Implementation Plan for WCRP Grand Challenge on Understanding and Predicting Weather and Climate Extremes

The "Extremes Grand Challenge"

Version 30th June 2016 by co-chairs

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This implementation plan follows on from the WCRP Grand Challenge on Extremes White Paper (http://www.wcrp-climate.org/index.php/gc-extreme-events).

OVERVIEW

The Extremes Grand Challenge goal is:-

Towards robust predictions and projections of extremes

In order to best progress us towards this goal, our implementation plan is divided into **four overarching themes,** which will be addressed broadly as follows:

1. DOCUMENT

Are existing observations sufficient to underpin the assessment of extremes?

2. UNDERSTAND

What are the relative roles of large-scale, regional and local scale processes, as well as their interactions, for the formation of extremes?

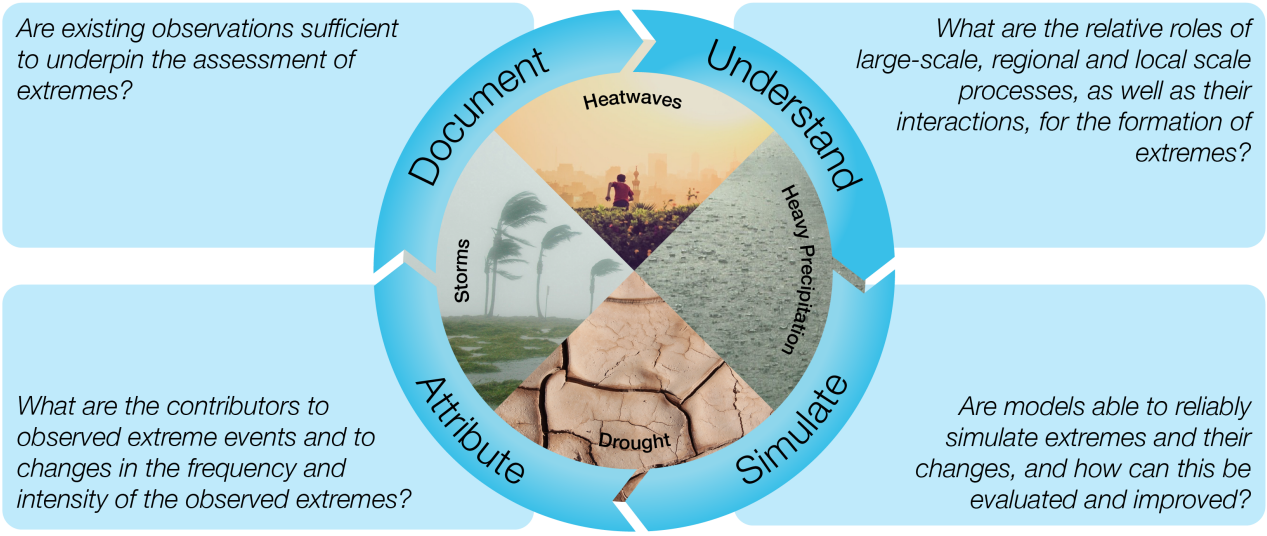
3. SIMULATE

Are models able to reliably simulate extremes and their changes, and how can this be evaluated and improved?

4. ATTRIBUTE

What are *the contributors to observed extreme events and to changes in the frequency and intensity of the observed extremes?*

The implementation plan focuses on what is *doable* by the end of 2017 while acknowledging the need for stretch targets beyond this. For that reason our main implementation strategy focuses on **four core events**: 1. heatwaves, 2. droughts, 3. heavy precipitation and 4. storms, while other types of events will benefit indirectly from advances made here. The storms theme will be primarily led by HIWeather (see below) but with joint workshop and symposium activities planned. The implementation plan is summarized in the following schematic.



All activities will be closely coordinated with the research activity on High Impact Weather (HIWeather) within the World Weather Research Programme (WWRP – see P15 on cross-cutting activities and http://www.wmo.int/pages/prog/arep/wwrp/new/documents/HIW_IP_v1_4.pdf) and relevant activities in the other Grand Challenges (see http://wcrp-climate.org/grand-challenges).

Each Theme will be driven by two or three lead coordinators who will push implementation forward, with input and vision from identified main contributors to this Grand Challenge to engage the worldwide research community on extremes.

For each theme we have split the implementation into a section which deals with coordination needs across and between existing activities, and a further section which highlights what new activities, research or data gathering needs to be undertaken.

The four themes are closely linked with much overlap, and we anticipate strong links between the themes. To further this, cross-cutting activities are proposed that address several of the theme questions and link to other WCRP Grand Challenges and international activities.

Particular focus should be given to providing “actionable information” in order that research makes real progress and to overcome barriers that have been in place for too long e.g. data availability issues, understanding regional-scale feedbacks. We have identified where this is possible, both due to advances in science and by bringing together different strands of expertise, such as extremes research with a strong meteorological focus, process studies, high resolution modelling, and statistics. We also aim to engage the wider research community to spark the public’s interest in extremes research.

THEME 1: DOCUMENT

Lead Coordinators: Lisa Alexander, Ali Behrangi

Are existing observations sufficient to underpin the assessment of extremes?

This theme deals with documenting and assessing past changes in extremes and in the process to determine the adequacy of our current observational suite of data. Observations are the key foundation for understanding long-term climate variability and change but observations are often not well-constrained and critical gaps exist in the amount, quality, consistency and availability of observations especially with respect to extremes. 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 model evaluation. This is due to data limitations (in time and/or space), differences in how extremes are defined, the spatial representativeness of point-based measurements, scaling issues between observations (in situ and remotely sensed) and models and uncertainties in variable estimates from satellite retrievals. We need to find, collate and better disseminate data from all existing sources that are relevant for extremes and to identify regions and time periods where we can fill in gaps and assess uncertainties.

Extremes are, by definition, rare. This means it takes longer time periods and better resolution in both space and time to properly characterize long-term changes in extreme events. This also means that some extreme values (e.g. amount of short duration rainfall) may be prone to be filtered out by the usual data quality control (QC) procedures. It is important to instigate efforts to undertake new and novel QC/homogenisation algorithms and benchmark their performance at daily and sub-daily timescales, work to create an integrated set of holdings of *in situ* data over global land areas which combines hourly, daily and monthly series across all elements including building datasets of parallel measurements to measure changes in observation systems including from satellite retrievals, to digitize data in as cost effective manner as possible and to improve data provision. WCRP should work with other organizations such as WMO and space agencies to promote free, open and easy access to all meteorological and climate data in a useable format.

In the case of data digitization, prior to the mid-20th century, we estimate that there are as many terrestrial and marine data that haven't been digitized as have been, and that we lose about half a million old records every day. This loss of our past, lack of coordination of activities, inability to store and access all data

readily, and reliance on small groups of key people means that unnecessary effort and resources always has to be applied to data projects which are already vastly under-resourced. The reoccurring tendency for data rescue projects to be ad hoc and to have been severely constrained by insufficient funding, resources and unrealistic deadlines has meant that we have inherited the accumulated legacy of a short sighted approach, making any task to remedy the situation a monumental undertaking (grand challenge) in itself. We need a grand vision for how we deal with these data issues before the situation becomes untenable but where the required data already exist, a minimal coordinated effort could reap enormous benefits.

Another issue for extremes is the general mismatch in the spatial scales between point-based observations, satellite estimates and 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. Various techniques have been used to grid or to interpolate station data to aid observation and model comparison. There are several intertwined issues including spatial averaging, uneven number of stations/observations across the space, the order of operation (i.e. scaling issues) and many other parametric and structural uncertainties. Work is required to understand these effects and if possible rule out certain approaches to avoid artificial spread. Some data sources may have been under-used (e.g. reanalyses, various satellite and radar data products) and could allow better characterization of the spatial footprint of extremes but in some cases these data sources are being used without understanding their suitability for assessing various extremes. We need to evaluate all existing products with respect to extremes with a particular focus on precipitation that will require extensive coordination with the Water Availability Grand Challenge in particular.

The main advance for this theme will be based on continuing and strengthening existing data gathering activities in order to fill gaps and better match the available data with what is required for diagnostics, model evaluation and detection/attribution. This should be done in close coordination with other grand challenges and data initiatives and should include:-

Coordination of existing and forthcoming activities specific to this theme

- 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, GPCC, HadISD, ICA&D etc. and raw data collection from HydroMet

services and researchers stored in central repository. This should be organized in such a way to also encourage new international data initiatives such as EUSTACE and INTENSE to be added and to follow the example for quality and accessibility from the International Surface Temperature Initiative (ISTI). Coordination should also ensue with existing data rescue initiatives e.g. ACRE to ensure that 'old weather' records are incorporated into above activities. Ensure, to the extent possible, that data adhere to common data quality assurance and metadata standards, and that they are disseminated using a common format, thereby improving the exchangeability of existing data and promoting development of community data analysis tools. WCRP continues to encourage free and open international exchange of existing high time resolution data to improve global coverage of daily and sub-daily observations for temperature and precipitation extremes in particular, and identify steps that would improve data sharing. [coordinate with GDAP, GHP]

- Collation of all ETCCDI *in situ* data including HadEX2, GHCNDEX and regional indices identified via a literature review. Similarly to above should be stored in a central repository and disseminated via a web portal such as climdex.org.

- **Workshop** (Sydney, Feb 2015): To assess the data requirements within and between existing observations of extremes (e.g. *in situ* and remote sensing, existing and future datasets). Thus this workshop provides interaction between communities that have not previously worked together before. In addition, it will deliver a strategy for data collection and indices calculation, coordination and best practice which may ultimately lead to requirements for new initiatives, software etc.

New research/activity/data gathering requirements

- ETCCDI indices to be reviewed and new indices added, especially those that better represent capture long-term precipitation surplus and deficit, soil moisture, drought, heatwaves, and more impacts-relevant indices. This would also include a few more indices to capture changes in the shape of the temperature distribution.

- Standardised software and an associated manual will be developed to ensure that all ETCCDI calculations are calculated in the same way for intercomparison. Coordination should then ensue between other groups who are already working towards the Global Framework on Climate Services. Input and output data formats, including metadata, should be coordinated across various communities [coordinated with WGRC, ET-SCI, TT-TCI, GDIS, CORDEX, Water Availability Grand Challenge].

- A 'best practice' guidance document to be produced on gridding data to best represent extremes and address scaling issues between observations and models. The recommendations will be used to produce revised global climate extremes datasets that extend over the 20th century, improve spatial and temporal coverage and provide uncertainty estimates. Approaches will be considered based on a variety of techniques including those based on spatial statistics of extremes.

- A guidance document to be produced on the suitability of existing datasets (e.g. in situ-based, satellite and reanalyses products) to study extremes with particular focus on the four core events: heavy precipitation, heatwaves, droughts and storms. Thought will be given on how to best disseminate the information to researchers such as through a dedicated website.

- A coordinated intercomparison of existing and new datasets should be conducted including the standard calculation of precipitation extremes from satellite retrievals. This intercomparison would provide a formal framework to address uncertainty and scaling issues with a recommended primary focus on the first three core events i.e. heatwaves, droughts and heavy precipitation. The data requirements for the fourth core event "storms" to be coordinated through WWRP. Furthermore, the requirements for the type of satellite observations needed to study the core events should be identified to guide current and future generation of the products. When considering ETCCDI indices, for example, existing satellite capabilities should be revised (e.g. appropriate calculation of daily Tmax and Tmin) or new indices should be added accordingly.

- **Workshop** (Columbia University, 2016) with a focus on the data needs for high impact weather (including tropical and extra tropical cyclones) coordinated by the WWRP research activity on High Impact Weather with input from the Extremes GC. Part-funding would come from Columbia University. This will also be a **cross-cutting activity**.

- While most of the above activities relate to land-based extremes, additional activities which focus on ocean extremes e.g. marine heatwaves, extreme wave height storm surges will be encouraged and supported (see cross-cutting activities on Page 15).

THEME 2: UNDERSTAND

Lead Coordinators: Sonia Seneviratne, Olivia Martius, Robert Vautard

What are the relative roles of large-scale, regional and local scale processes, as well as their interactions, for the formation of extremes?

A range of mechanisms can lead to the occurrence of extreme events such as heat waves, droughts or floods. Recent investigations have shown that the interaction between large-scale drivers and regional-scale (in particular land) feedbacks or forcings can be critical. For instance soil moisture-temperature feedbacks amplify heat waves in many regions, and were shown to play an important role in recent extreme hot events, such as the 2003 European heat wave, the 2010 Russian heatwave, or the 2012/2013 Australian summer. Moisture evaporated from the land was also identified as a major contributor to the precipitation events that led to the Pakistan floods in 2010 and the floods in Germany in 2013. Warm sea surface temperatures, combined with specific atmospheric circulation are known to drive heavy rains such as in Mediterranean regions. Additionally forcing from land cover and land use changes can be important for either amplifying or damping the occurrence of extreme events. Similarly, the role of the tropical SST anomalies, melting Arctic sea ice, changes in storm tracks and weather extremes in Eurasia needs to be clarified. These changes can affect the frequency, intensity and the pathways and persistence of individual weather systems such as cyclones, anticyclones and fronts, large-scale weather regimes and teleconnection patterns. Processes acting to trigger, favour duration or terminate persistent weather regime patterns need to be better understood, as well as their changes with increased greenhouse gases (baroclinic wave interactions, diabatic processes, tropical-extratropical interactions). For progress to occur, the link between dynamical meteorology and climate needs to be strengthened. Finally, there is an additional need to understand which events lead to specific impacts and which features of given events are most relevant to these impacts.

A better quantification of these processes, thanks to interactions between research communities working both on large-scale atmospheric drivers and regional land-atmosphere feedbacks is essential to reduce uncertainties in projections, improve sub-seasonal to decadal predictability of extremes as well as the attribution of past trends and single events. The role of internal climate variability for the occurrence of extremes also needs to be carefully evaluated, in particular for past recent trends and in order to assess their contribution to projections' uncertainty. This will entail a study of the link between climate variability and individual weather systems (blocking or cyclones) that cause the extremes. This also encompasses the increasing and necessary amount of work on statistical methods and models to detect changes in extreme events, their characteristics and clustering. Connection between large-scale circulation and individual, sometimes small-scale events will be strengthened using 'storylines'. This will be done in connection to the Simulate and Attribute themes of the implementation plan.

Many of the activities will be cross-cutting, providing links to the "Document", "Simulate" and "Attribute" themes.

Coordination of existing and forthcoming activities specific to this theme

Coordinated model experiments and analyses considering the respective role of large-scale versus regional/land drivers of extremes will be conducted using various frameworks:

- ExtreMEx experiments: Experiments isolating the role of large-scale drivers versus regional-scale feedbacks and forcings for observed recent extreme events (2010-2015). These experiments are in current planning and will be coordinated with the EU-FP7 EUCLEIA project and as a follow-up of the 2015 WCRP workshop on extremes in Oslo.
- LS3MIP CMIP6 experiment: Coordinated experiment between GEWEX and CliC addressing the role of soil moisture- and snow-climate feedbacks in historical simulations and climate projections (building upon the GLACE framework), as compared to the role of atmospheric circulation and SST.
- LUMIP CMIP6 experiment: Coordinated experiment investigating the role of land use forcing for climate simulations.
- Dedicated experiments coordinated among contributors to the Grand Challenge (e.g. focused on predictability issues, land cover and land use aspects, regional-scale CORDEX-type experiments and the investigation of regional case studies.
- In addition, several funded projects from the European Research Council will contribute to this theme:
    - "DROUGHT-HEAT" (ETH): Experiments assessing the role of land-climate feedbacks for extremes in present and future climate
    - ERC "A2C2" (LSCE): Use of atmospheric flow analogues to assess the impact of large-scale circulation drivers for extremes, which tackles in particular the issue of how to detect changes and exceptional atmospheric circulations
    - ERC "TITAN" (U. Edinburgh): Evaluating role of black carbon, forcing and SSTs in early 20th century extremes in Europe and North America

Summer schools are essential tools to foster in-depth understanding of underlying mechanisms leading to extremes and to train and develop young scientists:

- The WCRP/ICTP summer school Trieste, July 2014: Definition of extremes, attribution of extremes, physical drivers of extremes, observations of extremes. This school represented a cross-cutting activity (see Page 15) to train the next generation of leaders in this field, enhancing capacity. The workshop has resulted in 7 student-led papers based on the research problems tackled by the students during the workshop. These papers were included in a special issue for the journal "Weather and Climate Extremes" in 2015 (http://www.sciencedirect.com/science/journal/22120947/9).

- Swiss International Summer School on extremes, August 2015. This summer school is a further activity to train future leaders in the field of extremes research. This summer school also specifically included an interface to impacts research with presentations and workshops by representatives of the impacts community (Red Cross and Red Crescent, SwissRe, MeteoSwiss).

Workshops and conferences

- "Our common future under climate change" conference held at UNESCO in Paris in July 2015, with several parallel sessions on extreme events: "Climate Extremes", "Attribution of extreme events", "Extreme Hydrological Events", and a large parallel session.

- M-CLIX workshop, October 2015 (see also Simulate): Session and Break-out groups addressing "Understand" theme.

- LandMIP (Land modelling) workshop (October 2015): Coordination of LS3MIP and LUMIP CMIP6 experiments, including aspects relevant to extremes (e.g. model output, experimental set-ups). Jointly organized by GEWEX and CliC.

- Blocking workshop (6-8 April 2016 Reading): Overview of processes leading to blocking, evaluation of representation of blocking in current climate and weather models, links between blocking and regional (feedback) processes (http://www.sparc-climate.org/meetings/wwwsparc-climateorgmeetingssparc-blocking-workshop-april2016/)

- Synthesis "Understand" Workshop (TBA, late 2016 or 2017): workshop synthesizing results of first ExtreMEx modelling experiments and dedicated analyses, and planned special issue and review article.

New research/activity/data gathering requirements

- Modelling experiments conducted by WCRP projects can contribute to better determine the role of distinct drivers and feedbacks for extremes. Such experiments should be complemented with the analysis of observational datasets newly compiled within the Grand Challenge, as well as the respective validation activities. A database of reference modelling experiments will be made available for the research community, including within CMIP6.
- Links between GEWEX, CLIVAR and CliC are long established and will be built upon. In addition, SPARC and WWRP have also been newly integrated through the contribution of Olivia Martius. Some activities will be coordinated with other WCRP bodies (e.g. WGRC for CORDEX-type experiments, WGCM for CMIP6 experiments, possibly also WGSIP for predictability experiments). Links with the event attribution community are also already established through IDAG and EUCLEIA, in addition to links to Theme 4 (Attribute).

THEME 3: SIMULATE

Lead coordinators: Gabi Hegerl, Erich Fischer, Jana Sillmann

Are models able to reliably simulate extremes and their changes, and how can this be evaluated and improved?

There is a lack of understanding in the types of events that current models can provide credible and robust simulations for, and in the identification of key processes for climate models to capture in order to produce credible simulations of weather and climate extreme events and thus improve prediction of those events. Furthermore, the ability of models to simulate particularly small-scale extremes depends on resolution and sometimes requires downscaling. We propose the following three-pronged approach:

Evaluation of extremes at the level of storylines or processes (in coordination with theme Understand). Storylines that lead to extremes can be analysed and the models' ability to simulate the conditions leading to extremes can be evaluated. Understanding the interplay of various processes including atmospheric, land, and oceanic processes that lead to prolonged droughts or wet seasons may shed new light to guide model development. Contributions to the changing probability of extremes by anomalous sea surface and ice conditions, and by changing radiative forcing need to be quantified and evaluated in climate models. It is important to select a set of priority events/case for comprehensive

comparison, with an aim to understanding interactions of large-scale drivers and local (e.g. land-surface) feedbacks, using various approaches including event attribution. Events that are of large spatial-temporal (continental and seasonal) scales and that involve heavy precipitation or heat waves may provide better opportunity to advance. The selection of such events should consider geographical balance such that events that occurred in less developed world get selected and studied, although it is recognized that availability of data may be a more challenging issue in less developed world. Spatial scale may be important here as well, for example, blocking anti-cyclones are better simulated in high-resolution models.

A set of metrics informed by dynamical and physical concepts needs to be developed that aim to identify strengths and weaknesses in model simulations of conditions that are typically associated with extremes, such as blocking anti-cyclones or land-atmosphere feedbacks, and in the simulation of the extremes themselves, linking model performance of regional extremes to model performance in large-scale circulation and local feedbacks. Statistical modelling techniques based on general extreme value theory (e.g., to estimate return values) that complement widely used indices (e.g., ETCCDI) should be exploited for model evaluation in terms of incorporating co-variates that represent underlying processes. Furthermore, multivariate statistical techniques that account for physical and statistical relationships between extremes that occur at different locations and in different variables (i.e., temperature and precipitation) need to be developed so that they can more readily be applied to weather and climate problems. The potential of using well-established statistical concepts and methods from the field of Numerical Weather Prediction (NWP) forecast evaluation needs to be explored and further developed for the assessment of climate model performances. These activities imply close collaboration with dynamicists, statisticians and scientists working with NWP forecast evaluation.

An assessment of the benefit of high-resolution models in predicting/simulating extremes at small spatial scales at the margin of what can be resolved by present models, or beyond needs to be performed. Statistical methods to downscale unresolved processes also need to be evaluated. Links to the CORDEX community are established and will be developed further. Strategies to address events that require high resolution, such as tropical cyclones, need to be compared and evaluated. Where models do simulate the fundamental underlying processes that produce extremes, dynamically based scaling approaches need to be developed in order to be able to better link processes at model scales with local scales. It needs to be considered that observations provide point-data, and statistical methods to quantitatively

compare those with model data need to be improved and disseminated (see also Document theme).

Advances and analyses continue to rely on data for model evaluation and detection and attribution: long-control simulations to characterize the variability in both circulation states and extremes; single-forcing sensitivity experiments, and other MIPs need to be engaged to save and archive high frequency data. The conditions leading to rare extremes in observations inevitably pose a sampling problem in model-data comparison. This could be addressed to some extent by model evaluation using moderate extremes and through the use of large ensembles of model simulations covering the period of historical observations, and will also benefit from extending the record of historical observations (Document theme). The forced simulations should provide large ensembles to sample variability in extremes, which is a challenge from the relatively short observational record alone. Work is planned to pre-process high-frequency data in order to extract information relevant to extremes so that they are more easily accessible to the wider user community. Intra-seasonal to seasonal prediction, near-term prediction of probability of extreme events at impact relevant space/time scales will play an increasingly important role for climate services. This requires the Extremes GC to work and engage with other groups such as WGSIP and CFHP so that high resolution model data are made available and models are also evaluated using new metrics that explicitly take extremes into consideration.

In all cases it is vital that we work closely with statisticians to include the latest advances and best methods in statistical modelling into our approaches.

Coordination of existing and forthcoming activities specific to this theme

- **Workshop** (Oslo October 2015): The M-CLIX workshop in Oslo (Norway) in October 2015 was an excellent opportunity to discuss the following issues that need to be addressed for evaluating and improving the simulation of changes in extremes. This is important because climate model evaluation stops short of extremes generally, except for very simple diagnostics. The workshop brought together dynamicists/severe weather specialists with statisticians and people analysing models so that best practice can be developed for model evaluation, possibly to be published as a white or review paper based on CMIP5 data analysis. We will aim to find funding for a follow-up workshop in 2017 to document progress. We aim to illustrate model

evaluation focusing on extremes with key examples. The following questions were specifically addressed:-

- Can climate models be evaluated for more moderate extremes for which ample data are available (such as the ETCCDI indices), and what do we miss for more rare extremes (e.g., do we miss a stronger role of land surface feedbacks for rare hot extremes)? The latter can be addressed by linking to the individual event attribution community that determines what led to an event as well.
- Can we use 'storylines' that link specific high impact events to large-scale circulation situations to evaluate the ability of models to simulate the key mechanisms for extremes, including blocking, for example? What does this mean for model evaluation?
- What standard model diagnostics are important for extremes, and which of many possible choices of implementation should be compared (example: which circulation index)?
- How can the scale problem be overcome? Statisticians can advise on what new techniques are available to address the point versus area problem that particularly hampers the evaluation of precipitation extremes; and we need to link to regional modelling using e.g. embedded tropical cyclones models.
- Which features of extremes can be forecast for the next years/decade using initialized forecasts or forcing?
- What data are needed to better support model evaluation of extremes?

- Continued engagement with CORDEX community e.g. CORDEX meeting in Hamburg, February 2016, CORDEX conference in Stockholm, May 2016 - Keynote talk in the extremes session on the global modelling efforts in terms of climate extremes indices and their relevance and application for the CORDEX community.

New research/activity/data gathering requirements

- Develop storylines involved in observed extremes and a set of metrics needs to be developed for assessing the models' ability to simulate dynamical conditions conducive to extremes (e.g., for example, blocking). Propose metrics to compare and measure local feedbacks to extremes (e.g., dry conditions enhancing heatwaves). This should be coordinated with the regional climate modelling initiatives e.g. WGRC.

- Determine methods to quantify feedbacks involved in extremes in models and data. In connection with the Understand theme, observational diagnostics representative of physical drivers of extremes will be derived to allow the evaluation of climate models in both present and future climates. This will be disseminated in a guidance paper on extremes evaluation to be written in 2016.

- Specific funded research will address some of this topic; e.g. a postdoc funded by the National Centre for Atmospheric Science (NCAS; UK) is evaluating conditions leading to extremes in models; ERC advanced grant TITAN (Hegerl) is comparing simulations of extremes by weather@home with more recent single model runs; project submitted to the Newton Fund compares statistical extrapolation of extremes with large ensembles to identify feedbacks for China.

- Input from the detection/attribution and event attribution community from future IDAG meetings (see Attribute theme) and in the next EUCLEIA meeting is required to further advance this theme. Results to be disseminated via high impact commentary piece (see cross-cutting activities).

- Develop methods to evaluate small-scale extremes. This will be attacked at the Cargese summer school and the Banff workshop (see coordinated and co-sponsored activities on Pages 16-17).

- Session on Advanced methods for evaluating weather and climate extremes in climate model simulations (co-conveners: Jana Sillmann, Philippe Naveau and Erich Fischer) at the 13th International Meeting on Statistical Climatology (13IMSC), June 6-10 2016 in Canmore, Alberta.

THEME 4: ATTRIBUTE

Lead coordinators: Xuebin Zhang, Friederike Otto

What are the contributors to observed extreme events and to changes in the frequency and intensity of the observed extremes?

A key challenge for the community is to provide access to the latest information on how extremes have varied or are likely to vary under a changing climate and a range of likely greenhouse gas emissions scenarios. The extent to which humans are responsible for changes in extremes and particularly individual extreme weather events is a challenging topic. They are addressed both by

evaluating change in the global or large-scale pattern in the frequency or intensity of extremes (e.g., observed widespread intensification of precipitation extremes attributed to human influence, increase in frequency and intensity of hot extremes) and by event attribution methods. Since 2012, with the publication of the annual BAMS special issue on extremes in a climate context, the number of research groups and methodologies for the attribution of individual extreme weather events has increased rapidly and gathered a lot of interest from both the scientific community and particularly the wider public. Different methodologies and thus ways of framing the attribution question as well as different ways of defining an extreme event lead to differences in the quantification of the role that external climate drivers play.

Quantitative attribution statements necessarily rely on models to simulate the counterfactual world that might have been without anthropogenic influences on the atmospheric composition. Two fundamentally different modelling strategies are applied: physical modelling of the climate system under current and counterfactual climate conditions using coupled or sea surface temperature driven general circulation models on the one hand and statistical modelling based on observed records on the other. Depending on the spatial and temporal scales of extreme events, the type of event and the observational data used (see Document theme), one method might yield more robust results over the other in most cases, however, the highest confidence in results can be gained by applying at least two independent approaches and multiple observational datasets. Event attribution analyses as a less established field of research brings the largely independently developed scientific approaches together.

This is also true for large-scale attribution studies based on the spatial and temporal evolution of extremes but with the high media attention and efforts to develop operational event attribution approaches, the communication and dissemination of attribution results becomes an additional challenge. While the scientific community is aware of the fact that these different approaches will provide different answers to the attribution question, such results might be perceived as contradictory in some instances to a broader audience. Hence close interaction with stakeholders and potential users of attribution assessments is particularly important in event attribution activities.

The International Detection and Attribution Group (IDAG; with Zhang and Hegerl in the steering committee) provides a platform where both activities, event and large-scale attribution, interact as well as in several worldwide event attribution activities (US activities; European projects e.g. EUCLEIA, with Vautard, Otto, Seneviratne and Hegerl involved; World Weather Attribution

project led by Climate Central, including Otto as team lead and GC leaders and contributors in the Scientific Oversight Committee). Both projects have a large component of social scientific research and stakeholder engagement. We will ensure that these communities are engaged in the activities in the other overarching Themes (Document, Understand, Simulate) and can provide input.

Further implementation of this Theme was discussed at the IDAG meeting (Boulder, February 2016), and at the next EUCLEIA meeting. In particular in the cross-cutting initiatives of the WCRP Grand Challenge we will work on transferring the lessons learned from combining statistical and physical modelling approaches in attribution assessments to enhance our understanding of extremes and improve the simulation of extreme weather events.

Coordination of existing and forthcoming activities specific to this theme

- **Summer School** (Trieste, July 2014) **and special issue** (see also Understand theme): Definition of extremes, attribution of extremes, physical drivers of extremes, observations of extremes. This school represented a cross-cutting activity (see Page 15) to train the next generation of leaders in this field, enhancing capacity. The workshop has resulted in 7 student-led papers based on the research problems tackled by the students during the workshop. These papers were included in a special issue for the journal "Weather and Climate Extremes" in 2015 (http://www.sciencedirect.com/science/journal/22120947/9).
- A review paper on recent advances in the methodology of event attribution and challenges in framing the attribution question is forthcoming in WIRES, with Otto and Vautard as co-authors.
- Coordination of existing grants: ERC grant 'TITAN' (Hegerl, U Edinburgh) attributing early 20th century extremes in temperature in US and Europe and separating the role of circulation vs forcing; ERC grant "DROUGHT-HEAT" (Seneviratne, ETH Zurich) considering processes relevant to drought and heatwave attribution, planned activities under Belmont Forum.
- EU Project EUCLEIA developing an event attribution system (lead UK Met Office)
- Close links will be developed to the CLIVAR Dynamics Panel activities focusing on modes of climate variability.

- A large international effort in explaining each year's extreme events in the context of climate change is being undertaken and taking the form of a series of peer-reviewed articles in a supplementary issue of the BAMS journal. This initiative is becoming very popular in the scientific community working on extreme events and a large body of material is already present.

- The Board on Atmospheric Sciences and Climate (BASC) is commissioning a new National Research Council (NRC) fast-track study to examine the science of attribution of specific extreme weather events to human-caused climate change and natural variability. A workshop for the attribution community to input into the report is currently scheduled for late 2015 with the aim to publish the report in early 2016 (Hegerl on the panel).

New research/activity/data gathering requirements

- The community will continue to actively engage in the annual Bulletin of the American Meteorological Society (BAMS) report on attribution of climate-related events from the previous year.

- **Meeting** (IDAG January 2015): A brainstorming session at the IDAG meeting in Boulder has been held in order to provide a list of necessary steps, supported by the community, as to how CLIVAR/GEWEX can support and coordinate detection and attribution and ensure the robustness of results. The topic further arose during the EUCLEIA meeting in July 2015 and it is expected that a report on the way forward will be produced. A further brainstorming activity was planned in IDAG, Feb 2016, Boulder.

- **Workshop** (Canmore, Alberta, June 2016): A workshop on "Framing event attribution questions". Climate change detection and attribution (D&A) research over the past decade has increasingly focused on changes in the frequency and intensity of rare, high impact weather and climate events (extremes), including "event attribution". There are similarities and differences in the questions posed by D&A research, which focus on long-term changes in the statistics of extremes and event attribution of individual events, and in the methods addressing them. There is also an active debate about how to "frame" event attribution questions leading to different implementations of event attribution. The questions include "did humans affect its magnitude or the functioning of the processes responsible for the event?", "given the synoptic structure of an event, did human influence alter its impact?", "did human influence alter the odds?", "did other factors further modify the odds (e.g., the pattern of SST anomalies)?". All of these framings are valid, but not all are amenable to prospective risk assessment, risk

mitigation planning and risk sharing, and thus they may not all be equally useful. This workshop will bring together researchers from a community broader than the D&A community to discuss the path forward for event attribution. Issues to be discussed include the framing event attribution questions, how the framing relates to different purposes, scoping of further development in relation to its different objectives, and the interpretation and communication of results. Possible workshop outcomes could include producing a vision for the continued development of event attribution science and/or a good practice guidance document on the detection and attribution of changes in climate extremes to guide the AR6 assessment on this important topic.

- **Workshop** (RMetS/NCAS conference, Manchester, UK July 2016): A session on "Attribution of changes in extreme events" aims to advance a crucial and rapidly developing aspect of Extremes Grand Challenge - research into the attribution of past changes in extreme events. It brings together the community investigating mechanisms and the attribution community in order to nudge attribution science towards making quantitative use of mechanisms and feedbacks when attributing and evaluating models; and to raise awareness of quantitative attribution methods in the synoptic and modelling community. The overarching goal is to facilitate the UK community continuing to play a leading role in this international activity. Multiple short presentations by poster presenters, many Early Career Scientists, on their view of key challenges on extremes, followed by general discussion. Hegerl will report back on outcomes to Grand Challenge team.

CROSS-CUTTING ACTIVITIES

Training the next generation of scientists

- At all levels of the Extremes Grand Challenge we will entrain early career researchers including in leadership roles within each research theme. We will enable and continually support early career researcher networks, nominate early career researchers for keynotes, awards and to lead research topics as appropriate and we will pay special attention to **ensure that attendance and leadership of our meetings and workshops will be as balanced as possible in terms of age, gender and geographic region.**

- A WCRP Summer School on climate extremes was held in July 2014 to train **the next generation of leaders** in this field, enhancing capacity. The research problems that were tackled by the students during the summer

school have resulted in seven student-lead papers, which were produced for a special issue of the journal "Weather and Climate Extremes" (http://www.sciencedirect.com/science/journal/22120947/9). Follow-up activities will be planned to ensure continued support for young scientists.

- **Workshop** (Banff, June 2016): A workshop on "uncertainty modeling in the analysis of weather, climate and hydrological extremes" has been funded by the Banff International Research Station (BIRS). This workshop will bring together over 50 researchers from atmospheric and hydrological sciences on the one hand, and statistics and probability on the other with a strong focus on multivariate extreme value theory and its application in the context of climate and hydrological extremes (cross-cutting activity).

- The 13th International Meeting on Statistical Climatology (Canmore, June 2016): This meeting features multiple sessions on climate extremes organized by co-chairs and co-leads of the GC. This includes a dedicated WCRP GC on extremes session as an outreach event, a session on detection and attribution, a session on extreme value modelling, a session on event attribution.

Specific Extremes Grand Challenge and HIWeather cross-cuts

The High Impact Weather project (HIWeather) is a ten-year activity within the World Weather Research Programme to:

"Promote cooperative international research to achieve a dramatic increase in resilience to high impact weather, worldwide, through improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications."

See
http://www.wmo.int/pages/prog/arep/wwrp/new/documents/HIW_IP_v1_4.pdf

We will work closely with HIWeather to ensure an end-to-end improvement and transformation in our understanding of observations, processes, simulation and prediction of extreme weather and climate events. Specifically the Extremes Grand Challenge core events align well with their selected set of hazards: Urban flood (Heavy precipitation), Wildfire (Droughts and heatwaves), Localised Extreme Wind (Storm), Urban heatwaves and air pollution (Heatwaves) and two

of their research themes: Predictability and Processes (Understand and Attribute), Multi-Scale Forecasting of Weather-related Hazards (Document and Simulate).

This will be done through continued communication (including teleconferences) and through cross-cutting workshops (see below).

Also a joint Extremes Grand Challenge/HIWeather symposium will be proposed for the IAMAS-IAPSO-IAGA meeting in Cape Town in 2017, which will particularly encourage input from researchers whose work/activities cuts across both projects.

Cross-cutting workshops and conferences

- Cross-cutting workshops: one on drought (led by GDIS) and one on high-impact weather (including storms) and seasonal-to-subseasonal prediction of extremes organized in conjunction with WWRP and HIWeather will cut across the four research themes. We also recommend specific workshops targeting each of the other two core events: Heavy precipitation and Heatwaves. In addition a workshop on "uncertainty modelling in the analysis of weather, climate and hydrological extremes" will bring together atmospheric scientists, hydrologists and statisticians to make better use of statistics in extremes applications.

- The M-ClIX workshop will cut across the Understand and Simulate themes (see those sections above) and included participation from people involved in HIWeather and the Water Availability Grand Challenge.

- We recommend a workshop/meeting of relevant people in the CMIP6 and CORDEX community to discuss useful ways to coordinate activities related to the analysis of extremes in regional and global model simulations (e.g., indices choices, model evaluation, relevance of large-scale dynamics for the representation of extremes in regional climate simulations etc).

- We are building links with Future Earth, for instance, by engaging in the Future Earth E3S (Extreme Events and Environments - from climate to society) workshop. This cross-community/co-design workshop is aimed to identify and elaborate the scientific questions and associated research agendas, which are scientifically challenging and at the same time highly societally relevant. We contribute with a dedicated session on impact-relevant climate extremes metrics and active participation in a session on

integrating the potential of societal data, citizen science, Earth observation, and novel data analytic approaches in detecting and understanding extreme events.

- We propose a cross-cutting theme on 'compound events' which include hazards such as floods, wildfires, heatwaves and droughts which often result from a combination of interacting physical processes that take place across a wide range of spatial and temporal scales. This would likely lead to a workshop mid-2017.

- **Capacity building and data gathering workshops** such as those coordinated by the ETCCDI are ongoing and need to be continued. In addition we will provide continued support and coordination to data rescue activities.

Dissemination activities

- Where appropriate we will organize symposia at large international conferences such as AGU, EGU, IAMAS and IUGG. A joint symposium has already been held at IUGG 2015 in Prague on high-impact weather and climate events and another is proposed at the IAMAS-IAPSO-IAGA conference in Cape Town in 2017.

- The Grand Challenge leadership team will develop dissemination papers that explain the approach taken by the Extremes GC to the wider scientific community. We will target high-impact publications, e.g. Nature GeoScience. A planning workshop to write such a paper was held in Boulder in Feb 2016.

- A follow-up publication (e.g. in Bulletin of the American Meteorological Society) is tentatively planned at the end of the GC lifetime (end of 2017) to discuss progress and further action needs.

- The Grand Challenge leadership team will contribute to relevant workshops and conferences and will give keynote, overview talks where appropriate.

- Contribute to the **WCRP-wide open science conference on climate by organizing sessions on extremes** in 2018. This will review our achievements within the Grand Challenge and provide valuable input into the next IPCC Assessment.

A further important step is to **identify funding opportunities** for research on extremes, and to provide guidance to funding agencies for addressing these research needs. Avenues for funding to follow up are the Belmont Forum, the EU and any funding that would help foster research in this area on other continents will be investigated.

In the implementation plan, a conscious effort was made to define activities so as to address interfaces between the recommended four research themes and four core events in addition to theme-specific topics. This would aim to coordinate work on marine and atmospheric heatwaves, for example, much of which is currently being carried out in an ad hoc manner. Above all we aim to try and coordinate existing activities to the extent that they best optimize the advancements that will be an outcome of this Grand Challenge.

Timeline of new WCRP Extremes coordinated activities 2014-2017

Date	Activity	Title	Location	Coordinator(s)	Expected outcomes
July 2014	Summer school	Attribution and Prediction of Extremes Events	Trieste, Italy	Sonia Seneviratne, Francis Zwiers	Special Issue Weather and Climate Extremes
Sep 2014	Workshop	Lessons learnt for Climate Change Research and WCRP	Bern, Switzerland	Xuebin Zhang, Gabi Hegerl	Break out group summary
Feb 2015	Data workshop	Data requirements to address the WCRP Grand Challenge on Weather and Climate Extremes: Observations and Models	Sydney, Australia	Lisa Alexander, Xuebin Zhang, Gabi Hegerl, Sonia Seneviratne, Ali Behrangi	Data inventory. Best Practice documentation for gridding data. Data intercomparison
Oct 2015	Process understanding and model evaluation workshop	Advancing our understanding and modelling of climate extremes by combining physical insights with statistical methodology	Oslo, Norway	Jana Sillmann, Gabi Hegerl, Sonia Seneviratne, Xuebin Zhang	Storylines and set of metrics developed. BAMS-type paper outlining challenges and possible solutions
Oct 2015	LandMIP (land modelling) workshop	Coordination of CMIP6-related land modelling activities, including focus on representation and analysis of extremes-related processes	Zurich, Switzerland	Sonia Seneviratne, Bart van den Hurk, Gerhard Krinner	Experimental plan, details of output variables
Early 2016	Writing workshop	Outline for overview (possibly Nature Geoscience) paper (interest expressed from chief editor)	Boulder, USA	co-Chairs and Theme co-leads	Overview article introducing the grand challenge to the broader public TBA
Apr 2016	Blocking workshop	Understanding of processes leading to blocking, including feedbacks, simulation of blocking in models	Reading, UK	Giacomo Masato, Olivia Martius, Tom Woolings	TBA
Jun 2016	Workshop	Uncertainty modelling in the analysis of weather, climate and hydrological extremes	Banff, Canada	Francis Zwiers, Philippe Naveau, Peter Guttorp	Funded. Inviting attendees.
Jun 2016	Event attribution workshop	Framing Event Attribution Questions	Banff, Canada	Xuebin Zhang, Friederike Otto and others	Post workshop report
Late 2016/early 2017	Workshop	Process understanding, first analyses of ExtreMEx experiments	Paris, France	Robert Vautard, Olivia Martius, Sonia Seneviratne	First analyses of ExtreMEx experiments. Planning of coordinated articles.

Date	Activity	Title	Location	Coordinator(s)	Expected outcomes
Early 2017	Compound events/ multivariate extremes workshop	Addressing the challenge of compound events (invitation-only)	TBA - Europe	Seth Westra	Documented strategy for addressing compound events as part of the Grand Challenge
Late 2017	Process understanding and model evaluation workshop follow-up	Advancing our understanding and modelling of climate extremes by combining physical insights with statistical methodology: Update	TBA	Jana Sillmann; Gabi Hegerl	Update to Oslo 2015 workshop

Timeline of relevant co-sponsored WCRP Extremes activities coordinated 2014-2017

Date	Activity	Title	Location	Coordinator(s)
Dec 2014	Drought workshop	An International Global Drought Information System Workshop: Next Steps	Pasadena, USA	Siegfried Schubert GDIS
Jun 2015	IUGG 2015	IAMAS Symposium on Understanding and Predicting High-impact Weather and Climate Extremes	Prague, Czech republic	Richard Swinbank, Xuebin Zhang, Richard Grotjahn, Lisa Alexander, Julia Keller
Jul 2015	2015 United Nations Climate Change Conference	Sessions on extreme events research and climate services	Paris, France	Session 1: Robert Vautard, Peter Stott, Friederike Otto; Session 2: Jana Sillmann
Aug 2015	Summer School	Extreme events and climate	Ticino, Switzerland	Reto Knutti, Sonia Seneviratne
Sep 2015	ETCCDI software (RClimDEX) updated	Software updated to incorporate new relevant indices discussed at ETCCDI meeting in Paris, July 2015	N/A	Xuebin Zhang, Lukas Gudmundsson
Nov 2015	Autumn school on extremes. Improved input to GC by statistics and nonlinear dynamics community. Scheduled, funded.	Statistical and mathematical tools for the study of extremes https://mastacc.lsce.ipsl.fr/	Cargese, Italy	Pascal Yiou, co-organized by Hegerl
Feb 2016	E3S (Extreme Events and Environments) conference	http://www.futureearth.org/extreme-events-and-environments-climate-society-e3s	Berlin, Germany	Markus Reichstein MPI; session on impact-relevant climate extremes metrics by J. Sillmann; Steering committee discussion on future links between WCRP GC and E3S
Apr 2016	Atmospheric blocking workshop	http://www.sparc-climate.org/meetings/Workshop_on_Atmospheric_Blocking_Reading_April2016	University of Reading, UK	SSC members: Olivia Martius, Jana Sillmann and Sonia Seneviratne
Jun 2016	IMSC conference	The 13th International Meeting on Statistical Climatology (IMSC)	Canmore, Canada	Francis Zwiers

Date	Activity	Title	Location	Coordinator(s)
Jun 2016	Data rescue workshop	Providing a grand vision for finding, storing and accessing historical climate data	Maynooth, Ireland	Rob Allan, Lisa Alexander, Philip Brohan, Peter Thorne
Jul 2016	Workshop Attribution of changes in extreme events	RMetS/NCAS conference 2016	Manchester, UK	Gabriele Hegerl, Peter Stott, Simon Tett.
Dec 2016	WWRP S2S - Seasonal-to-subseasonal prediction of extremes	Seasonal-to-subseasonal prediction of extremes	New York, USA	Adam Sobel, WWRP
2017	Joint Extremes Grand Challenge/HIWeather symposium at IAMAS-IAPSO-IAGA conference	High-impact weather and climate extremes	Cape Town, South Africa	Richard Swinbank, Xuebin Zhang, Richard Grotjahn, Lisa Alexander, Julia Keller + other HIWeather reps

Timeline		2014				2015				2016				2017			
Document	Data issues workshop																
	Review of extremes indices & software development																
	Best practice guidance documents – datasets and gridding																
	Data repository & dataset intercomparison																
Understand	Plan CMIP6 land experiments																
	EUCLEIA meetings and MCliX workshop session																
	LandMIP workshop																
	Blocking workshop																
	Coordinated experiments and software																
	Synthesis workshop																
Simulate	IDAG/EUCLEIA meetings																
	MCliX workshop																
	Guidance paper on evaluation																
	NCAS Postdoc/evaluation																
Attribute	Summer school & special issue																
	Workshop on hydrological extremes																
	Review paper on attribution methodology																
	IDAG/EUCLEIA meetings																

	Framing workshop															
Cross-cuts	White Paper															
	Implementation Plan															
	WCRP-ICTP summer school and special issue publication															
	GDIS workshop															
	IDAG/EUCLEIA meetings															
	Heatwaves workshops & publications															
	M-CliX workshop															
	Nature Geoscience paper															
	Sesaonal-to-subseasonal prediction of extremes (WWRP-led)															
	Compound events															
	Open Science Conference planning															

Publications with Extremes Grand Challenge acknowledgements will be added to the website through time. We recommend an acknowledgement worded “This work contributes to the WCRP Grand Challenge on Extremes.

ACRONYMS

ACRE – Atmospheric Circulation Reconstructions over the Earth

CFHP – Climate Hubs Fellows Program

CliC – Climate and Cryosphere core project of the World Climate Research Programme

CLIVAR - core project of the World Climate Research Programme

CMIP – Coupled Model Intercomparison Project

CORDEX - Coordinated Regional Climate Downscaling Experiment)

ETCCDI – Expert Team on Climate Change Detection and Indices

ET-SCI – Expert Team on Sector-specific Climate Indices

EUCLEIA - EUropean CLimate and weather Events: Interpretation and Attribution

ExtreMEx – Extreme Modeling Experiment

GCOS – Global Climate Observing System

GDAP – GEWEX Data and Assessments Panel

GDIS – Global Drought Information System

GEWEX - core project of the World Climate Research Programme

GHP – GEWEX Hydroclimate Panel

GLACE – Global Land-Atmosphere Coupling Experiment

GPCC – Global Precipitation Climatology Centre

HIWeather - High Impact Weather project within the World Weather Research Programme

IAMAS – International Association of Meteorology and Atmospheric Science

IAPSO – International Association for the Physical Sciences of the Ocean

IDAG – The International ad hoc Detection and Attribution Group

ISTI – International Surface Temperature Initiative

IUGG – International Union of Geodesy and Geophysics

SPARC - core project of the World Climate Research Programme

TT-TCI – Task Team on Tailored Climate Information

WCRP – World Climate Research Programme

WGRC – Working Group on Regional Climate

WGSIP – Working Group on Seasonal to Interannual Prediction

WMO – World Meteorological Organisation

WWRP – World Weather Research Programme