WCRP REPORT
World Climate Research Programme

Summary Report

Workshop on Understanding, Modeling and Predicting Weather and Climate Extremes

Oslo, Norway
5-7 October 2015

WCRP Report No. 10/2016

Joint Planning Staff for WCRP
c/o World Meteorological Organization
Case Postale No. 2300
CH-1211 Geneva 2
Switzerland

NOTE

The World Climate Research Programme is jointly sponsored by the WMO, the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO.

M-CLIX

Workshop on understanding, modeling and predicting weather and climate extremes

Oslo Science Park, Oslo, Norway
October 5 - 7, 2015

Background

The recent fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) has once more shown that our climate is changing and with it its extremes. As the impacts of climate extremes (e.g., heat waves, floods, droughts, and wind storms) often lead to devastating consequences for society and the environment, reliable predictions of extremes on short and long time scales are needed to reduce their potential risks and damages. Understanding, modeling and predicting weather and climate extremes are key challenges in climate research and have thus been selected as one of the World Climate Research Program (WCRP) Grand Challenges.

As part of the implementation of the WCRP Grand Challenges on Climate Extremes (Extremes GC), a workshop on "Understanding, modeling and predicting weather and climate extremes" was held in Oslo, Norway (October 5-7, 2015). This workshop brought together 40 national and international experts and early career scientists from the weather, climate and statistical sciences to discuss some of the scientific challenges that are emphasized in Extremes GC white paper *(http://www.wcrp-climate.org/index.php/gc-extreme-events)*.

The participants had ample opportunity during the three-day workshop to present and discuss their latest research. They also spent a substantial amount of time assessing the current state of knowledge, identifying opportunities for cross-community collaborations to address the challenges (e.g., modeling experiments, data needs, storylines for model evaluation, scale issues), and discussing the coordination of future research and the communication of results. The workshop was structured in four sessions distributed over two days with presentations and discussions related to large-scale drivers of extreme events (session A-I), local-to-regional drivers and feedbacks (session A-II), predictability of extremes (session B), and model performance (session C). Workshop presentations are publically available through the WCRP workshop website (http://www.wcrp-climate.org/extremes-modeling-wkshp-about). The participants split up into three breakout groups on the third day of the workshop to discuss specific questions related to short-duration (i.e., less than three days) and long-duration (i.e., multi-day through to seasonal timescale) extreme events. The results of the discussions were summarized in a joint session and provided input to ideas and plans for future research needs and joint projects or collaborations.

Setting the scene

The workshop was opened by introductory talks emphasizing the importance of the workshop topic with regard to local and national adaptation challenges (Norwegian Environment Agency), global challenges in advancing climate sciences and modeling (WCRP) as well as cross-community challenges in terms of building resilience to high-impact weather events by improving their forecasts and predictability across temporal and spatial scales (World Weather Research Programme (WWRP) HiWeather: www.wmo.int/pages/prog/arep/wwrp/new/high_impact_weather_project.html).

The challenges

Large-scale drivers of extreme events and process-based model evaluation

This session focused on process understanding with respect to large-scale circulation patterns, which can be used in model evaluation and to improve predictability of extremes. Most presentations gave examples for processes relevant for the mid-to-high latitudes in the Northern Hemisphere, but a case for Australia was also discussed.

An important point raised in the keynote was the overall ability of current climate models to simulate (and predict) extremes and associated processes. For instance, climate models can have large biases in some regions and may not be able to simulate key processes (e.g., atmospheric blocking or tropical dynamics and teleconnections). An important challenge is, thus, to improve the models by targeting key processes that are relevant for a realistic (or at least sufficient) representation of extremes. This further involves increasing model resolution and using novel approaches for parameterizing sub-grid scale processes. It was emphasized that international collaboration would be necessary to ensure sufficient funding and to pool resources for coordinated high-resolution modelling on a global scale (such as in PRIMAVERA, https://www.primavera-h2020.eu/), and also to enable fine-tuning of high-resolution models to improve the simulation of extremes to ensure added-value. A combination of high-resolution simulations with lower resolution ensemble simulations would be beneficial to study effects of internal variability and better quantification of the signal-to-noise ratio, particularly for precipitation extremes.

Current attribution studies try to identify relevant physical large-scale drivers of observed extreme events using particular case studies. It was emphasized that the framing of the attribution question is crucial and affects the end result as well as the definition of the event and the size of region under consideration. From the examples discussed (e.g., the extreme precipitation event in the UK winter 2014/15 or the European heatwave in summer 2003), it became obvious that both dynamic and thermodynamic processes can be relevant for generating an extreme event, and should both be considered. A circulation analogue method was also discussed as an approach for attribution studies. However, it was pointed out that some events do not have good analogues, and that there seems to be a decreasing trend in the number of appropriate analogues for heat events in summer since the mid-20st century.

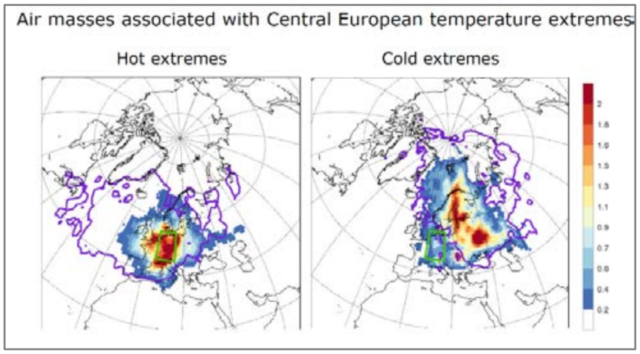

Figure 1: Trajectory densities (number of trajectories per area of 1000 km2) four days prior to the cold events for Central Europe. The contour line refers to the distribution of trajectories seven days before the cold events, representing a density level of 0.2. Adapted from Bieli et al. 2015 (QJRMS).

Examples for important large-scale dynamic drivers of extremes in the mid-to-high latitudes were discussed. For instance, in Europe most extreme temperature events occur during atmospheric blocking conditions, but processes are different for summer (local processes) and winter extremes (advection of cold air). Furthermore, there seems to be a regional dependency of the relationship between blocking anticyclone locations and the corresponding surface extreme event (e.g., heat wave or cold spell) *(Fig.1)*. It was further discussed that the weakening of the equator-to-pole temperature gradient due to global warming, particularly in summer, is associated with a decrease in eddy kinetic energy (EKE), a measure of transient wave activity. This can lead to more persistent summer weather and enhanced anti-cyclonic flow regimes in some regions. The European summers of 2003 and 2010 are good examples in which high-amplitude quasi-stationary waves were associated with extreme heat waves.

It became apparent in the discussions that we need to improve our understanding of the mechanisms that lead to the occurrence of extreme events in order to assess their predictability and enable prediction. Both dynamic and thermodynamic processes play a role, which is important to distinguish when evaluating model simulations. For instance, how do changes in temperature (i.e. Clausius Clapeyron relationship) or circulation patterns (e.g., displacement of circulation systems) contribute to changes in extreme precipitation?

Local-to-regional feedback processes and drivers of extreme events

This session addressed the importance of local-to-regional drivers of extreme events and relevant feedback processes in addition to the large-scale drivers. To disentangle the contribution of dynamical and thermodynamic processes, the need for cross-community modelling efforts was emphasized, as the contributions of these processes to different types of extremes are not always clear. In general, dynamical contributions to changes in temperature and precipitation extremes are more clearly represented in winter than in summer. For instance, in early summer the soil moisture conditions are important for the evolution of a heat wave. Therefore, controlled experiments within a coordinated modelling experiment (ExtremeX) are therefore planned to study the effects of circulation, soil moisture and SST in the formation of heat waves.

The separation of dynamic versus thermodynamic processes, although convenient for studying the respective effects, is by far not sufficient to understand (and being able to predict) the complexity of process interaction leading to extreme events because of non-linear interactions. For instance, SNOWGLACE experiments (http://uni.no/en/uni-climate/climate-services/snowglace/) were presented to study the impact of snow on sub-seasonal-to-seasonal forecast by "realistic" snow initialization.

Model uncertainty in heat wave or drought projections can be due to a misrepresentation of feedback mechanisms in the models. For instance, soil moisture is very uncertain in current generation climate models (i.e. CMIP5). Constraining soil moisture in model experiments may be similarly important as other factors, such as climate sensitivity and cloud feedbacks, on global scales (See also LS3MIP, http://www.climate-cryosphere.org/activities/targeted/ls3mip). Feedback mechanisms over land can be reflected, for instance, in changes in the shape of the temperature distribution, not only in a shift in the mean.

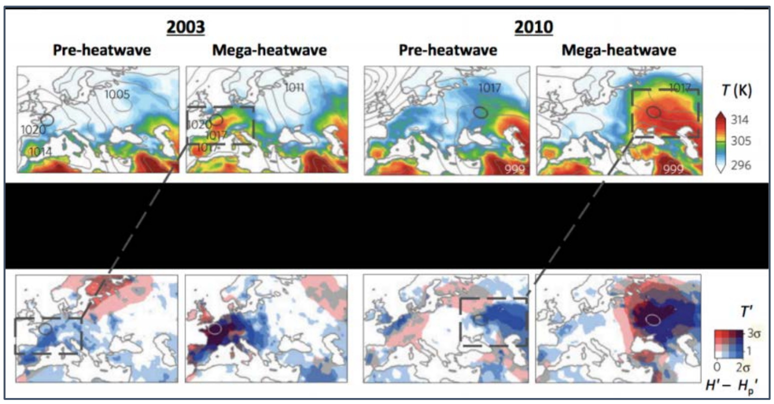

Figure 2: Air temperature (T) and soil moisture deficit (e) in Europe during recent mega-heatwave summers for 10-day pre-heatwave and mega-heatwave periods in 2003 and 2010. Upper panel: Anomalies in surface soil moisture expressed in the number of standard deviations (σ). Lower panel: Evolution of T and e for an area of 200 km radius around Trappes (marked in upper panel). Adapted from Miralles et al. 2014 (Nat Geoscience).

Satellite records have been shown to be very useful for statistical analysis and process understanding in conjunction with simple mechanistic models to help interpret them. The improved process understanding could then be applied to benchmark complex models. For instance, observations (i.e., remote sensing data) were linked to mechanistic simplified models in order to study coinciding periods of "dry soil" and "high temperature". For the European heatwaves 2003 and 2010 a clear spatial correlation between "prior" soil moisture (dryer) conditions and heat wave temperatures was shown *(Fig.2)*. However, correlation still does not necessarily imply causation.

Furthermore, high-resolution coupled model simulations are required to study feedback-driven preconditioning of extreme events, e.g. feedback of soil moisture/snow on circulation patterns. As an example, a study of small-scale thunderstorms over Lake Victoria and their changes in the future was discussed. Simulations with a regional climate model (COSMO-CLM2; flake) indicated that the lake effects are amplified for extremes (i.e., the thunderstorms were three times stronger over the lake compared to land). A process analysis to separate "lake" and "land" events and "thermodynamic" versus "meso-scale dynamic" showed that the dynamic processes dominate (3/4) in current climate conditions, but also implied changes in this relationship with climate warming. The "no-lake" simulations further indicated that persistence explains 40% and mesoscale dynamics explains 60% of the thunderstorm events. As a perspective to prevent loss of lives at Lake Victoria, it would be useful to utilize this process understanding in statistical forecasting (logistic-regression) for early warnings.

To realistically represent small-scale processes (e.g., convective storms, orographic rain), new climate change experiments were presented at km-scale (e.g., 1.5km resolution) over Europe. Convection permitting models have already been widely used in numerical weather forecasting. The high-resolution experiments have shown that mean changes in precipitation were not affected, but the very fine resolution is useful to better simulate summer precipitation and in particular convective events (i.e., hourly precipitation, extremes, steep orography). So far there are only a few studies available with such high-resolution model experiments, but for different regions (e.g., UK, Switzerland). In order to be able to compare model results and assess the robustness of present and future climate projections, coordinated high-resolution (i.e. convection permitting) modelling experiments are urgently needed.

The benefit of going to higher spatial resolution versus having a larger number of ensembles to study the effect of variability and a robust ensemble statistics was subject to intense discussion. For some types of extreme events, such as convective precipitation, the gains from increased resolution (i.e. 3km and less) are obvious, but for other types of extremes, such as droughts, it is not. Going from annual to monthly or daily to sub-daily scales in the analysis of extremes would also help to better understand the temporal variability and changes in extremes. For instance, the importance of reducing systematic biases in model simulations related to the seasonal cycle of precipitation or evapotranspiration, or the shift of precipitation from afternoon to the night was discussed.

A limiting factor for the analysis of such small-scale processes remains the availability of observational data. In many regions of the world (e.g., Africa, South America, Asia) even daily temperature and precipitation data are none-existent or not publically accessible, let alone other variables, such as soil moisture or wind measurements. This challenges any significant progress in process understanding and model evaluation. Besides that, the value of single measurements (i.e. case studies of single events) versus robust statistics over a series of similar events or regions for model evaluation was discussed. Particularly the assessment of trends in changes of extremes is hampered by the limited data availability and quality (see also the WCRP workshop on Data Requirements http://www.wcrp-climate.org/index.php/extremes-data-wkshp-about).

Drivers of extremes and their predictability

This session provided an overview of the state-of-the-art in terms of predicting climate extremes. It covered the user perspective, prediction timescales from seasonal-to-decadal and climate change, and the mechanisms for predictability and potentials to enhance predictions skill.

The long-term goal of climate prediction is to provide society with useful information about future changes in climate and weather. In this respect, the user needs must be taken into account when determining the products that climate prediction centres should provide. This should be addressed from a climate services perspective. What forecasters currently provide is far from what some users demand. For weather and climate extremes a key issue is to have user relevant definitions of extreme events. There are definitions from CCl/CLIVAR/JCOMM Expert Team (ET) on Climate Change Detection and Indices (ETCCDI), however weather forecasters also have very relevant lists. In addition, users are often interested in impact-related parameters, such as flood level, heat stress, and water availability. Communicating changes in frequency, probability of occurrence, and intensity of extremes is relevant for users. Fraction of attributable risk (FAR) appears less relevant and its computation might be highly sensitive. It is critically important to also convey the uncertainties and skill levels to the users.

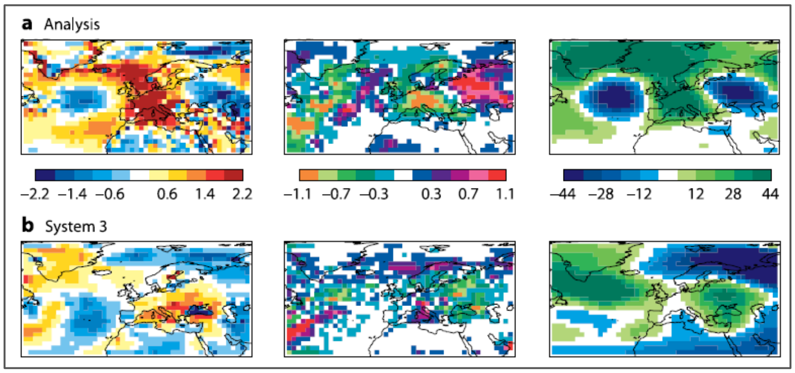

Figure 3: Anomalies of T2m, precipitation and Z500 in (a) the verification and (b) a seasonal re-forecast system. Adapted from Weisheimer et al. 2011 (GRL).

The skill in predicting changes in climate and weather extremes was mostly discussed in terms of a large-scale perspective. On seasonal timescales skill has been shown in predicting temperature and precipitation extremes. The skill was attributed to a relation between skill in predicting seasonal mean temperature and precipitation, and is consistent with large-scale factors causing shifts in distributions (e.g. *Fig 3*). On these timescales, most of the skill in predicting large-scale factors in current systems derives from the El Niño Southern Oscillation (ENSO). Presently much interest is also in understanding and accounting for the skill associated with sea ice variability. For example, winter NH variability has been linked to autumn and early winter sea ice anomalies through both tropospheric and stratospheric pathways, which are partially captured by models. Another interesting phenomenon discussed and yet not fully understood was the month-to-month persistence of winter and summer temperature extremes over Europe, with the temperature of the month before being a better predicator than common large-scale patterns (e.g., NAO).

Extremes are by definition rare events, and thus case studies may be the most effective means to assess model skill. Two examples were presented: seasonal predictions of the 2003 European dry summer and the 2013/2014 NH cold winters. In the former case, the predictability of the event was apparently less due to remote teleconnections effects and more due to in situ processes. These helped maintain the dry surface anomalies occurring at the beginning of the summer. Whereas tropical processes seem to be most relevant cause for the 2013/14 cold winter. Models suffer from large-systematic errors that can adversely affect prediction skill, and case studies of this type can be very useful to identify the key processes that should be better represented in order to enhance the prediction skill of climate and weather extremes. These two examples already identify two key areas: ocean-atmosphere interaction in the tropics, and land surface processes. Nevertheless, there is active research on assessing predictability arising from extra-tropical SST and arctic sea changes on short and long-timescales. Another issue raised was the question of how to do bias corrections on extremes.

Discussion in this session focused on how to improve understanding and to enhance prediction skill of climate and weather extremes. Given the limited number of events and data there should be a greater focus on mechanisms. Greatest predictability is expected for events in which large-scale thermodynamic changes dominate or in which dynamical process are linked to predictable climate variability (such as ENSO). Thus, it is useful to analyze the dynamic and thermodynamic factors in the initiation and evolution of extreme events. In this respect, quantifying the contributions from local feedbacks versus remote effects is useful. Further, it is important to perform numerical experiments to confirm such case study analysis.

Model performance and evaluation of climate extremes

This session was aimed at discussing statistical tools to assess model performance with regard to weather and climate extremes and including information about process understanding as covered in the previous sessions. The keynote focused on the statistical evaluation of forecasts, which is a well-established field in NWP modeling. Firstly, it is important to distinguish between forecast and model evaluation. Do we want models to simulate realistic climate or help us to forecast weather events? Probabilistic forecast is in principle a probability distribution representing forecast uncertainty. Probabilistic forecasts are commonly assessed using so-called proper scoring rules that assign a numerical score to each forecast-observation pair. An example of a frequently used measure is the Root Mean Square Error (RMSE). RMSE is often used in climate model evaluation studies; however, it evaluates only the average of the forecast against the observation and, thus, does not account for the forecast uncertainty or the tails (i.e. extremes) of a distribution.

When assessing performance of model ensembles, the focus should be on a probabilistic rather than a deterministic assessment of the model ensembles in terms of their abilities to represent climatological statistics as the entire ensemble distribution reflects the ability to simulate the climate realistically. Only fair scores favor optimal ensembles and can be chosen to evaluate specific features (e.g. mean, variance) of ensembles. Multiple scores are needed to identify which features are in error. When evaluating extremes, however, fair scores will not favor optimal ensembles (Forecaster's Dilemma). As alternative, weighted scores should be used, which require the whole ensemble distribution to match the observations (or truth). But it needs to be emphasized that scores always hide some key information, e.g. direction of bias. Thus, other methods are needed to understand performance. Important questions were raised, such as: Are existing scores sensitive to differences in underlying processes? What ensemble sizes are needed to detect differences? How can we handle observation error or lack of observations? What other forecast evaluation methods are useful for assessing model performance?

In this respect, feature-based methods provide a potentially powerful way of evaluating particular events/regimes/features in global NWP forecasts at weather and climate scales especially for the evaluation of current climate. One option is a method for Object-based Diagnostic Evaluation with identification of objects and the evaluation with respect to different attributes/features (location, intensity, shape, area, orientation) of these objects, which could be large-scale circulation patterns or small-scale feedback processes. The remaining challenge is to find adequate gridded data sets for studies like this, which opens up exciting opportunities for closer collaboration between statisticians and the climate community.

Internal variability represents another major challenge to the evaluation of extremes and trends, which can be addressed largely by spatial aggregation. It was further shown that model agreement on the forced response of precipitation and temperature extremes is higher than widely recognized. Particularly daily precipitation intensification is consistent across the model hierarchy and with observations. But are these changes consistent for the right reasons? Various issues have been raised in that context, which concern, for instance the underestimation of precipitation amounts due to parameterized convection; the reliability of trends in observations; inhomogeneities and gridding issues with observations; and model deficiencies in representation of driving processes e.g. representation of blockings, boundary layer dynamics and land-atmosphere interactions.

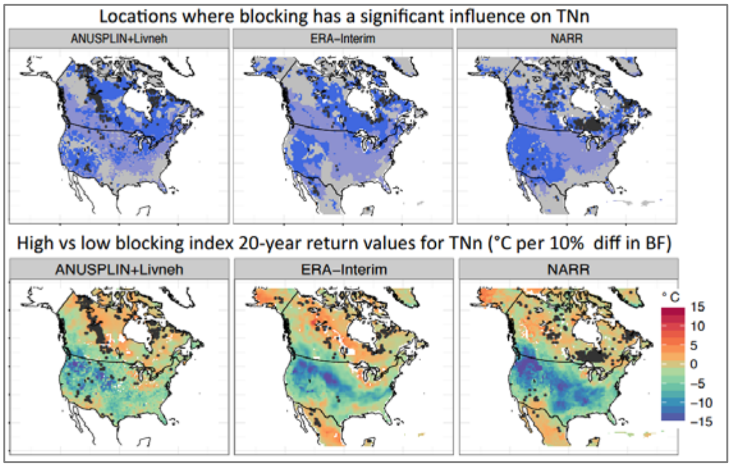

Figure 4: Results from fitting a General Extreme Value Distribution to minimum temperature extremes in regional climate models using atmospheric blocking conditions as covariate. Upper panel: Location parameter, Lower Panel: Differences in 20-year return values for periods with high and low blocking frequency.Adapted from Whan et al. 2016 (J. Climate)

Another study focused on the evaluation of dynamical or dynamically influenced phenomena in regional climate models (RCMs), which are often claimed to better represent extremes. The "added value" however depends in part on the extent to which the RCMs are able to generate their own additional internal variability. Model evaluation should therefore include whether large-scale circulation influences on extremes are well reflected, and whether they improve biases in simulating, for instance, extreme precipitation or intense storms. It was shown, for instance, that RCMs appear to reflect the effects of atmospheric blocking on minimum temperature reasonably well over the large CORDEX North America domain *(Fig. 4)*.

The final discussion centered on what scores are currently available to assess extremes, how to calculate them based on an ensemble, and how to evaluate deterministic forecasts using scores. Model evaluation is also inevitably dependent on the quality and availability of the underlying reference dataset (e.g., reanalysis or observations) and the methods applied need to account for uncertainty in the observations. New data sources (e.g. satellite or remote sensing data) and variables should therefore be explored and exploited to improve model evaluation. The application and development of model performance metrics suited for extremes statistics is currently a field that needs to be further expanded (e.g., new scores, divergence or comparison measures for distributions) and would benefit from close collaboration of climate and weather forecast modelers and statisticians. Following the workshop, solutions to some of these topics are currently in development.

Breakout Group Discussions

As an immediate result of the discussions in the sessions, the focus of the three breakout groups was set on short-duration (less than three days) and long-duration (weeks to months) extreme events and their different mechanisms and needs in terms of evaluation and prediction. The following main questions guided the group discussions:

1. What are relevant definitions of extremes on that time-scale?
2. What are necessary observations and model output requirements to analyze these extremes?
3. What are processes driving these extremes and their changes?
4. How do we best evaluate these extremes (including relevant processes)? (i.e. is the model right for the right reason)
5. What are relevant sources for predictability of these events that can support the attribution, prediction and projection of these extremes?

Short-duration extreme events

Short-duration Extremes (SDE) were defined as rare meteorological phenomena occurring over time scales from 10 minutes to 3 days and leading to hazards. Often these hazards are associated with strong impacts on society, such as infrastructural damage, economic disruption or affected public health. A framework was proposed to study long-term changes in SDEs and identify challenges associated with this study. The SDEs particularly addressed were (i) Convective events leading to heavy precipitation, hail, lightning, tornadoes, violent downdrafts; (ii) Extratropical cyclones leading to wind storms, storm surges, extreme precipitation (rainfall or snowfall), freezing rain; (iii) Anticyclones leading to fog and air pollution, cold outbreak (also if longer lived heatwaves and cold spells; (iv) Tropical cyclones. For each SDE, observations required for their study were identified and their current status was assessed. The proposed framework addresses the challenge of (i) detection of trends in the frequency and intensity of SDEs, (ii) attribution of these potential trends to various anthropogenic or natural forcings, and (iii) projection of their evolution into the future. Each of these challenges is difficult because observation data are scarce, non-evenly distributed, phenomena are of a scale often too small for climate models and long-term simulations, and models necessitates the representation of specific processes (e.g., hail, fog, lightning). However, a few areas with “low-hanging fruits” for which knowledge, data and models could provide results within a timeframe of about 2 years have been identified and a strategy is proposed with concrete actions. The group identified hourly precipitation events as a type of events for which progress in understanding, modelling and attributing could be achieved for the limited locations in which high quality, long-term, hourly precipitation measurements are available.

Long-duration extreme events

Long-duration Extremes (LDE) were defined as events lasting longer than 3 days. The discussion focused on drought, heat waves, cold spells, and floods caused by persistent rainfall, but Artic sea ice decline, increased storminess, and wild fire seasons were also considered. Heat and cold wave definitions should be based on percentile definitions, and account for clustering and reemergence of events. Heat waves definitions should also involve both minimum and maximum temperature and include unseasonably warm (high temperatures, but not extremes over the whole season). Snow accumulation, wet snow, strong winds, and frozen ground are also important factors in cold wave severity. Droughts involve rainfall deficit and excess evaporation, and may also arise from low snow pack; while repeated floods can arise from clustering of precipitation events. Compound events in the same region (e.g. large fires in Australia in 2009 came after a long period of droughts) and simultaneous extremes in several regions around the world should also be considered.

As for the SDE, the types of events we can analyze often depends on the data availability. Temperature and precipitation measurements are the best data we have currently, but not for all regions. Relevant variables to define some of the extremes mentioned are daily minimum and maximum temperature, soil moisture, daily-accumulated precipitation, daily minimum sea level pressure and maximum wind speed (surface, 850hPa, 200hPa). Respective measurement networks should be expanded, as often these data are lacking. Surface data in particular is very important to validate satellite and model-based product data, but in some cases (not necessarily for precipitation extremes), observation-driven model output data products are better than in-direct measurements (e.g. satellite-based products for snow and soil moisture). Furthermore, data assimilation uses integration techniques that can give smaller uncertainty than for each individual measurement. The danger of over-interpreting case studies calls for systematic large-samples (including models).

Processes driving LDE are, for instance, non-linear atmospheric dynamics, quasi-stationary Rossby wave trains, ENSO, Tropical and stratospheric forcing, initial conditions and feedbacks (e.g., soil moisture, SST, snow, sea ice) as well as anthropogenic drivers (e.g., atmospheric composition, greenhouse gases, land-use). To evaluate simulations of LDE, we need to define an event based on what directly affects people (e.g., wind, precipitation) and the underlying processes, and both should be evaluated in conjunction. Extremes should be defined in terms of model statistics, and there should be an emphasis on evaluating the contributing mechanisms to determine realism and assess model systematic errors. Mechanisms can be evaluated in terms of thermodynamics, large-scale circulation, and local feedbacks.

There is a difference between model understanding and model reliability or skill. Whereas it is important to analyze models in terms of their performance for simulating individual events, such analysis might not necessarily be informative regarding the general skill of the model to predict such events. Autopsies of individual cases involves a big challenge in generalizing across numerous cases and requires the development of diagnostics that can be reliably applied across multiple situations and that nevertheless produce insightful information. The models in general should have a reasonable performance and not just relative to a particular type of extreme. Large datasets exist for the evaluation of models in terms of simulating and predicting climate. The community should be encouraged to analyze these to identify models that represent a particular mechanism well or poorly, and quantify its effect on the simulation of extremes (e.g., stratosphere-troposphere interaction). Results should be confirmed by coordinated sensitivity experiments where key process can be identified and their representation can be improved.

Relevant sources for predictability of LDE can include SST, soil moisture, snow, the stratosphere, vegetation, greenhouse gases, and aerosols. Important aspects to investigate are whether the relevant sources of predictability are linear (additive) or not, and whether predictability can be understood in terms of thermodynamic, large-scale precursors, and local feedbacks. We can get different answer for different time scales, e.g. the influence of soil moisture is not the same for seasonal forecasts and projections.

Conclusion and Outlook

The research presented at the workshop and the following discussions lead to several conclusions regarding the need for further research. There is an overall need for better observations and model evaluation tools that are suited for extremes, which required dedicated cross-community efforts. Coordinated model experiments should be set-up for disentangling dynamic and thermodynamic drivers of extremes. As both large-scale circulation and local-to-regional feedbacks and drivers are important for the generation of extreme events, these phenomena should be studied in conjunction to improve process understanding and predictability of extremes. Extreme events occurring at temporal and spatial scales much smaller than that of current state-of-the-art climate models are generally difficult to predict, but there is certainly potential for long-duration extremes (particularly on monthly or seasonal scales). A better understanding of what level of predictability might be expected for these extreme events should be developed. Joint research and model development across scales involving climate and numerical weather prediction (NWP) models will be crucial to make progress in this regard.

References

Bieli, M., Pfahl, S. and Wernli, H. (2015), A Lagrangian investigation of hot and cold temperature extremes in Europe. Q.J.R. Meteorol. Soc., 141: 98–108. doi: 10.1002/qj.2339.

Miralles, D.G., Teuling, A., van Heerwaarden, C. & Arellano, J.V.d. (2014), Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. Nature Geoscience, 7, 345–349, doi:10.1038/ngeo2141.

Weisheimer, A., F. J. Doblas-Reyes, T. Jung, and T. N. Palmer (2011), On the predictability of the extreme summer 2003 over Europe, Geophys. Res. Lett., 38, L05704, doi:10.1029/2010GL046455.

Whan, K., F.W. Zwiers, J. Sillmann, 2016: The influence of atmospheric blocking on extreme winter minimum temperatures in North America, J. Climate, doi: 10.1175/JCLI-D-15-0493.1, in press.

List of Participants

Name	Affiliation	Email
Antje Weisheimer	University of Oxford & ECMWF	Antje.Weisheimer@pysics.ox.ac.uk
Boram Lee	World Climate Research Programme (WCRP)	blee@wmo.int
Brian Golding	Met Office	brian.golding@metoffice.gov.uk
Chris Ferro	University of Exeter	c.a.t.ferro@exeter.ac.uk
Diego G. Miralles	VU Amsterdam / Ghent University	diego.miralles@vu.nl
Dim Coumou	Potsdam Institute for Climate Impact Research, Potsdam, Germany	coumou@pik-potsdam.de
Erich Fischer	ETH Zurich	erich.fischer@env.ethz.ch
Erik Kolstad	Uni Research Climate and Bjerknes Centre for Climate Research	erik.kolstad@gmail.com
Francis Zwiers	PCIC Canada	fwzwiers@uvic.ca
Francisco Doblas-Reyes	Barcelona Supercomputing Center (BSC), Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut Català de Ciències del Clima (IC3)	francisco.doblas-reyes@bsc.es
Friederike Otto	University of Oxford	friederike.otto@ouce.ox.ac.uk
Fumiaki Ogawa	University of Bergen	fumiaki.ogawa@gfi.uib.no
Gabriele Hegerl	University of Edinburgh	gabi.hegerl@ed.ac.uk
Geert Jan van Oldenborgh	KNMI	gjvo@me.com
Hervé Douville	Météo-France/CNRM-GAME	herve.douville@meteo.fr
Hoffman H. N. Cheung	City University of Hong Kong	hncheung@cityu.edu.hk
Jana Sillmann	CICERO	jana.sillmann@cicero.oslo.no
Javier Garcia-Serrano	Earth Sciences Department, Barcelona Supercomputing Center (BSC-CNS)	javier.garcia@bsc.es
Lizzie Kendon	Met Office Hadley Centre	elizabeth.kendon@metoffice.gov.uk
Lukas Gudmundsson	ETH Zürich	lukas.gudmundsson@env.ethz.ch
Magne Aldrin	Norwegian Computing Center	magne.aldrin@nr.no
Maria Kvalevåg	Norwegian Environment Agency	maria.kvalevag@miljodir.no
Marion Mittermaier	Met Office	marion.mittermaier@metoffice.gov.uk
Nathalie Schaller	University of Oxford	nathalie.schaller@physics.ox.ac.uk
Noel Keenlyside	Geophysical Institute and Bjerknes Centre, University of Bergen	noel.keenlyside@gfi.uib.no
Noelia Otero Felipe	Institute for Advanced Sustainability Studies (IASS)	noelia.oterofelipe@iass-potsdam.de
Ola Haug	Norwegian Computing Center	ola.haug@nr.no
Pandora Hope	Australian Bureau of Meteorology	p.hope@bom.gov.au
Pascal Yiou	LSCE, Gif-sur-Yvette, France	Pascal.yiou@lsce.ipsl.fr
Peter Guttorp	Norwegian Computing Center	peter.guttorp@nr.no
Robert Vautard	LSCE, Gif-sur-Yvette, France	robert.vautard@lsce.ipsl.fr
Solrun Figenschau Skjellum	Norwegian Environment Agency	solrun.figenschau.skjellum@miljodir.no
Sonia Seneviratne	ETH Zurich	sonia.seneviratne@ethz.ch
Stephan Pfahl	ETH Zurich	stephan.pfahl@env.ethz.ch
Thordis Thorarinsdottir	NR	thordis@nr.no
Tim Cowan	The University of Edinburgh	tim.cowan@ed.ac.uk
Tim Palmer	University of Oxford	tim.palmer@physics.ox.ac.uk
Tobias Erhardt	Technische Universität München	tobias.erhardt@tum.de
Wim Thiery	ETH Zurich	wim.thiery@gmail.com
Yvan ORSOLINI	NILU - Norwegian Institute for Air Research, and University of Bergen	orsolini@nilu.no