Brussels, 13 April 2018

COST 020/19

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "Understanding and modeling compound climate and weather events" (DAMOCLES) CA17109**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action Understanding and modeling compound climate and weather events approved by the Committee of Senior Officials through written procedure on 13 April 2018.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA17109
UNDERSTANDING AND MODELING COMPOUND CLIMATE AND WEATHER EVENTS (DAMOCLES)

The COST Member Countries and/or the COST Cooperating State, accepting the present Memorandum of Understanding (MoU) wish to undertake joint activities of mutual interest and declare their common intention to participate in the COST Action (the Action), referred to above and described in the Technical Annex of this MoU.

The Action will be carried out in accordance with the set of COST Implementation Rules approved by the Committee of Senior Officials (CSO), or any new document amending or replacing them:

a. “Rules for Participation in and Implementation of COST Activities” (COST 132/14 REV2);
b. “COST Action Proposal Submission, Evaluation, Selection and Approval” (COST 133/14 REV);
c. “COST Action Management, Monitoring and Final Assessment” (COST 134/14 REV2);
d. “COST International Cooperation and Specific Organisations Participation” (COST 135/14 REV).

The main aim and objective of the Action is to Compound Events are high-impact events whose causes or effects show a complex combination of factors and pose major challenges to risk assessment and management. Current climate and impact modelling efforts are very limited in their ability to model Compound Events, making it difficult to design appropriate adaptation strategies.. This will be achieved through the specific objectives detailed in the Technical Annex.

The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 60 million in 2017.

The MoU will enter into force once at least seven (7) COST Member Countries and/or COST Cooperating State have accepted it, and the corresponding Management Committee Members have been appointed, as described in the CSO Decision COST 134/14 REV2.

The COST Action will start from the date of the first Management Committee meeting and shall be implemented for a period of four (4) years, unless an extension is approved by the CSO following the procedure described in the CSO Decision COST 134/14 REV2.

OVERVIEW

Summary

Hazards such as floods, wildfires, heatwaves, and droughts usually result from a combination of interacting physical processes that occur across multiple spatial and temporal scales. The combination of physical processes leading to an impact is referred to as a *Compound Event*. Examples of high-impact Compound Events include (i) droughts, heatwaves, wildfire and/or air pollution and their interactions involving a complex interplay between temperature, humidity and precipitation; (ii) extreme precipitation, river discharge and storm surge interactions, combining coastal storm processes with fluvial/pluvial and ocean dynamics; (iii) storms including clustering of major events leading to spatial and/or temporal dependence.

Climate change alters many of these processes and their interaction, making projections of future hazards based on single driver analyses difficult. Impact studies considering only one driver usually fail to assess the extent of the impacts of Compound Events. It is thus not clear whether climate models can capture major changes in risk associated with Compound Events. Existing modelling approaches used to assess risk may therefore lead to serious mal-adaptation.

DAMOCLES will (a) identify key process and variable combinations underpinning Compound Events; (b) describe the available statistical methods for modelling dependence in time, space, and between multiple variables; (c) identify data requirements needed to document, understand, and simulate Compound Events, and (d) propose an analysis framework to improve the assessment of Compound Events. DAMOCLES brings together climate scientists, impact modellers, statisticians, and stakeholders to better understand, describe and project Compound Events, and foresees a major breakthrough in future risk assessments.

Areas of Expertise Relevant for the Action	Keywords
● Earth and related Environmental sciences: Climatology and climate change ● Earth and related Environmental sciences: Hydrology, water resources ● Earth and related Environmental sciences: Applied mathematics, statistics, non computational modelling	● climate change ● multivariate climate extremes ● extreme value statistics ● disaster risk ● extreme events

Specific Objectives

To achieve the main objective described in this MoU, the following specific objectives shall be accomplished:

Research Coordination

- Establish and coordinate a network of previously unconnected communities including climate scientists, hydrologists, impact modellers, risk modellers, statisticians, and stakeholders to advance our knowledge on Compound Events.
- Develop a definition and common understanding of Compound Events and establish Compound Events as a new relevant research topic in climate and climate impact research.
- Develop a meta-database of relevant impact datasets. This will include databases reporting impacts on infrastructure, human mortality, and ecosystems.
- Identify characteristic classes of Compound Events and provide guidelines how to study them.
- Create awareness in climate and climate impact communities about the inherent modelling challenges associated with Compound Events.
- Lead development of methods to evaluate climate models based on multivariate dependencies.
- Improve physical understanding of Compound Events and their potential future changes by coordinating existing research at a European scale.
- Disseminate results on Compound Event research to relevant stakeholders.

Capacity Building

● Foster knowledge exchange and development of a joint research agenda on Compound Events.
● Connect climate and Earth system scientists, hydrologists, ecosystem modellers, impact modellers, risk modellers, and statisticians to combine knowledge on climate science and impact modelling with state-of-the-art statistical approaches to study Compound Events.
● Provide complementary training for Early Career Investigators (ECIs) in dynamical modelling, multivariate statistics, and extremes, inherently relevant for studying Compound Events.
● Design climate impact assessment protocols that take into account Compound Events.
● Improve stakeholders' understanding of Compound Events and limitations to modelling these, enabling them to plan more targeted.
● Improve stakeholders’ awareness of the importance to document physical and/or monetary impacts of Compound Events.

1. S&T EXCELLENCE

1.1. CHALLENGE

Compound Events are high-impact events whose causes or effects show a complex combination of factors. DAMOCLES will bring together climate and Earth system scientists, impact modellers, statisticians, disaster risk and resilience professionals, and stakeholders to (i) identify key variable combinations that must be investigated for different classes of Compound Events, (ii) identify data requirements to document, understand and simulate compound events, and (iii) coordinate the development of new methods to evaluate climate models based on multivariate dependencies.

1.1.1. DESCRIPTION OF THE CHALLENGE (MAIN AIM)

On August 25 2017, Hurricane Harvey hit the south of Texas, USA. Initially, rainfall intensities and wind speeds were severe but not exceptional and after landfall, the cyclone quickly weakened to a tropical storm. However, the hurricane's impact on the built environment was catastrophic because a sea surge, extreme rain and strong winds acted in combination. Critically, a blocking high prevented Harvey from continuing further inland such that the hurricane's destruction took place over an extended period causing extraordinary high total precipitation amounts (The Washington Post, 2017). Early estimates predict that the total economic cost of Harvey may be unprecedented in US history (The New York Times, 2017). Clearly, the socio-economic impacts of Hurricane Harvey were much greater than if the storm surge, rain and winds had not occurred simultaneously and over such a long duration. The weather phenomena associated with Hurricane Harvey also frequently affect Europe. Both tropical and extratropical cyclones can simultaneously produce windstorms, heavy rains, and floods (Kašpar et al., 2017).

Hazards such as floods, wildfires, heatwaves, and droughts often result from a combination of interacting physical processes that take place across a wide range of spatial and temporal scales. The combination of physical processes acting over various spatial and temporal scales and leading to a single or multiple hazards, for which Hurricane Harvey is a typical example, is referred to as a *Compound Event*. All climate-related hazards are associated with multiple climatic variables, processes, and phenomena (Westra et al., 2016). Considering a hazard as a Compound Event, for instance by decomposing it in contributing causes, allows for a better understanding of the underlying physical processes. This, in turn, favours a better modelling of the hazard, improving the associated risk estimates. If multiple physical processes underlying an event are causally and statistically related, such as the rain, winds and surge in the case of Hurricane Harvey, their simultaneous occurrence - and the associated impacts - has lower return times than what would be estimated assuming independent drivers. This underestimation of the actual recurrence frequency of such events is further amplified when known trends (e.g., in heavy precipitation; IPCC, 2012; IPCC, 2013) associated with increasing greenhouse gas forcing are not considered. Similar to the multiple processes leading to the extreme rainfall in the case of Hurricane Harvey, wildfire initiation probability depends on the weather conditions on a particular day, but the moisture content of the fuel depends on the surface moisture and energy balance over prior days to weeks (Ruffault et al., 2016). Temperature and rainfall over the period since fires last affected a region further influence trends in fuel loads. Thus, processes acting on different timescales have the potential to combine and cause a single hazard. In short, a flood, a fire or a drought might exist on timescales of days, months or years but the conditions leading to these phenomena may emerge over many timescales. Dependencies across variables, regions and timescales need to be taken into account to estimate the hazard probabilities and related impacts properly and accurately. This is currently not done in risk assessments.

Compound Events pose major challenges to risk assessment and management. Climate and impact modelling efforts are often limited in their ability to connect and combine multiple drivers of hazards and their dependencies. These challenges include research questions related to:

(i) Variable identification and data availability: Which climate variables need to be assessed jointly to properly estimate risks of a Compound Event? How much is currently known about the dependence between these variables? Are observations sufficient to estimate dependencies between variables?

(ii) Process understanding: Which processes cause the dependence between climate variables? Will these processes and dependencies change as a result of anthropogenic climate change?

(iii) Modelling: Are current global and regional (climate) models able to capture the dependence between climate variables? If not, what are the necessary dependencies required to capture Compound Events reliably? Can these dependencies be captured by statistical models? How do these dependencies affect modelled impacts?

A better understanding of the nature of Compound Events will strengthen the connection between climate science and risk management with immediate benefits to society. It is not clear whether climate and impact models currently can capture major changes in risk associated with Compound Events and it is therefore not known whether existing modelling products used to assess risk lead to serious mal-adaptation. Domain-specific research is limited in its ability to lead to major advances on Compound Events because, for instance, climate scientists need information on potential impacts from stakeholders and impacts modellers to evaluate their models with respect to the driving variables. Impact modellers, in turn, need precise information on climate drivers and their dependencies for adequate risk estimation. The complex nature of Compound Events requires close collaboration between climate scientists, impact modellers, social scientists, and stakeholders.

1.1.2. RELEVANCE AND TIMELINESS

Compound Events are characterized by multiple drivers, conditional dependencies, a complex chain of events and extreme return periods (Leonard et al., 2014). A better understanding and modelling of Compound Events will significantly improve our risk estimates for various societal impacts including agriculture, human health, ecosystem services, and infrastructure. For instance, if the return period of Compound Events such as hurricane Harvey could be determined more accurately through considering the interdependence of involved processes, local risk assessment could enable flood defence design to prevent damage more effectively. Another example for the relevance of the concept of Compound Events are crop yields, which are highly susceptible to multiple hazards such as droughts, heatwaves, frosts, hail, flooding, fires, and their interactions at various temporal scales, including lagged and indirect effects. Extremely hot temperatures in combination with high humidity or air pollution strongly affect human health. Wildfires can destroy crops, lead to air pollution, and affect ecosystem services such as carbon uptake. Floods can have devastating impacts on infrastructure, and in combination with extremes in wind speed, the impacts can be particularly severe (Martius et al., 2016). Long-term trends in driving factors related to anthropogenic climate change may affect the occurrence of Compound Events (Blöschl et al., 2017) such as the projected increase in wildfire risk in southern Europe and other semi-arid regions throughout the 21st century due to higher extreme temperatures and a drying trend (Sousa et al., 2015). Also in the ocean, co-occurring extreme events associated with warming, ocean acidification, ocean deoxygenation and nutrient stress have a much larger impact on marine organisms and ecosystems services than single-driver extreme events (IPCC, 2014).

Highly idealized conceptual frameworks of modelling, scenario construction and statistical analysis often have difficulties in capturing the complex features associated with Compound Events. Climate change and human activities are continuously altering the boundary conditions of human and natural systems, today much more than in the past. This means that a much more explicit understanding of the nature of potential changes affecting such events is required. Purely statistical relationships cannot be projected into the future under non-stationary conditions (Milly et al, 2002). In some cases, this insight has already led to a widening of the system boundaries. For example, flood frequency analysis (i.e., fitting a statistical distribution to annual maximum streamflow) is not appropriate as a basis for designing future infrastructure under considerations of significant land-use change, since the historical statistics may no longer reflect flood hazard in the future. This problem can be addressed by explicitly representing land-use in a hydrological model, and thus explicitly modelling the transformation from extreme rainfall into runoff assuming current or future catchment conditions. Frequently, the role of antecedent moisture conditions are treated as calibration parameters, for example through loss parameters of the hydrological model. However, under future climate, extreme rainfall may increase at a faster rate than average rainfall (Allen and Ingram, 2002), and evapotranspiration may change as well, so that the relationship between flood-producing rainfall and the catchment's antecedent conditions is no longer stable and may need to be modelled explicitly. Therefore, as more aspects of a system change, the boundaries of system models must necessarily become wider, leading to a greater need to consider dependencies between interacting processes. Understanding Compound Events will help to identify the relevant variables that need to be taken into account to model a given system.

In many cases, the impacts associated with present-day Compound Events are so severe that they change the functioning of the system, such that a similar event in the future will have substantially different impacts. For example, a flood that causes loss of lives and property is likely to be followed by the construction of additional infrastructure, modification of planning regulations, and many other features (see Bubeck et al, 2012; Thieken et al. 2016 for examples from Germany). Therefore, the act of experiencing an event leads to improved resilience to similar future events, such that areas of vulnerability are more likely to be due to events or combinations of events that have yet to occur, as was recently illustrated for cases round the world (Kreibich et al., 2017). Thinking about combinations of variables and processes that could cause an impact but have not yet occurred becomes more and more important as boundary conditions change. The Action on Compound Events, coordinating a wide range of expertise, will enable a suite of research coordination (Section 1.2.1) and capacity-building (Section 1.2.2) objectives to be achieved.

1.2. OBJECTIVES

1.2.1. RESEARCH COORDINATION OBJECTIVES

- Establish and coordinate a network of previously unconnected communities including climate scientists, hydrologists, impact modellers, risk modellers, statisticians, and stakeholders to advance our knowledge on Compound Events.
- Develop a definition and common understanding of Compound Events and establish Compound Events as a new relevant research topic in climate and climate impact research.
- Develop a meta-database of relevant impact datasets. This will include databases reporting impacts on infrastructure, human mortality, and ecosystems.
- Identify characteristic classes of Compound Events and provide guidelines how to study them.
- Create awareness in climate and climate impact communities about the inherent modelling challenges associated with Compound Events.
- Lead development of methods to evaluate climate models based on multivariate dependencies.
- Improve physical understanding of Compound Events and their potential future changes by coordinating existing research at the European scale.
- Disseminate results on Compound Event research to relevant stakeholders.

1.2.2. CAPACITY-BUILDING OBJECTIVES

- Foster knowledge exchange and development of a joint research agenda on Compound Events.
- Connect climate and Earth system scientists, hydrologists, ecosystem modellers, impact modellers, risk modellers, and statisticians to combine knowledge on climate science and impact modelling with state-of-the-art statistical approaches to study Compound Events.
- Provide complementary training for Early Career Investigators (ECIs) in dynamical modelling, multivariate statistics, and extremes, inherently relevant for studying Compound Events.
- Design climate impact assessment protocols that take into account Compound Events.
- Improve stakeholders' understanding of Compound Events and limitations to modelling these, enabling them to plan more targeted.
- Improve stakeholders' awareness of the importance to document physical and/or monetary impacts of Compound Events.

1.3. PROGRESS BEYOND THE STATE-OF-THE-ART AND INNOVATION POTENTIAL

1.3.1. DESCRIPTION OF THE STATE-OF-THE-ART

The impact of climate change on underlying systems is often analysed via “top-down” or “scenario-led” approaches (Hazeleger et al., 2015; Prudhomme et al., 2010). Top-down approaches use ensembles of climate model simulations, statistical bias correction, downscaling to the spatial and temporal scales relevant to decision-makers, and subsequent translation into quantities of interest through impact modelling. Adaptation responses are then studied to counter anticipated risks. Coupling climate models with impact models is challenging, as impact models depend on unbiased model output for both their driving variables and their interdependencies, in particular for risk estimation (Cannon, 2017).

Many climate change studies communicate univariate quantities of relevant climate extremes. These quantities include the hottest or coldest day of the year, changes in the frequency of heat waves, drought magnitude, extreme precipitation, and flood occurrence. A list of predefined indices facilitates this type of hazard projections (Zhang et al., 2011). However, many indices relevant to climate related hazards are dependent on multiple climate variables. For instance, indices quantifying heat stress and fire risk need to be computed from temperature and humidity (Chandler et al., 1983; Lee, 1980; Van Wagner and Forest, 1987). Commonly used drought indices such as the Standardized Precipitation Evapotranspiration Index (Vicente-Serrano et al., 2010) and the Palmer Drought Severity Index (Palmer, 1965) are based on precipitation and temperature. In addition, high-impact weather events may not necessarily be extreme in the meteorological record but involve multidimensional, nonlinear combinations of several variables that lead to extreme impacts for instance on the terrestrial biosphere or other dependent systems. Often it is not clear how well climate models capture the multiple driving conditions that affect all these quantities. Current model evaluation mostly relies on statistics such as correlations or root mean squared error between a modelled and an observed variable (Eyring et al., 2016). Based on these statistics, model performance for Compound Events cannot be assessed. Only recently, a dedicated evaluation of multivariate, spatial and temporal characteristics has been proposed (Maraun et al., 2015).

Often, many drivers combine to produce an extreme event (Kašpar and Müller, 2014). Dependencies between drivers make the estimation of hazard probabilities more difficult than if all drivers were independent (Leonard et al., 2014; Salvadori et al., 2015; Salvadori et al., 2016). In particular, the likelihood of high-impact hazards can be very different from a naïve independent combination of the univariate probabilities. For instance, extreme storm surge and rainfall events are often positively correlated along coastlines (Wahl et al., 2015, Zheng et al., 2013), increasing the probability of coastal floods. In addition, the co-occurrence of multiple climate-related hazards often has particularly large impacts. Recent pioneering work has estimated the likelihood of different hazard combinations including concurrent storm surge and rainfall in coastal areas, concurrent wind and precipitation extremes, and concurrent droughts and heatwaves (Kew et al., 2013; Wahl et al., 2015; Martius et al., 2016; Bevacqua et al., 2017; Zscheischler and Seneviratne, 2017). These studies have highlighted that the dependence between hazards or drivers of hazards can strongly vary across space.

Analyses of the dependence between rare events rely on non-standard statistical approaches such as copula theory (Nelsen, 2007) and multivariate extreme value theory (Coles and Tawn, 1991). In particular, copulas are being used more and more to study dependencies in the extremes (Wahl et al., 2015; Salvadori et al., 2016; Bevacqua et al., 2017; Zscheischler and Seneviratne, 2017). Robustly estimating the dependence between extremes requires large amounts of observational data, which typically is a limiting factor. An alternative approach for studying the effect of dependence between climatic drivers on the likelihood of a hazard is provided by well-calibrated dynamical models. By removing the dependence between storm surge and precipitation in a model environment, van den Hurk et al. (2015) showed a significant influence of the dependence of drivers on extreme water levels. The credibility of this approach depends strongly on the confidence we have in the quality of model simulations, which critically relies on observational data and how models are evaluated.

1.3.2. PROGRESS BEYOND THE STATE-OF-THE-ART

DAMOCLES will progress beyond the state of the art in three areas:

(a) <u>It will coordinate the development of novel statistical approaches to evaluate climate and impact model simulations against observations with respect to Compound Events</u>. This is important for judging the credibility of models for simulating Compound Events, and is relevant for increasing confidence in event attribution studies. Attribution metrics, such as the 'fraction of attributable risk' or 'probability ratios', which quantify the degree to which a certain driver such as anthropogenic climate change has altered the probability of event occurrence, are highly sensitive to biases in model simulations and to the representation of Compound Events. New approaches to test model performance will include metrics that evaluate multivariate dependencies between climate variables and metrics that are tailored to (multivariate) extremes. DAMOCLES will also review limitations of the statistical modelling of Compound Events and will provide guidelines for future developments in this area.

(b) DAMOCLES will develop a meta-database of climate impact datasets along with the climatological drivers. This is a crucial step in the effective study of Compound Events and will serve a wide community of researchers working on climate extremes and related impacts. Information on impacts on human and natural systems will be collected across various domains, disciplines and geographical zones and will catalyse new research relating climate extremes with impacts.

(c) Case studies based on individual events will demonstrate current modelling capabilities to simulate Compound Events. Case studies will also highlight limitations and necessary directions for model improvement. DAMOCLES will generalize knowledge from case studies to create classes of Compound Events that can be studied with a similar methodology. Case studies will require collaboration of climate modellers, impact modellers, statisticians and stakeholders in order to understand the features that are unique to every event.

1.3.3. INNOVATION IN TACKLING THE CHALLENGE

Outcomes of DAMOCLES will include novel ways of analysing climate model output, for instance by searching for multivariate climate constellations that have been identified as highly relevant for impacts. By classifying Compound Events and developing specific analysis guidelines, DAMOCLES will help improve forecasts and projections of climate-related hazards. The coordination of the development of statistical methods to analyse Compound Events, assess model simulations, and improve risk estimates will be highly relevant for risk management of climate-related hazards. In addition, the novel statistical methods can be used for multi-hazard risk estimation for geophysical hazards and other sectors. Further, the knowledge about the creation and evolution of Compound Events that will be obtained within DAMOCLES could be translated to early warning systems serving local meteorological offices. Finally, DAMOCLES will bridge several rather disconnected scientific communities and strongly promote stakeholder-scientist interaction with a focus on Compound Events. These interactions will lead to a sustainable dialog between involved groups that will continue beyond the end of the Action.

1.4. ADDED VALUE OF NETWORKING

1.4.1. IN RELATION TO THE CHALLENGE

Research on Compound Events requires expertise from various scientific domains and from stakeholders, who can help identify the most relevant events. DAMOCLES will actively involve stakeholders from the beginning of the Action for co-design, co-production and co-exploration of Compound Event research. DAMOCLES will create a new network to bridge scientific disciplines to exchange knowledge and create synergies between the different fields of research. This will enable the development of new tools that require a multidisciplinary approach. The network will also help to unify currently adopted approaches to study Compound Events. Data availability is a key challenge for Compound Event research. While data availability is often the limiting factor for studying rare events, identifying relevant datasets on impacts related to Compound Events within a large network of researchers and stakeholders from a variety of backgrounds will offer new research opportunities. In addition, the network, which will span many different geographical regions, will be able to identify and promote research on events that are most important for human societies in different regions of the world. DAMOCLES also aims to connect and create a network of stakeholders from different geographical regions but a similar interest (e.g., decision makers dealing with Compound Events in coastal zones), which will improve their ability to cope with Compound Events.

1.4.2. IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

DAMOCLES will complement and build upon current European and international research projects and research programs concerned with climate extremes, disasters, the development of Earth system models, and data collection. In particular, DAMOCLES will complement and collaborate with researchers from the ongoing EU H2020 projects IMproving PRedictions and management of hydrological EXtremes (IMPREX, 2015-2019), focusing on hydrological extremes and their impacts; EnhANcing emergencY management and response to extreme WeatHER and climate Events (ANYWHERE, 2016-2019), aiming to improve the capacity to respond to high-impact weather and climate events; Coordinated Research in Earth Systems and Climate: Experiments, kNowledge, Dissemination and Outreach (CRESCENDO, 2015-2020), focusing on the evaluation of climate and impact models, and the improvement of representation of key processes in such models; BRidging the GAp in Innovations for Disasters (BRIGAID, 2016-2020); and IMproving Drought and FLOOD early warning forecasting and mitigation (IMDROFLOOD, 2016-2020), focusing on the identification of the most suitable drought and flood indicators in hydrological and crop models for Iberia and Eastern Europe. DAMOCLES will further interact with international networks and ongoing projects of international programs including the World Climate Research Programme's (WCRP) Grand Challenge on Weather and Climate Extremes, the Global Energy and Water cycle EXchanges (GEWEX) project of the WCRP, the Future Earth initiative Extreme Events and Environments from climate to Society (E3S), Understanding Risk: a network of the Global Facility for Disaster Reduction and Recovery, the Global Flood Partnership, the European Training Network SYSTEM RISK - a large-scale systems approach to flood risk assessment and management, and the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). DAMOCLES will also interact with the scientist-stakeholder network that designs the open inter-sectoral impacts encyclopedia (ISIpedia), which will offer tailored access to state-of-the-art climate-impacts assessments and data, based on the cross-sectoral, multi-model simulations conducted within ISI-MIP.

By bringing together stakeholders and researchers from highly diverse fields in one network, DAMOCLES will enhance knowledge exchange between rather disciplinary networks associated with European projects, and create new synergies for Compound Event research.

2. IMPACT

2.1. EXPECTED IMPACT

2.1.1. SHORT-TERM AND LONG-TERM SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS

DAMOCLES will establish Compound Events as essential components in climate impact research. This recognition will lead to a paradigm shift in how potential impacts of climate extremes are currently forecasted and projected and will inspire new research programs at the national and international level. As a consequence, members of DAMOCLES will work on Compound Events research long beyond the project duration, within and outside future European projects.

A platform where available data on climate impacts and their drivers are integrated will provide crucial information for a large scientific community working on climate extremes and associated impacts. Linking existing databases on impacts with climate data and conducting case studies of specific Compound Events that lead to particularly high impacts will lead to improved analyses of high-impact extremes.

DAMOCLES will lead to a better scientific understanding of the physical processes involved in Compound Events. On the long term, this will help improve the ability to model Compound Events, which may be the starting point to help disentangle the human (including land-use change, changes in infrastructure/water use) and natural contributions to Compound Events, providing guidance for management and adaptation measures. In addition, a better understanding of Compound Events will pave the way for new research to improve mid-range/seasonal forecasts of high-impact weather/climate events and will contribute to improving risk estimates of high-impact weather/climate events over long (decadal and longer) timescales.

2.2. MEASURES TO MAXIMISE IMPACT

2.2.1. PLAN FOR INVOLVING THE MOST RELEVANT STAKEHOLDERS

DAMOCLES will maximise its impact by involving stakeholders from various sectors including (re-) insurance, policy makers/government branches, farmers/agriculture companies, humanitarian and developmental organisations, engineering companies and water companies (responsible for water supply and flood protection) who have to deal with the consequences of Compound Events throughout the entire duration of the Action. One full Working Group (WG2) is dedicated to the stakeholder-scientist dialog and will examine the specific user-needs of the stakeholders, invite stakeholders to cross-cutting events, match stakeholders and scientists with respect to bilateral interests, and organise sessions at international conferences. The Action will facilitate the collaboration between stakeholders and scientists on case studies to address user-defined research questions on Compound Event risk management. As such, communicating uncertainties of modelling Compound Events (spatial and temporal scale as well as magnitude) and their relevance for stakeholders will improve the understanding and the actions taken to reach a sustainable risk management.

2.2.2. DISSEMINATION AND/OR EXPLOITATION PLAN

DAMOCLES will disseminate its main findings via multiple strategies. Novel research-related insights will be published in scientific papers. Members of the Action will organize specialized conference sessions to promote the activities of DAMOCLES in their respective research fields. A website will be created in WG1 to collect previous studies on Compound Events and the portfolio of case studies coordinated within the Action. The website will host the newly created meta-database, which will provide links to impact datasets, including description, limitations, and possible usage. This information will be communicated to the broad research community working on climate extremes and related impacts via conferences and scientific papers, newsletters from research programs such as GEWEX, WCRP and Future Earth, and social media, to keep researchers updated and improve and coordinate research on Compound Events. An analysis framework for different classes of Compound Events, which will generalize knowledge from case studies, will be published at the end of the Action by WG1. By including lessons learnt during the case studies, this document will provide guidelines for future research on Compound Events.

The active use of Training Schools (WG4 and WG5) and Short-Term Scientific Missions (STSMs) will train a new generation of researchers in statistical and dynamical modelling of Compound Events and will increase the awareness of the limits of standard approaches in the broader climate extremes research community.

During the Action, an active dialog with stakeholders (WG2) will be maintained. This close collaboration will be used to inform stakeholders about the relevance of Compound Events for risk estimation and keep them updated about new insights obtained during the Action. In a final dissemination conference, researchers and stakeholders will be invited and major findings of DAMOCLES will be communicated and discussed in a transdisciplinary setting.

2.3. POTENTIAL FOR INNOVATION VERSUS RISK LEVEL

2.3.1. POTENTIAL FOR SCIENTIFIC, TECHNOLOGICAL AND/OR SOCIOECONOMIC INNOVATION BREAKTHROUGHS

A clear classification of Compound Events will help identify the necessary tools to increase the forecasting skill for such events and provide inputs to risk assessments. The unique structure of Compound Events potentially limits the Action’s ability to make a clear classification. However, this risk can be mitigated by tuning the classification rules or develop alternative approaches to generalize Compound Events and its analysis methodologies.

DAMOCLES will position Compound Events as essential components in climate impact research. This recognition will lead to a paradigm shift in how impacts of extremes are currently forecasted and projected from a top-down to a bottom-up perspective. It will inspire many new programs in different research areas (climate science, dynamical modelling, disaster risk management, event attribution). In the case that the activities in DAMOCLES are not large-scale enough to trigger this paradigm shift, the members of DAMOCLES will complement the Action via self-funded research and other funding opportunities to pursue the implementation of the full impact and relevance of Compound Events in climate impact research.

One objective of DAMOCLES is the appreciation of correlated hazards as a major contributor to risk, impacting socio-economic systems and ecosystems. This is highly relevant for stakeholders such as urban and water resource planners, farmers, (re-)insurance companies, and human aid and developmental organizations. Communicating the influence of correlated hazards on risks may change the way stakeholders deal with risks related to climate events. This communication might be impaired if DAMOCLES cannot provide clear results on identification of correlated hazards and their effects on risks. In this case, DAMOCLES will identify crucial research gaps that need to be addressed within national and international research projects.

The meta-database on impact datasets will be a platform for a broad research community working on climate extremes and related impacts. Production of this database can be challenging if data owners have a restrictive data policy and may impair the usability of the meta-database. The Action will concentrate on datasets that are available, relevant, and accessible (e.g., via a direct agreement with the data owners). The Network of Proposers has long-standing experience in dealing with and obtaining access to a variety of datasets from highly heterogeneous sources.

3. IMPLEMENTATION

3.1. DESCRIPTION OF THE WORK PLAN

3.1.1. DESCRIPTION OF WORKING GROUPS

DAMOCLES will address the identified challenges in five complementary Working Groups (WGs), which will strongly interact and exchange knowledge throughout the duration of the Action.

WG1: Synthesis and analysis framework

<u>Objectives</u>
WG1 will provide a generalized framework that serves the identification, analysis methodology and impact assessment of Compound Events. This framework will underlie the analyses performed within the overall project and will be developed in coordination with the other WGs. It will help in the selection of appropriate statistical and modelling techniques needed for the analysis and evaluation of the effects of Compound Events on existing weather and climate risk assessments. The framework will be continuously updated throughout the duration of the Action with input from the other WGs. Specifically WG1 will:

- Classify Compound Events according to a number of key attributes
- Provide an analysis protocol for studying different classes of Compound Events, including identification of tools, data and experimental design
- Organize one or more dissemination events to broadly share the results of the project.

<u>Tasks & Activities</u>
Task 1.1: Database of Compound Event studies
Conduct a literature survey collecting studies on compound events. Assign key attributes to each of the case studies and store the results in a central database. Attributes will include (i) the variables and processes jointly operating during the event, (ii) the spatial and temporal scales of dependencies, (iii) the contribution of the compounding nature of the events to the (societal) impact and risk, (iv) the potential role of human-induced climate change, other human influences (e.g., land use, urban development), and further non-stationarities on the events and their impacts, and (v) the available analysis and statistical/dynamical modelling tools. Identify key attributes for a Compound Event classification and classify events according to these attributes. Continuously update database with input from the other WGs.

Task 1.2: Synthesis and definition of an analysis protocol
Aggregate database from Task 1.1 to a generic analysis framework that can be used as template for future analyses of Compound Events and to determine their potential effects on existing and upcoming risk assessments. Generalize results of case studies from WG5 to refine the analysis framework.

Task 1.3: Communication of findings
Set up communication channels including website and social media accounts. Disseminate synthesis to a wider audience including scientific analysts, risk assessment experts and policy makers making use of weather/climate risk assessments. Organize one or more dissemination conferences between scientists and stakeholders. Further dissemination will take place via conference sessions (including a final conference, C2), scientific and review papers, and outreach publications.

<u>Milestones</u>
M1.1: Literature review completed
M1.2: Analysis protocol defined

M1.3: Case studies collected from WG5

Deliverables
D1.1: Action communication channels such as website and social media accounts
D1.2: Literature review on Compound Events and initial classification
D1.3: Analysis protocol for different types of Compound Events (scientific paper)
D1.4: Synthesis of case studies on Compound Events (either a book or special issue)

WG 2: Stakeholder involvement and science-user interface

Objectives
WG2 will connect the scientific network developed through the Action with a network of stakeholders for whom Compound Events are important in decision-making. Next to identifying stakeholders and stakeholder needs, WG2 will couple scientists and stakeholders in several case studies in which solutions to real-world problems relating to compound events will be examined. Specifically WG2 will:

- Add relevance to the science of Compound Events through stakeholder involvement
- Enable collaboration between scientists and stakeholders on Compound Event risk management
- Promote best practices of Compound Event risk management.

Tasks & Activities
Task 2.1: Identification of stakeholders and stakeholder needs
Identify current stakeholder network in the Action and map this on a time-space-hazard domain, building on the framework developed in WG1. Fill gaps in the Action's stakeholder network to develop an overview of potential stakeholders for whom the Compound Events framework is of relevance. Organize cross-cutting conference (C1) in year 1 including a matchmaking event between stakeholders and scientists. This will provide a basis for the selection of case studies coordinated by WG5. Continue identification of stakeholder needs throughout the duration of the Action by organizing events at key conferences.

Task 2.2: Stakeholder and science interaction in user-oriented case studies
Together with stakeholders, jointly identify user-defined research questions on Compound Event risk management. Couple the scientific partners of the Action with the stakeholders identified in Task 2.1. Continue matchmaking between scientists and stakeholders throughout the duration of the Action. Develop short objective and action plan (1-2 pages) for each case study.

Task 2.3: Demonstration of case study applications and best practices
Examine how each case study has contributed to enabling collaboration between scientists and stakeholders on Compound Event risk management. Compile white paper demonstrating best practices derived from these case studies.

Milestones
M2.1: Interactive gap analysis carried out at kick-off
M2.2: Case-study matchmaking completed at cross-cutting conference
M2.3: Initial teleconferences per case study between stakeholders and scientists completed

Deliverables
D2.1: Working paper on stakeholder and stakeholder needs
D2.2: Case study plans published online
D2.3: White paper on case studies and lessons learnt

WG3: A meta-database of impact data

Objectives
Studying Compound Events requires to link data on impacts such as crop failure, increased human mortality, destroyed infrastructure, and affected ecosystem services to climate data. While climate data are often homogenized and easily accessible, impact data are highly heterogeneous and difficult to obtain and interpret for a larger community. To improve this situation, WG3 will

- Achieve an overview of existing impact databases and explore their usability for Compound Event research
- Enable an inter-linkage of impact databases and climate information
- Ensure a critical appraisal of impact data for DAMOCLES and beyond.

Tasks & Activities
Task 3.1: Overview of impact databases.
Screen and compile impact databases into an overview in collaboration with the Action and stakeholders identified by WG2. Identify critical issues that could be limiting for linking impact data with climate data. The search will be based on the following criteria: (i) degree of openness and usability, (ii) accuracy and reliability of data the record (e.g. georeferencing), and (iii) possibilities to access via web interfaces. Starting points will be quantitative information bundled by the United Nations Office for Disaster Risk Reduction (UNISDR), national impact analyses, and independent international databases.

Task 3.2: Perspectives for data interlinkage
Investigate and document the most effective ways to connect existing impact information to climate data. Explore possibility to automatize links between impact data and climate data. Identify shortcomings of the different databases with an emphasis on spatial/temporal scales covered, data gaps, data quality, and the representation of uncertainties in each dataset.

Task 3.3: Support to in-depth analyses of Compound Events
Support exploration of specific impact datasets by linking impact data with climate data using exploratory techniques and new statistical approaches that are being coordinated in WG4. Document limitations of impact datasets that are relevant for Compound Event research.

Milestones
M3.1: Relevant databases/datasets on impacts identified
M3.2: Overview on impact datasets published on DAMOCLES project website
M3.3: Statistical approaches for in-depth analysis identified

Deliverables
D3.1: Report of available impact databases
D3.2: Description of limitations and usability for impact dataset on DAMOCLES project website
D3.3: Guidelines on linking impact datasets with climate data

WG4: New statistical approaches for model development and evaluation

Objectives
Statistical models are required to adequately assess the risk of Compound Events and to evaluate dynamical models. Compound Events are particularly affected by the high dimensionality: they are rare and they are multivariate, that is, they live in the sparsely sampled corner of a multidimensional space with limited observational coverage. Statistical models thus heavily rely on extrapolation. In principle, statistical approaches based on copulas and multivariate extreme value statistics exist to model moderately extreme Compound Events. These statistical approaches are also needed to evaluate dynamical models with respect to their performance during compound events. Against this background, WG4 will:

- Review statistical models and identify their structural strengths and weaknesses
- Promote best practice of statistical modelling of Compound Events for the broad research community
- Coordinate and support the development of novel statistical models
- Foster the exchange between climate scientists and statisticians.

Tasks & Activities
Task 4.1: Inventory of current practice in statistical modelling
Conduct an inventory of current practice in statistical modelling of compound events and other potentially suitable statistical approaches. Classify these approaches according to the underlying statistical models and their purpose. Determine strengths and weaknesses of these models based on their model structure, published literature and the experience of their developers and users.

Task 4.2: Identify and bridge research gaps
Link currently available statistical tools with the classification of compound events developed by WG1 (Task 1.1). Recommend appropriate statistical tools for studying a given class of Compound Events and identify limitations. Set up agenda of promising research strands for developing both highly sophisticated cutting-edge statistical models as well as pragmatic though defensible statistical models for a broader user community. Adapt methods that are relevant for Compound Events by combining the expertise from statisticians and climate scientists.

Task 4.3: New metrics and guidelines
List suitable metrics for evaluation and testing of statistical and dynamical models with respect to their performance in simulating Compound Events (relevant for WG5). Develop guidelines for best practice in statistical modelling of compound events. Coordinate the development of new statistical methods for compound events across different research projects in Europe.

Task 4.4: Training School (TS1) on statistical modelling of Compound Events
Organise and lead Trainings School on statistical modelling of Compound Events. The Training School will include teaching metrics to evaluate dynamical models with respect to their performance in capturing extremes and multivariate relationships. It will target ECIs focusing mostly on dynamical modelling. The Training School will be complementary to the Training School organised by WG5, focusing on dynamical modelling.

Milestones
M4.1: Inventory of statistical approached conducted
M4.2: Research gaps identified
M4.3: Metrics for the evaluation and testing of statistical and dynamical models identified

Deliverables
D4.1: Inventory of statistical methods and practice (contributes to review in D1.1)
D4.2: Guidelines for best practice how to use statistical tools to study Compound Events (white paper)

WG5: Realistic model simulations for specific event types

Objectives
Dynamical models are a powerful tool to analyse atmospheric processes and variables on various spatial and temporal scales. They will be used in this Action to obtain a sound understanding of the underlying mechanisms that drive Compound Events and the complex interactions of the variables determining the severity of these events. In combination with impact models and stochastic weather generators, the knowledge delivered by dynamical models is crucial to support informed decision making. WG5 will extend the available knowledge on the drivers of Compound Events and their relevance for risk assessment by:

- Improving risk estimates related to Compound Events via:
  (i) Identifying the physical mechanisms behind different types of Compound Events,
  (ii) Investigating the complex interaction of the underlying processes, and
  (iii) Highlighting the influence of these interactions on risk assessment analyses and estimates of return periods and failure probabilities
- Advancing the ability to project specific types of compound events on both short and long timescales (up to seasonal and decadal).

Tasks & Activities
Task 5.1: Selection of case studies
Select a portfolio of Compound Events as the basis for process-based model studies, including (i) wildfires, droughts and heatwaves, (ii) flood events, (iii) crop failures, and (iv) coastal erosion. Coordinate selection with all other WGs based on (i) the events' relevance for their respective type (within the classification scheme developed in WG1), (ii) the severity of their impact in terms of its socio-economical repercussions (relevance for stakeholders, WG2) and (iii) the availability of necessary data and tools, to either provide information about the event directly (e.g. observations, reanalysis data, relevant data on impacts as identified by WG3) or to perform relevant process-based model experiments.

Task 5.2: Coordinate data collection and analysis for case studies
Align data requirements for the selected case studies with data availability. Where necessary, mediate between working groups to coordinate data exchange. Sources of climate data are outputs from state-of-the-art numerical models including (i) dynamical models, such as regional and global weather and climate models as well as ensembles thereof; (ii) impact models, such as for instance numerical storm surge and crop yield models; (iii) stochastic weather generators; and (iv) observations and reanalysis products such as those provided by the European Centre for Medium-Range Weather Forecasts

(ECMWF). Oversee the performance of case studies to ensure consistent methodologies and relevance (WG2). The tools to perform these analyses will be provided by WG4.

Task 5.3: Present study results
Summarise and document individual studies in scientific papers, and communicate results to stakeholders in collaboration with WG2.

Task 5.4: Training School (TS2) on dynamical modelling of Compound Events
Organise and lead a Trainings School on dynamical models with a focus on Compound Events applications. This will be complementary to the Training School organised by WG4, and it is targeted at ECIs focusing mostly on statistical modelling.

Milestones
M5.1: Initial selection of case studies in cooperation with WG1, WG2 and stakeholders
M5.2: Online publication of full list of case studies selected
M5.3: Data collection for case studies finalized
M5.4: Submission of case studies for peer review

Deliverables
D5.1: Research papers on each case study
D5.2: Online database of the case studies

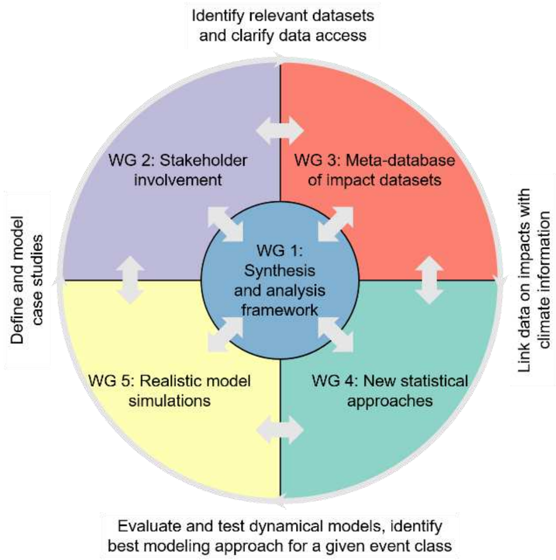
3.1.2. GANTT DIAGRAM

The following GANTT diagram lists the duration of the tasks (T, grey), milestones (M), deliverables (D), Training Schools (TS), and major conferences (C) in different quarters of the Action.

	Year (Y) and Quarter (Q)															
WG	Y 1				Y 2				Y 3				Y 4			
1	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
T1.1				M1.1		D1.2										
T1.2								M1.2	D1.3							
T1.3	D1.1												M1.3		D1.4	C2
2																
T2.1	M2.1	C1	D2.1	M2.2												
T2.2					D2.2		M2.3									
T2.3																D2.3
3																
T3.1				M3.1		M3.2		D3.1								
T3.2												D3.2				
T3.3												M3.3				D3.3
4																
T4.1			M4.1	D4.1												
T4.2						M4.2										
T4.3												M4.3				D4.2
T4.4				TS1												
5																
T5.1		M5.1				M5.2										
T5.2												M5.3				
T5.3												M5.4			D5.1	D5.2
T5.4										TS2						

3.1.3. PERT CHART (OPTIONAL)

The interaction between the five WGs and activities is shown in the neighbouring PERT chart. WG1 will closely interact with all other WGs to generalize knowledge and coordinate knowledge transfer.



3.1.4. RISK AND CONTINGENCY PLANS

Risks associated with the Action are related to administration and conduct of the activities, as well as short-term and long-term impact of the activities. Unanticipated personnel changes in the Action Chair, Management Committee or Working Groups may slow down work when new staff may need to be trained for networking tasks. The Network of Proposers has long-standing experience in project management, which will ensure continuity in staffing and preparedness for management duties. All of the work can be completed with COST Action support including STSMs, and resources of the Action members. In addition, Action members may submit proposals for external funding to support work of the Action. For each WG, DAMOCLES will have two WG Leaders, an ECI and a senior scientists. This will ensure (1) that activities are pushed by a motivated ECI and at the same time, a senior scientist overlooks the process, and (2) that the activities in a WG can continue in case one WG leader drops out.

WG tasks partly build on each other, bearing the risk that tasks in one WG may be delayed if a certain task in another is delayed. However, WGs are still sufficiently stand-alone such that most activities can continue or run in parallel if one WG is delayed in its deliverables.

A potential risk of the Action is related to having difficulties in stakeholder interaction and matchmaking between scientists and stakeholders. Members of the Network of Proposers have already had many discussions with stakeholders regarding the need to include Compound Events in decision-making. This has also been covered as a key concern at the World Bank's Understanding Risk conference in 2016. Therefore, many contacts are in place so that it will be possible to define the stakeholder case studies and perform a meaningful stakeholder-scientist matchmaking.

The development of a meta-database on impact is associated with risks. Data might be available but not directly accessible in an automated way or not publicly available. In this case, WG3 will establish bilateral solutions to support the tasks in the Action and communicate potential solutions and guidelines regarding the usage of these datasets for a wider community.

The dynamical models used to perform the selected case studies (WG5) may not be able to sufficiently represent the relevant climatological processes and interactions that cause Compound Events. This would be an important discovery but it would prevent the identification of the driving processes behind these events. If this should be the case, an in-depth analysis of the causes behind the limitations of the dynamical models would replace the original objective of driver identification in WG5. Accordingly, the deliverables would change to providing the broader research community with information of the shortcomings to trigger new research into model improvement.

3.2. MANAGEMENT STRUCTURES AND PROCEDURES

The Management Committee (MC) will coordinate and supervise the overall progress of the Action and the use of funds. At the first MC Meeting a Core Group (CG) will be established. The CG will include Action Chair, Vice Chair, a coordinator for STSMs, all WG Leaders and other horizontal roles. Regular meetings of the MC and WG Leaders (typically twice a year) will ensure an effective coordination of the different activities taking place in DAMOCLES. Each WG will be led by an ECI and a senior scientist. The ECI will lead the coordination and organization of meetings, whereas the senior scientist will provide guidance to make sure the longer-term objectives will be reached. DAMOCLES will actively use STSMs (4-8 per year) to exchange knowledge between the different WGs. This exchange will be further promoted by the two Training Schools. In addition, WG3 will send ECIs to data providers (e.g., institutions who gather data, stakeholders) to gain information on relevant datasets and how to access them. To allow for effective decision making also outside of MC meetings, a method for reaching MC decisions via email will be discussed and implemented at the first MC Meeting. The CG will meet regularly virtually to discuss pressing topics.

3.3. NETWORK AS A WHOLE

The Network of Proposers of DAMOCLES consists of members with a wide-ranging expertise covering all disciplines that are relevant for the Action such as climate and Earth system science, dynamical modelling, impact and risk modelling, engineering, health sciences, and statistics. The broadness of disciplines represented in the Network of Proposers demonstrates the overwhelming interest in the topic of Compound Events and shows that the Network is well prepared and qualified to address the identified challenges. More than half of the proposers are ECIs (including the main proposer), which will ensure capacity building in a new generation of researchers for the field of Compound Event research. 40% of the represented countries in the Network of Proposers are Inclusiveness Target Countries, ensuring an active knowledge transfer towards disadvantaged research institutions and countries. The broad coverage of the Network will improve the capacity to deal with the impacts of Compound Events in a wide range of distinct geographical regions of Europe and the world. Females represent more than 40% of the network of proposers. DAMOCLES aims for at least 40% of all major leading roles (MC, CG, WG Leaders) to be female.

DAMOCLES will invite the IPCs such as Australia and USA. Australia has been experiencing upward trends in some important natural hazards. Some of these, for example the compound floods on Australian coastlines (driven by upstream and ocean processes) or the connection between cyclone activity in Northern Australia and heatwaves in southern Australia are Compound Events. Australia’s experience in deciphering and explaining these phenomena, combined with world-class statistical approaches to Compound Events (Westra and Leonard, University of Adelaide) brings specific expertise to DAMOCLES. Similarly, various types of Compound Events in the USA have revealed how vulnerable society is to those high-impact events (e.g. during the Louisiana floods in 2016, Hurricanes Isaac in 2012 and Harvey in 2017, or the recent California drought). Both US partners AghaKouchak and Wahl are collaborating with many relevant stakeholders on the west and east coast, including the US Geological Service (USGS) within their Coastal and Marine Science program and USGS Natural Hazards Mission and US Army Corps of Engineers (USACE) Climate Preparedness and Resilience (CPR) efforts. Australia hosts the newly established ARC Centre of Excellence for Climate Extremes, a 7-year initiative led by Pitman (UNSW) to understand climate extremes, and improve their representation in climate models. The on-going activities in the broad field of Compound Event research in Australia, USA and within DAMOCLES in Europe will be mutually beneficial to each other and facilitate faster progress and implementation of new methodologies and tools to better adapt for Compound Events across multiple sectors.