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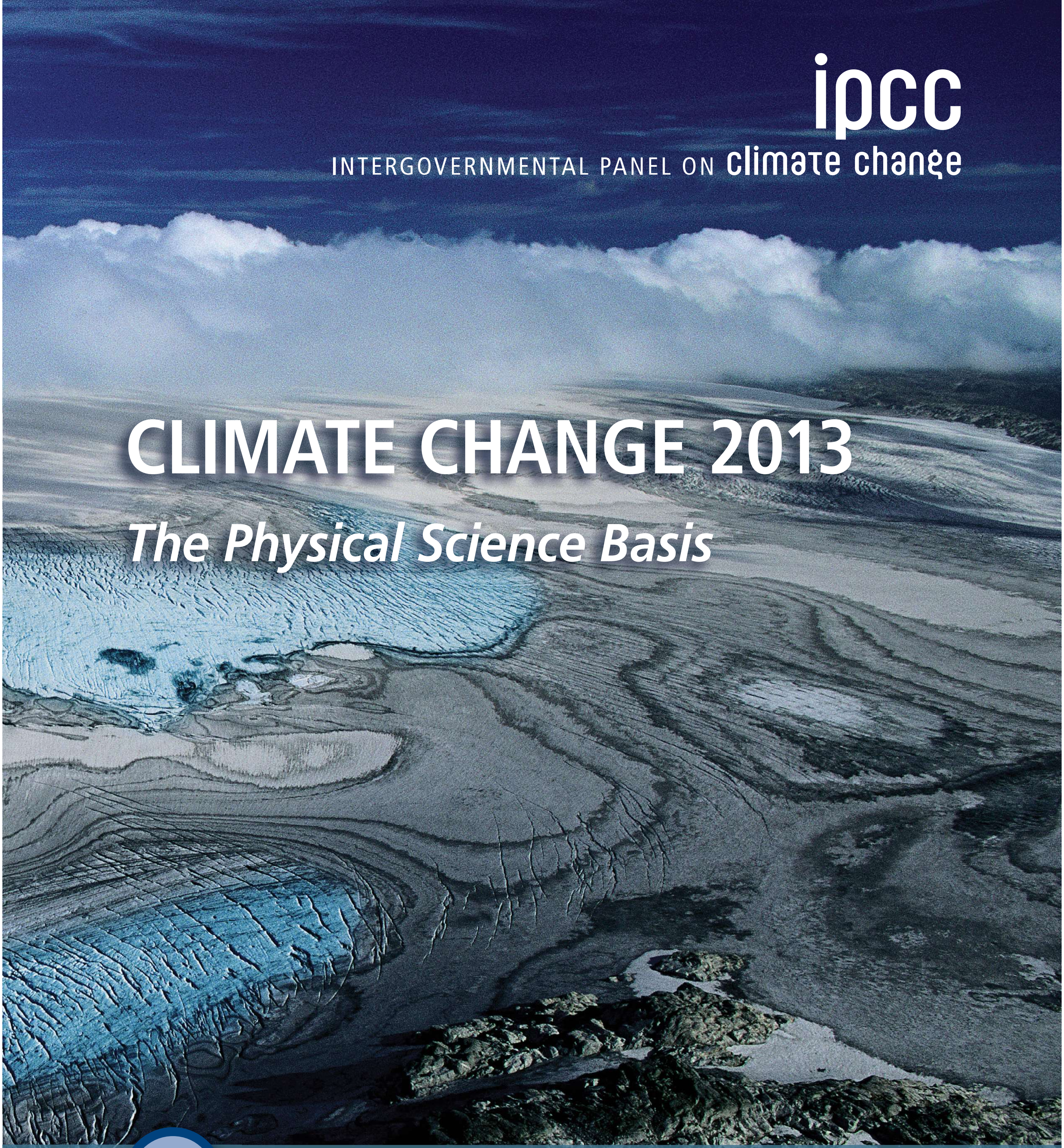
INTERGOVERNMENTAL PANEL ON climate change



CLIMATE CHANGE 2013

The Physical Science Basis

WG I

WORKING GROUP I CONTRIBUTION TO THE FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP

TS

TFE.9 (continued)

will at least double in frequency but in many regions will become an annual or a 1-in-2-year event by the end of the 21st century. The magnitude of both high and low temperature extremes is expected to increase at least at the same rate as the mean, but with 20-year return values for low temperature events projected to increase at a rate greater than winter mean temperatures in most regions. {10.6.1, 11.3.2, 12.4.3}

Precipitation Extremes
It is *likely* that the number of heavy precipitation events over land has increased in more regions than it has decreased in since the mid-20th century, and there is *medium confidence* that anthropogenic forcing has contributed to this increase. {2.6.2, 10.6.1}

There has been substantial progress between CMIP3 and CMIP5 in the ability of models to simulate more realistic precipitation extremes. However, evidence suggests that the majority of models underestimate the sensitivity of extreme precipitation to temperature variability or trends especially in the tropics, which implies that models may underestimate the projected increase in extreme precipitation in the future. While progress has been made in understanding the processes that drive extreme precipitation, challenges remain in quantifying cloud and convective effects in models for example. The complexity of land surface and atmospheric processes limits confidence in regional projections of precipitation change, especially over land, although there is a component of a 'wet-get-wetter' and 'dry-get-drier' response over oceans at the large scale. Even so, there is *high confidence* that, as the climate warms, extreme precipitation rates (e.g., on daily time scales) will increase faster than the time average. Changes in local extremes on daily and sub-daily time scales are expected to increase by roughly 5 to 10% per °C of warming (*medium confidence*). {7.6, 9.5.4}

For the near and long term, CMIP5 projections confirm a clear tendency for increases in heavy precipitation events in the global mean seen in the AR4, but there are substantial variations across regions (TFE.9, Figure 1). Over most of the mid-latitude land masses and over wet tropical regions, extreme precipitation will *very likely* be more intense and more frequent in a warmer world. {11.3.2, 12.4.5}

Floods and Droughts
There continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale over the instrumental record. There is *high confidence* that past floods larger than those recorded since 1900 have occurred during the past five centuries in northern and central Europe, western Mediterranean region, and eastern Asia. There is *medium confidence* that modern large floods are comparable to or surpass historical floods in magnitude and/or frequency in the Near East, India and central North America. {2.6.2, 5.5.5}

Compelling arguments both for and against significant increases in the land area affected by drought and/or dryness since the mid-20th century have resulted in a *low confidence* assessment of observed and attributable large-scale trends. This is due primarily to a lack and quality of direct observations, dependencies of inferred trends on the index choice, geographical inconsistencies in the trends and difficulties in distinguishing decadal scale variability from long term trends. On millennial time scales, there is *high confidence* that proxy information provides evidence of droughts of greater magnitude and longer duration than observed during the 20th century in many regions. There is *medium confidence* that more megadroughts occurred in monsoon Asia and wetter conditions prevailed in arid Central Asia and the South American monsoon region during the Little Ice Age (1450 to 1850) compared to the Medieval Climate Anomaly (950 to 1250). {2.6.2, 5.5.4, 5.5.5, 10.6.1}

Under the Representative Concentration Pathway RCP8.5, projections by the end of the century indicate an increased risk of drought is *likely* (*medium confidence*) in presently dry regions linked to regional to global-scale projected decreases in soil moisture. Soil moisture drying is most prominent in the Mediterranean, Southwest USA, and southern Africa, consistent with projected changes in the Hadley Circulation and increased surface temperatures, and surface drying in these regions is *likely* (*high confidence*) by the end of the century under RCP8.5. {12.4.5}

Extreme Sea Level
It is *likely* that the magnitude of extreme high sea level events has increased since 1970 and that most of this rise can be explained by increases in mean sea level. When mean sea level changes is taken into account, changes in extreme high sea levels are reduced to less than 5 mm yr^{-1} at 94% of tide gauges. In the future it is *very likely* that there will be a significant increase in the occurrence of sea level extremes and similarly to past observations, this increase will primarily be the result of an increase in mean sea level. {3.7.5, 13.7.2} *(continued on next page)*

2.6.2.4 Severe Local Weather Events

Another extreme aspect of the hydrological cycle is severe local weather phenomena such as hail or thunder storms. These 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, homogeneity of existing reporting is questionable (Verbout et al., 2006; Doswell et al., 2009). Alternatively, measures of severe thunderstorms or hailstorms can be derived by assessing the environmental conditions that are favourable for their formation but this method is very uncertain (Seneviratne et al., 2012). SREX highlighted studies such as those of Brooks and Dotzek (2008), who found significant variability but no clear trend in the past 50 years in severe thunderstorms in a region east of the Rocky Mountains in the USA, 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). Remote sensing offers a potential alterative to surface-based meteorological networks for detecting changes in small scale severe weather phenomenon such as proxy measurements of lightning from satellites (Zipser et al., 2006) but there remains little convincing evidence that changes in severe thunderstorms or hail have occurred since the middle of the 20th century (Brooks, 2012).

In summary, there is *low confidence* in observed trends in small-scale severe weather phenomena such as hail and thunderstorms because of historical data inhomogeneities and inadequacies in monitoring systems.

2.6.3 Tropical Storms

AR4 concluded that it was *likely* that an increasing trend had occurred in intense tropical cyclone activity since 1970 in some regions but that there was no clear trend in the annual numbers of tropical cyclones. Subsequent assessments, including SREX and more recent literature indicate that it is difficult to draw firm conclusions with respect to the confidence levels associated with observed trends prior to the satellite era and in ocean basins outside of the North Atlantic.

Section 14.6.1 discusses changes in tropical storms in detail. Current data sets indicate no significant observed trends in global tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Knutson et al., 2010). Regional trends in tropical cyclone frequency and the frequency of very intense tropical cyclones have been identified in the North Atlantic and these appear robust since the 1970s (Kossin et al. 2007) (*very high confidence*). However, argument reigns over the cause of the increase and on longer time scales the fidelity of these trends is debated (Landsea et al., 2006; Holland and Webster, 2007; Landsea, 2007; Mann et al., 2007b) with different methods for estimating undercounts in the earlier part of the record providing mixed conclusions (Chang and Guo, 2007; Mann et al., 2007a; Kunkel et al., 2008; Vecchi and Knutson, 2008, 2011). No robust trends in annual numbers of tropical storms, hurricanes and major hurricanes counts have been identified over the past 100 years in the North Atlantic basin. Measures of land-falling tropical cyclone frequency (Figure 2.34) are generally considered to be more reliable than counts of all storms which tend to be strongly influenced by those that are weak and/or short lived. Callaghan and Power (2011) find a statistically significant decrease in Eastern Australia land-falling tropical cyclones since the late 19th century although including 2010/2011 season data this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Significant trends are not found in other oceans on shorter time scales (Chan and Xu, 2009; Kubota and Chan, 2009; Mohapatra et al., 2011; Weinkle et al., 2012), although Grinsted et al. (2012) find a significant positive trend in eastern USA using tide-guage data from 1923–2008 as a proxy for storm surges associated with land-falling hurricanes. Differences between tropical cyclone studies highlight the challenges that still lie ahead in assessing long-term trends.

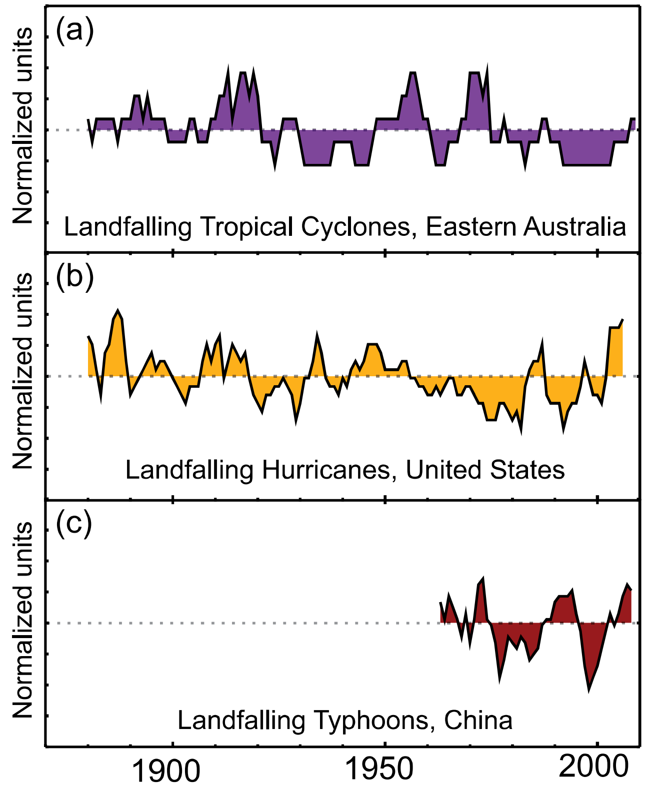


Figure 2.34 | Normalized 5-year running means of the number of (a) adjusted land falling eastern Australian tropical cyclones (adapted from Callaghan and Power (2011) and updated to include 2010//2011 season) and (b) unadjusted land falling U.S. hurricanes (adapted from Vecchi and Knutson (2011) and (c) land-falling typhoons in China (adapted from CMA, 2011). Vertical axis ticks represent one standard deviation, with all series normalized to unit standard deviation after a 5-year running mean was applied.

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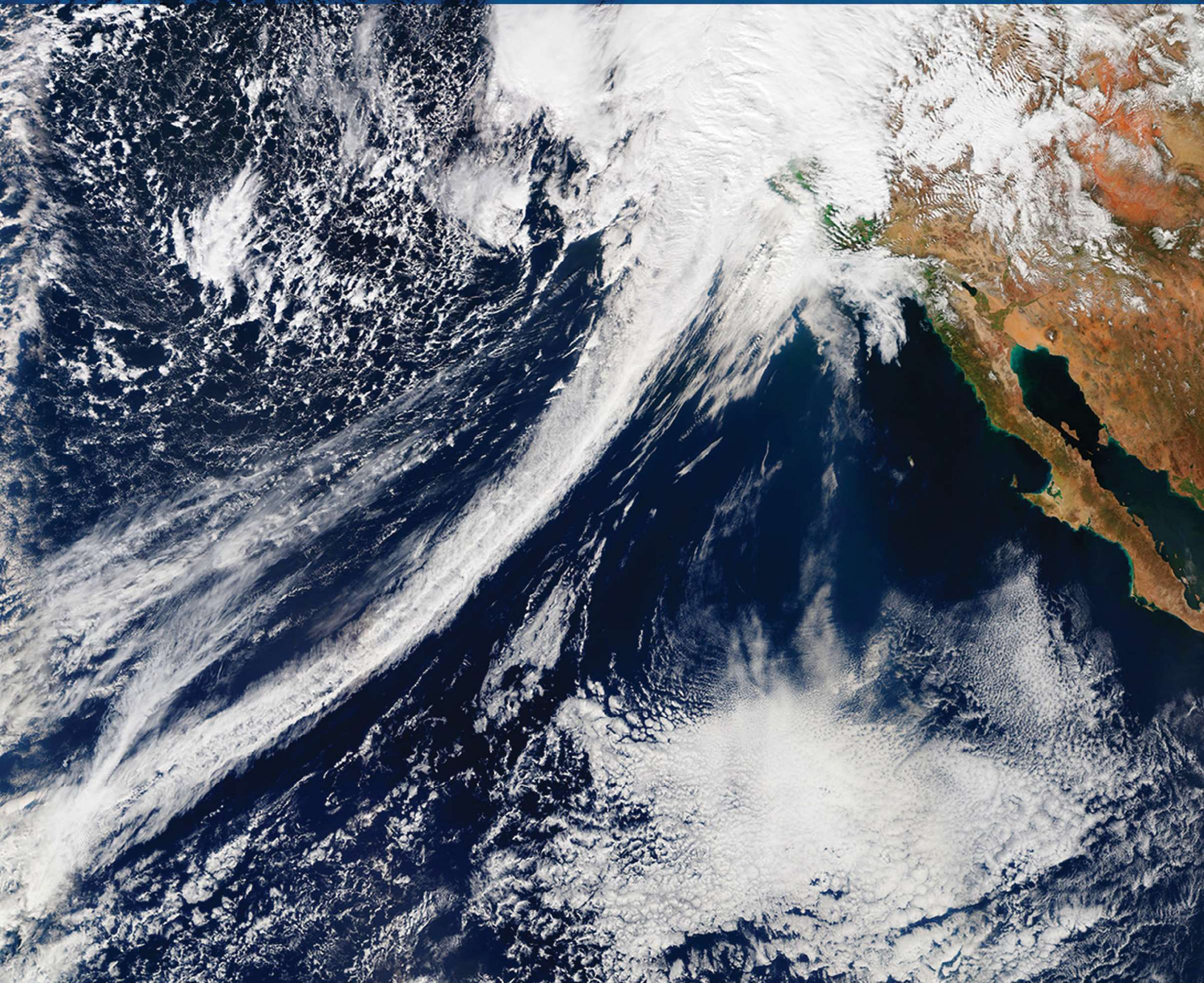

Fourth National Climate Assessment | Volume I sensitivity at depth-to-surface air temperature increases than at near-surface levels.[15, 38] Berg et al.[39] adjust for the differences in land component model vertical treatments, finding projected change in vertically integrated soil moisture down to 3 meters depth is mixed, with projected decreases in the Southwest and in the south-central United States, but increases over the northern plains. Nonetheless, the warming trend has led to declines in a number of indicators, including Sierra snow water equivalent, that are relevant to hydrological drought.[30] Attribution of the California drought and heat wave remains an interesting and controversial research topic.

In summary, there has not yet been a formal identification of a human influence on past changes in United States meteorological drought through the analysis of precipitation trends. Some, but not all, U.S. meteorological drought event attribution studies, largely in the "without detection" class, exhibit a human influence. Attribution of a human influence on past changes in U.S. agricultural drought are limited both by availability of soil moisture observations and a lack of subsurface modeling studies. While a human influence on surface soil moisture trends has been identified with *medium confidence*, its relevance to agriculture may be exaggerated.

Runoff And Hydrological Drought

Several studies focused on the Colorado River basin in the United States that used more sophisticated runoff models driven by the CMIP3 models[40, 41, 42, 43, 44] showed that annual runoff reductions in a warmer western Unites States climate occur through a combination of evapotranspiration increases and precipitation decreases, with the overall reduction in river flow exacerbated by human water demands on the basin's supply. Reduced U.S. snowfall accumulations in much warmer future climates are virtually certain as frozen precipitation is replaced by rain regardless of the projected changes in total precipitation amounts discussed in Chapter 7: Precipitation Change (Figure 7.6). The profound change in the hydrology of snowmelt-driven flows in the western United States is well documented. Earlier spring runoff[45] reduced the fraction of precipitation falling as snow[46] and the snowpack water content at the end of winter,[47, 48] consistent with warmer temperatures. Formal detection and attribution (Ch. 3: Detection and Attribution) of the observed shift towards earlier snowmelt-driven flows in the western United States reveals that the shift is detectably different from natural variability and attributable to anthropogenic climate change.[49] Similarly, observed declines in the snow water equivalent in the region have been formally attributed to anthropogenic climate change[50] as have temperature, river flow, and snowpack.[41, 51] As a harbinger, the unusually low western U.S. snowpack of 2015 may become the norm.[31]

In the northwestern United States, long-term trends in streamflow have seen declines, with the strongest trends in drought years[52] that are attributed to a decline in winter precipitation.[53] These reductions in precipitation are linked to decreased westerly wind speeds in winter over the region. Furthermore, the trends in westerlies are consistent with CMIP5-projected wind speed changes due to a decreasing meridional temperature and pressure gradients rather than low-frequency climate variability modes. Such precipitation changes have been a primary source of change in hydrological drought in the Northwest over the last 60 years[54] and are in addition to changes in snowpack properties.

We conclude with *high confidence* that these observed changes in temperature controlled

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 higher scenario (RCP8.5) from a high-resolution version of the Community Atmospheric Model, CAM5.[66]

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	−50.75	−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**

As earlier spring melt and reduced snow water equivalent have been formally attributed to human-induced warming, substantial reductions in western U.S. winter and spring snowpack are projected (with attribution) to be *very likely* as the climate continues to warm (*very high confidence*). Under higher 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*).

8.2 Floods

Flooding damage in the United States can come from flash floods of smaller rivers and creeks, prolonged flooding along major rivers, urban flooding unassociated with proximity to a riverway, coastal flooding from storm surge which may be exacerbated by sea level rise, and the confluence of coastal storms and inland riverine flooding from the same precipitation event (Ch. 12: Sea Level Rise). Flash flooding is associated with extreme precipitation somewhere along the river which may occur upstream of the regions at risk. Flooding of major rivers in the United States with substantial winter snow accumulations usually occurs in the late winter or spring and can result from an unusually heavy seasonal snowfall followed by a "rain on snow" event or from a rapid onset of higher temperatures that leads to rapid snow melting within the river basin. In the western coastal states, most flooding occurs in conjunction with extreme precipitation events referred to as "atmospheric rivers" (see Ch. 9: Extreme Storms),[72, 73] with mountain snowpack being vulnerable to these typically warmer-than-normal storms and their potential for rain on existing snow cover.[74] Hurricanes and tropical storms are an important driver of flooding events in the eastern United States. Changes in streamflow rates depend on many factors, both human and natural, in addition to climate change. Deforestation, urbanization, dams, floodwater management activities, and changes in agricultural practices can all play a role in past and future changes in flood statistics. Projection of future changes is thus a complex multivariate problem.[34]

The IPCC AR5[7] did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States.[34, 75, 76] Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude[77] but does not provide robust evidence that these trends are attributable to human influences. Significant increases in flood frequency have