Climate Change Impacts on Extreme Weather

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Executive Summary

"Men argue. Nature acts." So said Voltaire in the 18th century. While people today continue to argue about the scope, causes, effects, and sometimes even the very existence of climate change, nature is acting. But what are the implications for the insurance industry? Does climate change matter?

Even now, there is a far more certain driver of risk facing the insurance industry: the increase in the number and value of insured properties in areas of high hazard. Until the "Great Recession" of the late 2000s and early 2010s, AIR estimated that the value of properties in coastal areas of the United States grew annually by roughly 7%. That alone translates directly to a doubling of insured losses every ten years—exclusive of any effect of climate change—and although construction has yet to regain its pre-recession levels, recovery is underway. Another possible reason for the industry's seeming detachment is that the term of most insurance policies is one year; thus there is generally more concern about what will happen in the next twelve months than about the climate change that will occur over the coming decades.

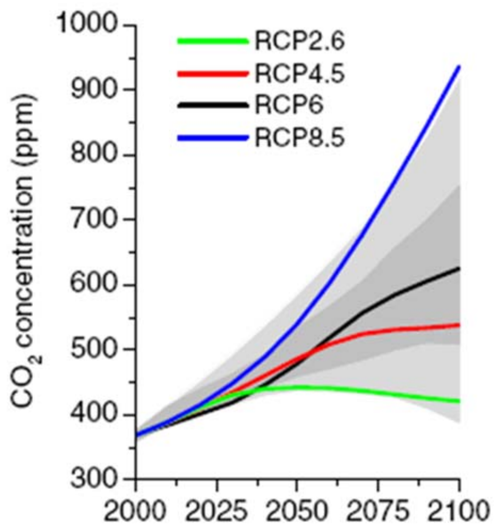
Still, many in the insurance world are paying increased attention to climate change in light of reports of increasing variability of atmospheric perils such as windstorms and floods. Meanwhile, regulators and rating agencies are beginning to ask companies to disclose how they are incorporating climate risk into their decision-making processes. As a result, clients have asked AIR to keep them apprised of the current state of the science regarding climate change impacts on extreme weather.

The goal of this paper is thus to bring a risk-based mindset to the challenge of climate change and its effects on atmospheric perils of relevance to catastrophe modeling. Section 1 summarizes some key elements of climate and climate change and its relevance for weather extremes. Section 2 provides a synthesis of the latest scientific knowledge about how specific weather extremes may be affected by climate change, especially toward the end of the 21st century. Section 3 identifies some of the complications and uncertainties surrounding the results and suggests a possible path forward for the developers and users of catastrophe models.

Climate change can be expressed both locally and globally, in the temporal mean of a given quantity (e.g., temperature, winds) or in its variability. Observed trends in climate are most robust at large spatial scales and over longer time periods. For example, globally averaged surface air temperature has increased roughly 0.85°C from 1880 to 2012, as summarized in the latest (Fifth) Assessment Report from the Intergovernmental Panel on Climate Change (IPCC 2013). Most of the increased heat has been stored in the ocean, especially recently. Other quantities that have exhibited robust trends during at least the past 30 years are snow cover, ice sheets, sea level, atmospheric moisture content, and ocean salinity.

The latest IPCC study has concluded that it is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by increases in carbon dioxide (CO2) concentrations and other emissions caused by human activity. Since 1850, the amount of CO2 in the atmosphere has increased by more than 40%, and is now higher ~407 ppm[1]) than it has been in the past 2-25 million years (Podest and others, 2013).

Although certain aspects of future climate change can be predicted from simple principles, quantitative estimates and regional projections demand computer models (General Circulation Models, or GCMs). Utilizing ensembles of GCMs to account for uncertainty, the IPCC (2013) concluded that global surface temperatures will likely increase by a few more degrees Celsius by the end of the 21st century (0.5-4.0 °C as simulated by various postulated greenhouse gas concentration trajectories, or Representative Concentration Pathways (RCPs) (see the fgure below).



Representative Concentration Pathways, or RCPs, are possible greenhouse gas concentration trajectories adopted by the IPCC. They describe four possible climate scenarios depending on how much greenhouse gases are emitted in years to come. (Source: SkepticalScience; https://s9.postimg.org/r26pjkzrj/Untitled.png)

Impacts on smaller-scale phenomena such as hurricanes, blizzards, and severe thunderstorms are more complicated to predict and often exhibit substantial differences across model ensembles.

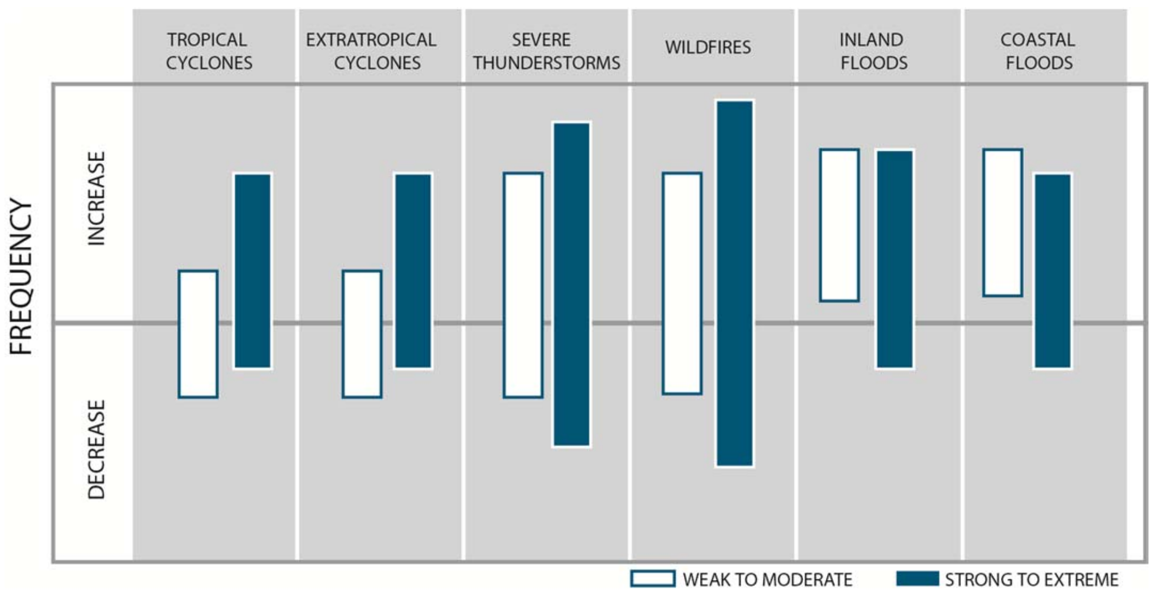
- For **tropical cyclones** (TCs), the historical record for both basinwide and landfall activity generally does not provide a clear indication of a long-term trend. Recent assessments have concluded that the frequency of weak TCs is likely to decrease, but that the frequency of strong hurricanes (Category 4 and 5 on the Saffir Simpson Scale) is likely to increase—along with lifetime maximum intensity of these storms. On balance, however, because weaker storms are relatively more frequent than strong ones, overall TC frequency is expected to decrease. Because of the relationship between moisture and temperature, precipitation from TCs is also likely to increase.

[1] Represents the seasonally corrected value at Mauna Loa for March 2017.

- **Extratropical cyclones** (ETCs), despite their larger size and hence their relative ease to be meteorologically observed, are not much easier to decipher in terms of historical trends or how they will be impacted by climate change. Near the surface, the pole-to-equator temperature difference, which is the primary energy source for ETCs, is expected to decrease—especially as polar ice continues to melt. At upper levels of the atmosphere, the temperature difference will likely increase. ETCs also grow by latent heat release from condensation, and that is expected to increase. The consensus result for changes in ETCs is similar to that for TCs: overall numbers will decrease but strong ETCs will occur more frequently. In addition, the storm track is expected to shift poleward—especially in the Northern Hemisphere (Mizuta 2012).
- **Severe thunderstorms** (STs), which generate damaging hail, straight-line winds, and tornadoes, are a convective phenomenon with a horizontal scale of 10-100 km—smaller than TCs and occurring over land. Their small size makes comprehensive reporting difficult—especially in unpopulated areas of the United States and around the world. High values of Convective Available Potential Energy (CAPE) and strong vertical wind shear are two key ingredients for the formation of STs. Most studies show that high-CAPE days will increase as a result of climate change but that vertical shear will decrease. However, the combined result is expected to increase the number of ST days and the frequency and severity of STs.
- Environments conducive for **wildfire**'s (WF) natural occurrence and spread also arise from atmospheric conditions. Relatively few studies projecting changes in this phenomenon due to climate change exist in the literature, especially at the global scale. Moritz et al. (2012) found that many areas in the Northern Hemisphere are expected to have increased risk of WF. In particular, the western United States extending northward into Alaska, the northern portions of Canada, the northern part of Africa extending eastward into Saudi Arabia, and into central Asia and northeast part of Russia.
- Heavy precipitation and concomitant pluvial (rain-induced) **inland flooding** show robust 20th century trends in many regions. The clear physical basis between increasing saturation vapor pressure and increasing temperature gives confidence that the increasing trend in precipitation observed in many locations is influenced by climate change. The heterogeneous nature of precipitation and its relation to the different types of weather systems that generate it mean that future changes will not be spatially uniform. Dankers et al. (2014) used global hydrological models coupled to an RCP 8.5 (high emissions scenario) GCM ensemble and found an increase in flooding frequency of what is currently the 30-year flood in more than 50% of global locations and decreases in approximately one-third of the global land grid points.
- The severity and frequency of **coastal floods** is clearly increasing (Sweet and Park 2014; Ezer and Atkinson 2014), largely due to the rise in mean sea level in most global locations (Zhang et al. 2000; Menendez and Woodworth 2010; Church et al. 2013). Mean sea level rise—e.g., ocean

warming and expansion, and glacier and ice sheet melting—is expected to continue to accelerate in the 21st century. Projections of an increase in flood frequency are robust; however, changes in the most extreme coastal floods will be driven more strongly by the characteristics of storm surge, which is more related to changes in TCs and ETCs.

Results from our synthesis are summarized in the figure below, which illustrates schematically the expected changes in weak-to-moderate events (approximately 2- to 10-year return period) and strong-to-extreme events (approximately 50- to 250-year return period) by the end of this century from a hazard-intensity perspective. We caution that regional differences may exist, which demand a more detailed assessment.



Likelihood of increases or decreases in frequency of weak-to-moderate intensity events (with a 2- to 10-year return period) and strong to extreme events (50- to 250-year return period) for different weather-related phenomena discussed in section 2 by the end of the 21st century. Length of bar indicates degree of uncertainty. Note that the relative positions of the bars represent globally-averaged estimates; significant regional differences may exist and would need to be considered separately. Note, too, that the direction of the bars is consistent with moderate-to-high emissions trajectories (RCP 4.5 – 8.5), but the degree of uncertainty may vary as a function of a given emissions scenario. (Source: AIR)

Despite projections of increases in late 21st century strong-to-extreme events for most of the phenomena discussed, existing historical data is often insufficient to identify a climate change–related trend. Often records are simply too short or coarse to reveal impacts on the frequency and intensity of relatively rare events. Furthermore, impacts are dependent upon emissions, and the impacts, which lag the emissions themselves, are expected to increase in the latter half of the century.

AIR has been actively researching the impacts of climate variability and climate change on insured losses since the 1990s. It should be noted that the catastrophe models used by the insurance industry rely on historical data, pre-historical data, and a deep scientific understanding of the physical processes that cause extreme events. In the model development process, AIR is careful to examine the stationarity of the time series so that biases are not inadvertently introduced. For atmospheric perils, the models generally incorporate the last 30-40 years of data; if biases (technology, reporting etc.) are identified in those datasets, we correct for them until the data-series appears stationary and more reflective of the frequency that has been observed in the recent past. Thus it is assumed that the models reflect warming that has already taken place, but no explicit assumptions are made concerning the impact of climate change on the frequency, intensity or locations of extreme weather events in the future.

However, where there are strong physical relationships and model consensus on linkages between large-scale climate and extremes, AIR has developed and is developing climate- and climate change–conditioned catalogs of simulated events as complements to the standard catalogs. In addition, we have undertaken sensitivity studies of climate impacts on specific perils and regions. Most recently, the Association of British Insurers (ABI) sponsored a project to update the results from a 2009 study on climate change impacts on ETCs and the latest results were just published.

AIR is continually stress-testing models to investigate their sensitivity to climate. Such work leads to research efforts—within AIR, AER, and the academic community at large—to investigate whether there is sufficient basis for developing alternate parameter distributions for incorporation into catastrophe models.

There are many possible research avenues to pursue regarding climate change and catastrophe modeling, but the most relevant information will only be identified with input from what is important to the insurance industry. We highlight three possible areas: first, more detailed investigations of changes in climate variability; second, more targeted analyses of parameters most relevant to catastrophes; third, the assessment of spatial and temporal correlations between extreme events (e.g., due to changes in sea level and atmospheric moisture) in a warming climate.

What actions are regulators taking?

Regulators have taken note of climate change and in some cases, such as in the U.S., have begun to require that insurance companies disclose how they are incorporating climate risk into their decisions.

In 2014, the National Association of Insurance Commissioners (NAIC) mandated that insurance regulators in six states (California, Connecticut, Minnesota, New Mexico, New York, and Washington) require insurers writing in excess of USD 100 million in premiums to fill out a Climate Risk and Disclosure survey. To comply with the mandate, 148 insurance companies representing approximately 71% of the U.S. insurance market in terms of 2014 direct premiums written, filled out responses to the NAIC survey.

Ceres, a non-profit sustainability organization, issued a report analyzing the responses from these insurance companies and characterized the NAIC survey as encompassing the following themes: “governance structures insurers have in place to address climate risk; climate risk management programs companies have instituted across their enterprises; how insurers are using catastrophe or other computer modeling tools and techniques to manage their climate risks; how insurers are engaging with stakeholders on the topic of climate risk; and how companies are measuring and reducing greenhouse gas (GHG) emissions.”

According to Ceres, many insurers have been slow to address climate change; however, there was some positive movement compared to how insurance companies scored on the 2012 version of the NAIC survey. It is clear though, that insurance regulators in the United States are taking the risk of climate change seriously and are beginning to hold insurance companies accountable.

In Europe, climate change disclosures have not been mandated; however, it appears that this could change soon because some insurance companies are already beginning to take action by voluntarily disclosing how they are handling climate risk. For example, in 2014, The Bank of England’s Prudential Regulatory Authority surveyed 30 insurance companies in their report “The impact of climate change on the UK insurance sector.” Also, in late 2016, Swiss Re, announced that it will adopt voluntary guidelines and recommendations that the *Task Force on Climate-Related Financial Disclosures* (TCFD) developed.

It is clear that regulators around the world are beginning to take note of the risk posed by climate change, and it is all the more likely those additional disclosures will become mandatory over the next few years.

Introduction

The goal of this paper is to bring a risk-based mindset to the challenge of climate change and its effects on perils of relevance to catastrophe modeling. In section 1, we briefly summarize key elements of climate and climate change and its relevance for weather extremes. This background (and references within) provides a basis for section 2, in which we review the state of scientific knowledge about how specific weather extremes may be affected by climate change, especially toward the end of the 21st century. Section 3 identifies some of the complications and uncertainties surrounding the results and suggests a possible path forward for the developers and users of catastrophe models.

1. What Is Climate and How Has It Been Changing?

Climate comprises the statistics of weather; it can describe either averages or variability of weather over specified temporal and spatial scales. Colloquially, it is used to describe the long-term average, typically over a 30-year period, according to the World Meteorological Organization (WMO).

Historically, the long term (i.e., annual or longer) globally averaged surface air temperature has served as a proxy statistic for the Earth's climate. Similar integrated measures of global climate include snow cover, sea ice and glacier area, and global mean sea level. Figure 1 illustrates the global average temperature since 1880. Averaged over all land and ocean surfaces, temperatures have increased roughly 0.85°C from 1880 to 2012, according to the latest (Fifth) assessment report from the Intergovernmental Panel on Climate Change (IPCC 2013). Because oceans tend to warm and cool more slowly than land areas, continents have warmed the most.

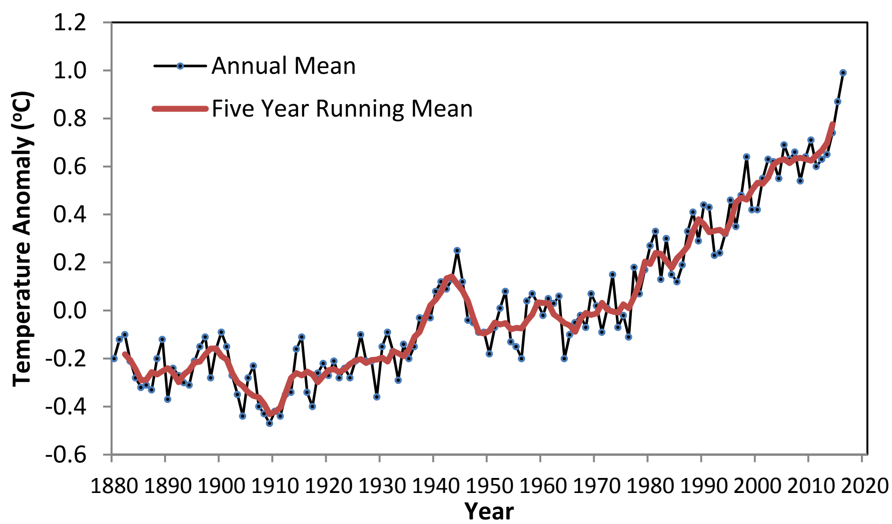


Figure 1. Global mean surface temperature change since 1880. (Source: AIR, data from NASA GISS)

In the Northern Hemisphere, where most of Earth's land mass is located, the three decades spanning 1983 through 2012 have likely been the warmest 30-year period of the last 1,400 years, according to the IPCC. Fifteen of the top 16 warmest years have occurred since 2000, and 2016 was the warmest year ever on record—breaking the previous record by the largest margin ever. The most recent IPCC report determined that it is extremely likely (99% certainty) that the Earth's climate has warmed during the last 100 years.

Although atmospheric temperatures have increased, most of the increased heat in the climate system has been stored in the ocean. This change in ocean heat content underlies most of the increase in global mean sea level of approximately 20 cm since 1880 (see next section: sea level changes). A recent analysis (Kopp et al. 2016) finds that the 20th century rate of global mean sea-level rise (1.4 ± 0.2 mm/yr) was *extremely likely* ($P > 95\%$) to be the highest rate over the past 3000 years. While part of this rise is due to the thermal expansion of the ocean, an increasing fraction of global mean sea level change is resulting from the melting of mountain glaciers and the Greenland and Antarctic ice sheets. Northern Hemisphere sea ice also shows a strong negative trend in its areal extent and thickness: September Arctic sea ice is now declining at a rate of 13.3% per decade, relative to the 1981-to-2010 average (NASA, 2017).

Regional climate changes may vary widely from the global mean, both in the long-term average and aspects of variability. Weather extremes are one such aspect of regional climate. Examples include so-called "nor'easters" that can dump 30 cm or more of snow on New England, Category 5 typhoons in the Philippines, or 50+ cm rainfall events in Brazil. Because events like these, in addition to average temperatures and/or precipitation over longer time periods, are integral aspects of climate, it is important to understand—to the extent possible—whether the frequency and intensities of such events have changed, or may change in the future.

Such studies can be conducted with a probabilistic approach conducive to risk management: climate change manifests in a different probability of exceeding some threshold (i.e., the probability that nor'easters will produce > 30 cm snow; that TC winds will exceed 39 mph, etc.) relative to a base period. This approach can be used to *attribute* changes or *project* changes in the expected frequency of events in the future. A useful analogy was introduced in Meehl (2012) to better illustrate to the general public the impact of climate change on weather extremes, comparing it to the impact of steroid use on a baseball player's ability to hit home runs. Meehl posits that one cannot deduce whether steroid use is directly responsible for any given home run, but after a period of time one can evaluate the percentage increase in home runs and deduce that there is a corresponding increased *likelihood* that steroid use has caused a particular homerun.

As a simple example of how such distributions might change, let's assume that the daily temperatures for a given region are normally distributed, with some small frequency of very low and very high temperatures. As the climate changes to a new mean, and assuming the normal distribution is maintained, there will be a concomitant increase (decrease) in the number of days that exceed a high (low) threshold. Thus, from an extreme high temperature standpoint, the expectation is that there will be more of them, in general. Of course, any aspect of the distribution may change.

In general, changes over shorter periods of time and changes in events with long return periods are more difficult to detect, attribute, and project. Changes in some quantities (temperature) are more easily assessed and predicted than others. In contrast, more difficult to detect are trends in phenomena that may be of particular interest to users of catastrophe models, such as the number of severe thunderstorm days, the number of intense winter storms, or the number of typhoons that develop in a particular basin each year. That's mainly because, by their nature, weather extremes are less frequent and therefore there are fewer observations, but also because the historical record becomes increasingly unreliable as one goes back in time. The changes in small (meso) scale phenomena like severe thunderstorms are particularly difficult to detect because of data limitations.

Why has the climate been changing?

Climate responds to many different forcing mechanisms (e.g., greenhouse gases, solar insolation, volcanoes); however, since 1950 and for the foreseeable future, the dominant forcing on global climate is carbon dioxide (CO2) and other *anthropogenic* emissions. Since 1850, the amount of CO2 in the atmosphere has increased by more than 40% (as shown in Figure 2), and is now higher (~410 ppm) than it has been in the last 2-25 million years (Podest, 2013 and others).

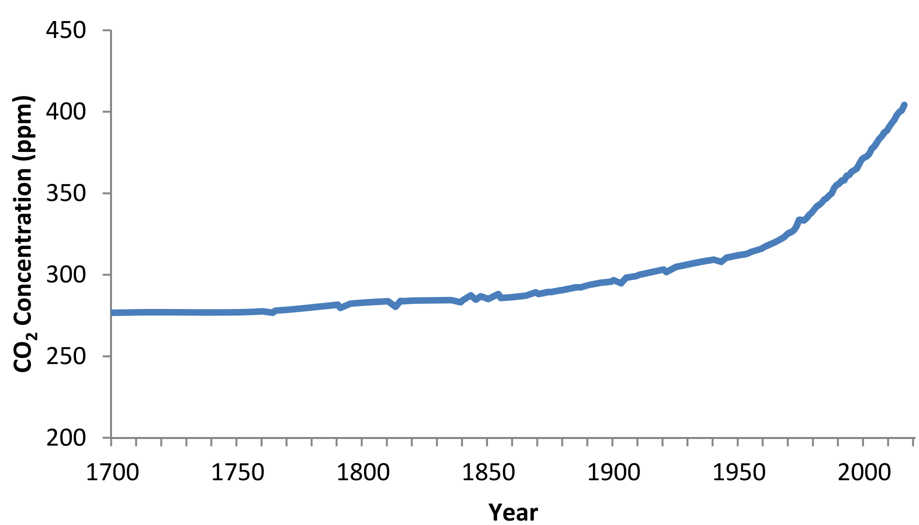


Figure 2. Global Atmospheric CO2 Levels (parts per million ppm) from 1700 to present. (Source: AIR, data from USEPA)

Climate has varied in tandem with CO_2 over the historical record, with swings of over 100 parts per million (ppm) every 100,000 years or so corresponding to global mean surface air temperature changes on the order on 1-2 °C. These global mean temperature swings were associated with dramatic changes in global climate, including the growth of Northern hemisphere ice sheets which locked up a volume of freshwater equivalent of 130 meters of global mean sea level. One only has to look back through history to see global impacts that have occurred from small changes in global means. In 1815, when Mt. Tambora erupted, it lowered global atmospheric temperatures by an average of only 0.58°C. Yet that event, and its concomitant temperature and precipitation changes, have been blamed for initiating the first worldwide cholera pandemic, expanding opium markets in China, and plunging the United States into its first economic depression (D'Arcy Wood 2015).

CO_2 is a naturally occurring gas. It is produced with every breath we exhale and is absorbed by plants both on land and in water as part of photosynthesis. CO_2 in the atmosphere influences global climate by absorbing long wave radiation emitted by Earth's surface and then re-radiates it back toward Earth, rather than allowing it to escape to space. Its presence in the atmosphere is the very reason why the Earth is as habitable as it is. This extra radiation boost effectively contributes globally on average about 35°C of warming. Without CO_2 in the atmosphere we would have sub-freezing temperatures in the mid-latitudes in the summer. This effect has been labeled the greenhouse effect.

Because atmospheric water vapor is dependent on temperature, it too has increased (about 3.5 % in the past 40 years), amplifying the influence of CO_2 (Schmidt et al. 2010). Although the direct impact of these forcings (CO_2 and H_2O) is well understood and has been observed (Feldman *et al*., 2015), there are indirect effects (feedbacks) present in the climate system that further amplify (or damp) the direct warming effect. An example of a feedback is the radiative effect of changes in polar ice extent. Melting polar ice, which has contributed to a reduction in Earth's reflectance, increases the uptake of energy into the ocean—thereby executing a positive feedback that reinforces the warming cycle. Several feedbacks resulting from changes in clouds are particularly important, and can be either positive or negative. These feedbacks are responsible for much of the uncertainty in climate and require sophisticated tools to evaluate.

To calculate the net impact of changes in anthropogenic emissions on global and regional climate, numerical models that solve the equations governing the evolution of the climate system (including the land, ice, ocean and atmosphere) must be employed. Such models, similar in many respects to numerical weather models, are referred to as General Circulation Models (GCMs). Some of the latest GCMs, historical climate, and climate change experiments used by the IPCC were part of the Coupled Model Intercomparison Project –Phase 5 or CMIP5 for short (Taylor et al. 2012). CMIP5 was established by the Working Group on Coupled Modeling under the auspices of the World Climate Research Programme as a standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models.

The IPCC has synthesized many observational and GCM analyses to determine whether observed warming can be attributed to anthropogenic emissions. Despite the fact that complex feedbacks are present, and that observed warming lags emissions, the latest IPCC study has concluded that it is *extremely likely* (i.e., 95–100% probability) that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic changes in climate forcings. The quantitative attribution is based in part on comparing results from GCMs with and without increasing emissions as they have actually occurred thus far. Without emissions, some warming does occur in the GCMs but with the observed amount of emissions even more warming occurs (and has occurred).

Likelihood

To ensure a consistent treatment of uncertainty, the IPCC provides calibrated language for describing quantified uncertainty. In particular, the IPCC defines "likelihood" according to Table 1.

Table 1. Standard terms used to define likelihood in the IPCC 2013 Report.

Term	Likelihood of the outcome
Virtually certain	>99% probability
Extremely likely	>95% probability
Very likely	>90% probability
Likely	>66% probability
More likely than not	>50% probability
About as likely as not	33 to 66% probability
Unlikely	<33% probability
Extremely unlikely	<5% probability
Exceptionally unlikely	<1% probability

What do we expect in the future and how do we project it?

GCMs can be used to project changes in climate subject to assumptions about how CO2 and other climate forcings will change. However, individual simulations are subject to assumptions that may lead to errors (or overconfidence).

One important uncertainty is the future evolution of external factors that influence the climate system—e.g., anthropogenic emissions (GHGs), atmospheric aerosols (which may be natural or human-made), and land use change. The most recent set of IPCC projections employed a set of four representative concentration pathways, or RCPs (see Figure 3), which represent various postulated greenhouse gas concentration trajectories (Moss et al. 2010). Geopolitical events, as well as technological, socioeconomic, and demographic change will lead to divergence from any one RCP; however, the set of RCPs are intended to span the range of reasonable trajectories.

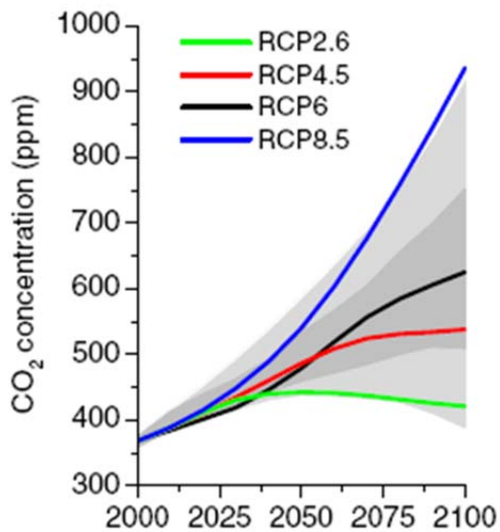


Figure 3. Representative Concentration Pathways, or RCPs, are possible greenhouse gas concentration trajectories adopted by the IPCC. They describe four possible climate scenarios depending on how much greenhouse gases are emitted in years to come. (Source: SkepticalScience; https://s9.postimg.org/r26pjkzrj/Untitled.png)

Another source of uncertainty is in the physical representation of the climate system by a GCM. A key factor underlying model differences is differing approaches to "parameterization": the representation of processes too small-scale to resolve in terms of other large-scale environmental variables. One key process underlying many meteorological and hence climatological phenomena is atmospheric convection. Many other examples abound—e.g. radiative forcing, cloud micro-physics, and turbulent diffusion.

Finally, natural fluctuations that arise in the absence of any external forcing can lead to divergence in projections over decadal or longer timescales. This "internal variability" of the climate system is identical to that seen in weather models, and arises solely due to uncertainties in the initial climate state.

To improve the robustness and utility of climate projections, most climate change assessments utilize not one GCM, but instead on model "ensembles" to generate climate change projections that, in concert, account for the aforementioned uncertainties and can be interpreted probabilistically. Using a wide range of coordinated simulations, the IPCC Fifth Assessment Report concluded that global surface temperature change by the end of the 21st century is likely to exceed 1.5°C relative to the period 1850 to 1900 for all RCP scenarios except RCP2.6, which is the lowest (most optimistic). It is *likely* to exceed 2°C for RCP6.0 and RCP8.5 (the highest), and *more likely than not* to exceed 2°C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6 (Figure 4). Although the dominant contributor to the uncertainty in projections is dependent upon the quantity, spatial scale, and lead time, in general the influence of the RCP scenario is largest at large spatial scales and long lead times (Hawkins and Sutton 2009). Internal variability decreases in importance with longer lead times and at larger scales.

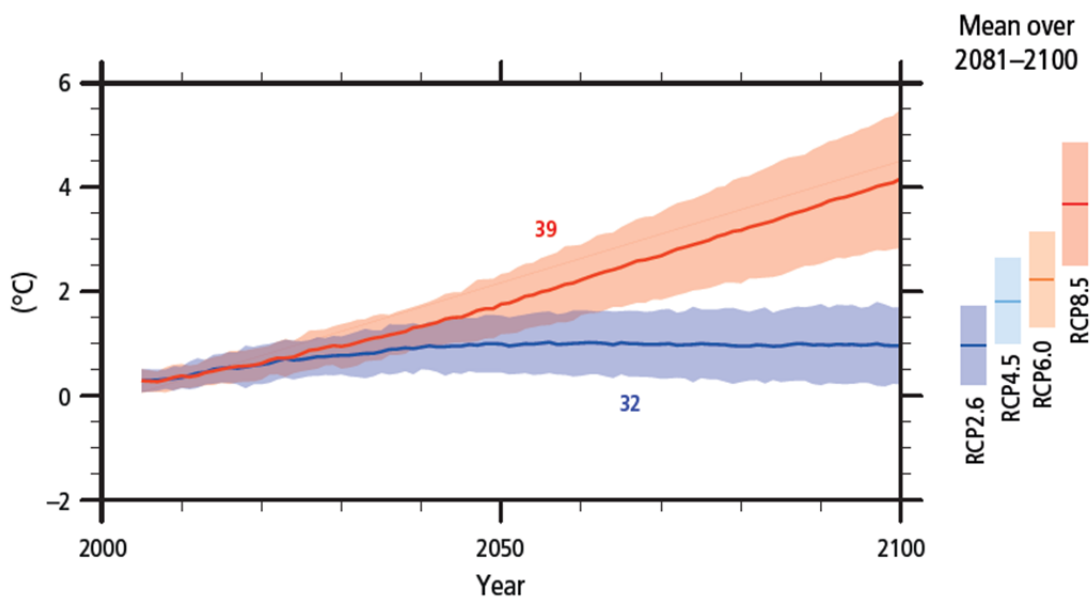


Figure 4. Projections of surface temperature change through end of 21st century for two of the four RCPs. Shading indicates uncertainty. Numbers above RCP2.6 and RCP8.5 curves indicate number of GCMs (i.e., CMIP5 models) used for those projections. Color bars to right indicate mean and uncertainty of surface air temperatures for the period 2081-2100 for the various RCPs. (Source: Fig. SPM.6, IPCC 2014)

What is the impact of climate change on extreme weather?

The IPCC findings indicate that global surface temperatures will likely increase by a few degrees Celsius by the end of the 21st century. However, due to the geographic variability in the climate response and to the presence of internal variability, warming (and changes in other climate variables) will continue to exhibit inter-annual-to-decadal variability and will not be regionally uniform. Understanding climate-driven changes in extreme weather at small spatial scales is thus a very daunting task. Some changes, such as increases in the number of 90°+ F degree days and increases in heavy precipitation, are easier to foresee because they are more robust across models and follow from first principles of what should happen when more CO_2 is put into the atmosphere. However, other impacts on other phenomena such as hurricanes, blizzards, and severe thunderstorms are more complicated to predict and often exhibit substantial differences across model ensembles.

2. Impacts on Weather and Weather-Related Phenomena

In this section we present the latest findings (e.g., 2000 to the present) from the scientific community about how climate change is likely to impact the characteristics of some key weather phenomena. The literature cited is limited to the last 15 years or so in order to consider only those numerical studies with the latest sophistication. In fact, many of the papers cited are published since the last available IPCC (2013) report and provide the very latest research results. In addition, the results focus for the most part on the last 20 or so years of the 21st century. Depending on the year of the study, different Representative Concentration Pathways (RCPs) representing different greenhouse gas scenarios are used. We limit our investigation to tropical cyclones, extratropical cyclones, severe storms, wildfire, and floods.

Tropical Cyclones

Tropical cyclones (TCs) derive their energy from latent heat acquired from evaporation of water at the ocean surface that is subsequently released upon condensation at greater heights. Earth's rotation drives cyclonic winds at low levels in the atmosphere toward the resulting low pressure (the eye). Although other factors are involved, the three primary conditions for TC formation are: sufficiently high (>26 °C) sea surface temperatures (SSTs); sufficiently low vertical wind shear (change in wind velocity with height); and sufficiently high contribution from Earth's rotation (formation >5 degrees N and S). Seasonal TC activity is highest in summer, when surface ocean waters are warmest and shear is minimized; however, formation is possible in all seasons. The Western North Pacific is the most active ocean basin, both in terms of the overall number and intensity of TCs (Woodruff et al. 2013).

Although individual TCs are subject to weather patterns that can vary widely on short timescales, the statistics of TC-related coastal flood and wind hazards are influenced by climate-driven changes (e.g., rising SSTs or changing jet stream positions) that would come about in part from more warming at the poles and melting of polar ice . These changes can affect TC intensity, size, frequency, seasonality, geographic distribution, or trajectory (Camargo et al. 2007; Vecchi and Soden 2007; Swanson 2008; Dwyer et al. 2012; Knutson et al. 2013; Kossin et al. 2014). Climate-driven changes may differ across basins (or smaller scales), and similar changes may affect TCs in different basins in different ways.

The climate drivers of observed trends in landfalling TCs are difficult to assess because of the storms' small scale, infrequent return period, and high natural inter-annual and even multi-decadal variability (Horton and Liu 2014; Knutson et al. 2010; Dailey et al. 2009a; Goldenberg et al. 2001). It is easier to assess trends at larger scales, using basinwide measures of TC intensity, frequency, and duration, such as the Power Dissipation Index (PDI) or the Accumulated Cyclone Energy (ACE), which are defined as the sum of the maximum one-minute sustained wind speeds cubed or squared respectively, at six-hourly intervals, for all periods when the cyclone is at least tropical storm strength. These measures indicate a robust increase in North Atlantic TC activity since the 1970s. At a global scale, Holland and Bruyère (2014) estimate that the proportion of Category 4 and 5 storms has increased over the last several decades by ~25-30% per degree of warming.

The extent to which this observed trend is the result of anthropogenic forcing, however, remains contentious (Goldenberg et al. 2001; Knutson et al. 2010; Dunstone et al. 2013, Kossin et al. 2013). For example, in the North Atlantic, the Atlantic Multi-decadal Oscillation is known to exert a strong control on TC activity (Mann et al. 2009; Goldenberg et al. 2001; Knutson et al. 2010). In addition, TC trends may be modulated regionally by trends in aerosols (Dunstone et al. 2013; Booth et al. 2012) and may not be indicative of expected greenhouse gas–driven trends. Other basins show less definitive trends, due to data limitations and high natural variability (Walsh et al. 2016).

Given the sparse historical record, much of the evidence used to assess 21st century TC changes is based on model simulations and theory. Model simulation can either be done numerically (e.g., using GCMs), or stochastically, by generating a synthetic set of storms from large-scale climate variables. Most of the analyses of climate change impacts on TCs assess change at the basin-scale. It remains possible that the proportion of storms that make landfall may change in a warming climate, perhaps as a result of shifted steering currents or a shift in the location of storm genesis (Wang et al. 2011); however, there is currently only a limited basis for an assessment. Our focus here, therefore, is on basin-scale changes and assumes the proportion of landfalling storms remains stationary.

Large-scale metrics (“predictors”) permit the assessment of changes in TCs across a large ensemble of climate models. For example, in the North Atlantic, monthly to decadal variability in PDI is well predicted by a statistical formulation based on “relative SST” in the tropical North Atlantic (e.g., Villarini et al. 2010). The cubing adds significance to the most intense (portions of) storms. Applying this relative SST-derived formulation to a 17-member CMIP5 ensemble provides a 21st century change in North Atlantic PDI that ranges from -30 to +450% (Villarini and Vecchi 2012).

Others have applied similar large-scale indices for TC genesis and/or activity to the historical record and climate models. These indices include atmospheric variables such as vertical wind shear, potential intensity (PI), mid-tropospheric relative humidity, and SST, and ventilation (e.g., Bruyère et al. 2012; Tang and Emanuel 2012). Although some of these predictors show dramatic increases in TC activity, they are sometimes conflicting. Furthermore, it remains unclear whether large-scale predictors even hold under significantly different climates: Reed et al. (2015) find that simple SST-based indices are likely only a partial predictor of PDI over the last millennium. Regardless, they reinforce the finding that much of the spread in future TC projections originates in large-scale climate variables (Lin et al. 2012; Emanuel 2013; Tory et al. 2013; Woodruff et al. 2013; Tang and Camargo 2014; Shaevitz et al. 2014).

Because there are so many interacting factors that contribute to changes in TC activity—such as sea surface temperature, air temperature in the outflow region, wind shear, mid-troposphere moisture content, oceanic stratification (Emanuel 2013, 1987; Vecchi and Soden 2007; Tang and Emanuel 2012; Vincent et al. 2014), as well as possible positive or negative feedbacks (Balaguru et al. 2014; Mei et al. 2013)—it would be ideal if assessments of TC activity could employ numerical simulations using comprehensive GCMs that would account for all these factors. Such simulations remain limited, however, by computational resources and the physical understanding of small-scale processes included in these models. Currently, only some GCMs represent observed TC formation numbers and geographic distributions well. There is some evidence that model biases (particularly with respect to frequency) are lessened with horizontal resolutions below 50 km, but also evidence that even 10-km resolution is insufficient to accurately model intensity (Murakami et al. 2014; Walsh et al. 2016).

Another hybrid approach is to synthetically generate storms from large-scale climate data. Such techniques address the limited (and non-stationary) historical record and allow the tails of the TC distribution to be probed. There remains, however, a limited ability to calibrate to the observed record. Using such techniques, one can also simulate the set of storms under changed climate conditions. A study by Emanuel (2013) using CMIP5 model output and a synthetic storm generator yields more—and more intense—tropical cyclones in a warmer world.

CMIP5 GCMs with a “reasonable” TC climatology project decreases in global TC frequency varying between 7% and 28% (Walsh et al. 2016, Shaevitz et al. 2014; Tory et al. 2013; Mallard et al. 2013). These results are consistent with results from earlier-generation GCMs; globally decreasing frequency has been shown to be related to a decrease in mid-tropospheric rising air motion e.g., vertical velocity (Sugi et al. 2002, 2012; Oouchi et al. 2006; Held and Zhao 2011) or on increased mid-level saturation deficits (drying) (e.g. Rappin et al. 2010). Some general rising motion and mid-level moisture supply are both important ingredients for TC formation and decreases in both of these could occur because of an expected poleward expansion of the Hadley Circulation (Kang and Lu 2012; Bell et al. 2013). However, lessened frequency is not universal; for example, some studies suggest that the North Pacific, near Hawaii, may experience an increase in TC frequency (Murakami et al. 2014; Tory et al. 2013). A graphical summary of the latest IPCC results (Christensen 2013) is shown in Figure 5. Almost all of the basins share the same qualitative result. The North Atlantic shows a particularly large increase in the frequency of strongest storms, although this may simply reflect a greater source of data for the assessments to incorporate. Perhaps the most robust result from GCMs is increasing amounts of precipitation per storm in a warmer world (Knutson et al. 2010; Walsh et al. 2015), with important implications on freshwater flooding.

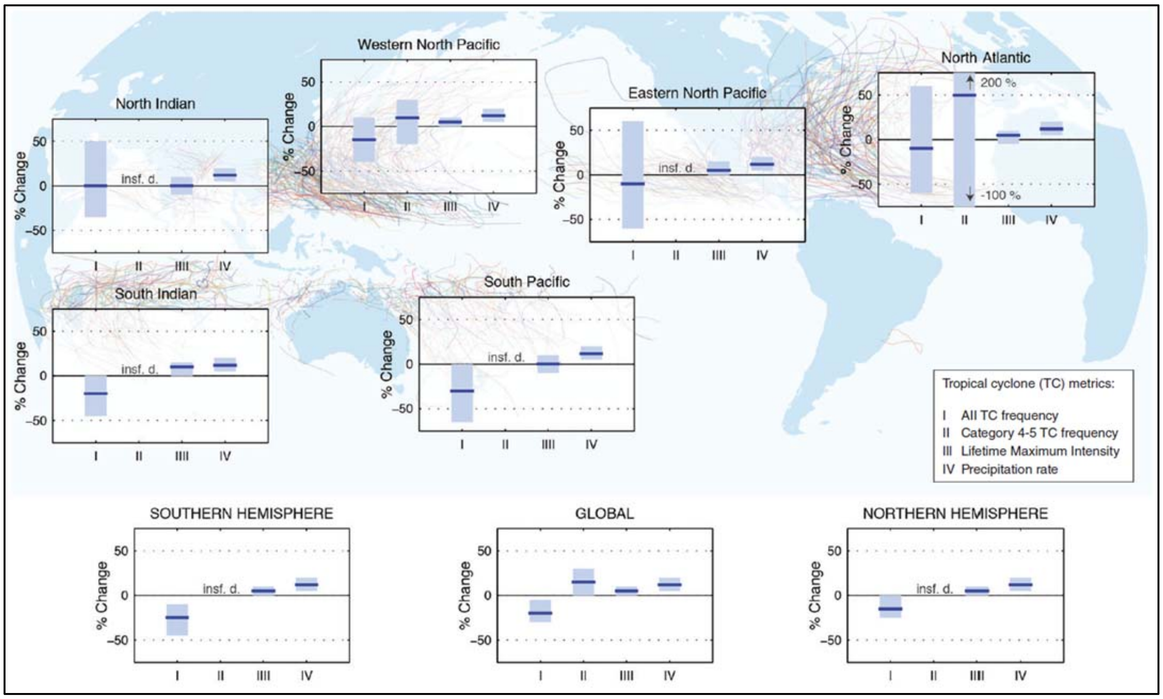


Figure 5. Projected changes in tropical cyclone statistics. All values represent expected percent change in the average over the period 2081–2100 relative to 2000–2019, under a moderate emissions scenario, based on expert judgment after subjective normalization of the model projections. For each metric plotted (see map legend), the solid blue line is the best guess of the expected percent change, and the colored bar provides the 67% (likely) confidence interval for this value (note that this interval ranges from -100% to +200% for the annual frequency of Category 4 and 5 storms in the North Atlantic). Where a metric is not plotted, there are insufficient data (denoted insf.d.) available to complete an assessment. A randomly drawn (and colored) selection of historical storm tracks are underlaid to identify regions of tropical cyclone activity. (Source: Fig. TS.26, Stocker et al. 2013)

These robust changes, however, are not the only factors that may influence future TC risk. Less studied climatic controls on the size of storms could be very important, as storm surge increases dramatically in larger storms (e.g., Sandy 2012; see also the sensitivity analysis of Lin et al. 2012).While the latest results do point to some definitive changes within basins, timing will be influenced by decadal and multi-decadal variability, which may dominate local changes through mid-21st century (LaRow et al. 2014; Villarini and Vecchi 2012). That said, a very recent study by Kang and Elsner (2016) using 30 years of historical track data from the Joint Typhoon Warning Center and the Japan Meteorological Agency found evidence that such changes are already evident in the Northwest Pacific Basin. Moreover, they provided an explanation for the reduced frequency—attributing it to reduced upward air motion as in some previous studies, but with an added explanation that it is likely the result of increased high pressure at upper levels of the troposphere making it more difficult for deep convection to occur. Weak storms will be less likely to overcome this barrier. But, higher SSTs will provide increased opportunities for the stronger storms to do so.

Extratropical Cyclones

Unlike tropical cyclones, extratropical cyclones (ETCs) derive much of their energy from the ambient horizontal temperature (and associated density) difference (gradient) in the atmosphere. This gradient represents a pool of potential energy that a developing storm can convert to rotational wind, or kinetic, energy. As colder, denser air wedges itself under the warmer air, the center of gravity is lowered and the resulting reduction in potential energy is manifested as kinetic energy by the developing cyclone. The density difference across the temperature front is supported by vertical wind shear—or increasing westerly wind speed with height in the mid-latitudes, which is responsible for the existence of the jet stream at higher altitudes. The juxtaposition of air masses of different density is the basic premise behind the Norwegian Cyclone Model (e.g., Bjerknes and Solberg 1922) that was introduced in the 1920s.

In the 1940s, Charney (1947) and Eady (1947) demonstrated theoretically that extratropical cyclones developed through a process called baroclinic instability, which could only occur when a certain threshold of horizontal temperature gradient (or baroclinicity) existed. Theories since then have explained other aspects of extratropical cyclones—in terms of development or features and a comprehensive listing of them is beyond the scope of this paper. However, a relatively recent theory is worth mentioning because it includes another relevant process that is significant from a climate change perspective. Shapiro and Keyser (1990), as the result of a field study that was conducted over the Atlantic in the mid-1980s (called ERICA Explosive and Rapid Intensification of Cyclones over the Atlantic), observed that extratropical cyclones can begin to take on characteristics that are present in tropical cyclones, such as a warm core. In addition, they noted that the release of latent heat can become very significant for development, just as for tropical cyclones. The latent heat flux at the surface is a combined result of wind speed and the difference in specific humidity between the Earth's surface (be it land or water) and the air 10 meters above it. Cold dry air blowing across a warm moist surface will allow for the upward transfer (flux) of latent heat energy into the atmosphere.

The low to mid-level horizontal temperature gradient and the latent heating are significant from a climate change perspective because the way these features are changing—and will continue to change—will counter each other and hence complicate our understanding of how climate change will impact extratropical cyclone activity. Specifically, one of the anticipated changes regarding temperature changes is that the poles (north and south) will warm more than equatorial regions at least at low to mid levels. This differential warming will therefore reduce the ambient pole-to-equator temperature gradient. Consider that the zonal mean pole to equator temperature difference at the surface in 1970 was (288K - 234K =) 54K so that an increase of 5°C at the pole and a 1°C increase in the tropics by 2100 will mean a difference of (289-239 =) 50K , or a reduction of about 7.5%. The reduced gradient will mean less available potential energy at low to mid levels of the atmosphere for storm development.

At mid to high levels, studies have shown (e.g., Yin 2005) that the temperature gradient is expected to increase because of greater release of latent heat in the tropics at high altitudes. This greater release is related to the nonlinear nature of the temperature dependence of saturation vapor pressure (SVP), which represents the maximum amount of water that can exist as vapor in the atmosphere. At high temperatures in the tropics, a small increase in temperature yields a large increase in SVP. As cumulus towers in the tropics grow upward, however, they release that much more latent heat—thereby warming the upper atmosphere considerably. Stronger and more frequent development at mid to high levels can and often does translate to the surface.

Besides basic considerations of temperature gradient and moisture availability, other controlling features such as the polar and subtropical jet streams and larger-scale climate factors such as the North Atlantic Oscillation and El Niño can and do certainly influence important aspects of ETCs, such as storm track trajectory.

The historical record has provided some insight into how climate change may affect ETC activity later this century. For example, Sickmöller et al. (2000) and Gulev et al. (2001) have found negative trends in cyclone counts over reanalysis periods (1979– 1997 and 1958–1999, respectively) in both the North Atlantic and North Pacific sectors. Similarly, McCabe et al. (2001) found decreases in mid- (but not high-) latitude cyclone frequencies and Wang et al. (2006) and Raible et al. (2008) confirmed similar results for the North Atlantic region. More recently, Feser et al. (2015) found increases in cyclone activity over the North Atlantic and Western Europe north of 55°N using reanalysis data from the last 40–60 years, although the finding was not supported with proxy data. With respect to the frequency and intensity of strong (e.g., maximum 3s wind gusts > 30 m/s) ETCs , Geng and Sugi (2003) and Paciorek et al. (2002) have found an increase over both the North Atlantic and North Pacific during the second half of the 20th century. According to the study of Gulev et al. (2001), however, there is only a small positive trend for North Pacific deep ETCs (e.g., core pressure < 980 hPa) in NCEP-NCAR reanalysis data, and even a negative trend for the Atlantic sector. At the same time, these authors (confirmed by McCabe et al. 2001) computed significant increases in deep cyclone counts over the Arctic.

In all of these historical studies, the greatest changes have been found over the open oceans and in almost all cases there have been little to no change identified over continents, including Europe, Asia, and North America. The difficulty in reaching a consensus regarding the recent historical changes likely stems from the fact that climate variability is larger than the mean effect from climate change. The complexity of ETC development ideally requires a numerical approach to understand its development—especially under climate change.

Sinclair and Watterson (1999) examined output from 1 and 2XCO2 GCM simulations and found an overall decrease in the number of cyclones that was the net result of a decrease in the number of weak-to-moderate-strength cyclones and an increase in the number of strong cyclones. This finding was even observed by some earlier studies, such as Lambert (1995). However, they did not give detailed geographical distributions of the increases in the number of strong cyclones. A study by Knippertz et al. (2000) similarly showed increasing frequencies of strong cyclones and a northward shift of the strong cyclone activity in the North Atlantic associated with greenhouse warming. Geng and Sugi (2003) used a high resolution Atmospheric General Circulation Model (AGCM) (T106) from the Japan Meteorological Agency (JMA) to simulate present and future activity. They also found a decrease in the number of (weak) ETCs in winter and summer (less in summer). The number of intense ETCs increased. Weaker baroclinic instability was the explanation for the decreased frequency of weaker ETCs, but no reason was given for the increased frequency of strong ETCs. They did speculate, however, that increased moisture associated with melting sea ice in the model enhanced the latent heat release.

Yin (2005) evaluated an ensemble of 21st century climate simulations that were performed with 15 coupled climate models and found a consistent poleward and upward shift and intensification of the storm tracks. The shift of the storm tracks was accompanied by a poleward shift and upward expansion of the mid-latitude baroclinic regions that was the result of the enhanced warming in the tropical upper troposphere and increased tropopause height. The poleward shift in baroclinicity was augmented in the Southern Hemisphere and partially offset in the Northern Hemisphere by changes in the surface meridional temperature gradient. Finnis et al. (2007) used CCSM3 to evaluate changes in the frequency and precipitation characteristics of ETCs. They found a decrease in the frequency (in the Northern Hemisphere) but an increase in precipitation, although they did not distinguish between weak and strong ETCs. Ulbrich et al. (2009) analyzed output from a suite of GCMs and found that the number of all cyclones was reduced in winter, but in specific regions (over the Northeast Atlantic and British Isles, and in the North Pacific) the number of intense cyclones increased in most models. For the average over the hemisphere, an increase in the number of extreme cyclones was found only when “extreme” was defined in terms of minimum central (sea level) pressure, while there was a decrease in several models when “extreme” was defined in terms of the relative vorticity around the center.

More recently, Mizuta (2012) examined results from 11 GCM runs from CMIP5 and found that most predict an increase of strong ETCs (<980mb) on the downwind and poleward side of the polar jet stream. Figure 6 illustrates that strong ETCs are expected to increase mainly over the North Pacific, with slight decreases in those cyclones over the North Atlantic. O’Gorman (2012) showed that storm track intensity is not related in a simple way to global mean surface temperature so that, for example, a stronger southern storm track in response to present-day global warming does not imply it was also stronger in hothouse climates of the past. But no clear impact is given of climate change on ETCs. The results from Mizuta (2012) over the North Atlantic and Europe are mostly consistent with those from

Zappa et al (2013) who found a decrease in overall activity but a slight increase in frequency and strength of storms over central Europe, with decreases in the number of storms over the Norwegian and Mediterranean seas.

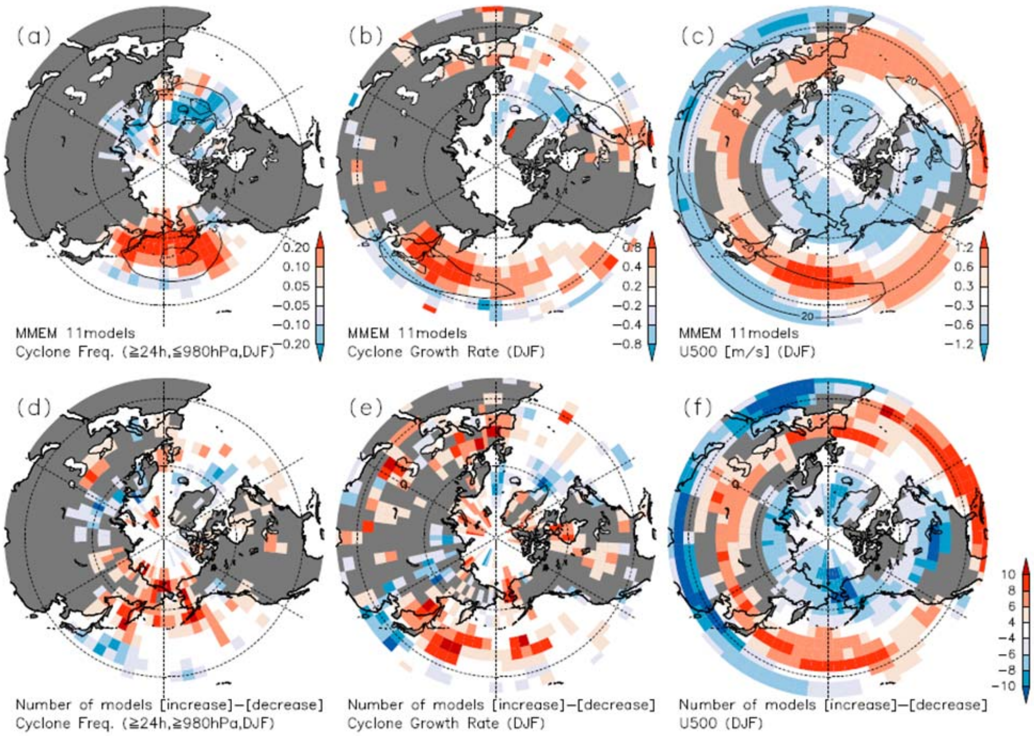


Figure 6. Ensemble means of the change from the historical runs to the end-of-century RCP4.5 runs (top), and the number of models that project increases minus the number of models that project decreases (bottom). (a, d) density of intense cyclones (1 per month per box); (b, e) mean growth rate of cyclones (hPa/day); and (c, f) zonal wind at 500 hPa (m/s). Contours in panels a-c denote the ensemble means of the Historical runs. (Source: Fig. 2, Mizuta 2012)

The consensus view, regardless of the vintage of the study, is that the number of ETCs will likely decrease, primarily as a result of fewer weak cyclones. But, and importantly, the number of strong cyclones is expected to increase. The explanation for this may be that, with a weaker ambient horizontal temperature gradient, there will be fewer opportunities for storms to initiate development. However, once they do, other processes that complement baroclinic development, such as latent heat release, will lead to considerable intensification. While this is a consensus view, it is important to note that it is less strongly supported than the expected overall decrease in ETC frequency. There is a consensus also that associated precipitation will increase, likely as a result of increased temperature and saturation vapor pressure. As for regional changes, there is more variability in the results although there is some consensus that storm activity will increase over the North Pacific and more or less uniformly in the Southern Hemisphere.

Severe Thunderstorms

Severe thunderstorms (STs) are mesoscale convective storms that generate damaging hail, wind, or tornadoes; in the United States, a thunderstorm that produces hail of at least 1-inch in diameter hail, three-second gust wind speeds of 50-knots or more, or a tornado of at least EF-1 intensity is considered severe. STs require a specific type of environment in which to grow. Namely, convective instability is required both to lift moist air parcels from the surface to generate precipitation in the form of rain and hail, and to generate updrafts that are strong enough to support hailstones in the air long enough to grow to threshold or greater size. To generate damaging winds, falling precipitation has to be sufficiently intense to drag air downward with it forcefully enough so that when this dragged-down air hits the ground it can spread outward horizontally with damaging velocity. These downbursts, or straight-line winds or derechos as they are sometimes called, can contribute significantly to the damaging wind potential of a thunderstorm. The convective available potential energy, or CAPE, is a vertically integrated measure of the convective instability of the atmosphere, and is a key ingredient for the formation of STs.

Another key ingredient for ST growth is vertical shear of the horizontal wind (hereafter referred to as vertical wind shear). Vertical wind shear is a reference to how the environmental wind speed and direction change with height. This shear helps to separate the updrafts from the downdrafts and helps thunderstorms reach their peak intensity and maintain it for longer periods of time. Without any vertical wind shear, heavy precipitation falling through the core updraft region limits storm growth. How the shear changes direction with height is also important factor for influencing tornado development.

Because of the requirement for convective instability, STs typically form in the summer months in both hemispheres, although in some locations the requisite instability can exist during cold seasons albeit over shallower depths. Because of the vertical shear requirement, however, severe storms do not occur everywhere there is warm air at the surface. Severe storms, for example, do not typically develop in the tropics because vertical shear, which is a function of the environmental horizontal temperature gradient, or baroclinicity, is weak. Although the specific conditions required for hail, damaging wind, and tornadoes differ slightly, the two basic ingredients of high CAPE and high shear are common to all three.

Geography also plays a role in generating preferred environments. One of the reasons the United States has the highest probabilities of severe weather has to do with the country's geography. The Gulf of Mexico is the primary source of warm moist unstable air for the Great Plains. As low pressure systems develop on the lee side of the Rocky Mountains, southeasterly winds ahead of the low draw the warm moist unstable air northwestward. At upper levels, strong southwesterly winds bring air from the Mexican Plateau, which is much drier and cooler. This configuration creates both a thermodynamically unstable environment as well as one with both wind speed and directional shear.

How the shear changes with height is also important. A veering (i.e., clockwise turning with height in the Northern Hemisphere) wind shear profile, for example, is necessary for tornadoes to develop.

In the global mean, Earth's surface will warm in the 21st century—especially in polar regions and at mid latitudes, where vertical wind shear is currently most prominent. Although warming at the surface alone does not guarantee increased thermodynamic instability, climate change is also expected to result in cooling or at least less warming at upper levels—especially at mid latitudes. The net result in this case will increase the inherent convective instability of the atmosphere. As for vertical wind shear, from a globally averaged standpoint, the fact that warming in the polar regions is greater than in the equatorial regions will, as we saw with ETCs, result in a weaker horizontal temperature gradient, which will in turn be reflected by a weaker vertical wind shear. The increased instability would favor an increase in ST activity (frequency and intensity) while the decrease in shear would do the opposite. Once again GCMs are necessary to determine the net result on the large-scale environmental conditions conducive to severe storm development.

Trapp et al. (2007) examined output from a GCM over the United States and found that (late 21st century) increases in CAPE for the summer months are as high as 500 J/Kg over the southeast but that in general there are increases across the eastern two-thirds of the country. Decreases in shear would be greatest across the central latitudes of the United States, with greatest increases over the northern intermountain region of the West. The net result would be an increase in the number of ST days for much of the country east of the Rockies—with the greatest increases coming over the Central Great Plains and the North and South Carolina coastal region (2-3+ days / season).

More recently, Diffenbaugh et al. (2013) analyzed ST environments using daily output from CMIP5 and also found robust increases in the number of Severe Convective Environment days in the eastern half of the United States in all seasons even before a mean global warming of 2°C occurred. Moreover, they found that the days with low shear often occurred on days with low CAPE, and days with high CAPE occurred when convective inhibition was low and vertical shear was high. No explanation was given regarding why days with sufficiently high CAPE (>2000 J/kg) also exhibited the requisite amount of vertical shear. Some of the results from that study are shown in Figure 7.

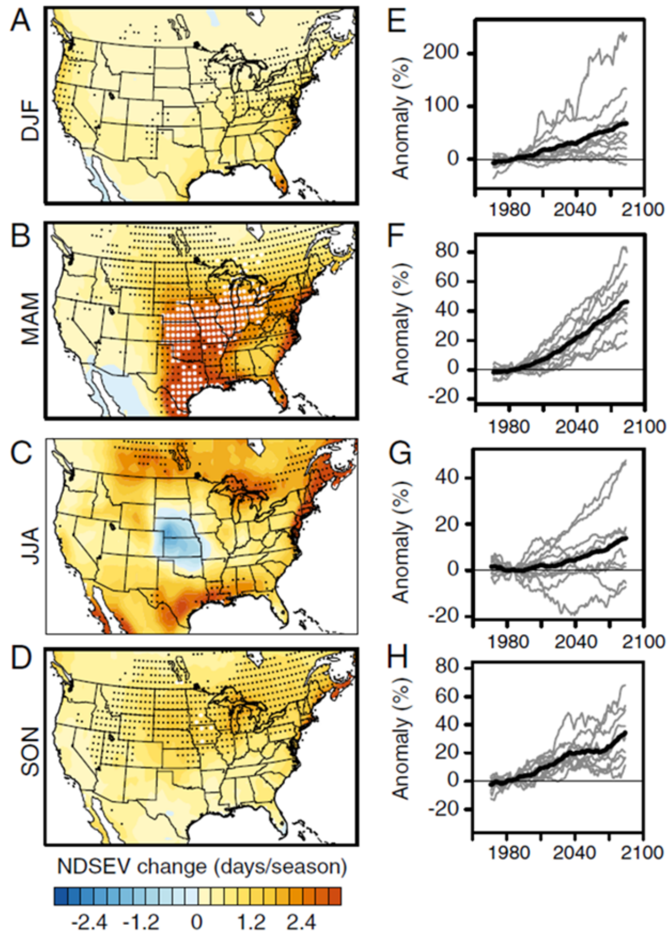


Figure 7. Response of severe thunderstorm environments in the late 21st century period of RCP8.5 during winter (DJF), spring (MAM), summer (JJA), and autumn (SON). (A–D) Color contours show the difference in the number of days on which severe thunderstorm environments occur (NDSEV) between the 2070–2099 period of RCP8.5 and the 1970–1999 baseline, calculated as 2070–2099 minus 1970–1999. Black (gray) dots identify areas where the ensemble signal exceeds one (two) standard deviations of the ensemble noise, which we refer to as robust (highly robust). (E–H) Each gray line shows an individual model realization. For each realization, the anomaly in the regional average NDSEV value over the eastern United States (105–67.5°W, 25–50°N; land points only) is calculated for each year in the 21st century, with the anomaly expressed as a percentage of the 1970–1999 baseline mean value. A 31-year running mean then is applied to each time series of percentage anomalies. The black line shows the mean of the individual realizations. (Source: Fig. 1, Diffenbaugh 2013)

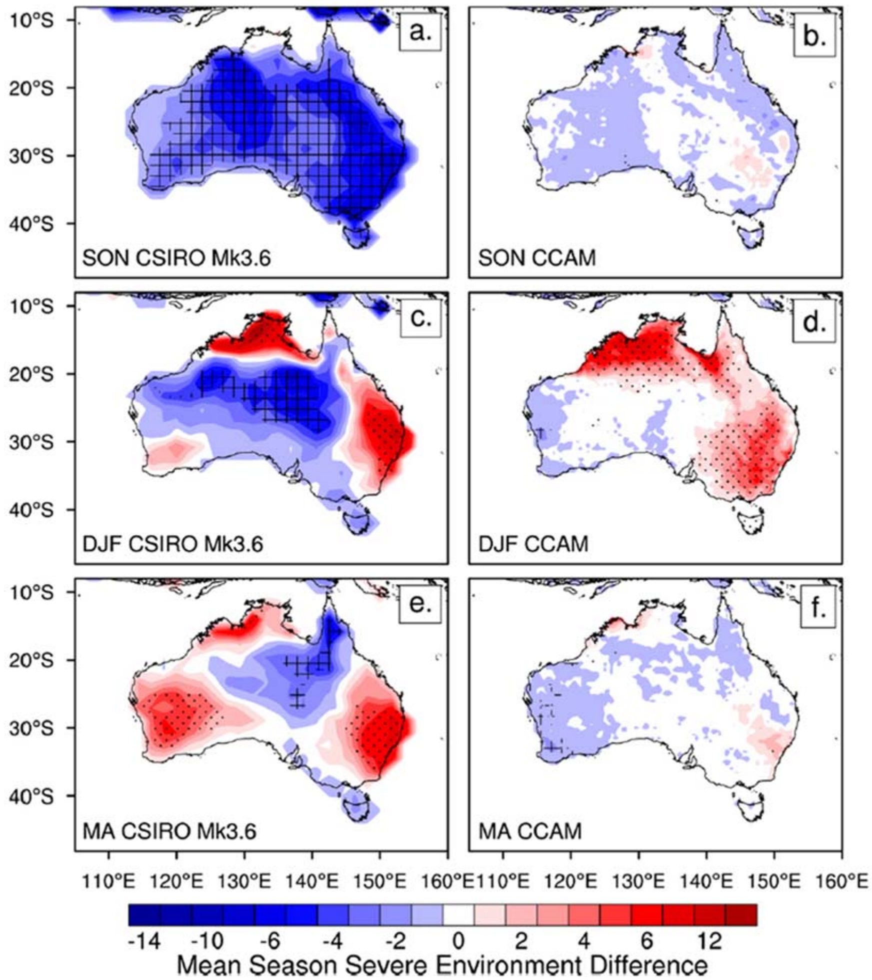


Figure 8. Differences between the mean seasonal frequency of Severe Storm Environments for the 21st-century period and the 20th-century period over the Australian continent for (left) CSIRO Mk3.6 and (right) CCAM. Periods correspond to (a), (b) SON; (c), (d) DJF; and (e), (f) MA. Stippling is indicative of significant increases to the 21st-century mean above the 97.5th percentile, while hatching indicates significant decreases below the 2.5th percentile as determined using the bootstrapping procedure described in the text. Units are in terms of changes to the number of environments per season. (Source: Fig. 12, Allen et al. 2014)

Allen and Walsh (2014) evaluated output over Australia from two GCMs and found similar results for the end of the 21stcentury: increases in CAPE would outweigh decreases in vertical shear especially over northern and eastern Australia. The increases in CAPE were a result of increases in surface temperatures relative to those in the upper atmosphere and increases in low-level moisture. They noted that the implications of this potential increase would be significant, with the overall frequency of potential ST days per year likely to rise over the major population centers of the east coast by 14%

for Brisbane, 22% for Melbourne, and 30% for Sydney. Some of the results from that study are shown in Figure 8.

Marsh et al. 2009 used the NCAR Community Climate Model to evaluate climate change impacts in Europe and determined that average CAPE values would decrease during the warm season but that there would be enough overlap in days with increased CAPE and suitable shear conditions so that much of Spain, Switzerland, Austria, Poland, southern Germany, much of Turkey, and Cyprus would see increases in the number of ST days. Some of the results from that study are shown in Figure 9.

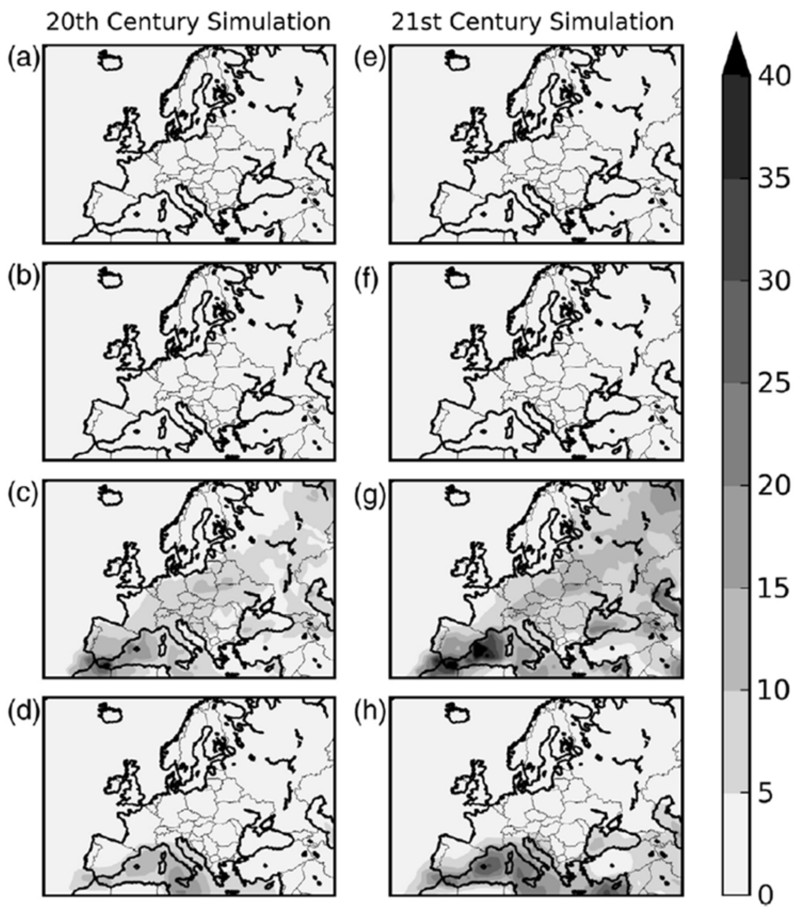


Figure 9. Spatial distribution of the number of environments favorable for severe thunderstorms for (a) December through February from 20th century simulation, (b) March through May from 20th century simulation, (c) June through August from 20th century simulation, (d) September through November from 20th century simulation, (e) December through February from 21st century simulation, (f) March through May from 21st century simulation, (g) June through August from 21st century simulation, and (h) September through November from 21st century simulation. CAPE values of 0 were included in these calculations. (Source: Adapted from Marsh et al. 2009)

From a more observationally based approach, Hov et al. (2013) more recently used data from the European Severe Weather Database (EWSD) to suggest essentially the same result over Europe—namely that areas prone to frequent occurrences of severe weather are likely to see increases because of increases in CAPE outweighing decreases in shear.

The aforementioned studies reach similar conclusions for different regions of the world, using different models and different vintages. The commonality supports the notion that STs will likely become more frequent in many parts of the world, regardless of season, and especially in areas where STs already occur frequently.

While the aforementioned studies have addressed the frequency aspects of ST behavior under climate change, the intensity aspects—e.g., in terms of hail size, wind speed, and tornado strength—have not been addressed. Damaging winds from STs may be the easiest of the three perils to understand, although they have not been the focus of very many studies. Given the similarity in environments that spawn derechos and hail, it is likely that the same sorts of increases in the frequency of events will occur as for hail.

Understanding hail size requires additional information, for example with respect to freezing level as well as the microphysical aspects of liquid cloud water. Tornadoes are even more difficult and less frequently studied, not only because of their smaller size but also because they are even more difficult to understand; they require a particular type of vertical shear [i.e., veering wind shear]. Diffenbaugh et al. (2008) indicated that global warming would likely cause some increases but did not elaborate quantitatively because of the aforementioned difficulties and uncertainties. More recently, Lee (2012) used a synoptic climatology approach involving principal components analysis, cluster analysis, and discriminant function analysis to determine that F2 or stronger tornadoes will likely increase by 3-28% by 2090. The paucity of studies and lack of observational evidence demonstrate the high degree of uncertainty associated with projections of climate change impacts on tornadoes.

The number of studies found focusing on climate change impacts on severe weather is relatively small and likely related to the difficulty of modeling them, which in turn is likely related to the small scale of the phenomenon. The difficulty is exacerbated/supported by the lack of any historical trends. The IPCC noted that severe weather aspects are not well observed in many parts of the world because the density of surface meteorological observing stations is too coarse to measure all such events. Moreover, the homogeneity of existing reporting is questionable (Verbout et al., 2006; Doswell et al., 2009).

Some examples are Brooks and Dotzek (2008), who found significant variability but no clear trend in the past 50 years in STs in a region east of the Rocky Mountains in the United States; Cao (2008), who found an increasing frequency of severe hail events in Ontario, Canada, during the period 1979–2002; and Kunz et al. (2009), who found that hail days significantly increased during the period 1974–2003 in southwest Germany. Hailpad studies from Italy (Eccel et al., 2012) and France (Berthet et al., 2011) suggest slight increases in larger hail sizes and a correlation between the fraction of precipitation falling as hail with average summer temperature while in Argentina between 1960 and 2008 the annual number of hail events was found to be increasing in some regions and decreasing in others (Mezher et al., 2012). In China between 1961 and 2005, the number of hail days has been found to generally decrease, with the highest occurrence between 1960 and 1980 but with a sharp drop since the mid-1980s (CMA, 2007; Xie et al., 2008). However, there is little consistency in hail size changes in different regions of China since 1980 (Xie et al., 2010).

Wildfire

Wildfire (also known as bushfire in Australia) requires knowledge not only of how meteorological and hydrological factors will change, but also of how biomass characteristics will change. The meteorological conditions are complex because there are two different sets to consider that are somewhat hydrologically different from each other: convective storms and drought. Convective storms generate heavy rain, which is capable of extinguishing fire and, more importantly, lightning, which can ignite fire. These storms do not have to be severe, i.e., produce hail, damaging winds, or tornadoes; they just need to produce lightning. Lightning strikes can initiate fires even when the vegetation is not exhibiting drought conditions; however, drier biomass is more likely to ignite and facilitate the spread of fire. Wind can also contribute to the spread of wildfire. And even in the absence of lightning, anthropogenic sources such as cigarettes, campfires, arson, and even downed power lines frequently start fires. Four out of five wildfires in the United States start this way. Marlon et al. (2008) provide more detail on the climate and human factors associated with wildfire.

Given the strong connection between fire and climate (e.g., Swetnam and Betancourt 1990, Marlon et al. 2008, Aldersley et al. 2011), there is little doubt that climate-induced changes in fire activity will occur in many areas, but the climate change relationship is complex. Even the same temperature change can have opposite effects. For example, an increase in precipitation in some warm grasslands and shrublands can lead to higher productivity, more fuel, and hence increased fire activity during the dry season. However in climates characterized by a well-balanced supply of moisture, the same precipitation increase could diminish fire activity (Meyn et al. 2007, van der Werf et al. 2008, Littell et al. 2009, Krawchuk and Moritz 2011). Warmer and drier weather may therefore increase fire activity in biomass -rich areas but have the opposite effect in moisture-stressed environment, as increased evaporationdecreases growth of biomass necessary to carry fire.

Understanding how climate change will affect regional temperature, precipitation, lightning, drought, surface wind speed and direction, and the growth of biomass is challenging and requires more than just the output from a general circulation model (GCM). A standard approach is to use output from GCMs as input to Dynamic Global Vegetation Models (DGVMs). The DGVMs simulate the climate-based processes controlling plant growth and death in different vegetation types, and many of these models have incorporated a fire module (e.g., Lenihan et al. 1998, Fosberg et al. 1999, Thonicke et al.

2001, Arora and Boer 2005). Recent advances in some DGVMs have improved their ability to represent historical patterns of burning (Thonicke et al. 2010, Prentice et al. 2011), although this remains an active area of research.

Many of the wildfire studies cited in this section use output from the CMIP3 (Coupled Model Intercomparison Project – Phase 3) suite of models, which has been available since ~2006 (Meehl et al. 2007) but which was also used by the IPCC for their Fourth Assessment in 2007. Because an important driver of change in fire risk is related to temperature change, and because temperature projections are relatively consistent between CMIP3 and CMIP5 (Knutti and Sendlacek 2013) it is reasonable to assume that the fire results obtained using output from CMIP5 would be similar.

Regardless of the modeling framework, future projections of fire risk at the global scale are relatively rare (Scholze et al. 2006, Krawchuk et al. 2009, Gonzalez et al. 2010, Liu et al. 2010, Pechony and Shindell 2010). Regional studies seem to be more common in the literature than global ones and because the regional studies likely use different GCM output as well as different DGVMs, comparison of results from one country/continent to another is challenging. This issue is significant because discrepancies among GCMs, especially with respect to precipitation, may be important in the context of fire.

Moritz et al. (2012) is one of the few truly global studies performed in the recent past. It evaluated the impacts of climate change using climate norms from 16 GCMs (using the A2 emissions scenario which predated the RCP ones but similar to RCP 8.5) to assess the magnitude and direction of change over two time periods, 2010–2039 and 2070–2099 at 0.5 degree resolution globally. The study found that many areas in the Northern Hemisphere are expected to have increased risk of wildfire. In particular, the western United States extending northward into Alaska, the northern portions of Canada, the northern part of Africa extending eastward into Saudi Arabia, and into central Asia and northeast part of Russia. Their results are shown in Figure 10.

In general the increases occur at mid to high latitudes with projected decreases in equatorial regions. The increases at mid and high latitudes are primarily the result of increased precipitation seasonality superimposed on an increase in temperature. The decreases are a result of relatively strong increases in precipitation during the dry season, reducing the amount of dry fuel available for burning. However, these results are far from guaranteed. Even though significant portions of the globe indicate an increase in wildfire risk, many areas lack significant consensus. For example, Southern California, southern Chile, and south-central Australia all show what appears to be increases in fire probability but less than 33% of the models agree in that respect. Importantly, Figure 10 shows that wildfire is expected to increase where it is relatively significant already. Decreases are expected to occur where wildfire is not so significant already (e.g., in the equatorial and tropical rain forests).

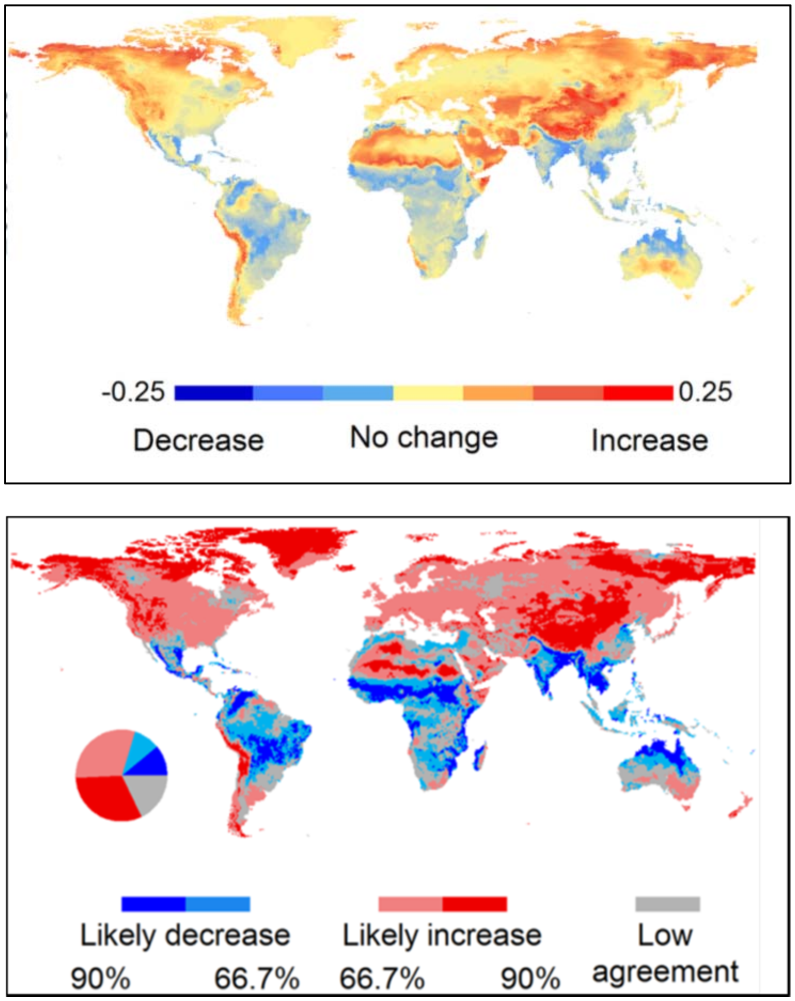


Figure 10. Upper: Ensemble mean change in predicted fire probability among the 16 GCMs for the 2070–2099 time period (change assessed from baseline probabilities 1971–2000). Lower: degree of model agreement. Pie charts indicate global proportions in each agreement class: Likely decrease, Likely increase, and Low agreement correspond to 20.2%, 61.9%, and 17.9%, respectively. (Source: Moritz et al. 2012)

Several other published studies, which also leverage other models within the suite of CMIP3 models, corroborate the results from Moritz et al. (2012) for selected regions but with added detail, perhaps because of the regional focus and perhaps because of the different vegetation and fire models that use the CMIP3 climate information. For example, Wotton et al. (2010) used output from the 1st generation Canadian Climate Model (CGCM1; Flato et al. 2000) and from the Hadley Climate Centre (HadCM3; Hulme et al.1999) from a ~3 x CO2 scenario by the end of the century as well as a Fire Weather Index System (FWI, 2009) into which the GCM output was fed. Findings from the CGCM1 showed an increase in fire risk almost everywhere across Canada—with highest increases in eastern Manitoba, western Ontario, and western Northwest Territories. The increased risk was almost equally from increases in lightning and human cause. Overall, the average increases were approximately 75%, but some places in the areas of highest risk showed over 100% increases. Findings from the HadCM3 also showed increases that were generally twice those from the Canadian Model, but the highest risk areas were southern British Columbia, central Ontario, and central Quebec. Moreover, the majority of increases were from lightning rather than human cause.

King et al. (2012) used output from GCMs and an agricultural pasture model GRAZPLAN (see Gill et al. 2010) to model temporal dynamics of grassland curing and fuel loads in southeastern Australia. They found that it was really the reductions in fuel loads of the specific perennial grasses in the region—driven by the expected temperature increases and increases in drought conditions—that would offset any increase in fire danger from the meteorological changes that would exist by the end of the century.

Khabarof et al. (2014) used output from three GCMs as well as a stand-alone fire model (SFM) to examine the impact of climate change on wildfires in Europe by the end of this century. The GCMs were all part of the CMIP3 Project: MRI-CGCM2.3.2 (Meteorological Research Institute, Japan), CNRM-CM3 (Meteo-France/Centre National de Recherches Meteorologiques, France), and CSIRO-Mk3.0 (CSIRO Atmospheric Research, Australia). The CO2 scenario was the A2 one. Despite the vintage of the climate models, the publication was recent enough to note that the CO2 scenario falls between the newer RCP6.0 and RCP8.5 ones (Moss et. al 2010, Rogelj et al. 2012). They also looked at changes with different levels of adaptation. But, with no adaptation, they concluded that Europe as a whole would experience about a 200% increase in the number of fires.

More recently, An et al (2015) used historical averages from 1991-97 as a baseline against which to compare the impact of climate change from two GCMs and two different RCPs on wildfire danger in the United States. Figure 11 shows the changes in wildfire risk (relative to the baseline) for the period 2030-2050. The results show the largest changes in risk will occur in the south central states, including Texas, Oklahoma, Louisiana, and Kansas—where a significant risk exists already. Although the study did not examine changes at the end of the century, the pattern of change would likely be the same. The results are somewhat different than those from Moritz et al. (2012), where the greatest changes for the United States were shown to occur in the West by the end of the century.

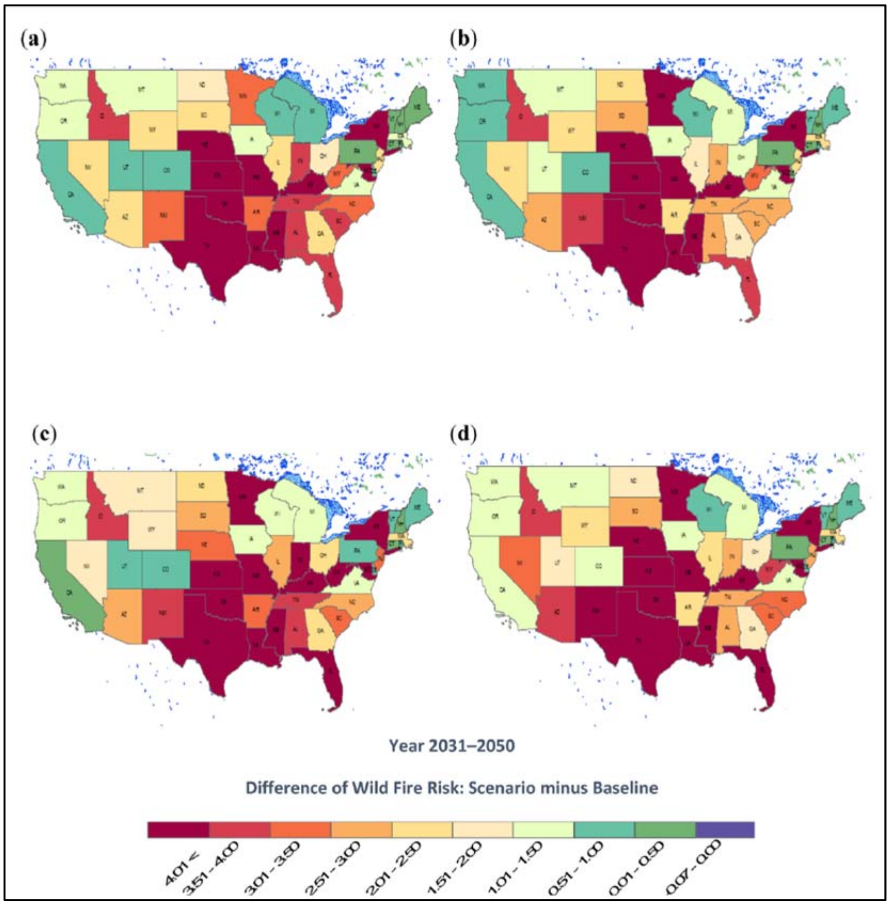


Figure 11. The long-run (2031–2050) impact of climate change on wildfire risk. a) Change in wildfire risk relative to baseline (historical average) with the future climate projected by the HadCM3 model under the RCP 4.5 scenario; (b) Change in wildfire risk relative to the baseline with the future climate projected by the NOAA-GFDL model under the RCP 4.5 scenario; (c) Change in wildfire risk relative to the baseline with the future climate projected by the HadCM3 model under the RCP 8.5 scenario; (d) Change in wildfire risk relative to the baseline with the future climate projected by the NOAA-GFDL model under the RCP 8.5 scenario. The changes in wildfire risk are calculated by subtracting the historical average wildfire risk from the projected future wildfire risk based on the climatic conditions projected by the GCMs. (Source: Fig. 3, An et al. 2015)

Heavy Precipitation and Inland Flooding

To understand the projected impacts of climate change on flooding, one must consider the climatological parameters that affect the severity of different types of flooding. Fluvial, or riverine, flooding is perhaps the most difficult, as it involves an understanding of how temperature and precipitation patterns may behave over extended (e.g., weeks, months, years) periods of time—such as the ones in place during the 1993 floods over the Midwestern United States—as well as flood management practices. Pluvial, or rain-related, flooding, is perhaps more straightforward, as it principally involves knowledge of how heavy precipitation events may change in the future. Coastal flooding, which will be discussed in the next section, is less related to precipitation characteristics than to the winds—from both tropical and extratropical weather systems—that drive storm surges. Here we will focus primarily on pluvial flooding and from a heavy precipitation standpoint.

Unlike the analyses of how climate change will impact specific types of weather systems such as tropical cyclones, extratropical storms, and severe thunderstorms, the thermodynamics connecting a warming atmosphere to changes in precipitation are fairly straightforward. The Clausius-Clapeyron relationship states that the saturation vapor pressure for water increases exponentially with temperature. More simply stated, the warmer the air, the more moisture it can hold (which is not entirely correct because the water vapor can exist even in the absence of any air). And as that moister (from an absolute standpoint) air rises, more of it condenses, which leads to the expected result that more intense, if not more frequent, precipitation events will occur as climate change proceeds. In a unique approach, Durack et al. (2012) quantified the basic effect of temperature on precipitation by using ocean salinity as a complementary integrated measure of long-term changes in the water cycle. Their result showed an intensified global water cycle at a rate of 8 +/- 5% per degree of surface warming.

Finding direct evidence of precipitation changes can be complicated by its significant spatial heterogeneity. Despite that complication, however, there is relatively strong evidence in the historical record that precipitation-related quantities including heavy precipitation events, have been increasing. Ren et al. (2013) found significant increasing precipitation trends in the global mean and in equatorial and sub-polar regions and decreasing trends in the subtropics. The 2013 IPCC report concluded that precipitation over the mid-latitude land areas of the Northern Hemisphere has also increased (Collins et al. 2013). Figure 12 shows some of the observed widespread increases in average annual precipitation in the United States, eastern South America, much of Europe, much of India, northwestern Asia and southeastern China. The signals are more robust for the latter half of the 20th century than for the whole because of greater data availability and better quality. Figure 13 shows more detail for selected regions.

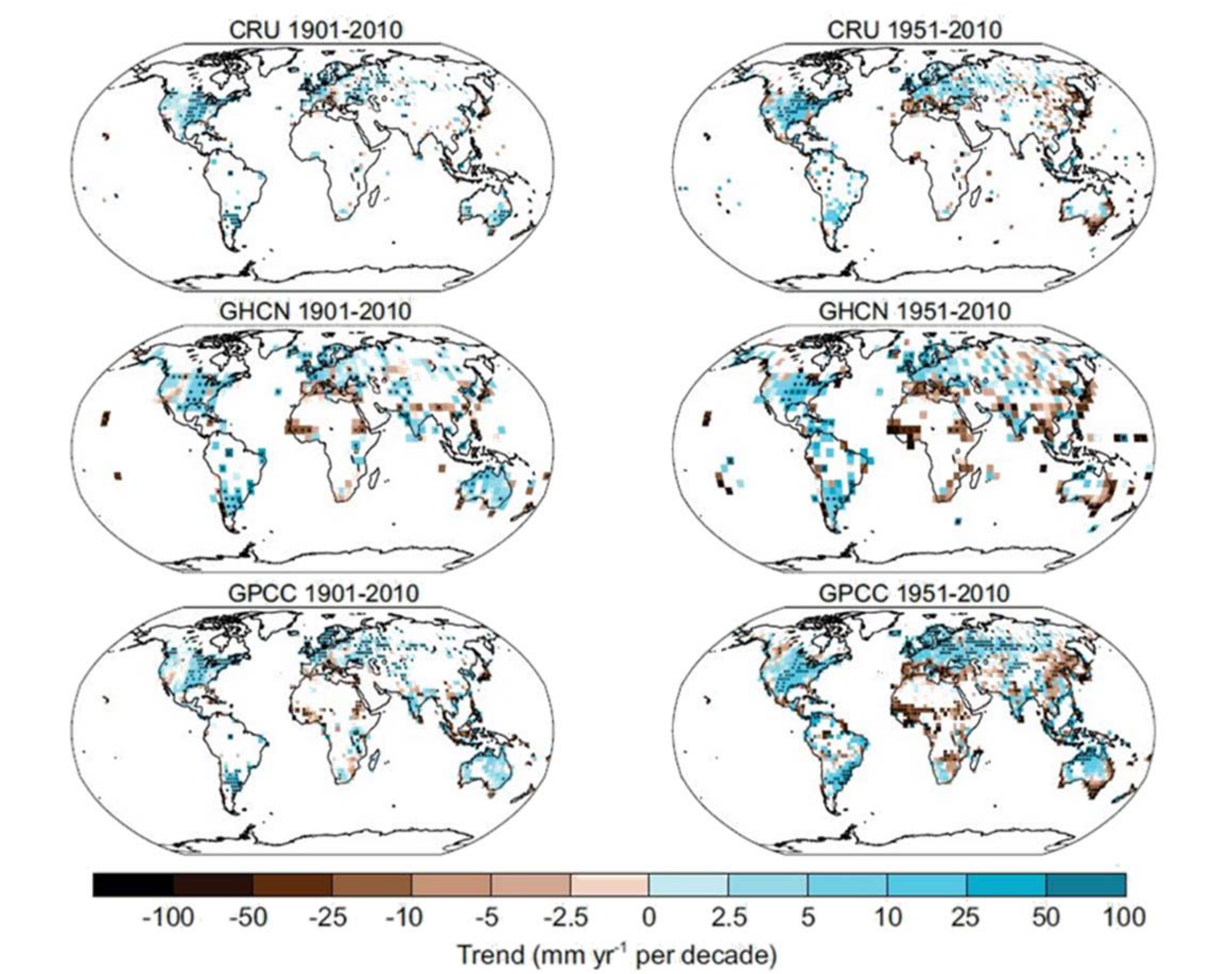


Figure 12. Maps of observed precipitation change over land from 1901 to 2010 (left-hand panels) and 1951 to 2010 (right-hand panels) from the Climatic Research Unit (CRU), Global Historical Climatology Network (GHCN) and Global Precipitation Climatology Centre (GPCC) data sets. Trends in annual accumulation have been calculated only for those grid boxes with greater than 70% complete records and more than 20% data availability in first and last decile of the period. White areas indicate incomplete or missing data. Black plus signs (+) indicate grid boxes where trends are significant (i.e., a trend of zero lies outside the 90% confidence interval). (Source: TFE.1 Fig. 2, Stocker et al. 2013)

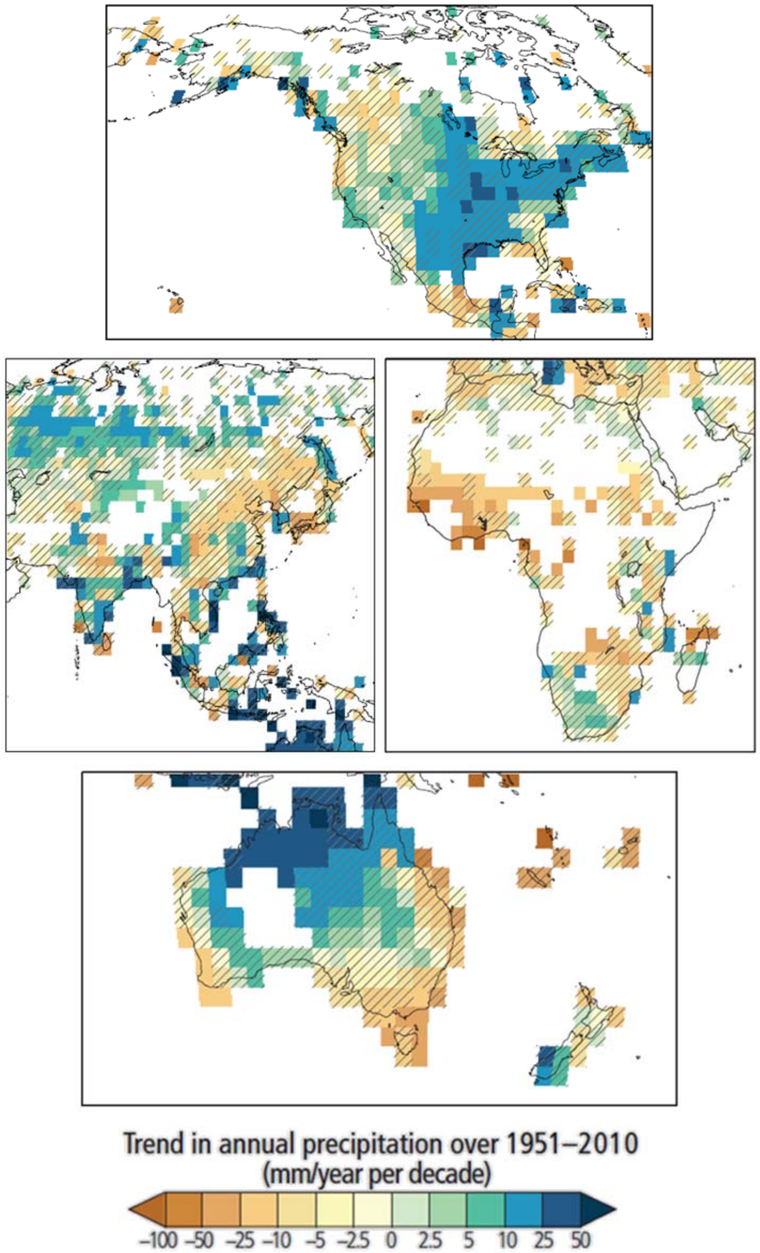


Figure 13. Observed annual precipitation changes for selected regions from 1951–2010, derived from a linear trend. Trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. (Source: Fig. 24-2, Hijioka et al. 2014 (Asia); Fig. 25-1, Reisinger et al. 2014 (Australia); Fig. 26-3, Romero-Lankao 2014 (N. America); and Fig. 22-1, Niang et al. 2014 (Africa))

Regarding Asia, a detailed study by Yao et al. (2008) (which is somewhat dated but still valid because of its historical focus) shows statistically significant decreases of precipitation in southwest, central, and northeast Asia; and statistically significant increases of precipitation in northwest and southeast Asia during the period of 1978 to 2002. Areas of significant precipitation reduction are fewer: parts of western Canada, equatorial Africa, eastern Asia, and eastern Australia. In general, precipitation totals have been increasing in areas where precipitation occurs with some relative frequency. The explanation for this behavior has been documented by many authors (e.g., O'Gorman and Schneider 2009; Lehmann et al. 2015). Despite the strong confidence that precipitation has increased, the IPCC (2013) concluded that there is only medium confidence that it is the result of climate change. A very recent study by Lehmann et al. (2015), however, found that the number of record-breaking rainfall events peaked in 2010 and that every time there is a record-breaking rainfall event there is a 26% chance it is the result of climate change.

Increases in total precipitation will not necessarily yield, or even lead to, increased flooding episodes. Rather, it is the increase in heavy precipitation events, when the absorptive capacity of the soil or underlying surface is exceeded, that yields [pluvial] flood conditions. Such events, where data is available, tend to show a faster rate of rise than the mean precipitation intensity (Fischer and Knutti 2015; Shiu et al. 2012; Collins et al. 2013; Jiménez Cisneros et al. 2014). Global analyses from two different data sets show increases in very heavy rainfall (up to a 100% increase for the annual top 10% of heavy precipitation events) and decreases in moderate precipitation (about 20% decrease for the light and moderate precipitation) (Shiu et al. 2012). In the United States, trends in mean precipitation (+0.6% decade^{-1}) are less than for extreme precipitation (2% decade^{-1} in the top 1% of events), reflecting a change in the tails of the distribution (U.S. Global Change Research Program 2014). Figure 14 shows that extreme precipitation trends are positive and significant for the Midwest and Southeast during the 1901–2011 period. For a shorter period (1957–2010), changes are positive and significant for the Northeast (U.S. Global Change Research Program 2014). In Europe, the frequency and intensity of heavy precipitation events has also increased, while in other continents the trends are less clear, perhaps reflecting data availability or limited analysis (Collins et al. 2013). Finally, even though climate models tend to under-predict change, especially in extremes, historical GCM runs also show increases in the mean and extremes (Shiu et al. 2012; Collins et al. 2013; Jiménez Cisneros et al. 2014).

All of the noted precipitation changes appear more robust since the middle of the 20th century. In addition, despite the preponderance of observational evidence, the IPCC (WG5) expressed only medium confidence in a human contribution to observed changes. Finally, despite the observed changes in precipitation and the well-understood thermodynamical connection with the observed changes in temperature, there is medium confidence that these are the result of climate change.

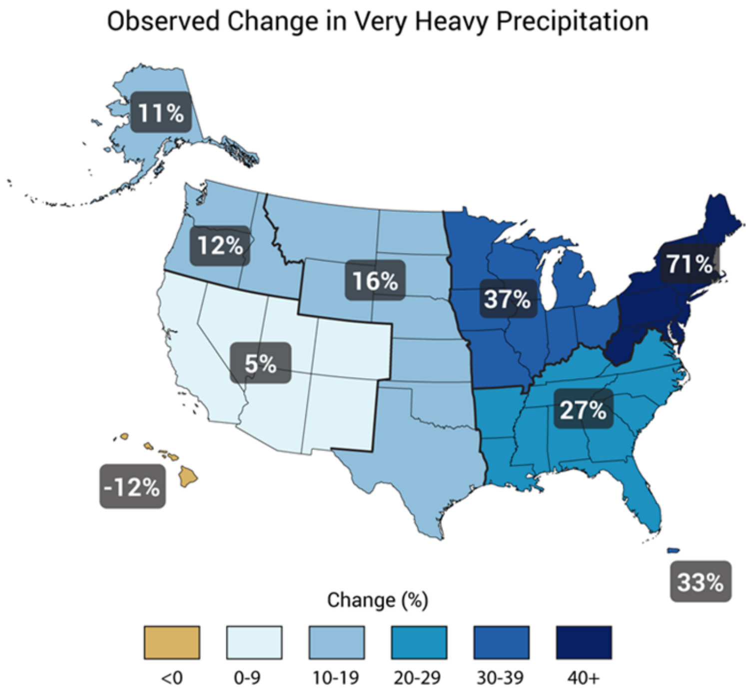


Figure 14. The map shows percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) from 1958 to 2012 for each region of the continental United States. These trends are larger than natural variations for the Northeast, Midwest, Puerto Rico, Southeast, Great Plains, and Alaska. The trends are not larger than natural variations for the Southwest, Hawaii, and the Northwest. The changes shown in this figure are calculated from the beginning and end points of the trends for 1958 and 2012. (Updated from Karl 2009. Source: Fig. 2.18, Walsh et al. 2014)

In general, although not always, heavier rains lead to a larger fraction of rainfall running off and, depending on the surface conditions, more potential for flooding. However, observed trends in floods are slightly less robust than precipitation, likely because of the role of snowmelt seasonality and compensating feedbacks with evapotranspiration and soil moisture. In regions with snowfall, climate change has altered observed streamflow seasonality (Jiménez Cisneros et al. 2014; U.S. Global Change Research Program 2014). Observed warming has led to earlier spring discharge maxima because more winter precipitation falls as rain. Furthermore, in almost all parts of the world glaciers are losing mass (Chen et al. 2013). However, the response of floods to climate can differ even within general regions (e.g., the Himalayas), for example, depending on fraction of water sourced from glaciers (Immerzeel et al. 2010).

For changes in the future, GCMs give relatively robust results with respect to precipitation intensity. By the middle and certainly by the end of the 21st century, it is expected that many of the changes already observed in total (annual) precipitation, as well as the number of and contributions from heavy precipitation events, will continue. A relatively recent study by Scoccimarro et al. (2013)

analyzed CMIP5 output and found end-of-century increases in total annual precipitation, heavy precipitation events (90th %-ile), and width of tail events (99p-90p) for many of the regions where such changes have already been observed to have changed. For Northern Hemisphere locations, percent changes were greatest in winter almost everywhere, with the exception of Spain and the Mediterranean region, where increases in dryness were found to be greatest in summer. For Southern hemisphere locations, percent changes were found to be greatest also in Northern Hemisphere winter (austral summer). The results of the this study are reproduced in Figure 15.

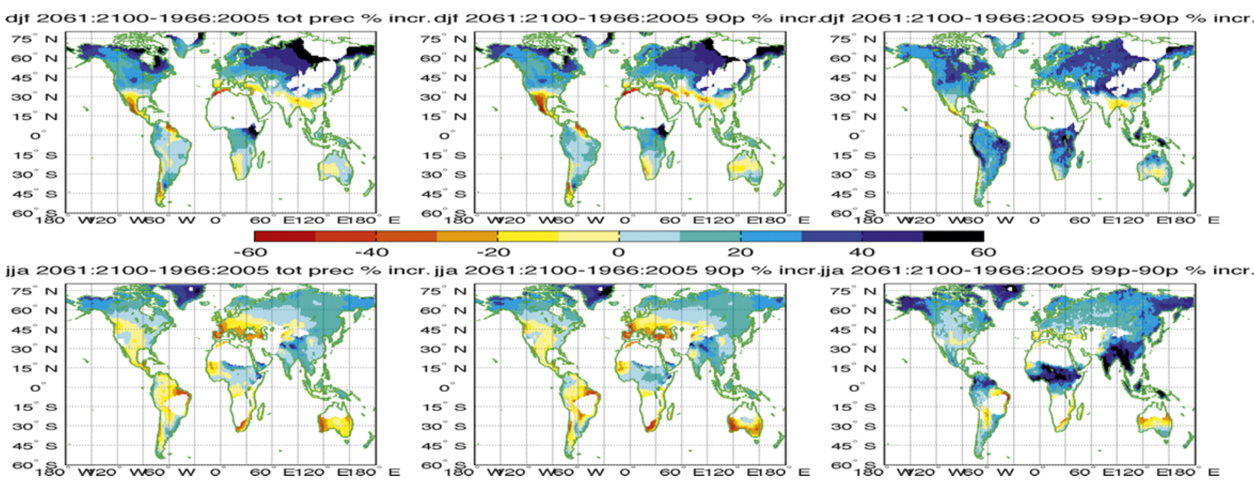


Figure 15. Future changes (%; 2061–2100 with respect to 1966–2005) in (left) total precipitation, (center) 90p, and (right) width of the right tail of the precipitation events distribution (99p to 90p) following the RCP8.5 CMIP5 scenario, as averaged over the CMIP5 models for (top) DJF and (bottom) JJA. White patterns over land indicate regions with seasonal precipitation lower than 0.5 mm day.$^{-1}$ (Source: Fig. 4, Scoccimarro et al. 2013)

Dankers et al. (2014) used global hydrological models coupled to a RCP 8.5 climate model ensemble and found an increase in flooding frequency of the current 30-year flood in more than 50% of global locations, with a substantial increase (to less than one in five years) across 5–30% of land grid points. Decreases occurred in approximately one-third of the global land grid points, particularly in areas where the hydrograph is dominated by the snowmelt flood peak in spring. For snowmelt-dominated regimes, although trends in seasonality are expected to continue, the magnitude of the peak flows is subject to offsetting changes: warmer and possibly shorter winters, and increases or decreases in the total amount of precipitation during the winter season. Despite regional variations, by the end of the 21st century, the number of people exposed annually to the equivalent of a 20th-century 100-year river flood is projected to be three times greater for very high emission scenarios (e.g., RCP8.5) than for very low ones (e.g., RCP2.6). Although global models give broad trends in riverine flooding, these global models must be complemented by local, more detailed models, to assess flooding risk at the catchment scale.

Sea Level Rise and Coastal Flooding

In contrast to the complicated picture for freshwater floods, the severity and frequency of coastal floods is clearly increasing (Sweet and Park 2014; Ezer and Atkinson 2014). In New York City, for example, flooding that occurred an average of 19 days per year from 1920 to 1970 now occurs an average of 99 days per year (Ezer and Atkinson 2014). Current evidence suggests that the rise in mean sea level as shown in Figure 18a is generally the dominant cause of any observed increase in the frequency of extreme coastal flooding events (Zhang et al. 2000; Menendez and Woodworth 2010; Church et al. 2013), although there is some evidence for multi-decadal variability in sea level extremes (Wahl and Chambers 2015).

Figure 16 shows cumulative changes in sea level for world's oceans since 1880. Most of the global average increase in sea level since 1900 (approximately 1.5 mm/yr) is attributable to global warming—divided almost equally between the contribution from thermal expansion of ocean water (50%) and the contribution from melting continental ice sheets and glaciers (40%) (Church et al. 2013). All reconstruction techniques support a recent (approximately the last two decades) increase in the rate of sea level rise to more than 3 mm/year (Hay et al. 2015). This acceleration is commonly attributed to an increased contribution from melting ice on land, and is supported by satellite-derived observations of thinning, accelerating, and mass change of glaciers and ice sheets (Church et al. 2013; Pritchard et al. 2009; Rignot et al. 2011)

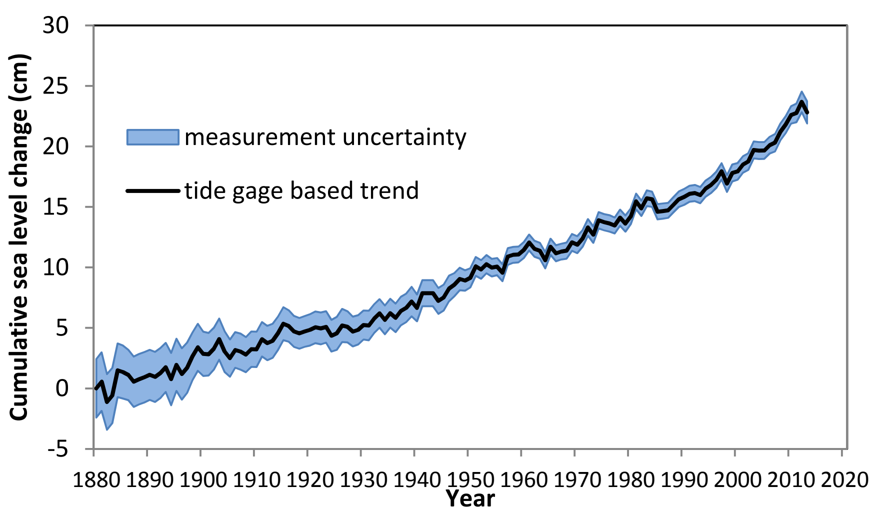


Figure 16. Cumulative changes in sea level for world's oceans since 1880, based on long-term tide gauge measurements. Average absolute sea level change is shown and refers to height of ocean surface, regardless of whether nearby land is rising or falling. Shaded band shows likely range of values, based on the number of measurements collected and the precision of the methods used. (Source: AIR, data from CSIRO, NOAA)

Significant regional variability of sea level exists as a result of changes in weather patterns, ocean circulation, and non-climate change–related processes such as land subsidence (Kopp et al. 2015). Subsidence, or more generally vertical land motion (VLM), is the combined result of tectonic activity, soft-sediment compaction due to overburden or the withdrawal of groundwater or hydrocarbons, and deformation associated with ice–ocean mass transfer (Milne et al. 2009; Stammer et al. 2013; Kopp et al. 2015).

Land subsidence is the primary contributor to relative sea level rise along the U.S. Gulf Coast and some mega-cities in Asia (Woodruff et al. 2013; Kopp et al. 2014). Another area where sea level increases have been significantly higher than the global average is along the coast of the U.S. Northeast/Mid-Atlantic, where increases of two to four times the global average of 2-3 mm/year have been observed during the last 30 years. Goddard et al. (2015) have attributed the extremely sharp increases observed in the New York City region of 128 mm during 2009–2010 in part to a slowing of the Gulf Stream and a negative North Atlantic Oscillation. The western tropical Pacific has also seen dynamic changes in sea level on the order of 10 mm/year, driven by winds and currents. Reanalysis products show strong evidence of long-term climate oscillations, with moderation or reversal of some trends observed over the satellite period (e.g., Carton and Giese 2014). However, some of the contribution to sea level rise in these regions may be indicative of secular, anthropogenic climate change. It remains difficult to distinguish natural variability in sea level rise from a forced trend at a local level (Kopp 2013; Chambers et al. 2012; Hamlington et al. 2014).

As climate change continues, coastal flood frequency is expected to increase dramatically. Projections of an increase are robust, mainly because regional sea level will continue to rise at most global locations and over the long run (although there may be periods during which it could go down) from continued thermal expansion of ocean water, melting of ice, and changes in terrestrial water storage. Ocean warming and expansion, generally projected using GCMs, is expected to continue and to penetrate deeper into the ocean, with a rate that is linked to atmospheric feedbacks and ocean heat uptake (diffusivity) (Kuhlbrodt and Gregory 2012; Church et al. 2013). Glaciers (land ice) are expected to shrink dramatically over the 21st century, with the maximum contribution to sea level arising from the Arctic, Alaska, and glaciers peripheral to the Antarctic and Greenland ice sheets. Finally, other factors, like storage on land (i.e., reservoirs and groundwater withdrawal) may influence sea level, but are generally assumed to be smaller and have less uncertainty. It is important to note that in many locations, projections must account for VLM changes that may be influenced by human behaviors (e.g., via fluid withdrawals).

Figure 17 shows the net result of all these processes, namely that sea levels are expected to increase globally by an additional 0.5 to 1.0 meter by the end of the 21st century, depending on the RCP scenario. By the end of the century, uncertainty in the behavior of the Antarctic ice sheet dominates projected sea level rise at most locations. Regionally, changes in sea level will be enhanced or muted by VLM and changes in ocean dynamics (e.g., through wind patterns) as shown in Figure 18. Notably, 21st century GCM projections indicate high rates of sea level rise north of Cape Hatteras, North Carolina (Yin et al. 2009; Little et al. 2015b; Perrette et al. 2013).

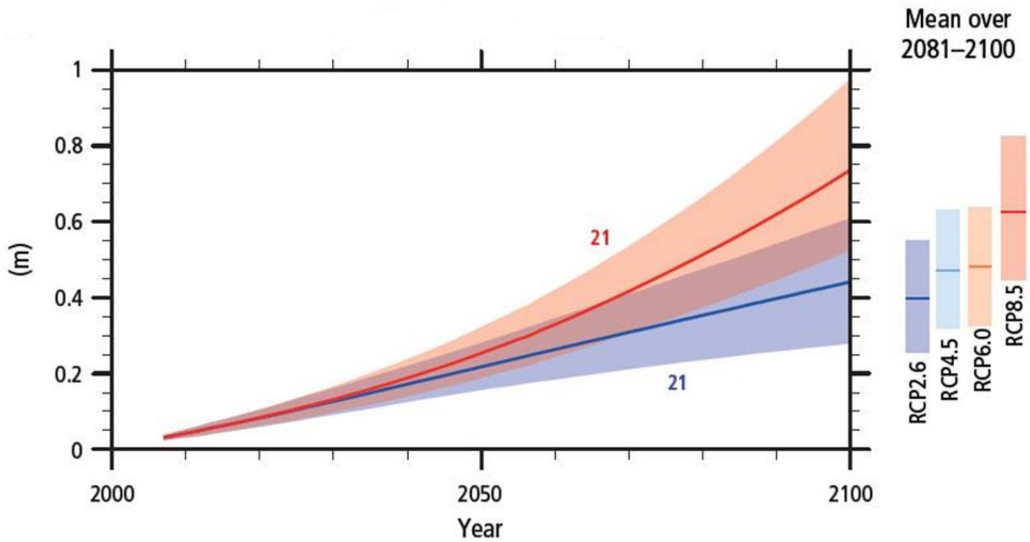


Figure 17. Projections of sea level rise through end of 21st century for various RCPs. Shading indicates uncertainty. Numbers above RCP2.6 and RCP8.5 curves indicate number of CMIP5 models used for those projections. Color bars to right indicate mean and uncertainty of sea level rise for the period 2081-2100 for the various RCPs. (Source: Fig. SPM.6, IPCC 2014)

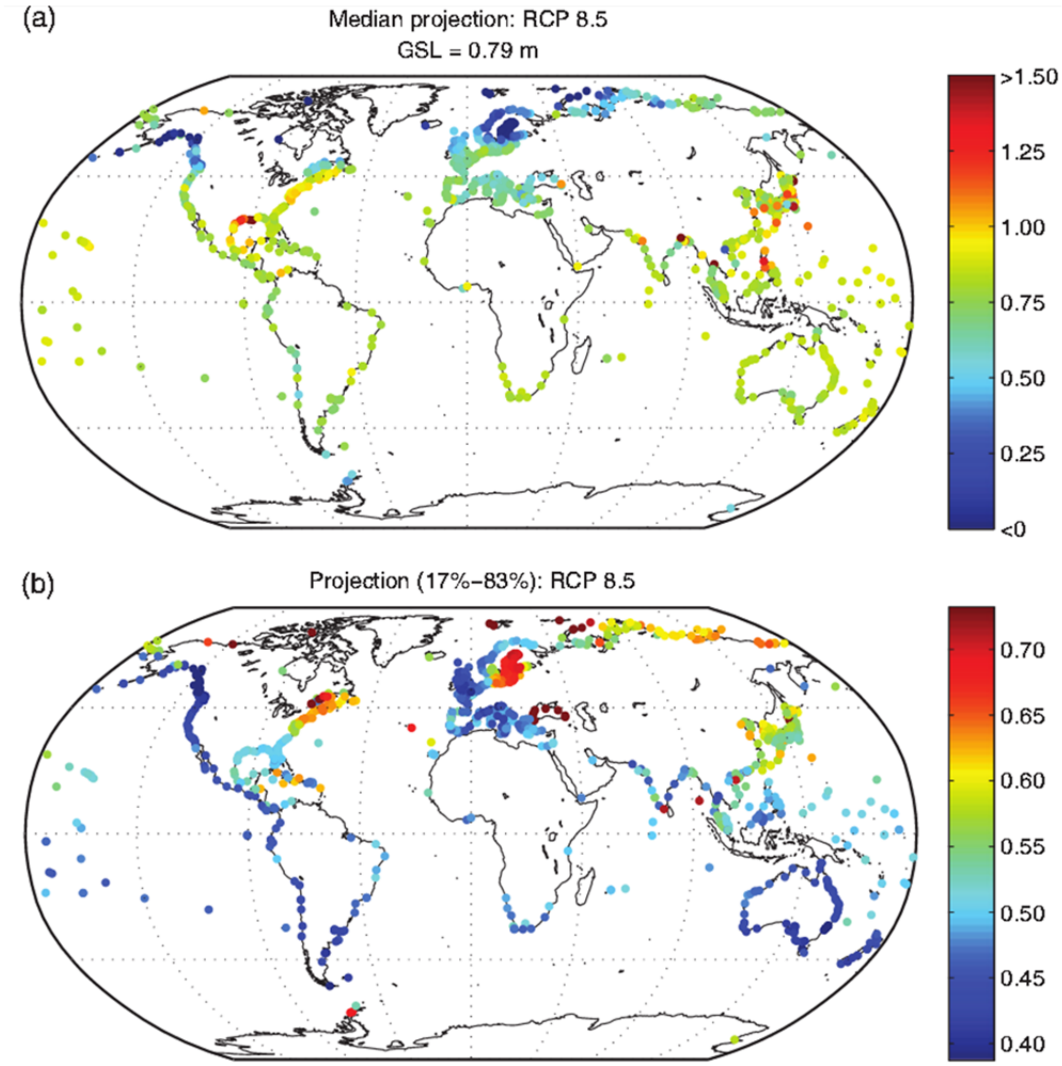


Figure 18. Median projection (a) and width of 17-83% uncertainty of likely range of local sea level rise in meters (b) in 2100 under RCP 8.5. (Source: Fig. 5, Kopp et al. 2014)

Flood risk thus substantially increases even in the absence of any change in storms. Kopp et al. (2014) showed that sea level rise at U.S. tide gauges increases the likelihood of a 1-in-100-year flood by 4 to 48 times (dependent on emissions and location) during the 21st century. These increases in flood risk in response to sea level changes are similar to those found by others for other regions (Hinkel et al. 2014; Sweet and Park 2014; Hunter 2010; Church et al. 2013).

The effects that changes in storm characteristics will have on storm surges are more difficult to assess. Studies have taken several different approaches to modeling a non-stationary distribution of storms, including modifying the distribution of winds from the historical record (McInnes et al. 2009; Hoffman et al. 2010); modeling changes in storms and associated surges with coastal hydrodynamic models (Aerts et al. 2014; Neumann et al. 2015; Orton et al. 2015); and developing a transfer function that links larger-scale climate conditions to surges at coastal sites (Grinsted et al. 2013; Little et al. 2015b). From an extratropical cyclone–induced storm surge perspective, Western Europe (British Isles, France, and Portugal) and the U.S. Northwest Pacific coast will also see increased risk. Tebaldi et al. (2012) notes that regions such as the latter may be at significantly increased risk owing to a lack of existing infrastructure, such as sea walls. Regardless of methodology, it will remain difficult to assess changes in the frequency of truly rare events and more efforts into new methodologies will be required to quantify them (Lin and Emanuel 2015).

The compound impacts of increases in sea level and strong TCs, and their correlation in climate models, have been highlighted in several recent studies (e.g., Neumann et al. 2015; Reed et al. 2015a; Kemp and Horton 2013; Little et al. 2015a). Furthermore, although we have separated inland and coastal flood drivers in this literature review, observations and projections (Wahl et al. 2015) point out that inland floods and coastal floods are actually synchronous. For New York City—as an example—the observed increase in compound events is attributed to a shift toward storm surge weather patterns that also favor high precipitation. This finding is similar to that found by Little et al. (2015a) in that the correlations are significant drivers of risk. Patterns of extreme weather may lead to extended periods of flooding if the storms occur in clusters. Even if surge and precipitation events are not coincident, clustering of extreme events in time and/or space may impact recovery and subsequent damage (Wadey et al. 2014).

3. Interpreting the State of Knowledge

While there remains uncertainty in numerical model-based projections of 21st century climate, diverse model ensembles and numerous independent studies support the direction of change toward a warmer planet, with less ice and higher global mean sea levels. Model results can often be explained through simple physical arguments, which gives added confidence. Furthermore, trends are apparent in the observational record for these globally integrated quantities.

However, as evidenced in section 2 and as noted in section 1, it is more difficult to attribute and forecast changes in climate-driven *regional* extremes; there are limited records for validation, and dynamical explanations become more complicated. In general, results are most robust for the end of the 21st century than for the near term.

We attempt to summarize section 2 in Figure 19, schematically illustrating the scientific understanding of the direction of 21st century change and its associated uncertainty for phenomena of interest to the insurance industry.

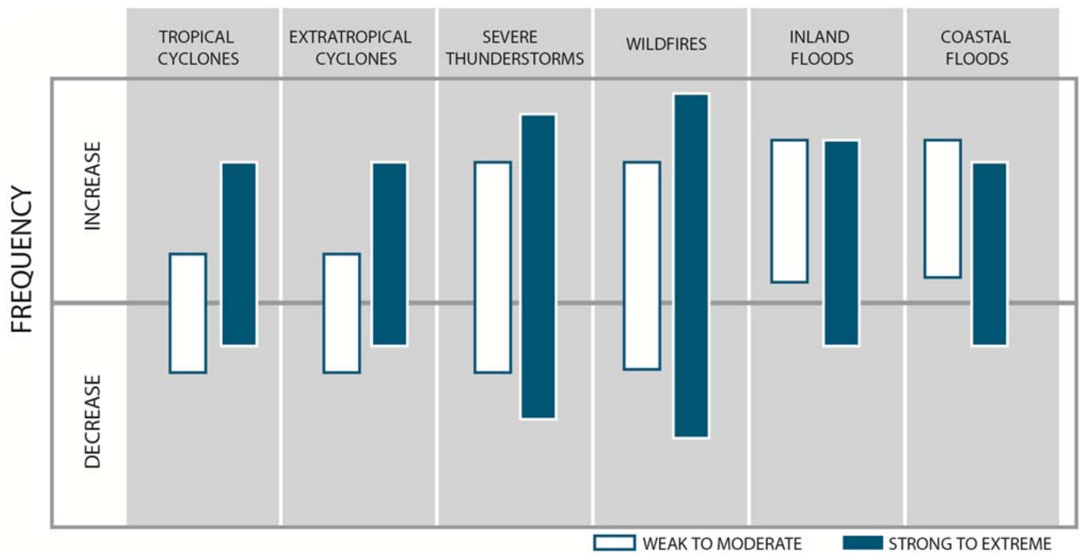


Figure 19. Likelihood of increases or decreases in frequency of weak-to-moderate intensity events (with a 2- to 10-year return period) and strong-to-extreme events (50- to 250-year return period) for different weather-related phenomena discussed in section 2 by the end of the 21st century. Length of bar indicates degree of uncertainty. Note that the relative positions of the bars represent globally-averaged estimates; significant regional differences may exist and would need to be considered separately. Note, too, that the direction of the bars is consistent with moderate-to-high emissions trajectories (RCP 4.5 – 8.5), but the degree of uncertainty may vary as a function of a given emissions scenario. (Source: AIR)

As we show in Figure 19, it is easier (lower associated uncertainty) to assess the climate impact on more frequent (i.e., weak to moderate) events, especially where changes in the mean (e.g. sea level) will influence the extremes (e.g. coastal floods), even if the statistical properties of extreme events do not change.

In the shorter term (e.g., 1-20 years), the direction and magnitude of changes in extremes remains difficult to identify for the following reasons:

- **Existing data is insufficient to identify a trend.** A key reason is that the data quality is too poor or the historical record is too short or too coarse to detect impacts on frequency/intensity. If end-of-century projections (e.g., 80 years from now) are showing changes in frequency of 10%, then even 40 years of comprehensive satellite measurements may not be adequate to identify a trend.
- **Variability is so large that it is masking the trend.** Whether the inter-annual variability is changing or not, if it is large compared to any climate-change trend, then identifying that trend may be difficult.
- **Trends are currently smaller than expected for the early 21st century.** There are two reasons for this. The first is that CO2 levels have not reached sufficiently high levels to yield observed impacts consistent with those found in the late-21st century analyses. The second is that there is a multi-decadal lag between emission levels at any given time and the climate impact that would ultimately result. The IPCC 2013 report (see Figure 5) indicated that TC frequency will more likely than not decrease. But it used RCP 8.5, which corresponds to a maximum CO2 level near 1,000 ppm by the end of the century. Our current value is still only at 410 ppm and the climate system is still likely responding to that level. (However, for those interests with longer time horizons, it may be relevant that climate impacts are essentially "locked-in" far before they are felt.)
- **Impacts may result from processes that are not included in models or event characteristics not yet evaluated in GCMs or the observational record.** Existing scientific analyses may not focus on the appropriate characteristics for assessing changes in catastrophe risk. As an example, for TCs, many of the climate change analyses have focused on changes in frequency and intensity; however, other characteristics instead may be changing, such as forward speed and storm size. Kossin et al. (2014) recently showed that the latitude where the lifetime maximum intensity for typhoons is occurring in the Pacific Northwest has been progressing northward and that climate change may be the reason for this progression. In addition, the inter-annual variability, intra-seasonal distributions, and earliest date for a Category 5 storm, for example, may be changing.

A heightened focus on variability and catastrophe-relevant features of extreme events may serve to increase the relevance of climate change to the insurance industry. As noted in the beginning, an important aspect of climate change is our understanding of the impact on variability—inter-annual, inter-seasonal, and intra-seasonal. Inter-annual variability can change the view of risk over several years, if not within one year. In this regard there have been fewer studies than those focusing on extremes, and there may be less observational information to work with to validate them. But because of the relative infrequency of data, gauging such changes is very difficult—at least from an observational standpoint. And, if it is hard to identify a feature in the data, then it is even harder to include it in the model, as many risk models depend to a large degree on the historical record—e.g., to parameterize important processes that cannot be explicitly modeled.

Because frequency and intensity are important from an impacts standpoint, not to mention easily quantifiable and relatable from a general public perspective, they tend to be the focus of much attention and research effort. But hurricane size, orientation of fronts with respect to extratropical storm motion, and hail density, to give a few examples, also all matter from an impacts standpoint. Again, however, limitations in the quality, if not quantity, of the data may preclude such investigations or validation of model results, but to date such studies have not really permeated the literature.

Despite the uncertainties in future projections, particularly in forecast changes in the most extreme events (catastrophes), AIR is pursuing a staged approach to understanding the impacts to insured losses via a catastrophe modeling approach and has been advising clients on the state of the science since the 1990s.

It should be noted that catastrophe models use historical data, pre-historical data, and a deep scientific understanding of the physical processes that cause extreme events. In the model development process, AIR is careful to examine the stationarity of the time series so that biases are not inadvertently introduced. For atmospheric perils, the models generally incorporate the last 30-40 years of data; if biases (technology, reporting etc.) are identified in those datasets, we correct for them until the data-series appears stationary and more reflective of the frequency that has been observed in the recent past. Thus it is assumed that the models reflect warming that has already taken place, but no explicit assumptions are made concerning the impact of climate change on the frequency, intensity or locations of extreme weather events in the future.

However, where there are strong physical relationships and model consensus on linkages between large-scale climate and extremes, AIR has developed and is developing climate- and climate change–conditioned catalogs of simulated events as complements to the standard catalogs. Several years after the very active Atlantic hurricane season in 2005, AIR published a study (Dailey et al. 2009a) that quantified the sensitivity of U.S. landfalling hurricanes to sea surface temperature. In particular, an analysis of warm ocean conditions (i.e., high sea surface temperatures) demonstrated that U.S. hurricane landfalls increase by about 8% when sea surface temperatures are above the normal 30-year mean. The results of that study were then converted to a product that clients can use to help them estimate their risk.

In 2009, AIR completed a study funded by the Association of British Insurers (ABI) to evaluate the impact of climate change on loss from inland flood in the United Kingdom, extratropical cyclones (wind) in the United Kingdom, and typhoons (wind and inland flood) in China. The strategy for each of these three models was to use climate change information provided by the UK Met Office Hadley Centre for Climate Science and Services on how precipitation and winds would change by the end of the century. This information was then used to construct climate change–conditioned catalogs (C4) by drawing from a very large inventory of events in such a way that that the climate change conditions were satisfied. The C4s were then run through the respective loss estimation models just as other standard catalogs are run at AIR. The results suggested some significant changes in all three models (Dailey et al., 2009b). More recently, a study similar to the one sponsored by ABI was completed in 2013 with a focus on island nations of the South Pacific and impacts from typhoons (wind and inland flood). Most recently, ABI sponsored a project to update the results from 2009 and the results have just recently been published (Robinson et al., 2017).

In addition, because catastrophe risk models aim to include all and especially the most recent climate data, the climate change effects may already be incorporated to some extent—at least to the satisfaction of the industry. As an example, AIR regularly updates the sea level and terrain height for its storm surge, inland flood, and tsunami models.

Given the industry focus on shorter-period changes, we are continuing to pursue research and improvements to the models. Such climate conditioned catalogs may be able to be used on shorter timescales (e.g. ENSO phases) but require more research.

Finally, we are continually stress-testing risk models to key climate-sensitive parameters. Such work leads to research efforts, within AIR, AER, and the academic community, to investigate whether there is sufficient basis for developing alternate parameter distributions and to target research on the most important parameters.

Studies such as these, as well as more focused studies that better evaluate the extent and cause of changes in the recent past are definitely worth examining as next steps for research projects. And if such changes or trends are identified, a valid question to ask is how to incorporate the results when the time series during which the change or trend has been observed is relatively short. For example, if one typically uses 100 years of hurricane data and an observed trend is present in the last 20 years, how should that feature be included (or should it)?

Thus in terms of a climate change research agenda, it is certainly worth exploring some of these above-mentioned aspects by looking more carefully into the historical records for changes in variability and other risk-relevant characteristics. Similar types of studies could also be conducted using output from climate change simulations—perhaps using output from Coupled Model Intercomparison Project 6 (CMIP6), which will soon be released to the research community.

In closing, the fact that expected changes are most robust at larger scales implies that the regional risk changes might be correlated in a warming climate, i.e., coastal and inland flood risk in different regions is likely to be correlated given rising global sea levels and atmospheric moisture. Such a correlation could be negative or positive, but it is worth further research.

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