days is projected in some mid-latitude and semi-arid regions, at about 1.5 times to twice the rate of global warming (*high confidence*). The highest increase of temperature of coldest days is projected in Arctic regions, at about three times the rate of global warming (*high confidence*). The probability of temperature extremes generally increases nonlinearly with increasing global warming levels (*high confidence*). Confidence in assessments depends on the spatial and temporal scales of the extreme in question, with *high confidence* in projections of temperature-related extremes at global and continental scales for daily to seasonal scales. There is *high confidence* that, on land, the magnitude of temperature extremes increases more strongly than global mean temperature.

11.4 Heavy Precipitation

This section assesses changes in heavy precipitation at global and regional scales. The main focus is on extreme precipitation at a daily scale where literature is most concentrated, though extremes of shorter (sub-daily) and longer (five-day or more) durations are also assessed to the extent the literature allows.

11.4.1 Mechanisms and Drivers

The SREX (Chapter 3, Seneviratne et al., 2012) assessed changes in heavy precipitation in the context of the effects of thermodynamic and dynamic changes. Box 11.1 assesses thermodynamic and dynamic changes in a warming world to aid the understanding of changes in observations and projections in some extremes and the sources of uncertainties (see also Section 8.2.3.2). In general, warming increases the atmospheric water-holding capacity following the Clausius–Clapeyron (C-C) relation. This thermodynamic effect results in an increase in extreme precipitation at a similar rate at the global scale. On a regional scale, changes in extreme precipitation are further modulated by dynamic changes (Box 11.1).

Large-scale modes of variability, such as the North Atlantic Oscillation (NAO), El Niño–Southern Oscillation (ENSO), Atlantic Multi-decadal Variability (AMV), and Pacific Decadal Variability (PDV) (Annex IV), modulate precipitation extremes through changes in environmental conditions or embedded storms (Section 8.3.2). Latent heating can invigorate these storms (Nie et al., 2018; Z. Zhang et al., 2019a); changes in dynamics can increase precipitation intensity above that expected from the C-C scaling rate (Sections 8.2.3.2 and 11.7; Box 11.1). Additionally, the efficiency of converting atmospheric moisture into precipitation can change as a result of cloud microphysical adjustment to warming, resulting in changes in the characteristics of extreme precipitation; but changes in precipitation efficiency in a warming world are highly uncertain (Sui et al., 2020).

It is difficult to separate the effect of global warming from internal variability in the observed changes in the modes of variability (Section 2.4). Future projections of modes of variability are highly uncertain (Section 4.3.3), resulting in uncertainty in regional projections of extreme precipitation. Future warming may amplify monsoonal extreme precipitation. Changes in extreme storms, including tropical/extratropical cyclones and severe convective storms, result in changes in extreme precipitation (Section 11.7). Also, changes in sea surface temperatures (SSTs) alter land–sea contrast, leading to changes in precipitation extremes near coastal regions. For example, the projected larger SST increase near the coasts of East Asia and India can result in heavier rainfall near these coastal areas from tropical cyclones (Mei and Xie, 2016) or torrential rains (Manda et al., 2014). The warming in the western Indian Ocean is associated with increases in moisture surges on the low-level monsoon westerlies towards the Indian subcontinent, which may lead to an increase in the occurrence of precipitation extremes over central India (Krishnan et al., 2016; Roxy et al., 2017).

Decreases in atmospheric aerosols results in warming and thus an increase in extreme precipitation (Samset et al., 2018; Sillmann et al., 2019). Changes in atmospheric aerosols also result in dynamic changes such as in tropical cyclones (Takahashi et al., 2017; Strong et al., 2018). Uncertainty in the projections of future aerosol emissions results in additional uncertainty in the heavy precipitation projections of the 21st century (Lin et al., 2016).

There has been new evidence of the effect of local land-use and land-cover change on heavy precipitation. There is a growing set of literature linking increases in heavy precipitation in urban centres to urbanization (Argüeso et al., 2016; Y. Zhang et al., 2019b). Urbanization intensifies extreme precipitation, especially in the afternoon and early evening, over the urban area and its downwind region (*medium confidence*) (Box 10.3). There are four possible mechanisms: (i) increases in atmospheric moisture due to horizontal convergence of air associated with the urban heat island effect (Shastri et al., 2015; Argüeso et al., 2016); (ii) increases in condensation due to urban aerosol emissions (Han et al., 2011; Sarangi et al., 2017); (iii) aerosol pollution that impacts cloud microphysics (Box 8.1; Schmid and Niyogi, 2017); and (iv) urban structures that impede atmospheric motion (Shepherd, 2013; Ganeshan and Murtugudde, 2015; Paul et al., 2018). Other local forcing, including reservoirs (Woldemichael et al., 2012), irrigation (Devanand et al., 2019), or large-scale land-use and land-cover change (Odoulami et al., 2019), can also affect local extreme precipitation.

In summary, precipitation extremes are controlled by both thermodynamic and dynamic processes. Warming-induced thermodynamic change results in an increase in extreme precipitation, at a rate that closely follows the C-C relationship at the global scale (*high confidence*). The effects of warming-induced changes in dynamic drivers on extreme precipitation are more complicated, difficult to quantify, and are an uncertain aspect of projections. Precipitation extremes are also affected by forcings other than changes in greenhouse gases, including changes in aerosols, land-use and land-cover change, and urbanization (*medium confidence*).

11.4.2 Observed Trends

Both SREX (Chapter 3, Seneviratne et al., 2012) and AR5 (IPCC, 2014 Chapter 2) concluded it was *likely* that the number of heavy precipitation events over land had increased in more regions than it had decreased, though there were wide regional and seasonal variations, and trends in many locations were not statistically significant. This assessment has been strengthened with multiple studies finding *robust evidence* of the intensification of extreme precipitation at global and continental scales, regardless of spatial and temporal coverage of observations and the methods of data processing and analysis.

The average annual maximum precipitation amount in a day (Rx1day) has significantly increased since the mid-20th century over land (Du et al., 2019; Dunn et al., 2020) and in the humid and dry regions of the globe (Dunn et al., 2020). The percentage of observing stations with statistically significant increases in Rx1day is larger than expected by chance, while the percentage of stations with statistically significant decreases is smaller than expected by chance, over the global land as a whole and over North America, Europe, and Asia (Figure 11.13; Sun et al., 2021) and over global monsoon regions (Zhang and Zhou, 2019) where data coverage is relatively good. The addition of the past decade of observational data shows a more robust increase in Rx1day over the global land region (Sun et al., 2021). Light, moderate, and heavy daily precipitation has all intensified in a gridded daily precipitation dataset (Contractor et al., 2020a). Daily mean precipitation intensities have increased since the mid-20th century in a majority of land regions (*high confidence*) (Section 8.3.1.3). The probability of precipitation exceeding 50 mm/day increased during 1961–2018 (Benestad et al., 2019). The globally averaged annual fraction of precipitation from days in the top 5% (R95pTOT) has also significantly increased (Dunn et al., 2020). The increase in the magnitude of Rx1day in the 20th century is estimated to be at a rate consistent with C-C scaling with respect to global mean temperature (Fischer and Knutti, 2016; Sun et al., 2021). Studies on past changes in extreme precipitation of durations longer than a day are more limited, though there are some studies examining long-term trends in annual maximum five-day precipitation (Rx5day). On global and continental scales, long-term changes in Rx5day are similar to those of Rx1day in many aspects (Zhang and Zhou 2019; Sun et al., 2021). As discussed below, at the regional scale, changes in Rx5day are also similar to those of Rx1day where there are analyses of changes in both Rx1day and Rx5day.

Overall, there is a lack of systematic analysis of long-term trends in sub-daily extreme precipitation at the global scale. Often, sub-daily precipitation data have only sporadic spatial coverage and are of limited length. Additionally, the available data records are far shorter than needed for a robust quantification of past changes in sub-daily extreme precipitation (C. Li et al., 2019a). Despite these limitations, there are studies in regions of almost all continents that generally indicate intensification of sub-daily extreme precipitation, although there remains *low confidence* in an overall increase at the global scale. Studies include an increase in extreme sub-daily rainfall in summer over South Africa (Sen Roy and Rouault, 2013), annually in Australia (Guerreiro et al., 2018b), over 23 urban locations in India (Ali and Mishra, 2018), in Peninsular Malaysia (Syafrina et al., 2015), and in eastern China in the summer season during 1971–2013 (Xiao et al., 2016). In some regions in Italy (Arnone et al., 2013; Libertino et al., 2019) and in the USA during 1950–2011 (Barbero et al., 2017), there is also an increase. In general, an increase in sub-daily heavy precipitation results in an increase in pluvial floods over smaller watersheds (Ghausi and Ghosh, 2020).

There is a considerable body of literature examining scaling of sub-daily precipitation extremes, conditional on day-to-day air or dew-point temperatures (Westra et al., 2014; Fowler et al., 2021). This scaling, also termed 'apparent scaling' (Fowler et al., 2021), is robust when different methodologies are used in different regions, ranging between the C-C and two-times the C-C rate (e.g., Formayer and Fritz, 2017; Lenderink et al., 2017; Burdanowitz et al., 2019). This is confirmed when sub-daily precipitation data collected from multiple continents (Lewis et al., 2019) are analysed in a consistent manner using different methods (Ali et al., 2021). It has been hoped that apparent scaling might be used to help understand past and future changes in extreme sub-daily precipitation. However, apparent scaling samples multiple synoptic weather states, mixing thermodynamic and dynamic factors that are not directly relevant for climate change responses (Section 8.2.3.2; Prein et al., 2016b; Bao et al., 2017; X. Zhang et al., 2017; Drobinski et al., 2018; Sun et al., 2020). The spatial pattern of apparent scaling is different from those of projected changes over Australia (Bao et al., 2017) and North America (Sun et al., 2020) in regional climate model simulations. It thus remains difficult to use the knowledge about apparent scaling to infer past and future changes in extreme sub-daily precipitation according to observed and projected changes in local temperature.

In Africa (Table 11.5), evidence shows an increase in extreme daily precipitation for the late half of the 20th century over the continent where data are available; there is a larger percentage of stations showing significant increases in extreme daily precipitation than decreases (Sun et al., 2021). There are increases in different metrics relevant to extreme precipitation in various regions of the continent (Chaney et al., 2014; Harrison et al., 2019; Dunn et al., 2020; Sun et al., 2021). There is an increase in extreme precipitation events in Southern Africa (Weldon and Reason, 2014; Kruger et al., 2019) and a general increase in heavy precipitation over East Africa, the Greater Horn of Africa (Omondi et al., 2014). Over sub-Saharan Africa, increases in the frequency and intensity of extreme precipitation have been observed over the well-gauged areas during 1950–2013; however, this covers only 15% of the total area of sub-Saharan Africa (Harrison et al., 2019). There is *medium confidence* about the increase in extreme precipitation for some regions where observations are more abundant, but for Africa as whole, there is *low confidence* because of a general lack of continent-wide systematic analysis, the sporadic nature of available precipitation data over the continent, and spatially non-homogenous trends in places where data are available (Donat et al., 2014a; Mathbout et al., 2018b; Alexander et al., 2019; Funk et al., 2020).

In Asia (Table 11.8), there is *robust evidence* that extreme precipitation has increased since the 1950s (*high confidence*), however, this is dominated by high spatial variability. Increases in Rx1day and Rx5day during 1950–2018 are found over two-thirds of stations. The percentage of stations with statistically significant trends is larger than can be expected by chance (Figure 11.13; Sun et al., 2021). An increase in extreme precipitation has also been observed in various regional studies based on different metrics of extreme precipitation and spatial and temporal coverage of the data. These include an increase in daily precipitation extremes over central Asia (Hu et al., 2016), most of South Asia (Zahid and Rasul, 2012; Pai et al., 2015; Sheikh et al., 2015; Adnan et al., 2016; Malik et al., 2016; Dimri et al., 2017; Priya et al., 2017; Roxy et al., 2017; Hunt et al., 2018; Kim et al., 2019; Wester et al., 2019), the Arabian Peninsula (Rahimi and Fatemi, 2019; Almazroui and Saeed, 2020; Atif et al., 2020), South East Asia (Siswanto et al., 2015; Supari et al., 2017; Cheong et al., 2018); the north-west Himalaya (Malik et al., 2016), parts of East Asia (Baek et al., 2017; Nayak et al., 2017; Ye and Li, 2017), the western Himalayas since the 1950s (Ridley et al., 2013; Dimri et al., 2015; Madhura et al., 2015), West and East Siberia, and Russian Far East (Donat et al., 2016a). A decrease was found over the eastern Himalayas (Sheikh et al., 2015; Talchabhadel et al., 2018). Increases have been observed over Jakarta (Siswanto et al., 2015), but Rx1day over most parts of the Maritime Continent has decreased (Villafuerte and Matsumoto, 2015). Trends in extreme precipitation over China are mixed with increases and decreases (G. Fu et al., 2013; Jiang et al., 2013; Ma et al., 2015; Yin et al., 2015; Xiao et al., 2016) and are not significant over China as whole (Jiang et al., 2013; Hu et al., 2016; Ge et al., 2017; Deng et al., 2018; He and Zhai, 2018; W. Li et al., 2018a; Tao et al., 2018; M. Liu et al., 2019b; Chen et al., 2021). With few exceptions, most South East Asian countries have experienced an increase in rainfall intensity, but with a reduced number of wet days (Donat et al., 2016a; Cheong et al., 2018; Naveendrakumar et al., 2019), though large differences in trends exists if the trends are estimated from different datasets, including gauge-based, remotely sensed, and reanalysis data, over a relatively short period (Kim et al., 2019). There is a significant increase in heavy rainfall (>100 mm day^{-1}) and a significant decrease in moderate rainfall (5–100 mm day^{-1}) in central India during the South Asian monsoon season (Deshpande et al., 2016; Roxy et al., 2017).

In Australasia (Table 11.11), available evidence has not shown an increase or a decrease in heavy precipitation over Australasia as a whole (*medium confidence*), but heavy precipitation tends to increase over Northern Australia (particularly the north-west) and decrease over the eastern and southern regions (e.g., Jakob and Walland, 2016; Guerreiro et al., 2018b; Dey et al., 2019b; Dunn et al., 2020; Sun et al., 2021). Available studies that used long-term observations since the mid-20th century showed nearly as many stations with an increase as those with a decrease in heavy precipitation (Jakob and Walland, 2016) or slightly more stations with a decrease than with an increase in Rx1day and Rx5day (Sun et al., 2021), or strong differences in Rx1day trends with increases over Northern Australia and Central Australia in general, but mostly decreases over Southern Australia and Eastern Australia (Dunn et al., 2020). Over New Zealand, decreases are observed for moderate–heavy precipitation events, but there are no significant trends for very heavy events (more than 64 mm in a day) for the period 1951–2012. The number of stations with an increase in very wet days is similar to that with a decrease during 1960–2019 (MfE and Stats NZ, 2020). Overall, there is *low confidence* in trends in the frequency of heavy rain days, with mostly decreases over New Zealand (Harrington and Renwick, 2014; Caloiero, 2015).

In Central and South America (Table 11.14), evidence shows an increase in extreme precipitation, but in general there is *low confidence;* while continent-wide analyses produced wetting trends are not robust. Rx1day increased at more stations than it decreased in South America between 1950 and 2018 (Sun et al., 2021). Over the period 1950–2010, both Rx5day and R99p increased over large regions of South America, including North-Western South America, Northern South America, and South-Eastern South America (Skansi et al., 2013). There are large regional differences. A decrease in daily extreme precipitation is observed in north-eastern Brazil (Skansi et al., 2013; Bezerra et al., 2018; Dereczynski et al., 2020). Trends in extreme precipitation indices were not statistically significant over the period 1947–2012 within the São Francisco River basin in the Brazilian semi-arid region (Bezerra et al., 2018). An increase in extreme rainfall is observed in the Amazon with *medium confidence* (Skansi et al., 2013) and in South-Eastern South America with *high confidence* (Skansi et al., 2013; Valverde and Marengo, 2014; Barros et al., 2015; Ávila et al., 2016; Wu and Polvani, 2017; Lovino et al., 2018; Dereczynski et al., 2020). Among all sub-regions, South-Eastern South America shows the highest rate of increase for rainfall extremes, followed by the Amazon (Skansi et al., 2013). Increases in the intensity of heavy daily rainfall events have been observed in the southern Pacific and in the Titicaca basin (Skansi et al., 2013; Huerta and Lavado-Casimiro, 2021). In Southern Central America, trends in annual precipitation are generally not significant, although small (but significant) increases are found in Guatemala, El Salvador, and Panama (Hidalgo et al., 2017). Small positive trends were found in multiple extreme precipitation indices over the Caribbean region over a short time period (1986–2010) (Stephenson et al., 2014; McLean et al., 2015).

In Europe (Table 11.17), there is *robust evidence* that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. There is a significant increase in Rx1day and Rx5day during 1950–2018 in Europe as a whole (Sun et al., 2021, also Figure 11.13). The number of stations with increases far exceeds those with decreases in the frequency of daily rainfall exceeding its 90th or 95th percentile in century-long series (Cioffi et al., 2015). The five-, 10-, and 20-year events of one-day and five-day precipitation during 1951–1960 became more common since the 1950s (van den Besselaar et al., 2013). There can be large discrepancies among studies and regions and seasons (Croitoru et al., 2013; Willems, 2013; Casanueva et al., 2014; Roth et al., 2014; Fischer et al., 2015); evidence for increasing extreme precipitation is more frequently observed for summer and winter, but not in other seasons (Madsen et al., 2014; Helama et al., 2018). An increase is observed in central Europe (Volosciuk et al., 2016; Zeder and Fischer, 2020), and in Romania (Croitoru et al., 2016). Trends in the Mediterranean region are in general not spatially consistent (Reale and Lionello, 2013), with decreases in the western Mediterranean and some increases in the eastern Mediterranean (Rajczak et al., 2013; Casanueva et al., 2014; de Lima et al., 2015; Gajić-Čapka et al., 2015; Sunyer et al., 2015; Pedron et al., 2017; Serrano-Notivoli et al., 2018; Ribes et al., 2019). In the Netherlands, the total precipitation contributed from extremes higher than the 99th percentile doubles per 1°C increase in warming (Myhre et al., 2019), though extreme rainfall trends in Northern Europe may differ in different seasons (Irannezhad et al., 2017).

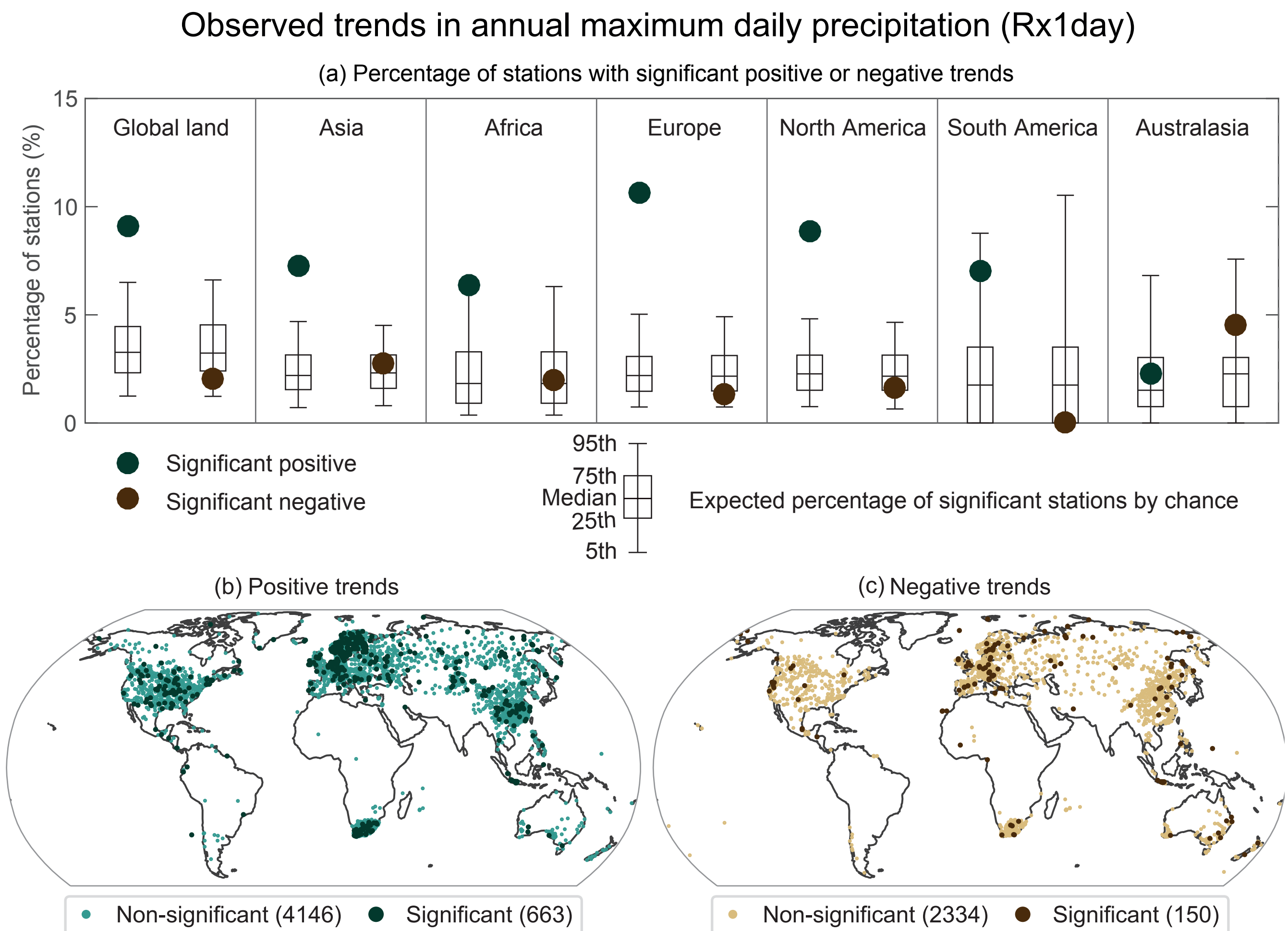

Figure 11.13 | Signs and significance of the observed trends in annual maximum daily precipitation (Rx1day) during 1950–2018 at 8345 stations with sufficient data. (a) Percentage of stations with statistically significant trends in Rx1day; green dots show positive trends and brown dots negative trends. Box and 'whisker' plots indicate the expected percentage of stations with significant trends due to chance estimated from 1000 bootstrap realizations under a no-trend null hypothesis. The boxes mark the median, 25th percentile, and 75th percentile. The upper and lower whiskers show the 97.5th and the 2.5th percentiles, respectively. Maps of stations with positive **(b)** and negative **(c)** trends. The light colour indicates stations with non-significant trends, and the dark colour stations with significant trends. Significance is determined by a two-tailed test conducted at the 5% level. Adapted from Sun et al. (2021). Figure copyright © American Meteorological Society (used with permission). Further details on data sources and processing are available in the chapter data table (Table 11.SM.9).

In North America (Table 11.20), there is *robust evidence* that the magnitude and intensity of extreme precipitation has *very likely* increased since the 1950s. Both Rx1day and Rx5day have significantly increased in North America during 1950–2018 (Sun et al., 2021, also Figure 11.13). There is, however, regional diversity. In Canada, there is a lack of detectable trends in observed annual maximum daily (or shorter duration) precipitation (Shephard et al., 2014; Mekis et al., 2015; Vincent et al., 2018). In the USA, there is an overall increase in one-day heavy precipitation, both in terms of intensity and frequency (Villarini et al., 2012; Donat et al., 2013b; Wu, 2015; Easterling et al., 2017; H. Huang et al., 2017; Howarth et al., 2019; Sun et al., 2021), except for the southern USA (Hoerling et al., 2016) where internal variability may have played a substantial role in the lack of observed increases. In Mexico, increases are observed in R10mm and R95p (Donat et al., 2016a), very wet days over the cities (García-Cueto et al., 2019) and in total precipitation (PRCPTOT) and Rx1day (Donat et al., 2016b).

In Small Islands, there is a lack of evidence showing changes in heavy precipitation overall. There were increases in extreme precipitation in Tobago from 1985–2015 (Stephenson et al., 2014; Dookie et al., 2019) and decreases in south-western French Polynesia and the southern subtropics (*low confidence*) (Table 11.5; Atlas.10). Extreme precipitation leading to flooding in the Small Islands has been attributed in part to tropical cyclones, as well as being influenced by ENSO (Box 11.5; Khouakhi et al., 2016; Hoegh-Guldberg et al., 2018).

In summary, the frequency and intensity of heavy precipitation have *likely* increased at the global scale over a majority of land regions with good observational coverage. Since 1950, the annual maximum amount of precipitation falling in a day, or over five consecutive days, has *likely* increased over land regions with sufficient observational coverage for assessment, with increases in more regions than there are decreases. Heavy precipitation has *likely* increased on the continental scale over three continents (North America, Europe, and Asia) where observational data are more abundant. There is *very low*