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EUCLEIA

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EUropean CLimate and weather Events: Interpretation and Attribution

Deliverable D8.4

Summary report on the new attribution service and future directions

Deliverable Title	*Summary report on the new attribution service and future directions*	
Brief Description	*The work of WP8 has laid the foundation of an attribution service that can potentially move its science into operations. Attribution of extreme events can be provided on a range of timescales. Firstly, the HadGEM3-A system, the most sophisticated system of its kind currently available, delivers assessments of events in the preceding season following the operational pattern of seasonal forecasting systems. Secondly, fast response on media timescales has been prototyped and applied to high profile extreme events during the course of the project. Finally, in-depth analyses that dig deeper into the characteristics peculiar to each individual event can be produced within about a year after the event and several such assessments have been published in the annual special report of the Bulletin of the American Meteorological Society (BAMS).*	
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3.0	07/12/2016	N. Christidis	Final version

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1. Executive Summary

- A prototype state-of-the-art operational attribution system has been developed. It is built on the HadGEM3-A model, upgraded to the highest spatial resolution used in event attribution studies.
- In the final stage of EUCLEIA, the HadGEM3-A system has been set up to run on a seasonal cycle, i.e. it generates ensembles of simulations every quarter for the assessment of events in the preceding season.
- Alongside seasonal assessments, advanced capabilities have been developed to enable rapid event attribution. Several different fast-track methodologies have been applied to the study of events, including empirical trend analyses, pre-computed estimates of the odds of extremes from global models, real-time regional model output and a number of high-statistics coupled model ensembles.
- EUCLEIA partners have been contributing studies to the annual special report of the Bulletin of the American Meteorological Society (BAMS) on extreme events throughout the lifetime of the project, demonstrating the range of scientific output that can be obtained with a range of methodologies. 23 studies were published during the project.
- The final recommendation from EUCLEIA concerning future directions is that future operational event attribution systems will need to be linked to operational prediction systems.

2. Project Objectives

With this deliverable, the project has contributed to the achievement of the following objectives (DOW, Section B1.1):

No.	Objective	Yes	No
1	Derive the requirements that targeted user groups (including regional stakeholders, re-insurance Companies, general public/media) have from attribution products and demonstrate the value to these users of the attribution products developed under EUCLEIA.	✓	
2	Develop experimental designs and clear ways of framing attribution studies in such a way that attribution products provide a fair reflection of current evidence on attributable risk.		✓
3	Develop the methodology for representing the level of confidence in attribution results so that attribution products can be trusted to inform decision making.		✓
4	Demonstrate the utility of the attribution system on a set of test cases of European weather extremes.		✓
5	Produce traceable and consistent attribution assessments on European climate and weather extremes on a range of timescales; on a fast-track basis in the immediate aftermath of extreme events, on a seasonal basis to our stakeholder groups, and annually to the BAMS attribution supplement.	✓	

3. Detailed Report

Devastating extreme weather and climate events often raise questions about the role of anthropogenic climate change. Event attribution seeks to address these questions by estimating how possible causes like human influence on the climate might have altered characteristics of such events like their frequency and magnitude. In turn, effective adaptation planning that helps minimise the socio-economic impact of extremes is expected to benefit from robust and reliable attribution assessments. EUCLEIA's Work Packages (WPs) 3 and 4 made it clear that different users require attribution information on different timescales: a fast-track response on the media timescale of about a week after events occur, a more robust response at the end of each season delivered, for example, by an operational system, and a targeted assessment of individual events within about a year after they occur, delivered by more detailed research papers. In response to these requirements WP8 a) has developed a state of the art event attribution system that in the last year of the project operates on a seasonal cycle, b) has demonstrated how fast-response methodologies can be applied to real events and c) has produced detailed assessments of high-impact events published in the annual special supplement of BAMS. These main achievements are reviewed in this Section, followed by a discussion on future directions.

3.1 Response on seasonal timescales: The HadGEM3-A attribution system

Work Package 8 has not only enabled EUCLEIA to stay at the forefront of event attribution research, but has also prototyped the operationalisation of its science with the view of integrating it into the developing climate services. The upgraded Hadley Centre's attribution system, built on the high-resolution version of the HadGEM3-A model, constitutes the backbone of an emerging attribution service, modelled after the structurally similar seasonal forecasting system that has been operational in the UK Met Office for several years. While both systems generate ensembles of simulations that can provide probabilistic assessments for the occurrence of extremes, the attribution system looks at the recent past rather than the near future and further attempts to quantify the anthropogenic impact by generating a second ensemble of simulations representing what the climate would have been without human influence.

The novelty of the HadGEM3-A system lies in its unprecedented high resolution, only beaten by regional models nested within coarser global counterparts. By running the atmospheric model without coupling to an ocean model and instead supplying boundary conditions representing the observed oceanic state the system generates large ensembles at a lower computational cost. Moreover it allows the system to specifically address events that did occur or could have occurred under the circumstances that acted as controlling influences on the weather of the immediate past.

As part of the move toward an operational service the attribution system has been developed to allow flexible use of computer and human resources. Experiments are run through Rose / cylc suites on a shared IT account that allows a small team of scientists to manage parallel batches of simulations whose number may be scaled up or down to match available capacity. Code is kept on a version controlled repository aiding transparency and reproducibility.

Below we shall briefly describe the model configuration, the ensembles experiments conducted thus far, data dissemination and some brief notes on model validation. A more detailed description of the model configuration including more references can be found in D8.1.

Model description

With each round of experiments two ensembles are generated that differ through the external climate forcings included, one with both natural and anthropogenic forcings present (ALL) and the other with only natural (NAT). Natural external forcings are, firstly, variability in total solar irradiance at the top of the atmosphere, and secondly volcanic activity represented through a latitudinal variation of stratospheric aerosol optical depth. Other external forcings provided are well-mixed green house gases (GHG) and zonal-mean ozone concentrations, aerosol emissions and land use change. The prescription of lower boundary conditions (the sea surface temperatures and sea ice coverage) also integrate historical external forcings. In the NAT experiments forcings are held at pre-industrial levels (taken to be 1850).

The core atmospheric model, land model, initial conditions and method of stochastic ensemble generation remain identical between experiments. The attribution system can therefore be visualised as in Fig. 1 where the core atmosphere and land model which underlie many diverse Met Office systems are supplemented by inputs specific to this system.

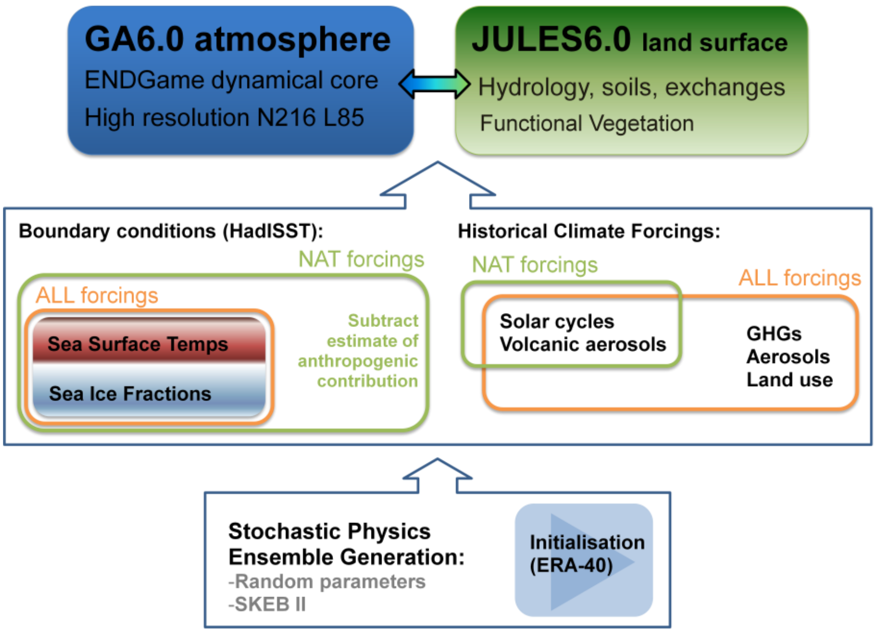

Figure 1. Components of the Met Office modelling system for event attribution using ALL and NAT experiments described in the text.

Scientific configurations of Met Office global coupled and atmospheric models are described by their Global Coupled (GC) and Global Atmospheric (GA) number. The new attribution system was developed using the GA6 atmospheric science package (Walters et al., 2016). GC2 and GA6 science are currently operational across Met Office NWP and climate systems.

Two significant upgrades to the previous HadGEM3-A based system are to the non-hydrostatic dynamical core of the model and the resolution. GA6 uses the ENDGame dynamical core (Wood et al., 2014) while the previous version used New Dynamics (Davies et al., 2005), bringing improvements in atmospheric dynamics that include synoptic scale features such as extra-topical storms. Resolution has increased from N96 L38 to N216 L85. This refers to a horizontal latitude/longitude grid that is 2N cells East-West by 1.5N cells North-South where N = 216, which gives 0.83˚×0.56˚ angular resolution equivalent to around 60km at mid-latitudes. There are 85 vertical levels: 50 tropospheric and 35 stratospheric. As demonstrated in D6.3, a realistic representation of stratosphere-troposphere interactions will give the Met Office model an advantage over systems lacking a proper stratosphere, for e.g. when addressing European cold events whose likelihood is influenced by the strength of the stratospheric vortex.

The land surface and hydrology schemes are also upgraded from the previous system, which used the MOSES-II model, to JULES (Joint UK Land Environment Simulator, Best et al., 2011) version 6.0, a community land surface model. This handles fluxes of heat, moisture and gases between the atmosphere and land, surface hydrology as well as deep soil processes through 4 sub-surface layers. JULES assigns fractions of 9 surface types to each gird cell of which 5 are vegetation functional types with seasonally modulated leaf area and canopy height parameterizations. The non-plant types are: land water, land ice, bare soil and urban.

Horizontal boundary conditions at the bottom of the atmosphere are given by series of Sea Surface Temperatures (SST) and Sea Ice (SIC) fields. The ALL experiments takes these from observed values (HadISST, Rayner et al., 2003) while for the NAT experiments an estimate of the change due to anthropogenic influence is removed from the observations. A current limitation on the speed of response of the system is in waiting for the HadISST dataset update at the end of a season and we are investigating means of speeding this up.

Monthly emissions from four basic categories of aerosols or their chemical precursors are also supplied: sulphates from various industrial sectors, soot (black carbon), organic carbon fossil fuels and biomass burning. These are handled by the CLASSIC aerosol scheme and the model sees both direct and 1st and 2nd indirect radiative effects where appropriate.

Land use changes have been shown to have a detectable effect on the occurrence of extremes (Christidis et al., 2013a) and so are represented in the system through the variation of the 9 surface type fractions which are ultimately derived from the HYDE3.1 dataset (Goldewijk et al., 2011). The model interpolates to annual values between data supplied on a decadal basis.

The natural forcings, GHGs, aerosols and land use are obtained from sources used by the CMIP5 generation of models and beyond the historical data use RCP4.5 values. With future upgrades to the system forcings data sets will also be updated.

Two parallel stochastic physics schemes generate small differences between the physics of each simulation to produce ensembles that are able to explore the space of possible solutions consistent with the supplied boundary conditions, ensuring that the possibility of generating extreme events is always open. The two schemes are called Random Parameters and Stochastic Kinetic Energy Backscatter II (SKEB II). These were developed for the Met Office Global and Regional Ensemble Prediction System (MOGREPS) and operate every 3 hours throughout the simulations such that the long term average physics is not biased between individual members of the ensemble.

Both ensembles share a common atmospheric initialisation at 0000Z on 1st December 1959 from ERA-40 reanalysis fields so that to begin with simulations differ only the random seed supplied to the stochastic physics schemes. Within days of initialisation the atmospheric solutions across the ensembles differ dramatically though later we will see that some aspects of the land and atmosphere do retain memory for a significant length of time.

Experiments

The first pair of experiments performed with the model, designed to allow its validation, consisted of ALL and NAT ensembles of 15 members each simulating the 54 year period 1960 – 2013, hence allowing one month spin down from the common initialisation. These experiments have been disseminated as *historical* and *historicalNat*. Successive pairs of experiments then continue all of these simulations beyond the validation period into the recent past and scale up the ensemble to a size that allows it to sample the tails of the probability distributions populated by extreme weather and climate events.

Ensemble sizes are scaled up by branching sub-ensembles of members from each of the original 2 x 15 members used for validation. Each sub-ensemble shares the initialisation provided by the final state of the *historical* or *historicalNat* member it continues but supplies each new member with a different stochastic physics seed. Experiments named *historicalShort* and *historicalNatShort* each ran ensembles of size 105 = 15 x 7 simulating the period 2014 - 2015. These were continued in the same manner by extensions named *historicalExt01* and *historicalNatExt01* with ensemble sizes of 525 = 105 x 5 members simulating the period Jan – May 2016.

From June 2016 the system entered a seasonal quasi-operational mode, running 3 month experiments (*historicalExt02* and *historicalExt02*), covering the last season June – August 2016 by a pure continuation of the existing pair of 525 member ensembles. Figure 2 shows the seasonal cycle of the operational attribution system.

Figure 3 depicts the ensemble genealogy as just described and Table 1 summarises the experiments performed to date.

Table 1. Experimental details (name, period and ensemble size) with example purpose summarised.

Experiment name	Simulating period	Size	Purpose e.g.
historical, historicalNat	1960 – 2013	15	Model validation
historicalShort, historicalNatShort	2014 – 2015	105	EUCLEIA test cases
historicalExt01, historicalNatExt01	Jan – May 2016	525	Operational attribution
historicalExtxy, historicalNatExtxy	Seasonal from JJA 2016	525	Operational attribution

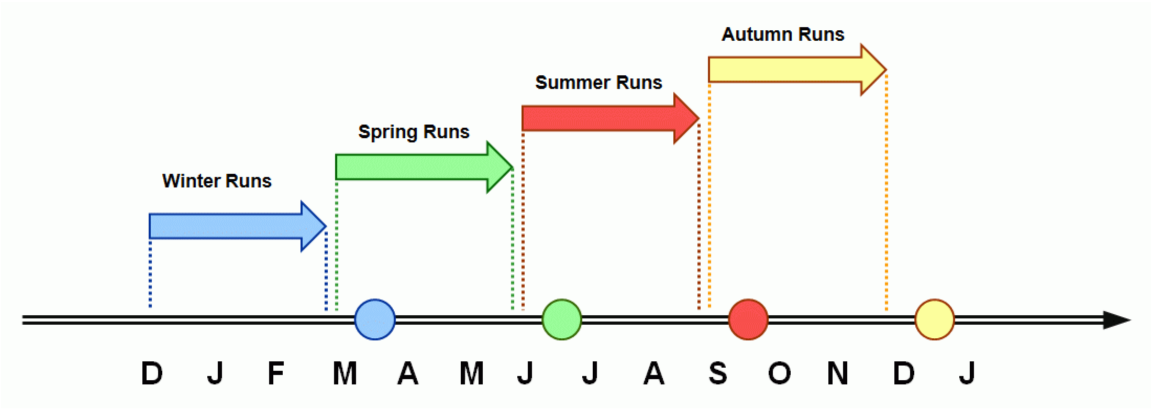

Figure 2. Operational attribution runs for each season in the year. The arrows represent the period covered by the runs and the circles mark the point in real time when the runs are carried out.

Data dissemination

Where possible our experimental and diagnostic naming conventions abide by the CMIP5 controlled vocabulary which is already familiar to many in the community. Individual members thus receive an *rip* index where the 'realisation index' *r* distinguishes members that share a common initialisation, and the 'perturbed physics index' *p* is adopted to distinguish members by stochastic physics seed (the 'initialisation method index' *i* always equals 1). Diagnostic outputs are placed in single variable files with the corresponding atomistic naming convention identifying the variable, meaning period, experiment and the *rip* code that indicates the continuation history and stochastic physics seeding of that member.

Data from the system has been made available to EUCLEIA partners and the general community first via the JASMIN collaborative work space, then the BADC node of ESGF and finally via full ESGF-wide records. Adopting a well defined experimental vocabulary with high standards of metadata entry was crucial in acceptance into the ESGF archive. Though a large effort for a relatively small project this was assisted by essentially adopting the CMIP5 standards which should enable easier, more rapid dissemination of data where necessary in the future.

Model validation

A thorough validation of the multi-decadal *historical* experiment has been conducted by WP6, summarised in document D6.3, as well as an assessment of the model's hindcast reliability and its use in assessing the confidence in Fraction of Attributable Risk in D6.4. Here we simply reiterate some of the conclusions regarding model performance relevant to European weather and climate.

Overall performance of the modelling system in regional mean values, interannual variability and trends in surface temperature and precipitation is good. The observed frequency of the four circulation regimes (as represented through sea-level pressure anomalies) that explain most of European hot and cold weather extremes are reproduced extraordinarily well. Land-atmosphere interactions are reasonable. A good representation is found of the downward propagating influence of the state of the stratosphere on highly variable European winters through the NAO.

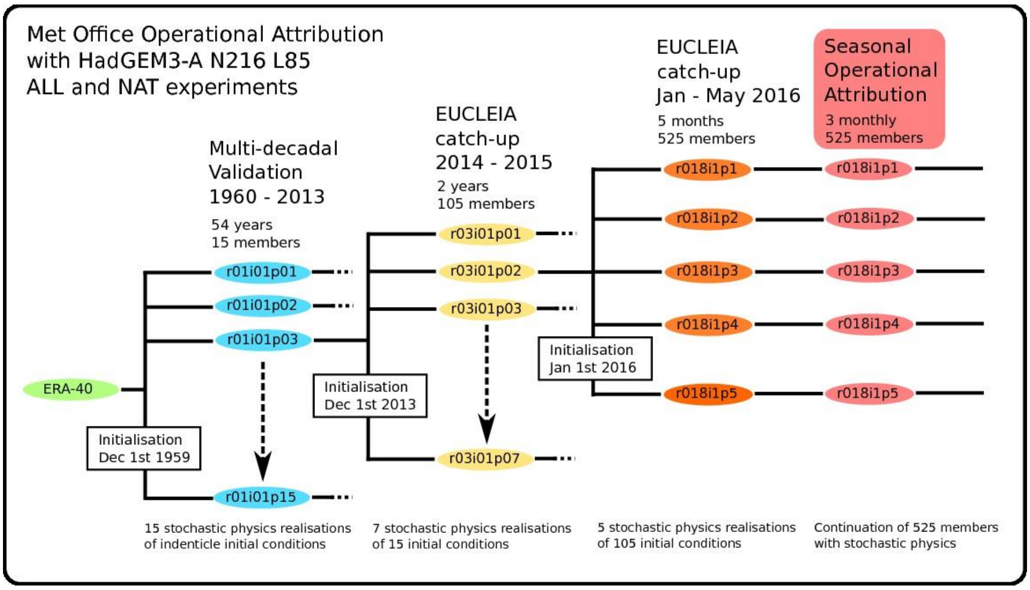

Figure 3. Ensemble genealogy for the experiments carried conducted with the attribution system. Each experiment performs multiple continuations of the members of the previous ensemble until there are 525 members.

Where model error may be found is in finer spatial details, such as negatively biased temperature trends over Spain and a corresponding lack of drying. While the coupling between soil moisture and evapotranspiration is found to be well represented across most of Europe the Iberian peninsula is again in discrepancy with the observations. However, the ensemble spread in all of these quantities can be regionally significant and a complete assessment of the significance of these biases is still required.

Example of a study with the new system

The upgraded HadGEM3-A system was used to study the record winter sunshine of 2014/15 in then UK. The work is described in a paper published in the BAMS special supplement (Christidis et al., 2016). Observational data of sunshine duration since 1930 from the Met Office National Climate Information Centre (NCIC; Perry and Hollis, 2005) reveal that winter 2014/15 was the sunniest in the UK (Fig. 4a). An increasing trend of 2.4 sunshine hrs/decade is found during the observational period. The downward solar (SW) flux at the surface is employed as a proxy for sunshine duration (correlation coefficient of 0.9 over the common observational period). The study used the ensembles of 15 simulations generated with HadGEM3-A over 1960-2013 for each of the ALL and NAT experiments. Figure 1b depicts the modelled timeseries of the SW winter flux anomaly relative to 1961-1990 corresponding to the ensemble mean of the two experiments, together with their ± 2 standard deviation (SD) range. An increase relative to the natural world becomes evident after the 1990s. The 2014/15 flux was 1.55 times above mean during the observational period (1998-2012), which corresponds to an anomaly estimate of 4.1 Wm-2 (green line in Fig. 4b). This estimate is subsequently used as a threshold to calculate the probabilities of extreme events with (P1) and without (P0) the effect of human influence. Comparisons between modelled fluxes for the actual climate and NCIC observations show the model can represent well the winter mean SW flux in the UK region.

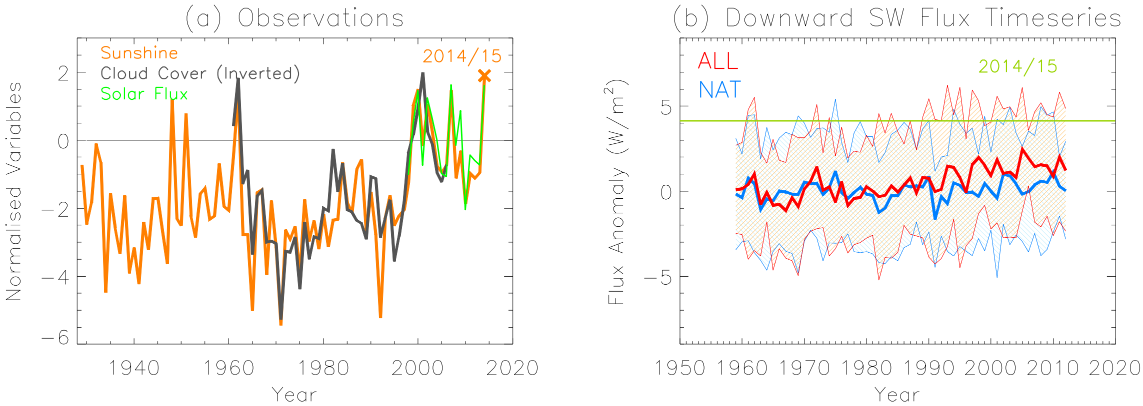

Figure 4. (a) UK winter sunshine (orange), inverted cloud cover (grey) and solar flux (green) timeseries constructed with NCIC observations and normalised relative to the common observational period. (b) Timeseries of winter flux anomalies relative to 1961-1990 from the ALL (red) and NAT (blue) experiments. The thick lines correspond to the ensemble mean and the thin lines mark the ±2 standard deviation range. The 2014/15 anomaly estimate is shown in green.

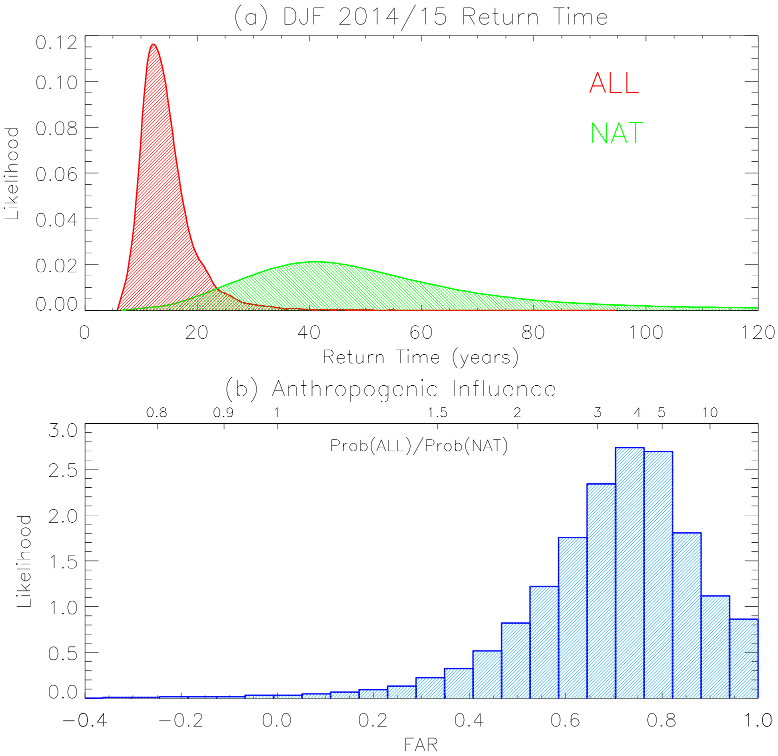

Figure 5. (a) Normalised distributions of the return time of an extreme winter sunshine event in the UK, defined as an exceedence of the 2014/2015 solar flux anomaly. The distributions were constructed with (red) and without (green) anthropogenic climate change. (b) Normalised FAR distribution measuring how much human influence changes the likelihood of an extreme winter sunshine event. The change in probability is shown on the top x-axis.

The return time corresponding to the 2014/15 solar flux anomaly is estimated first and its change due to anthropogenic climate change and investigated. Winters of the most recent simulated decade (2004-2013) are used as a proxy of the present climate (i.e. 150 seasons for each experiment) and distributions of the solar flux anomaly are constructed with and without human influence. Threshold exceedence probability estimates (P1 and P0) are then obtained from the two distributions using the generalised Pareto Distribution, while uncertainties are derived with a Monte Carlo bootstrap procedure (Christidis et al., 2013b). In that way return time (inverse probability) distributions are constructed (Fig. 5a). The results indicate anthropogenic forcings lead to a marked decrease in the return time from 48 to 14 years (best estimates, defined as the 50th percentile of the distributions). The distribution of the FAR is shown in Fig 5b. The best estimate of the FAR is 0.72, suggesting that human influence increases the chances of extreme events by a factor of 3.6 (5-95% uncertainty range: 1.6 - 17.2). The study also considered the role of the atmospheric flow in winter 2014/15 and found that winters with circulation patterns similar to the one in 2014/15 are about 14 times less likely to break the SW flux record.

In conclusion, this new attribution study provides evidence of human influence on winter sunshine extremes in the UK, consistent with the observed increasing trend in sunshine hours in recent decades. This trend appears to have been a key driver of the 2014/15 record, which occurred within a meteorological context not typical of sunny conditions. Changes in aerosol emissions constitute the component of the anthropogenic forcing most likely to affect sunshine (Sanchez-Romero, 2014).

3.2 Response on media timescales: Fast-track attribution

In addition to the HadGEM3-A system which can assess the human influence on extreme events up to about a season after they occur, EUCLEIA has also developed a fast-track capability to enable response on media-timescales, e.g. a few days after events. A number of methodologies and data sources have been pooled together to this end, including empirical trend analyses (van Oldenborgh, 2007; Vautard et al., 2015) applied to observations and downscaled model data from regional models, as well as pre-computed estimates of the risk ratio based on global climate models (Christidis et al., 2015a). Before rapid event attribution can be performed routinely several challenges need to be overcome. Firstly, from an impact point of view the events analysed often need to be defined on small spatio-temporal scales like, for example, localised extremes lasting less than 3 days. Global models and methods like optimal fingerprinting are typically applied to larger scales and therefore alternative methods that better handle short and small scales were developed jointly with the WWA project and employed in fast-track studies (van Oldenborgh et al., 2016a). A second challenge relates to the availability and timely provision of observational data. To meet this challenge, KNMI updates daily (or on demand) its Climate Explorer website up to yesterday or the day before. ECMWF (re)analyses data are also used and often extended five days into the future using forecasts, so that events may be investigated even before they occur. Finally, the collection of model output requires well-tested data extraction programs and can take up to a day. As each event is unique, it may involve the definition of a new indicator and generation and testing of new extraction scripts. Therefore, fast-track analyses require focussed work from one or more scientists.

A typical procedure to produce a fast response assessment involves the following steps. The first task is defining the event, usually by setting a threshold on a meteorological variable that can adequately describe it and its associated impacts (e.g. maximum temperature or rainfall amount). Impact models may also be used for direct attribution of impacts. The following step is the collection of observational and modelled data. Standard evaluation tests are employed to assess whether models are fit for purpose and thereby select only those deemed reliable. Simple bias correction techniques may be applied at this stage to match the modelled with the observed climate, ensuring that the return time of the extreme event under consideration is the same in both cases. The change in the likelihood of the event due to anthropogenic forcings is subsequently estimated by means of the risk ratio, i.e. the ratio of the probability of this class of events in the current climate and the probability in a climate not affected by human influence. This can be done either by deriving the probabilities from two separate ensembles of model simulations for the two types of climate, or by fitting the trend in the probability over the historical record (e.g. using an extreme value distribution with a climate change metric as a covariate) and comparing the present probability relative to that in some earlier period. The latter can provide simple attribution assessments that use observational data only. Finally, results from different methods need to be synthesised and communicated properly. Provided that different approaches give rise to a consistent outcome that also agrees with the scientific understanding of the climate system, an attribution statement is formulated. The best way to do this is to tailor the information for different target audiences. A press release can thus be produced that is understood by the general public, a non-technical summary for science journalists and a scientific text that provides the necessary transparency and traceability of the assessment. The scientific text can also be submitted to a scientific journal, though in future, when the service moves towards operationalisation, this will no longer be the case.

Fast-track analyses have been produced for a number of events over the course of EUCLEIA. These include the 2016 summer heatwave in Western Europe (Sippel et al., 2016), Storm Desmond, the Seine and Loire floods (van Oldenborgh, 2016a), but also events outside Europe (e.g. the Southern Brazil water shortages in 2014/15; Otto et al., 2015) and large scale extremes (e.g. the record global mean temperature in 2014). Figure 6 shows results from the study of the Seine floods, a work that started on the 3rd of June 2016 while the event was still ongoing (24 May – 4 June 2016). A multi-method analysis was carried out and the results were communicated on the 9th of June, while a discussion paper was published later in the month. Results from a trend analysis with observational data are shown in Fig. 6a. Return times for the 3-day basin-averaged extreme precipitation event are larger than can be determined with the observed timeseries. Setting the shape parameter to zero, a best estimate of 180 years is obtained (uncertainty range of 50-3000 years). The analysis with data from HadGEM3-A experiments (Fig. 6b) yields a return time of 200 years (uncertainty range of 100-500 years). The risk ratio for the event is found to be is 1.9 (1.1 to 3.4) relative to 1960, or 0.95 (0.5-2.2) relative to the natural climate. Using larger ensembles generated with the HadRM3P model (Fig. 6c) the probability of the event if found to have increased relative to the natural world by a factor of 2 (0.6-5). Data from experiments with the EC-Earth model were downscaled with the RACMO2 regional model (Fig. 6d) and were also analysed. A risk ratio of 2 (1.3-4.9) was estimated. Finally, an analysis with a subset of the EURO-CORDEX climate projections led to a risk ratio estimate of 1.6 (0.5-4.9). The multi-method study concluded that the event had a return time of a few hundred years. The risk ratios were adjusted when necessary to match conditions in the natural world with the climate in the 1960s. A combined result was obtained by averaging the results from individual analyses and adding the uncertainties in quadrature. It was concluded that the best estimate of the risk ratio is 2.3 (>1.6). The change is equivalent to a 6-7% increase in precipitation intensity, which is consistent with the expected water vapour increase in a warming world (Clausius-Clapeyron) and the heating of the Mediterranean and subtropical Atlantic (by almost a degree) that are likely sources of moisture for the event.

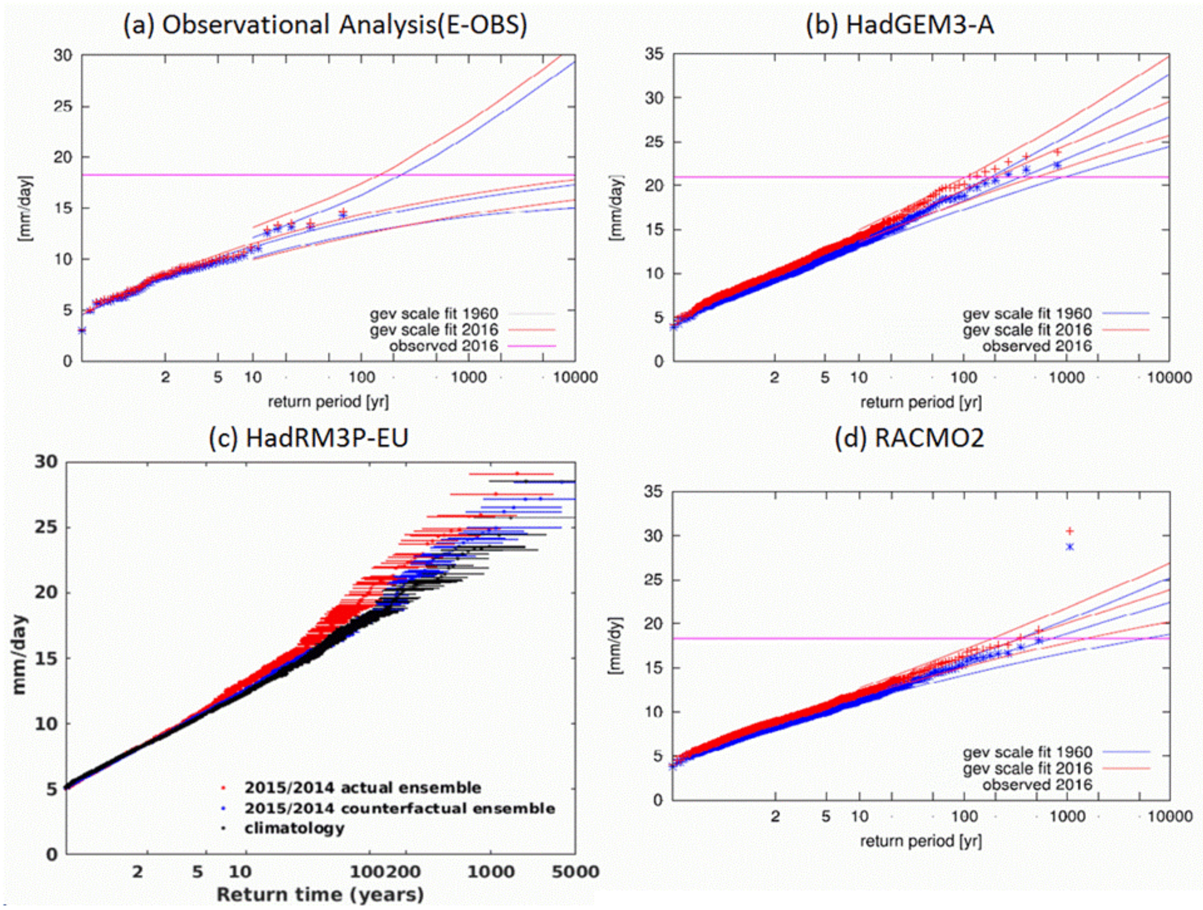

Figure 6. Fast track attribution analyses for the Seine floods. Return time estimates over a range of 3-day rainfall amounts in the Seine basin obtained from analyses with different datasets (see titles of panels a-d). The colours correspond to different climatic conditions (see legends).

Taking a different approach, Christidis et al. (2015a) pre-computed the changing odds of very warm years and seasons in regions across the world. Events are defined based on the exceedence of temperature thresholds and their changing odds are measured over a range of pre-specified thresholds, which means assessments can be made as soon as a new event happens. The methodology employs optimal fingerprinting (Allen and Stott, 2003) to obtain observationally constrained estimates of the simulated global temperature response to external forcings, from which regional information is extracted. Soon after this work was completed, year 2014 was confirmed to be the warmest on record, both globally and also in the UK. This provided an immediate opportunity to produce the first fast-track attribution assessment based on the pre-computed annual temperature distributions, which subsequently featured as a research highlight in the WMO statement on the status of global climate in 2014 (WMO, 2015). Global and UK annual mean temperatures were constructed based on a multi-model analysis that combined the fingerprints of all seven GCMs (Fig. 7). Regarding the global mean surface temperature, the observed record (vertical black line in Fig. 7a) lies within the red distribution, but in the extreme warm tail of the green distribution. This suggests that the record would not have been equalled or broken in natural climate without the effect of anthropogenic forcings. The UK record of 2014 lies within both distributions, albeit more to the extreme warm tail of the green distribution (Fig. 7b).It is estimated that human influence has increased the likelihood of record-breaking temperatures in the UK by a factor of ten.

Studies like the analyses of the Seine floods and the temperature extremes of 2014 demonstrate how EUCLEIA has contributed to the development of tools that can provide scientifically reliable early assessments of extreme events within about a week. These can subsequently be complemented by more detailed studies (e.g. based on the HadGEM3-A system described earlier) that can investigate in more detail the role of possible key drivers like the atmospheric circulation, modes of variability and the state of the ocean.

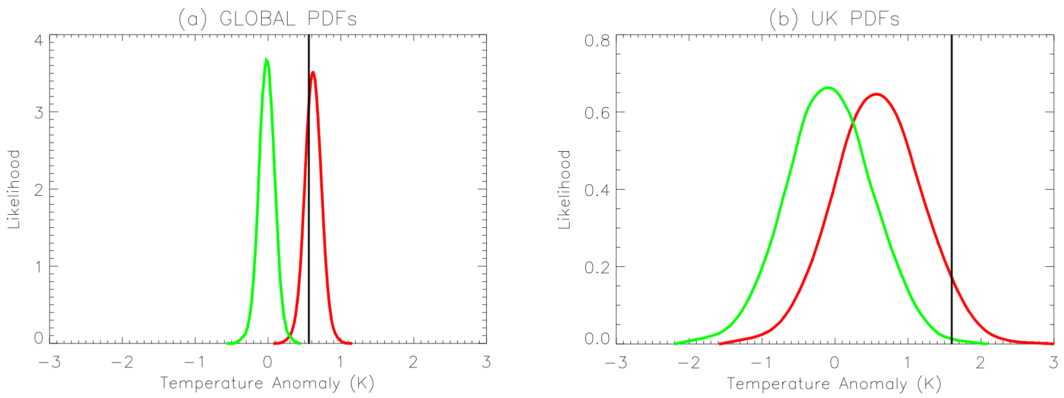

Figure 7. Distributions of a) annual mean and b) UK mean temperature anomalies relative to 1961-1990 from the fast-track attribution methodology with (red line) and without (green line) the effect of human influence on the climate. The temperature records of 2014 are represented by the black vertical lines.

3.3 Response on annual timescales: In-depth attribution studies

While fast-track approaches and the regular production of attribution assessments with the HadGEM3-A system are very useful, tailor-made studies of individual events allows a more detailed investigation of possible causes. Such targeted studies not only improve our scientific understanding, but may also help develop new research tools. For example, Vautard et al. (2016) considered the extreme rainfall in southern UK in winter 2013/14 and developed a methodology that separates the dynamical and thermodynamical contributions. Looking at the same event, Christidis et al. (2015b) assessed the prominent role of the large scale atmospheric flow present at the time of the event. In-depth analyses of extremes require longer time than operational assessments, as they involve planning of the research approach and a rigorous peer-review process and are typically available about a year after the event occurs. An extremely successful example of attribution research available on this timescales is the annual special report of BAMS that provides attribution assessments of some key events of the previous year.

The BAMS reports on extreme events have proved very popular both with the scientific community and the public. Press releases and media briefings after the publication of each issue have attracted considerable attention. The first report published in July 2012 became the most read paper on the journal's website. In recognition of the importance of event attribution, the editors of the second report were selected by the Foreign Policy magazine as Leading Global Thinkers of 2013 and the work presented in the report was acknowledged as a "breakthrough in climate science". Being at the forefront of event attribution research, EUCLEIA scientists have made significant contributions to the report since the beginning of the project with 6 papers published in 2014, 9 papers in 2015 and 8 papers in 2016. These papers demonstrate a range of methodologies used in, or developed by, EUCLEIA, consider a range of different types of extremes and give examples of different ways of framing attribution questions. EUCLEIA's contributions to BAMS are summarised in Table 2.

Table 2. Papers published in the BAMS special reports with EUCLEIA authors/co-authors

Event	Reference
The 2013 hot, dry summer in Western Europe	Dong et al. (2014)
The wet southern European winter of 2013	Yiou and Cattiaux (2014)
Heavy precipitation in the Danube and Elbe basins in May-June 2013	Schaller et al. (2014)
Extreme snow accumulation in the Pyrenees in winter/spring 2013	Añel et al. (2014)
October 2013 storm in northern Germany and Demark	Von Storch et al (2014)
The cold spring of 2013 in the UK	Christidis et al. (2014)
The cold winter of 2013/14 in the Upper Midwest	Wolter et al. (2015)
2014/15 water shortages in southeast Brazil	Otto et al. (2015)
The Argentinian heatwave of December 2013	Hannart et al. (2015)
The 2013/14 extreme winter rainfall in the UK	Christidis et al. (2015)
Extreme rainfall in the Cévennes mountain range in autumn 2014	Vautard et al. (2015)
The drought of 2014 in the southern Levant region	Bergaoui et al. (2015)
The 2014 drought in the Horn of Africa	Marthews et al. (2015)
Extreme precipitation in Jakarta in January 2014	Siswanto et al. (2015)
Extreme rainfall in New Zealand in July 2014	Rosier et al. (2015)
The record sunshine of winter 2014/15 in the UK	Christidis et al. (2016)
Extreme rainfall in south-eastern China in May 2015	Burke et al. (2016)
Heavy precipitation, Chennai, India, December 2015	van Oldenborgh et al. (2016b)
Cold North America, February 2015	Bellprat et al. (2016)
Northern hemisphere sea ice extent, March 2015	Fuckar et al. (2016)
Indonesian heat and drought, July-October 2015	King et al. (2016)
Extreme heat in Western China, June-August 2015	Sun et al. (2016)
European heat wave, Summer 2015	Dong et al. (2016)

3.4 Future directions

Over the course of the project, EUCLEIA has developed a much clearer understanding of the potential uses of a future operational attribution system. In depth work with stakeholder groups has shown that that there is widespread interest in assessments of the extent to which recent extreme weather and climate events can be linked to climate change. An important consideration is that different sectors can have different requirements. For example, insurance companies and regional managers scientific robustness may be more important than speed of analysis whereas the media may want very rapid assessments. EUCLEIA has shown that there are interested users for a future operational attribution system that produces well calibrated attribution assessments of the extent to which extreme weather and climate events can be linked to climate variability and change.

EUCLEIA has also developed the underpinning attribution science needed to support an operational attribution service and has demonstrated how such a service might deliver attribution assessments through a set of test case studies on a specific heat wave, drought, rain storm, cold spell and storm surge.

Developments internationally have also under-scored the potential for event attribution. For example a recent report by the US National Academies of Science on event attribution concluded that "[It] is now often possible to make and defend quantitative statements about the extent to which human-induced climate change (or another causal factor, such as a specific mode of natural variability) has influenced either the magnitude or the probability of occurrence of specific types of events or event classes. The science behind such statements has advanced a great deal in recent years and is still evolving rapidly. Still further advances are necessary, particularly with respect to evaluating and communicating event attribution results and ensuring that event attribution studies meet the information needs of stakeholders." Regarding operational attribution the NAS report recommended: "As more researchers begin to attempt event attribution, their efforts would benefit from coordination to make sure that there is a systematic approach and that uncertainties are explored across methods and framing." It also stated that "Some future event attribution activities could benefit from being linked to an integrated weather-to-climate forecasting effort on a range of timescales."

The results from the EUCLEIA project support a future strategy consistent with the recommendations from the NAS report. The next step in the development of operational attribution is to develop a framework to ensure that different methods and framing are properly explored and to facilitate the links of operational attribution to operational prediction centres. Research carried out under EUCLEIA has clearly shown the importance of taking account of multiple methods and framing and of clear communication of these aspects. Research carried out under EUCLEIA has also shown the clear links between attribution and prediction activities. It seems clear therefore what the future direction needs to be for this activity.

The EUCLEIA research project has also demonstrated what is currently lacking if operational attribution systems are to become a reality. Clearly operational attribution systems rely on a continuing development of event attribution science in order to support an enhanced capability to attribute a greater variety of events in future. Attribution science is still a relatively young science and if mid latitude cyclones or localised extreme flooding events for example are to be attributed routinely then more research needs to be done. The best approach for operational attribution systems would be analogous to operational seasonal forecasting whereby methodologies are published in the peer-reviewed literature and are then applied in operational systems.

Such systems will also need the development of a scientific platform which hosts data, supports data processing and provides collaboration space for scientists from partner institutions to develop and carry out attribution analyses using complementary models, methods and data sources. Such cross institutional collaboration is similar to that operating in the seasonal forecasting field where different centres compare results and there is the opportunity to coordinate forecasts for different users.

The final recommendation from EUCLEIA concerning future directions is that future operational event attribution systems will need to be linked to operational prediction systems. Under EUCLEIA a system has been pioneered that runs parallel to a seasonal forecasting system. This has been shown to have all sorts of benefits of the sort also highlighted by the NAS report. These would include

- clearer communication of attribution results by putting them in to the context of future changes as well as benefiting from best practice in seasonal forecasting
- the use of verification measures similar to (or developed from) those used in seasonal forecasting and skill scores similar to (or developed from) those used in numerical weather prediction;
- a systematic approach to managing the operational attribution system similar to those used in operational forecasting activity including system updates and incorporation of new scientific developments in operational upgrades.

4. Lessons Learnt

The development of the HadGEM3-A system

• Initialisation of the ensembles 1 month prior to the start of the multi-decadal validation period was chosen on the assumption that memory of initialisation is lost very quickly in the atmosphere. This is broadly true though a couple of instances of multi-year memory in the interacting land and atmosphere have been found that may have a small bearing on attribution studies using the system.

• Spin down of soil moisture: at least 4-5 years of nonlinear adjustment from the initialisation in the northern hemisphere was followed by linear drift over full period. As soil moisture is an important factor in the strength of heat waves future initialised experiments could do with a longer spin down.

• The quasi-biennial oscillation (QBO), which has a remarkably robust period of around 29 months over its 60 years of observation and well captured in this model, may possibly have a small effect on surface weather regimes over Europe (via the stratosphere-troposphere interactions described above). To sample the full spread of mechanisms affecting European weather we should like to have an ensemble with all phases of the QBO present. Through identical initialisation of the 15 members of the validation experiments the QBO remained in phase across the ensemble for around 40 years. The large ensemble continuations therefore have the required phase scrambling of the QBO which the validation runs largely do not.

Other lessons learnt

• There is a clear demand from a variety of sectors for event attribution systems that put recent extreme weather and climate events into the context of climate variability and change.

• EUCLEIA has demonstrated the potential capability for an operational attribution system based on using a climate model that is similar to that used in seasonal forecasting.

• Upgrading the HadGEM3-A system used in EUCLEIA to high resolution has provided an efficient system that can now run on a seasonal cycle.

• Dissemination of data produced with HadGEM3-A can be slow, but speed has been gradually increasing. Availability of the data through ESGF has raised the profile of the project and allowed EUCLEIA data to be used by the international scientific community.

• Fast event attribution is in many cases possible by doing the groundwork even before the event. Challenges in fast-track studies include the definition of the event, timely data collection, synthesis of results from different methods and communication of the findings.

• As the majority of event attribution studies rely on climate models, the robustness of the results depends heavily on the ability of models to represent extremes. Validation methodologies researched by EUCLEIA's WP6 are therefore valuable. Moving towards an operational service it is important to develop evaluation techniques that can be utilised in a systematic way as part of an operational setup.

5. Links Built

• WPs 3 and 4 have informed the work of WP8 with regard to the production of attribution assessments that meet the needs of different stakeholder groups.

• WP5 has guided the design of attribution experiments.

• The event attribution system developed by WP8 has been extensively evaluated by WP6.

• Our attribution systems have been employed in the case studies carried out by WP7.

• Data dissemination via ESGF has enabled collaborations with the international scientific community. Collaboration papers have been published as a result (e.g. Angélil et al., 2016).

• Data from the HadGEM3-A experiments have been contributed to the C20C+ attribution project led by D. Stone (Lawrence Berkeley National Lab).

• EUCLEIA collaborators have made a major contribution to the annual BAMS reports Explaining Extreme Events of the previous year.

• EUCLEIA collaborators have developed collaborations with researchers in other parts of the World through the International Detection and Attribution Group (IDAG), C20C+ and other projects resulting in co-authored papers with Asian, African, South American, North American, and Australian scientists. Not only have EUCLEIA scientists been able to support the development of capacity to carry out event attribution studies in places like China and Brazil, this international collaboration has also facilitated the faster development of event attribution science in Europe.

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