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Global observed long-term changes in temperature and precipitation extremes: A review of progress and limitations in IPCC assessments and beyond

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ABSTRACT

The Intergovernmental Panel on Climate Change (IPCC) first attempted a global assessment of long-term changes in temperature and precipitation extremes in its Third Assessment Report in 2001. While data quality and coverage were limited, the report still concluded that heavy precipitation events had increased and that there had been, very likely, a reduction in the frequency of extreme low temperatures and increases in the frequency of extreme high temperatures. That overall assessment had changed little by the time of the IPCC Special Report on Extremes (SREX) in 2012 and the IPCC Fifth Assessment Report (AR5) in 2013, but firmer statements could be added and more regional detail was possible. Despite some substantial progress throughout the IPCC Assessments in terms of temperature and precipitation extremes analyses, there remain major gaps particularly regarding data quality and availability, our ability to monitor these events consistently and our ability to apply the complex statistical methods required. Therefore this article focuses on the substantial progress that has taken place in the last decade, in addition to reviewing the new progress since IPCC AR5 while also addressing the challenges that still lie ahead.

1. Introduction and definitions of temperature and precipitation extremes

From droughts to flooding rains and damaging frosts to heatwaves, there is no doubt that climate extremes are of substantial societal importance. Observations provide a key foundation for understanding their long-term variability and change and for providing the underpinning for climate model evaluation and projections. The Intergovernmental Panel on Climate Change (IPCC) Working Group I Fifth Assessment Report (AR5; Intergovernmental Panel on Climate Change (IPCC) et al., 2013a, 2013b) and specifically the Chapter dealing with Observations: surface and atmosphere (Hartmann et al., 2013) assessed the latest literature (at that time) on global and regional changes in climate extremes. For temperature and precipitation extremes, they assessed that over land the number of warm days and nights had *very likely* increased, the number of cold days and nights had *very likely* decreased and that heavy precipitation events had *likely* increased in more regions than they had decreased (see Supplementary material for a description of italicised terms). This assessment represents the culmination of research from many researchers from around the globe over many years. Despite this, there are still many gaps in data and in our understanding of changes.

While information on the number of days above and below fixed thresholds (e.g. number of frost days in a year) has been published routinely since the 19th century it was not until the second half of the 1990s that the first papers appeared using relative thresholds for daily extremes (e.g. Karl et al., 1996; Plummer et al., 1999). Subsequently a lot of effort went into the coordination of studies on temperature and precipitation extremes, led by groups such as the Asia Pacific Network (e.g. Manton et al., 2001) and the European Climate Assessment (e.g. Klein Tank et al., 2002; Moberg et al., 2006), so that they can be inter-compared and assessed on a large regional scale. Much of the coordination and analysis on a global scale (and in many developing countries) has been done under the auspices of the Expert Team on Climate Change Detection and Indices (ETCCDI)[1]. Even with such coordination, the collation and analysis of extremes datasets has not been straightforward (e.g. Nicholls and Alexander, 2007). One

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[1] A joint group of the World Meteorological Organisation (WMO) Commission for Climatology (CCl), the World Climate Research Programme (WCRP) and the Joint Commission for Ocean Monitoring (JCOMM)-http://www.wcrp-climate.org/etccdi

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2212-0947/

Table 1

: Extreme temperature and precipitation indices recommended by the ETCCDI. The full list of all recommended indices and precise definitions is given at http://etccdi.pacificclimate.org. Indices in bold are those used in the IPCC Fifth Assessment Report (IPCC 2013 – see P 221).

ID	Indicator name	Indicator definitions	Units
TXx	**Max Tmax**	**Monthly maximum value of daily max temperature**	**°C**
TNx	**Max Tmin**	**Monthly maximum value of daily min temperature**	**°C**
TXn	**Min Tmax**	**Monthly minimum value of daily max temperature**	**°C**
TNn	**Min Tmin**	**Monthly minimum value of daily min temperature**	**°C**
TN10p	**Cool nights**	**Percentage of time when daily min temperature < 10th percentile**	**%**
TX10p	**Cool days**	**Percentage of time when daily max temperature < 10th percentile**	**%**
TN90p	**Warm nights**	**Percentage of time when daily min temperature > 90th percentile**	**%**
TX90p	**Warm days**	**Percentage of time when daily max temperature > 90th percentile**	**%**
DTR	Diurnal temperature range	Monthly mean difference between daily max and min temperature	°C
GSL	Growing season length	Annual (1st Jan to 31st Dec in NH, 1st July to 30th June in SH) count between first span of at least 6 days with TG > 5 °C and first span after July 1 (January 1 in SH) of 6 days with TG < 5 °C	days
FD0	**Frost days**	**Annual count when daily minimum temperature < 0 °C**	**days**
SU25	Summer days	Annual count when daily max temperature > 25 °C	days
TR20	**Tropical nights**	**Annual count when daily min temperature > 20 °C**	**days**
WSDI	Warm spell duration indicator	Annual count when at least 6 consecutive days of max temperature > 90th percentile	days
CSDI	Cold spell duration indicator	Annual count when at least 6 consecutive days of min temperature < 10th percentile	days
RX1day	**Max 1-day precipitation amount**	**Monthly maximum 1-day precipitation**	**mm**
RX5day	**Max 5-day precipitation amount**	**Monthly maximum consecutive 5-day precipitation**	**mm**
SDII	**Simple daily intensity index**	**The ratio of annual total precipitation to the number of wet days (> =1 mm)**	**mm per day**
R10	Number of heavy precipitation days	Annual count when precipitation > =10 mm	days
R20	Number of very heavy precipitation days	Annual count when precipitation > =20 mm	days
CDD	**Consecutive dry days**	**Maximum number of consecutive days when precipitation < 1 mm**	**days**
CWD	Consecutive wet days	Maximum number of consecutive days when precipitation ≥ 1 mm	days
R95p	**Very wet days**	**Annual total precipitation from days > 95th percentile**	**mm**
R99p	Extremely wet days	Annual total precipitation from days > 99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total precipitation from days ≥ 1 mm	mm

reason is that few meteorological services have the capacity or mandate to freely distribute daily data. Another reason is that rigorous quality control needs to be applied to extremes data to make it suitable for long-term analysis and this can often be too laborious or too difficult to apply (see Section 2). Since the IPCC Third Assessment Report (TAR) highlighted that there were many gaps in the global assessment of temperature and precipitation extremes (Folland et al., 2001), the ETCCDI has organised and run a series of regional workshops in data sparse areas of the globe to fill in these data gaps (Peterson and Manton, 2008) in addition to overseeing the development of a standard software package (RClimDex[2], Zhang et al., 2011) which calculates a number of extremes indices derived from daily data. Despite the fact that the daily data are rarely exchanged, there have been few obstacles in exchanging the climate extremes indices data which have been combined into global datasets for assessment (e.g. Frich et al., 2002; Alexander et al., 2006; Donat et al., 2013b). Specifically, the ETCCDI developed a suite of 27 indices (Table 1) that are derived from daily temperature and precipitation data to represent the more “extreme” ends of the probability distribution (Zhang et al., 2011) and these have been used widely in IPCC and other assessments.

Extremes are rare by definition and this means it takes longer time periods and often better resolution in both space and time to properly characterize long-term changes in extreme events. However, the term “extreme” can be classified in different ways and the language used in climatology can be imprecise in this regard making the job of clearly articulating hypotheses and analyses all the more difficult (Seneviratne et al., 2012; Zwiers et al., 2013). In statistics, extremes are often defined using Extreme Value Theory (EVT) and its variants (Coles, 2001) and usually require analysis using quite sophisticated techniques. While there has been some limited success in analysing observed temperature and precipitation extremes using these types of methods on a global scale (Westra et al., 2013, Brown et al., 2008), as techniques become more sophisticated, their implementation becomes computationally very expensive on these large scales (Westra et al., 2013) so there is an increasing need for us to be cleverer in how we use computer resources. In addition, often the data that are required for such analysis (usually daily or sub-daily station data) are not available due to restrictions set by data providers. The indices developed by ETCCDI do not often suffer from these data restrictions and while many of them could be classified as “moderate extremes” (Klein Tank et al., 2009) since they reflect events that occur at least once per year, it does generally make them more statistically robust. Hence for these reasons much of the climate literature over the past two decades has focussed primarily on these more moderate extremes which are more readily available, and more robust to analysis from less sophisticated statistical methods (Klein Tank et al., 2009). This has generally led to more robust statements being made through time with subsequent IPCC Assessment Reports and has formed the basis for our understanding of how temperature and precipitation extremes have changed globally over the observational record.

Despite the extensive progress that has been made in recent years, there are still a number of limitations regarding the assessment of temperature and precipitation extremes (Zwiers et al., 2013). For example, a number of studies have shown differences between different precipitation datasets including their representation of extremes (Avila et al., 2015; El Kenawy and Mccabe, in press; Guo et al., 2015) and critical gaps exist in the amount, quality, consistency and availability of data (Alexander et al., 2015; Zwiers et al., 2013). This is a particular issue for precipitation data. Large uncertainties also relate to how gridding methods are applied and what assumptions are made (e.g. Dunn et al., 2014). A major problem for extremes is that they are

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[2] http://etccdi.pacificclimate.org/software.shtml

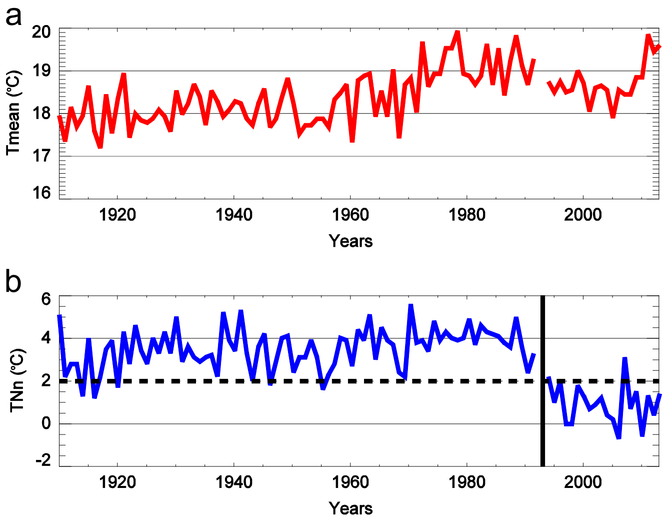

Fig. 1. Example of how inhomogeneity can affect extremes differently from the mean. Top panel shows annual mean temperatures for Perth, Australia while bottom panel shows the annual daily temperature minima at the same location. The solid vertical line indicates a station move in 1993 and the dashed horizontal line indicates a 2 °C threshold below which there were few annual minima before the station move but after which almost all years are below this threshold (data courtesy Blair Trewin and the Australian Bureau of Meteorology).

particularly sensitive to “scaling issues” in which there is a fundamental mismatch between the spatial representativeness of point-based and gridded values (e.g. Chen and Knutson, 2008; Alexander and Tebaldi, 2012; King et al., 2013; Gervais et al., 2014). These data issues are not just important for climate observations research but if not properly addressed are also critical, for example, for impacts studies or attribution of climate extremes (e.g. see Easterling et al., this issue). Avila et al. (2015) recently showed that this point versus grid mismatch combined with uncertainties related to the gridding method by which temperature and precipitation extremes were calculated, could lead to substantial differences in return period estimates. Specifically they showed in their study region that a 1 in 100 year return value from one method could be equivalent to about a 1 in 5 year return value in another when considering annual daily temperature or precipitation maxima. This difference was mostly related to the ‘order of operation’ in which extremes were calculated. One could imagine that this might have serious implications for engineering or design strategies particularly in trying to plan for the future under climate change. Despite these substantial differences however their analysis suggested that the impact on long-term trends and inter-annual variability was minimal.

Clearly there are many ways to assess historical changes in temperature and precipitation extremes. In the last few years, the climate community has already produced a comprehensive review of the challenges involved (Zwiers et al., 2013) and in 2012 the IPCC produced a Special Report Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) with a chapter which included observed changes (Seneviratne et al., 2012). Therefore this review is necessarily limited so as not to repeat those comprehensive assessments and in order to be concise I will focus on relatively narrow definitions of temperature and precipitation extremes with most focus on those events which are land-based. It is however important to provide some context to global analyses by reviewing the history of the assessment of extremes and recounting some of the issues that continue to be faced. Thus the purpose of this paper is to look primarily at global changes in temperature and precipitation extremes as defined through the indices of the ETCCDI with a focus on some of the major advances in the analysis of observed temperature and precipitation extremes over the period of the IPCC assessments and importantly to highlight where there are still gaps. Then some new insight is revealed by providing an update from global coordination initiatives and relevant literature that has appeared since the AR5. Finally I will discuss some limitations going forward.

2. The importance of data quality and consistency when studying extremes

Before undertaking any analyses of extremes, whether it is at a regional or global level, it is particularly important to ensure that the input data are of high quality and free from artificial inconsistencies (so-called inhomogeneities). Nicholls (1996) observed that a major problem undermining our ability to determine whether extreme weather and climate events were changing was that it is more difficult to maintain the long-term homogeneity of observations required to observe changes in extremes, compared to monitoring changes in means of variables. Inhomogeneities affecting station records can most commonly be introduced through site moves, changes in instrumentation, changes in local site conditions (through urbanization for example), or changes in observing practices (Trewin, 2010). Removing these inhomogeneities is particularly important because errors or inconsistencies are likely to show up as outliers or ‘extremes’ and may be erroneously included in analyses unless correctly accounted for (Nicholls and Alexander, 2007). Conversely, real extremes may be incorrectly removed or flagged as being suspect.

As an example, Fig. 1 illustrates how a station move can have differential impacts on the extremes compared to the mean in addition to highlighting how inhomogeneities can show up as break points in a timeseries. In this example a station located in Perth, Australia moved from a metropolitan location to an inner-suburban park. Fig. 1 shows that the station move while probably having some impact on the homogeneity of the annual mean temperature led to a clear break point in the lowest daily temperature minima (TNn – see Table 1) around 1993 when the station moved. In this particular example, the post-move annual mean temperature was warmer than the pre-move average (Fig. 1a) whereas the record low temperature (1.2 °C) at the old site has been surpassed in 11 out of 20 years at the new one (Fig. 1b), and the mean value of TNn is 2.6 °C lower (0.9 °C compared to 3.5 °C). For the annual minima to go below 2 °C at the old site was rare but it has occurred almost every year since 1994, thus suggesting an extreme almost every year. The difference in annual mean minima for the same periods (1910–1992 old site, 1994–2013 new site) is 0.7 °C, and for winter means 1.5 °C (in summer the new site is actually 0.1 °C warmer – pers comm Blair Trewin). In addition to showing the differential impacts on means versus extremes this also highlights how inhomogeneities can substantially affect the conclusions made from the analysis of timeseries of extremes.

Most methods in the literature either remove stations with identified or assumed inhomogeneities, use only the data before or after an identified break point or use various statistical techniques to adjust the station record to remove such break points to create a homogeneous timeseries. Removing inhomogeneous stations has generally been the approach taken by the ETCCDI in most of the analysis that is undertaken through their regional workshops (Peterson and Manton, 2008). In practice, however, it is unlikely that only homogeneous stations will be included in analyses due to limited availability of reference station data or because removing all inhomogeneous stations would severely limit the number stations available for analysis (e.g. Vincent et al., 2005). Indeed, more detailed national-level studies often find very few completely homogeneous stations on century-long timescales (e.g. the Australian ACORN-SAT data set, Trewin, 2013) so when global datasets are produced, while they usually contain a mixture of homogeneity tests depending on region (e.g. Alexander et al., 2006; Donat et al., 2013b), they can also not be guaranteed to be inhomogeneity-free. Adjusting data to remove inhomogeneities is complex and there are a plethora of available techniques each with their own pros and cons (e.g. Peterson et al., 1998) and more often than not studies that attempt to homogenise data focus mostly on monthly data (e.g. Venema et al., 2012) or on regional adjustments of daily data (e.g. Trewin, 2013). Methods to homogenise daily data usually only consider one statistical adjustment technique and have generally been developed over many years by the author of the method, often requiring a lot of time-consuming work that means that the methods can only be applied locally or regionally. More recently there has been a push to intercompare methods by developing blind benchmarking frameworks using the same underlying data with inhomogeneities that are known to the data providers but not to the data receivers (those applying a chosen homogenisation method). These types of frameworks aim to assess the ability of each method to best replicate the original timeseries once adjustments have been applied thus providing a more consistent benchmark for intercomparison (e.g. Venema et al., 2012; Willett et al., 2014). However to date this has generally only been possible using monthly temperature data and while initiatives such as the International Surface Temperature Initiative (ISTI, Thorne et al., 2013) are planning to focus more on changes in extremes and weather variability, a global scale initiative to homogenise daily temperatures using multiple methods is still reasonably far off. In addition, homogenising precipitation data is still often put in the "too hard" basket and the author is unaware of any large-scale initiatives of similar scope (with regard to blind benchmarking) to those focussing on temperature. Indeed, very little work has been performed on daily precipitation homogeneity even at large regional scales, the most prominent study probably being Mekis and Vincent (2011) for Canada. It is also worth noting at this point, that "climate quality" precipitation data that are suitable for long-term extremes research are severely limited compared to the datasets that are available for analysis of temperature extremes. This remains a major data and knowledge gap in the existing literature.

Quality and consistency of data at daily and sub-daily timescales are obviously of great importance when trying to make assessments of observations of extremes. While we have come far in our understanding of how inhomogeneities affect extremes and in applying the statistical techniques to effectively adjust data, there are still major gaps that exist. Therefore it is important to understand where these gaps are in the literature, both in terms of data gaps and in our understanding, and this can be best done by understanding how we have assessed changes in the past and what progress has or has not been made. The next section therefore outlines the history of the assessment of temperature and precipitation extremes as outlined in the IPCC Working Group I Assessment Reports.

3. History of assessment of temperature and precipitation extremes in the IPCC Reports

In the first assessment report of the IPCC (IPCC, 1990) no assessment was made of changes in extremes (Nicholls and Alexander, 2007). By 1995, the Second Assessment Report (SAR) of the IPCC (Intergovernmental Panel on Climate Change (IPCC), 1995) concluded that there was "no evidence that extreme weather events, or climate variability, has increased" but acknowledged that this was mostly due to a lack of suitable data or to the limited availability of data. Given the societal importance of extremes, this lack of assessment motivated international coordination and collaboration and prompted a flurry of studies in the ensuing decades that would transform what we know in particular about temperature and precipitation extremes.

Since the SAR, the IPCC Working Group I (Physical Science Basis) has produced the Third, Fourth and Fifth Assessments in 2001, 2007 and 2013 respectively in addition to a Special Report on Extremes (SREX) in 2012. While there are of course many publications that contribute to making the confidence and likelihood statements used in IPCC (see Supplementary material), there have been a few main publications which have contributed to the global (land-based) assessment of temperature and precipitation extremes. In particular, three studies which analysed station data derived from daily temperature and precipitation observations, Frich et al. (2002), Alexander et al. (2006) and Donat et al. (2013b) contributed substantially to the conclusions drawn in the Third, Fourth and Fifth Assessment Reports respectively. Each of these publications represented a concerted global effort to gather, quality control and assess global temperature and precipitation extremes (Peterson and Manton, 2008; Zhang et al., 2011). With each assessment, the amount of observed data available has increased and more land areas of the globe could be filled in and assessed to derive a global picture – the number of stations analysed increasing by an order of magnitude between Frich et al. (2002) and Donat et al. (2013b) (~300 to ~7000 for temperature and ~300 to ~11000 for precipitation). Fig. 2 shows how this improvement in station density improved spatial coverage (particularly in regions with previous poor coverage) for the analysis of cold extremes – frost days and cold nights. While each of these panels (that appeared in the TAR, AR4 and AR5) indicates a slightly different metric and time period, it is clear that the amount and coverage of data improved over the intervening 12 years. However as indicated the assessment of the likelihood that changes had occurred since the mid-20th century changed little between the Third and Fifth Assessment Reports, that is, it remains *very likely* that the numbers of cold nights and frost days have decreased since the middle of the 20th century (see Table 2). Despite an even greater increase in the number of precipitation stations available for analysis compared to temperature, the improvements in coverage for precipitation extremes are less impressive than for temperature (e.g. see Fig. 3). This is perhaps not too surprising since for precipitation extremes the number of stations would have to improve by several orders of magnitude to greatly improve spatial coverage due to the small decorrelation length scales for precipitation, and include regions where there is either a high signal to noise ratio and/or there are not many stations already. All of this had relatively little effect on the assessment of extreme precipitation changes between the TAR and AR5 (Table 2).

While this may seem that not much progress has been made over the last decade, what did happen though is that the likelihood statements could become more nuanced in some cases e.g. for extreme precipitation or heatwaves. For extreme precipitation the assessment went from indicating that increases in heavy precipitation had been *likely* observed over many Northern Hemisphere mid-to-high latitude land areas since the mid-20th century to an assessment that it was likely that there had been more land areas with observed increases than decreases (Table 2). This assessment not only relied on the global land-based studies described above but on an increase in the amount of literature that was being written for regional studies (see Table 2.13 of Hartmann et al. (2013)). In the case of heatwaves, the seeming "downgrade" from *likely* increases in the Fourth Assessment Report to *medium confidence* that there had been increases in SREX and AR5 was mostly due to the fact that there is little literature in South

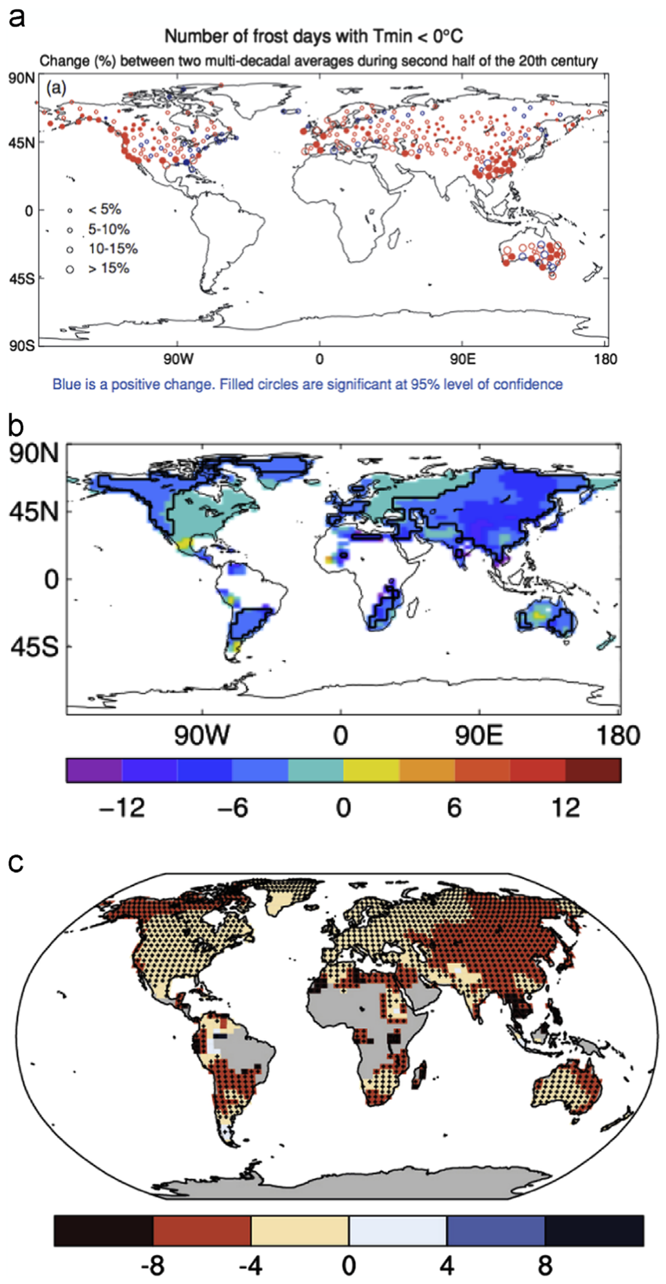

Fig. 2. Examples of how the assessment of cold extremes has changed over the course of IPCC Assessments using the example of (Top) percent of frost day changes over the period 1946 to 1999 in the IPCC TAR (from Frich et al. (2002)), (Middle) trends in cold nights (days/decade) over the period 1951 to 2003 in IPCC AR4 (from Alexander et al. (2006) and (Bottom) trends in cold nights (days/decade) over the period 1951 to 2010 in IPCC AR5 (data sourced from Donat et al. (2013b)).

America and Africa in particular on heatwave change (see Table 2.13 of Hartmann et al. (2013)) and due to differences in aspects being considered (e.g. AR4 only considered frequency changes rather than other aspects such as length or intensity considered by the latter reports (Nicholls and Seneviratne, 2013)), in addition to other 'expert judgments' made (see Supplementary material).

While over the years confidence in the assessments made on observed changes in temperature and precipitation extremes in the IPCC reports has changed little, statements that are "less confident" can appear somewhat counterintuitive. This has led to perceived inconsistencies in the IPCC assessments of extremes over time (Nicholls and Seneviratne, 2013).

Table 2

Global scale assessment of changes in temperature and precipitation related weather and climate extremes over the course of the relevant IPCC Assessment Reports (the First and Second IPCC Assessments did not include analysis of extremes). Based on Table SPM.1 (Intergovernmental Panel on Climate Change (IPCC) et al., 2013b) and Fig 1.9 (Cubasch et al., 2013). Italicised words are explained in Supplementary material.

Changes in phenomenon	Assessment that changes occurred (typically since mid-20th Century)			
	TAR (2001)	AR4 (2007)	SREX (2012)	AR5 (2013)
Warmer and/or fewer cold days and nights over most land areas	*Very Likely* over nearly all land areas	*Very Likely*	*Very Likely*	*Very Likely*
Warmer and/or more frequent hot days and nights over most land regions	*Likely* over nearly all land areas	*Very Likely*	*Very Likely*	*Very Likely*
Warm spells/heatwaves. Frequency and/or duration increases over most land areas	Not assessed	*Likely*	*Medium confidence* in many (but not all) regions	*Medium confidence* on a global scale. *Likely* in some regions
Heavy precipitation events. Increase in frequency, intensity, and/or amount of heavy precipitation	*Likely* over many Northern Hemisphere mid- to high latitude land areas	*Likely* over most land areas	*Likely* more land areas with increases than decreases	*Likely* more land areas with increases than decreases
Increases in intensity and/or duration of droughts	*Likely* increased summer continental drying and associated risk of drought, in a few areas	*Likely* in many regions, since 1970 (area affected by drought)	*Medium confidence* in some regions	*Low confidence* on a global scale. *Likely* changes in some regions

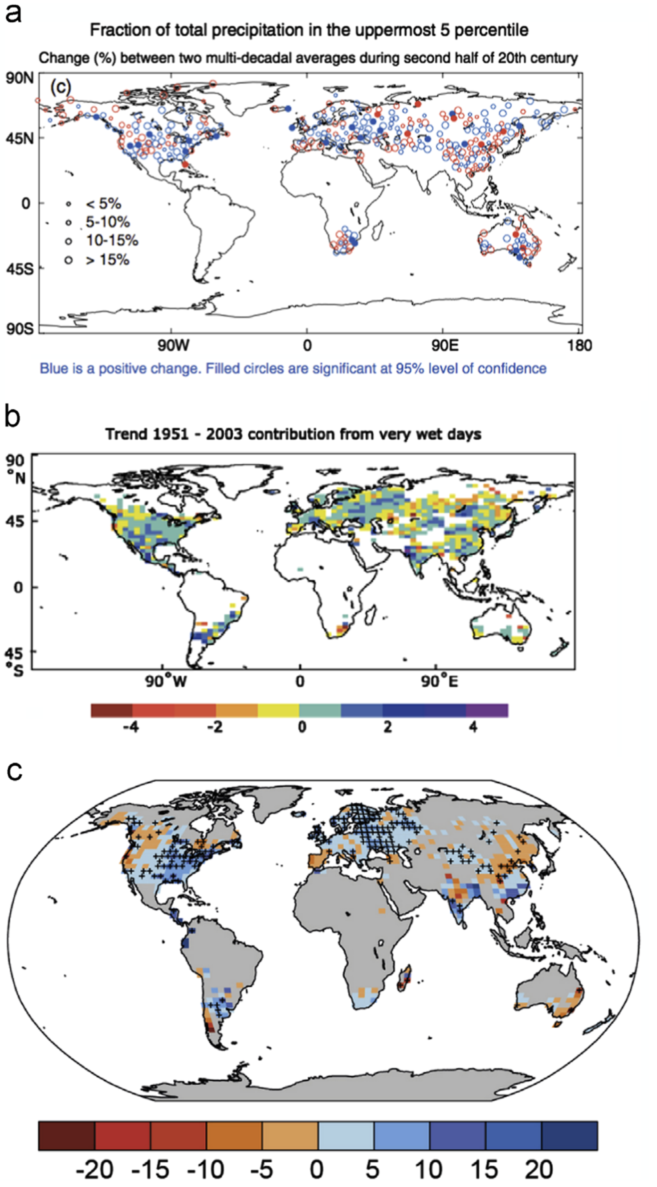

Fig. 3. Examples of how the assessment of wet extremes has changed over the course of IPCC Assessments using the example of (Top) very wet day contribution ((R95p/PRCPTOT)*100 – see Table 1) changes over the period 1946 to 1999 in the IPCC TAR (from Frich et al. (2002)), (Middle) trends in very wet day contribution (%/decade) over the period 1951 to 2003 in IPCC AR4 (from Alexander et al. (2006)) and (Bottom) and trends in very wet days (%/decade) over the period 1951 to 2010 in IPCC AR5 (data sourced from Donat et al. (2013b)).

Over subsequent IPCC reports, we appear to have become less confident about observed increases in the intensity and/or duration of droughts since the mid-20th century (see Table 2). Nicholls and Seneviratne (2013) explain that there are several reasons for this. One reason is that in AR4, Trenberth et al. (2007) assessed the area affected by drought rather than intensity and duration. Another is that different language and different approaches were used to estimate uncertainty and this has caused some inconsistency. Definitions in how drought is characterised and the variables incorporated in that definition also vary. For example, drought can be characterised as meteorological (precipitation deficit), agricultural (soil-moisture deficit) and hydrological (groundwater deficit) so identifying changes in duration, intensity, severity, and spatial extent are complex and can depend on definition (Hao and Singh, 2015). Throughout the IPCC Assessments most of the focus has been on meteorological drought. Nicholls and Seneviratne (2013) when talking about the differences between AR4 and SREX conclude that "*definitional issues and lack of data…plus the inability of models to include all the factors likely to influence droughts have led to overall weaker SREX assessments than was the case in AR4, both for observed and projected changes, although differences in the statements being assessed also explain some of the differences*". IPCC AR5 broadly agreed with the SREX conclusions with Hartmann et al. (2013) also noting that studies which appeared to come to different conclusions (e.g. Dai, 2013 and Sheffield et al., 2012) used different input precipitation datasets with various data quality and that the conclusions drawn from these were equally plausible. Subsequent to AR5, Trenberth et al. (2014) further assessed these seeming inconsistencies in drought assessments and concluded that these were due to different formulations of the drought index and the data sets used to determine the evapotranspiration component. Improved precipitation datasets will ultimately be able to improve our categorisation of drought but these issues highlight some of the reasons why it has been difficult to 'improve' our confidence in the long-term trend in global drought. Despite this, substantial progress has been made more broadly in the analysis of temperature and precipitation extremes as outlined above through the IPCC Assessment process and this has continued since the AR5 WGI report was completed in 2013.

4. Progress since the IPCC Fifth Assessment Report

While it would be impossible to outline all of the activities that have ensued since the release of the IPCC AR5, it is worth noting some activities and research which will hopefully improve what assessment can be made if there is to be an IPCC Sixth Assessment Report. Since the IPCC AR5, a number of high-level coordination activities have ensued around temperature and precipitation extremes in addition to a number of papers that have been produced that could extend IPCC's assessment. This section deals with these activities and papers, explaining how they might provide input for subsequent IPCC assessments.

4.1. International coordination activities and dataset intercomparisons

In international coordination activities, the World Climate Research Programme (WCRP) has initiated a Grand Challenge on Weather and Climate Extremes while the World Weather Research Programme (WWRP) has a research activity on High Impact Weather. This consists of a program over the coming years in which the weather and climate communities are tasked with addressing some of the most important and challenging scientific questions for addressing current research gaps. For the WCRP Grand Challenge, this includes how to better address data issues and analyze observed changes in extremes, how to better understand and attribute changes in extremes, and how to better simulate and predict extreme events (see Alexander et al. (2015) and http://www.gewex.org/gewex-content/files_mf/1432239231Feb2015.pdf). Included is a focus on temperature and precipitation extremes including heavy precipitation, heatwave and droughts, with the ultimate aim of mobilising the research community to improve assessment and understanding. The Grand Challenge has four overarching themes (Document, Understand, Simulate and Attribute) which each carry a question that is aimed at addressing the overall grand challenge "Towards robust predictions and projections of extremes". For observations (the Document theme), the question that is posed is "Are existing observations sufficient to underpin the assessment of extremes?". This has already led to a workshop on data issues in

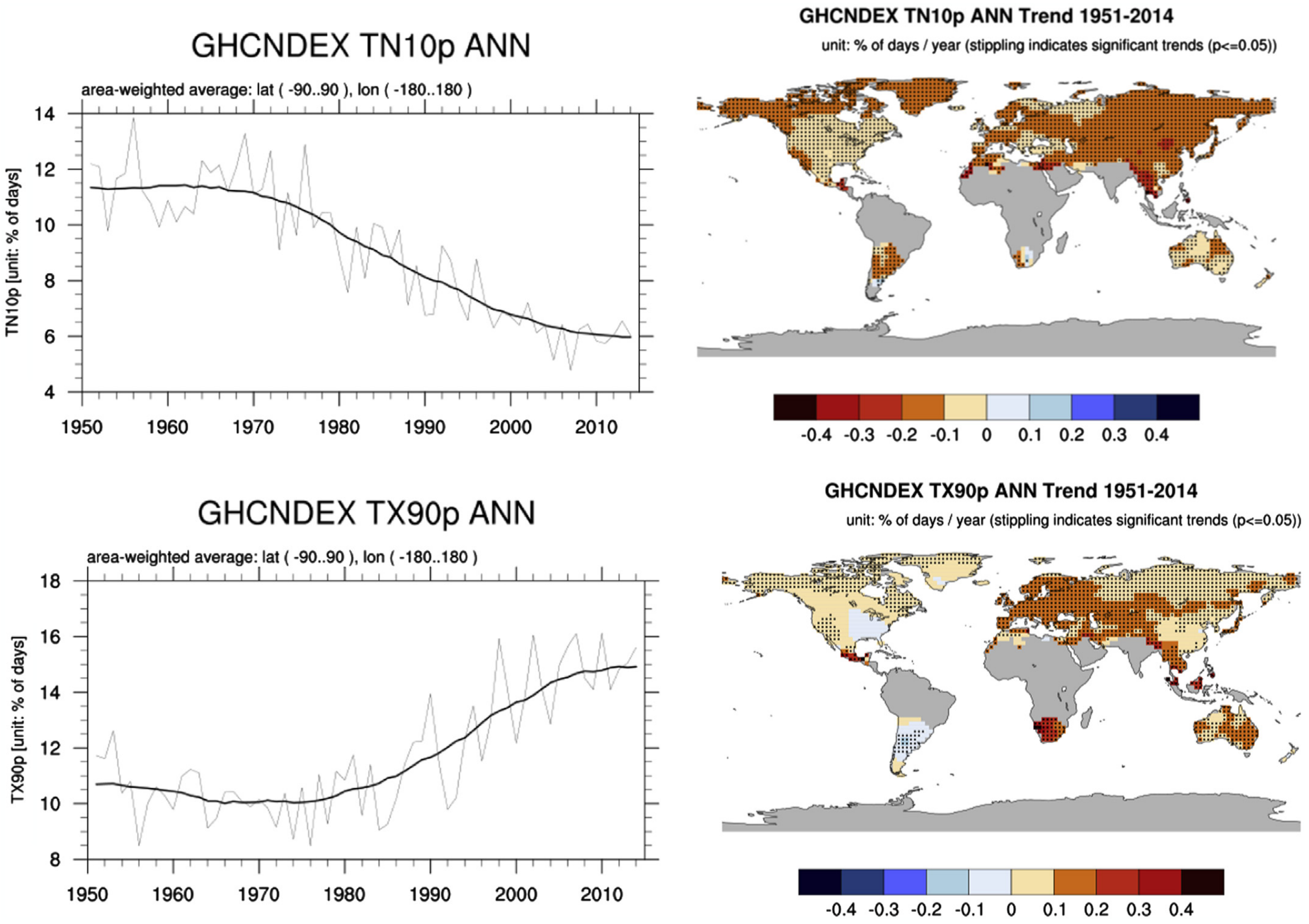

Fig. 4. Example of near-real time monitoring of temperature extremes. Calculated over the period 1951 to 2014 shows (Top left) Timeseries of globally averaged values of TN10p with decadal filter (black line), (Top right) Trends in TN10p (%days/year), (Bottom left) Timeseries of globally averaged values of TX90p with decadal filter (black line), (Bottom right) Trends in TX90p (%days/year). See Table 1 for index definitions. Stippling on maps indicates where trends are statistically significant at 5% level. As downloaded from www.climdex.org 28th June 2015.

Sydney, Australia in February 2015 which has laid out some strategies for dealing with these issues. The Grand Challenge suggests that the current suite of climate extremes datasets is inadequate to properly assess climate variability and change and to provide the required underpinning for detection and attribution studies and climate model evaluation. This is due to data limitations (in time and space), differences in how extremes are defined, the spatial representativeness of point-based measurements, scaling issues between observations and climate models and uncertainties in variable estimates from satellite retrievals. Therefore strategies have been planned around the need to collate and better disseminate data from all existing sources (e.g. ISTI and a World Meteorological Organisation data resolution – see Section 5) that are relevant for extremes and to identify regions and time periods where we can fill in gaps and assess uncertainties. This includes coordination of the collation and quality control of all existing *in situ* daily data sources for temperature and precipitation (and sub-daily for precipitation) e.g. GHCN-Daily (Durre et al., 2010), HadISD (Dunn et al., 2012), ECA&D (Klein Tank et al., 2002) and raw data collection from National Hydro-Meteorological Services and researchers stored in central repository and an intercomparison of all ETCCDI datasets including those calculated from *in situ*, remote sensing and reanalyses products (e.g. Donat et al., 2014).

4.2. Regional assessments

One important part of a global assessment is the combination of results from regional assessments. The ETCCDI have been successful at this because of the manner in which indices can be consistently calculated by researchers from a wide range of countries and institutions. In Hartmann et al. (2013) Table 2.13, the IPCC indicated that for both hot and cold temperature extremes there was at least *medium confidence* of warming in all regions except for warm and cold days in Africa and the Middle East where there was only *low confidence* due to limited data in many regions. Since IPCC AR5 there have been several studies over this region, resulting from both regional workshops and national-level datasets, that would undoubtedly increase confidence in trends in these regions e.g. Omondi et al., 2014 (Greater Horn of Africa), Chaney et al., 2014 (sub-Saharan Africa), Almazroui et al., 2014 (Saudi Arabia), in addition to updates in other data sparse regions e.g. Sheikh et al., 2015 (South Asia), Zandonadi et al., in press (Brazil).

While this is undoubted positive progress for regional assessments there is yet no mechanism by which to incorporate the data from these studies into global datasets. The WCRP Grand Challenge on Extremes therefore recommends that following an assessment of the literature, there should be some method for researchers to upload the output of their results to a central repository in order that it can be incorporated into global analyses. While making data/metadata access much easier for researchers, it could especially help with the task of assessing literature and analyses for subsequent IPCC Assessment Reports.

4.3. *The global warming 'hiatus' and temperature extremes*

Considerable attention has been paid to the so-called hiatus period in recent years, which indicates that the rate of global average surface temperature increase has slowed in the last decade or so. Studies that have tried to untangle the causes of this 'pause' in global warming have attributed it to various possible causes including internal climate variability, minimum in solar energy output, heat uptake in lower ocean layers, increased stratospheric water vapour, emission reductions of ozone-depleting substances and methane, data sampling, and/or stronger shifts to La Niña states (e.g. Easterling and Wehner, 2009; Held, 2013; Cowtan and Way, 2014). However, Karl et al. (2015) argue that data issues have, seemingly, enhanced this slow-down and therefore the pause does not really exist. It does appear from Fig. 4, however, that there is some evidence of a pause in the timeseries of temperature extremes but note that this is likely related, at least in part, to limited data coverage over large parts of Asia, Africa and South America in the GHCNDEX dataset (see Donat et al. (2013a) and Section 4.4). Indeed Seneviratne et al. (2014) argued that no such slow down was seen in observations of temperature extremes over land when using a mixture of temperature data sources and that hot extremes have continued to rise "unabated". In any case, the 'hiatus' may be coming to an end with 2014 recorded as the warmest year so far (Blunden and Arndt, 2015) and 2015 already substantially warmer than average, the developing El Niño also likely to influence temperature and precipitation extremes globally (Kenyon and Hegerl, 2008; Alexander et al., 2009; Kenyon and Hegerl, 2010).

4.4. *Near-real time monitoring of temperature and precipitation extremes*

One of the main limitations of the IPCC Assessments is that on global scales they often rely on assessment of 'static' datasets of temperature and precipitation extremes which are not always updated frequently or routinely and therefore when the report is published the datasets are already out of date. Several efforts have been made in recent years to have more automated approaches in place so that temperature and precipitation extremes datasets can be continually updated. One such dataset is GHCNDEX (Donat

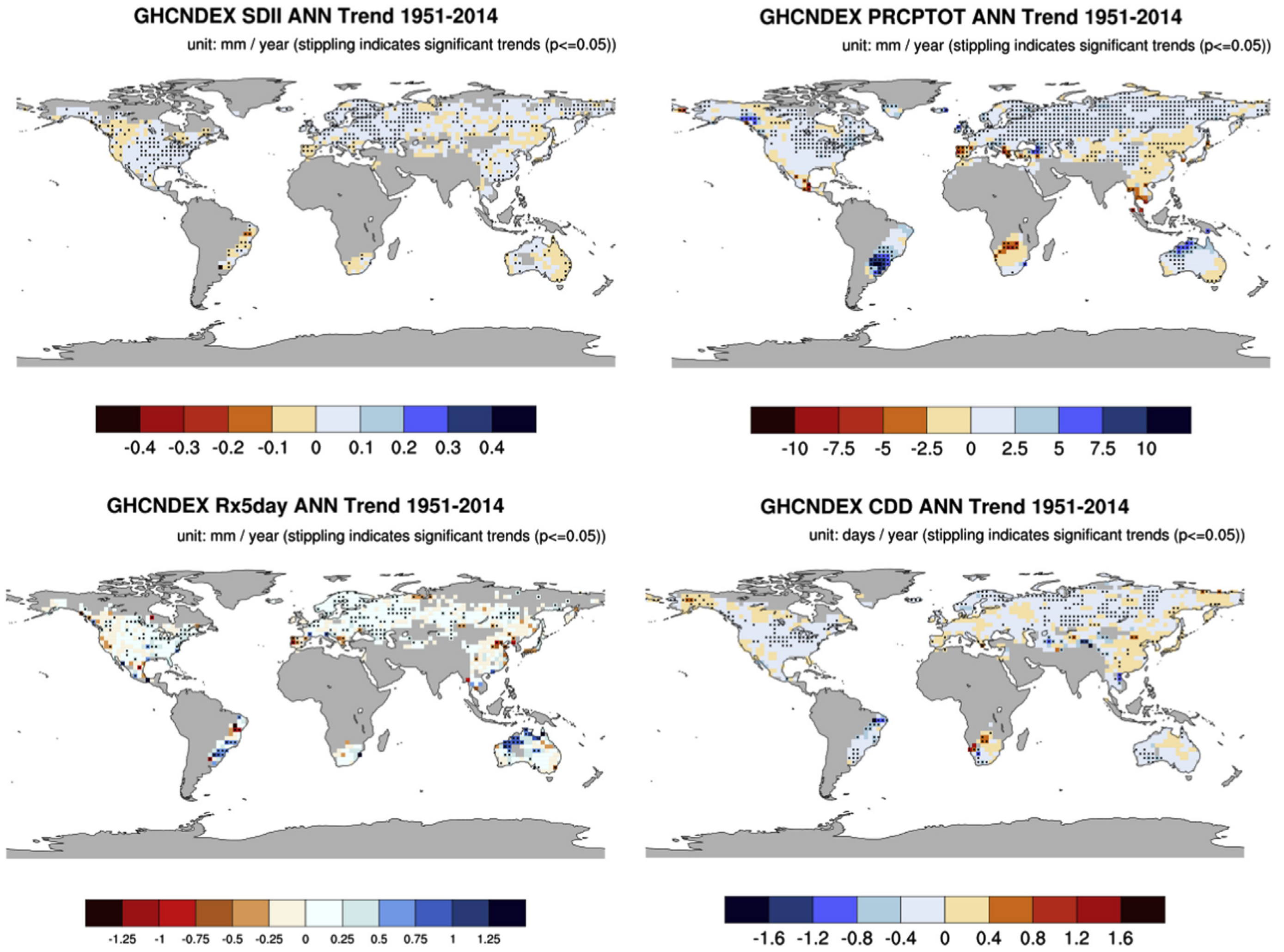

Fig. 5. : Example of near-real time monitoring of precipitation extremes. Calculated over the period 1951 to 2014 shows trends in (Top left) SDII (mm/year), (Top right) PRCPTOT (mm/year), (Bottom left) Rx5day (mm/year), (Bottom right) CDD (days/year). See Table 1 for index definitions. Stippling on maps indicates where trends are statistically significant at 5% level. As downloaded from www.climdex.org 28th June 2015.

et al., 2013a) which is operationally updated, delivering the suite of ETCCDI indices every month and thus putting recent results in the context of a 60+ year analysis. Trends over the period 1951 to 2014 for a selection of temperature and precipitation extremes are shown in Figs. 4 and 5. Fig. 4 indicates that the frequency of coldest nights (TN10p) have substantially declined over that period by about a factor of 2 (from 12% of nights in 1951 to about 6% of nights in 2014). Nearly all regions assessed have seen statistically significant decreases in TN10p. Global land-based trends in the hottest days (TX90p) have also substantially increased but not to as large an extent as decreases in cold nights (Fig. 4). This is due in part to the fact that in some regions the numbers of warm days has actually decreased (e.g. southern South America). Unsurprisingly the trends for precipitation extremes are less spatially coherent (Fig. 5) although with clear statistically significant trends across Eurasia and parts of North America in intensity measures which agrees well with the conclusions drawn in IPCC AR5.

Note however that the GHCN-Daily data (Durre et al., 2010) upon which GHCNDEX is based have no bias adjustments to account for historical changes in instrumentation, observing practice, station location, or site conditions and may also suffer from issues related to the poor quality of some of the real-time data included in the dataset e.g. maxima/minima not being measured over a full 24 h (Van den Besselaar et al., 2012) or missing precipitation data.

While this sort of monitoring enables a near-real time assessment of changes in temperature and precipitation extremes from one region to the next using a consistent approach, the disadvantage is that the coverage (and quality) is generally not as good as some of the other global datasets. Obviously for finer scale assessments, individual countries or regions often supply their own similar regional analysis using their own datasets (e.g. see http://eca.knmi.nl/utils/mapserver/indices.php for Europe and http://www.bom.gov.au/cgi-bin/climate/extremes/extreme_maps.cgi for Australia).

4.5. Sub-daily precipitation

One area of research that received limited coverage in the IPCC AR5 report was that of observed changes in sub-daily precipitation extremes. This was due to the lack of studies that existed from which to make a global assessment in addition to the fact that regional studies show complex spatial patterns of trends. IPCC AR5 however concluded that for sub-daily precipitation "…*regional studies show indications of more increasing than decreasing trends (Sen Roy, 2009; for India) (Sen Roy and Rouault, 2013; for South Africa) (Westra and Sisson, 2011; for Australia)*". This has been further emphasized in a review paper by Westra et al. (2014) which assessed that although there was inconsistency in the trends from regional studies on the whole they pointed to an increase in intensity of short-duration events (minutes to hours), if not necessarily in the frequency of extreme events. Westra et al. (2014), however, also point out that there is a lack of studies of observed sub-daily precipitation generally even at regional scales, with most published studies focused on a single station or a small number of stations. Where studies have been available, sub-daily precipitation intensity has been predominantly increasing (see Fig. 6) although the strength of sub-daily rainfall trends is dependent on region, season and duration (Westra et al., 2014). In addition there is still a lack of literature for many parts of the world especially Africa, South America and South–east Asia. However even since Westra et al. (2014) review paper was published, additional studies have started to fill in some of these gaps (e.g. Beck et al., 2015 for Singapore, Chen et al., 2015 for Hainan Island in South China) which continue to indicate increases in the intensity of precipitation on short-duration timescales.

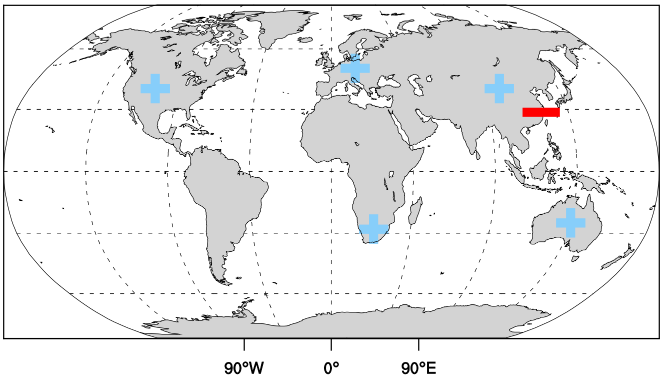

Fig. 6. Synthesis of regional trends in sub-daily extreme rainfall as identified by Westra et al. (2014). Increasing trends are shown with plus signs and decreasing trends with minus signs.

Further regional studies are starting to untangle the complexities of the temporal patterns of rainfall i.e. the distribution of rainfall within storms (e.g. Wasko and Sharma, 2015; Zheng et al., 2015) showing that temperature more strongly influences the short-duration or peak rainfall rates that can lead to flash flooding rather than total storm rainfall. However, studies come to somewhat different conclusions in exactly how intense precipitation scales with temperature with some suggesting evidence of scaling outside of that expected from the Clausius–Clapeyron relation (about 7% per degree Celsius) (e.g. Lenderink and Van Meijgaard, 2008; Jones et al., 2010; Utsumi et al., 2011) while others show little evidence of this (Blenkinsop et al., 2015). IPCC AR5 notes that scaling beyond that expected from thermodynamic theories is controversial and thus it is clear that more work needs to be done in understanding precipitation extremes at sub-daily timescales and their response to temperature change.

4.6. Marine heatwaves

All of the previous discussion has focused mainly on land-based extremes because that is where the main body of past literature on long-term changes has been targeted. Extreme temperatures in the ocean are increasingly seen as an important influence on biological systems and have been associated with adverse impacts, including shifts in species ranges, local extinctions and economic impacts on seafood industries through declines in important fishery species and impacts on aquaculture (Hobday et al., 2015). The majority of existing literature on marine extreme climate events has been centred on coral bleaching and this is the most advanced field of thermal stress-related marine ecology (e.g. Donner et al., 2005). However, recent marine heatwaves in the northern Mediterranean in 2003 (Garrabou et al., 2009), the Western Australia 'Ningaloo Niño' in 2011 (Feng et al., 2013), and an event in the northwest Atlantic in 2012 (Mills et al., 2013) had profound ecological impacts beyond coral bleaching, and have led to a push for a more coordinated approach in how marine heatwaves are defined, similar to that recommended by ETCCDI (Hobday et al., 2015). While this coordination is in its very early days and as it progresses will have to deal with the same data issues outlined above (and possibly some different ones), it should ultimately lead to an assessment of how marine heatwaves have changed globally over the observational period.

4.7. Sector-specific extremes

One of the criticisms that has been directed towards the ETCCDI indices is that in many cases the so-called moderate extremes are not useful for the "impacts" or sector communities. With the advent of the Global Framework for Climate Services (GFCS), the World Meteorological Organisation (WMO) proposed that to effectively address this gap required the input from sectors in the development process of indices so that they were more application-relevant to better support decision-making and adaptation. GFCS has a vision to "*to enable better management of the risks of climate variability and change and adaptation to climate change, through the development and incorporation of science-based climate information and prediction into planning, policy and practice on the global, regional and national scale*" (WMO, 2011). To that aim, the WMO Commission for Climatology (CCl) set up the Expert Team on Sector-specific Climate Indices (ET-SCI) with a primary focus on the development of tailored climate information, products and services for user application in adaptation and risk management focussing on the priority sectors: agriculture, water resources and health (Alexander and Herold, 2015). Similarly to ETCCDI, ET-SCI have initially developed a suite of indices based on daily temperature and precipitation data, the only difference being that development of the indices was done "bottom up" (i.e. with input from the sectors involved) with the intension that a larger suite of indices based on more variables (e.g. wind, humidity) would be included at a later stage. Moving forward it is likely that these sector-based indices will become increasingly important in trying to understand observed changes in temperature and precipitation extremes and their impacts on important sectors such as health and agriculture.

5. Limitations for future assessments of global temperature and precipitation extremes

Previous assessments have acknowledged that data quality, availability and accessibility remain the most fundamental roadblocks in the global assessment of temperature and precipitation extremes (Seneviratne et al., 2012; Zwiers et al., 2013). As Zwiers et al. (2013) note "*We cannot state strongly enough the importance of continuing and enhancing such efforts to develop datasets of high-frequency in situ observations that are as spatially and temporally complete as possible, as homogenous as possible, and that are accompanied by as much metadata as possible concerning the history of each observing system or station.*" Increased efforts being solicited to rescue and digitize data stored on paper in many countries (e.g. Page et al., 2004) and so-called "crowd-sourcing" and "citizen science" activities (Hennon et al., 2015) offer promising ways to improve our climate datasets. In addition in June 2015 the WMO at its 17th Congress Meeting agreed to update the resolution on the policy and practice relating to the exchange of meteorological and related data to include historical data. This implies that countries would be "urged" to exchange their daily temperature and precipitation records for free to weather and climate researchers for non-commercial research purposes. This points to the broader recognition of the importance of data sharing and the gradual move towards more open data policies, however, WMO can only provide guidelines for countries to follow and as such it remains to be seen whether this recent advance will actually bear real fruit.

Another issue for extremes is the general mismatch in the spatial scales between observations (usually taken at point locations) and climate model simulations (typically interpreted as representing an area of a model grid), making it difficult to conduct a like-with-like comparison between observations and models. This is a particularly a problem for precipitation extremes and limits our confidence in the interpretation of not only the observed extreme event itself but in our ability to understand observed changes in the frequency and intensity of such events. Various techniques have been used to grid or to interpolate station data to aid observation and climate model comparison (e.g. Donat et al., 2013b; Dunn et al., 2014). There are several intertwined issues including spatial averaging, uneven number of stations/observations across the space, the order of operation (i.e., gridding anomalies, first difference or absolute values etc.) and many other parametric and structural uncertainties. Work is still required to understand these effects and if possible rule out certain approaches to avoid artificial spread. Some data sources are currently being under-utilised (e.g. reanalyses, various satellite, radar and remote sensing products) which could allow better characterization of the spatial footprint of extremes. We need to evaluate those products with respect to extremes with a particular focus on precipitation and it is envisaged that this will be done under the coordination of the WCRP Grand Challenge on Extremes with extensive collaboration with another WCRP Grand Challenge on Water Availability.

As stated in the introduction, the computing resources now required to implement some of the extreme value analysis methods are intensive and it will become increasingly difficult for individual researchers to get access to the necessary computation power necessary to conduct global scale analyses especially if statistical techniques become more sophisticated and complex, and more climate model simulations become available. This either means that we will have to rely on the advances being made in computer hardware and storage or it may imply a shift in our thinking about how we implement such techniques perhaps looking to the computer science community for novel ways in which to optimise computer resources. This relates more broadly to issues surrounding the coordination of activities to transform our understanding of global changes in temperature and precipitation extremes. For this we will need to ensure that we use best practice from other related fields (e.g. computer science, statistics) to truly address this "Grand Challenge".

6. Conclusions

This overview attempts to show how assessments of temperature and precipitation extremes have progressed over the last couple of decades and where we are with regards to the latest information on these extremes. It outlines the importance of quality and consistency of data in underpinning any analyses and what international initiatives exist to improve data availability and to develop methods to assess the homogeneity of timeseries. Broadly speaking, warm temperature extremes have continued to increase and cold temperature extremes have continued to decrease despite the warming hiatus in global mean surface temperature. Precipitation extremes also appear to have increased in more regions than they have decreased and this appears also to be the case for short-duration, intense rainfall for which there were limited data and studies from which to draw firm conclusions in IPCC AR5. While it is clear that substantial progress has been made in certain areas, particularly in the amount of data that is available, there are still clear gaps that require to be filled going forward. This includes a lack of access to data in regions such as Africa and South America, a lack of intercomparison of existing products to understand structural uncertainties, a lack of understanding of the scaling issues between point-based observations and grids and the need for better coordination between climatologists, statisticians and computer scientists.

Primarily analysis of observed temperature and precipitation extremes cannot proceed until there is free and unrestricted access to the daily and sub-daily data that are required for this type of analysis. The author therefore welcomes the most recent WMO Resolution on this issue but awaits a concrete demonstration of its effectiveness.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.wace.2015.10.007.

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