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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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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