Recent Progress and Emerging Topics on Weather and Climate Extremes Since the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

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Abstract
Weather and climate extremes impose serious impacts on natural and human systems. In its fifth assessment report (AR5) and a special report [Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)], the Intergovernmental Panel on Climate Change provided a thorough assessment of observed and projected changes in extremes in a warming climate, with evidenced scientific gaps in the understanding of these responsive changes being reported. Reviewing post-AR5 literature, this article synthesizes recent advances regarding these previous gaps with respect to detection, attribution, and projection of extremes. We focus on constraints for the assessment confidence, overlooked types and
characteristics of extremes, and changes in their thermodynamic-dynamic drivers. We also stress potential misinterpretations of existing results, propose an update of earlier key findings, and identify burgeoning topics.

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1. INTRODUCTION

Weather and climate extremes, which by definition should be rare and relevant to serious impacts and disasters, affect multiple facets of human and natural systems. Due to the importance of risk management, this topic has attracted a growing interest from policymakers and a diversity of stakeholders, including the insurance sector and local administrators, for instance at the city scale. The understanding of relationships between characteristics of extreme events and climate change has also attracted intense scrutiny from media and the general public. Hence, better serving climate
adaptation planning requires improved understanding in observed changes, near-term predictions, and long-term projections of weather and climate extremes (1).

The recent Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; 2) and the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC; 3) have assessed the scientific literature published between 2007 and 2013. These reports provided an overview of the state of knowledge regarding the relationship between climate change and extremes. Each key conclusion from these IPCC reports is grounded in the evaluation of underlying evidence and agreement and is based on the IPCC guidance note for consistent treatment and communication of certainty of major findings (4). A synthesis of evidence and agreement supports an assignment of confidence level (for detailed uncertainty languages, see 4).

During the past five years, post-AR5 studies on extremes have been proceeding at a furious pace, with important outcomes springing up. The purpose of this article is to summarize these post-AR5 scientific and methodological advances on extremes, provide an overview on the prevailing challenges and gaps, and shed some light on directions for future research. The AR5 and SREX looked at various kinds of extremes, including temperature extremes, precipitation extremes, floods, droughts, tropical and extratropical cyclone-related extremes, extreme winds, extreme sea level, and local weather events. Instead of outlining progress of all these types of extremes since the AR5, this article devotes particular attention to temperature and precipitation extremes, types with low confidence in AR5, and newly defined types of extremes. The article’s narrative follows a basic storyline of detection and attribution of observed changes, as well as projection of future changes in extremes. Section 2 summarizes key conclusions from AR5 and SREX. Section 3 discusses gaps and emerging topics of observed changes in extremes. Section 4 focuses on the attribution of extremes. Section 5 addresses projected changes. Section 6 lists conclusions and future directions.

2. CURRENT UNDERSTANDING ON CHANGES IN EXTREMES

The AR5 and SREX (2, 3) assessed the literature on observed global- and regional-scale changes in climate extremes. A large body of literature was based on the use of so-called extreme indices, which can be derived either from the probability of occurrence of given quantities or from threshold exceedances. Typical extreme indices include the number or fraction of days with maximum temperature ($T_{\text{max}}$), minimum temperature ($T_{\text{min}}$), or precipitation, below the first, fifth, or tenth percentile, or above the 90th, 95th, or 99th percentile, as generally defined for given timeframes (e.g., days, months, seasons, annual) with respect to a reference period (e.g., 1961–1990). Other definitions relate to, for example, the number of days above specific absolute temperature or precipitation thresholds, or more complex definitions relate to the length or persistence of climate extremes. One advantage of using predefined extreme indices is that they allow comparability across modeling and observational studies and across regions.

For temperature extremes over land, AR5 concluded that it is very likely that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, since the 1950s, at the global scale, but with varying levels of confidence for conclusions across continents (3). In many regions, there is medium confidence that the length or number of warm spells or heat waves has increased since the middle of the twentieth century.

The SREX stated that “the warming of extreme daily minimum and maximum temperatures at the global scale likely results from anthropogenic influences” (2, p. 141). AR5 further reinforced the statement by highlighting that “it is very likely that human influence has contributed to the observed changes in the frequency and intensity of daily temperature extremes on the global
scale since the mid-twentieth century” (3, p. 19). Models project virtually certain increases in the frequency and magnitude of daily hot extremes and decreases in cold extremes through the twenty-first century at the global scale. In this context, it is very likely that the length, frequency, and/or intensity of warm spells or heat waves will increase over most land areas.

For precipitation extremes, AR5 concluded that there have been likely statistically significant increases in the number of heavy precipitation events (e.g., 95th percentile) in more regions than there have been statistically significant decreases, but there are strong regional peculiarities in trend sign, significance, and magnitude (3). There is medium confidence that anthropogenic influences have contributed to a global-scale intensification of heavy precipitation over the second half of the twentieth century in land regions. It is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy rainfalls will increase in the twenty-first century over much of the globe, particularly in the high latitudes and tropical regions, and during winter in the northern mid-latitudes (2, p. 13).

From a global viewpoint, the confidence of observed trends for droughts or dryness since the mid-twentieth century is not higher than low level (3), considering lack of direct observations, geographical nonuniformity in the trends, and dependency of inferred trends on the index choice. There is medium confidence that since the 1950s some regions of the world have experienced a trend toward more intense and longer droughts, in particular in southern Europe and West Africa. The AR5 highlighted, however, that in some regions droughts have become less frequent, less intense, or shorter, for example, in central North America and northwestern Australia (2, p. 170). At the time of SREX, the conclusion about attributing “some changes in drought patterns” to anthropogenic influence in the second half of the twentieth century was granted medium confidence, based on attributable changes in precipitation and temperature components. But at a regional level, the confidence for “the attribution of changes in droughts” (2, p. 172) is low. The AR5 further degraded the conclusion, stating that we have low confidence in detecting and attributing changes in drought over global land areas since the mid-twentieth century. There is medium confidence that droughts will intensify in the twenty-first century in some seasons and areas (southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa), due to reduced precipitation and/or increased evapotranspiration (2, pp. 113–114).

The AR5 stressed low confidence on long-term (i.e., 40 years or more) increases in tropical cyclone activity, despite a virtually certain increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in the North Atlantic Basin (3, p. 217). There is only low confidence for the attribution of any detectable changes in tropical cyclone activity to any particular cause (3, p. 914; referred to as “anthropogenic influences” in 2, p. 163). In the future, although the global frequency of tropical cyclones will likely either decrease or remain essentially unchanged (2, p. 113), it is more likely than not to see substantial increases in the frequency of the most intense storms in some ocean basins (2, p. 161), such as in the western North Pacific and North Atlantic in the late twenty-first century (3, p. 7), concurrent with a likely increase in both global mean tropical cyclone maximum wind speeds and precipitation rates.

3. EMERGING TOPICS AND CHALLENGES FOR OBSERVED CHANGES IN EXTREMES

In general, the assessment confidence of observed changes in extremes depends on data quality (e.g., homogeneity and completeness), quantity (availability and record length), definitions, methods used for trend estimates, choices of reference periods (especially for magnitude changes; 2,
p. 117), and the availability of relevant studies (2, p. 135). Therefore, potential gaps and uncertainties arise mainly from these constraints.

### 3.1. Temperature Extremes

Conclusions for temperature extremes have been granted the highest-level confidence by AR5, although several regional aspects remain uncertain. They include unexpected decreases in daily maximum temperatures in some regions [for example, the warming hole in southeast North America (5) and Huang-Huai Valley in China (6)], inconsistent changes in signs, significance, and magnitude (2, p. 133) between the trends for moderate—percentile-based—and the severest—annual maximum/minimum—extremes, and trend sensitiveness to definitions (3, p. 212), which all deserve further investigation. Circumventing potential entanglement of previous event identifications and emphasizing close relevance to impacts, recent studies have categorized general hot days and nights into three non-overlapping subtypes (7, 8), daytime events (hot day–normal night), nighttime events (normal day–hot night), and complex events (hot day–hot night). Such classification brought into prominence previously masked significant changes (see 6, figure 2). For instance, intercomparisons among changes in these subtypes point to the significantly increasing (declining) prevalence of complex (daytime) hot extremes in America, the Carpathian region, and China (6–9). Whether similar alternation of dominant types has occurred at a continental or even global scale is worth assessing with existing and emerging evidence.

The AR5 and SREX did not address changes in attendant relative humidity during hot extremes, although the impacts of heat waves on physiology and health would be substantially exacerbated by elevated ambient humidity (10). Such “humid heat waves” have been observed more frequently with higher magnitude (10). To the contrary, hot extremes combined with low-humidity conditions can aggravate risks for fire occurrence and agricultural impacts (11). High-confidence conclusions on recent changes of events combining hot extremes and anomalous humidity have not yet been achieved at a global scale, because of the scarcity of pertinent literature and limited availability of reliable long-term relative humidity observations.

A new concept referred to as marine heat waves has attracted the growing attention of a scientific community realizing these oceanic temperature extremes’ devastating impacts on marine ecosystems (12). Ocean reanalysis data, in situ observations, and remote sensing sea surface temperature have all been employed to quantify marine heat waves across multiple temporal-spatial scales (13, 14). To date, the lack of studies in most oceans hinders a global-scale picture for changes in marine heat waves. There is a thus critical need for consistent definitions and investigations of hot-spots, trends, impacts, and drivers of marine heat waves at the individual oceanic basin- and global scale (14).

Beyond the general expectation of warming tendency, winter surface air temperature over central Eurasia, parts of North America, and eastern China has exhibited cooling trends during the past two decades, bringing more frequent and severe (even record-breaking) cold waves there (15–17). Nonetheless, views on the underlying mechanisms for the resurgence of cold extremes, including connection with sea ice losses, Arctic amplification, changes in Northern Hemisphere circulations, and the relationship with low-frequency sea surface temperature modes of variability (e.g., Pacific Decadal Oscillation—PDO—and Atlantic Multidecadal Oscillation—AMO) still diverge markedly or even are completely opposing (17–19). Thus, a better consensus on physical explanations for recent changes in cold extremes calls for more compelling evidence. Exact mechanism understandings would be pivotal for attribution and projection for cold extremes in a warming climate.
3.2. Precipitation Extremes

The confidence of conclusions for precipitation extremes is not higher than medium in Central and South America, Asia, and Africa, the uncertainty of which may result from inaccurate and insufficient understanding of changes in monsoonal circulations (2, pp. 152–155). Apart from the widely estimated frequency and intensity, changes in persistence (intermittency) of precipitation extremes were also emphasized in post-AR5 studies (20, 21). Precipitation extremes of different durations, on one hand, may have distinct or even opposing trends; on the other hand, they are linked to different weather patterns (22, 23). Hence, separate estimates of trends for precipitation extremes of differing durations may favor unearthing significant changes overlooked in previous investigation of duration-mixed events. Also, changes in precipitation structure, on the basis of both duration and intensity, may upgrade non-extremes into extremes. For instance, if the total number of wet days remains unchanged but they occur in a cluster, resultant lengthened wet spells and dry spells may evolve into floods and droughts simultaneously (21).

Another emerging topic is the issue of subdaily precipitation extremes, which is increasingly critical yet insufficiently assessed in AR5 and SREX. Gauge observations as well as radar and satellite data are used to estimate changes in characteristics of subdaily precipitation extremes (24, 25). A central issue pertaining to subdaily precipitation extremes is the scaling relationship of their intensity with temperature rises. By binning subdaily precipitation into daily temperature categories (26), multiple scaling rates, including a close C-C (Clausius–Clapeyron relationship) rate, a super C-C rate, and a sub C-C rate, have all been reported (24, 27, 28). A more common feature could be generalized into a peak-like structure wherein the intensity of subdaily precipitation extremes increases with warming first, followed by a decrease with subsequent temperature rise. However, recent studies questioned this binning approach, and also challenged the validity of the implied super C-C rate (29, 30). Statistically, temperature-binning hourly precipitation extremes represent conditional quantiles, which could also be conditioned on other variables independent of temperature, such as seasonal evolutionary large-scale weather patterns (30), types of stratiform/convective cloud cells (31, 32), and local climate and topography (31, 33). Hence, the conclusions via this univariate binning approach neither reflect any causation nor can be used as a predictor/indicator for the response of short-duration precipitation extremes to future warming (30, 34). The scaling rate may also be dedicated by the timescale of extremes, i.e., events of minutes, hourly, and daily scales, but the most appropriate timescale to portray the scaling relationship remains a pending issue under hot debate (34, 35).

The SREX did not distinguish between rain and snowfall, thus no definitive statements about extreme snowfall appeared in the report—or in AR5. However, trends and impacts of extreme snowfall and rainfall obviously differ. Post-AR5 literature provides an opportunity to revisit changes in extreme snowfall, which exhibit an overall tendency toward decreases in several metrics at both regional and continental scales (36–38). Precipitation occurring at temperatures near 0°C (freezing rain, freezing drizzle, ice pellets, snow pellets, and wet snow), albeit of low intensity, could also seriously impact societal sectors and ecosystems (39), therefore deserving further efforts with regard to definition, climatologic statistics, and trends at regional-continental scales (40).

3.3. Drought

The IPCC Fourth Assessment Report (AR4) concluded that “there has likely been a large drying trend since the mid-1950s over many land areas, with widespread drying over much of Africa, southern Eurasia, Canada and Alaska, owing to more intense and longer droughts over wider
areas” (41). AR5 (3, p. 215) and the SREX (2, p. 170), however, believed that this AR4 conclusion was overstated. The confidence for drought changes over large sections of the world remains low (2, p. 171). Greve et al. (42) and Sheffield et al. (43) confirmed and further reinforced such low confidence, showing that over much of the global continents, robust dryness tendencies failed to be detected. Thus, the AR5 projections (3, p. 20) that “the contrast in precipitation between wet and dry regions and between wet and dry seasons will increase” (summarized as a “dry gets drier” pattern) does not emerge as a robust feature in observational records, especially after adjusting the definition of dry and wet areas (44). Furthermore, some misunderstandings in previous literatures also arise from the diversity of indices used to measure droughts, as well as the selection of baseline periods for trend estimates (43, 45, 46). Data quality is a critical factor determining the robustness of trend detection for extremes, but is comparatively underemphasized in the case of drought studies. Global precipitation and other meteorological forcing datasets (such as radiation and winds) related to droughts are not homogenized formally and may contain spurious errors due to changes in observational instruments and protocols (43, 46, 47). A simple usage of the same forcing data for constructing multiple indices, such as the maximum number of consecutive dry days (CDD), the standardized precipitation index (SPI), the standardized precipitation evapotranspiration index (SPEI), the evaporative demand drought index (EDDI), the Palmer drought severity index (PDSI), and soil moisture anomaly (SMA), may degrade their independence in quantifying drought changes, even if some regions may register general consistency in the sign, significance, and magnitude of trends among them (48). Alternatively, the confidence in assessments about droughts can be improved through direct comparison of independent observational lines of evidence, such as precipitation from rain gauges, streamflow from stream gauges, and soil moisture measurements (47), as well as by leveraging their remote-sensing counterparts (49). Added confidence of conclusions could also be gained through considering respective types for diverse sectors, i.e., meteorological drought, agricultural drought, and hydrological drought, because observational variables, indicators, physics, impacts, and trends in both observations and projections may differ significantly among them (50).

The recent IPCC assessments have devoted little attention to the spatial extent of drought/dryness. Some recent studies have reported significant expansion of dryness globally in both observational records and projected results (e.g., 51); however, there exists some contrasting regional expressions (52). Instead of using actual evapotranspiration, some studies, which detected increasingly extensive dryness, used a controversial measurement of dryness by potential evapotranspiration, which tends to show strong tendency to exaggerate dryness coverage (53). Thus, additional evidence remains to be gathered to underpin or rebut the view of dryness expansion. Timescale is another critical parameter influencing trend estimates for droughts/dryness. A distinction is suggested between short-term and long-term droughts, because they may exhibit different trends in magnitude, and sometimes even in sign (2, p. 172; 3, p. 214). Trends of a much shorter-lasting type—flash droughts (shorter than a month)—have been investigated in some regions, showing that these events prefer to be concomitant with heat waves (54).

3.4. Tropical Cyclones

The IPCC AR4 reported that “it is likely that an increase had occurred in intense tropical cyclone activity since 1970 in some regions” (41, p. 239). But this message was contradicted by the SREX and a World Meteorological Organization assessment (55), which found that, with the
exception of the Atlantic Basin, there is low confidence in any observed long-term trend in tropical cyclone activity in other ocean basins, after accounting for past changes in observational system capabilities. Inhomogeneity in tropical cyclone records (e.g., different data sources, operational protocols, analysis methods, nonuniform improvements in observational technology) is the overarching constraints on the confidence of assessments. Some recent studies, using multiple datasets (some including satellite data), reported significant intensification of landing tropical cyclones in the northwest Pacific, with their lifetime-maximum intensity center advancing poleward significantly (56, 57). Such poleward migration of the intensity center seems a global-scale phenomenon (58). However, changes in duration and frequency remain equivocal based on existing evidence (59). For tropical cyclone-related extremes, apart from strong precipitation and wind, increases in storm surge and expansions in the scale of impacted zones have been detected (60, 61). Multiple lines of evidence still have to be incorporated into further assessments to draw more consistent conclusions about changes in tropical cyclones.

3.5. Compound Extremes and Simultaneous Extremes

Compound extremes, such as the above-mentioned concomitant heat waves and flash droughts, remain strikingly underexplored. Much of the existing analysis of extremes has adopted a univariate framework (2, p. 118). Nevertheless, compound extremes tend to be more devastating, due to their manifold impacts (62). Candidate definitions for compound extremes were actually presented in SREX (2, p. 118) as: (a) two or more extreme events occurring simultaneously or successively, (b) combinations of extreme events with underlying conditions that amplify the impact of the events, or (c) combinations of events that are not themselves extremes but lead to an extreme impact when combined. The constituent events can be of similar (clustered multiple events) or different type(s). However, changes in compound extremes were not assessed in SREX and AR5. Recent studies have started to develop definitions and dedicated statistical frameworks (mainly based on empirical methods, copulas, and Markov chains) to measure compound extremes and evaluate their changes, e.g., heat wave–drought (11, 63), extreme precipitation–storm surge (64), and hot extreme–air pollution (65). Particularly, each constituent component may be moderate or even non-extremes (e.g., precipitation near 0°C), but interplayed/overlaid impacts may result in severe impacts. This can be illustrated with the 2014 California drought. The return period for the precipitation deficit in this event is approximately 24 years, but the combination of dry and scorching conditions renders this event much more dangerous as a 1-in-200-year event (see 66, figure 3). Moreover, the magnitude and significance of trends for compound extremes may be much greater than for each component (63, 65). The inspection of compound extremes therefore permits accentuation of changes and resultant risks that in many instances would be overlooked or underestimated by analyzing univariate extremes (62).

Recent studies have also proposed simultaneous extremes, a type of extreme event marked by the coincidence of extremes in adjacent or remote regions (67). The notion of compound extremes emphasizes the temporal linkage of multiple extremes in the same place, whereas the notion of simultaneous extremes attaches more emphasis to spatial connections among extremes. Adverse impacts of simultaneous extremes are not only sourced from their extraordinary magnitude, but are also enhanced by their extensive coverage, which poses special challenges for organizations coping with disasters across different countries/regions (2, p. 155). The spatial connection of simultaneous extremes is associated with recurrent large-scale circulation drivers, e.g., regional or global teleconnection and intraseasonal oscillations (65, 68). Few standard methods currently exist to define and identify such spatial linkage of extremes, so little has been known about their climatologic statistics and changes.
4. ATTRIBUTION OF OBSERVED CHANGES IN EXTREMES

4.1. Recent Developments

Attribution of climate change is formally defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence (69). Such a definition clearly delivers two core aspects, i.e., trend attribution and event attribution. In AR5, Chapter 10 was dedicated to the assessment of progress in detection and attribution, with attribution of extremes involved. In SREX Chapter 3, “the causes behind the changes” also centered on anthropogenic contributions to detected trends of extremes. For event attribution, at the time of the AR5 cycle (2, 3), it is claimed that “anthropogenic warming remains a relatively small contributor to the overall magnitude of any individual short-term event (3, p. 916), so attributing a single extreme event to a specific cause remains challenging” (2, p. 127).

The rapid development of attribution science, particularly in the field of event attribution, has progressively updated our knowledge about anthropogenic influences on many individual extremes and classes of events. Since 2012, the Bulletin of American Meteorological Society (BAMS; 70–74) published a special issue each year to perform attribution analyses on the previous year’s high-impact events. As indicated by the statistics in the 2016 issue (71), among all types being investigated over the past five years, approximately 65% of papers reported that human-caused climate changes alter their frequency and/or intensity in a measurable manner. The event types most-frequently investigated are heat waves (29 papers, 28%), heavy rainfall events (24 papers, 23%), and droughts (17 papers, 16%). Almost all studies on temperature extremes (28/29) found an imprint of human-caused climate change, in spite of varying contributing degrees; whereas for precipitation extremes, the majority (62%) did not find human influences on the event. Results of drought attribution are split with approximately 50% finding and 50% not finding a role of climate change. Since the 2014 issue (70), attribution of storminess began to appear but attribution of occurrence of devastating storms to any anthropogenic cause remains challenging. Two studies on wild fire both concluded that human-induced climate change possibly has increased the risk of fire. But widespread uncertainties still remain, due to models’ improper representation of local human interference (e.g., human ignition and suppression) and small-scale nature phenomena such as lightning caused by thunderstorms (75, p. 115). Although attribution of individual tropical cyclones is becoming technically possible (75, p. 111), attribution of single tropical cyclones, with anthropogenic influences quantitatively partitioned, has not been performed to date. For local-scale extremes (such as tornado and hail), constrained by observations as well as models’ inability in resolving micro-physical processes, almost no attribution conclusions have been reached. A growing range of methodologies and novel event types (e.g., extreme sunshine, snowpack droughts, and sunny day flooding) are emerging (71).

Caution is warranted when interpreting attribution conclusions on individual events (76), as results may be fairly sensitive to the used data (availability, spatial coverage, record length, quality, etc.), types of extremes, ways of framing questions (77), attribution methods (78), the selection of coupled versus atmosphere-only models, and their ability to reproduce key physical processes (79, 80). In particular, poorly understood large-scale dynamics, slow-varying internal variability modes (e.g., PDO, AMO), and their interactions may mask the anthropogenic signals that should have been detected by the attribution method used (75, 81–83). Uncertainties may also be added by climate models’ systematic overestimation in thermodynamic feedbacks (84) or strong model dependency (85).
4.2. Changes in Dynamic Drives: Large-Scale Circulation Patterns

The IPCC AR5 focused on changes in certain types of circulation regimes, but disconnected them from changes in characteristics of extremes. Compared to thermodynamic drivers, dynamic arguments have been subject to few discussions and have substantially larger uncertainties (83). To fill this obvious gap, several recent studies directly attributed trends of extremes to significant changes in various features (frequency, duration, and amplitude) of responsible weather patterns (86, 87, 88). For instance, Horton et al. (88) attributed much (~75%) of the recent increases in cold extremes over central Asia to a robust increase in “ridge-trough” pairs (see 88, figures 4b,f), reasonably explaining the phenomena deviated from the prevalent warming backdrop. García-Valero et al. (89) reported a fairly high contribution (~50%) of changes in circulation patterns in determining trends of hot extremes in Spain and the Balearic Islands. Chang et al. (90) revealed that the weakening activity of extratropical cyclones led to the warming of maximum temperature in the mid-latitudes in Northern Hemisphere. When examining dynamical drivers of changes in weather and climate extremes, one must evaluate and specify uncertainties stemming from the methodology for identifying circulation patterns (91). Albeit the commonly performed separation between dynamic and thermodynamic changes in attribution studies, whether and how atmospheric circulations respond to anthropogenic warming should also be checked, to make the adopted attribution method more physically sound (92).

4.3. Changes in Thermodynamic Drivers

Thermodynamic contributions to changes in extremes have been well understood from both theory and observations. An illustrating example is the upward trend in hot extremes and downward trend in the majority of cold extremes because of the continuous heat accumulation in the atmosphere (2). In theory, as temperature keeps rising, increased water holding capacity in the atmosphere will facilitate heavier precipitation, a mechanism known from atmospheric physics, which has been validated by observational studies around the globe (93). Similarly, such increased water holding capacity may also elevate the amount (intensity) of snowfall extremes in a warmer climate (37, 94). Beyond above straightforward contributions, surface warming could also aggravate precipitation extremes via enhancing thermodynamic instability (95).

4.4. Changes in Surface-Atmosphere Interactions

A large body of literature has highlighted the important role of soil-atmosphere interactions in the onset and enhancement of heat waves (e.g., 96). However, most of them only focused on single cases, leaving changes in the land-atmosphere coupling and their contributions to changes in hot extremes less explored. Several recent works suggested that enhanced land-atmosphere couplings have resulted in a growing number of extremely hot-dry summers (11, 63, 85). The covariance between changing circulations and surface conditions as well as associated feedbacks should also be considered. For instance, during winter, warming-induced losses of sea ice and snow cover may alter local albedo and heat fluxes, which can in turn excite or modulate local or remote circulation anomalies, potentially affecting winter cold extremes at mid-latitudes (18, 97). During summer, the coexistence of low soil moisture and blocking high acts to markedly lengthen the duration of heat waves through cascading feedback processes (98).
4.5. Atmospheric Rivers and Hydrological Extremes

We have previously discussed how large-scale atmospheric circulation can affect extreme events. At a smaller spatial scale, atmospheric rivers (ARs; long, narrow filaments of large integrated water vapor transport) also play an important role in the occurrence and changes in hydrological extremes, such as precipitation extremes, heavy snow, floods, and droughts (99). However, AR5 and SREX presented almost no assessments about ARs and their interplay with extremes. New datasets (reanalysis, satellite observations, and aircraft dropsondes) and detection methods have provided new insights about ARs and their impacts (100), indicating positive contributions from landfalling ARs to occurrences of precipitation extremes (including heavy snow), especially to severest cases along coastal and mountainous regions in North America and Europe (101, 102). Largely relying on process-based analyses or composites, these studies have rarely estimated changes in key properties (such as frequency, intensity, scale, and persistency) of ARs and their connections to changes in precipitation extremes. Changes in ARs essentially reflect a juxtaposition of changes in dynamic (circulations) and thermodynamic (atmospheric moisture) effects.

4.6. Challenges and Opportunities for Event Attribution

Although the current warming tendency directs major scientific attention toward hot extremes, attribution of cold extreme events (cold temperatures, heavy snowfall, and ice events) have also emerged in the BAMS annual reports (70–72). There are different prevailing views in making sense of cold extremes in a warming climate: One is that severe or even record-breaking cold extremes arose mainly from natural variability (e.g., rare pattern of atmospheric circulation); the other interpretation is that without anthropogenic warming, cold extremes should have happened more frequently and with much greater severity. For instance, circulation analogue methods have shown that the record negative North Atlantic Oscillation and strong blockings in Europe during winter 2009–2010 would have triggered much colder weathers than observed if it had happened a few decades ago (103). The confidence of attribution for cold extremes is hampered by models’ inability to simulate cold temperatures for the right reasons (such as clear skies, calm conditions, wind chills, and multidecadal variability) (75, p. 89). Additionally, the attribution for changes in cryosphere extremes requires first the construction of universal metrics assessing heavy snow and ice events, followed by coordinated attribution efforts (75, p. 102).

Precipitation extremes are most often ascribed to internal variability, due to atmospheric circulation patterns and sea surface temperature anomaly patterns (El Niño and PDO). Even for studies successfully detecting anthropogenic signals, natural variability can still play a governing role (see, e.g., Australia’s heavy precipitation in March 2012, in Reference 73). Similar situations also prevail in attribution of droughts (Argentina’s heat wave in December 2013, in Reference 72). Specifically, in drought attribution, anthropogenic effects contribute more to hot condition, whereas natural variability seems more dominant in facilitating dry condition (lack of precipitation) (2014 droughts in Horn and Singapore in Reference 72; 2015 western Canada drought, 2015 Indonesia drought, and 2015 southern Africa drought in Reference 71). As multiple interacting causes of individual droughts have not been fully understood, an alternative feasible method for drought attribution is to disentangle droughts into attributable components (temperature, precipitation, winds, and evapotranspiration). Emerging approaches for drought attribution also include the use of a large ensemble of climate simulations combined with a full hydrologic model (104).
We stress that the failure in detecting anthropogenic signals does not prove anthropogenic climate change had no influences on those events (76). Vice versa, attribution studies of individual events should not be used to be generalized as the impact of climate change on extreme events as a whole (75, p. 129). Geographical coverage and type of events being already investigated remain markedly patchy and based on the interests and capabilities of individual research groups (80); as such, their representativeness of other areas and types is problematic. Local-scale anthropogenic effects, such as emissions of aerosols, land and water use, irrigation, and urbanization, can now be incorporated into future attribution analyses by utilizing single-forcing simulations (e.g., the 2014 hot spring in northern China, 2014 Himalaya snowstorm, and 2014–2015 southeast Brazil drought, discussed in References 72 and 105). Future attribution efforts are also expected to better account for indirect influences of anthropogenic climate warming, such as heating SSTs and moistening air, conditioned on certain weather regimes (94, 104).

It is essential to deepen the understanding of the role of dynamics and thermodynamics in the evolution of extremes and their potential responses to anthropogenic forcers (75, 81, 104). Recently, Vautard et al. (87) and Freychet et al. (106) built physically sound attributions by clearly addressing the way in which anthropogenic forcers influenced dynamic and thermodynamic drivers responsible for the occurrence and evolution of extremes. These physically sound attribution approaches favor enhancing confidence and broadening implication of attribution conclusions (75, 80).

In the annual BAMS attribution reports, several different studies, using differing attribution approaches, distinct observational datasets, and climate models, targeted at the same cases (e.g., precipitation and droughts), but reported pronouncedly equivocal conclusions (such as the 2013–2014 California droughts in Reference 70 and 2014 East Africa droughts in Reference 72). Such intercomparisons are imperative to trace sources of uncertainty which would not have emerged from single studies. Accordingly, it is suggested that the confidence of event attribution could be improved by the development of transparent community standards (75), which may include quality-controlled data, consistent definitions, and a well-accepted multimodel and multimethod framework (107). Such efforts have been implemented by Angélil et al. (78), who used a single analytical approach and a single set of climate model and observational data source to revisit events analyzed in BAMS reports. Their conclusions do disagree with previous results about attribution of precipitation extremes.

In addition to event attribution, impact attribution has emerged and has been highlighted in the 2016 BAMS assessment report (case No. 14 in Reference 71), and is further recommended as a key area with opportunities for future progress (108). In the AR5 cycle, the subsection (18.4.3.2) on “Attribution of the Impacts of Single Extreme Weather Events to Climate Change” in the WG-II report (109) merely listed the observed consequences (e.g., economical losses) during some high-profile cases, but didn’t build the connection of these losses to anthropogenic warming. In contrast, Mitchell et al. (2017; case No. 14 in Reference 71) clearly stated that “human discomfort increased due to anthropogenic climate change,” and quantitatively partitioned the contribution of anthropogenic warming to the discomfort experienced during the 2015 Egypt heat wave. Impact attribution efforts have also been made toward the role of anthropogenic warming in increasing vulnerable populations’ exposure to deadly heat waves and dampening outdoor manual labor productivity (108). To provide rigorous and rapid answers to the concerns expressed by policymakers and by the general public—eager to make sense of extreme events—there is thus a potential to develop and implement operational (near real-time) attribution systems, as advocated by the 2011 BAMS special issue (74). The first step in this direction is the maturation of attribution theory and methodologies.
5. PROJECTED CHANGES IN EXTREMES

5.1. Projected Changes in Temperature Extremes

We have virtually certain confidence in projected substantial warming of temperature extremes by the end of the twenty-first century. New knowledge is expanding the projections of changes in frequency, intensity, and duration, especially through the assessment of future transitions among dominating types of hot extremes (daytime, nighttime, and complex type) and resultant impacts. For instance, Gershunov & Guirguis (110) found the coastal area of California would be seriously exposed to nighttime heat waves in the future, which has implications for public health and for the development of air conditioning, including energy needs. Concerning future impacts of hot extremes, projection studies have started to consider confounding effects from relative humidity for human health (using wet-bulb temperature or apparent temperature as a proxy; 10) and from soil moisture for crop yields and fire risks (11). Future shifts in the timing of occurrence of heat waves (late spring–early summer events; late summer–autumn events) are also of high relevance for human health, but they have been so far largely overlooked in most projection studies (111). Another burgeoning topic is the assessment of relationships between changes in regional temperature extremes against global mean surface temperature levels (112), with the scaling relationship (linear or nonlinear) being reportedly contingent on indicators (e.g., frequency, intensity, heat stress; 10, 93, 112). A robust scaling would enable a quantification of added or avoided regional risks from extremes at specific levels of future global temperature warming or cumulative CO₂ budget (112).

Further projection work is also needed on extreme cold events. Historical simulations in CMIP5 failed to capture the trend of enhanced wintertime cold extremes during the so-called hiatus period at mid- to high latitudes of the Northern Hemisphere (113). In a continuously warming climate, despite projected virtually certain decreases in frequency, the intensity and persistence of future cold-temperature extremes (until the late twenty-first century) may be as great as current cases in some regions (114, 115).

5.2. Projected Changes in Hydrological Extremes

Despite growing confidence of future increases in heavy precipitation, there still exist large uncertainties and pronounced model biases in projections of precipitation extremes (2, p. 147), arising from inadequate spatial-temporal resolution of models, flawed dynamical and statistical downscaling methods, and asymmetric changes in extremes of different intensities/durations. These gaps have motivated considerable efforts in post-AR5 studies to develop and use high-resolution models or to refine downscaling schemes (e.g., 116, 117).

Indeed, when the resolution of climate model is high enough to resolve correctly key processes affecting precipitation amounts, this strongly improves the accuracy of simulations and therefore the confidence for projections of precipitation extremes, especially for shorter-lived events at regional to local levels (118, 119).

Trenberth et al. (20) reported that current models remained largely incapable of representing the characteristics of subdaily precipitation extremes, for all aspects of frequency, intensity, duration, and intermittency. Some recent studies took advantages of convection-permitting models to evaluate future changes in subdaily precipitation extremes (119), and reported significant future growth in both frequency and intensity of short-duration events in some regions (120). The comparison between the observed scaling rate between subdaily precipitation extremes—temperature rise with their projected counterpart—has also received considerable interest since AR5 (29, 121).
Post-AR5 studies have highlighted large uncertainties and thus low confidence levels in the projections of both floods and droughts (47, 122). Much evidence is still needed to converge toward new understandings or consolidate existing conclusions on future changes in droughts and floods in different emission scenarios and for different regions. Despite diverging conclusions in projected changes in tropical cyclone activities, continuous improvements of climate models’ resolution and representation of key physical processes have increased the confidence in projecting future changes in typhoon intensity as well as their potential damages (123, 124).

5.3. Time of Emergence
In AR5, the concept of “time of emergence (ToE)” for climate averages was introduced as (3, p. 928) “when local mean climate emerges from the ‘noise’ of year-to-year variability,” but the ToE was not assessed for extremes. Since then, a burgeoning topic in the field of climate projection is to confirm possible ToEs of extremes, i.e., when influences of anthropogenic effects on extremes will emerge distinctly from the background noise of internal variability. Some studies assumed that emergence would only occur in the future (e.g., 125), whereas other studies detected ToEs that have already occurred in historical records, even as early as the 1930s (126). Such discrepancies arise mainly from differing statistical frameworks measuring the degree of departure (e.g., signal-to-noise ratio versus significantly shifted distribution; 125–128), different reference periods for comparison (126, 128), model structural differences (125), and dependence on emission scenarios (126, 129) and on the representation of internal climate variability, especially large-scale atmospheric circulation variability (130) and oceanic internal variability (129). Standardized methodologies are thus needed to identify and report sources of uncertainties for the identification of ToEs of extremes, to provide robust guidance for climate risk management and mitigation planning (129).

Both observed and projected ToEs exhibited conspicuous nonuniformity in geographical distributions (126, 128) and seasons (130). Despite these uncertainties, a general consensus could be generalized that the ToE for precipitation extremes is obviously later than that for temperature extremes (see 126, figure 1), even later than the twenty-first century in some areas under the business-as-usual scenario. Another consensus indicates that lower temperature variability in the tropics leads to earlier ToEs for temperature extremes there than higher latitudes (126, 127). The current studies on ToEs have overwhelmingly centered on temperature extremes, and secondarily on precipitation extremes, still leaving ToEs for other types, such as droughts, floods, tropical cyclones, oceanic extremes, and compound extremes, strikingly underexplored.

5.4. Projected Changes Compatible with Specific Global Warming Levels
The Paris Agreement, which committed governments worldwide to “holding the increase in global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C,” has inspired considerable new efforts to answer in what way and to which extent extremes will respond to global warming at specific levels (see https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf). Exact evaluations for implications of these specific warming levels require consistent definitions and common methodologies. The baseline, i.e., preindustrial period, needs first to be defined explicitly and used consistently (131, 132); however, this crucial concept was strikingly specified neither by the UNFCCC (United Nations Framework Convention on Climate Change) nor by AR5, leading to a highly variable reference period used in the literature. The second methodological issue relates to the way unfolding the 1.5°C and 2°C warmer world. Rogelj et al. (133) recommended using specific warming levels that refer to anthropogenic-driven changes in climatological
averages (normally 20 or 30 years) of global mean surface temperature relative to preindustrial levels, rather than a single year when these levels of warming are reached, as the latter is heavily influenced by internal climate variability. A common understanding of how to define a global warming of 1.5°C or 2°C not only lays a solid basis for estimating projected responses of extremes, but also matters for carbon budget estimates compatible with specific warming levels (112, 132, 133).

At the current stage, the most commonly used tools to quantify projected changes of extremes at 1.5°C and 2°C levels are CMIP (Coupled Model Intercomparison Project in AR5, 3) scenario-driven experiments (134, 135). However, these RCP (Representative Concentration Pathways) based model outputs are somewhat limited in addressing impacts at 1.5°C, owing to their coarse resolution, large uncertainties, relatively small ensembles of initial condition, and inadequate consideration of mitigation scenarios (136, 137). Although RCP 2.6 could provide some samples never exceeding 2°C, the differentiation between 1.5°C and 2°C seems basically impossible (138) in this low-emission scenario. Moreover, identified 1.5°C and 2°C warmer worlds using higher emission scenarios in the CMIP dataset represent a transient status, which have clear warming trends during the 20 or 30 years used for period framing and will be passed through after this period (139). In this context, whether and how projected changes in extremes are sensitive to the RCP selection should be documented more definitively (compare 112 and 139), as this is particularly critical for projection of hydrological extremes (136). New dedicated simulations, sometimes including temperature overshoots, have already been designed to explore the implications of stabilized levels of global warming [e.g., HAPPI (138) and CESM (140)]. Several recent studies have used these dedicated simulations to investigate potential impacts of stabilized 1.5°C and 2°C of global warming on hot extremes (141, 142), heavy precipitation (143), and droughts (144), with some of the derived results being distinct from those in transient warming worlds. Regardless of pathways (different RCPs and long-term stabilized status) to achieve these temperature targets, extremes are projected to increase in frequency and intensity in a 1.5°C warming world compared to today, but adverse consequences would be substantially reduced compared with 2°C and higher warming levels (134, 144), in particular for hot temperature extremes and droughts (135, 141). Larger uncertainties still exist in projections of precipitation extremes associated with 0.5°C differences in global warming levels (93, 135). Responsive changes in extremes in observational records have also been revisited with respect to the recent observed global warming of 0.5°C (145). Results indicate that the global warming of this magnitude has already exerted detectable impacts on observed increases in the frequency, intensity, and duration of extremes (145). The quantification of avoided risks would particularly profit from a regional-scale implementation that permits identifying hot-spots and potential tipping points (112). The usage of ensembles of high-resolution regional climate projections, such as CORDEX (Coordinated Regional Climate Downscaling Experiment), could offer added values to inform regional risk assessment and adaptation planning with respect to specific warming levels (146). Regional to local anthropogenic forcings such as aerosols and land use changes accompanying emission scenarios also need to be considered, because they may pose noticeable impacts on extremes for the same level of global warming (147).

Even in the context of climate stabilizations, future changes in extreme events may be affected by the rates (rapid versus gradual) of warming toward 1.5°C/2°C and the occurrence of temperature overshoots with different temporal spans and peaks (140). Few existing studies have quantified the implications of these diverse trajectories approaching the equilibrated warming targets on changes of extremes, especially due to the lack of outputs for overshoot scenarios. In particular, some insights into effects of temperature overshoots could be gained from studies centering on committed warming, which actually reflects lagged consequences of existing anthropogenic emissions (142,

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Similarly, if the global mean air temperature warming was to stabilize at 1.5°C and 2°C level, studies are needed to assess the committed variations in the characteristics of extremes, especially for the ocean (e.g., sea level) and cryosphere components (e.g., sea ice, permafrost, glacier), which are characterized by lagged responses (149).

6. CONCLUSIONS

Reviewing progress through post-AR5 studies, we have identified emerging research directions, the maturation of the science of climate extremes since the AR5, as well as scientific gaps. We have highlighted burgeoning topics associated with very active researches covering detection, attribution, and projection of temperature and precipitation extremes, as well as recent developments related to topics granted with low confidence in the AR5 (e.g., drought, tropical cyclones). We have also emphasized the societal importance of multidimensional approaches for investigating extremes, considering compound and simultaneous extremes. Since the AR5, major progress has been accomplished in the framing of dynamic and thermodynamic drivers of extremes. Below we list identified key gaps and their progress, along with some challenges and prospects.

6.1. Temperature Extremes

In addition to frequency and intensity, duration, spatial scale, occurrence timing, and transitions of prevailing types (e.g., daytime-nighttime-complex, dry heat wave–humid heat wave) should be incorporated into the assessment of temperature extremes in detection, attribution, and projection. New information is under development to frame and assess changes in marine heat waves, and their impacts on marine ecosystems. The recent cooling over Eurasia and North America renewed the scientific attention toward cold extremes, yet with conclusions about trends and underpinning mechanisms obviously diverging or even opposing.

6.2. Precipitation Extremes

Basically, as the climate warms, subdaily precipitation extremes intensify obviously. However, calculated scaling rate of intensification against temperature rise varies among literature. The scaling relationship also conditions on seasonal evolutionary weather patterns, types of stratiform/convective cloud cells, local topography, and regional to local anthropogenic influences (land cover change and aerosols). Projection of changes in subdaily precipitation extremes increasingly relies on convection-permitting models, which rightly resolve the relevant mesoscale physics. At both regional and global scales, observed and projected changes in extreme snowfall and freezing rain near 0°C have been emphasized in post AR5-studies.

6.3. Droughts and Tropical Cyclones

Among post-AR5 studies, the confidence for any observed and projected changes in droughts seemingly remains low. Limitations associated with drought metrics can be circumvented by analyses of directly observed ground-based/remote-sensed variables (e.g., precipitation, streamflow, and soil moisture) in commensurate with targeted categorization (meteorological drought, agricultural drought, and hydrological drought). Any detected and projected trends for tropical cyclones should be treated with enough caution, except for increases in their intensity and damages in some coastal areas, and a poleward migrating trend of the maximum intensity center around the globe.
6.4. Compound and Simultaneous Extremes

Both compound and simultaneous extremes emphasize the imperative to adopt a multivariable framework to investigate extremes, with the former one centering on the temporal linkage and the latter one accentuating spatial connections of multiple extremes. Definitions, statistic methods, trend estimates, and risk quantification for compound extremes have experienced extensive progress. There are only a few studies on definitions and trend estimates for simultaneous extremes. Research on attribution and projection of compound and simultaneous extremes remain scarce.

6.5. Changes in Drivers for Extremes

The AR5 did not assess exhaustively the linkage between changes in thermodynamic-dynamic drivers and trends for extremes. New studies have estimated the trend for frequency, duration, and amplitude for large-scale circulation patterns (on a daily scale), and further used these dynamic changes to explain changing characteristics of extremes. Other studies ascribed trends for extremes to evolutionary thermodynamic drivers, such as warming-induced moistening tendency and instable atmosphere for precipitation extremes, strengthened soil-air coupling for hot-dry extremes, and increasing atmospheric rivers for coastal and inland downpours.

6.6. Event Attribution

Rapid development of event attribution makes it possible to answer whether and to which extent anthropogenic climate changes contribute to the characteristics of a particular high-profile event. Although human-induced warming has already affected most of the studied hot extremes, consensus about the role of anthropogenic warming is still hard to reach for other types of extreme events. The state of knowledge is limited by the patchy selection in studied event types, indicators, and regions in existing attribution analyses. The robustness and implication of attribution conclusions are also limited by the representation of local human interventions in models (e.g., local land use/change and aerosols), the understanding of the relationships between global warming and dynamic drivers (circulations), and methods to account for slow-varying modes (e.g., PDO and AMO). Impact attribution and operational attribution are fertile fields for future progress.

6.7. Burgeoning Topics in Projection

The exact timing when anthropogenic influences on extremes markedly emerge from internal noisy variability, as termed the “time of emergence (ToE),” is crucial for future preparedness against climate-change consequences. In this regard, post-AR5 literature has mainly addressed past versus future ToEs, uncertainties, and determinants influencing ToE identifications. The Paris Agreement has inspired studies on changes in extremes compatible with specific warming levels instead of prescribed emission scenarios, as handled in the AR5. Both CMIP5 outputs and newly designed dedicated experiments have been employed to start quantifying future changes in extremes in a 1.5°C and 2°C warmer world, and further assessed added and avoided risks benefiting from the 0.5°C global warming difference. Gaps are related to the implications of transient warming versus climate stabilization, the implications of temperature overshoots, and the assessment of extremes associated with the lagged responses of the ocean and cryosphere.

Despite these gaps, scientific research in detection, attribution, and projection of extremes has achieved remarkable progress during the past five years. A more precise understanding of changes
in extremes would benefit from coordinated efforts in increasing the quality and availability of observational data, formulating clear and well-accepted definitions, enhancing the comprehension of thermodynamic-dynamic mechanisms and their responses to anthropogenic forcings, refining detection-attribution methods, and improving the representation of physical processes leading to extremes in models.

SUMMARY POINTS

1. Since the IPCC AR5, considerable advances in detection, attribution, and projection of extremes have been made in terms of theoretical frameworks, methodologies, and physical understandings.

2. New definitions, classifications, and indices are under development to frame and measure changes in both land-based and oceanic temperature extremes.

3. Changes in subdaily precipitation intensity may be conditioned on temperature-independent factors, which make the relationship between subdaily precipitation and air temperature more complex than previously assumed.

4. The current lack of high-quality direct observations of related variables still constrains the confidence for observed and projected changes in droughts and tropical cyclones.

5. The field of event attribution has experienced rapid development, but the state of knowledge is limited by the patchy selection of events, indicators and regions, as well as by poor understanding of large-scale dynamics and their interplay with anthropogenic warming.

6. Analysis of simulations dedicated to stabilized levels of global warming indicates that limiting the global warming at 1.5°C instead of 2°C would make a big difference in terms of reducing/avoiding risks related to extremes.

FUTURE ISSUES

1. Theoretical frameworks and statistical methods for defining and quantifying changes in compound extremes and simultaneous extremes need to be developed to improve risk assessment and management.

2. Efforts to build a direct linkage between changes in characteristics of extremes and changing dynamic-thermodynamic drivers are worth enhancing, to make detection and attribution methods more physically sound and to promote the confidence of attribution conclusions.

3. The time of emergence of a novel regime of extremes is a burgeoning topic, and is critical for adaptation and mitigation planning against climate risks. Reducing uncertainties of evaluated time of emergence calls for standardized methodologies, which at least require the consistent use of a statistical framework and reference period.

4. To differentiate risks of extremes in a 1.5°C and a 2°C warmer world, more efforts need to be exerted to better account for implications of transient warming versus climate stabilization, temperature overshoots of diverse temporal spans/magnitudes, and lagged responses of the ocean and cryosphere.
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