that there is *medium confidence* that detectable (though not attributable to anthropogenic forcing changes) increases in flood statistics have occurred in parts of the central United States. Key Finding 3 of Chapter 7: Precipitation Change states that the frequency and intensity of heavy precipitation events are projected to continue to increase over the 21st century with *high confidence*. Given the connection between extreme precipitation and flooding, and the complexities of other relevant factors, we concur with the IPCC Special Report on Extremes (SREX) assessment of "medium confidence (based on physical reasoning) that projected increases in heavy rainfall would contribute to increases in local flooding in some catchments or regions" (IPCC 2012).

Existing studies of individual extreme flooding events are confined to changes in the locally responsible precipitation event and have not included detailed analyses of the events' hydrology. Gochis et al. (2015) describes the massive floods of 2013 along the Colorado front range, estimating that the streamflow amounts ranged from 50- to 500-year return values across the region. Hoerling et al. (2014) analyzed the 2013 northeastern Colorado heavy multiday precipitation event and resulting flood, finding little evidence of an anthropogenic influence on its occurrence. However, Pall et al. (2017) challenge their event attribution methodology with a more constrained study and find that the thermodynamic response of precipitation in this event due to anthropogenic forcing was substantially increased. The Pall et al. (2017) approach does not rule out that the likelihood of the extremely rare large-scale meteorological pattern responsible for the flood may have changed.

8.3 Wildfires

A global phenomenon with natural (lightning) and human-caused ignition sources, wildfire represents a critical ecosystem process. Recent decades have seen a profound increase in forest fire activity over the western United States and Alaska (Westerling et al. 2006; Running 2006; Higuera et al 2015; Abatzouglou and Williams 2016). The frequency of large wildfires is influenced by a complex combination of natural and human factors. Temperature, soil moisture, relative humidity, wind speed, and vegetation (fuel density) are important aspects of the relationship between fire frequency and ecosystems. Forest management and fire suppression practices can also alter this relationship from what it was in the preindustrial era. Changes in these control parameters can interact with each other in complex ways with the potential for tipping points—in both fire frequency and in ecosystem properties—that may be crossed as the climate warms.

Figure 8.3 shows that the number of large fires has increased over the period 1984–2011, with high statistical significance in 7 out of 10 western U.S. regions across a large variety of vegetation, elevation, and climatic types (Dennison et al. 2014). State-level fire data over the 20th century (Littell et al. 2009) indicates that area burned in the western United States decreased from 1916 to about 1940, was at low levels until the 1970s, then increased into the more recent period. Modeled increases in temperatures and vapor pressure deficits due to anthropogenic

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climate change has increased forest fire activity in the western United States by increasing the aridity of forest fuels during the fire season (Abatzouglou and Williams 2016). Increases in these relevant climatic drivers were found to be responsible for over half the observed increase in western U.S. forest fuel aridity from 1979 to 2015 and doubled the forest fire area over the period 1984–2015 (Abatzouglou and Williams 2016). Littell et al. (2009, 2010, 2016) find that two climatic mechanisms affect fire in the western United States: increased fuel flammability driven by warmer, drier conditions and increased fuel availability driven by antecedent moisture. Littell et al. (2016) find a clear link between increased drought and increased fire risk. Yoon et al. (2015) assessed the 2014 fire season, finding an increased risk of fire in California. While fire suppression practices can also lead to a significant increase in fire risk in lower-elevation and drier forest types, this is less important in higher-elevation and moister forests (Harvey 2016; Stephens et al. 2013; Schoennagel et al. 2004). Increases in future forest fire extent, frequency, and intensity depend strongly on local ecosystem properties and will vary greatly across the United States. Westerling et al. (2011) project substantial increases in forest fire frequency in the Greater Yellowstone ecosystem by mid-century under the older SRES A2 emissions scenario, and further state that years without large fires in the region will become extremely rare. Stavros et al. (2014) project increases in very large fires (greater than 50,000 acres) across the western United States by mid-century under both the RCP4.5 and RCP8.5 emissions scenarios. Likewise, Prestemon et al. (2016) project significant increases in lightning-ignited wildfire in the Southeast by mid-century but with substantial differences between ecoregions. However, other factors, related to climate change such as water scarcity or insect infestations may act to stifle future forest fire activity by reducing growth or otherwise killing trees leading to fuel reduction (Littell et al. 2010).

[INSERT FIGURE 8.3 HERE]

Historically, wildfires have been less frequent and of smaller extent in Alaska compared to the rest of the globe (Flannigan et al. 2009; Hu et al. 2015). Shortened land snow cover seasons and higher temperatures have made the Arctic more vulnerable to wildfire (Flannigan et al. 2009; Hu et al. 2015; Young et al. 2016). Total area burned and the number of large fires (those with area greater than 1,000 square km or 386 square miles) in Alaska exhibits significant interannual and decadal scale variability from influences of atmospheric circulation patterns and controlled burns, but have *likely* increased since 1959 (Kasischke and Turetsky 2006). The most recent decade has seen an unusually large number of severe wildfire years in Alaska, for which the risk of severe fires has *likely* increased by 33%–50% as a result of anthropogenic climate change (Partain et al. 2016) and is projected to increase by up to a factor of four by the end of the century under the moderate RCP6.0 scenario (Young et al. 2016). Historically less flammable tundra and cooler boreal forest regions could shift into historically unprecedented fire risk regimes as a consequence of temperatures increasing above the minimum thresholds required for burning. Alaska's fire season is also *likely* lengthening—a trend expected to continue (Flannigan et al. 2009; Sanford et al. 2015). Thresholds in temperature and precipitation shape Arctic fire

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regimes, and projected increases in future lightning activity imply increased vulnerability to future climate change (Flannigan et al. 2009; Young et al. 2016). Alaskan tundra and forest wildfires will *likely* increase under warmer and drier conditions (Sanford et al. 2015; French et al. 2015) and potentially result in a transition into a fire regime unprecedented in the last 10,000 years (Kelly et al. 2013). Total area burned is projected to increase between 25% and 53% by the end of the century (Joly et al. 2012).

Boreal forests and tundra contain large stores of carbon, approximately 50% of the total global soil carbon (McGuire et al. 2009). Increased fire activity could deplete these stores, releasing them to the atmosphere to serve as an additional source of atmospheric CO_2 and alter the carbon cycle if ecosystems change from higher to lower carbon densities (McGuire et al. 2009; Kelly et al. 2013). Additionally, increased fires in Alaska may also enhance the degradation of Alaska's permafrost, blackening the ground, reducing surface albedo, and removing protective vegetation.

Both anthropogenic climate change and the legacy of land use/management have an influence on U.S. wildfires and are subtly and inextricably intertwined. Forest management practices have resulted in higher fuel densities in most of U.S. forests, except in the Alaskan bush and the higher mountainous regions of the western United States. Nonetheless, there is *medium confidence* for a human-caused climate change contribution to increased forest fire activity in Alaska in recent decades with a *likely* further increase as the climate continues to warm, and *low to medium confidence* for a detectable human climate change contribution in the western United States based on existing studies. Recent literature does not contain a complete robust detection and attribution analysis of forest fires including estimates of natural decadal and multidecadal variability, as described in Chapter 3: Detection and Attribution, nor separate the contributions to observed trends from climate change and forest management. These assessment statements about attribution to human-induced climate change are instead multistep attribution statements (Ch. 3: Detection and Attribution) based on plausible model-based estimates of anthropogenic contributions to observed trends. The modeled contributions, in turn, are based on climate variables that are closely linked to fire risk and that, in most cases, have a detectable human influence, such as surface air temperature and snow melt timing.

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TRACEABLE ACCOUNTS

Key Message 1

Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (*Very high confidence*). While by some measures, drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.

Description of evidence base

Recent droughts are well characterized and described in the literature. The Dust Bowl is not as well documented, but available observational records support the key finding. The last sentence is an "absence of evidence" statement and does not imply "evidence of absence" of future anthropogenic changes. The inferred decreases in some measures of U.S. drought or types of drought (heat wave/flash droughts) are described in Andreadis and Lettenmaier (2006) and Mo and Lettenmaier (2015).

Major uncertainties

Record breaking temperatures are well documented with low uncertainty (Meehl et al 2009). The magnitude of the Dust Bowl relative to present times varies with location. Uncertainty in the key finding is affected by the quality of pre-World War II observations but is relatively low.

Assessment of confidence based on evidence and agreement

Precipitation is well observed in the United States, leading to *very high confidence*.

Summary sentence or paragraph that integrates the above information

The key finding is a statement that recent U.S. droughts, while sometimes long and severe, are not unprecedented in the historical record.

Key Message 2

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)

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Description of evidence base

Observational records of meteorological drought are not long enough to detect statistically significant trends. Additionally, paleoclimatic evidence suggests that major droughts have occurred throughout the distant past. Surface soil moisture is not well observed throughout the CONUS, but numerous event attribution studies attribute enhanced reduction of surface soil moisture during dry periods to anthropogenic warming and enhanced evapotranspiration. Sophisticated land surface models have been demonstrated to reproduce the available observations and have allowed for century scale reconstructions.

Major uncertainties

Uncertainties stem from the length of precipitation observations and the lack of surface moisture observations.

Assessment of confidence based on evidence and agreement

Confidence is *high* for widespread future surface soil moisture deficits, as little change is projected for future summer and fall average precipitation. In the absence of increased precipitation (and in some cases with it), evapotranspiration increases due to increased temperatures will lead to less soil moisture overall, especially near the surface.

Summary sentence or paragraph that integrates the above information

The precipitation deficit portion of the key finding is a conservative statement reflecting the conflicting and limited event attribution literature on meteorological drought. The soil moisture portion of the key finding is limited to the surface and not the more relevant root depth and is supported by the studies cited in this chapter.

Key Message 3

Future decreases in surface (top 10 cm) soil moisture from anthropogenic forcing over most of the United States are *likely* as the climate warms under the higher emissions scenarios. (*Medium confidence*)

Description of evidence base

First principles establish that evaporation is at least linearly dependent on temperatures and accounts for much of the surface moisture decrease as temperature increases. Plant transpiration for many non-desert species controls plant temperature and responds to increased temperature by opening stomata to release more water vapor. This water comes from the soil at root depth as the plant exhausts its stored water supply (*very high confidence*). Furthermore, nearly all CMIP5 models exhibit U.S. surface soil moisture drying at the end of the century under RCP8.5, and the

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multimodel average exhibits no significant annual soil moisture increases anywhere on the planet (Collins et al 2013).

Major uncertainties

While both evaporation and transpiration changes are of the same sign as temperature increases, the relative importance of each as a function of depth is less well quantified. The amount of transpiration varies considerably among plant species, and these are treated with widely varying of sophistication in the land surface components of contemporary climate models. Uncertainty in the sign of the anthropogenic change of root depth soil moisture is low in regions and seasons of projected precipitation decreases (Ch. 7: Precipitation Changes). There is moderate to high uncertainty in the magnitude of the change in soil moisture at all depths and all regions and seasons. This key finding is a "projection without attribution" statement as such a drying is not part of the observed record. Projections of summertime mean CONUS precipitation exhibit no significant change. However, recent summertime precipitation trends are positive, leading to reduced agricultural drought conditions overall (Andreadis and Lettenmaier 2006). While statistically significant increases in precipitation have been identified over parts of the United States, these trends have not been clearly attributed to anthropogenic forcing (Ch. 7: Precipitation Change). Furthermore, North American summer temperature increases under RCP8.5 at the end of the century are projected to be substantially more than the current observed (and modeled) temperature increase. Because of the response of evapotranspiration to temperature increases, the CMIP5 multimodel average projection is for drier surface soils even in those high latitude regions (Alaska and Canada) that are confidently projected to experience increases in precipitation. Hence, in the CONUS region, with little or no projected summertime changes in precipitation, we conclude that surface soil moisture will likely decrease.

Assessment of confidence based on evidence and agreement

CMIP5 and regional models support the surface soil moisture key finding. Confidence is assessed as "medium" as this key finding—despite the high level of agreement among model projections—because of difficulties in observing long-term changes in this metric and because, at present, there is no published evidence of detectable long-term decreases in surface soil moisture across the United States.

Summary sentence or paragraph that integrates the above information

In the northern United States, surface soil moisture (top 10 cm) is *likely* to decrease as evaporation outpaces increases in precipitation. In the Southwest, the combination of temperature increases and precipitation decreases causes surface soil moisture decreases to be *very likely*. In this region, decreases in soil moisture at the root depth are *likely*.

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Key Message 4

Substantial reductions in western U.S. winter and spring snowpack are projected as the climate warms. Earlier spring melt and reduced snow water equivalent have been formally attributed to human induced warming (*high confidence*) and will *very likely* be exacerbated as the climate continues to warm (*very high confidence*). Under higher emissions scenarios, and assuming no change to current water resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*).

Description of evidence base

First principles tell us that as temperatures rise, minimum snow levels also must rise. Certain changes in western U.S. hydrology have already been attributed to human causes in several papers following Barnett et al. (2008) and are cited in the text. The CMIP3/5 models project widespread warming with future increases in atmospheric GHG concentrations, although these are underestimated in the current generation of global climate models (GCMs) at the high altitudes of the western United States due to constraints on orographic representation at current GCM spatial resolutions.

CMIP5 models were not designed or constructed for direct projection of locally relevant snowpack amounts. However, a high-resolution climate model, selected for its ability to simulate western U.S. snowpack amounts and extent, projects devastating changes in the hydrology of this region assuming constant water resource management practices (Rhoades et al 2017). This conclusion is also supported by a statistical downscaling result shown in Figure 3.1 of Walsh et al. 2014 and Cayan et al. 2013 and by the more recent statistical downscaling study of Klos et al. 2014.

Major uncertainties

The major uncertainty is not so much "if" but rather "how much" as changes to precipitation phase (rain or snow) are sensitive to temperature increases that in turn depend on greenhouse gas (GHG) forcing changes. Also, changes to the lower-elevation catchments will be realized prior to those at higher elevations that, even at 25 km, is not adequately resolved. Uncertainty in the final statement also stems from the usage of one model but is tempered by similar findings from statistical downscaling studies. However, this simulation is a so-called "prescribed temperature" experiment with the usual uncertainties about climate sensitivity wired in by the usage of one particular ocean temperature change. Uncertainty in the equator-to-pole differential ocean warming rate is also a factor.

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Assessment of confidence based on evidence and agreement

All CMIP5 models project large-scale western U.S. warming as GHG forcing increases. Warming is underestimated in most of the western United States due to elevation deficiencies that are a consequence of coarse model resolution.

Summary sentence or paragraph that integrates the above information

Warmer temperatures lead to less snow and more rain if total precipitation remains unchanged. Projected winter/spring precipitation changes are a mix of increases in northern states and decreases in the Southwest. In the northern Rocky Mountains, snowpack is projected to decrease even with a projected precipitation increase due to this phase change effect. This will lead to, at the very least, profound changes to the seasonal and sub-seasonal timing of the western U.S. hydrological cycle even where annual precipitation remains nearly unchanged with a strong potential for water shortages.

Key Message 5

Detectable changes in some classes of flood frequency have occurred in parts of the United States and are a mix of increases and decreases. Extreme precipitation, one of the controlling factors in flood statistics, is observed to have generally increased and is projected to continue to do so across the United States in a warming atmosphere. However, formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change and the timing of any emergence of a future detectible anthropogenic change in flooding is unclear. (*Medium confidence*)

Description of evidence base

Observed changes are a mix of increases and decreases and are documented by Walsh et al. 2014 and other studies cited in the text. No attribution statements have been made.

Major uncertainties

Floods are highly variable both in space and time. The multivariate nature of floods complicates detection and attribution.

Assessment of confidence based on evidence and agreement

Confidence is limited to *medium* due to both the lack of an attributable change in observed flooding to date and the complicated multivariate nature of flooding. However, confidence is *high* in the projections of increased future extreme precipitation, the principal driver (among several) of many floods. It is unclear when an observed long-term increase in U.S. riverine

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flooding will be attributed to anthropogenic climate change. Hence, confidence is *medium* in this part of the key message at this time.

Summary sentence or paragraph that integrates the above information

The key finding is a relatively weak statement reflecting the lack of definitive detection and attribution of anthropogenic changes in U.S. flooding intensity, duration, and frequency.

Key Message 6

The incidence of large forest fires in the western United States and Alaska has increased since the early 1980s (*high confidence*) and is projected to further increase in those regions as the climate warms with profound changes to certain ecosystems (*medium confidence*).

Description of evidence base

Studies by Dennison et al. 2014 (western U.S.) and Kasischke and Turetsky 2006 (Alaska) document the observed increases in fire statistics. Projections of Westerling et al. (2011) (western U.S.) and Young et al. 2016 and others (Alaska) indicate increased fire risk. These observations and projections are consistent with drying due to warmer temperatures leading to increased flammability and longer fire seasons.

Major uncertainties

Analyses of other regions of the United States, which also could be subject to increased fire risk do not seem to be readily available. Likewise, projections of the western U.S. fire risk are of limited areas. In terms of attribution, there is still some uncertainty on how well non-climatic confounding factors such as forestry management and fire suppression practices have been accounted for, particularly for the western United States. Other climate change factors, such as increased water deficits and insect infestations could reduce fuel loads, tending towards reducing fire frequency and/or intensity.

Assessment of confidence based on evidence and agreement

Confidence is *high* in the observations due to solid observational evidence. Confidence in projections would be higher if there were more available studies covering a broader area of the United States and a wider range of ecosystems.

Summary sentence or paragraph that integrates the above information

Wildfires have increased over parts of the western United States and Alaska in recent decades and are projected to continue to increases as a result of climate change. As a result, shifts in certain ecosystem types may occur.

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TABLES

Table 8.1: A list of U.S. droughts for which attribution statements have been made. In the last column, "+" indicates that an attributable human induced increase in frequency and/or magnitude was found, "–" indicates that an attributable human induced decrease in frequency and/or magnitude was found, "0" indicates no attributable human contribution was identified. As in tables 6.2 and 7.1, several of the events were originally examined in the *Bulletin of the American Meteorological Society*'s (*BAMS*) State of the Climate Reports and reexamined by Angélil et al. (2017). In these cases, both attribution statements are listed with the original authors first. Source: M. Wehner.

Authors	Event Year and Duration	Region or State	Type	Attribution Statement
Rupp and Mote 2012 / Angélil et al. 2017	MAMJJA 2011	Texas	Meteorological	+/+
Hoerling et al. 2013	2012	Texas	Meteorological	+
Rupp et al. 2013 / Angélil et al. 2017	MAMJJA 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/0
Rupp et al. 2013 / Angélil et al. 2017	MAM 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/0
Rupp et al. 2013 / Angélil et al. 2017	JJA 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/+
Hoerling et al. 2014	MJJA 2012	Great Plains/Midwest	Meteorological	0
Swain et al. 2014 / Angélil et al. 2017	ANN 2013	California	Meteorological	+/+
Wang and Schubert 2014 / Angélil et al. 2017	JS 2013	California	Meteorological	0/+

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Knutson et al. 2014 / Angélil et al. 2017	ANN 2013	California	Meteorological	0/+
Knutson et al. 2014 / Angélil et al. 2017	MAM 2013	U.S. Southern Plains region	Meteorological	0/+
Diffenbaugh et al. 2015	2012-2014	California	Agricultural	+
Seager et al. 2015	2012-2014	California	Agricultural	+
Cheng et al. 2016	2011-2015	California	Agricultural	-
Mote et al. 2016	2015	Washington, Oregon, California	Hydrological (snow water equivalent)	+

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Table 8.2: Projected changes in western U.S. mountain range winter (DJF) snow-related hydrology variables at the middle and end of this century. Projections are for the RCP8.5 scenario from a high-resolution version of the Community Atmospheric Model, CAM5 (Rhoades et al. 2017).

Mountain Range	Snow Water Equivalent (% Change)		Snow Cover (% Change)		Snowfall (% Change)		Surface Temperature (Change in K)	
	2050	2100	2050	2100	2050	2100	2050	2100
Cascades	-41.5	-89.9	-21.6	-72.9	-10.7	-50.0	0.9	4.1
Klamath	-50.7	-95.8	-38.6	-89.0	-23.1	-78.7	0.8	3.5
Rockies	-17.3	-65.1	-8.2	-43.1	1.7	-8.2	1.4	5.5
Sierra Nevada	-21.8	-89.0	-21.9	-77.7	-4.7	-66.6	1.1	4.5
Wasatch and Uinta	-18.9	-78.7	-14.2	-61.4	4.1	-34.6	1.8	6.1
Western USA	-22.3	-70.1	-12.7	-51.5	-1.6	-21.4	1.3	5.2

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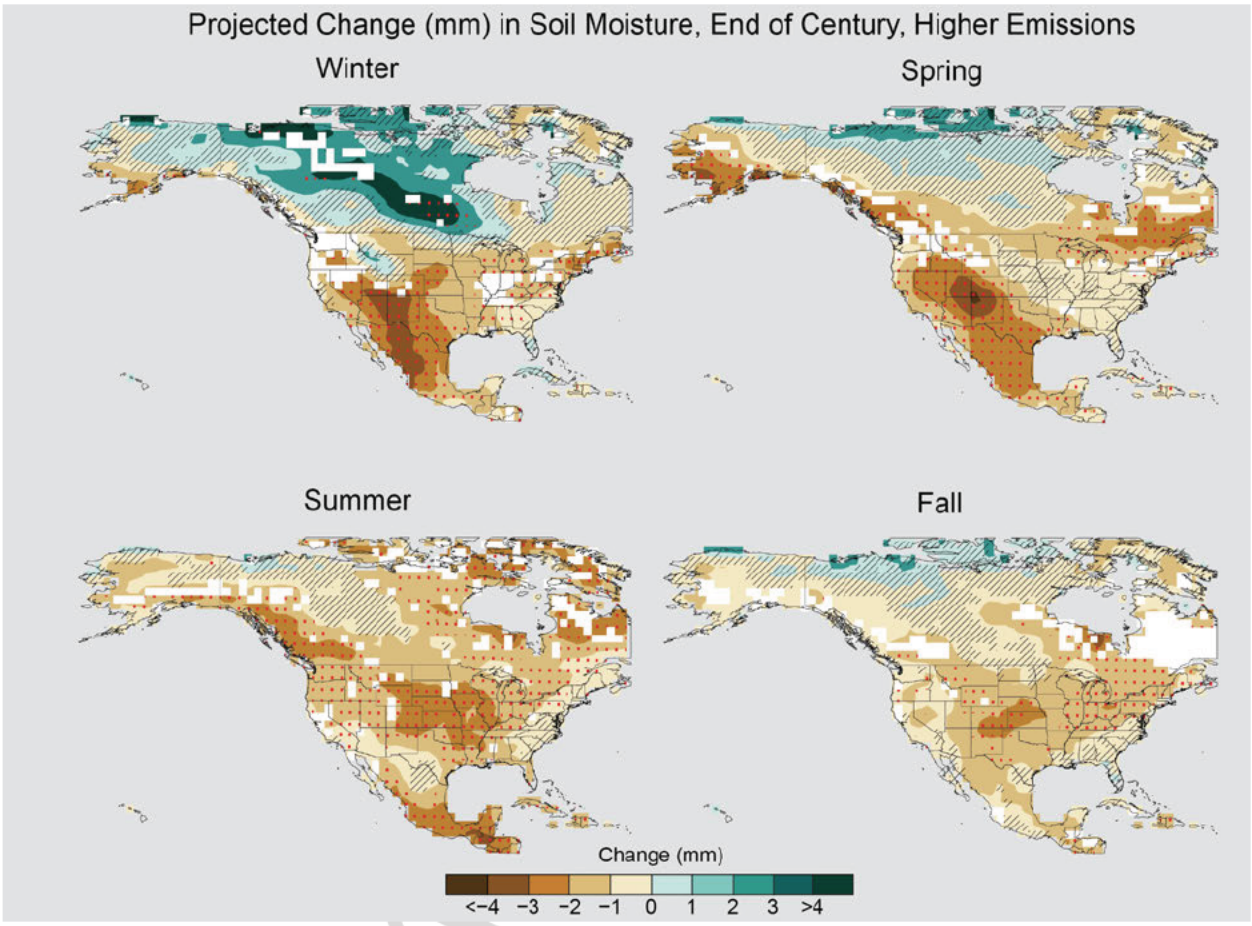
1 **FIGURES**

2



3

4 **Figure 8.1**. Projected end of the 21st century weighted CMIP5 multimodel average percent
5 changes in near surface seasonal soil moisture (mrsos) under the RCP8.5 scenario. Stippling
6 indicates that changes are assessed to be large compared to natural variations. Hashing indicates
7 that changes are assessed to be small compared to natural variations. Blank regions (if any) are
8 where projections are assessed to be inconclusive (Appendix B). (Figure source: NOAA NCEI /
9 CICS-NC).

10

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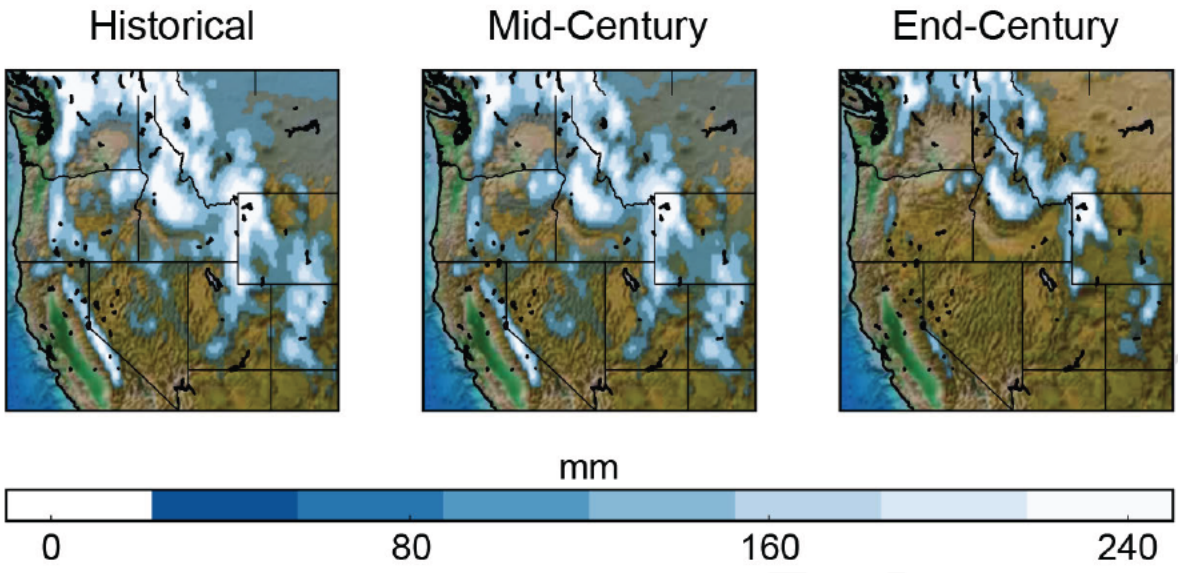

Figure 8.2. Projected changes in winter (DJF) snow water equivalent at the middle and end of this century under the RCP8.5 scenario from a high-resolution version of the Community Atmospheric Model, CAM5 (Rhoades et al. 2017). (Figure source: H. Krishnan, LBNL).

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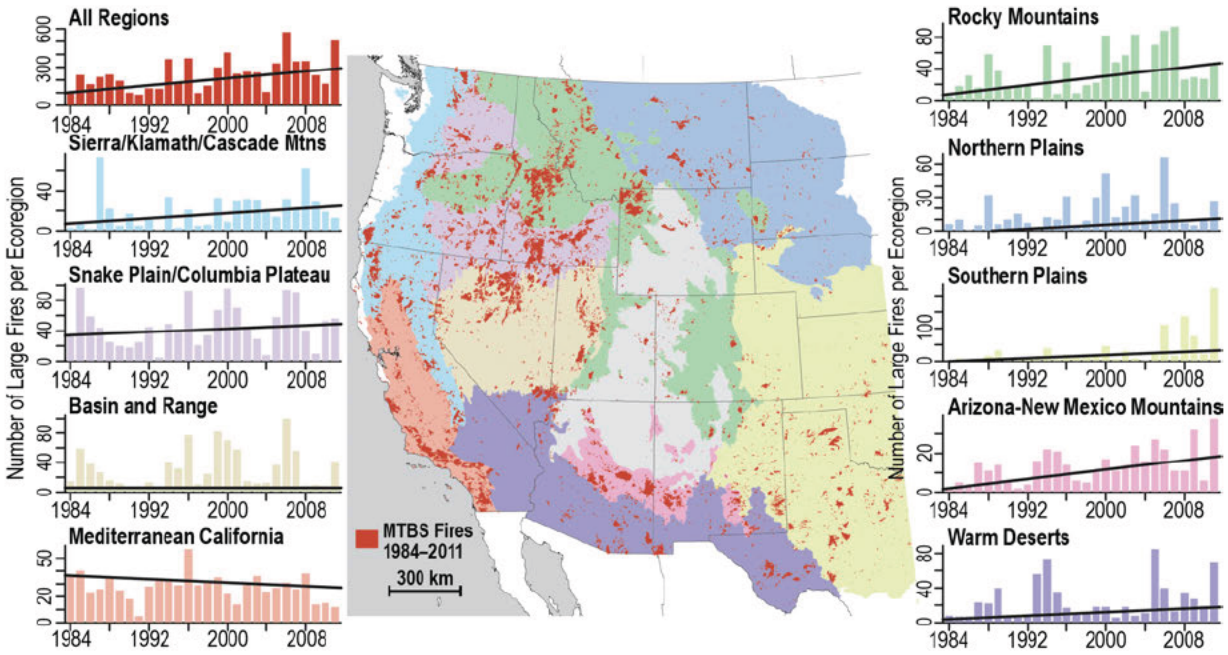
1



2

3 **Figure 8.3.** Trends in the annual number of large fires in the western United States for a variety
4 of ecoregions. The black lines are fitted trend lines. Statistically significant at a 10% level for all
5 regions except the Snake Plain/Columbian Plateau, Basin and Range, and Mediterranean
6 California regions. (Figure source: Dennison et al. 2014).

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9. Extreme Storms

KEY FINDINGS

1. Human activities have contributed substantially to observed ocean–atmosphere variability in the Atlantic Ocean (*medium confidence*), and these changes have contributed to the observed upward trend in North Atlantic hurricane activity since the 1970s (*medium confidence*).

2. Both theory and numerical modeling simulations (in general) indicate an increase in tropical cyclone (TC) intensity in a warmer world, and the models generally show an increase in the number of very intense TCs. For Atlantic and eastern North Pacific hurricanes and western North Pacific typhoons, increases are projected in precipitation rates (*high confidence*) and intensity (*medium confidence*). The frequency of the most intense of these storms is projected to increase in the Atlantic and western North Pacific (*low confidence*) and in the eastern North Pacific (*medium confidence*).

3. Tornado activity in the United States has become more variable, particularly over the 2000s, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). Confidence in past trends for hail and severe thunderstorm winds, however, is *low*. Climate models consistently project environmental changes that would putatively support an increase in the frequency and intensity of severe thunderstorms (a category that combines tornadoes, hail, and winds), especially over regions that are currently prone to these hazards, but confidence in the details of this projected increase is *low*.

4. There has been a trend toward earlier snowmelt and a decrease in snowstorm frequency on the southern margins of climatologically snowy areas (*medium confidence*). Winter storm tracks have shifted northward since 1950 over the Northern Hemisphere (*medium confidence*). Projections of winter storm frequency and intensity over the United States vary from increasing to decreasing depending on region, but model agreement is poor and confidence is *low*. Potential linkages between the frequency and intensity of severe winter storms in the United States and accelerated warming in the Arctic have been postulated, but they are complex, and, to some extent, contested, and confidence in the connection is currently *low*.

5. The frequency and severity of landfalling “atmospheric rivers” on the U.S. West Coast (narrow streams of moisture that account for 30%–40% of precipitation and snowpack in the region and are associated with severe flooding events) will increase as a result of increasing evaporation and resulting higher atmospheric water vapor that occurs with increasing temperature. (*Medium confidence*)

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9.1 Introduction

Extreme storms have numerous impacts on lives and property. Quantifying how broad-scale average climate influences the behavior of extreme storms is particularly challenging, in part because extreme storms are comparatively rare short-lived events and occur within an environment of largely random variability. Additionally, because the physical mechanisms linking climate change and extreme storms can manifest in a variety of ways, even the sign of the changes in the extreme storms can vary in a warming climate. This makes detection and attribution of trends in extreme storm characteristics more difficult than detection and attribution of trends in the larger environment in which the storms evolve (e.g., Ch. 6: Temperature Change). Projecting changes in severe storms is also challenging because of model constraints in how they capture and represent small-scale, highly local physics. Despite the challenges, good progress is being made for a variety of storm types, such as tropical cyclones, severe convective storms (thunderstorms), winter storms, and atmospheric river events.

9.2 Tropical Cyclones (Hurricanes and Typhoons)

Detection and attribution (Ch. 3: Detection and Attribution) of past changes in tropical cyclone (TC) behavior remain a challenge due to the nature of the historical data, which are highly heterogeneous in both time and among the various regions that collect and analyze the data (Kossin et al. 2013; Klotzbach and Landsea 2015; Walsh et al. 2016). While there are ongoing efforts to reanalyze and homogenize the data (e.g., Landsea et al. 2015; Kossin et al. 2013), there is still low confidence that any reported long-term (multidecadal to centennial) increases in TC activity are robust, after accounting for past changes in observing capabilities (which is unchanged from the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) assessment statement [Hartmann et al. 2013]). This is not meant to imply that no such increases have occurred, but rather that the data are not of a high enough quality to determine this with much confidence. Furthermore, it has been argued that within the period of highest data quality (since around 1980), the globally observed changes in the environment would not necessarily support a detectable trend in tropical cyclone intensity (Kossin et al. 2013). That is, the trend signal has not yet had time to rise above the background variability of natural processes.

Both theory and numerical modeling simulations (in general) indicate an increase in TC intensity in a warmer world, and the models generally show an increase in the number of very intense TCs (Bindoff et al. 2013; Camargo 2013; Christensen et al. 2013; Walsh et al. 2015; Knutson et al. 2015). In some cases, climate models can be used to make attribution statements about TCs without formal detection (see also Ch. 3: Detection and Attribution). For example, there is evidence that, in addition to the effects of El Niño, anthropogenic forcing made the extremely active 2014 Hawaiian hurricane season substantially more likely, although no significant rising trend in TC frequency near Hawai‘i was detected (Murakami et al. 2015).

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Changes in frequency and intensity are not the only measures of TC behavior that may be affected by climate variability and change, and there is evidence that the locations where TCs reach their peak intensity has migrated poleward over the past 30 years in the Northern and Southern Hemispheres, apparently in concert with environmental changes associated with the independently observed expansion of the tropics (Kossin et al. 2014). The poleward migration in the western North Pacific (Kossin et al. 2016), which includes a number of U.S. territories, appears particularly consistent among the various available TC datasets and remains significant over the past 60–70 years after accounting for the known modes of natural variability in the region (Figure 9.1). The migration, which can substantially change patterns of TC hazard exposure and mortality risk, is also evident in 21st century Coupled Model Intercomparison Project Phase 5 (CMIP5) projections following the RCP8.5 emissions trajectories, suggesting a possible link to human activities. Further analysis comparing observed past TC behavior with climate model historical forcing runs (and with model control runs simulating multidecadal internal climate variability alone) are needed to better understand this process, but it is expected that this will be an area of heightened future research.

[INSERT FIGURE 9.1 HERE]

In the Atlantic, observed multidecadal variability of the ocean and atmosphere, which TCs are shown to respond to, has been ascribed (Ch. 3: Detection and Attribution) to natural internal variability via meridional overturning ocean circulation changes (Delworth and Mann 2000), natural external variability caused by volcanic eruptions (Thompson and Solomon 2009; Evan 2012) and Saharan dust outbreaks (Evan et al. 2009, 2011), and anthropogenic external forcing via greenhouse gases and sulfate aerosols (Mann and Emanuel 2006; Booth et al. 2012; Dunstone et al. 2013). Determining the relative contributions of each mechanism to the observed multidecadal variability in the Atlantic, and even whether natural or anthropogenic factors have dominated, is presently a very active area of research and debate, and no consensus has yet been reached (Carslaw et al. 2013; Zhang et al. 2013; Tung and Zhao 2013; Mann et al. 2014; Stevens 2015; Sobel et al. 2016). Despite the level of disagreement about the relative magnitude of human influences, there is broad agreement that human factors have had a measurable impact on the observed oceanic and atmospheric variability in the North Atlantic, and there is *medium confidence* that this has contributed to the observed increase in hurricane activity since the 1970s. This is essentially unchanged from the IPCC AR5 statement (Bindoff et al. 2013), although the post-AR5 literature has only served to further support this statement (Kossin et al. 2015). This is expected to remain an active research topic in the foreseeable future.

The IPCC AR5 consensus TC projections for the late 21st century (IPCC Figure 14.17; Christensen et al. 2013) include an increase in global mean TC intensity, precipitation rate, and frequency of very intense (Saffir-Simpson Category 4–5) TCs, and a decrease, or little change, in global tropical cyclone frequency. Since the IPCC AR5, some studies have provided additional support for this consensus, and some have challenged an aspect of it. For example, a recent study

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(Knutson et al. 2015) projects increased mean hurricane intensities in the Atlantic Ocean basin and in most, but not all, other TC-supporting basins (see Table 3 in Knutson et al. 2015). In their study, the global occurrence of Saffir–Simpson Category 4–5 storms was projected to increase significantly, with the most significant basin-scale changes projected for the Northeast Pacific basin, potentially increasing intense hurricane risk to Hawai‘i (Figure 9.2) over the coming century. However, another recent (post-AR5) study proposed that increased thermal stratification of the upper ocean in CMIP5 climate warming scenarios should substantially reduce the warming-induced intensification of TCs estimated in previous studies (Huang et al. 2015). Follow-up studies, however, estimate that the effect of such increased stratification is relatively small, reducing the projected intensification of TCs by only about 10%–15% (Emanuel 2015; Tuleya et al. 2016).

Another recent study challenged the IPCC AR5 consensus projection of a decrease, or little change, in global tropical cyclone frequency by simulating increased global TC frequency over the 21st century under the RCP8.5 scenario (Emanuel 2013). However, another modeling study has found that neither direct analysis of CMIP5-class simulations, nor indirect inferences from the simulations (such as those of Emanuel 2013), could reproduce the decrease in TC frequency projected in a warmer world by high-resolution TC-permitting climate models (Wehner et al. 2015), which adds uncertainty to the results of Emanuel (2013).

In summary, despite new research that challenges one aspect of the AR5 consensus for late 21st century projected TC activity, it remains *likely* that global mean tropical cyclone maximum wind speeds and precipitation rates will increase; and it is *more likely than not* that the global frequency of occurrence of TCs will either decrease or remain essentially the same. Confidence in projected global increases of intensity and tropical cyclone precipitation rates is *medium* and *high*, respectively, as there is better model consensus. Confidence is further heightened, particularly for projected increases in precipitation rates, by a robust physical understanding of the processes that lead to these increases. Confidence in projected increases in the frequency of very intense TCs is generally lower (*medium* in the eastern North Pacific and *low* in the western North Pacific and Atlantic) due to comparatively fewer studies available and due to the competing influences of projected reductions in overall storm frequency and increased mean intensity on the frequency of the most intense storms. Both the magnitude and sign of projected changes in individual ocean basins appears to depend on the large-scale pattern of changes to atmospheric circulation and ocean surface temperature (e.g., Knutson et al. 2015). Projections of these regional patterns of change—apparently critical for TC projections—are uncertain, leading to uncertainty in regional TC projections.

[INSERT FIGURE 9.2 HERE]

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----- START BOX 9.1 HERE -----

Box 9.1: U.S. Landfalling Major Hurricane "Drought"

The last major hurricane (Saffir–Simpson Category 3 or higher) to make landfall in the continental United States was Wilma in 2005. The current 11-year (2006–2016) absence of U.S. major hurricane landfall events (sometimes colloquially referred to as a "hurricane drought") is unprecedented in the historical records dating back to the mid-19th century and has occurred in tandem with average to above-average basin-wide major hurricane counts. Is the absence of U.S. landfalling major hurricanes due to random luck, or are there systematic changes in climate driving this?

One recent study indicates that the absence of U.S. landfalling major hurricanes cannot readily be attributed to any sustained changes in the climate patterns that affect hurricanes (Hall and Heried 2015). Based on a statistical analysis of the historical North Atlantic hurricane database, the study found no evidence of a connection between the number of major U.S. landfalls from one year to the next and concluded that the 11-year absence of U.S. landfalling major hurricanes is random. A subsequent recent study did identify a systematic pattern of atmosphere/ocean conditions that vary in such a way that conditions conducive to hurricane intensification in the deep tropics occur in concert with conditions conducive to weakening near the U.S. coast (Kossin 2017). This result suggests a possible relationship between climate and hurricanes; increasing basin-wide hurricane counts are associated with a decreasing fraction of major hurricanes making U.S. landfall, as major hurricanes approaching the U.S. coast are more likely to weaken during active North Atlantic hurricane periods (such as the present period). It is unclear to what degree this relationship has affected absolute hurricane landfall counts during the recent active hurricane period from the mid-1990s, as the basin-wide number and landfalling fraction are in opposition (that is, there are more major hurricanes but a smaller fraction make landfall as major hurricanes). It is also unclear how this relationship may change as the climate continues to warm. Other studies have identified systematic interdecadal hurricane track variability that may affect landfalling hurricane and major hurricane frequency (Kossin and Vimont 2007; Wang et al. 2011; Colbert and Soden 2012).

Another recent study (Hart et al. 2016) shows that the extent of the absence is sensitive to uncertainties in the historical data and even small variations in the definition of a major hurricane, which is somewhat arbitrary. It is also sensitive to the definition of U.S. landfall, which is a geopolitical-border-based constraint and has no physical meaning. In fact, many areas outside of the U.S. border have experienced major hurricane landfalls in the past 11 years. In this sense, the frequency of U.S. landfalling major hurricanes is not a particularly robust metric with which to study questions about hurricane activity and its relationship with climate variability. Furthermore, the 11-year absence of U.S. landfalling major hurricanes is not a particularly relevant metric in terms of coastal hazard exposure and risk. For example, Hurricanes Ike (2008), Irene (2011), Sandy (2012), and most recently Hurricane Matthew (2016) brought severe impacts

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to the U.S. coast despite not making landfall in the United States while classified as major hurricanes. In the case of Hurricane Sandy, extreme rainfall and storm surge (see also Ch. 12: Sea Level Rise) during landfall caused extensive destruction in and around the New York City area, despite Sandy's designation as a post-tropical cyclone at that time. In the case of Hurricane Matthew, the center came within about 40 miles of the Florida coast while Matthew was a major hurricane, which is close enough to significantly impact the coast but not close enough to break the "drought" as it is defined.

In summary, the 11-year absence of U.S. landfalling major hurricanes is anomalous. There is some evidence that systematic atmosphere/ocean variability has reduced the fraction of hurricanes making U.S. landfall since the mid-1990s, but this is at least partly countered by increased basin-wide numbers, and the net effect on landfall rates is unclear. Moreover, there is a large random element, and the metric itself suffers from lack of physical basis due to the arbitrary intensity threshold and geopolitically based constraints. Additionally, U.S. coastal risk, particularly from storm surge and freshwater flooding, depends strongly on storm size, propagation speed and direction, and rainfall rates. There is some danger, in the form of evoking complacency, in placing too much emphasis on the recent absence of a specific subset of hurricanes.

----- END BOX 9.1 HERE -----

9.3 Severe Convective Storms (Thunderstorms)

Tornado and severe thunderstorm events cause significant loss of life and property: more than one-third of the $1 billion weather disasters in the United States during the past 25 years were due to such events, and, relative to other extreme weather, the damages from convective weather hazards have undergone the largest increase since 1980 (Smith and Katz 2013). A particular challenge in quantifying the existence and intensity of these events arises from the data source: rather than measurements, the occurrence of tornadoes and severe thunderstorms is determined by visual sightings by eyewitnesses (such as "storm spotters" and law enforcement officials) or post-storm damage assessments. The reporting has been susceptible to changes in population density, modifications to reporting procedures and training, the introduction of video and social media, and so on. These have led to systematic, non-meteorological biases in the long-term data record.

Nonetheless, judicious use of the report database has revealed important information about tornado trends. Since the 1970s, the United States has experienced a decrease in the number of days per year on which tornadoes occur, but an increase in the number of tornadoes that form on such days (Brooks et al. 2014). One important implication is that the frequency of days with large numbers of tornadoes—tornado outbreaks—appears to be increasing (Figure 9.3). The extent of the season over which such tornado activity occurs is increasing as well: although tornadoes in the United States are observed in all months of the year, an earlier calendar-day start

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to the season of high activity is emerging. In general, there is more interannual variability, or volatility, in tornado occurrence (Tippett 2014: see also Elsner et al. 2015).

[INSERT FIGURE 9.3 HERE]

Evaluations of hail and (non-tornadic) thunderstorm wind reports have thus far been less revealing. Although there is evidence of an increase in the number of hail days per year, the inherent uncertainty in reported hail size reduces the confidence in such a conclusion (Allen and Tippett 2015). Thunderstorm wind reports have proven to be even less reliable, because, as compared to tornadoes and hail, there is less tangible visual evidence; thus, although the United States has lately experienced several significant thunderstorm wind events (sometimes referred to as "derechos"), the lack of studies that explore long-term trends in wind events and the uncertainties in the historical data preclude any robust assessment.

It is possible to bypass the use of reports by exploiting the fact that the temperature, humidity, and wind in the larger vicinity—or "environment"—of a developing thunderstorm ultimately control the intensity, morphology, and hazardous tendency of the storm. Thus, the premise is that quantifications of the vertical profiles of temperature, humidity, and wind can be used as a proxy for actual severe thunderstorm occurrence. In particular, a thresholded product of convective available potential energy (CAPE) and vertical wind shear over a surface-to-6 km layer (S06) constitutes one widely used means of representing the frequency of severe thunderstorms (Brooks et al. 2003). This environmental-proxy approach avoids the biases and other issues with eyewitness storm reports and is readily evaluated using the relatively coarse global data sets and global climate models. It has the disadvantage of assuming that a thunderstorm will necessarily form and then realize its environmental potential.

Upon employing global climate models (GCMs) to evaluate CAPE and S06, a consistent finding among a growing number of proxy-based studies is a projected increase in the frequency of severe thunderstorm environments in the United States over the mid- to late 21st century (Van Klooster and Roebber 2009; Diffenbaugh et al. 2013; Gensini et al. 2014; Seely and Romps 2015; Trapp et al. 2007, 2009). The most robust projected increases in frequency are over the U.S. Midwest and Southern Great Plains, during March-April-May (MAM) (Diffenbaugh et al. 2013). Based on the increased frequency of very high CAPE, increases in storm intensity are also projected over this same period (see also Del Genio et al. 2007).

Key limitations of the environmental proxy approach are being addressed through the applications of high-resolution dynamical downscaling, wherein sufficiently fine model grids are used so that individual thunderstorms are explicitly resolved, rather than implicitly represented (as through environmental proxies). The individually modeled thunderstorms can then be quantified and assessed in terms of severity (Trapp et al. 2011; Robinson et al. 2013; Gensini and Mote 2014). The dynamical-downscaling results have thus far supported the basic findings of the environmental proxy studies, particularly in terms of the seasons and geographical regions

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projected to experience the largest increases in severe-thunderstorm occurrence (Diffenbaugh et al. 2013).

The computational expense of high-resolution dynamical downscaling makes it difficult to generate model ensembles over long time periods, and thus to assess the uncertainty of the downscaled projections. Because these dynamical downscaling implementations focus on the statistics of storm occurrence rather than on faithful representations of individual events, they have generally been unconcerned with specific extreme convective events in history. So, for example, such downscaling does not address whether the intensity of an event like the Joplin, Missouri, tornado of May 22, 2011, would be amplified under projected future climates. Recently, the "pseudo-global warming" (PGW) methodology (see Schär et al. 1996), which is a variant of dynamical downscaling, has been adapted to address these and related questions. As an example, when the parent "supercell" of select historical tornado events forms under the climate conditions projected during the late 21st century, it does not evolve into a benign, unorganized thunderstorm but instead maintains its supercellular structure (Trapp and Hoogewind 2016). As measured by updraft strength, the intensity of these supercells under PGW is relatively higher, although not in proportion to the theoretical intensity based on the projected higher levels of CAPE. The adverse effects of enhanced precipitation loading under PGW has been offered as one possible explanation for such shortfalls in projected updraft strength.

9.4 Winter Storms

The frequency of large snowfall years has decreased in the southern United States and Pacific Northwest and increased in the northern United States (see Ch. 7: Precipitation Change). The winters of 2013/2014 and 2014/2015 have contributed to this trend. They were characterized by frequent storms and heavier-than-normal snowfalls in the Midwest and Northeast and drought in the western United States. These were related to blocking (a large-scale pressure pattern with little or no movement) of the wintertime circulation in the Pacific sector of the Northern Hemisphere (e.g., Marinaro et al. 2015) that put the midwestern and northeastern United States in the primary winter storm track, while at the same time reducing the number of winter storms in California, causing severe drought conditions (Chang et al. 2015). While some observational studies suggest a linkage between blocking affecting the U.S. climate and enhanced arctic warming (arctic amplification), specifically for an increase in highly amplified jet stream patterns in winter over the United States (Francis and Skific 2015), other studies show mixed results (Barnes and Polvani 2015; Perlwitz et al. 2015; Screen et al. 2015). Therefore, a definitive understanding of the effects of arctic amplification on midlatitude winter weather remains elusive. Other explanations have been offered for the weather patterns of recent winters, such as anomalously strong Pacific trade winds (Yang et al. 2015), but these have not been linked to anthropogenic forcing (e.g., Delworth et al. 2015).

Analysis of storm tracks indicates that there has been an increase in winter storm frequency and intensity since 1950, with a slight shift in tracks toward the poles (Wang et al. 2006, 2012; Vose

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et al. 2014). Current global climate models (CMIP5) do in fact predict an increase in extratropical cyclone (ETC) frequency over the eastern United States, including the most intense ETCs, under the high RCP8.5 scenario (Colle et al. 2013). However, there are large model-to-model differences in the realism of ETC simulations and in the projected changes. Moreover, projected ETC changes have large regional variations, including a decreased total frequency in the North Atlantic, further highlighting the complexity of the response to climate change.

9.5 Atmospheric Rivers

The term "atmospheric rivers" (ARs) refers to the relatively narrow streams of moisture transport that often occur within and across midlatitudes (Zhu and Newell 1998) (Figure 9.4), in part because they often transport as much water as in the Amazon River (Newell et al. 1992). While ARs occupy less than 10% of the circumference of the Earth at any given time, they account for 90% of the poleward moisture transport across midlatitudes (a more complete discussion of precipitation variability is found in Ch. 7: Precipitation Change). In many regions of the world, they account for a substantial fraction of the precipitation (Guan and Waliser 2015), and thus water supply, often delivered in the form of an extreme weather and precipitation event (Figure 9.4). For example, ARs account for 30%–40% of the typical snow pack in the Sierra Nevada mountains and annual precipitation in the U.S. West Coast states (Guan et al. 2010; Dettinger et al. 2011)—an essential summertime source of water for agriculture, consumption, and ecosystem health. However, this vital source of water is also associated with severe flooding—with observational evidence showing a close connection between historically high streamflow events and floods with landfalling AR events—in the west and other sectors of the United States (Ralph et al. 2006; Neiman et al. 2011; Moore et al. 2012). More recently, research has also demonstrated that ARs are often found to be critical in ending droughts in the western United States (Dettinger 2013).

[INSERT FIGURE 9.4 HERE]

Given the important role that ARs play in the water supply of the western United States and their role in weather and water extremes in the west and occasionally other parts of the United States (e.g., Rutz et al. 2014), it is critical to examine how climate change and the expected intensification of the global water cycle and atmospheric transports (e.g., Held and Soden 2006; Lavers et al. 2015) are projected to impact ARs (e.g., Dettinger and Ingram 2013). Under climate change conditions, ARs may be altered in a number of ways, namely their frequency, intensity, duration, and locations. In association with landfalling ARs, any of these would be expected to result in impacts on hazards and water supply given the discussion above. Assessments of ARs in climate change projections for the United States have been undertaken for central California from CMIP3 (Dettinger et al. 2011) and a number of studies have been done for the West Coast of North America (Warner et al. 2015; Payne and Magnusdottir 2015; Gao et al. 2015; Radić et al. 2015; Hagos et al. 2016), and these studies have uniformly shown that ARs are likely to become more frequent and intense in the future. For example, one recent study reveals a large

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increase of AR days along the West Coast by the end of the 21st century in the RCP8.5 scenario, with fractional increases between 50% and 600%, depending on the seasons and landfall locations (Gao et al. 2015). Results from these studies (and Lavers et al. 2013 for ARs impacting the United Kingdom) show that these AR changes were predominantly driven by increasing atmospheric specific humidity, with little discernible change in the low-level winds. The higher atmospheric water vapor content in a warmer climate is to be expected because of an increase in saturation water vapor pressure with air temperature (Ch. 2: Physical Drivers of Climate Change). While the thermodynamic effect appears to dominate the climate change impact on ARs, leading to projected increases in ARs, there is evidence for a dynamical effect (that is, location change) related to the projected poleward shift of the subtropical jet that diminished the thermodynamic effect in the southern portion of the West Coast of North America (Gao et al. 2015).

Presently, there is no clear consensus on whether the consistently projected increases in AR frequency and intensity will translate to increased precipitation in California. This is mostly because previous studies did not examine this explicitly and because the model resolution is poor and thus the topography is poorly represented, and the topography is a key aspect of forcing the precipitation out of the systems (Pierce et al. 2013). The evidence for considerable increases in the number and intensity of ARs depends (as do all climate variability studies based on dynamical models) on the model fidelity in representing ARs and their interactions with the global climate/circulation. Additional confidence comes from studies that show qualitatively similar projected increases while also providing evidence that the models represent AR frequency, transports, and spatial distributions relatively well compared to observations (Payne and Magnusdottir 2015; Hagos et al. 2016). A caveat associated with drawing conclusions from any given study or differences between two is that they typically use different detection methodologies that are typically tailored to a regional setting (cf. Guan and Waliser 2015). Additional research is warranted to examine these storms from a global perspective, with additional and more in-depth, process-oriented diagnostics/metrics. Stepping away from the sensitivities associated with defining atmospheric rivers, one study examined the intensification of the integrated vapor transport (IVT), which is easily and unambiguously defined (Lavers et al. 2015). That study found that for the RCP8.5 scenario, multimodel mean IVT and the IVT associated with extremes above 95% percentile increase by 30%–40% in the North Pacific. These results, along with the uniform findings of the studies above examining projected changes in ARs for western North America and the United Kingdom, give *high confidence* that the frequency of AR storms will increase in association with rising global temperatures.

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TRACEABLE ACCOUNTS

Key Finding 1

Human activities have contributed substantially to observed ocean–atmosphere variability in the Atlantic Ocean (*medium confidence*), and these changes have contributed to the observed upward trend in North Atlantic hurricane activity since the 1970s (*medium confidence*).

Description of evidence base

The Key Finding and supporting text summarizes extensive evidence documented in the climate science literature and is similar to statements made in previous national (NCA3; Melillo et al., 2014) and international (IPCC 2013) assessments. Data limitations are documented in Kossin et al. 2013 and references therein. Contributions of natural and anthropogenic factors in observed multidecadal variability are quantified in Carslaw et al. 2013; Zhang et al. 2013; Tung and Zhao 2013; Mann et al. 2014; Stevens 2015; Sobel et al. 2016; Walsh et al. 2015.

Major uncertainties

Key remaining uncertainties are due to known and substantial heterogeneities in the historical tropical cyclone data and lack of robust consensus in determining the precise relative contributions of natural and anthropogenic factors in past variability of the tropical environment.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Confidence in this finding is rated as *medium*. Although the range of estimates of natural versus anthropogenic contributions in the literature is fairly broad, virtually all studies identify a measurable, and generally substantial, anthropogenic influence. This does constitute a consensus for human contribution to the increases in tropical cyclone activity since 1970.

Summary sentence or paragraph that integrates the above information

The key message and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. The uncertainties and points of consensus that were described in the NCA3 and IPCC assessments have continued.

Key Finding 2

Both theory and numerical modeling simulations (in general) indicate an increase in tropical cyclone (TC) intensity in a warmer world, and the models generally show an increase in the number of very intense TCs. For Atlantic and eastern North Pacific hurricanes and western North Pacific typhoons, increases are projected in precipitation rates (*high confidence*) and intensity

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(*medium confidence*). The frequency of the most intense of these storms is projected to increase in the Atlantic and western North Pacific (*low confidence*) and in the eastern North Pacific (*medium confidence*).

Description of evidence base

The Key Finding and supporting text summarizes extensive evidence documented in the climate science literature and is similar to statements made in previous national (NCA3; Melillo et al. 2014) and international (IPCC 2013) assessments. Since these assessments, more recent downscaling studies have further supported these assessments (e.g., Knutson et al. 2015), though pointing out that the changes (future increased intensity and tropical cyclone precipitation rates) may not occur in all ocean basins.

Major uncertainties

A key uncertainty remains in the lack of a supporting detectable anthropogenic signal in the historical data to add further confidence to these projections. As such, confidence in the projections is based on agreement among different modeling studies and physical understanding (for example, potential intensity theory for tropical cyclone intensities and the expectation of stronger moisture convergence, and thus higher precipitation rates, in tropical cyclones in a warmer environment containing greater amounts of environmental atmospheric moisture). Additional uncertainty stems from uncertainty in both the projected pattern and magnitude of future sea surface temperatures (Knutson et al. 2015).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Confidence is rated as *high* in tropical cyclone rainfall projections and *medium* in intensity projections since there are a number of publications supporting these overall conclusions, fairly well-established theory, general consistency among different studies, varying methods used in studies, and still a fairly strong consensus among studies. However, a limiting factor for confidence in the results is the lack of a supporting detectable anthropogenic contribution in observed tropical cyclone data.

There is *low* to *medium confidence* for increased occurrence of the most intense tropical cyclones for most ocean basins, as there are relatively few formal studies that focus on these changes, and the change in occurrence of such storms would be enhanced by increased intensities, but reduced by decreased overall frequency of tropical cyclones.

Summary sentence or paragraph that integrates the above information

Models are generally in agreement that tropical cyclones will be more intense and have higher precipitation rates, at least in most ocean basins. Given the agreement between models and support of theory and mechanistic understanding, there is *medium* to *high confidence* in the

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overall projection, although there is some limitation on confidence levels due to the lack of a supporting detectable anthropogenic contribution to tropical cyclone intensities or precipitation rates.

Key Finding 3

Tornado activity in the United States has become more variable, particularly over the 2000s, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). Confidence in past trends for hail and severe thunderstorm winds, however, is *low*. Climate models consistently project environmental changes that would putatively support an increase in the frequency and intensity of severe thunderstorms (a category that combines tornadoes, hail, and winds), especially over regions that are currently prone to these hazards, but confidence in the details of this projected increase is *low*.

Description of evidence base

Evidence for the first and second statement comes from the U.S. database of tornado reports. There are well known biases in this database, but application of an intensity threshold (greater than or equal to a rating of 1 on the [Enhanced] Fujita scale) and the quantification of tornado activity in terms of tornado days instead of raw numbers of reports are thought to reduce these biases. It is not known at this time whether the variability and trends are necessarily due to climate change.

The third statement is based on projections from a wide range of climate models, including GCMs and RCMs, run over the past 10 years (e.g., see the review by Brooks 2013). The evidence is derived from an "environmental-proxy" approach, which herein means that severe thunderstorm occurrence is related to the occurrence of two key environmental parameters: CAPE and vertical wind shear. A limitation of this approach is the assumption that the thunderstorm will necessarily form and then realize its environmental potential. This assumption is indeed violated, albeit at levels that vary by region and season.

Major uncertainties

Regarding the first and second statements, there is still some uncertainty in the database, even when the data are filtered. The major uncertainty in the third statement equates to the aforementioned limitation (that is, the thunderstorm will necessarily form and then realize its environmental potential).

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Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Medium: That the variability in tornado activity has increased.
Medium: That the severe-thunderstorm environmental conditions will change with a changing climate, but
Low: on the precise (geographical and seasonal) realization of the environmental conditions as actual severe thunderstorms.

Summary sentence or paragraph that integrates the above information

With an established understanding of the data biases, careful analysis provides useful information about past changes in severe thunderstorm and tornado activity. This information suggests that tornado variability has increased in the 2000s, with a concurrent decrease in the number of days per year experiencing tornadoes and an increase in the number of tornadoes on these days. Similarly, the development of novel applications of climate models provides information about possible future severe storm and tornado activity, and although confidence in these projections is low, they do suggest that the projected environments are at least consistent with environments that would putatively support an increase in frequency and intensity of severe thunderstorms.

Key Finding 4

There has been a trend toward earlier snowmelt and a decrease in snowstorm frequency on the southern margins of climatologically snowy areas (*medium confidence*). Winter storm tracks have shifted northward since 1950 over the Northern Hemisphere (*medium confidence*). Projections of winter storm frequency and intensity over the United States vary from increasing to decreasing depending on region, but model agreement is poor and confidence is *low*. Potential linkages between the frequency and intensity of severe winter storms in the United States and accelerated warming in the Arctic have been postulated, but they are complex, and, to some extent, contested, and confidence in the connection is currently *low*.

Description of evidence base

The Key Finding and supporting text summarizes evidence documented in the climate science literature.

Evidence for changes in winter storm track changes are documented in a small number of studies (Wang et al. 2006, 2012). Future changes are documented in one study (Colle et al. 2013), but there are large model-to-model differences. The effects of arctic amplification on U.S. winter storms have been studied, but the results are mixed (Francis and Skific 2015; Barnes and Polvani 2015; Perlwitz et al. 2015; Screen et al. 2015), leading to considerable uncertainties.

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Major uncertainties

Key remaining uncertainties relate to the sensitivity of observed snow changes to the spatial distribution of observing stations and to historical changes in station location and observing practices. There is conflicting evidence about the effects of arctic amplification on CONUS winter weather.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *high confidence* that warming has resulted in earlier snowmelt and decreased snowfall on the warm margins of areas with consistent snowpack based on a number of observational studies. There is *medium confidence* that Northern Hemisphere storm tracks have shifted north based on a small number of studies. There is *low confidence* in future changes in winter storm frequency and intensity based on conflicting evidence from analysis of climate model simulations.

Summary sentence or paragraph that integrates the above information

Decreases in snowfall on southern and low elevation margins of currently climatologically snowy areas are likely but winter storm frequency and intensity changes are uncertain.

Key Finding 5

The frequency and severity of landfalling "atmospheric rivers" on the U.S. West Coast (narrow streams of moisture that account for 30%–40% of precipitation and snowpack in the region and are associated with severe flooding events) will increase as a result of increasing evaporation and resulting higher atmospheric water vapor that occurs with increasing temperature. (*Medium confidence*)

Description of evidence base

The Key Finding and supporting text summarizes evidence documented in the climate science literature.

Evidence for the expectation of an increase in the frequency and severity of landfalling atmospheric rivers on the U.S. West Coast comes from the CMIP-based climate change projection studies of Dettinger et al. 2011; Warner et al. 2015; Payne and Magnusdottir 2015; Gao et al. 2015; Radić et al. 2015; and Hagos et al. 2016. The close connection between atmospheric rivers and water availability and flooding is based on the present-day observation studies of Guan et al. 2010; Dettinger et al. 2011; Ralph et al. 2006; Neiman et al. 2011; Moore et al. 2012; and Dettinger 2013.

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Major uncertainties

A modest uncertainty remains in the lack of a supporting detectable anthropogenic signal in the historical data to add further confidence to these projections. However, the overall increase in atmospheric rivers projected/expected is based to a very large degree on the *very high confidence* there is that the atmospheric water vapor will increase. Thus, increasing water vapor coupled with little projected change in wind structure/intensity still indicates increases in the frequency/intensity of atmospheric rivers. A modest uncertainty arises in quantifying the expected change at a regional level (for example, northern Oregon vs. southern Oregon) given that there are some changes expected in the position of the jet stream that might influence the degree of increase for different locations along the West Coast. Uncertainty in the projections of the number and intensity of ARs is introduced by uncertainties in the models' ability to represent ARs and their interactions with climate.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Confidence in this finding is rated as *medium* based on qualitatively similar projections among different studies.

Summary sentence or paragraph that integrates the above information

Increases in atmospheric river frequency and intensity are expected along the U.S. West Coast, leading to the likelihood of more frequent flooding conditions, with uncertainties remaining in the details of the spatial structure of theses along the coast (for example, northern vs. southern California).

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FIGURES

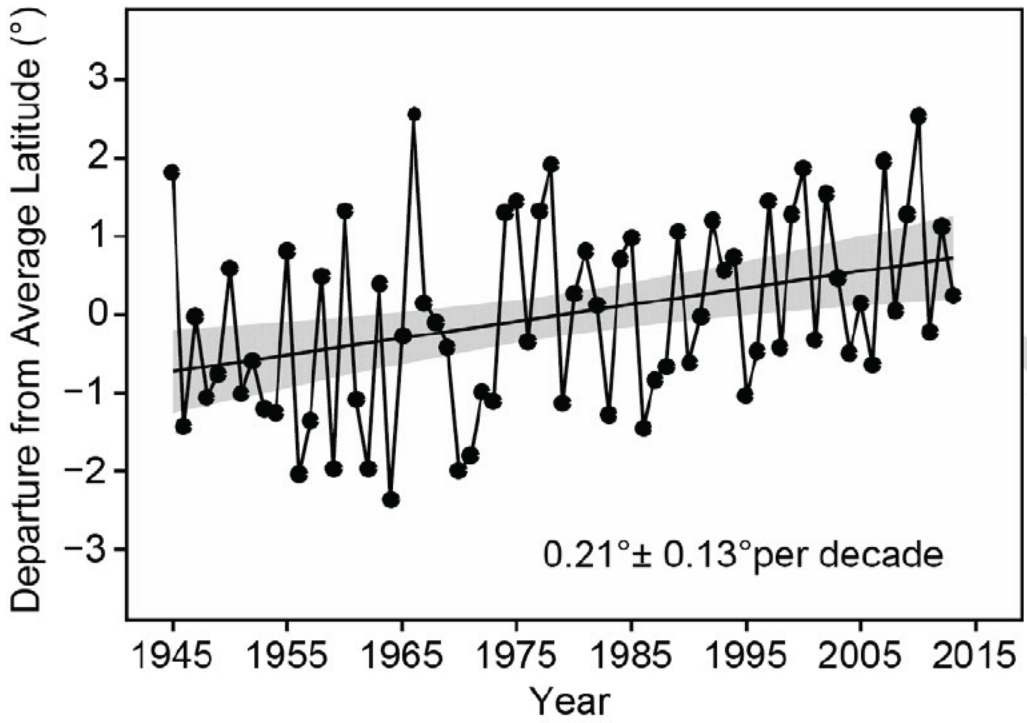

Figure 9.1: Poleward migration, in degrees of latitude, of the location of annual mean tropical cyclone (TC) peak lifetime intensity in the western North Pacific Ocean, after accounting for the known regional modes of interannual (El Niño–Southern Oscillation; ENSO) and interdecadal (Pacific Decadal Oscillation; PDO) variability. The time series shows residuals of the multivariate regression of annually averaged latitude of TC peak lifetime intensity onto the mean Niño-3.4 and PDO indices. Data are taken from the Joint Typhoon Warning Center (JTWC). Shading shows 95% confidence bounds for the trend. Annotated values at lower right show the mean migration rate and its 95% confidence interval in degrees per decade for the period 1945–2013. (Figure source: adapted from Kossin et al. 2016; © American Meteorological Society. Used with permission.).

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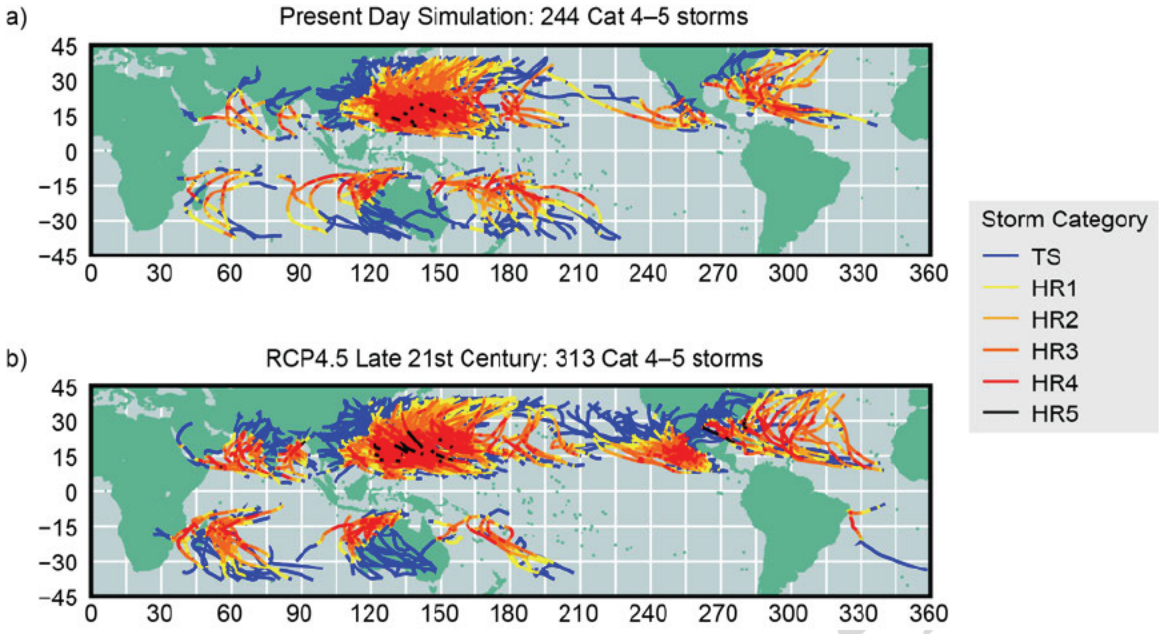

Figure 9.2: Tracks of simulated Saffir–Simpson Category 4–5 tropical cyclones for (a) present-day or (b) late-21st-century conditions, based on dynamical downscaling of climate conditions from the CMIP5 multimodel ensemble (RCP4.5 scenario). The tropical cyclones were initially simulated using a 50-km grid global atmospheric model, but each individual tropical cyclone was re-simulated at higher resolution using the GFDL hurricane model to provide more realistic storm intensities and structure. Storm categories or intensities are shown over the lifetime of each simulated storm, according to the Saffir–Simpson scale. The categories are depicted by the track colors, varying from tropical storm (blue) to Category 5 (black; see legend). (Figure source: Knutson et al. 2015; © American Meteorological Society. Used with permission.).

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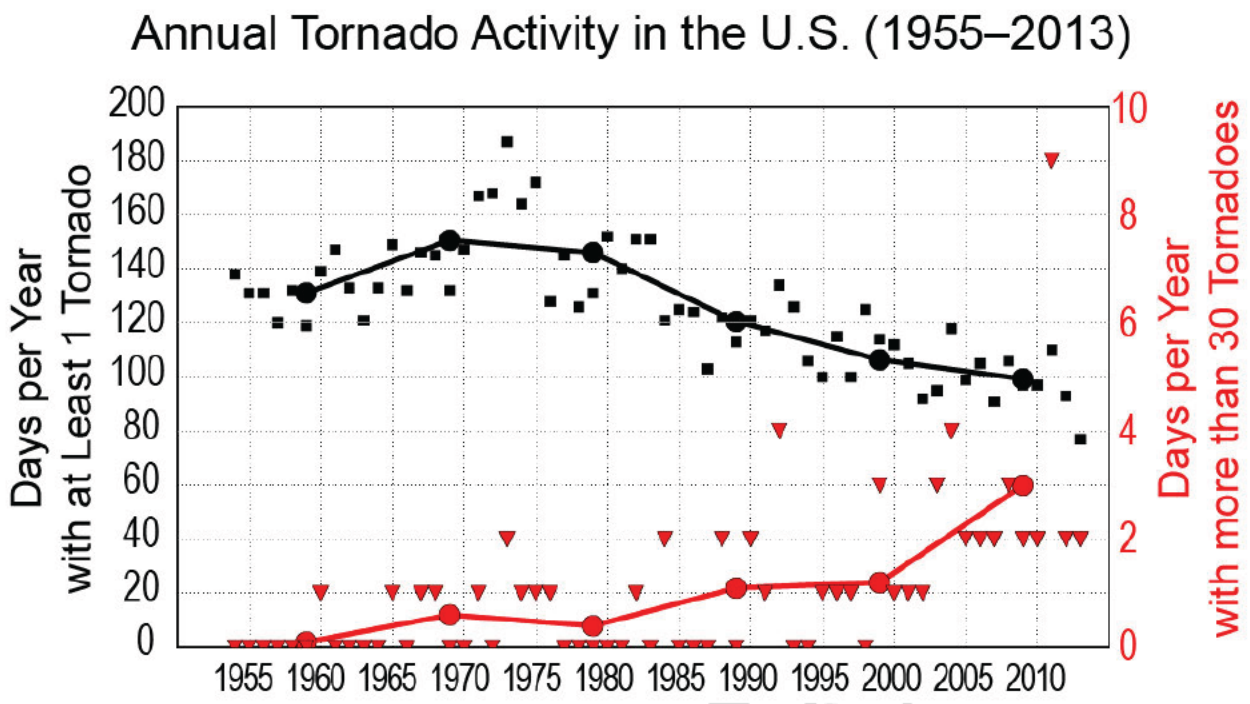

Figure 9.3: Annual tornado activity in the United States over the period 1955–2013. The black squares indicate the number of days per year with at least one tornado rated (E)F1 or greater, and the black circles and line show the decadal mean line of such *tornado days*. The red triangles indicate the number of days per year with more than 30 tornadoes rated (E)F1 or greater, and the red circles and line show the decadal mean of these *tornado outbreaks*. (Figure source: redrawn from Brooks et al. 2014).

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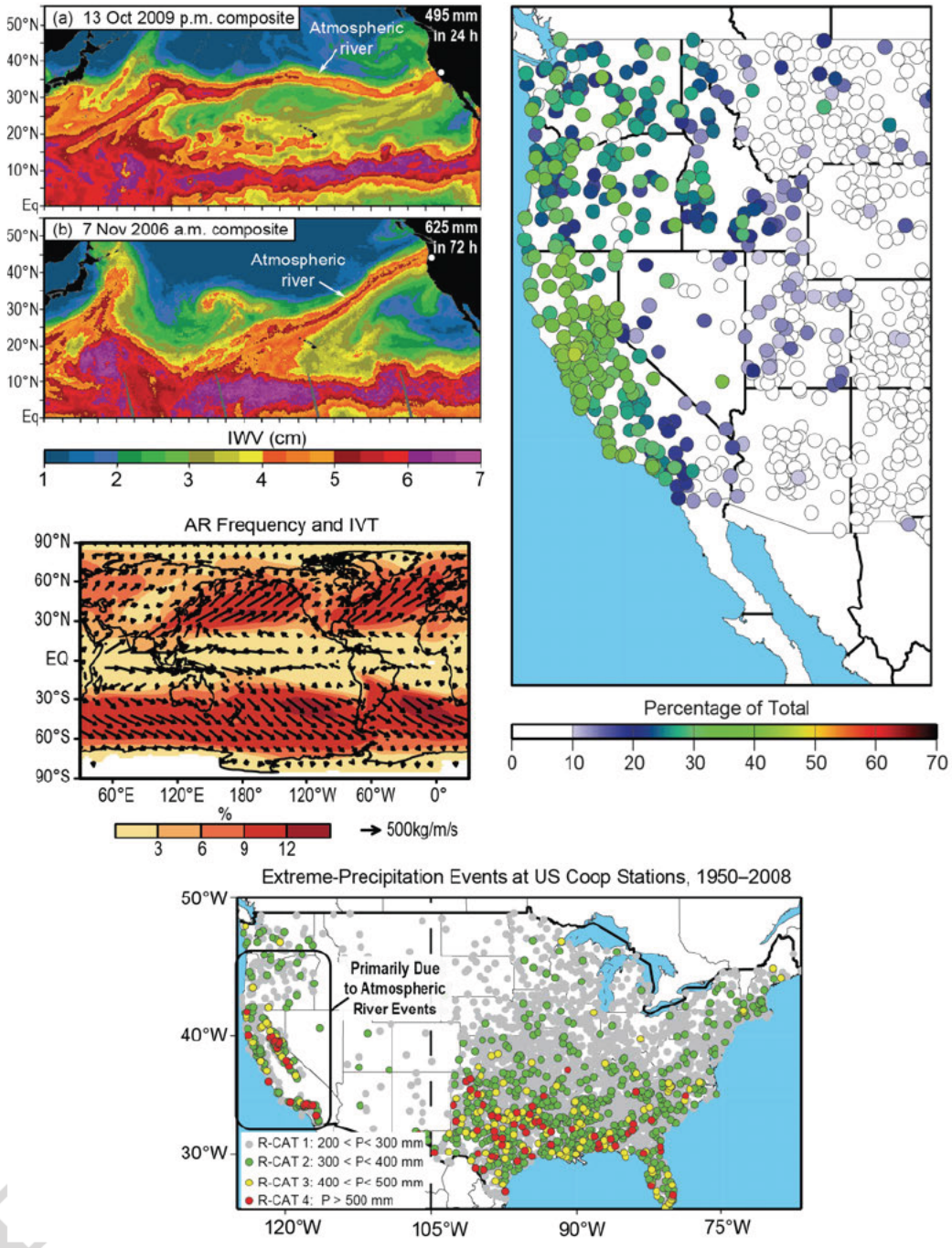

Figure 9.4: (upper left) Atmospheric rivers depicted in Special Sensor Microwave Imager (SSM/I) measurements of SSM/I total column water vapor leading to extreme precipitation events at landfall locations. (middle left) Annual mean frequency of atmospheric river occurrence (for example, 12% means about 1 every 8 days) and their integrated vapor transport (IVT) (Guan and Waliser 2015). (bottom) ARs are the dominant synoptic storms for the U.S. West Coast in terms of extreme precipitation (Ralph and Dettinger 2012) and (right) supply a large fraction of the annual precipitation in the U.S. West Coast states (Dettinger et al. 2011). (Figure source: [upper and middle left] Ralph et al. 2011, [upper right] Guan and Waliser 2015,

[lower left] Ralph and Dettinger 2012, [lower right], Dettinger et al. 2011; left panels, © American Meteorological Society. Used with permission.)

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10. Changes in Land Cover and Terrestrial Biogeochemistry

KEY FINDINGS

1. Changes in land use and land cover due to human activities produce physical changes in land surface albedo, latent and sensible heat, and atmospheric aerosol and greenhouse gas concentrations. The combined effects of these changes have recently been estimated to account for 40% ± 16% of the human-caused global radiative forcing from 1850 to present day (*high confidence*). As a whole, the terrestrial biosphere (soil and plants) is a net "sink" for carbon (drawing down carbon from the atmosphere), and this sink has steadily increased since 1980 (*very high confidence*). Because of the uncertainty in the trajectory of land cover, the possibility of the land becoming a net carbon source cannot be excluded (*very high confidence*).

2. Climate change and induced changes in the frequency and magnitude of extreme events (e.g., droughts, floods, and heat waves) have led to large changes in plant community structure with subsequent effects on the biogeochemistry of terrestrial ecosystems. Uncertainties about how climate change will affect land cover change make it difficult to project the magnitude and sign of future climate feedbacks from land cover changes (*high confidence*).

3. Since 1901, regional averages of both the consecutive number of frost-free days and the length of the corresponding growing season have increased for the seven contiguous U.S. regions used in this assessment. However, there is important variability at smaller scales, with some locations actually showing decreases of a few days to as much as one to two weeks. Plant productivity has not increased commensurate with the increased number of frost-free days or with the longer growing season due to plant-specific temperature thresholds, plant–pollinator dependence, and seasonal limitations in water and nutrient availability (*very high confidence*). Future consequences of changes to the growing season for plant productivity are uncertain.

4. Recent studies confirm and quantify that surface temperatures are higher in urban areas than in surrounding rural areas for a number of reasons, including the concentrated release of heat from buildings, vehicles, and industry. In the United States, this urban heat island effect results in daytime temperatures 0.9°–7.2°F (0.5°–4.0°C) higher and nighttime temperatures 1.8°– 4.5°F (1.0°–2.5°C) higher in urban areas, with larger temperature differences in humid regions (primarily in the eastern United States) and in cities with larger and denser populations. The urban heat island effect will strengthen in the future as the structure, spatial extent, and population density of urban areas change and grow (*high confidence*).

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10.1 Introduction

Direct changes in land use by humans are contributing to radiative forcing by altering land cover and therefore albedo, contributing to climate change (Ch. 2: Physical Drivers of Climate Change). This forcing is spatially variable in both magnitude and sign; globally averaged, it is negative (climate cooling; Figure 2.3). Climate changes, in turn, are altering the biogeochemistry of land ecosystems through extended growing seasons, increased numbers of frost-free days, altered productivity in agricultural and forested systems, longer fire seasons, and urban-induced thunderstorms (Kunkel 2016; Galloway et al. 2014). Changes in land use and land cover interact with local, regional, and global climate processes (Brown et al. 2014). The resulting ecosystem responses alter Earth's albedo, the carbon cycle, and atmospheric aerosols, constituting a mix of positive and negative feedbacks to climate change (Myhre et al. 2013; Ward et al. 2014; Figure 10.1 and Chapter 2, Section 2.6.2). Thus, changes to terrestrial ecosystems or land cover are a direct driver of climate change and they are further altered by climate change in ways that affect both ecosystem productivity and, through feedbacks, the climate itself. The following sections describe advances since the Third National Climate Assessment (NCA3) (Melillo et al. 2014) in scientific understanding of land cover and associated biogeochemistry and their impacts on the climate system.

[INSERT FIGURE 10.1 HERE]

10.2 Terrestrial Ecosystem Interactions with the Climate System

Other chapters of this report discuss changes in temperature (Ch. 6: Temperature Change), precipitation (Ch. 7: Precipitation Change), hydrology (Chapter 8: Droughts, Floods, and Wildfires), and extreme events (Ch. 9: Extreme Storms). Collectively, these processes affect the phenology, structure, productivity, and biogeochemical processes of all terrestrial ecosystems, and as such, climate change will alter land cover and ecosystem services.

10.2.1 Land Cover and Climate Forcing

Changes in land cover and land use have long been recognized as important contributors to global climate forcing (e.g., Feddema et al. 2005). Historically, studies that account for the contribution of the land cover to radiative forcing have accounted for albedo forcings only and not those from changes in land surface geophysical properties (e.g., plant transpiration, evaporation from soils, plant community structure and function) or in aerosols. Physical climate effects from land-cover or land-use change do not lend themselves directly to quantification using the traditional radiative forcing concept. However, a framework to attribute the indirect contributions of land cover to radiative forcing and the climate system—including effects on seasonal and interannual soil moisture and latent/sensible heat, evapotranspiration, biogeochemical cycle (CO_2) fluxes from soils and plants, aerosol and aerosol precursor emissions, ozone precursor emissions, and snowpack—was reported in NRC (2005). Predicting

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