetts, specifically, the CMIP5 data suggest as much as a 32.5% increase in annual total precipitation exceeding the daily 99th percentile by 2050 in a Current Policies Scenario with all scenarios highlighting a significant increase in extreme precipitation under this parameter (Figure 2). Bottom line: wet days will be even wetter.

PROJECTED TOTAL ANNUAL PRECIPITATION INCREASE			
YEAR	RCP 2.6	RCP 4.5	RCP 8.5
2020-2035 Average	1.2%	2.0%	2.9%
2036-2050 Average	2.6%	3.0%	4.1%

Table 2: Raw CMIP5 model total annual precipitation data for Eastern Massachusetts under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

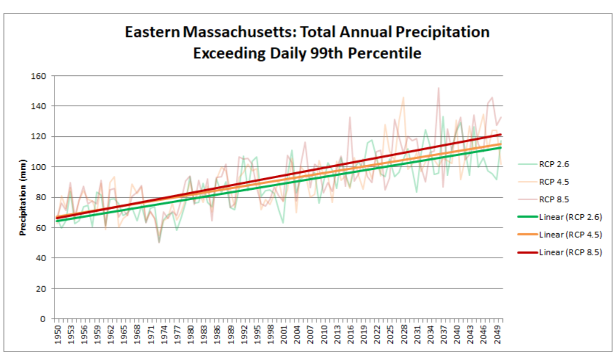

Figure 2: Raw CMIP5 model extreme precipitation data for Eastern Massachusetts under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

Significant seasonal variability in precipitation can be expected to change in a warmer climate. A 2006 study suggested that a slight decrease in summer precipitation is anticipated for the state, when river flows are low, whereas winter would experience as much as a 30% increase in a Current Policies Scenario. Due to a warming climate, winter precipitation will trend towards rain vs. snow as warmer temperatures delay the onset of winter precipitation and shorten the season. This change in precipitation type will have a significant effect on spring snowmelt and peak stream flows, according to the Massachusetts Climate Change Adaptation Report.

PROJECTED Δ PRECIPITATION: SUSTAINABLE FUTURE			
PARAMETER	1961-1990 AVG	2050	2077-2099
Annual Precipitation	41"	5%	7%
Winter Precipitation	8"	6%	12%
Summer Precipitation	11"	-1%	-1%

Table 4: Change in precipitation for Massachusetts. Source: Massachusetts Climate Change Adaptation Report, Hayhoe et al, 2006.

PROJECTED Δ PRECIPITATION: CURRENT POLICIES			
PARAMETER	1961-1990 AVG	2050	2077-2099
Annual Precipitation	41"	8%	14%
Winter Precipitation	8"	16%	30%
Summer Precipitation	11"	-3%	0%

Table 5: Change in precipitation for Massachusetts. Source: Massachusetts Climate Change Adaptation Report, Hayhoe et al, 2006.

Furthermore, a shift towards rainier and icier winters would have significant impacts. According to recent research, the Northeast is projected to lose between 25% and 50% of their snow-covered days by the end of the century in a Current Policies Scenario.[25] While winter rain will be far more common, a concern is the higher likelihood of ice storms as the climate transitions. Anticipating and adequately preparing for more frequent icing events would not be unfounded.

Radiation

The impact of climate change on solar radiation remains unclear. Emerging research, however, is starting to give us clues. One major factor is the effects of increased water vapor in the atmosphere due to warming.
An increase in overall precipitation and extreme precipitation events is anticipated for Eastern Massachusetts. That said, seasonal variability is a factor. Research suggests that hotter, drier summers will become the new norm and, in turn, less cloudiness. An increase in precipitation during winter is the expectation, which may result in more cloudy days, limiting solar radiation. A recent study on mean solar radiation seems to follow along with this narrative, showing a significant increase in solar radiation in the summer months and a decrease in the winter months.[26]

[25] https://www.ncdc.noaa.gov/extremes/cei/
[26] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-15-0011.1

The raw CMIP5 model surface downwelling shortwave radiation data show significant variability among the selected scenarios, without a clear correlation between emissions and this specific radiation parameter (Figures 3 & 4). That said, it is noted that the model output shows an increase in mean surface downwelling shortwave radiation and anomalies.

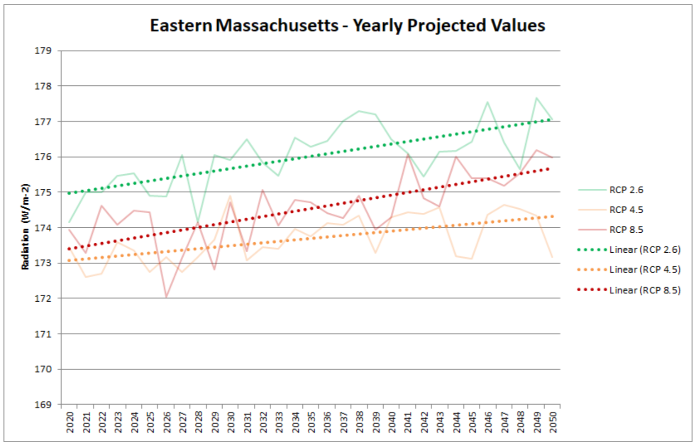

Figure 3: Raw CMIP5 Surface Downwelling Shortwave Radiation data for all 3 climate scenarios.

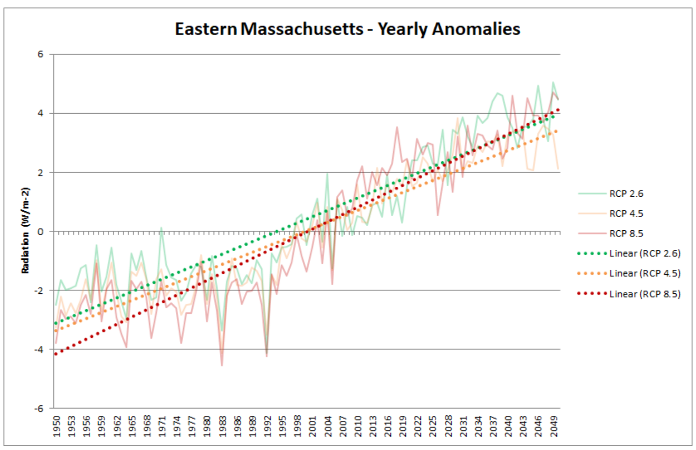

Figure 4: Raw CMIP5 Surface Downwelling Shortwave Radiation Anomaly data for all 3 climate scenarios.

KERN COUNTY, CALIFORNIA

Key Takeaways:

- *Temperature* – Models suggest a temperature rise of at least 0.9°C and 1.0°C by 2035 and 2050 respectively is "baked in" regardless of scenario.
- *Extreme Heat* – Dangerous heat days may increase by as much as 43% by 2050. The hottest day of the year may be up to 10°F warmer by 2050.
- *Precipitation* – Greater variability is expected. Dry and wet extremes are projected to increase greatly in a warming climate.
- *Wildfires* – Large wildfires could become up to 50% more frequent by the end of the century.
- *Radiation* – Research suggests an increase in radiation during winter and spring.

Extreme Temperatures

California is one of the most vulnerable states in the United States when it comes to the impact of climate change. With an already highly variable climate, California has been subject to more frequent and severe weather extremes.[27] Temperatures in the state have already been warming with more frequent heat waves. Southern California, specifically, has warmed about 3°F in the last century and has warmed more than the rest of the state.[28]

In our analysis of the raw CMIP5 data in Kern County, California, the data suggest a 0.9°C (1.6°F) temperature increase by 2035 and 1.0°C (1.8°F) by 2050 under a Sustainable Future Scenario. Under the Current Policies Scenario, the increase is significantly higher with a temperature rise of 1.4°C (2.5°F) by 2035 and 2.1°C (3.8°F) by 2050.

PROJECTED TEMPERATURE RISE			
YEAR	RCP 2.6	RCP 4.5	RCP 8.5
2035	0.9°C	1.0°C	1.4°C
2050	1.0°C	1.4°C	2.1°C

Table 6: Raw CMIP5 model data for the Kern County area under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

Figure 5 below shows the annual average maximum temperatures from 1960 to 2005 over the Los Angeles area using historical observations and model simulations along with 2006 to 2100 climate model projections under the 2-Degree Scenario (RCP4.5) and the Current Policies Scenario (RCP8.5). Note that temperatures are similar during the early part of the 21st century for both scenarios though there is significant divergence in the second half of the century as emissions continue to rise under the Current Policies Scenario.

[27] https://www.energy.ca.gov/sites/default/files/2019-08/20180827_Summary_Brochure.pdf
[28] https://www.epa.gov/sites/production/files/2016-09/documents/climate-change-ca.pdf

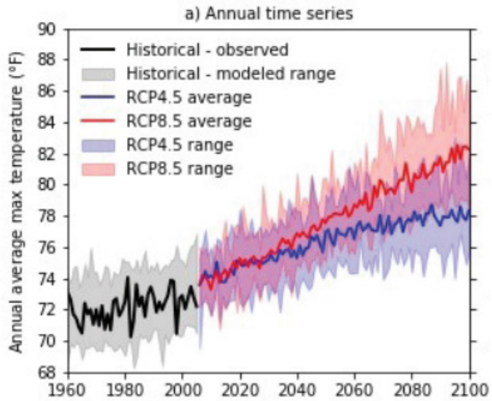

Figure 5: Historical-observed (black), historical-modeled (grey), and projected future (RCP4.5 - blue, RCP8.5 - red) annual average maximum temperature over the Los Angeles region. Source: Los Angeles Region Report.[29]

One of the major concerns with temperatures rising in Kern County is the threat of dangerous heat. California currently averages 35 days a year classified as dangerous or extremely dangerous according to the National Weather Service Heat Index. By 2050, California is projected to see almost 50 dangerous heat days. The hottest day of the year may be up to 10°F warmer by the late century under the Current Policies Scenario. Additionally, by 2050, the typical number of heat wave days in California is projected to more than triple, increasing from fewer than 15 to more than 45 days a year under a Current Policies Scenario.[30] According to the Kern County Climate Adaptation Report in April 2019, by 2050, *summer* average temperatures are projected to increase by 5°F to 6°F. By 2100, an increase of 9°F to 11°F is projected.[31]

Precipitation

Model data of *overall* annual precipitation trends show a lack of agreement, though they do reflect increasing variability. Across all simulations, a warmer climate can be linked to precipitation extremes. Higher temperatures have been shown to lead to drier conditions due to an increase in evaporation and plant stress.[32] This points towards more frequent and intense droughts. According to States of Risk, by 2050, the severity of widespread summary drought is projected to almost triple under a Current Policies Scenario. An analysis of Kern County presented in the Kern County Climate Adaptation Report in April 2019 suggests an overall decline in precipitation of 1 to 2 inches by 2050 and a decline of up to 3.5 inches by 2100.

While the models indicate increasingly dry conditions for the region of interest, they also present a tendency for increased precipitation on wet days. The raw CMIP5 extreme precipitation data returns an increase in all three scenarios—an increase of over 20% or more in two of the three scenarios (Table 3, Figure 5).

INCREASE IN ANNUAL TOTAL PRECIPITATION EXCEEDING DAILY 99th PERCENTILE			
YEAR	RCP 2.6	RCP 4.5	RCP 8.5
2020-2035 AVERAGE	27.8%	16.3%	23.4%
2036-2050 AVERAGE	20.5%	12.3%	25.2%

Table 3: Raw CMIP5 model extreme precipitation data for the Kern County area under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

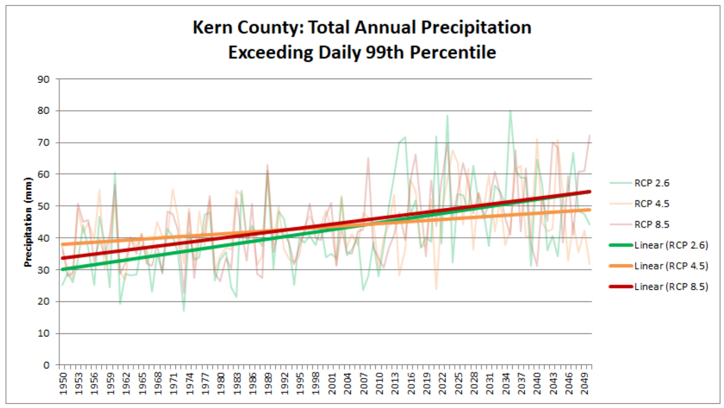

Figure 5: Raw CMIP5 model extreme precipitation data for Eastern Massachusetts under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

In conclusion, dry and wet extremes are expected to increase in a warming climate in Kern County. The wettest day of the year is projected to increase for much of southern California by as much as 25% to 30% under a Current Policies Scenario.[33] Extreme precipitation is generally forged by "atmospheric river" events in southern California. This is an area of high water vapor transportation from the tropics to the Pacific Coast of the United States and is known to produce periods of intense precipitation that can often lead to flooding, landslides, and mudslides. Research points to an increase in atmospheric river events with higher water vapor transport rates compared to current averages. Additionally, the peak season for such events may lengthen, which will extend the threat period for areas such as Kern County. Under a Current Policies Scenario, climate models project a nearly 40% increase in precipitation during such events by the late 21st century, according to the State of California Energy Commission.

[29]https://www.energy.ca.gov/sites/default/files/2019-07/Reg%20Report-%20SUM-CCCA4-2018-007%20LosAngeles.pdf
[30]http://assets.statesatrisk.org/summaries/California_report.pdf
[31]https://www.advancementprojectca.org/wp-content/uploads/2019/05/AP-Kern-Climate-Adaptation-May-2019-8.5-x-11-single-page.pdf
[32]https://www.energy.ca.gov/sites/default/files/2019-08/20180827_Summary_Brochure.pdf
[33]https://www.energy.ca.gov/sites/default/files/2019-07/Reg%20Report-%20SUM-CCCA4-2018-007%20LosAngeles.pdf

Wildfires

More than 400,000 acres have burned each year, on average, on U.S. Forest Service land in California. This is three times the annual amount burned in the 1970s.[34] In a warmer and drier climate, California's wildfires are likely to continue to increase in severity and frequency. Added plant stress will contribute to wildfire "fuel," which includes trees, underbrush, and dry grasses. The dryness of such vegetation directly affects the behavior of wildfires. According to States at Risk, by 2050, California is projected to see more than 140 days a year with high wildfire potential under a Current Policy Scenario.

Modeling data suggest large wildfires, greater than 25,000 acres, could become up to 50% more frequent by the end of the century if emissions are not reduced (Current Policies Scenario). Additionally, more years with extremely high areas burned are projected, comparable to the historical wildfires of 2017 and 2018.[35] The projection in Kern County is more modest than other counties in California (as seen in Figure 6 below). We note a slight increase in hectares burned mainly in the central and western tier of the county with a more significant increase in the north central part of the county.

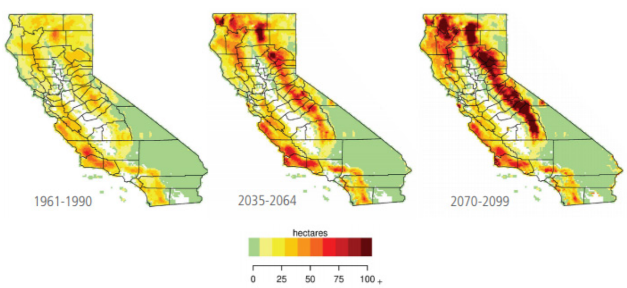

Figure 6: Modeled area burned by wildfires from current time (modeled as 1961-1990), for 2035-2064, and for 2070-2099. Source: California's Fourth Climate Change Assessment.

Radiation

Under a warmer climate, California will be subject to longer, drier summers and more severe droughts. In Kern County, one can propose that such a trend would yield less annual cloud cover overall. Recent research suggests little change in radiation patterns during the summer and fall season, though increasing in the winter and spring months.[36]

The raw CMIP5 model surface downwelling shortwave radiation data show significant variability among the selected scenarios, without a clear correlation between emissions trajectories and this specific radiation parameter. That said, it is noted that the model output shows a slight increase in mean surface downwelling shortwave radiation and anomalies in all scenarios through 2100 (Figure 7 & 8).

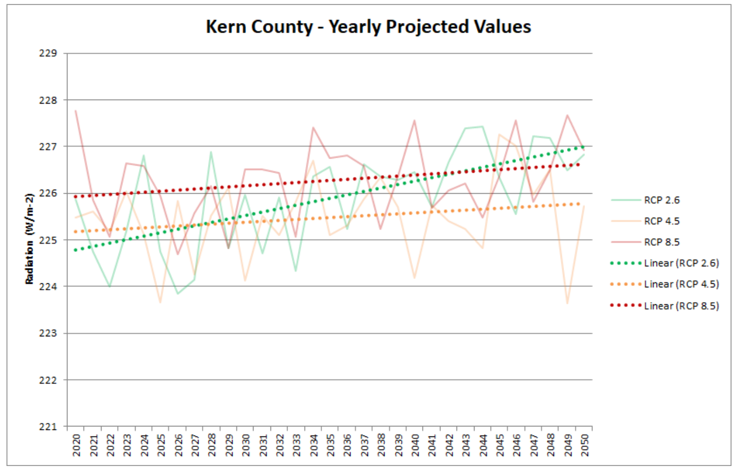

Figure 7: Raw CMIP5 Surface Downwelling Shortwave Radiation data for all 3 climate scenarios.

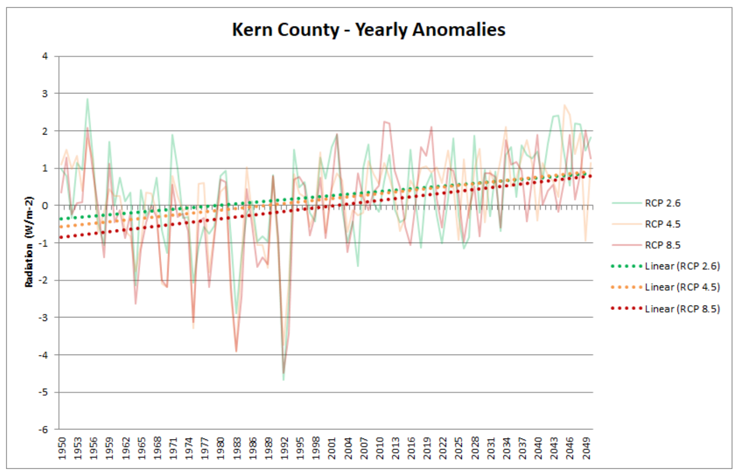

Figure 8: Raw CMIP5 Surface Downwelling Shortwave Radiation Anomaly data for all 3 climate scenarios.

PETERSBURG, NEBRASKA

Key Takeaways:

- *Temperature* — Models suggest a temperature rise of at least 0.9°C and 1.1°C by 2035 and 2050 respectively is "baked in" regardless of scenario.
- *Extreme Heat* — A warming climate will result in Dangerous heat days may increase by as much as 167% in a Current Policies Scenario.
- *Precipitation* — While heavy precipitation events are projected to be more intense, summer droughts are likely to become more severe. The magnitude of floods is expected to increase.

[34] http://assets.statesatrisk.org/summaries/California_report.pdf
[35] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-15-0011.1
[36] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-15-0011.1

- *Radiation* — Research suggests a slight increase in the summer and winter months with decreasing radiation during the spring and fall.

Extreme Temperatures

The climate has already begun to change in Nebraska. The state has warmed by approximately 1°F since 1895, which is consistent with the trends occurring across the Plains states and the Midwest. Generally, the data reflect the greatest warming during the winter and spring months in particular.[37]

In our analysis of the raw CMIP5 data for the area including and surrounding Petersburg, Nebraska, the data suggest a 0.9°C (1.6°F) temperature increase by 2035 and 1.1°C (2°F) by 2050 under a Sustainable Future Scenario. Under the Current Policies Scenario, the increase is significantly higher with a temperature rise of 1.2°C (2.2°F) by 2035 and 1.9°C (3.4°F) by 2050.

PROJECTED TEMPERATURE RISE

YEAR	RCP 2.6	RCP 4.5	RCP 8.5
2035	0.9°C	1.0°C	1.2°C
2050	1.1°C	1.4°C	1.9°C

Table 6: Raw CMIP5 model data for the Petersburg, Nebraska, area under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

Additional research by the University of Nebraska-Lincoln proposes that Nebraska will experience an increase of 4°F to 5°F under a Sustainable Future Scenario and an 8°F to 9°F increase by the last quarter of the century (2071-2099). While the greatest warming is projected to occur during the winter vs. summer and in minimum overnight temperatures vs. maximum daytime temperatures, heat will still be a factor in Nebraska's future climate. In reviewing extreme heat parameters, the data clearly present an increase in 90th percentile heat events (Figure 9). Note that the frequency of such events "stabilizes" in the mid-century under a Sustainable Future Scenario and 2 Degree Scenario vs. the continued and rapid increase of heat events under a Current Policies Scenario.

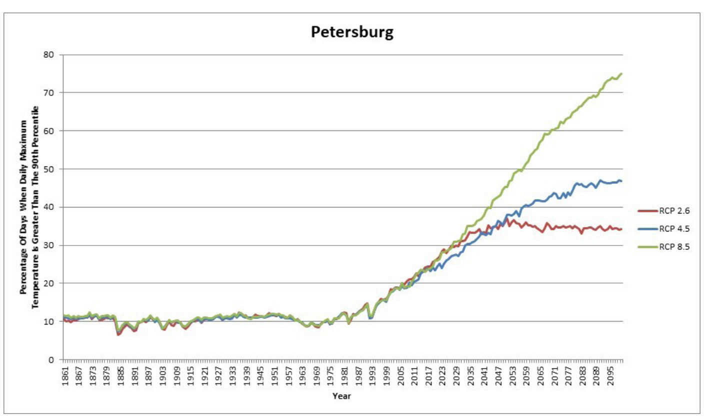

Figure 9: Raw CMIP5 annual extreme data displaying Percentage of Days when Daily Maximum Temperature is greater than the 90th percentile for all 3 climate scenarios in the Petersburg, Nebraska, area.

Nebraska averages 15 days a year with temperatures reaching dangerous levels. By 2050, in a Current Policies Scenario, the state may see up to 40 days of extreme and dangerous heat.[38] Under both a Sustainable Future Scenario and Current Policies Scenario, the number of 100° days (days where the temperatures reach or exceed 100°F) are forecast to rise dramatically in Nebraska. As dew points are projected to climb[39], the state will experience more dangerous heat days where heat indices reach or exceed 105°F. In Lincoln, Nebraska, the number of days where the heat index is greater than 105°F is projected to rise from 17 (year 2000) to 43 (year 2030) to 56 (2050) under a Current Policies Scenario (Figure 10).

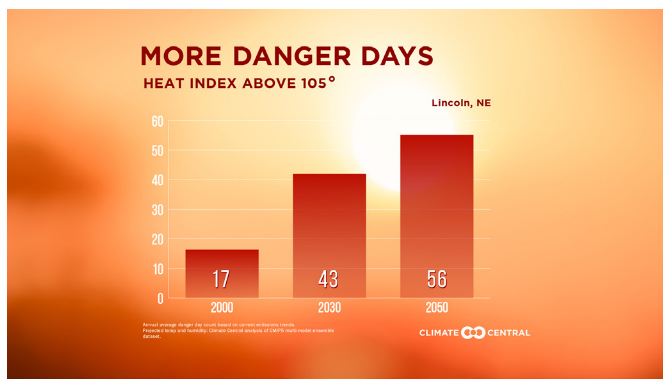

Figure 10: Number of "danger days" where heat index exceeds 105°F in Lincoln, NE. Source: Climate Central.

In the summer of 2012, one of the nation's worst heat waves occurred and was a high-impact event for the state of Nebraska. The record-breaking heat experienced by the state in 2012 is projected to become the "new norm" by mid-century (2041-2070).[40] Adequate preparations need to be made to handle such dangerous heat events as they are likely to become much more frequent in the coming decades.

Precipitation

In the Great Plains, the amount of precipitation falling

[37] http://snr.unl.edu/download/research/projects/climateimpacts/2014ClimateChange.pdf
[38] http://assets.statesatrisk.org/summaries/Nebraska_report.pdf
[39] https://www.climatecentral.org/gallery/graphics/summers-getting-muggier-as-dewpoint-temp-rises
[40] http://snr.unl.edu/download/research/projects/climateimpacts/2014ClimateChange.pdf

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during the wettest four days of the year has increased by approximately 15%. Despite the thought that summer droughts will likely become more severe, flooding is also projected to become more intense in the coming decades. Heavy rain events will account for an increasing fraction of all precipitation.[41] Essentially, wet days will become wetter.

Most of Eastern Nebraska has already witnessed some of the greatest precipitation increases in the Great Plains region. The region has already experienced a higher percentage of the average annual precipitation falling during heavy rainfall events—a trend that is likely to continue, according to the University of Nebraska-Lincoln. Our findings when reviewing the raw CMIP5 extreme precipitation data for the area further substantiates these thoughts. A significant increase in extreme precipitation is noted in all three scenarios—an increase of over 30% under a Current Policies Scenario.

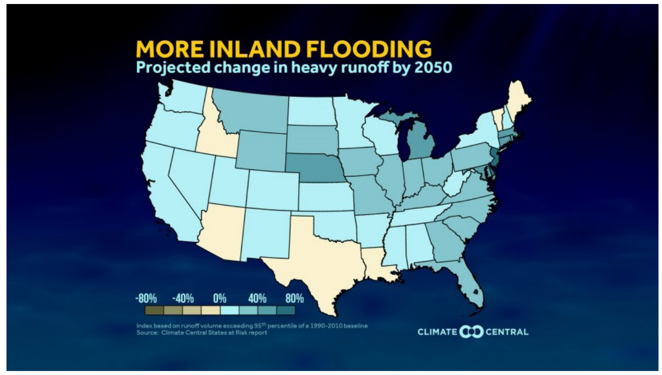
INCREASE IN ANNUAL TOTAL PRECIPITATION EXCEEDING DAILY 99th PERCENTILE			
YEAR	RCP 2.6	RCP 4.5	RCP 8.5
2020-2035 AVERAGE	14.1%	13.6%	16.3%
2036-2050 AVERAGE	19.3%	22.3%	30.7%

Table 7: Raw CMIP5 model extreme precipitation data for the Petersburg, Nebraska, area under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

While heavy precipitation events will become more intense, it's important to note that summer droughts are likely to become more severe. The drought of 2012 was the driest and hottest year ever recorded for Nebraska with records dating back to 1895—events such as these will become more frequently. The raw CMIP5 data supports this expectation with an increase in consecutive dry spell days—rising to, approximately, 3.5% by 2050 under a Current Policies Scenario (Table 8). This "feast-or-famine" narrative gives rise to an increased threat of flooding. The magnitude of floods has been increasing. As more intense rainfall events occur on wet days, a drier soil makes will be more conducive for run-off and flooding. Soil moisture is projected to decrease by 5-10% under a Current Policies Scenario.[42]

INCREASE IN MAXIMUM LENGTH OF DRY SPELL DAYS			
YEAR	RCP 2.6	RCP 4.5	RCP 8.5
2020-2035 AVERAGE	0.7%	0.8%	1.1%
2036-2050 AVERAGE	0.7%	1.7%	3.5%

Table 8: Raw CMIP5 model maximum length of dry spell days for the Petersburg, Nebraska, area under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).



Severe Weather

Nebraska experiences more than 50 tornadoes a year and the impact of climate change on severe trends is still an active area of research. That said, rising concentrations of greenhouse gases generally lead to increase in humidity. From a meteorological perspective, a more humid atmosphere favors more atmospheric instability, which would, in theory, encourage the development of tornadoes. However, there are many more factors that come into play when it comes to severe weather. For example, a favorable environment for tornadoes usually has elevated wind shear, change in speed or direction in wind with height. Research suggests that a warming climate would result in a decrease in windshear, which would discourage tornado development.[43] The frequency of severe storms will continue to be monitored and studied by scientists to assess the impact of climate change.

Radiation

Recent research highlights Nebraska as seeing a slight increase in the summer and winter months with decreasing radiation during the spring and fall.[44] Under both a Sustainable Future Scenario and a Current Policies Scenario, the number of consecutive dry days for Nebraska is expected to increase by 1 to 3 days.[45] This may point towards an increase in consecutive less cloudy days as well—in particular in the summer where drought conditions are projected to worsen.

The raw CMIP5 model surface downwelling shortwave radiation data show significant variability among the selected scenarios, without a clear correlation between emissions trajectories and this specific radiation parameter. That said, it is noted that the model output shows a slight increase in mean surface downwelling

[41] https://www.epa.gov/sites/production/files/2016-09/documents/climate-change-ne.pdf
[42] http://snr.unl.edu/download/research/projects/climateimpacts/2014ClimateChange.pdf
[43] https://www.epa.gov/sites/production/files/2016-09/documents/climate-change-ne.pdf
[44] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-15-0011.1
[45] http://snr.unl.edu/download/research/projects/climateimpacts/2014ClimateChange.pdf

shortwave radiation and anomalies in all scenarios through 2100 (Figure 10 & 11).

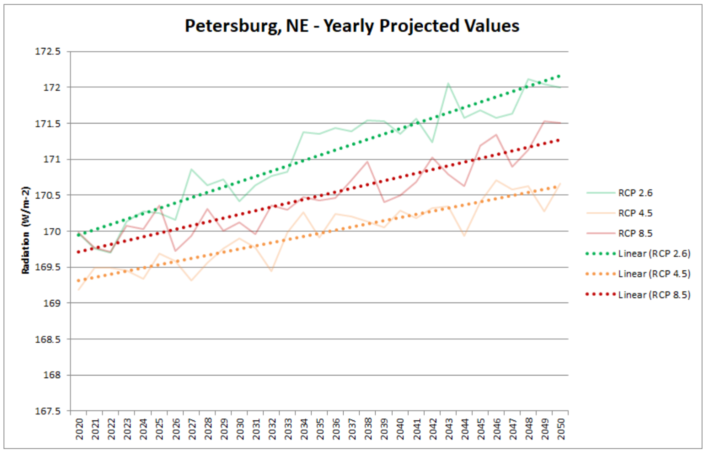


Figure 10: Raw CMIP5 Surface Downwelling Shortwave Radiation data for all 3 climate scenarios.

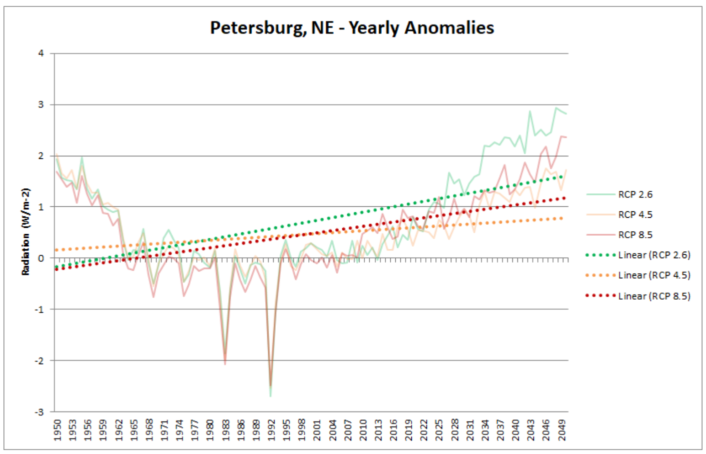


Figure 11: Raw CMIP5 Surface Downwelling Shortwave Radiation Anomaly data for all 3 climate scenarios.

STERLING CITY, TEXAS

Key Takeaways:

- *Temperature* — Models suggest a temperature rise of at least 1.1°C is "baked in" regardless of scenario by 2035.
- *Extreme Heat* — Dangerous heat is one of the leading concerns. The number of dangerous heat days in Texas is projected to quadruple under a Current Policies Scenario.
- *Precipitation* — More precipitation on wet days is expected along with an increase in frequency and intensity with drought.
- *Radiation* — Research suggests a significant increase in radiation during the winter months with a slight decrease in the spring. Little change is projected during the summer and fall.

Extreme Temperatures

Dangerous heat is one of the leading concerns for Texas when it comes to climate change. Most of the state has warmed by between 0.5°F and 1.0°F in the past century.[46] In our analysis of the raw CMIP5 data for the area including and surrounding Sterling City, Texas, the data suggest a temperature increase of 1.1°C (2°F) by 2035 and holding steady through 2050 under a Sustainable Future Scenario. Under the Current Policies Scenario, the increase is significantly higher with a temperature rise of 1.5°C (2.7°F) by 2035 and 1.9°C (3.4°F) by 2050.

PROJECTED TEMPERATURE RISE

YEAR	RCP 2.6	RCP 4.5	RCP 8.5
2035	1.1°C	1.4°C	1.5°C
2050	1.1°C	1.6°C	2.2°C

Table 9: Raw CMIP5 model data for the Sterling City, Texas, area under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

Currently, Texas averages the greatest number of dangerous heat days according to the NWS Heat Index (just over 60 days). By 2050, under a Current Policies Scenario, the state is projected to see 115 such days annually.[47] Additionally, by 2050, the typical number of heat wave days in Texas is projected to quadruple from 15 to nearly 60 days a year under a Current Policies Scenario (Figure 12). On average, the state of Texas is warming faster than the United States, as a whole, based on annual average temperatures since the 1970s.[48]

The Sterling City region, specifically, is now seeing roughly 14 more 100° days a year since 1970 (days where the maximum temperature reaches or exceeds 100°F. Figure 12, below, showcases this rise for nearby Abilene. Under a Current Policies Scenario, the region is projected to experience an additional 30 to 60 days per year above 100°F.[49]

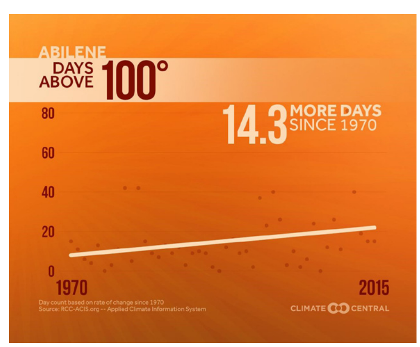


Figure 12: Number of 100° Days where maximum temperatures reach or exceed 100°F in Abilene, TX. Source: Climate Central.

[46] https://www.epa.gov/sites/production/files/2016-09/documents/climate-change-tx.pdf
[47] http://assets.statesatrisk.org/summaries/Texas_report.pdf
[48] https://statesatrisk.org/texas/all
[49] https://www.climatecentral.org/news/sizzling-summers-20515#dangerdays

A warmer climate means higher humidity. As dew points are projected to climb[50], Texas will experience more dangerous heat days where heat indices reach or exceed 105°F. In Abilene, for example, the number of days where the heat index is greater than 105°F is projected to rise from 71 (year 2000) to 95 (year 2030) to 113 (2050) under a Current Policies Scenario (Figure 13).

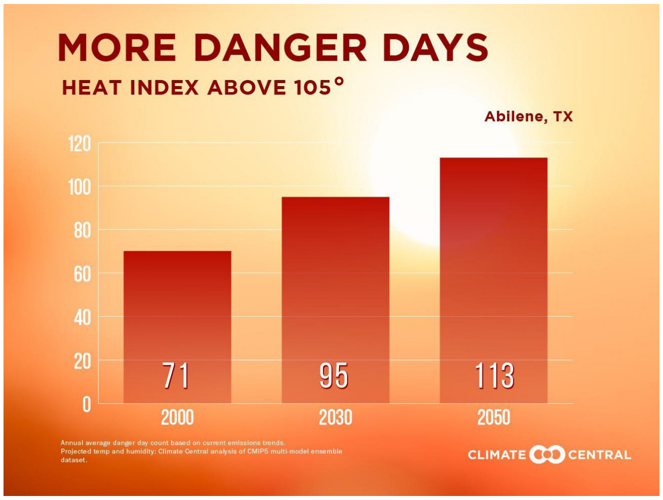


Figure 13: Number of "danger days" where heat index exceeds 105°F in Abilene, TX. Source: Climate Central.[51]

In reviewing extreme heat parameters, our findings clearly present a significant increase in 90th percentile heat events (Figure 14). Note that the frequency of such events "stabilizes" in the mid-century under a Sustainable Future Scenario and 2 Degree Scenario vs. the continued and rapid increase of heat events under a Current Policies Scenario.

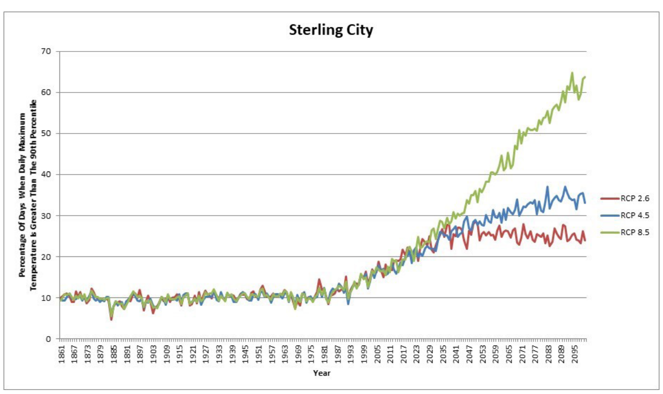


Figure 14: Raw CMIP5 annual extreme data displaying Percentage of Days when Daily Maximum Temperature is greater than the 90th percentile for all 3 climate scenarios in the Sterling City, Texas, area.

In the summer of 2011, the southern United States experienced a deadly, record-breaking heat wave that severely impacted Texas.[52] Such heat events will likely become more and more frequent. With summers projected to be longer and hotter, adequate preparations need to be made to handle a higher frequency of heat stress days in the coming decades—especially in a Current Policies Scenario.

Precipitation

In reviewing the average annual precipitation trends for Texas, only modest changes in the winter and summer is noted—a slightly wetter winter with a drier summer. However, a strong climate signal is apparent when looking at the frequency and intensity of heavy precipitation events—particularly in a Current Policies Scenario. The Southern Plains has seen a significant rise in record-breaking flooding over the past 30 years.[36] In contrast, by 2050, the severity of widespread summer drought is projected to see the third greatest increase among the lower 48 states.[53]

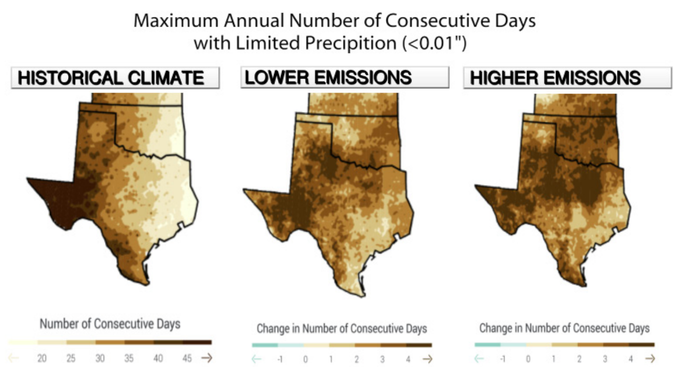


Figure 15: Maximum annual number of consecutive days in which limited precipitation was recorded (less than 0.01"). Historical climate vs. projected changes in a Sustainable Future Scenario (lower emissions) vs. a Current Policies Scenario (higher emissions). Source: NOAA NCDC / CICS-NC.[54]

According to the Fourth National Climate Assessment, "over the past 50 years, significant flooding and rainfall events followed drought in approximately one-third of the drought-affected periods in the region when compared against the early part of the 20th century."[55] Understanding the role of climate change in such a dramatic swing in extreme precipitation conditions is an active area of research.

As with other parts of the Great Plains, we're seeing a similar trend in Texas: a trend for more precipitation on wet days is expected along with an increase in frequency and intensity with drought—with Texas as the poster child for this juxtaposition. Texas faces the worst threat from widespread summer drought among the continental United States.[56] An increase in precipitation intensity vs. steady rainfall events suggests more time to dry out in

[50] https://www.climatecentral.org/gallery/graphics/summers-getting-muggier-as-dewpoint-temp-rises
[51] https://www.climatecentral.org/news/sizzling-summers-20515#dangerdays
[52] https://www.weather.gov/shv/event_2011_heatdroughtfire
[53] http://assets.statesatrisk.org/summaries/Texas_report.pdf
[54] https://nca2014.globalchange.gov/report/regions/great-plains
[55] https://nca2018.globalchange.gov/chapter/1/
[56] https://statesatrisk.org/texas/all

between periods of rain, which is anticipated to increase soil moisture stress. Some studies suggest that in a warmer climate, future conditions could possibly be drier than anything experienced by the region in the last 1,000 years.[57] A very dry ground is also more conducive to flooding, implying an elevated threat of flooding during high intensity rainfall events.

Severe Weather

Texas is no stranger to severe weather. The state is notorious for tornadoes, large hail, and damaging wind events. Scientists are still unsure of how climate change will increase the frequency and severity of tornadoes.[58] As stated earlier in this report, rising concentrations of greenhouse gases generally lead to increase in humidity. A more humid atmosphere favors more atmospheric instability, which would, in theory, encourage the development of tornadoes and large hail events. However, wind shear is projected to decrease, which would not favor the development of tornadoes. This remains an active area of research.

Radiation

Recent research highlights Texas as seeing a significant increase in radiation during the winter months with a slight decrease in the spring. Little change is projected during the summer and fall.[59] The raw CMIP5 model surface downwelling shortwave radiation data show significant variability among the selected scenarios, without a clear correlation between emissions trajectories and this specific radiation parameter. That said, it is noted that the model output shows a slight increase in mean surface downwelling shortwave radiation and anomalies in all scenarios through 2100 (Figure 16 & 17).

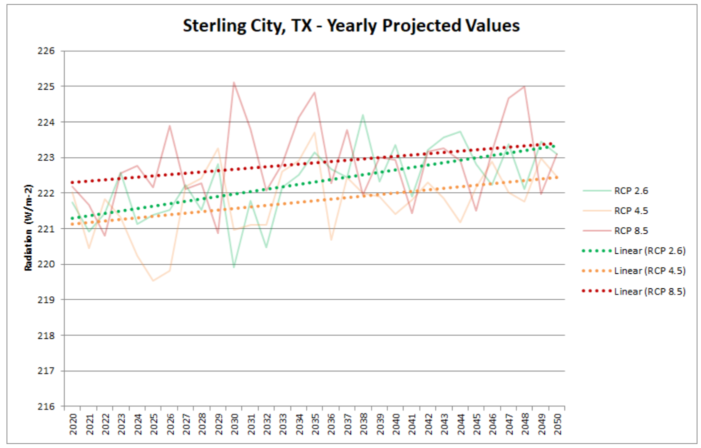


Figure 16: Raw CMIP5 Surface Downwelling Shortwave Radiation data for all 3 climate scenarios.

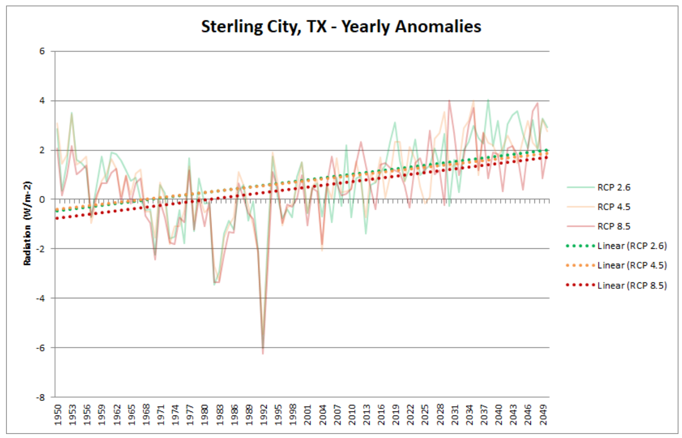


Figure 17: Raw CMIP5 Surface Downwelling Shortwave Radiation Anomaly data for all 3 climate scenarios.

SOUTHEAST MINNESOTA

Key Takeaways:

- Temperature - Models suggest a temperature rise of at least 0.9°C and 1.0°C by 2035 and 2050 respectively is "baked in" regardless of scenario.
- More Heat - Even under a Sustainable Future Scenario (lower emissions), the average annual temperatures are shown to most likely exceed historical record levels by around 2050.
- Precipitation - An increase in frequency and intensity of precipitation events is a significant threat. A significant increase in extreme precipitation is noted in all three scenarios—an increase of over 30% under a Current Policies Scenario
- Radiation - Research suggests a slight decrease in winter, spring, and fall radiation for southeast Minnesota along with an increase during the summer months.

[57] https://statesatrisk.org/massachusetts
[58] https://www.epa.gov/sites/production/files/2016-09/documents/climate-change-tx.pdf
[59] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-15-0011.1

Extreme Temperatures

There already have been significant changes to Minnesota's overall climate in recent decades. The state has warmed by nearly 3°F since 1895. The 10 warmest years on record have all occurred in the past 20 years. Periods of extreme cold are waning in the winter months. Winter, specifically, is warming much faster than summer in Minnesota with fewer days and nights of frigid conditions.[60]

In our analysis of the raw CMIP5 temperature data in southeast Minnesota, the data suggest a 0.9°C (1.6°F) temperature increase by 2035 and 1.0°C (1.8°F) by 2050 under a Sustainable Future Scenario. Under the Current Policies Scenario, the increase is significantly higher with a temperature rise of 1.1°C (2°F) by 2035 and 1.9°C (3.4°F) by 2050.

PROJECTED TEMPERATURE RISE			
YEAR	RCP 2.6	RCP 4.5	RCP 8.5
2035	0.9°C	0.9°C	1.1°C
2050	1.0°C	1.4°C	1.9°C

Table 10: Raw CMIP5 model data for Southeast Minnesota under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

While Minnesota's overall extreme heat threat level is considered low due to its northern location. Additionally, winters are warming at a far faster pace than summers which will still limit the extent of the overall manifestation of climate change on extreme summer heat. However, there still is likely to be an increase in the number of annual dangerous heat days. By 2050, in a Current Policies Scenario, Minnesota's typical number of heat wave days is projected to increase from 10 to more than 55 days a year in a Current Policies Scenario.[61]

Historically unprecedented warming is projected by the second half of the century in Minnesota. Even under a Sustainable Future Scenario (lower emissions), the average annual temperatures are shown to most likely exceed historical record levels by around 2050 (Figure 18). Increases in the number of extremely hot days are projected along with a decrease in extremely cold days as the winter season shortens.[62]

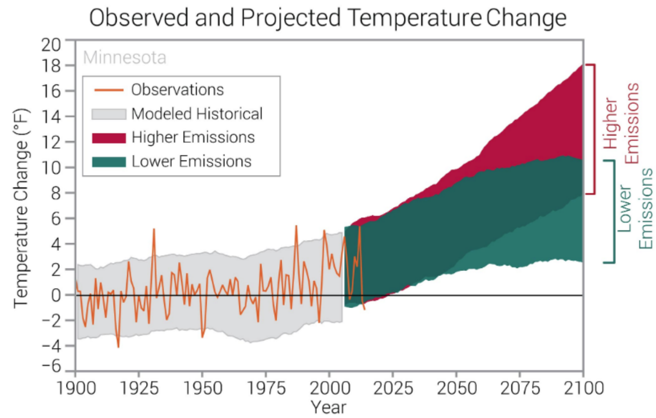


Figure 18: Observed and projected changes (compared to the 1901-1060 average) in temperature for Minnesota through 2100. Shading indicates the range of annual temperatures from the set of models. Source: NCICS.

In reviewing extreme heat parameters, our findings reaffirm a significant increase in 90th percentile heat events (Figure 19). Note that the frequency of such events "stabilizes" in the mid-century under a Sustainable Future Scenario and 2 Degree Scenario vs. the continued and rapid increase of heat events under a Current Policies Scenario.

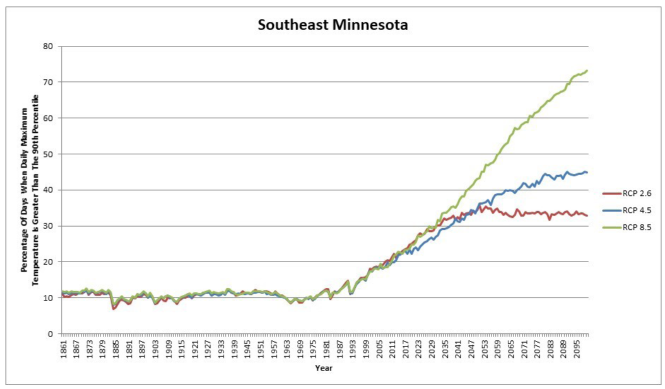


Figure 19: Raw CMIP5 annual extreme data displaying Percentage of Days when Daily Maximum Temperature is greater than the 90th percentile for all 3 climate scenarios in Southeast Minnesota.

Precipitation

The primary concern for Minnesota is the increase in frequency and intensity of precipitation events—a trend that is projected to continue in the coming decades in a warming climate. Since 2000, widespread rain events of 6 inches or more have been 4 times more frequent than in the previous three decades. Additionally, the 10 wettest years on record have all occurred in the past 20 years.[63]

In this next century, spring and annual precipitation is projected to increase, elevating the threat of flooding.[64]

[60] https://files.dnr.state.mn.us/natural_resources/climate/change/climatechange-factsheet.pdf
[61] http://assets.statesatrisk.org/summaries/Minnesota_report.pdf
[62] https://statesummaries.ncics.org/chapter/mn/
[63] https://files.dnr.state.mn.us/natural_resources/climate/change/climatechange-factsheet.pdf
[64] https://statesummaries.ncics.org/chapter/mn/

Figure 20 below showcases the projected change in spring precipitation by the middle of the 21st century under a Current Policies Scenario. The hatched areas represent areas where climate models indicate a significant change. Note that southeast Minnesota is under the hatched region.

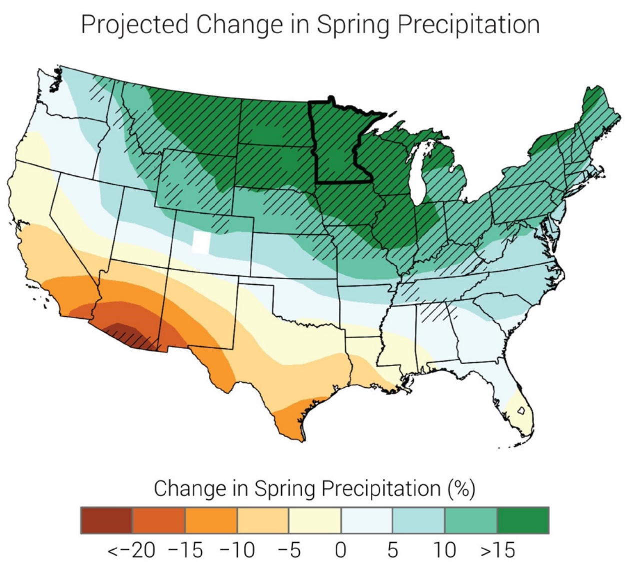


Figure 20: Projected change in spring precipitation (%) by the middle of the 21st century compared to the late 20th century under a Current Policies Scenario (high emissions). Source: NCICS.

Less snow and more rain has already been documented for much of the state, including the southeastern region. A 2016 review of weather stations in Minnesota performed by Climate Central found that 72% of stations are reporting more rain vs. snow based on 65 years of winter precipitation data (Figure 21).

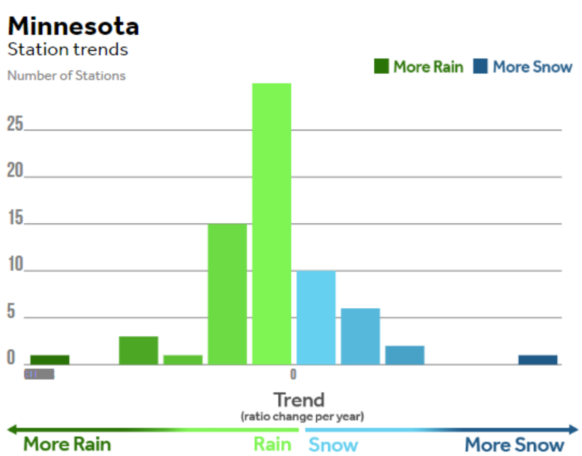


Figure 21: Station trends in Minnesota. Source: Climate Central.

Our findings when reviewing the raw CMIP5 extreme precipitation data for southeast Minnesota further substantiates the wetter trends projected. A significant increase in extreme precipitation is noted in all three scenarios—an increase of over 30% under a Current Policies Scenario (Table 11). Recent research concludes a 20% increase in the number of 1-inch rain events and a 65% increase in the number of 3-inch rain events.[65]

INCREASE IN ANNUAL TOTAL PRECIPITATION EXCEEDING DAILY 99th PERCENTILE			
YEAR	RCP 2.6	RCP 4.5	RCP 8.5
2020-2035 AVERAGE	13.6%	13.4%	16.4%
2036-2050 AVERAGE	19.6%	22.4%	31.8%

Table 11: Raw CMIP5 model extreme precipitation data for the Petersburg, Nebraska, area under three emissions scenarios: Sustainable Future (RCP2.6), 2-Degree (RCP4.5), Current Policies (RCP 8.5).

All evidence suggests that adequate preparations be made to face a wetter climate with an enhanced flooding threat. Severe precipitation events are projected to increase and flooding, particularly in the spring, will be a significant concern for southeast Minnesota.
It is important to note that despite the increases in precipitation for Minnesota, it is possible that a warmer climate will intensify naturally occurring droughts. According to the NCICS State Climate Summary, "in 2007, 24 counties in Minnesota received federal drought designations, while 7 counties were declared flood disasters. Again in 2012, 55 counties received drought designations at the same time that 11 counties declared flood emergencies."[66] The contrasting events of droughts vs. severe flooding can and do occur simultaneously. In conclusion, severe flooding remains a top disruption concern for the region.

Radiation

Recent research suggests a slight decrease in winter, spring, and fall radiation for southeast Minnesota along with an increase during the summer months.[67] The raw CMIP5 model surface downwelling shortwave radiation data show significant variability among the selected scenarios, without a clear correlation between emissions trajectories and this specific radiation parameter. That said, it is noted that the model output shows a slight increase in mean surface downwelling shortwave radiation and anomalies in all scenarios through 2100 (Figure 22 & 23). As mentioned in the previous section, precipitation is trending much wetter during the spring months.

[65] https://files.dnr.state.mn.us/natural_resources/climate/change/climatechange-factsheet.pdf
[66] https://statesummaries.ncics.org/chapter/mn/
[67] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-15-0011.1

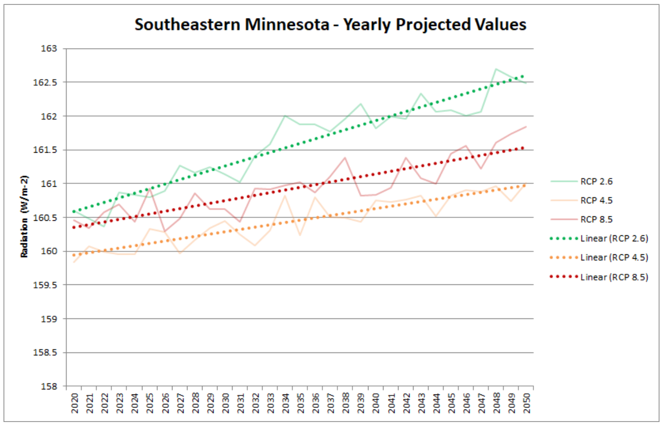


Figure 22: Raw CMIP5 Surface Downwelling Shortwave Radiation data for all 3 climate scenarios.

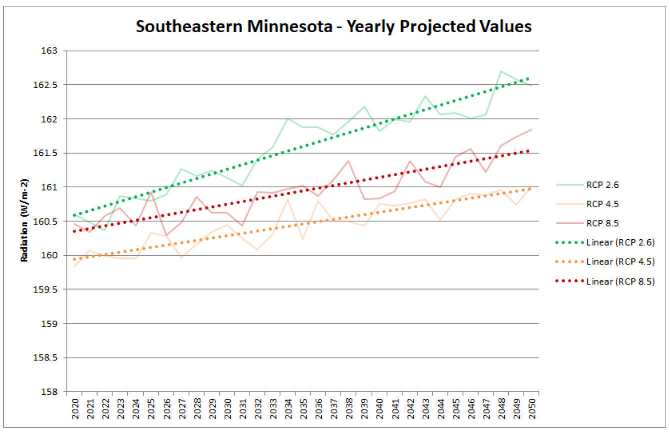


Figure 23: Raw CMIP5 Surface Downwelling Shortwave Radiation Anomaly data for all 3 climate scenarios.

RADIATION COMPARISON

In comparing shortwave radiation projections for all 5 locations, we note a significant positive anomaly trend for Eastern Massachusetts in all climate scenarios. While it is worth noting that this is raw CMIP5 model data and cannot be taken as a high confidence forecast, it is a point of interest in the data set. Furthermore, research in solar radiation forecasting has indicated a significant increase in summer radiation for the northeast with projections through 2060.[67]

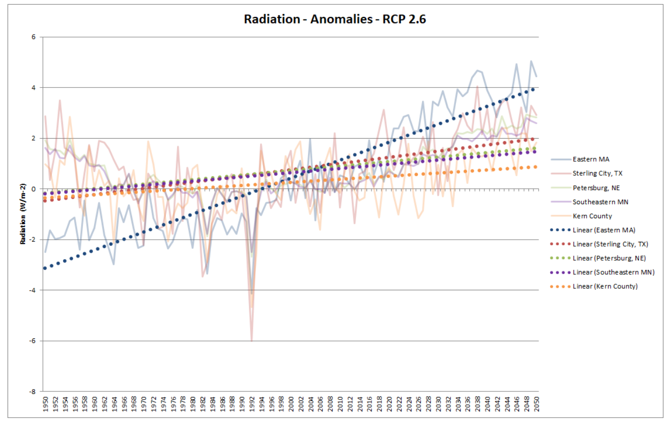


Figure 24: Raw CMIP5 Surface Downwelling Shortwave Radiation Anomaly data for all 5 locations under a Sustainable Future Scenario.

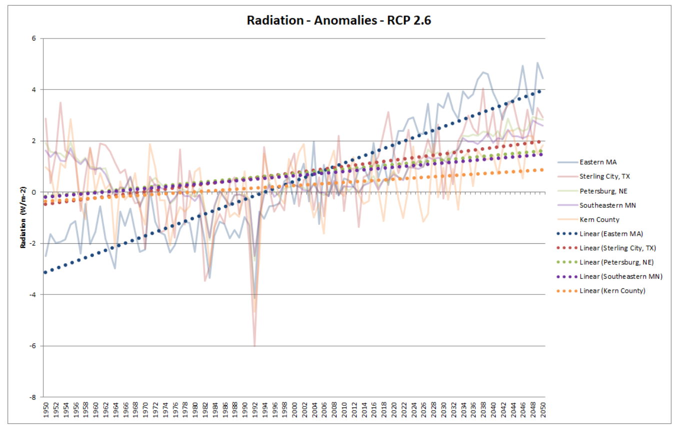


Figure 25: Raw CMIP5 Surface Downwelling Shortwave Radiation Anomaly data for all 5 locations under a 2-Degree Scenario.

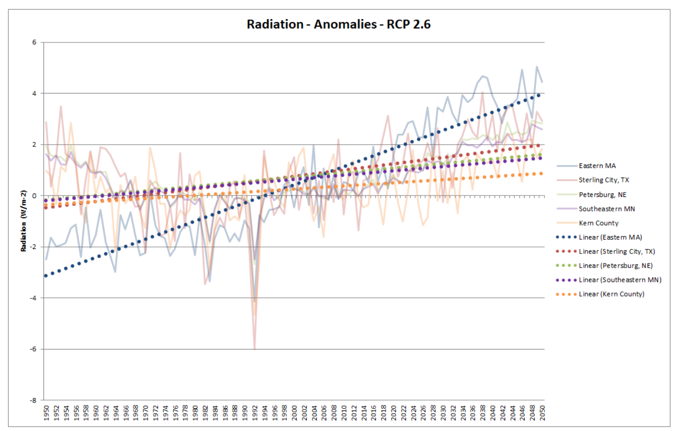


Figure 26: Raw CMIP5 Surface Downwelling Shortwave Radiation Anomaly data for all 5 locations under a Current Policies Scenario.

[67] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-15-0011.1

3

TRANSITIONAL RISK ANALYSIS

Author: Josh Prigge

Summary of Transitional Risk Trends Seen Across Most Scenarios

Policy

- Renewable portfolio standards and clean energy targets will push states to increase renewable energy use.
- Cap and trade schemes in several states and potential carbon tax in the future.
- Business Energy Investment Tax Credit, funding for efficient technologies and new appliance efficiency standards to help reduce energy use in buildings.
- Individual states setting offshore wind capacity targets.

Renewable Energy

- Renewable energy continues to grow and plays a larger role in overall energy use in the United States.

Electrification

- Increasing role of electricity within final energy consumption.
    - The share of electricity in total final consumption in the United States grows from 21% in 2018 to around 24% in 2040.
- Growth in electricity use over the next several decades is led by industrial motors followed by household appliances, cooling and electric vehicles.

Technology

- Global average levelized cost of electricity of offshore wind expected to drastically decrease by 2040.
    - Improvements in the wind turbine design and more efficient construction processes and operation and maintenance procedures expected to reduce costs while deployment increases.
- Increase in electric vehicle adoption across country.
- Reduced cost and increase use of battery storage technology.

Energy Use

- Current Policies Scenario - Higher overall energy demand in US with lack of emphasizing energy efficiency.
- Sustainable Future and 2 Degree Scenarios - Overall energy demand reduced by 2050 due to energy efficiency.
- Reduced use of energy in residential sector.
- Increase use of energy in industrial sector (primarily natural gas and electricity).

Sustainable Future Scenario

The first scenario we look at is the Sustainable Future Scenario, with all projected data and information being pulled from the World Energy Outlook 2019 report's Sustainable Development Scenario.

This is the most ambitious future scenario in regard to a sustainable and low-carbon society. In this scenario we see a total drop in primary energy demand in the United States from 2018 levels of 2,230 million metric tons of oil equivalent to a 2040 total primary energy demand of 1,687 million metric tons of oil equivalent. The overall reduced demand for energy comes primarily as a result of energy efficiency practices across the building sector, industry and transportation.

Fossil Fuel Use

As you might expect, in a sustainable future there is a drastic reduction in the use of fossil fuels. To achieve a minimal global temperature increase of .3 to 1.7 degrees, society moves to a future of clean and renewable energy while reducing the use of carbon intensive fossil fuels. We see global oil demand peak within the next few years and then total consumption falling by around 1.5% per year as oil use declines drastically for passenger cars and for other uses. In 2040, oil use in transportation around the world is 40% lower than it is today.

We also see big reductions in the use of coal. Coal use in the US declines steeply, but it continues to be used

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in industry for the production of cement, iron and steel. The use of natural gas increases through the late 2020's as it replaces more polluting fuels and then peaks in the mid-2020's as battery storage and demand side management take on a much larger role in meeting short term flexibility needs. In the 2030's, the use of natural gas begins to decline as other alternatives are used such as electrification, hydrogen and biomethane.

			Sustainable Development	
	2000	2018	2030	2040
North America	800	1 067	1 052	791
United States	669	860	870	646

Natural Gas Demand in the United States (billion cubic meters)
Source: IEA World Energy Outlook 2019

			Sustainable Development	
	2000	2018	2030	2040
North America	23.5	22.8	17.7	11.7
United States	19.6	18.5	14.2	9.1

Oil Demand in the United States (million barrels/day)
Source: IEA World Energy Outlook 2019

Renewable Energy

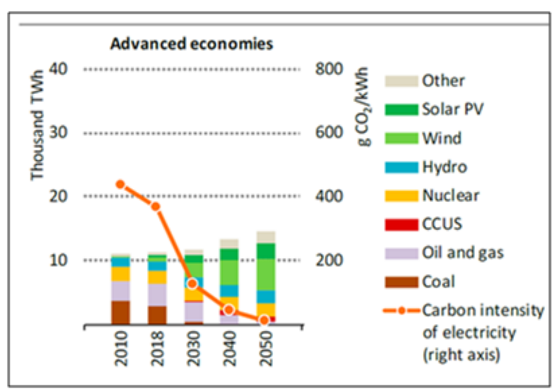
Renewable energy plays a big role within the energy growth of the Sustainable Future Scenario. Renewables make up the large majority of energy capacity additions in all regions around the world including the United States. The pace of solar photovoltaic deployment around the world increases from 97 gigawatts in 2018 to nearly 210 gigawatts in 2030 and over 300 gigawatts in 2040. Wind power grows as well, as additions average close to 130 gigawatts per year up to 2040, which is two and a half times the additions we saw in 2018.

Electricity

The Sustainable Future Scenario is an electrified future. Electricity increases its share in the fuel mix throughout all major sectors including industry, buildings and transportation. Globally, electricity doubles its current share of total fuel mix of 19% by 2050. In advanced economies such as the United States, growth linked to increasing digitalization and electrification is largely offset by energy efficiency improvements. Electric vehicles play a big role in the growth of electricity usage as the total number of EV's surpass conventional vehicles.

			Sustainable Development	
	2000	2018	2030	2040
North America	4 260	4 786	4 966	5 602
United States	3 589	4 011	4 099	4 573

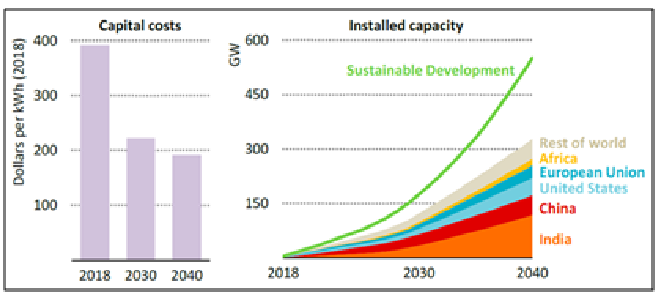
Electricity Demand in the US (TWh)
Source: IEA World Energy Outlook 2019



Electricity Generation by Source and Carbon Intensity of Electricity
Source: IEA World Energy Outlook 2019

Technology

Most of the technology needed to achieve a sustainable future and a 1.5 degree temperature increase limit are currently available today. The issue is not the development of new technology, but rather accelerating the adoption of the current technologies, improving the performance of the technologies and lowering the cost of the technologies efficiently. In the Sustainable Future Scenario governments play a role in establishing the market framework that helps these technologies become more attractive and adopted throughout society. As the power sector moves towards a low-carbon future and electric mobility spreads, the need for flexibility in the power sector will continue to increase. Batteries become increasingly important to meet these flexibility needs, and the outlook for batteries is improved by the prospect of economies of scale and advances in chemistry. Battery storage system costs are projected to be reduced by 50% in the next two decades falling from $400 per kilowatt-hour to less than $200 per kilowatt-hour. In addition, the capital costs of solar photovoltaic fall towards $600 per kilowatt by 2030.



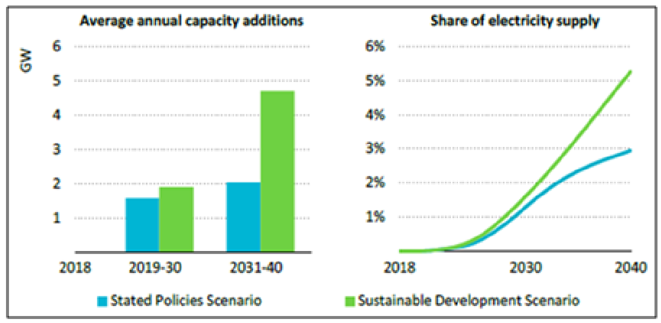
Battery Storage Capital Costs and Installed Capacity
Source: IEA World Energy Outlook 2019

	By 2030	After 2030
Liquids supply	Bio-liquids (jet fuel, diesel and gasoline)	CCUS on refinery hydrogen supply.
Natural gas supply	Remote, continuous methane leak detection	Biomass gasification. Clean hydrogen in gas supply to buildings.
Power generation and supply	Solar PV Smart meters	Small modular nuclear reactors. Battery storage. Biomass-fired power generation.
Buildings	Heat pumps Near-zero emissions buildings Home biogas digesters for clean cooking	Hydrogen fuel cells and boilers.
Transport	Electric cars and trucks	Alternative drivetrains for ships. Hydrogen-powered heavy trucks.
Industry	CCUS for iron and steel and cement	Electrolytic hydrogen feedstock for industrial processes. Heat pumps for industrial heat.

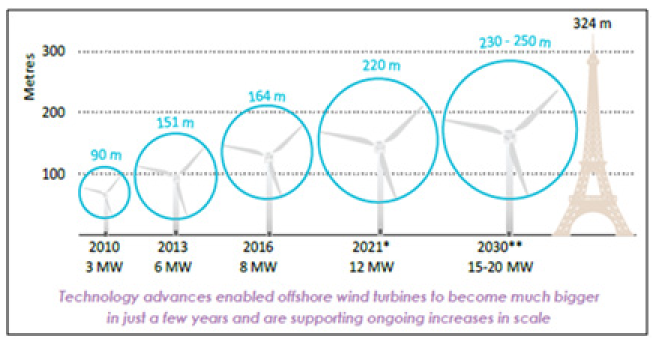
Technologies that will Scale to Over 3% of Market Share (market share defined as global sales of equipment for provision of equivalent energy services) Source: IEA World Energy Outlook 2019

Offshore Wind

The offshore wind market expands significantly over the next several decades. The growth of offshore wind is accelerated by falling technology costs and government policy frameworks that promote the technology's adoption. Offshore wind gains significant ground in the United States over the next two decades. The United States increases its offshore wind capacity by 80%, reaching nearly 70 gigawatts by 2040. This pace of growth for offshore wind in the United States will require an average investment of over $7 billion dollars per year. By the year 2040, offshore wind provides over 5% of the US electricity supply.



Outlook for Offshore Wind in the US
Source: IEA World Energy Outlook 2019



Further Technology Improvement of Offshore Wind
Source: IEA World Energy Outlook 2019

Policies

The numerous policies projected to be in place to achieve the Sustainable Future Scenario are adopted globally in regions across the world, including the United States.

- Staggered introduction of CO2 prices
- Fossil fuel subsidies phased out by 2025 in net-importing countries and by 2035 in net-exporting countries.

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Power Sector Policies

- Increased low-carbon generation from renewables and nuclear.
- Efficiency and emissions standards preventing the refurbishment of old inefficient plants.
- Stringent pollution emissions limits for industrial facilities above 50 MWth input

Industry Sector Policies

- Stringent emissions limits for industrial facilities above 50 MWth input using solid fuels
- Emission limits for facilities below 50 MWth based on size, fuel and combustion process.
- Enhanced minimum energy performance standards by 2025, in particular for electric motors; incentives for the introduction of variable speed drives in variable load systems, and implementation of system-wide measures.
- Mandatory energy management systems or energy audits.

Building Sector Policies

- Phase out least efficient appliances, light bulbs and heating or cooling equipment by 2030 at the latest.
- Introduction of mandatory energy efficiency labeling requirements for all appliances.
- Mandatory energy conservation building codes, including net-zero emissions requirement for all new buildings, by 2030 at the latest.
- Digitalization of buildings electricity demand to increase demand-side response potential, through greater flexibility and controllability of end use devices

Transportation Sector Policies

- Strong support for electric mobility, alternative fuels and energy efficiency.
- CO2 tax for vehicle fuel
- Light Duty Vehicle emissions intensity limits
- Heavy-duty diesel vehicles: limit emissions to 3.5 g/km NOX and 0.03 g/km PM.

Region	Sector	2030	2040
Sustainable Development			
Advanced economies	Power, industry, aviation**	100	140
Selected developing economies	Power, industry, aviation**	75	125

CO2 prices ($ per metric ton)
Source: IEA World Energy Outlook 2019

Investment

The largest increase in energy supply investment comes from renewable power, which by the year 2040, doubles from today's levels of investment to nearly $610 billion a year on average. This increased support for renewable energy development is also supported by additional spending to update electricity grids and battery storage. Total investment worldwide in clean energy assets reaches nearly $115 trillion of investments over the next three decades. New financial solutions are also scaled up to bring in larger pools of capital. Small-scale projects are aggregated from developers into portfolios that are then securitized, and investors such as pension funds and insurance companies will begin providing long-term capital at lower cost than developers and banks.

Transportation

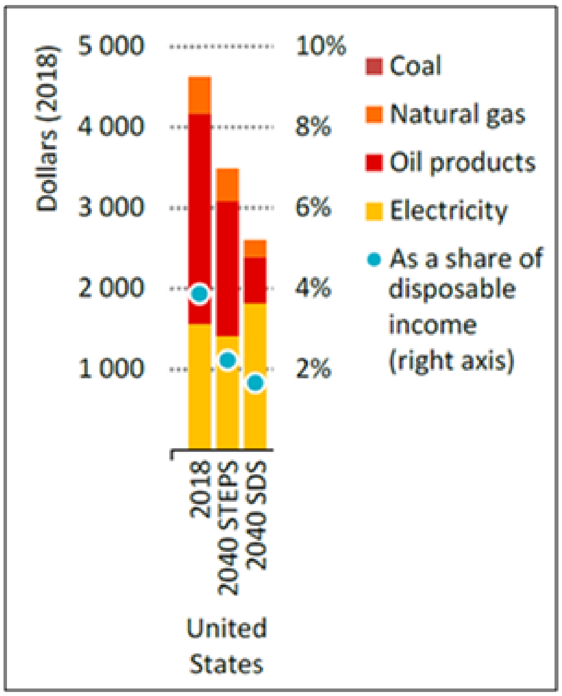
In the Sustainable Future Scenario, we see a large increase in electrification of the transportation sector. A strong push for electrification leads to a peak in conventional car sales in the mid-2020's. Over 80 million electric cars are sold globally each year by 2040 and the electric car fleet reaches almost 900 million around the world. All small, medium and large cars sold in 2040 are electric, as well as 40% of all SUVs. In addition to passenger vehicles and SUVs, 26% of freight vehicles are electric by the year 2040.

Buildings

The building sector sees a big push towards electrification and energy efficiency around the world over the next several decades. Stronger building codes and standards mean energy consumption falls in buildings more than 10% by 2040. A number of policies are introduced over the next several decades to facilitate the transition to clean energy use in buildings with energy efficiency being the most prominent. More efficient refrigerators, cleaning appliances, televisions, computers, light bulbs and appliances further to help reduce energy demands in buildings. The use of natural gas in buildings is also cut 60% by 2050 as demand for space and water heating is reduced.

Residential

Residential electricity prices in the US increase in the Sustainable Future Scenario as a result of moving away from the use of fossil fuel-based power plants and an urgent roll out of new capital-intensive investments in low-carbon technologies. Residential electricity prices in the Sustainable Future Scenario increases by about 25% in the United States. This increase in spending on electricity is a result of further electrification in buildings, but it's also combined with a reduction in spending on other fuels such as reduced fuel costs related to passenger vehicles.



Household Energy Bill by Fuel
Source: IEA World Energy Outlook 2019

2 Degrees Scenario

The 2 Degrees Scenario looks at a future scenario of approximately 2 degree temperature rise which is in line with the Paris Climate Accord. If all countries follow through on their commitments to reducing emissions nationally, leading to reduced emissions globally that are in line with the Paris Climate Accord, the intended outcome is to limit global temperatures to a 2 degree temperature increase.

In this scenario, total primary energy demand in the United States drops from 2,230 million metric tons of oil equivalent in 2018 to 2,142 million tons metric tons of oil equivalent in 2040. An overall decrease in energy use but not as drastic as the reduction in the Sustainable Future Scenario. As in the Sustainable Future Scenario, the 2 Degree Scenario also sees a rapid increase in the use of renewable energy in the United States. Bioenergy has a slight increase in overall demand and all other renewable energy sources have the largest increase in demand of any energy source, going from a primary demand of 44 million metric tons of oil equivalent in 2018 to 157 million metric tons of oil equivalent in 2040. From 2018 to 2040, we see overall decreases in total primary demand for coal, oil and nuclear energy, while natural gas and hydro energy hover around the same demand.

Fossil Fuel Use

While the United States accounts for 85% of the increase in global oil production up to 2030, global growth in oil demand slows post 2025 before flattening out in the 2030s. The use of natural gas increases in all regions around the world except for Europe and Japan as there is a rising need for energy system flexibility and an increase in the availability of cheap natural gas. The United States accounts for 30% of the increase in natural gas production up to 2030 and also produces more natural gas then the entire Middle East up through 2040. We see declines in the use of coal by 40% in the United States. In most advanced economies such as the United States, the demand for coal is in a deep decline by 2040 due to a number of factors including phase-out commitments, the continued rise of renewables, competition from natural gas and the introduction of CO2 taxes in the United States.

Renewable Energy

Wind and solar photovoltaic generation continue to expand and overtake coal in the power generation mix in the mid-2020s. Around the world, wind and solar photovoltaic provide more than half of the additional electricity generation up to 2040. Renewable energy in total primary energy demand doubles in the United States from 2018 to 2040 while strong support policies for renewable energy boost their penetration. Within the total energy capacity additions in the United States from 2018 to 2040, renewable energy makes up the largest percentage with solar photovoltaic and wind power contributing to about 40% and 20% of those additions respectively.

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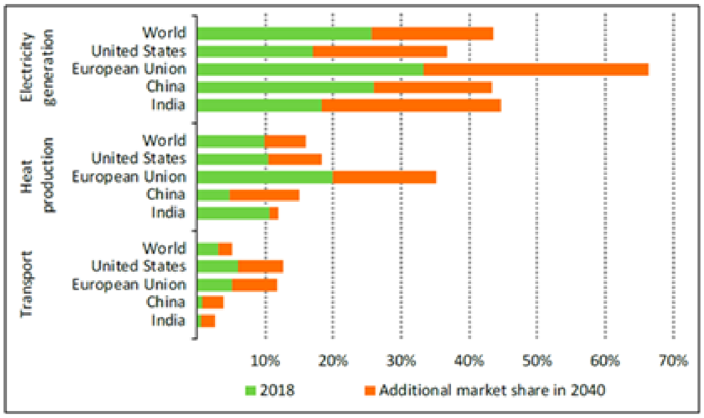
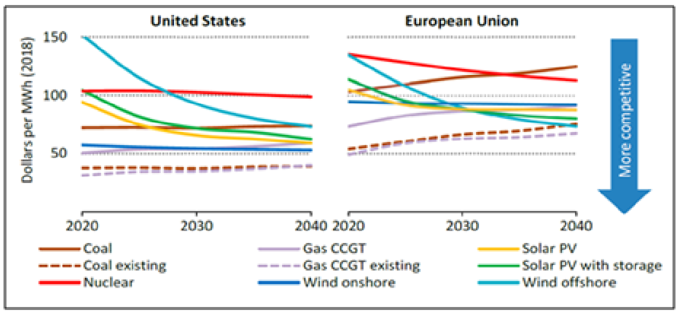


Renewable Energy in Total Primary Energy Demand
Source: IEA World Energy Outlook 2019



Value Adjusted Levelized Cost of Electricity by Technology
Source: IEA World Energy Outlook 2019

Electricity

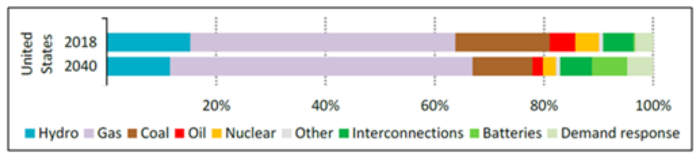
The modern economy of 2040 is an electrified economy. Growth in electricity use over the next several decades is led by industrial motors followed by household appliances, cooling and electric vehicles. The share of renewables in the electricity supply continues to increase globally from 26% in 2018 to 44% in 2040. The share of electricity in total final consumption in the United States grows from 21% in 2018 to 24% in 2040. Total electricity demand in the United States grows from 4,011 terawatt-hours in 2018 to 4,517 terawatt-hours in 2040.

	Electricity generation (TWh)							Shares (%)		CAAGR (%)
	2010	2017	2018	2025	2030	2035	2040	2018	2040	2018-40
Total generation	4 354	4 264	4 445	4 555	4 639	4 763	4 939	100	100	0.5
Coal	1 994	1 321	1 255	960	861	802	749	28	15	-2.3
Oil	48	32	44	17	16	12	7	1	0	-7.9
Natural gas	1 018	1 338	1 542	1 711	1 714	1 734	1 803	35	37	0.7
Nuclear	839	839	841	741	696	628	564	19	11	-1.8
Renewables	452	728	758	1 125	1 350	1 585	1 814	17	37	4.0
Hydro	262	302	294	304	311	321	331	7	7	0.5
Bioenergy	73	79	79	85	93	101	110	2	2	1.5
Wind	95	257	278	458	542	643	728	6	15	4.5
Geothermal	18	19	20	21	27	35	41	0	1	3.4
Solar PV	3	67	84	252	368	473	584	2	12	9.2
CSP	1	4	4	4	7	10	16	0	0	6.6
Marine	-	-	-	0	1	3	4	-	0	n.a.

Electricity in the United States
Source: IEA World Energy Outlook 2019

Technology and Flexibility

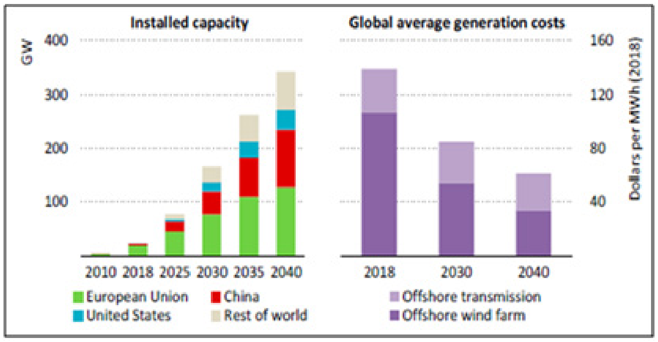
Over the next several decades up to 2040, we see a growing need for power system flexibility. All regions around the world including the United States will have an increased need for flexibility within their power systems. In fact, flexibility needs will be increasing faster than electricity demand. Today thermal power plants and hydropower provide the bulk of flexibility requirements in electricity systems in 2018, but over the next several decades, battery storage will become the fastest growing source of power system flexibility. Economies of scale help the outlook for batteries up to 2040 as well as advances in chemistry. Battery system costs are cut in half over the next two decades with four-hour storage systems falling from $400 per kilowatt-hour to less than $200 per kilowatt hour.



Sources of Flexibility in the United States
Source: IEA World Energy Outlook 2019

Offshore Wind

As we see in the Sustainable Future Scenario, offshore wind also gained significant growth in the 2 Degree Scenario. By 2040, the United States adds nearly 40 gigawatts of offshore wind capacity with investments totaling over $100 billion over the period. State-level targets and federal incentives kick-start and help grow the offshore market over the next several decades in the United States. Globally, offshore wind becomes a $1 trillion business by 2040 with capacity increasing 15-fold. By 2030, the global average levelized cost of electricity (LCOE) from offshore wind declines to around $80 per megawatt-hour, which is almost 40% below the cost in 2018.



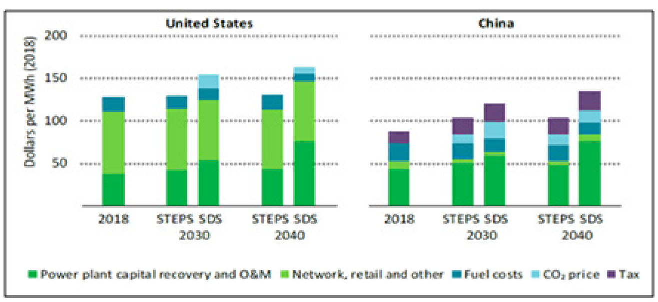
Growing Markets and Falling Costs for Offshore Wind
Source: IEA World Energy Outlook 2019

Industry

The industrial sector accounts for the largest share of growth in final energy consumption by 2040 (35%). Nearly all of this growth in final energy consumption is in the form of natural gas and electricity.

Residential

In advanced economies such as the United States, the overall spend on energy by households declines by 2040 as a share of the households' total disposable income. The main reduction in this overall energy spend is due to more energy efficient cars and heating systems.



Residential Electricity Prices in the United States
Source: IEA World Energy Outlook 2019

Transportation

Global annual electric car sales grow from about 2 million cars sold per year in 2018 to around 20 million sold per year in 2030 and over 30 million per year in 2040. Increasingly strict fuel economy targets, restrictions on the sale or use of conventional cars, fleet procurement decisions by public agencies and private logistics companies and investment in new recharging infrastructure are some of the key factors that help the growth of electric vehicles around the world.

Manufacturing alliance or brand	Total car sales in 2018 (million)	Electric car share of sales in 2018 (%)	Automaker plans for electric cars for given year		
			Sales (million)	Share of company sales	Number of models
VW group	9.4	0.7%	0.4 (in 2020) 22* (by 2030)	25% (in 2025)	80 (by 2025)
Volkswagen	6.5	0.8%			
Audi	1.8	0.9%	0.8 (in 2025)		
Skoda	1.2	0.0%		25% (by 2025)	10 (by 2022)
Toyota	8.0	0.6%	1 (by 2030)		more than 10 (by early 2020s)
Renault-Nissan	6.8	2.2%			12 (by 2022)
Nissan	4.7	2.1%	1 (by 2022)		
Renault	2.2	2.4%		20% (in 2022)	
Hyundai-Kia	6.8	1.2%			12 (by 2020)
Hyundai	4.2	1.1%			
Kia	2.6	1.5%			
Ford	5.2	0.2%			40 (by 2022)
Honda	5.1	0.4%		15% (in 2030)	
Chevrolet (GM)	3.7	1.3%			20 (by 2023)
Suzuki	3.1	0.1%	1.5 (in 2030)		1 (in 2020)
FCA group	2.8	0.1%			28 (by 2022)
Jeep	1.4	0.0%			14 (by 2022)
Fiat	1.4	0.2%			2 (by 2022)
Mercedes (Daimler)	2.5	1.5%		15-25% (by 2025)	50 (by 2022)
SAIC	2.4	4.1%	0.6 (by 2020)		
BMW	2.0	6.4%		15-25% (in 2025)	25 (by 2025)
Geely	1.5	4.7%	1 (in 2020)	32% (in 2020)	30 (by 2020)
Peugeot (PSA group)	1.5	0.3%	0.9 (in 2022)		40 (by 2025)
Mazda	1.4	0.0%		5% (by 2030)	1 (in 2020)

* Target refers to cumulative sales.

Electric Car Targets of the World's 20 Top Car Manufacturers
Source: IEA World Energy Outlook 2019

Policy

The numerous policies projected to be in place in the United States to achieve the 2 Degree Scenario include the following:

US Power Sector Policies

- Extension and strengthening of support for renewables, nuclear and CCUS.
- Affordable Clean Energy Rules.

US Industry Sector Policy

- Further assistance for SME manufacturers to adopt "smart manufacturing technologies" through technical assistance and grant programs.

US Building Sector Policies

- Partial implementation of the Energy Efficiency Improvement Act of 2015.
- Mandatory energy efficiency requirements in building codes in some states, including California's 2019 Building Energy Efficiency Standards and recent code updates in other states.
- Tightening of efficiency standards for appliances.

US Transportation Sector Policies

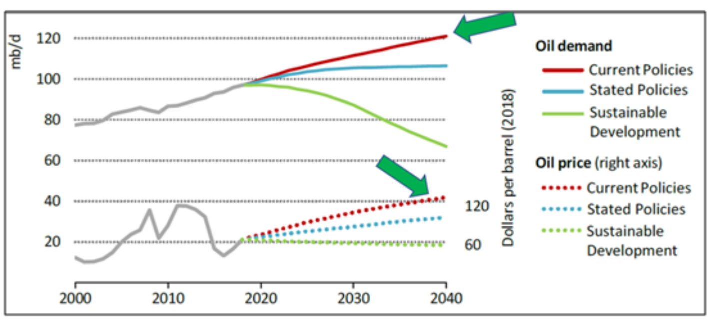
- Moderate increase of ethanol and biodiesel use after 2022 driven by state policies.

- Electric cars: stock target of 4 million by 2025 across eight states.
- Road freight: support for natural gas.

Current Policies Scenario

The current policy scenario looks at the future in 2040 as if policies currently in place around the world are followed, with no new policies added. It is the business as usual scenario with no changes in regional or global climate policy.

As opposed to the previous two scenarios, the Current Policies Scenario does not have a big focus on energy efficiency, thus we see higher overall energy demand. This higher energy demand pushes up natural gas consumption as demand for natural gas increases globally by 2 trillion cubic meters, a level that is 50% higher than it was in 2018. With no further support for renewable energy or energy efficiency policies, natural gas is used to support one third of total energy demand growth, which is more than any other energy source. North America provides one fifth of the total additional natural gas by 2040.



Global Oil Demand and Crude Oil Price
Source: IEA World Energy Outlook 2019

	Energy demand (Mtoe)		Shares (%)	CAAGR (%)
	2030	2040	2040	2018-40
Total primary demand	2 269	2 267	100	0.1
Coal	246	226	10	-1.5
Oil	800	760	34	-0.3
Natural gas	791	806	36	0.6
Nuclear	184	159	7	-1.4
Hydro	27	28	1	0.5
Bioenergy	124	148	7	1.7
Other renewables	96	140	6	5.4
Power sector	816	814	100	-0.3
Coal	221	200	25	-1.7
Oil	3	2	0	-6.6
Natural gas	268	266	33	0.0
Nuclear	184	159	20	-1.4
Hydro	27	28	3	0.5
Bioenergy	24	29	4	1.5
Other renewables	90	129	16	5.3
Other energy sector	215	227	100	1.3
Electricity	53	54	24	0.2
Total final consumption	1 654	1 663	100	0.2
Coal	17	16	1	-0.4
Oil	755	712	43	-0.3
Natural gas	417	427	26	0.6
Electricity	354	375	23	0.5
Heat	6	5	0	-0.9
Bioenergy	101	119	7	1.7
Other renewables	6	10	1	6.0
Industry	307	313	100	0.6
Coal	16	16	5	-0.4
Oil	20	21	7	0.7
Gas	154	153	49	0.7
Electricity	77	81	26	0.7
Heat	4	4	1	-0.8
Bioenergy	34	38	12	0.9
Other renewables	0	1	0	n.a.
Transport	620	606	100	-0.3
Oil	540	504	83	-0.7
Electricity	2	4	1	6.5
Biofuels	52	65	11	2.3
Other fuels	25	33	6	2.7
Buildings	509	527	100	0.3
Coal	0	0	0	-2.8
Oil	22	17	3	-2.1
Natural gas	196	198	38	0.0
Electricity	271	287	55	0.5
Heat	1	1	0	-1.0
Bioenergy	12	15	3	1.6
Traditional biomass	-	-	-	n.a.
Other renewables	6	9	2	5.5
Other	219	217	100	1.1
Petrochem. feedstock	92	92	42	1.7

United States Energy Demand
Source: IEA World Energy Outlook 2019

Electricity

In the Current Policy Scenario, we see an increasing role of electricity within final energy consumption. Globally, the share of electricity rises from 19% in 2018 to 23% in 2040.

	Electricity generation (TWh)		Shares (%)	CAAGR (%)
	2030	2040	2040	2018-40
Total generation	4 685	4 937	100	0.5
Coal	977	902	18	-1.5
Oil	18	10	0	-6.7
Natural gas	1 679	1 703	34	0.5
Nuclear	706	611	12	-1.4
Renewables	1 304	1 709	35	3.8
Hydro	311	330	7	0.5
Bioenergy	92	108	2	1.5
Wind	525	685	14	4.2
Geothermal	28	42	1	3.5
Solar PV	342	527	11	8.7
CSP	6	13	0	5.8
Marine	1	4	0	n.a.

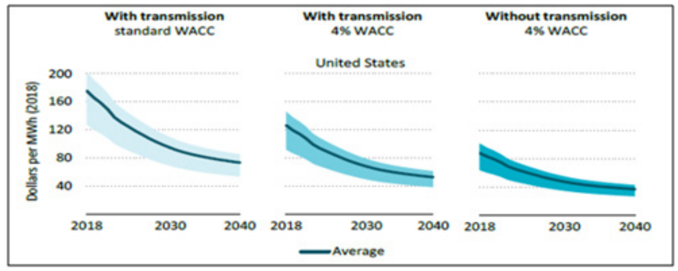
Electricity in the United States
Source: IEA World Energy Outlook 2019

Offshore Wind

Offshore wind costs are still set to decline in the United States even with a business-as-usual scenario. Through improvements in the wind turbine design and more efficient construction processes and operation and maintenance procedures, costs decline as deployment increases. By 2040, the global average levelized cost of electricity of offshore wind is reduced by 60% from 2018 levels. In the United States, there are state-level targets as well as federal incentives that support the strong growth of offshore wind. Some of these initiatives include:

- The US Bureau of Ocean and Energy Management has tendered over 15 licenses for offshore wind development along the east coast that are capable of supporting 21 GW of offshore capacity.
- There have been proposals in the US Congress to extend the tax credits available to offshore wind developers.
- Individual states are setting offshore wind capacity targets totaling over 20 GW by 2035.
- New York revised its offshore wind target upwards from 2.4 GW to 9 GW by 2030.

Global average upfront capital costs for offshore wind (including transmission) are projected to decline to below $2,500/kW by 2030, more than 40% below today's average. This is based on the assumed learning rate that sees capital costs decline by 15% each time global capacity doubles. By 2040, global average offshore wind costs are projected to fall to $1,900/kW.



Levelized Cost of Electricity for New Offshore Wind Projects in the United States
Source: IEA World Energy Outlook 2019

Policies

The following are a list of current stated policies in the United States that have an impact on energy use and the future 2040 Current Policies Scenario:

US Policies

- State-level renewable portfolio standards.
- Regional Greenhouse Gas Initiative: mandatory cap-and-trade scheme covering fossil fuel power plants in nine northeast states, and economy-wide cap-and-trade scheme in
- California with binding commitments.

US Power Sector Policies

- Extension of Investment Tax Credit and Production Tax Credit.
- State renewable portfolio standards.
- State 100% clean energy target by 2050.
- New Source Performance Standards.
- Clean Air Interstate Rule regulating SO2 and NOX.

US Industry Sector Policies

- Better Buildings, Better Plants Program and Energy Star Program for Industry.
- Boiler Maximum Achievable Control Technology to impose stricter emissions limits on industrial and commercial boilers, and process heaters.

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- Permit program for GHGs and other air pollutants for large industrial installations.
- Business Energy Investment Tax Credit and funding for efficient technologies.

US Building Sector Policies

- Association of Home Appliance Manufacturers—American Council for an Energy-Efficient Economy Multi-Product Standards Agreement.
- Energy Star: new appliance efficiency standards.
- Steady upgrades of building codes; incentives for utilities to improve building efficiency.
- Weatherization programs: funding for refurbishments of residential buildings.
- Federal and state rebates for renewables-based heat, including Residential Renewable Energy Tax Credit for solar water heaters, heat pumps and biomass stoves.

US Transportation Sector Policies

- Renewables Fuel Standard
- LDVs: Phase 2 of CAFE standards until 2020 and Safer Affordable Fuel Efficient rule for model years 2021-2026.
- LDVs: Tier 3 Motor Vehicle Emission and Fuel Standards, equivalent to Euro 6.
- Medium and heavy-duty trucks: low range of Phase 2 of EPA/NHTSA GHG emissions and fuel efficiency standards.
- HDVs: Tier 3 Motor Vehicle Emission and Fuel Standards, equivalent to Euro VI.


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