Workshop on

Compound Weather and Climate Events

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Abstracts

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100 Dmitri Alexander Kalashnikov

Increasing co-occurrence of particulate matter and surface ozone extremes during wildfire season in the western United States

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Air pollution is an urgent global health problem resulting in millions of premature deaths annually. Co-occurrence of elevated levels of fine particulate matter (PM2.5) and surface ozone (O3) can lead to disproportionately higher human health impacts relative to their individual occurrences. Wildfires are a source of PM2.5 and O3 precursors, and increasing wildfire activity has already increased extreme PM2.5 levels in the western U.S. (WUS). However, trends in PM2.5/O3 co-occurrence, associated physical mechanisms and current population exposure to such conditions have not been investigated. In this work, we quantify the spatial and temporal characteristics of extreme PM2.5/O3 co-occurrence across the WUS during the wildfire season (April-September) and identify their large-scale drivers using observed PM2.5 and O3 (1° x 1°; 1999-2018) and ERA5 reanalysis datasets (0.25° x 0.25°; 1979-2019). We perform Self-Organizing Map (SOM) clustering of large-scale meteorological patterns (1979-2019) during the wildfire season and for each cluster, we quantify co-occurrences across the region along with the fraction of the population exposed to high PM2.5/O3 levels. We find that the large-scale weather patterns that amplify the risk of extreme PM2.5/O3 co-occurrence over areas affecting >10M people in the WUS show robust increasing trends in both frequency (+18.7 days) and persistence (+4.6 days) over the 41-y period. The most widespread co-occurrence events were associated with the 2017 and 2018 intense wildfire seasons, abnormally high frequency of favorable large-scale weather patterns and record warm conditions across much of the WUS. Our results show that there is increasing co-occurrence of PM2.5/O3 during the wildfire season highlighting the potential for compounding human health stressors with projected increases in warming, ridging, and wildfire activity in the WUS.

101 Gabriele Messori

Compound Climate Extremes in Europe and North America

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Cold extremes over North America and stormy (wet and windy) weather over Europe, have typically been discussed separately. However, their repeated co-occurrence in recent winters raises the question of whether there may be a systematic, physicallly-based link between the two.
In this presentation, I will first provide a statistical analysis of these compound extremes, showing that they are unlikely to be a result of random variability. Next, I will leverage dynamical systems theory to provide a bridge between a statistical and a physical understanding of the phenomenon. I will specifically discuss how this points to the existence of a common dynamics underlying the occurrence of the cold-wet(-windy) compound extremes. I will end with an analysis of the large-scale atmospheric circulation anomalies associated with the compound extremes. This supports the notion of a systematic link between extremes on the two sides of the North Atlantic, mediated by anomalous configurations of the Jet Stream.

Shorter cyclone clusters modulate changes in European wintertime precipitation extremes

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Wintertime extreme precipitation from cyclone clusters, i.e. consecutive cyclones moving across the same region, can lead to flooding and devastating socioeconomic impacts in Europe. Previous studies have suggested that the future direction of the changes in these events are uncertain across climate models. By employing an impact-based metric of accumulated precipitation extremes, we show that projections of cyclone clusters are instead broadly robust, i.e. consistent in sign, across models. A novel physical diagnostic shows that accumulated precipitation extremes are projected to grow by only +1.0%/K on average across Europe, although the mean precipitation per cyclone increases by +4.7%/K. This results from a decreased number of clustered cyclones, associated with decreased wintertime storminess, the extent of which varies from northern to southern Europe. Neglecting these dynamical changes may affect policy-making, e.g., it would lead to overestimating the population affected by increased accumulated wintertime precipitation extremes by 130-490 million across Europe.

103 Emanuele Bevacqua

Global projections of changes in meteorological drivers of compound coastal flooding

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Compound flooding arising from the concurrence of extreme meteorological tides (i.e., the superposition of storm surge and waves) and inland precipitation from atmospheric storms can result in catastrophic impacts in densely populated low-lying coastal areas. Here, we provide a link between the concurrence of these meteorological extremes and the storm tracks at the global scale during present climate. Under a high emissions scenario, the concurrence probability of these meteorological extremes would increase by more than 25% on average along coastlines worldwide by 2100 compared to present. In latitudes above 40o north, these compound meteorological extremes would become more than 2.5 times as frequent, while they would happen less frequently in parts of the subtropics. Changes in precipitation extremes account for about 77% of the projected change in concurrence probability, while changes in meteorological tides account for 20% and changes in the dependence between the two for only 3%. The evolution of the dependence dominates the uncertainty in the projections of the concurrence probability. Our results indicate that not accounting for these effects in adaptation planning could leave coastal communities insufficiently protected against flooding.

104 Peter Pfleiderer

Simulating compound weather extremes responsible for critical crop failure with stochastic weather generators

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In 2016, northern France experienced an unprecedented wheat crop loss. This extreme event was likely due to a sequence of particular meteorological conditions, i.e. too few cold days in late autumn-winter and an abnormally high precipitation during the spring season. The cause of this event is not fully understood yet and none of the most used crop forecast models were able to predict the event (Ben-Ari et al (2018)). Here we focus on a compound meteorological hazard (warm winter and wet spring) that could lead to a crop loss.
This work is motivated by two main questions: were the 2016 meteorological conditions the most extreme under current climate? and what would be the worst case meteorological scenario that would lead to the worst crop loss? To answer these questions, instead of relying on computationally intensive climate model simulations, we use an analogue-based importance sampling algorithm that was recently introduced into this field of research (Yiou and Jézéquel (2020)). This algorithm is a modification of a stochastic weather generator (SWG) that gives more weight to trajectories with more extreme meteorological conditions (here temperature and precipitation). This approach is inspired from importance sampling of complex systems (Ragone et al (2017)). This data-driven technique constructs artificial weather events by combining daily observations in a dynamically realistic manner and in a relatively fast way.
This paper explains how a SWG for extreme winter temperature and spring precipitation can be constructed in order to generate large samples of such extremes.
We show that, with some adjustments, both types of weather events can be adequately simulated with SWGs, highlighting the wide applicability of the method.
We find that the number of cold days in late autumn 2015 was close to the plausible maximum. But our simulations of extreme spring precipitation show that considerably wetter springs than what was observed in 2016 are possible. Although the crop loss of 2016 relation to climate variability is not fully understood yet, these results indicate that similar events with higher impacts could be possible in present-day climate conditions.

105 John Hillier

Multi-hazard dependencies can increase or decrease risk

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The interplay among natural hazards affects risk globally. Over meteorological timescales (hours to weeks), hazards like wind and precipitation extremes can combine to exacerbate total risk. However, infrastructure operators, government agencies, (re)insurance and health services are also interested in aggregated risk over climatological timescales (seasonal to annual). Using Australia and Great Britain (GB) as examples we illustrate that, from this perspective, hazards can be influenced by modes of atmospheric variability in ways that reduce the likelihood of some hazard combinations, thereby moderating tail-end (worst-case) compound risk. In other words, purely pairwise views of a multi-hazard environment that target instances where risk is exacerbated might overestimate worst-case risk. We highlight this aspect of the need for a broader and more holistic view of multi-hazard risks. [Nature Climate Change 10, 595–598, doi:10.1038/s41558-020-0832-y]

Modelling the Ruin of Forests under Climate Hazards

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Estimating the risk of collapse of forests due to extreme climate events is one of the challenges of adaptation to climate change. We adapt a concept from ruin theory, which is widespread in econometrics of the insurance industry, to design a growth/ruin model for trees, under climate hazards that can jeopardize their growth. This model is an elaboration of a classical Cramer-Lundberg ruin model that is used in the insurance industry. The model accounts for the interactions between physiological parameters of trees and the occurrence of climate hazards. The physiological parameters describe interannual growth rates. The hazard parameters describe the probability distributions of occurrence and intensity of events. We focus on a drought/heatwave hazard. The goal of the paper is to determine the dependence of ruin and average growth probability distributions as a function of physiological and hazard parameters.
From extensive Monte Carlo experiments, we show the existence of a threshold on the frequency of hazards beyond which forest ruin becomes certain in a centennial horizon. We also detect a small effect of strategies to cope with hazards. This paper is a proof-of-concept to quantify collapse (of forests) under climate change.

107 Bart van den Hurk

Inventory of compound events from the perspective of societal impacts

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The notion that many extreme weather and climate conditions are governed by compounding drivers and hazards is clearly increasing. Literature on defining, explaining and analysing compound events is rapidly increasing. Simultaneously, many societal practitioners are aware of their exposure or vulnerability of compound events, and increasingly seek scientific assistence to support infrastructure design, policy strategies and awareness raising addressing this notion of compound events.
In the context of the European COST action DAMOCLES a survey is being carried out that collects, groups and characterizes impact-driven cases where compound event methodologies are needed or useful. The inventory is partly based on a literature review of practical case studies, and by experience from practitioners. We find many examples where “thinking compound” is well embedded in the impact assessment and solution pathway. However, the approaches that are useful to address compounding drivers and/or hazards are usually very context-specific, and cannot easily be generalized in tools and models. Various targeted science/practice interactions have generated increased awareness, but did not lead to “ready-to-go” approaches.
The inventory is intended to support the development of practice-oriented concepts and tools in which compound drivers/hazards are digested. This is achieved by a first typological classification of impact case studies, and the exploration of potential matches between requested and available analysis and modelling concepts.

Assessing crop failure risk on a global level: a compound perspective

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Agriculture is one of the sectors most vulnerable to changes in climatic conditions. Global gridded crop models (GGCMs) are used to simulate historical and future crop yield in a changing climate. Crop-climate ensembles (multiple GGCMs forced by several climate models) from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) coupled with the CLIMADA impact platform allow for the assessment of current and future risks of crop failure. Based on a global assessment of crop failure risk, this presentation will explore agricultural risk modelling under multiple dimensions of a compound paradigm:

Compound environmental drivers: GGCMs simulate yearly, site-specific crop yield based on multiple climate variables on a high temporal resolution. The most relevant environmental drivers include temperature and water availability, but also CO2 concentration and nitrogen availability. Therefore, simulating the interaction of multiple drivers on different time scales (short time events like heat waves, mean weather conditions during a growing season, long term CO2 trends, etc.) is at the very core of why GGCMs were developed in the first place. The complexity of GGCMs come at the cost of considerable uncertainties on different time scales, that are difficult to disentangle. Furthermore, climate forcing data (partly) resolves other hazards not considered in GCCMs, e.g. wind gust and TC surge, opening up the floor for the combination of crop yield simulations with the impacts not only from multiple drivers but also from several other natural hazards.

Multiple "breadbaskets" and multiple crop types: What are the consequences and probabilities of maize production in the USA and Brazil failing in the same year? Or of a reduced rice production in China or India coinciding with wheat failure in Australia and Russia? The assessment of compound extreme events on a multi-regional and multi-crop level, including uncertainties, their meteorological drivers, and socio-economic consequences (e.g. food security, conflict and migration, market dynamics, supply-chains) opens up a societally relevant and intriguing field of research.

By highlighting the open questions, uncertainties, and potentials related to the use of simulated crop yield for risk assessment, I hope to engage with the audience in an open discussion on the frontiers of this complex field.

Recommended preliminary reading:

Challinor, A. J., Müller, C., Asseng, S., Deva, C., Nicklin, K. J., Wallach, D., Vanuytrecht, E., Whitfield, S., Ramirez-Villegas, J. and Koehler, A.-K.: Improving the use of crop models for risk assessment and climate change adaptation, Agricultural Systems, 159, 296–306, doi:10.1016/j.agsy.2017.07.010, 2018.

Blanc, E. and Reilly, J.: Approaches to Assessing Climate Change Impacts on Agriculture: An Overview of the Debate, Review of Environmental Economics and Policy, 11(2), 247–257, doi:10.1093/reep/rex011, 2017.

109 Natacha Legrix

Compound high temperature and low chlorophyll extremes in the ocean over the satellite period

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Extreme events are well known to severely impact marine organisms and ecosystems. Of particular concern are compound events, i.e. when conditions are extreme for multiple potential ecosystem stressors. In 2013-2015 for example, an extensive marine heatwave, known as the Blob, cooccurred with low chlorophyll concentration and severely impacted marine life in the northeast Pacific, with cascading impacts on fisheries. Yet, little is known how the occurrence, intensity and duration of such ocean compound events have changed in the past and what the potential drivers are. Here, we use satellite observations of sea surface temperature and chlorophyll concentration to provide a first assessment of compound hot extreme temperature (aka marine heatwaves – MHWs) and low chlorophyll (LChl) events. We reveal hotspots of compound MHW and LChl events in the Equatorial Pacific, along the boundaries of the subtropical gyres, in the Arabian Sea and in the Weddell Sea. In these regions, compound events occur 3 to 7 times more often than expected under the assumption of independence between MHWs and LChl events. The occurrence of compound MHW and LChl events also varies over time. At the annual time-scale, most compound events occur in summer. At the interannual time-scale, the frequency of compound MHW and LChl events is strongly affected by the state of large-scale modes of climate variability such as the El Niño Southern Oscillation, whose positive phase is associated with increased occurrence in the Eastern Pacific and in the Indian Ocean by a factor of up to 3. Our results provide a first understanding of where, when and why compound MHW and LChl events might occur. Further studies are needed to pin down the exact physical and biological drivers of these potentially strongly harmful events in the ocean.

110 Simona Meiler

Sub-hazard risk assessment of tropical cyclone damage in CLIMADA

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So far, tropical cyclone (TC) risk assessment methods primarily consider wind as the driving physical hazard for the resulting socio-economic impact. However, as most high-impact events, TC damages emerge from multiple drivers and factors acting together (wind, storm surge, and rain/flood) on various temporal and spatial scales. Therefore, traditional risk assessment methods are likely to underestimate the possible impact. We thus aim towards a consistent, fully integrated sub-hazard risk assessment of TC damage now and in the future. Using a state-of-the-art probabilistic damage model (CLIMADA) allows us to estimate the expected economic damage as a measure of risk today, the increment from economic growth, and the further aggravation due to climate change. However, at its current status, CLIMADA only permits to analyze multiple hazards successively and independently. Our goal is to explicitly account for wind (Aznar-Siguan et al., 2019), storm surges (Vogt et al., in preparation), and freshwater flooding from hurricane precipitation (e.g., adapted from Feldmann et al., 2019) and combine these sub-hazards. We will present a coupled modeling approach and address some of the methodological challenges we face.

111 Manuela I. Brunner

Compound influences of hydro-meteorological drivers on streamflow drought spatial extent

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Droughts can have particularly severe impacts and seriously challenge water management if they are spatially compounding and have large spatial extents. These extents may change in a warming climate along with changes in underlying hydro-meteorological drivers. Therefore, we ask (1) how streamflow drought spatial extent has changed over the period 1981-2018 in the United States, (2) which physical drivers govern drought spatial extent, and (3) whether/how the importance of these drivers has changed over time. We analyze temporal changes in streamflow drought extents and their drivers using drought events extracted for 671 catchments in the conterminous United States using a variable threshold-level approach. Drought spatial extents are determined as the percentage of catchments affected by drought during a certain month. Then, important drivers are identified by determining the spatial percentage overlap of the area under streamflow drought with precipitation droughts, temperature anomalies, snow-water-equivalent deficits, and soil moisture deficits. Finally, the spatial extent and overlap time series are used in a trend analysis to determine changes in drought spatial extent and to identify changes in the importance of different variables as drivers of drought spatial extent. Our analyses show that (1) drought spatial extents have increased, mainly because of increases in the extent of small droughts; (2) drought extents overall substantially overlap with soil moisture deficits and the relationship of drought to precipitation and temperature varies seasonally; (3) the importance of temperature as a driver of drought extent has increased over time. We therefore conclude that continued global warming may further increase the probability of spatially compounding drought events, which requires adaptation of regional drought management strategies.

112 Elisabeth Tschumi

The effect of differing drought-heat signatures on terrestrial carbon dynamics and vegetation composition

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Droughts and heatwaves have large impacts on the terrestrial carbon cycle. They lead to reductions in gross and net carbon uptake or anomalous carbon emissions by the vegetation to the atmosphere because of responses such as stomatal closure, hydraulic failure and vegetation mortality. The impacts are particularly strong when drought and heat occur at the same time. Climate model simulations diverge in their occurrence frequency of compound hot and dry events, and so far it is unclear how these differences affect carbon dynamics. Furthermore, it is unknown whether a higher frequency of droughts and heatwaves leads to long-term changes in carbon dynamics, and how such an increase might affect vegetation composition.

To study the immediate and long-term effects of varying signatures of droughts and heatwaves on carbon dynamics and vegetation composition, we employ the state-of-the-art dynamic global vegetation model LPX-Bern (v1.4) under different drought-heat scenarios. We constructed six 100-yr long scenarios with different drought-heat signatures: a “control”, “no extremes”, “no compound extremes”, “drought only”, “heat only”, and “compound drought and heat” scenario. This was done by sampling daily climate variables from a 2000-year stationary simulation of a General Circulation Model (EC-Earth) for present-day climate conditions. Such a sampling ensures physically-consistent co-variability between climate variables in the climate forcing.

The scenarios differ little in their mean climate conditions (global mean land temperature differences of around 0.3°C and global mean land precipitation differences smaller than 7%), but vary strongly in the occurrence frequency of extremes such as droughts, heatwaves, and compound drought and heatwaves (up to five times more compound extremes in the “hotdry “scenario than in the “control”), allowing us to study the effects of the extremes on vegetation. Combined hot and dry extremes reduce all tree types and promotes grassland, while only hot extremes favours trees, especially in higher latitudes. No extremes are preferred by all tree types in LPX. Our results provide a better understanding of the links between hot and dry conditions and vegetation dynamics as well as carbon dynamics. These analyses may help to reduce uncertainties in carbon cycle projections, which is important for constraining carbon cycle-climate feedbacks. The presented scenarios can be used for a variety of purposes such as studying the effects of differing drought-heat signatures on crop yield or the occurrence of fire besides others.

113 Poulomi Ganguli

Impact of Sea Level Rise on Projected Changes in Compound Flood Hazard

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Compound floods resulting from co-occurrence or successive occurrence of high coastal water levels and peak river discharges may lead to significant impacts due to simultaneous inundation from interacting drivers. In a changing climate, the extreme river discharges together with storm surges and Relative Sea Level Rise (RSLR, the combination of land subsidence and offshore sea-level rise) are expected to amplify the risk of flooding in low-lying delta areas. Quantifying compound flood hazard under climate change is challenging, given the cascade of uncertainty across multiple modeling components, such as model structural differences (emerges due to incomplete understanding of model physics) and relative roles of internal variability (owing to inherent variabilities of the earth-system models). Here we investigate future changes in compound floods driven by extreme storm surges, RSLR, and peak fluvial discharges in an ensemble of high-resolution regional climate model experiments participating in the EURO-CORDEX initiative. We identify compound floods when hourly high coastal water level coincides with d-day lagged peak fluvial discharge within ±7 days of the event; implying a lagged responses, because two events do not necessarily tend to occur on the same day to enhance their impacts. In the present-day (1981-2005) climate, we find a spatially coherent strong positive upper tail dependence between surge and peak discharge along the western coast (for example, western coast of the United Kingdom and Germany), whereas weakly negative to insignificant positive dependence clustered across southeast England both in observations and climate model simulations. However, models tend to overestimate the dependence strength. In the projected climate, overall, we find a weakening in the strength of dependence over most of the sites resulting in a decrease in compound flood hazard, by solely considering extreme surge and fluvial discharge as drivers of compound floods. However, with the inclusion of RSLR, compound floods are projected to be more frequent. While models' simulation of present-day climate suggest attribution of observed dependence to anthropogenic forcings remain uncertain, we show that under RSLR, the 21st-century anthropogenic warming could amplify the compound flood hazard at ~23% low-elevated deltas by a factor of 1.13 – 2.20, potentially increasing the risk of inundation-related flood damages.

114 Rene Orth

Contrasting biophysical and societal impacts of weather extremes

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Extreme weather can severely affect ecosystems, economy, and consequently society. These impacts are expected to be aggravated by climate change. Here we analyze and compare the impacts of multiple types of extreme events across several domains in Europe, to reveal corresponding impact signatures. We characterize the distinct impacts of droughts, floods, heat waves, frosts and storms on a variety of biophysical and societal variables. We find strong biophysical impacts of droughts, heat waves and frosts, while society is more affected by storms and floods. We show unexpected impact patterns such as reduced human mortality during floods and storms, and interpret these via indirect effects. Our approach also includes an analysis of Google search interests. Respective attention on heat waves and even more for droughts is surprisingly low despite the significant overall impacts. Resolving these impact patterns enables more focused extreme event management and vulnerability analyses, consequently reducing disaster risks.

115 Kirien Whan

Multivariate ensemble post-processing to improve the dependence structure in medium-range forecasts

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Statistical post-processing is an indispensable tool for providing accurate weatherforecasts and early warnings for weather extremes. Most statistical post-processingis univariate, with dependencies introduced via use of an empirical copula. Standard empirical methods take a dependence template from either the raw ensemble output (ensemble copula coupling, ECC) or the observations (Schaake Shuffle, SSh). There are drawbacks to both methods. In ECC it is assumed that the raw ensemble simulates the dependence well, which is not always the case (e.g. 2-meter temperature in The Netherlands). The Schaake Shuffle is notable to capture flow dependent changes to the dependence and the choice ofobservations is key.
Here we compare a re-shuffled standard ensemble model output statistics (EMOS) approach with two multivariate bias adjustment approaches that have not been used before in a post-processing context: 1) the multivariate bias correction with N-dimensional probability density function transform (MBCn) and 2) multivariate ranks that are defined with optimal assignment (OA). These methods have the advantage that they are able to explicitly capture the dependence structure that is present in the observations.
We apply ECC, the Schaake Shuffle, MBCn and OA to 2-meter and dew point temperature forecasts at seven stations in The Netherlands. Forecasts are verified with both univariate and multivariate methods, and using a heat index derived from both variables, the wet-bulb globe temperature (WBGT).
Our results demonstrate that the spatial and inter-variable dependence structure is more realistic in MBCn and OA compared to ECC or the Schaake Shuffle.The variogram score shows that while ECC is most skilful for the first two days, at moderate lead times MBCn is most skilful and at the longest lead times OAis more skilful than both ECC and MBCn. Overall, we highlight the importance of considering the dependence between variables and locations in the statistical post-processing of weather forecasts.

116 Claudia Di Napoli

Forecasting concurrent wildfire and heat stress risk: the role of mapping in improving evidence-based decision making

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Heat and forest fires are considered highly correlated hazards in summertime with extreme temperatures playing a key role in driving their occurrences. This commonality may influence how first responders deploy resources on the ground and could lead to an underestimation of potential impacts, as people could be less resilient when exposed to multiple hazards. In this presentation a methodology to identify areas prone to two concurrent hazards – heat stress and fire danger – will be illustrated. The combined heat and forest fire event that affected Europe in June 2017 will be described as a case study of how the methodology can be used for analysing past events as well as making predictions by using reanalysis and medium-range weather forecasts, respectively. Spatial layers mapping the combined danger will be shown and suggestions on how these could be used in the context of a multi-hazard early warning system will be presented. Finally, the role of mapping products as valuable tools in disaster risk reduction and emergency response management will be discussed particularly within the context of civil protection, humanitarian agencies and other first responders whose role is to identify priorities during pre-interventions and emergencies.

117 Ondřej Lhotka

Capability of CORDEX regional climate models to simulate precipitation-temperature regimes and droughts over Europe

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Drought and excessively high temperatures are considered among the natural hazards with serious impacts on society and environment. The impacts tend to be larger when dryness and heat combine, resulting in a compound event associated with negative effects, among others, on food production, ecosystems, water resources and electricity production. Although climate models agree on continuous temperature increase during the 21st century, projections of drought frequency and magnitude are accompanied by uncertainties. These uncertainties arise mainly due to a limited physical understanding of spatial and temporal interactions between precipitation and evapotranspiration, i.e. the main driving mechanisms of drought. In this study, we analyse regional patterns of links between precipitation and temperature over Europe, using the E-OBS 21.0e dataset in the 1950–2019 period. Correlations between monthly Standardised Precipitation Index (SPI) and monthly temperature anomalies are studied, and seasonal changes of the correlation patterns are identified. Positive correlations (wet and warm or dry and cold) prevail during winter over most of Europe, while negative values (dry and warm or wet and cold) are dominant in summer, supporting drought development. In the next step, analogous analyses are performed for regional climate models (RCMs) from the EURO-CORDEX project. We evaluate the RCMs' capability to reproduce observed regional patterns of correlations between SPI and temperature anomalies and their seasonal changes. The role of RCMs' spatial resolution and driving data is also studied. A better insight into RCMs' capability to simulate relationships between precipitation and temperature is crucial for interpreting future drought scenarios and may ultimately lead to more precise projections of future droughts.

118 Corey Lesk

The hidden signature of temperature-moisture couplings in the heat sensitivity of global crops

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Rising air temperatures are a leading risk to global crop production and food security under climate change. Recent research has emphasized the critical role of moisture availability in regulating crop responses to heat and the importance of temperature-moisture couplings in the genesis of concurrent hot and dry conditions. In this work, we demonstrate that the heat sensitivity of key global crops is itself dependent on the local strength of couplings between temperature and moisture in the atmospheric circulation and at the land-atmosphere interface. Over 1970-2013, maize and soy yields declined more during hotter growing seasons where decreased precipitation and evapotranspiration more strongly accompanied higher temperatures. Based on this historical pattern and a suite of climate model projections, we show that changes in temperature-moisture couplings in response to warming could enhance the heat sensitivity of these crops as temperatures rise, worsening the impact of warming by ~5% on global average. However, these changes will benefit crops in some areas, and are highly uncertain in others. Our results demonstrate that climate change will impact crops not only through warming, but also through changes in temperature-moisture couplings, which may alter the sensitivity of crop yields to heat as warming proceeds. Robust adaptation of cropping systems will need to consider this underappreciated risk to food production from climate change.

119 Syed Mubashshir Ali

Recurrent Rossby waves and persistent surface weather

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Synoptic-scale Rossby wave packets are well-known to affect surface weather as well as surface extremes. The persistence of surface weather conditions (e.g., warm or cold temperatures, precipitation) amplifies their impact on society. Rossby waves are sometimes organised in a recurrent pattern which is termed as "recurrent Rossby wave pattern" (RRWP). RRWPs arise when multiple transient synoptic-scale wave packets amplify in the same geographical region in a short period.
Previously, mostly stationary flow is considered as an important driver of persistent surface weather. Here, we demonstrate the importance of RRWPs, which is a non-stationary mechanism for modulating persistent weather. The analysis uses ERA-interim reanalysis data for 1980-2016. We find that RRWPs are associated with both longer-lasting hot, cold, dry and wet spells but also a more frequent interruption of spells in both the Northern and the Southern Hemispheres. Distinct latitudinal patterns where RRWPs significantly extend or shorten spells are present in the Southern Hemisphere. In the Northern Hemisphere, wave-like patterns of significant spell extension and shortening exist. Heuristic arguments based on the processes that lead to hot, cold, dry and wet conditions are made to explain these spatial patterns. Our results demonstrate that RRWPs can lead to persistent high-impact surface weather through recurrence; RRWPs should be considered as an important feature for understanding and predicting sub-seasonal weather patterns.

Wind and Rain, the Impact of Tropical Cyclones on the Economy - A Copula Approach

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This study investigates the compound impact of extreme windspeed and heavy rainfall on economic activity during tropical cyclones (TCs) in the Caribbean. For that reason, physical wind speed model and remote sensing precipitation data are linked to small scale changes in economic activity during the passage of TCs. The nature of compound effects is investigated in a empirical copula framework. Specifically, non-parametric estimation of bivariate copulas between windspeed and rainfall flexibly models the dependence structure between the two variables. Asymmetric tail-dependence and regional variation is explored. In a second step, the compound effect on economic activity is estimated via parametric copula regression. Compared to regular regression, this approach inherently models interdependence within dependent variables. As such, the compound damage effect of wind speed and rainfall during TCs is quantified.

121 Halina Kowalewska-Kalkowska

Assessment of effects of river discharge and ice phenomena on the storm surge propagation in the Odra River Estuary (the southern Baltic Sea) using multivariate methods of data analysis

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The tideless Odra River Estuary (the southern Baltic Sea) is particularly exposed to storm surges associated with low-pressure systems moving over the Baltic Sea. The resultant water backflow in the lower Odra branches may penetrate high up the river, leading in some cases to flooding of low-lying areas within the estuary. In the study multivariate exploratory methods of data analysis were applied to assess the effects of the amount of river discharge and the formation of ice phenomena on the storm surge propagation within the Odra Estuary. The analyses involved hourly water level readings collected at 10 gauges located at the coasts of the Szczecin Lagoon and the Pomeranian Bay as well as in the downstream Odra reach in the stormy seasons from 2008/09 to 2019/20. The data series used for calculations in this study were provided by the Institute of Meteorology and Water Management, National Research Institute, Poland. Methods used in this research were found to be helpful in offering reliable information on effects of river discharge and ice phenomena on the storm surge propagation in the Odra Estuary. The cluster analysis allowed to identify natural clustering patterns based on similarities/ dissimilarities between data series. In the analysis, the Ward's method and the one-minus Pearson correlation coefficient distance were employed. The factor analysis enabled to detect and describe structure in the relationships between data sets. The factors were extracted using principal component analysis and the varimax rotation method. Finally multidimensional scaling facilitated the detection of meaningful underlying dimensions and the visualization of similarities/ dissimilarities between the water level data series. The study revealed that in case of the increased water supply from the Odra River catchment and/or the formation of ice phenomena on the lower Odra channels, the extent of storm surges was often limited only to the Szczecin Water Area (c. 65 km south from the sea). The storm surge impact increased with the decrease of the Odra discharge, and during low water periods it was noticeable as far up the river as to 130 km south from the sea.

Investigating the relationship between droughts and extreme rainfall events

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Research on compound extremes often focusses on well-known combinations of hazards or drivers such as droughts and heatwaves or flooding from storm surge and heavy rainfall. However, some hazards may be less obviously connected to each other but still have a significant impact. An example of this could be observed during the 2019/2020 Australian fire season. After months of droughts and fire, the rainfall that brought relief also caused major flooding in some locations.
Although the common perception is that these kinds of rapid transitions from droughts to floods happen frequently, there is only limited research on if and to what extent such a connection exists between these two extremes. In order to investigate this relationship, we study long Australian precipitation records in daily and sub-daily resolution. This approach allows us to analyse frequency, intensity, duration and timing of rainfall extremes causing flooding during droughts and their terminations on different spatial and temporal scales. Both droughts and extreme rainfall events pose great challenges for many sectors including water resource management and agriculture, especially if they occur as a temporally compounding hazard. Understanding how and to what degree these events co-occur could help mitigate the impacts caused by them.

123 Zengchao Hao

A comparison of prediction methods for compound dry-hot events

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Prediction of compound dry and hot events, which may cause far larger impacts than isolated dry or hot events, would provide useful information for early warning of these events. However, the development of prediction methods of compound events is still in its infancy. The aim of this study is to compare different prediction methods of compound dry and hot events in Northeast China. First, different properties (e.g., occurrence, severity) of compound dry and hot events are illustrated to show the quantity of interest in characterizing compound events. Second, potential driving factors of compound dry and hot events (e.g., North Atlantic Oscillation, NAO) are evaluated to determine suitable predictors. Finally, different methods are then employed for predicting these properties. Results from this study could provide useful insights for predicting compound dry-hot events and developing early warning systems.

Foehn in Sofia: climatology and circulation type classification 1979-2014

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Foehn is a well-known example of local atmospheric circulation and in addition it is an extreme weather event with warm and dry wind blowing on the leeward side of the mountains triggering snowmelt in spring or spread of forest fires in summer and resulting in large economic losses. The foehn in Bulgaria is observed on the northern slopes of the mountains, as a result of warm air advection from the south and southwest associated with approaching cyclones. Foehn occurrence is highest north of the Vitosha mountain where the Bulgarian capital Sofia is located. A study for the period 1979 - 2014, identified 261 days with foehn in Sofia. The average annual number of foehn days is 8.1, 8.3 and 4.5 for 1985-1994, 1995-2004 and 2005-2014, respectively. After 2004, a decrease of the average annual number of days with foehn is found and the lowest maximum wind gust is registered. Two automated circulation classifications types namely GrossWetterTypen (GWT) and Jenkinson-Collinson Type (JCT) are computed based on ERA5 reanalysis of mean sea level pressure and 850 hPa geopotential height for Southeast Europe. The most common circulation type for foehn in Sofia is found to be due to approaching cold front associated with a cyclone passing over Central Europe. The decrease in average annual number of foehn days from 8.3 in 1995-2004 to 4.5 in 2005-2014 is found to be due to the decreasing number of the cyclonic circulation types: 1) passing over Central Europe as well as 2) Mediteranean cyclones with trajectory over Hungary. The goal of this work is to facilitate foehn analysis and operational forecasting in Bulgaria.

125 Andreia Filipa Silva Ribeiro

Estimating agricultural impacts of compound dry and hot extremes using nested copulas

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Within the context of climate change, agricultural systems are expected to be increasingly affected by co-occurring drought and hot conditions, which can cause larger damages than the individual hazards alone.
In this work we propose to estimate, based on nested copulas, the conditional probabilities of crop loss under different dry and hot severity levels based on their trivariate joint distribution. In order to accomplish that, we use annual wheat and barley yield data over two province regions in Spain during 1986-2016, and model the trivariate dependence between spring maximum temperature, spring precipitation and crop yields. First, we estimate the impact of compound dry and hot conditions on crop loss and secondly, we estimate the additional impact due to compound hazards compared to the individual drought or hot conditions. In general, we found that the agricultural impacts aggravate during concurrent dry and hot conditions, when compared with the crop loss induced by the individual hazards. The results suggest that drought plays the dominant role in the compound event, as drought stress does not require to be so extreme as heat stress to cause a similar damage. Moreover, the probability of crop loss increases with the severity of the compound event in both regions and cereals. Finally, we found that barley in the southern region is the more susceptible crop to the interacting effects between drought and heat. These findings suggest that Spanish crop production would beneficiate of lower crop losses if it could be more focused on wheat.
Our results highlight the additional value of this methodology for estimating the agricultural risks caused by compounding effects of dry and hot extremes, for ultimately contribute to design management options and guide the decision-making process in agricultural practices.

126 Johannes Vogel

Assessment of ecosystem vulnerability under climatic extreme events in the Mediterranean

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The study analyses extreme ecosystem responses evoked by climatic drivers in the Mediterranean. A analyis of ecosystem vulnerability is performed to quantify which combinations of drivers – namely temperature and soil moisture – leads to extreme reductions in the fraction of absorbed photosynthetically active radiation (fAPAR). Ecosystem vulnerability is the difference of the climatic variable in time spans of extreme ecosystem conditions to the respective values during normal conditions. We investigate how the vulnerability differs seasonally between various land covers and subregions. Temperature, soil moisture and fAPAR data are obtained from ERA5 Land, ESA CCI and Copernicus Global Land Service. Our findings show, that low fAPAR values are often related to cold and dry conditions in spring and autumn, whereas they are often associated with hot and dry conditions in summer and wet conditions in winter, respectively. Particularly, vulnerability in croplands expresses a strong seasonally distinct pattern altering between energy-limited and soil-moisture limited conditions. Our approach allows identifying particularly sensitive areas in the Mediterranean, which can potentially serve to undertake adaptation measures at a regional scale.

127 Eva Plavcová

Intensified Impacts on Mortality Due to Compound Winter Extremes in the Czech Republic

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Background: Although impacts of extremely cold temperatures on human health have been widely studied, adverse effects of other extreme weather phenomena have so far received much less attention.
Objectives: We employed a high-quality long-term mortality time series (1982–2017) to evaluate impacts of extreme winter weather in the Czech Republic. We aimed to clarify whether compound events of extreme weather cause larger impacts on mortality than do each type of extreme if evaluated individually.
Methods: Using daily data from the E-OBS and ERA5 datasets, we analyzed 9 types of extreme events: extreme wind gust, precipitation, snowfall, and sudden temperature and pressure changes. Relative mortality deviations from the adjusted baseline were used to estimate the immediate effect of the selected extreme events on excess mortality. The impact was adjusted for the effect of extreme cold.
Results: Extreme events associated with sudden warming of minimum temperature (Tmin) and pressure drops had generally significant impact on excess mortality (3.7% and 1.4% increase). The impacts were even more pronounced if these events occurred simultaneously or were compounded with other types of extremes, such as heavy precipitation, snowfall, maximum temperature warming, and their combinations (increase as great as 14.4%). Effects of some compound events were significant even for combinations of extremes having no significant impact on mortality when evaluated separately. On the other hand, a “protective” effect of pressure increases reduced the risk for its compound events. Meteorological patterns during extreme events linked to excess mortality indicate passage of a low-pressure system northerly from the study domain.
Discussion: We identified extreme winter weather events other than cold temperatures with significant impact on excess mortality. Our results suggest that occurrence of compound extreme events strengthen the impacts on mortality and therefore analysis of multiple meteorological parameters is a useful approach in defining adverse weather conditions.

Investigation of common drivers behind co-occurring terrestrial and marine heatwaves

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Despite numerous studies that have examined terrestrial or marine heatwaves independently, little work has been done investigating any association between the two. There is a notion that co-occurring terrestrial and marine heatwaves may have common drivers, or may influence each other via other links. For example, a recent study (Rodrigues et al., 2019) identified common drivers behind the major marine heatwave that developed in South Atlantic during the summer of 2013/14 and high heat events over South America. Co-occurring events could also potentially interact with each other, thereby altering the characteristics of the events. This study will explore possible links between adjacent coastal marine and terrestrial heatwaves. We will investigate the likelihood of co-occurrence of terrestrial and marine heatwaves, using statistical analysis of observational temperature data. We will also investigate the mechanisms driving co-occurring events, including the local fluxes, synoptic conditions, and links to large scales modes of climate variability. Preliminary results will be presented.

129 Ana Bastos

Increased vulnerability of European ecosystems to prolonged drought in 2018/19

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Extreme summer temperatures in western and central Europe have become more frequent and heatwaves more prolonged over the past decades. The drought and heat that affected central and northern Europe in summer 2018 (DH2018) was one of the strongest events in the first two decades of the 21st century, comparable in magnitude and extent to the extreme summers of 2003 and 2010. In central Europe, below- or close to average rainfall and warm temperatures persisted during the subsequent seasons, thereby prolonging the drought conditions throughout 2019.
Although forests can regulate water-use during droughts, access water deeper in the ground and make use of carbon reserves, this might not be enough to support trees under prolonged drought such as the case of 2018/19. Crops, on the other hand, are more susceptible to droughts than trees, but farmers might be able to respond to a long-lasting drought by changing cultures or adapting management practices, e.g. irrigation or early harvesting.
Using Enhanced Vegetation Index (EVI) from MODIS, we evaluate how ecosystems in the drought-affected region in central and eastern Europe responded to the occurrence of two consecutive dry summers. We find that only ca. 21% of the area negatively impacted by drought in summer 2018 fully recovered in 2019 and that 18% of the area showed a worsening of plant status during summer 2019. For those pixels. We find that the strongest EVI anomalies in 2018/19 diverge from the long-term relationships between EVI and climate, which suggests increased vulnerability of ecosystems to heat and drought events or potential degradation trajectories. We evaluate whether this divergence is related with climate (supporting increased vulnerability to drought) or by other factors (indication a potential role of other processes such as ecosystem degradation from increased mortality or disturbances). Finally, we compare results with simulations from land-surface models and show that they are not able to capture the increased vulnerability/degradation patterns from the remote-sensing signal.

Critical infrastructures risk - a spatially explicit connected events perspective on crucial networks

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Critical infrastructures (CIs)– such as transportation, water and energy services - are essential for upholding a society's daily functioning, are crucial during response and recovery following (natural hazard-induced) emergency situations, and may exacerbate adverse impacts in case of failure. Yet, risk from disruption of CIs is mostly anecdotal, limited to non-systemic, single-hazard or locally constrained scopes.

Representing CIs as spatially explicit networks hence provides an interesting lens for thinking about multi-hazard risks under a connected events paradigm:

The scale of such infrastructures naturally provides a larger catchment area for (natural) hazards, such that spatially disjoint events can affect the same system.

The inherent network character of such infrastructure types may lead to the propagation of risk beyond immediately affected components and beyond initial time-scales, adding further temporal and spatial dependence between events.

This network character may equally introduce absorptive capacity, reducing the overall risk compared to an independent additive view on events. Together, these characteristics may have important, even opposing, effects on the long tail of modelled natural catastrophe impacts.

This poster contribution motivates the benefits of taking on a connected events and network perspective when studying multi-hazard risks to critical infrastructures by

Þ providing an overview on research gaps and shortcomings of traditional "static" methods, recent developments, methodological & data-related challenges.

Þ outlining how the combination of a spatially explicit, probabilistic natural catastrophe impact platform (CLIMADA) with a network model may provide a more comprehensive view on the issue.

Based on this input, I ask for critical feedback from attendees on the project's ideas, scope and feasibility.

131 Torsten Weber

Identifying and quantifying population exposure to future compound climate extremes in Africa

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Africa is exposed to various climate extremes such as heat waves, droughts and intense rainfall events, whose frequency, duration and intensity may increase in a changing climate. Africa is already vulnerable to individual climate extremes, which cause significant socio-economic damage. When two or more climate extremes co-occur (compound climate events) then the socio-economic damage will likely be even greater. Currently, little is known about the exposure of the African population to future compound climate events. This study provides the first analysis of how the African population may be exposed to such events at the end of this century. For this analysis, we use the ERA5 reanalysis data set and an ensemble of the newly available regional climate projections from the CORDEX-CORE data set to calculate the frequency and duration of compound climate events. We analyze the projected changes in the co-occurrence of five such compound climate events in Africa, under a low (RCP2.6) and high (RCP8.5) emissions scenario. These changes are combined with population projections for a correspondingly low (SSP1) and high (SSP3) population growth scenario to estimate the population exposure to such events at the end of the century. We provide a regional analysis of population exposed to the five compound events, where we investigate the questions: which regions are most exposed to such events at the end of the century, and which compound events are associated with the largest changes in exposed population. We also provide an analysis of the relative importance of the drivers of change in the exposed population.

132 Freya Garry

Assessing current and future risk of compound events using UK agricultural case studies

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Assessments of current and future climate risk are required for adaptation planning to increase resilience and enable society to cope with future climate hazards. We identify case studies of compound hazard events of interest to the UK agricultural sector that span different types of compound events. We compare the frequency and duration of compound events now to those projected in 50 years' time, and combine hazard, vulnerability and exposure information to generate estimates of current and future climate risk that can be used for preparedness and adaptation. We demonstrate use of different products from the UK Climate Projections, which includes a 12-member perturbed parameter ensemble 12 km resolution regional model that extends across Europe. We are developing a code base for analysing compound events, which will eventually be made open source. To demonstrate the use of our code base, we use daily temperature and humidity bias corrected data to provide assessments of current and future risk for thermal heat stress for livestock and potato blight conditions over the UK. Risk of dairy cattle thermal heat stress is projected to increase by over 1000 % in the south west of the UK, whilst potato blight occurrences may increase by up to 70 %. We also consider UK average consecutive seasonal changes, such as those in 2018, where a cold spring followed by a warm/dry summer resulted in hay/silage shortages. In addition to reduced crop yields, cattle were kept inside for longer in the cold spring and due to thermal heat stress and poor grass quality in the summer. Large (3000 member) probabilistic ensembles from the UK Climate Projections indicate that the probabilities of cold spring/warm summer conditions will decrease in future, but the probabilities of longer dry/warm summers will increase. We conclude that the agricultural sector should consider suitable climate adaptation measures to minimise the risk of dairy cattle thermal heat stress, increased potato blight, and longer dry/warm summer conditions.

133 Alois M. Tilloy

Assessment of the Multi-hazard Landscape of Western Europe with hazard interrelation networks

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Globally and yearly, natural hazard interrelations have the potential to result in socio-economic losses. In that context, understanding potential drivers and processes leading to hazard interrelations is of prior interest. This piece of work aims to go beyond the study of pairs of hazards and to examine the multi-hazard landscape of the European Atlantic Region (EAR). 16 natural hazards were selected to characterize the multi-hazard landscape of the EAR. These 16 natural hazards are grouped based on physical drivers (e.g., meteorological, geophysical) and prior knowledge on interrelations between hazards to create five multi-hazard networks: Ground movements, convective storms, extratropical cyclones, compound dry hazards and compound cold hazards. A multi-hazard network is composed of a set of interrelated hazards occurring in given space-time frame. A catalogue of 50 events (10 per network) is constructed to illustrate the approach. This catalogue also aims to bring together different sources and databases of single hazard events. Evidences used to build the catalogue comes from a range of sources of the following types: (i) Single hazards catalogues (e.g., BGS Tsunami, SurgeWatch); (ii) Catalogue of reported hydrometeorological events (e.g., Met Office, Infoclimat); (iii) Disaster databases (e.g., EM-DAT); (iv) Peer review articles. Based on this catalogue, the spatial and temporal scales of each of the five multi-hazard networks is assessed. The prevalence of each hazard and hazard interrelation in each network is discussed. The development of multi-hazard networks allows to focus on restricted number of hazard interrelations and links interrelations to physical processes and drivers. It also provides a clear view on existing multi-hazard interrelations in the EAR.

134 Kai Kornhuber

Cold season Rossby Wave Regimes and associated surface patterns of concurrent and compound hot, cold, wet and dry extremes.

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Zonal asymmetries in the stationary thermal and orographic structure of the earth's surface give rise to the existence of preferred modes in the large-scale atmospheric circulation of the mid-latitudes. Such flow patterns are characterised by amplified Rossby Waves of certain wavenumbers with a preferred longitudinal phase. Being recurrent in space and of sufficient persistence they meet the classic definition of weather regimes, while their hemispheric character promotes the concurrence of persistent anomalous weather conditions in specific mid-lat. locations (Kornhuber 2019), exploitable for the early prediction of extreme weather (Teng 2013).

While sub-seasonal Rossby Wave Regimes have been identified in the Northern hemisphere (NH) summer circulation (Kornhuber 2017, Kornhuber 2020), the NH wintertime circulation has been studied from a seasonal mean perspective, mostly, where it was suggested that such climatological waves have no single preferred position (e.g. Branstator 2002). In spite of their importance for setting the stage of the following season, Fall and Spring seasons have been omitted in most studies on the topic.

Here we provide evidence for the existence of specific hemispheric Rossby Wave Regimes throughout Fall, Winter and Spring on sub-seasonal time-scales. We show that these newly identified regimes are associated with specific patterns of concurrent and persistent compound hot, cold, wet and dry surface conditions across the mid-latitudes and provide examples of how they contributed to past high impact events such as (unseasonal) cold spells and heatwaves.

135 Alexandre M. Ramos

The role of a major drought and hurricane Ophelia winds in the destructive forest fires of October 2017 in Portugal

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Portugal is regularly affected by large and destructive wildfires leading to serious impacts at social, economic, and ecological levels. The 2017 fire season was particularly conspicuous, with a record total burned area of about 540 000 hectares, representing nearly 60 percent of the total area burnt in the entire EU in 2017. The two most tragic events occurred between 17-20 June and 15-17 October, i.e. outside the “official fire” season in Portugal that spans between July and September, with a tragic toll of 113 fatalities. About 280.000 ha, i.e roughly half of the total burned area, were burned in the mid-October event, implying some of the highest hourly burn rates ever observed in the world (close to 10.000 ha per hour)

The event which started on October 15 was characterized by unseasonable high temperature anomalies and very low relative humidity values in a large part of central and northern Portugal. However, besides the unusual warm and dry conditions there were other drivers that played a role in the outstanding spread of fires during this event.

The preconditioning record-breaking drought, as observed when using the Standardized Precipitation-Evapotranspiration Index (SPEI), that had been affecting western and central Europe since July 2016 was one of the significant drivers that contributed to this outcome. This is clearly reflected when analyzing the Normalized Difference Vegetation Index (NDVI), where extremely low values are found for Portugal in mid-October, revealing that the vegetation was under significant water stress.

Strong winds also occurred on October 15, associated with the unusual nearby passage of hurricane Ophelia. This storm was centered 500 km off the coast of Portugal and moving northeastward at that date. This unusual location fostered very intense warm advection, yet, at the same time, not being close enough to provide relieving precipitation or moisture which would have minimized fire risk.

In summary, we show how the very dry and stressed vegetation due to the extreme drought situation by mid-October, along with strong and persistent southerly winds associated with a peculiar synoptic setup driven by the presence of hurricane Ophelia, were the main ingredients for this tragic compound event.

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Concurrent dry and hot events during the Indian summer monsoon and its linkages to ENSO

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Concurrent dry and hot events (CDHE) pose severe impacts on society and ecosystems worldwide. Indeed, individual extremes have been studied comprehensively; the knowledge on the emerging concurrent extremes is limited owing to the complexity involved. Besides, due to global warming, the frequency and spatial extent of CDHE are increasing, leading to teleconnection to dominant modes of climate variability. Therefore, there is an emergent need to quantify the effect of dominant modes of climate variability on the spatial extent of CDHE. The present study investigates the changes in frequency and spatial extent of CDHE over the Indian mainland during the summer monsoon (JJAS) from the period 1951 to 2019. We employed wavelet coherence analysis to detect significant oscillation periods between the El Nino-Southern Oscillation (ENSO) phenomenon and the spatial extent of CDHE. Our results revealed an increase in the frequency of CDHE from 1985 to 2019 relative to the time window 1951-1984 in July, August and September. The temporal changes in the spatial extent of CDHE showed a significant increasing trend during July, August and September, at a rate of 450 km2, 700 km2 and 610 km2 per decade during July, August and September, respectively across India. Further, we notice that the ENSO phenomenon had a statistically significant in-phase relationship with the spatial extent of CDHE at inter-annual scale (2-8 years). The preliminary results from the present study are useful for further exploration and provide new insights into emerging changes in CDHE during recent decades.

137 Edoardo Vignotto

Towards dynamical adjustment of the full temperature distribution

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Internal variability due to atmospheric circulation can dominate the thermodynamical signal present in the climate system for small spatial or short temporal scales, thus fundamentally limiting the detectability of forced climate signals. Dynamical adjustment techniques aim to enhance the signal-to-noise ratio of trends in climate variables such as temperature by removing the influence of atmospheric circulation variability. Forced thermodynamical signals unrelated to circulation variability are then thought to remain in the residuals, allowing a more accurate quantification of changes even at the regional or decadal scale. The majority of these methods focus on climate variable's averages, thus discounting important distributional features. Here we propose a machine learning dynamical adjustment method for the full temperature distribution that recognizes the stochastic nature of the relationship between the dynamical and thermodynamical components. Furthermore, we illustrate how this method enables evaluating how specific events would have unfolded in a different, counterfactual climate from a few decades ago, thereby characterizing the emergent effect of climatic changes over decadal time scales. We apply our method to observational data over Europe and over the past 70 years.

Evaluating CMIP5 and CMIP6 climate models in their representation of long-duration, dry and hot events over Europe

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The propagation of drought from meteorological drought to soil moisture drought can be accelerated by high temperatures during dry periods. The occurrence of extremely long-duration dry periods in combination with extremely high temperatures may drive larger soil moisture deficits than either extreme occurring alone, and lead to severe impacts. Previous research has shown that a strong relationship exists between the duration of dry periods, defined as the consecutive number of days with precipitation < 1mm, and the maximum temperature within these periods. However, little attention has been given to the representation of the duration of such events in global climate models (GCMs) or the likelihood of long duration events co-occurring with extremely high temperatures. Adequate representation of such events in GCMs is important as it limits the confidence we may have in estimations of current and future risk of soil moisture drought derived from climate model ensembles. In this study, we assess the performance of GCMs in their representation of such events over Europe. Specifically, we asses an ensemble of CMIP5 and CMIP6 models. Initial results from CMIP5 show a systematic underestimation in the likelihood long duration dry periods, and a subsequent underestimation in the probability of long-duration, dry and hot events. These shortcomings may have further implications for the estimation of current and future risk of soil moisture drought from these models. Further analysis will look to shed light on the sources of this bias and if an improvement is found within the CMIP6 ensemble compared to CMIP5.

139 Alessio Ciullo

A downward counterfactual approach to assess the impact of climate events affecting the European Union's outermost regions on the financial stability of the European Union Solidarity Fund

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Climate risk analysis and assessment studies are typically conducted relying on historical data. These data, however, represent just one single realization of the past, which could have unfolded differently. As an example, Hurricane Irma might have struck South Florida at Category 4 and, had it done so, damages could have been as high as 150 billion, about three times higher than the damage estimated from the actual event. To explore the impacts of these potentially catastrophic near-misses, downward counter-factual risk analysis (Woo, Maynard and Seria, 2017) complements standard risk analysis by exploring alternative, plausible realization of past climatic events. As downward counter-factual risk analysis frames risk in an event-oriented manner, corresponding more closely to how people perceive risk, it is expected to increase climate risk awareness among people and policy makers (Shepherd et al., 2018).
We present a counter-factual climate risk analysis of tropical cyclones affecting the European Union's (EU) outermost regions. The goal is to estimate whether, and to what extent, consequences of climate events in such regions can hamper the availability of capital of the European Union Solidarity Fund (EUSF), a fund set by the EU to help members states coping with natural disasters. The analysis is conducted using the natcat modelling platform CLIMADA (Aznar-Siguan and Bresch, 2019). As counterfactuals, we use past forecasts of tropical cyclones tracks from the THORPEX Interactive Grand Global Ensemble (TIGGE) dataset.
Results show that the contribution of the outermost regions cannot alone compromise the availability of the EUSF. However, should a major event happen in mainland Europe, high-impact events affecting the outermost regions would compromise a full and prompt recovery of the fund. For example, counterfactuals are identified whose impact in the outermost regions would have hampered a recovery of the fund for two years after large pay-outs were made following the Italian earthquake of 2016. The adopted framework is general and can be applied to any model-based climate risk analysis problem.

Forest vitality-oriented weather analyses on time scales from days to years: case studies using NDVI forest information and ERA5 reanalyses

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Hot and dry conditions in central to northern Europe during summer 2018 had a strong impact on forest vitality. Early leaf senescence, secondary insect outbreaks, forest fires, and tree die-off were obvious indications of how extreme seasonal weather conditions can impair forests. Despite this seemingly direct causation, several interlinked disturbances as well as unknown ecological thresholds of complex forest ecosystems complicate our understanding of how weather and climate affect forest vitality. A well-established forest disturbance is drought, which can result from so-called compound extreme conditions, that is, from a lack of precipitation co-occurring with hot temperatures.
In addition to compound meteorological extremes (e.g., individual droughts), trees are susceptible to the long-term sequence of weather conditions, and potentially of extreme events, with cascading impact due to the sessile and long-lived nature of trees. Therefore, the time scale of potential meteorological forest disturbances ranges from days (windthrow) to years (accumulated water deficit) and the underlying meteorological processes differ greatly. On the one hand, a single cyclone can cause extensive windthrow within one day, as did storm Lothar in 1999. On the other hand, hot/dry summers in Europe often arise from stationary anticyclonic circulation patterns and land-atmosphere interactions, as e.g., in summers 2003 and 2018. In this project, we plan to investigate the relevant time scale(s) of meteorological forest disturbances and the involved weather systems. As a starting point, we consider forest disturbance events between February 2000 and present-day, identified from an anomalous vegetation greenness evolution measured by changes of the monthly normalized difference vegetation index (NDVI), observed by satellite. From ERA5 reanalysis data, we then explore meteorological conditions on various time scales prior to these events. One specific question addressed by our approach is whether temperature and/or precipitation anomalies are particularly intense during certain time periods before the events (e.g., a one-week heat wave, a multi-month accumulated precipitation deficit, or a combination thereof). The resulting knowledge will increase the physical understanding of atmospheric phenomena that are relevant for forest vitality. Furthermore, finding relevant weather systems motivates research on the change of their (compound/sequential) frequency and other characteristics with global warming, with direct implications for forest vitality.

141 Sven Kunze

The Global Long-term Effects of Storm Surge Damages on Human Settlements in Coastal Areas

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Do people relocate from storm surge prone areas? This paper analyses the influence of tropical cyclone damages on human population count in a spatial panel analysis from 1860 until 2015 at a global scale. To this end we hydrologically model global storm surges, as well as deploy an asymmetric wind field model to derive a damage index for tropical cyclones. We find evidence that population in affected areas falls due to both wind as well as storm surge damage. This effect is particularly large in low elevation coastal zones and developing countries.

An Assessment of Temperature and Precipitation Extremes related Compound events in Greece

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Greece's diverse topography, containing mountanous ranges, plains, and numerous islands leads to many different local climates. Also, this diversity may enhance the probability of extreme Temperatures or Precipitation, or the joint probability of these compound events. Our aim is to determine this joint probability of daily extremes happening on a monthly basis, in order to show its interannual change. Daily precipitation is divided in convective and non-convective precipitation by the ERA-Interim Reanalysis, and we examine for each type of precipitation and the total precipitation the joint probability of simultaneous occurence with extremely low or extremely high temperatures. Our analysis is based on gridded 5km spatial resolution data produced by in-house dynamical downscaling using the Advanced Weather Research and Forecasting numerical model (WRF-ARW) driven by the ERA-Interim Reanalysis for the time period 1980-2009.

143 Jérôme Kopp

Temporal Clustering of Heavy Precipitation

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Temporal clustering of extreme precipitation events on subseasonal time scales can cause large precipitation accumulations and lead to floods in rivers catchments. So far, no study has quantified the frequency of subseasonal clustering episodes nor their contribution to large subseasonal precipitation accumulations on a global scale. Moreover, little is known about the synoptic-scale dynamics (or precursors) responsible for the clustering of extreme precipitation. The goal of the present master thesis is to address those two research gaps using ERA5 precipitation data for 1979-2019, aggregated by catchment areas obtained from HydroBASINS. First, non-overlapping subseasonal clustering episodes are identified by using a novel algorithm.

Based on those non-overlapping episodes, two metrics are defined to assess the occurrence of subseasonal clustering episodes (S) and their contribution to large subseasonal precipitation accumulations (NS). A sensitivity analysis of the metrics is performed by varying the parameters used to define the extreme events. In a second part, two subseasonal clustering episodes happening in the Iberian Peninsula are selected to perform diagnostic studies. The potential role of Recurrent Rossby Wave Patterns (RRWPs) and blocking anticyclones in the subseasonal

clustering of extreme precipitation is investigated. Computation of the NS metrics for 6466 catchments reveals that subseasonal clustering episodes contribute substantially to 14- to 28-days precipitation accumulations for a majority of catchments. This result is robust to variations of the parameters, but any conclusion about individual catchments requires a closer investigation as some catchments exhibit large variations in NS. The diagnostic studies show that RRWPs, blocking anticyclones and the position of the midlatitude jet likely play a role in the subseasonal clustering of extreme precipitation events in the considered catchments.

144 Hilla Afargan-Gerstman

Stratospheric drivers for marine cold air outbreaks in the North Atlantic

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Marine cold air outbreaks (MCAOs) in the North Atlantic are compound events associated with a range of hazardous conditions, posing risks for marine activity and infrastructure. MCAOs can cause multiple correlated hazards, including cold temperature extremes, strong surface winds, and the occurrence of extreme cyclones known as polar lows in the Arctic. MCAO frequency has been linked to the strength of the stratospheric polar vortex. However, the dynamical connection between the stratospheric conditions, through associated weather patterns, and the occurrence of MCAOs remains unresolved. In this study, we examine the remote influence of extreme stratospheric events, known as sudden stratospheric warmings (SSWs), on MCAOs using reanalysis datasets.

Generally, SSW events are found to be associated with more frequent MCAOs in the Barents Sea and the Norwegian Sea compared to climatology, and less frequent MCAOs in the Labrador Sea. An anomalous dipole pattern of 500-hPa geopotential height, which consists of a ridge anomaly over Greenland and a trough anomaly over Scandinavia, is found to be a key element for increasing the likelihood of MCAOs in the Barents Sea and the Norwegian Sea. We show that changes in the large-scale tropospheric circulation patterns in the North Atlantic after SSW events contribute to the anomalous dipole pattern, and thereby affect the variability of MCAOs in this region, their frequency and magnitude. In contrast, a positive geopotential height anomaly over Greenland after SSW events is found to play a role in reducing the probability of MCAOs in the Labrador Sea. As SSW events tend to have a long-term influence on surface weather, these results could help improve the predictability of marine CAOs in the Nordic Seas for winters with SSW events.

145 Katarzyna Starosta

Wind analysis on the Polish Baltic coast in 2020

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Following the increased interest in renewable wind energy projects in Poland, the subject of our presentation are wind characteristics of the Polish coastal area of the Baltic Sea based on numerical weather forecasts of the COSMO (Consortium for Small-scale Modelling) model and observational data in 2020 year.

The Polish coastal areas are located in the extremely favorable zone with a wind energy potential above 1000 kWh / m2 / year, and even locally in the vicinity of Łeba above 1500 kWh / m2 / year (based on the calculations for the reference period 1971-2000, H. Lorenc, IMGW-PIB). Taking advantage of these natural conditions Poland plans recently to build an offshore wind farm in the Baltic Sea. Wind energy is strongly dependent on the meteorological conditions, thus an increasingly accurate wind forecasts are one of the necessary elements for assessing the local climatology at the wind farm site and further to provide warnings and decisive support to its operation. The Polish Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI) runs an operational model COSMO using two nested domains at horizontal resolutions of 7 km and 2.8 km. This model produces 36 hour and 78 hour forecasts four times per day for 2.8 km and 7 km domain resolutions respectively.

The distribution of wind speed and wind direction based on the COSMO model forecasts with resolution of 2.8km starting at 00UTC and their verification with 24 hour measurements are presented. We show hourly, daily, monthly and seasonal wind analyzes at five synoptic stations: Świnoujście, Kołobrzeg, Ustka, Łeba and Hel.

Disastrous Discretion - The Nonlinear Political Bias in U.S. Hurricane Relief

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Natural disasters require fast and effective aid, but relief allocation is vulnerable toward political influence. Little is known about when politicians use their discretion in order to pursue their political goals. We show the nonlinearity of political favoritism in an exogenous framework. Based on a simple theoretical model, we demonstrate that political biases are most pronounced when the necessity for relief provision is ambiguous. Exploiting the randomness of all hurricane strikes in the United States from 1965-2018, we find that presidents favor areas governed by their fellow party members when allocating disaster declarations. Our nonlinear estimations reveal that political influence varies immensely with respect to storm intensity. The alignment bias for medium-strength hurricanes exceeds standard linear estimates eightfold.

147 Daniela Domeisen

Remote forcing of extreme events

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Extreme temperature or precipitation events can be caused, triggered, or maintained by remote causes, in addition to local feedbacks. Many of these extremes are therefore related to preconditioned compound events. The remote forcing can itself be an extreme event, as is the case for extreme sea surface temperature anomalies driving heatwaves over land, or stratospheric warmings linked to cold air outbreaks over Europe and drought over Australia. Hence, it is important to understand extremes and their evolution, their potential remote causes, the pathways of communication between extremes, and their potential remote impacts. In particular, remote forcings can allow for increased long-range predictability of extremes on timescales of weeks to months, thereby allowing for increased lead times for emergency preparedness. Furthermore, both causes and effects of extreme events are suggested to change in a changing climate, which renders the projection of extremes significantly more difficult. This talk will give an overview of some of the dominant remotely forced extremes and provide a tentative outlook to future climates.

148 Bernat Jiménez-Esteve

On the Role of Large-scale Topography in Shaping the Characteristics of Extratropical Heatwaves in a Hierarchy of Model Simulations.

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Heatwaves are weather events characterized by extreme near-surface temperature anomalies that persist for several days. In the extratropics, these often occur as compound events with drought, exacerbating the potentially catastrophic impacts on natural ecosystems, agriculture, human health, and economies. Moreover, heatwaves are not only driven by the atmospheric circulation, but the frequency, duration, and intensity are influenced by the shape and properties of the underlying land and ocean.
To understand the role of large-scale topography on shaping heatwave characteristics, we use the ICOsahedral Nonhydrostatic (ICON) climate model in a hierarchical complexity approach. This model hierarchy ranges from a simple zonally symmetric temperature relaxation and dry dynamics to a simulation using full physics, coupled land and sea surface temperature forcing. The sensitivity to large-scale topography is tested in the temperature relaxation configuration by using idealized and realistic topography. We show that in the zonally symmetric experiment, i.e. only dry dynamics and no surface coupling, extreme temperature events are generally shorter but produce more intense temperature anomalies in the midlatitudes, where the horizontal temperature gradient is strongest. In the sensitivity experiments, we isolate the effect of topography on the heatwave characteristics, and find that heatwaves upstream of an idealized mountain are longer-lasting due to enhanced blocking occurrence. A consistent effect is observed in atmospheric reanalysis and the most complex model configuration during boreal summer over Western Russia, i.e. upstream of the Urals and northwest of the Mongolian Mountains, where the effect of the neighboring ocean is weaker than over North America. The role of atmospheric blocking and Rossby wave packets is also analyzed in the different model experiments, demonstrating that heatwaves are compound events that can be driven by a combination of dynamical processes.

149 Biliana Mircheva

Analysis of the 2014 wet extreme in Bulgaria: anomalies of temperature, precipitation and terrestrial water storage

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One of the most noticeable consequences of climate change is projected to be the impact on the hydrology cycle. The dry and wet extremes that are already being observed on a regional scale and are associated with large economic losses. The 2014 wet conditions in Bulgaria present a valuable case study for analysing the interaction between multiple drivers which are essential for early forecasting and warning of flood events. In this study time series analysis of temperature, precipitation and Terrestrial Water Storage Anomaly (TWSA) is performed and cross-correlations between observations and climate variability indices are computed for a 12-year period. In Bulgaria, a positive linear temperature trend is found with precipitation and TWSA exhibiting negative trends for the period 2003-2014. 2014 starts with a drier and warmer than usual winter followed by 5 consecutive wet months from March to July. Long-term variation of: 1) temperature shows a local minimum in November 2014, 2) precipitation peaks in July 2014 and 3) TWSA local maximum is in December 2014. Over the 12-year period, weak to moderate negative correlations are observed between the long-term components of temperature, precipitation and TWSA. Moderate positive correlations with 3 to 6-month lag are obtained between precipitation and TWSA long-term components. The long-term trends of temperature and precipitation from surface observations and ERA5 show very good alignment. Very large subseasonal precipitation residuals from observations and ERA5 reanalysis are obtained for April and September 2014. Two oscillation indices show: 1) weak correlations with precipitation and 2) weak to moderate correlations with TWSA.

150 Carlo De Michele

Dependence types in a binarized precipitation network

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In a network of binarized precipitation (i.e., wet or dry value), the connection or dependence between each pair of nodes can occur following one or more of the following conditions: wet wet, dry-dry, wet-dry or dry-wet. Here, we firstly investigate the different types of dependence within a precipitation network of binarized variables, comparing the sample estimate of the probability of co-occurrence of each of the four possible combinations with respect to the correspondent confidence interval in hypothesis of independence. We develop a procedure to efficiently assess the dependence behavior of all couples of nodes within the network, and illustrate the methodology to a network of raingauges covering Europe and north Africa.

151 Erich Fischer

Challenges in developing low-likelihood high-warming storylines for compound extremes

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Recent IPCC reports focused their assessment primarily on the likely range of changes in univariate extremes. However, it has recently been argued that such a focus on the likely range ignores changes with high levels of warming that are less likely to occur but nevertheless associated with the highest risks. This is particularly the case for multi-variate extremes where impacts often non-linearly depend on changes in hazards and where uncertainties are typically large both due to model response uncertainty and internal variability. Low-likelihood high-warming storylines have been proposed as a powerful tool to assess and communicate the risk associated with such future climates.
Here, we compare different approaches for developing low-likelihood high-warming storylines based on CMIP6 models, and discuss their strength and limitations with a specific focus on compound extremes. We reveal that several approaches proposed to develop low-likelihood high-warming storylines do not guarantee physical consistency across different variables and are thus not suited for compound extremes. We further argue that the choice of the storyline approach needs to be adapted depending on the research question and informed by the purpose of the assessment. We show that regional storylines are very powerful for regional or national assessments over a well-defined region but do not preserve spatially coherent response patterns. Nearest-neighbour model selection anchored on global mean temperatures have the advantage of generating storylines of globally coherent patterns that also preserve physical consistency across variables.
We demonstrate that all approaches yield storylines in which changes in combined heat-stress (hot and humid) and combined hot-and-dry extremes (hot and low P-E) strongly exceed the multi-model mean over large parts of the globe. This suggests that a focus on the likely range may indeed substantially underestimate the risk associated with changes particularly in compound extremes.

152 James M Done

Understanding the Drivers of Connected Precipitation Extremes

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The goal of the COEXIST (COnnected EXtremes In Space and Time) project is to mitigate adverse societal impacts of U.S. floods and droughts through understanding how extreme meteorological events are connected and how these connections might yield more accurate forecasts. This presentation will report on our latest results.
The project has created a foundational dataset of historical extreme wet and extreme dry events across the U.S. using reanalysis climate data. A preliminary analysis using a simple dispersion metric shows strong regional and seasonal variability in temporal clustering of extreme events. This presentation will focus on the wet events and delve deeper into the multi-scale physical processes driving this temporal clustering. Specifically, the following questions will be addressed using a combination of statistical and dynamical approaches: To what extent are large-scale weather patterns associated with clustering? How does clustering change by event intensity or event size? Regional variability will be linked to the weather phenomena associated with the extreme precipitation. One aim of presenting at this Workshop is to strengthen the science by identifying intersections and potential collaborations with other projects on compound weather and climate events.

153 Cassandra D W Rogers

Increasing risk of concurrent heatwaves in the Northern and Southern Hemisphere mid- to high latitudes

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Simultaneous heatwaves across multiple regions pose coinciding and compounding threats to natural and human systems. While global heating is increasing heatwave risk across most regions, interactions between the pattern of heating and changes in atmospheric circulation patterns that yield concurrent heatwaves have not yet been investigated. Here, we quantify long-term (1979-2019) trends in warm-season concurrent heatwaves across the Northern and Southern Hemisphere mid- to high-latitudes. We use Self-Organising Maps to identify characteristic atmospheric circulation patterns in the mid-latitudes and examine the relative contributions of changes in the frequency of these patterns and thermodynamics in driving concurrent heatwave trends. Changes in concurrent heatwave metrics are greatest in the Northern Hemisphere where we find a significant increase of ~46% in the mean spatial extent of concurrent heatwaves, ~17% increase in their maximum intensity, and ~7-fold increase in their frequency. While both hemispheres experience an increase in the number of concurrent heatwave days per year due to thermodynamic changes, only the Northern Hemisphere sees a substantial contribution to these trends from dynamics. We identify significant increases in circulation patterns associated with concurrent heatwave hotspots over eastern North America, eastern Europe, western Asia, eastern Asia, north-eastern Africa, the Barents and Kara Seas, the north-east Pacific, and the north Atlantic. Further, we show that changes in specific circulation patterns in the Northern Hemisphere have a greater dynamical influence on concurrent heatwave frequency than others. Our results highlight the increasing risk of concurrent heatwaves in a warming world and show how thermodynamic and dynamic contributions interact to generate global hotspots at risk of simultaneous heatwaves. These findings are indispensable for evaluating projected climate risks on interconnected societal systems and fostering regional preparedness to extreme weather.

154 Raphael Neukom

Unexpected and cumulative future climate risks in Switzerland: analysis and management

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A recent study on ‘climate-related risks and opportunities’ of the Swiss Federal Office for the Environment (FOEN) provided a comprehensive analysis of climate-related risks and opportunities for Switzerland until 2060. The synthesis of the study results has been the basis for the development of adaptation strategies and measures in Switzerland. The study moreover identified knowledge gaps and related missing planning tools for risks, which are difficult to assess as they typically have a low probability of occurrence but potentially very severe impacts for society and/or the environment. Such risks refer in particular to risks which (i) are triggered by meteorological/climatic extremes events, cumulate and are exacerbated through process cascades or (ii) return within shorter time intervals than statistically expected.
To address these gaps, a collaborative effort including academic and government institutions at different administrative levels is undertaken in order to explore and analyse the potential of such large cumulative, complex risks and actions needed to manage them in Switzerland. The project focuses on two case studies, which are developed in consultation with stakeholders from science, policy and practice at the national and sub-national level.
The case studies analyse risks triggered by meteorological events based on projected and recently published Swiss Climate Scenarios CH2018, considering rare but plausible scenarios where such triggering events cumulate and/or occur in combinations.
The first case study investigates mountain systems, in the southern Swiss Alps by using semi-quantitative methods of risk analysis. A potential reduction of the protective capacity of forests caused by extreme drought and the subsequent increased risks of multiple natural hazards (fires, snow avalanches, landslides) are assessed. We present first results of an expert survey to estimate probabilities of occurrence and tipping thresholds for sub-processes that may cumulatively lead to a loss of the protective function of the forest in the Val Mesolcina.
The second case study is concerned with amplified effects of recurrent large-scale drought and heat in urban centres. Its assessment is based on the analysis of the cascading and interlinked impacts from precedent dry-heat events around the globe, which is presented in a separate contribution to this conference.
Our study is expected to provide important information concerning highly vulnerable systems and elements and their protection, tipping points towards severe risk amplification, and feasible risk management and transformative adaptation required.

155 Riccardo Hénin

A ranking of concurrent precipitation and wind events for the Iberian Peninsula

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The Iberian Peninsula (IP) is often affected by extreme precipitation and severe winds that are mostly associated with extratropical cyclones and their atmospheric fronts. ERA5 reanalysis data are used to revise and update two existing rankings of extreme precipitation and extreme potential wind-loss days for the extended winter months on the IP. A ranking of concurrent precipitation and wind extreme events is produced by matching the two individual rankings for the IP and for specific IP subregions, including its main river basins. The intensity and the variability at the interannual and decadal scale are evaluated for precipitation, wind and concurrent precipitation and wind events. A systematic analysis of the underlying synoptic conditions is pursued for the top100 most extreme concurrent events including (1) cyclones' trajectories, (2) the presence of an Atmospheric River (AR), (3) recurrent patterns in the locations affected by precipitation and wind extremes, (4) possible long-term trends. Results show that 85% of concurrent precipitation and wind extreme events are clearly associated with a cyclonic feature and most of these cyclones either cross the IP or pass to the northwest. Concurrent events are more likely occurring in the northwestern sectors of the IP on wintertime as in recent decades a downward trend for the events' frequency is observed in autumn. ARs are more likely associated with the strongest events occurring on the western sector of IP. Accordingly, the areas that mostly experience concurrent precipitation and wind extremes related to those systems are located in the northwestern sector of the peninsula.

Combined heat and drought events on global urban systems: a synthesis of observed impacts and adaptation strategies

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Urban areas are particularly at risk from extreme heat events due their high population density and higher temperatures compared to surrounding rural areas, also in industrialized countries. In addition, vital sectors such as healthcare, infrastructure, transportation, and energy and water supply are strongly interlinked in urban systems. As a consequence, impacts on one of these sub-systems can directly or on longer terms strongly affect other domains of the system, particularly if heat extremes are re-occurring and are combined with other meteorological triggers such as persistent drought. Combined stressors, either caused by the same trigger (e.g. a double burdening of the health system through heat related symptoms and respiratory ailments due to increased air pollution or nearby wildfires), or independent but simultaneous causes (e.g. additional burdening by an infectious disease), can lead to unexpectedly strong disruptions of a sub-system, which may quickly propagate to other domains of the strongly interlinked urban life.

Knowledge of past effects on the various sub-systems and how they were connected and propagating would be a key basis to prepare for future heat-drought events in urban systems and prioritize adaptation measures. However, such an overview is currently lacking to our knowledge.

Here we present the results of a literature review identifying the effects of past and recent combined heat-drought events on urban systems from the following cases: the "Dust bowl drought" in southwestern USA in the 1930's, the European heatwave of 2003, the "Black Saturday bushfires" in Australia in 2009, the "Angry Summer" in Australia in 2012/13, the heatwave in eastern and central Europe in 2015, the multi-year drought and water crisis in Cape Town between 2016 and 2018, the European drought and heatwave in 2018 with severe wildfires in Greece and the Australian summer bushfires in 2019/20.

This analysis allows us to identify the most severely affected domains and to map the key cascading processes leading to impacts on different elements of urban sub-systems.

The results mark the baseline of a case study aiming at identifying the potential impacts of future heat and drought events on Swiss cities, which is undertaken as a collaborative effort including academic and government institutions at different administrative levels. The case study is part of a project of the Swiss Federal Office for the Environment (FOEN) to better understand the risks arising from unexpected and compound events in a future climate. The project is expected to provide important information concerning highly vulnerable systems and their protection, tipping points towards severe risk amplification, and the required feasible risk management and transformative adaptation.

157 Sabrina Wahl

Investigation of compound events from reanalysis data - A statistical approach based on copulas

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Compound events can be understood as a combination of several events or hazards where the simultaneous or successive occurrence causes an amplified impact. In a statistical framework, the dependent occurrence of multiple parameters can be fully described by their underlying joint probability distribution. We employ a two step approach for a statistical investigation of compound events using copulas. Copulas provide a sound statistical framework to assess such multivariate statistical distributions by modeling the dependence structure of variables separately from their marginal distributions. For an adequate description of the involved parameters, we rely on a comprehensive 4-dimensional representation of the atmospheric state provided by reanalysis data sets. At first, we aim at evaluating the multivariate statistical distribution between two or more parameters as a comparison between reanalysis and observations. In a second step, the identified dependencies are then related to different compound events based on the specific multivariate sample space. We will present results for a joint copula-based evaluation of temperature and humidity related to natural hazards like droughts, heat stress and wildfires.

Spatial clustering of heavy clustering in ERA-5 precipitation over Europe

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Extreme precipitation may cause important floods that can induce huge damage. Rainfall is subject to local orography features and their intensities can be highly variable. In this context, identifying climatologically coherent regions is paramount to increase any signal strength, e.g. with respect to climate change, in precipitation data.
The concept of Regional Frequency Analysis (RFA) consists of gathering stations into homogeneous regions. RFA is based on clustering sites according to their marginal precipitation distribution. Originally, RFA relies on clustering based on station-descriptors (e.g. elevation) and homogeneity tests.
Subjectivity remains in the choice of relevant descriptors. We propose a new regionalisation approach based on clustering of precipitation. One limiting assumption in the RFA approach is the need to specify a parametric form for the marginal distributions, up to a normalizing factor. We use the Extended Generalized Pareto Distribution [Naveau et al., 2016], for a smooth transition between moderate and extreme rainfall. We combine this threshold-free approach with RFA techniques. We identify homogeneous regions in ERA-5 precipitation over Europe and benefit from this clustering to better estimate extreme precipitation behaviour. At-site estimation of the tail index is subject to high variability. A regional fitting increases the estimation consistency. We present an iterative algorithm for regional fitting and an application on ERA-5 precipitation clusters.

159 Vera Melinda Galfi

On large deviations of temperature, persistent events, and large-scale circulation anomalies

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In this talk, we explore the connection between the mathematical concept of large deviations and persistent extreme events. We consider CMIP6 simulations of the MPI-ESM-LR model and study the convergence of large deviation rate functions of near-surface, summer and winter temperature, over several regions of the Northern Hemisphere. We find that, in general, rate functions converge in case of land regions on time scales shorter than one season. This suggests that they can be used to compute the probability of persistent temperature events. However, these persistent events are slightly different from the traditional definition of heat waves or cold spells. Their persistence stems from the fact that the instantaneous values over a restricted period fluctuate around a mean value, which is substantially larger than the long term mean. In case of oceanic regions, the rate functions do not converge, pointing to the low-frequency variability of temperature over the oceans. Furthermore, we study the large-scale atmospheric field anomalies related to the temperature large deviations, discussing also the occurrence of compound events.

Co-occurring temperature and humidity extremes in CMIP6: Estimating future trends of heat stress indicators and exceedances of impact-relevant thresholds

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The combined exposure to high temperatures and elevated levels of humidity can exert substantial heat stress on humans. An extensive number of heat stress indicators (HSIs) has been developed to measure the associated impacts on human health. To investigate how different HSIs evolve with changing temperature and humidity due to global warming, we calculate eight HSIs for global climate models participating in the Coupled Model Intercomparison Project phase 6 (CMIP6). We compare their future trends as function of global mean temperature, with particular focus on highly populated regions. All analysed HSIs increase significantly ($p<0.01$) in all considered regions. Moreover, the different HSIs reveal a substantial spread ranging from trends close to the rate of global mean temperature up to an amplification of more than a factor of two. Normalising the HSIs by accounting for the different scales on which they are defined changes trends considerably, meaning that other HSIs show the highest rates of increase compared to the unnormalized trends. Consistent with the trends, exceedances of impact-relevant thresholds are strongly increasing globally, including in several densely populated regions, but also show substantial spread across the selected HSIs. The indicators with the highest exceedance rates vary for different threshold levels, suggesting that the large indicator spread is associated both to differences in trend magnitude and the definition of threshold levels. These results highlight that quantifying the effects of combined heat and humidity extremes on human health importantly depends on the selected HSIs and that the choice of indicators is a crucial step for the impact assessment of compound events. To reliably assess the impacts of future heat stress, further research is needed to validate HSIs regarding their capability to quantify heat impacts on human health.

161 Roberto Villalobos Herrera

A copula-based decomposition of multivariate biases in climate models, with an application to compound fire and heat stress hazards

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Understanding climate change induced alterations to multivariate climate hazards is challenging due to their multivariate nature and complexity which may lead to high impacts even if the driver variables are not extreme. A correct representation of the variables which drive multivariate climate hazards is therefore an important requirement for an accurate assessment of future risks, however, climate model output is generally accepted to contain important biases. Here we introduce a methodology based on copula theory for the evaluation of biases in multivariate climate hazard indices. Using the simplified wet-bulb globe temperature (WBGT) and the Chandler Burning Index (CBI) indices of heat stress and fire risk as case studies, we assess biases in CMIP5 models against ERAI reanalysis of: temperature, relative humidity, and their statistical dependence. We use a bias decomposition method to quantify how the overall bias in the WBGT and CBI indices can be traced back to biases in the driving variables and their dependency structure. We make use of a suite of univariate and multivariate statistical tests to evaluate the model biases.
We find that our proposed bias decomposition provides valuable insight into the source of bias in our example indices. While CBI biases are mainly dominated by biases in relative humidity, the biases in WBGT are driven by biases in temperature, relative humidity, and their statistical dependence. Moreover, the bias decomposition of WBGT highlights regions (such as the Amazon basin and South Africa) with a certain degree of compensating biases as a result of the cancellation of the contribution of the temperature bias and the contribution of the relative humidity bias. In this way, the results show regions where a careful interpretation of heat stress and fire risk assessments is required and where multivariate bias corrections should be considered for risk assessment.
The presented procedure may be useful for evaluating the model representation of other compound events, with benefits for disaster risk reduction and climate model development processes. Ultimately, the present bias decomposition method aims to contribute to climate model development processes and feedback into the design of efficient bias-adjustment methods.

162 Nina Schuhen

Quantifying the combined effect of climate change and air pollution on future crop yield in Europe

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One of the most important aspects of climate change is its potential impact on agriculture. Crop yields are sensitive to changes in temperature and precipitation but can also be negatively affected by increased air pollution. Consequently, crops will be exposed to multiple stresses due to climate change, resulting in reduced productivity and thus major implications on crop sustainability, food security and international trade. Within the project SUSCAP (Developing resilience and tolerance of crop resource use efficiency to climate change and air pollution), the combined effects of climate change and air pollution, in particular ozone, to wheat crops in different parts of Europe are investigated. To this end, experimental studies are carried out, measuring the direct impact of interacting stresses on plants, with a view towards identifying resilient plant traits and best practices. The findings from these studies are also used to develop, calibrate and evaluate crop models designed to simulate crop yield under different conditions. By combining the crop models with high-resolution climate projections, we strive to understand how climate and air pollution conditions will change in the next decades and how these changes affect crop yield. Specifically, we will make use of the EURO-CORDEX (Coordinated downscaling experiment – European domain) data set, where several global climate models are downscaled to form a comprehensive ensemble of regional climate simulations. These projections -- run under several different RCP (representative concentration pathway) emission scenarios -- are first subjected to bias-correction, a procedure that is especially important in this study, as we are interested in absolute thresholds critical for crop growth. These thresholds might not be considered extreme per se, in the sense that they do not exceed extreme percentiles of the respective climatological distributions. However, simultaneous exceedance of these thresholds in several meteorological parameters results in a compound event that severely impacts crop yield, such as co-occurring high temperatures and low precipitation, with high levels of ozone increasing any detrimental effects. We therefore apply statistical methods to define multivariate extreme events relevant to wheat productivity, spanning several meteorological parameters, locations and time periods. Cattiaux and Ribes (2018) propose an objective roadmap for obtaining impact event definitions, especially with regards to their spatiotemporal characteristics, by maximizing the rarity of the event across several scales. We extend their method to cover multiple parameters to investigate the probability of occurrence of compound extreme events, both in the current climate, as well as under different global warming levels.

Cattiaux, J., and A. Ribes, 2018: Defining Single Extreme Weather Events in a Climate Perspective. Bull. Amer. Meteor. Soc., 99, 1557–1568, https://doi.org/10.1175/BAMS-D-17-0281.1.

163 Joel Zeder

Changing spatial patterns of concurrent Northern Hemispheric extreme weather events

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Recent findings provide evidence for an increasing large-scale risk of compound climate extremes such as the potentially adverse effect of concurrent heat wave events around the Northern Hemisphere on global food security (Kornhuber et al., 2020). In climate research, such large-scale patterns are frequently analysed with empirical orthogonal functions (principle component analysis). However, the underlying eigenvalue-decomposition is usually applied to the covariance matrix estimating linear dependence in the bulk of the data. Thus, the traditional approach is not suitable to study the dependency structure in the upper tail of the distribution relevant for extremes. Cooley and Thibaud (2019) propose the tail pairwise dependence matrix TPDM, which can be decomposed analogously to a covariance matrix in order to obtain dominating spatial dependence patterns (loadings) of climate extremes and time series of the respective temporal importance (scores).
We apply this method to more than 6000 years of stationary pre-industrial and 2xCO2 control simulations and an ensemble of 84 transient historical and RCP8.5 simulations, performed with the Community Earth System Model CESM1.2. Principal component loadings provide insight into the large-scale dependency structure of drought and heat wave events, and score time series related to driving mechanisms like Rossby wave dynamics (Kornhuber et al., 2019) or El Niño - Southern Oscillation (Jiang et al., 2020). Furthermore, the anthropogenically forced changes in tail dependence from pre-industrial to 2xCO2 conditions of such climate extremes are evaluated. We further test how well the statistically derived dependency patterns generalise by comparing against other single-model initial condition ensembles collected within the US CLIVAR Working Group on Large Ensembles.
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164 Johannes Vogel

Identifying meteorological drivers of extreme impacts: an application to simulated crop yields

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Compound weather events may lead to extreme impacts that can affect many aspects of society including agriculture. Identifying the underlying mechanisms that cause extreme impacts, such as crop failure, is of crucial importance to improve their understanding and forecasting. In this study we investigate whether key meteorological drivers of extreme impacts can be identified using Least Absolute Shrinkage and Selection Operator (Lasso) in a model environment, a method that allows for automated variable selection and is able to handle collinearity between variables. As an example of an extreme impact, we investigate crop failure using annual wheat yield as simulated by the APSIM crop model driven by 1600 years of daily weather data from a global climate model (EC-Earth) under present-day conditions for the Northern Hemisphere. We then apply the logistic Lasso regression to predict which weather conditions during the growing season lead to crop failure.

We obtain good model performance in Central Europe and the eastern half of the United States, while crop failure years in regions in Asia and the western half of the United States are less accurately predicted. Model performance correlates strongly with annual mean and variability of crop yields, that is, model performance is highest in regions with relatively large annual crop yield mean and variability. Overall, for nearly all grid points the inclusion of temperature, precipitation and vapour pressure deficit is key to predict crop failure. In addition, meteorological predictors during all seasons are required for a good prediction. These results illustrate the omnipresence of compounding effects both between meteorological drivers and different periods of the growing season for creating crop failure events. Especially vapour pressure deficit and climate extreme indicators such as diurnal temperature range and the number of frost days are selected by the statistical model as relevant predictors for crop failure at most grid points, underlining their overarching relevance.

We conclude that the Lasso regression model is a useful tool to automatically detect compound drivers of extreme impacts, and could be applied to other weather impacts such as wildfires or floods. As the detected relationships are of purely correlative nature, more detailed analyses are required to establish the causal structure between drivers and impacts.

165 Laura E. Owen

Unprecedented precipitation and wind extremes over Europe

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Extreme precipitation and winds can have a severe impact on society and the co-occurrence between the two extremes is important when assessing risk. Whilst these extremes and their co-occurrence have been studied at the 99th percentile, there is a need to look at unprecedented precipitation and wind extremes. The current chances of unprecedented precipitation and wind extremes are hard to calculate as, by definition, there are no such events in the observational record. However, using the UNSEEN method (UNprecedented Simulated Extremes using ENsembles) this risk can be estimated from large ensembles of climate simulations. We use the Met Office near term climate prediction system to provide multiple simulations of the current climate. The GloSea5 model simulations provide 24 times more data than is available from observations.

Before we can use these simulations, we need to know whether they can capture extreme events and the synoptic situations leading to them. To evaluate the GloSea5 model, 100 different timeseries between the years 1993 to 2016 for the winter season are created and compared against the ERA5 reanalysis. The 3 hourly mean 99th percentile wind speed of these ensembles compare well with ERA5 spatially over Europe. The magnitude of the 99th percentile extreme wind is also similar, however the model overestimates wind speed over areas of high topography . The 99th percentile precipitation also has a similar spatial pattern between ERA5 and the ensemble mean. However, GloSea5 overestimates 99th percentile extreme precipitation in regions around the Mediterranean and over the North Atlantic. The frequency and spatial pattern of the co-occurrence of the extremes compare well, particularly over land. But, GloSea5 underestimates co-occurrence over the north Atlantic storm track and differences are found over areas of high topography. For particular locations throughout Europe, how co-occurrence changes with extreme thresholds are investigated. To evaluate the synoptic patterns, mean sea level pressure composites for co-occurring extreme events are compared between ERA5 and GloSea5.

The model ensembles are then used to assess the current chance of unprecedented 3 hourly compound precipitation and wind extremes for winter over Europe. This method allows us to look at higher precipitation and wind extremes than previously investigated, as well as the co-occurring extremes.

Exploring Extended Warm Periods in an Observational Large Ensemble of Historical European Temperature

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Contextualizing extended periods of extreme regional heat, such as persistently mild conditions in Siberia during the first half of 2020, is challenging within the order 100-year observational temperature record. A robust understanding of these events amid historical climate variability, crucial for compound climate risk assessments, necessitates the use of model simulations to increase the temporal sample. Models and observations can combine to form alternative sequences of historical climate; these “observational large ensembles” have been generated using a model-derived forced signal and observationally-generated “climate noise”.

Here, we create an observational large ensemble of European Surface Air Temperature (SAT) over the historical period (1950-2014) using model-derived climate noise and an observationally-generated signal. The components are computed using constructed circulation analogue dynamical adjustment (Deser et al. 2016) applied to 8 large ensembles in the Multi-Model Large Ensemble Archive and the Berkeley Earth Surface Temperature observational record. Noise is typically computed in large ensembles by subtracting the ensemble mean from each member, a method with no observational equivalent. Dynamical adjustment, however, allows any SAT record to be empirically separated into a dynamic component (associated with atmospheric variability) and a residual, or climate noise estimate and signal, respectively.

We assess to what extent dynamic components from different models are distinguishable using out-of-sample testing and document systematic biases between model and observational dynamic components. Sets of models are selected such that observed statistical properties are maintained at each grid point. Finally, model-derived climate noise is combined with the observationally-generated signal, and the resulting observational large ensemble is evaluated via a multi-month extreme SAT frequency metric against the state-of-the-art observational large ensemble developed by McKinnon et al. 2018.

167 Tobias Sieg

Estimating impacts to companies and residential buildings

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The management of risks arising from natural hazards requires a reliable estimation of the hazards' impact on exposed objects. Most approaches of hazard impact modeling ignore the uncertainties associated with the components of risk (hazard, exposure, vulnerability). The influence of these components on the estimated risk is rarely assessed as well. Furthermore, current approaches imply problems of missing consistency when predicting the damage at different spatial scales due to different types of exposure data sets.

We present a object-based method which enables the seamless estimation of hydro-meteorological hazard impacts across spatial scales including uncertainty quantification. Data sets containing individual buildings (e.g. OpenStreetMap.org) are used for the identification of affected companies and residential buildings. The application and validation of this method in a post-event analysis resulted in plausible estimations at all spatial scales without overestimating the uncertainty. The influence of different data sets and methods describing the components (hazard, exposure, vulnerability) on the risk is assessed. The results suggest that a stronger focus on exposure could improve the reliability of impact estimations considerably.

In general, probabilistic object-based impact estimation enhances informed risk management and decision making. The individual assessment of the influence of the different components on the overall risk points out promising next steps for further investigations.

168 Davide Faranda

Changes in Future Synoptic Circulation Patterns associated with extreme events

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Anthropogenic emissions can modify the frequency and intensity of extreme weather events such as cold spells, heatwaves, and heavy precipitations. A major challenge is to detect changes in the atmospheric circulation patterns associated with those extreme events. The emergence of patterns depends on the chaotic behavior of the atmospheric flow and can also be modified by anthropogenic emissions. By embedding the circulation patterns observed during selected extremes into historical climate simulations and projections based on emission scenarios, we find major changes in probability, predictability, and persistence of atmospheric patterns observed during extreme events using an analog-based method. The results highlight the need to take into account the role of atmospheric circulation in attribution studies as future extremes will be associated with modified circulation patterns.

169 Cristina Deidda

Elucidating the spatial dependence between extreme floods: a compound perspective

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Compound and cascading natural events have rapidly grown of interest for the strong impacts associated.The dependence has a fundamental role in the dynamics of these events and causative investigations about its origin could contribute to elucidate their dynamics. Here, we address the pairwise spatial dependence between maximum annual daily discharge occurred in river stations located in United Kingdom.
The analysis shows how there exists a dependence between annual maxima pertaining to catchments located very far one from each other. We formulate a general conjecture to explain the dependence between annual maxima. The origin of dependence is more complex than what is presently stated in literature. We introduce three dissimilarity indices and dependence-dissimilarity maps to illustrate the conjecture.

About the origin of statistical dependencies between peak, volume, and duration of flood events.

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Floods are among the most common and impactful natural events. The hazard of a flood event depends on its peak (Q), volume (V) and duration (D), which are interconnected each other. Here, we used a worldwide database of daily discharge to calculate the pairwise statistical dependence between peak, volume, and duration, with different thresholds, for the identification of flood event. We considered also a conceptual hydrological rainfall-runoff as model-dependent realism to investigate the factors controlling and the origin of the dependence between each couple of flood characteristics.

171 Saeid Vaghefi

Understanding the implications of compound extremes for human health and adaptation using exploratory modelling

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The simultaneous occurrence of hot days and hot nights can amplify the heat waves effects and can have serious consequences for human health, since cool nights play an essential role to recover from daytime heat and in human thermoregulation (Hendel 2016). In this study, we focus on compound extremes of hot days and hot nights in two large cities of Switzerland, i.e. Zürich and Basel. Using historical climate data, we analyzed the frequency and duration of compound extreme events of hot days and nights from January 1981 to September 2020 to find the historical pattern of this compound event. The quantile analysis of long-term historical climate data defined 27-28 oC and 15-16 oC as the 95th percentiles of maximum and minimum temperatures (Tmax and Tmin), respectively, for two cities. We found an increasing trend in the frequency of compound extremes from 4, and 5 events in 1981 to 10 and 11 in 2018 in Basel and Zürich respectively. Also, the average duration increased from 2 to 4 consecutive days over time. From May 27, 2018, to August 7, 2018, Zurich has been struck with 10 events (ranging from 2 to 10 consecutive days) with the average Tmax of 28.8 oC and Tmin of 16.7 oC. To project multivariate hot days and nights extremes in the future, we used an exploratory modeling framework (EMA_workbench) (Kwakkel et al. 2017) to capture different sources of uncertainty derived from the diverse realization of climate scenarios and a number of selected adaptation policies. New high-resolution climate projections (CH2018) were used to represent climate uncertainty. To improve the coverage of the uncertainty space and accounting for the intra-annual variability of the climate models, a resampling technique was used to produce new climate realizations. We used an extreme compound analysis approach suggested by Zscheischler et al. (2018) to define events of hot days and nights in Zürich and Basel as the number of days where Tmax > 27 to 32 oC and Tmin > 15 to 20 oC. In our framework, different adaption policies are used in combination with thresholds of maximum and minimum temperature. Implications for human health and future pathways of adaptation are presented.

173 Meriem Krouma

Ensemble weather forecast with a stochastic weather generator based on analogues of circulation

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The aim of this study is to assess the skills of a stochastic weather generator (SWG) to forecast precipitation in Europe. The SWG was developed and tested by Yiou and Déandréis (2019) to forecast daily average temperature and the NAO index. It is based on the random sampling of circulation analogues. In this study, we adapt the parameters of the analogue SWG to optimize the simulation of European precipitations. The SWG use ECA&D precipitation data (Haylock. 2002), and the analogues of circulation computed from geopotential heights (Z500) from the NCEP reanalysis. This provides 100-member ensemble forecasts on a daily time increment. We then analyze the performance of this SWG for lead times of 5 to 20 days, with the forecast skill scores such as CRPSS scores against climatology and persistence forecasts. The seasonal dependence of the forecast skills of precipitation and the conditional dependence to weather regimes are also studied. Thus, comparisons with medium range forecasts from the ECMWF was performed in order to evaluate the performance of SWG.

174 Florian Ellsäßer

Analyzing and predicting impacts of compound extreme events on crop productivity and yield losses

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In the last decades, Europe experienced an increase in occurrences of extreme summer heat and rainfall deficit (Hari et al., 2020; Sutanto et al., 2020). The compound impact of several hazardous events causes extreme drought events which are likely to increase in frequency under the RCP 8.5 scenario (Hari et al., 2020) with large impacts decreasing ecosystem respiration and gross primary productivity (Ciais et al., 2005). On the other hand, heavy precipitation in combination with storm surge can lead to compound flooding events in coastal regions (Bevacqua et al., 2019). Since compound events have much more severe impacts than single hazard events alone (Sutanto et al., 2020), it is essential to understand the factors that cause compound extreme events to be able to model and predict their regional occurrence and impact (Mukherjee et al., 2020).
To characterize the impact of compound events on irrigated and rainfed crops, two distinct approaches have widely been used: The process-based approach that includes assumptions on e.g. environmental variables, soil and management practices (Jones et al., 2003; Stöckle et al., 2003) and the statistical approach that is based on regression models which link historic weather aggregates to yield records and simulations (Schlenker and Roberts, 2009). However, both approaches have their individual strength and weaknesses and a combination of both showed significant improvements in prediction performance (Roberts et al., 2017).
To analyse and predict the importance of compound extreme events at subnational level for Germany and adjacent countries on a variety of irrigated and rainfed crops, we will perform a systematic comparison between statistical models and process-based crop models and elaborate several combined approaches. The results of this comparison will provide valuable insights on the strengths and weaknesses of each approach and reveal the most suitable options on how to improve the prediction of changes in crop productivity and yield losses due to extreme events. With this, we will develop an integrated approach of statistical and process-based crop models aiming to establish an agro-climatic service by combining with seasonal climate forecast.

175 Katherine Towey

The coaction of cyclones and blocking in producing persistent storm surge

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Coastal areas are prone to flooding as a result of storm surge produced by tropical cyclones (TCs) and extratropical cyclones (ETCs). Storm surge events are influenced by cyclone-generated winds, while the path of a cyclone is influenced by the large-scale circulation (e.g., atmospheric blocks, or upstream jet stream), but this connection is not yet well understood. This presentation will focus on persistent storm surge events along the northeastern United States, utilizing both observational and reanalysis data. We define persistent surge as the occurrence of storm surge greater than 0.5 meters for a period of at least 24 hours. The probabilistic role of atmospheric blocking in generating persistent surge is explored. Our results indicate that for persistent storm surge events at New York City, downstream blocks occur over 75% of the time. In these cases, the block likely acts to guide the winds along a specific trajectory, increasing the fetch. However, our analysis also shows that the path of the cyclone is secondary to the existence of the block – i.e., winds generating the surge are not dictated by the path of the cyclone. As one might expect, the role of blocking is most notable when the surge metric investigated is persistent surge. In a separate analysis of the strongest surge events based on maximum surge (regardless of persistence), we find that blocks are present only 40% of the time. This work pinpoints the most common mechanism that generates persistent surge and provides new guidance for medium-range forecasts.

178 Colin Raymond

Extreme Heat-Humidity Combinations and Their Relationship to Hydroclimatic Extremes

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Increasing heat stress from extreme near-surface accumulations of heat and moisture is one of the strongest trends in observations and most confident projections from global climate models. Unlike in univariate temperature or precipitation analyses, we find there are several distinct regions with different geographies that experience similar levels of high-end moist static energy. These include the Persian Gulf, Red Sea, and Gulf of California basins, all arid subtropical maritime areas; South Asia and the Midwest US, both subject to intense long-range moisture transport and associated moist convection; the western Amazon basin, along the interface between forest and pastureland; and the Western Pacific and northwest Atlantic coastlines. In each of these four groupings, our results indicate that a substantial portion of extreme heat-humidity combinations are closely associated with hydroclimatic extremes — either drought or heavy precipitation. The key relationships hinge upon high-end moist static energy's requisite ingredients of suppressed convection and large low-level moisture supply. Our findings emphasize the interlinked nature of moisture-related climate extremes and the continued need for regional perspectives to reveal insights about them.

179 Shouro Dasgupta

Climate change induced crop yield efficiency loss and the impact on children's health

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There is increasing evidence that climate change is already threatening food security and thereby harming human health in several complex ways (Haile, 2005; Krishnamurthy et al., 2020). In lower-income countries, the focus of the climate-food-health nexus literature has tended to be the increasing frequency of extreme weather events such as droughts and floods, and shifting seasonal climatic patterns, on agricultural yields (Edame et al., 2011; Tong et al., 2016). However, whilst many studies provide a compelling rationale for such a link, few have attempted to make any quantifiable attribution from climate change to human health. The existing literature has found it difficult to identify a link between climate change and undernutrition, as mediated through the impact on crop production, is that the links are complex and difficult to attribute. For example, individual weather events cannot be attributed to climate change. Detection and attribution studies address this by looking at how a system is changing as compared to a baseline, and the extent to which climate change contributes to that change.
Our paper makes an important contribution to the climate change and health literature by exploring and quantifying the links between both gradual (Growing-degree days anomaly) and extreme climate change (droughts measured by Standardized Precipitation Index), food production, and child health. Specifically, we explore the extent to which climate change is affecting children's health through its negative impact on crop yields and crop harvests. To proxy health outcomes, we focus on stunting (growth retardation) and wasting (low weight for height).

We focus on four crops, maize, wheat, rice, and soybeans, which account for almost 75% of the caloric base of the world's population. We focus on four crops, maize, wheat, rice, and soybeans, which account for almost 75% of the caloric base of the world's population. We take account of two key aspects of climate change, increasing heat and heatwaves, and change in the frequency of of droughts and floods, that are known to have a negative impact on both harvests and crop yield potential (Watts et al., 2019).

We take a two-stage approach to our analysis. First, we undertake a stochastic frontier analysis to determine the impact of controlling for location (country) and time (year) fixed effects to estimate the impact of climatic stressors on crop yields. We then determine the impact of both climatic stressors and harvest shocks on health, using child stunting and wasting as a proxy for the health effects.

Results from our stochastic frontier analysis suggest a significant loss in production efficiency for maize (7.4%), rice (8.4%), and wheat (7.4%) due to climate change during 1971 to 2016. For maize and wheat, the loss in efficiency is driven by both the anomaly in growing degree-days and increased frequency of agricultural droughts. However, only agricultural droughts are found to be responsible for loss in production efficiency in the case of rice. An additional agricultural drought event results in a yield decline of between 0.09 and 0.6 percentage points decline in yields depending on the crop.

Results from the second-stage of our analysis suggest that both increase in anomaly of growing degree-days (0.002 percentage point) and six-month SPI (0.24 percentage point) result in an increase in the percentage of stunted children in the full sample. In the case of Africa, the impact of agricultural drought is higher, an additional drought event results in a 0.41 percentage point increase in stunting among children. Harvest shocks also increase the prevalence of stunting, with an additional harvest shock increasing stunting by 0.03 percentage point in the full-sample and by 0.06 percentage point in Africa.
In the case of wasting in the full-sample, the impact of both GDD anomaly (0.003 percentage point) and six-month SPI (0.33 percentage point) are larger compared to the impact on stunting. In the case of Africa, the impact of GDD anomaly and droughts are 0.004 percentage point and 0.44 percentage point, respectively. Annual harvest shocks also have had higher adverse effects on wasting in Africa compared to the full sample.

Compound marine heatwaves and ocean acidity extremes

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Some of the recently observed marine heatwaves and ocean acidity extremes have demonstrated the high vulnerability of marine ecosystems and fisheries to such extreme climate events. Traditional analysis of ocean extreme events tend to focus on one ecosystem stressor, such as temperature and acidity, at a time, potentially leading to underestimation of risk, as the processes that cause extreme events often interact. In fact, seawater temperature and acidity are connected in many ways. An increase in temperature directly increases acidity due to a shift in the chemical equilibria. This positive perturbation in acidity during high temperature events is often modulated by concurrent changes in air-sea gas exchange, ocean circulation, and biology. As a result, marine heatwaves and acidity extreme events can not be expected to occur independently from each other, but the relative importance of the different processes is not well understood.
Here, we present a first global assessment of compound extreme high temperature and acidity events (hot-sour extremes), identify hot-spot regions and driving mechanisms by using a 30-member ensemble simulation of a comprehensive fully coupled Earth system model (GFDL ESM2M). We show that such compound events have the highest probability of occurrence in the subtropics and the lowest probability in the equatorial Pacific and the high latitudes. These differences are mainly linked to the correlation between temperature and dissolved inorganic carbon being strongly negative in regions of low compound event probability while being close to zero in regions of high event probability. We will also present the changes in compound event occurrence over the historical period and those projected for the 21st century under high and low CO2 emission scenarios.

181 Piia Post

How severe are the convective storms in Estonia?

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Weather radar provides a profound observational basis for detection of severe convective storms. Such storms are a result of deep moist convection, that produces large water droplets and ice particles, that can easily be detected by a radar. But severe storm is a compound event, that has at least two more ingredients: existence of conditional static instablity and some process that lifts the moist air to the level of free convection. CAPE - convective available potential energy index is most often used to characterise the static instablity. From synoptic scale factors the direction of midtropospheric flow is selected to present the favorable setting for the storm development.
The main aim of this work is to find suitable thresholds for these three ingredients of convective storms, that could be detected combining radar reflectivities and reanalysis data. Additionally the study intends to give a better understanding about the spatial and temporal distribution of convective storms over Estonia. Impact of the detected storms is evaluated using the data collected by citizen scientists.

182 Eva Plavcova

Projections of compound winter weather extremes in EURO-CORDEX climate models and their links to large-scale atmospheric circulation

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Regional Climate Models (RCMs) are powerful tools to study changes in the climate system on the regional scale. Compound events of weather extremes considerably affect various sectors of human society and natural environment and therefore it is essential to understand projected changes of their characteristics in the future climate. We focus on the links between low temperature and high wind velocity, because their compound effect strongly influences human thermal comfort in cold weather, as characterized by the wind chill factor. In our study, we analyse frequency and persistence of this extreme compound events and projected changes of their characteristics in simulations of RCMs from the EURO-CORDEX project. We focus on the Central European domain (defined roughly between 48–52°N and 10–19°E). We investigate a set of 9 simulations of 3 different RCMs driven by 3 different global climate models which allow us to analyse the influence of driving data on the RCM’s outputs. Model simulations are validated against observed data from the E-OBS database and the ERA5 reanalysis over the 1979-2017 period. The RCP8.5 emission scenario is used in the projections for the 21st century. Since local climate is relatively tightly linked to a large-scale atmospheric circulation over Europe in winter, we also evaluate links of the compound events to the atmospheric circulation.

183 Jennifer Louise Catto

A weather system typology for compound hazard analysis

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Natural hazards such as extreme wind, rainfall and ocean waves can have severe impacts on built and natural environments, contributing to the occurrence of disastrous events in some cases. These hazards are often caused by weather systems such as cyclones, fronts and thunderstorms. Here we systematically examine compound hazards (extreme precipitation, extreme wind gusts, and extreme waves) using a weather system typology framework. The hazards, and the cyclones and fronts are identified using ERA-Interim reanalysis data, while thunderstorms are identified using lightning observations over the period 2005-2015.
We find that the frequency of co-occurring extreme precipitation and wind events is high during the winter in the midlatitudes, and are most commonly associated with combined cyclone and front or front-only weather systems. During summer there is a large frequency of compound precipitation and wind, as well as the triple hazard of precipitation, wind and waves, which are most commonly associated with tropical cyclones (indicated by cyclone and thunderstorm weather system type). Despite the low frequency of the triple weather system type of cyclone, front, and thunderstorm, this gives the highest probability of producing an extreme event on a global average.
Using this framework, we can also investigate the characteristics of the hazards associated with the weather system types, in terms of their duration, and spatial extent, which are important aspects for considering their impacts. It is intended that a greater understanding of compound hazards and the weather systems that cause them in regions throughout the world will help lead to improved preparedness and disaster risk reduction, given the importance of this for our rapidly changing world.

The Physical Climate Storyline Approach: Emerging Concepts of Climate Risk

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A storyline approach is emerging to explore plausible climate change impacts and better understand their consequences for society. Storylines consider ways in which extreme or significant climatic events can evolve in a warming world and can include consequences for ecosystems and society. The narrative structuring inherent in a storyline approach links information from physical and social systems to better understand how climate risk will change over time. By bridging analytic modes in climate and social science, storylines navigate disciplinary boundaries to account for different assumptions, scales and approaches to uncertainty. When related to physical climatic processes, a storyline has been defined as a physically self-consistent unfolding of past events, or of plausible future events or pathways. However, storylines are inconsistently referenced in climate change literature where the term may also relate to socio-economic scenarios, climate or energy narratives, or tales about futures affected by climate change. The small body of existing literature directly related to physical climate storylines offers insight into how storylines have been developed with, and without, stakeholder engagement. This integrative review considers 18 peer-reviewed articles published since 2015 that present climate storylines at different temporal and spatial scales, considers societal involvement in development and communication and compares their handling of uncertainty. Where physical climate storylines also reflect societal consequences and associated risk, we refer to them as ‘climate risk storylines’. The review showed that climate risk storylines describe causal links centred on climatic extremes, often to inform analysis of interdependencies and relationships of risks across different methods of analysis. Climate risk storylines offer a flexible approach to better link science and society to visualise plausible climate impacts and explore how to manage their consequences.

185 Meredith Anne Fish

Large-scale environment of successive atmospheric river events in California

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Successive atmospheric river (AR) events—known as AR families—can result in elevated hydrological impacts relative to single ARs due to the lack of recovery time between periods of precipitation. Despite the outsized societal impacts that often stem from AR families, the large-scale atmospheric conditions associated with these compound events remain poorly understood. A new 39-year catalog of 248 AR family events impacting California between 1981 and 2019 is introduced based on atmospheric reanalysis data. Using K-means clustering on the 500-hPa geopotential height field, six distinct clusters of large-scale patterns associated with AR families are identified. These clusters broadly represent two types of predominant patterns: those characterized by meridional flow and persistent ridging upstream of California, and those characterized by strongly zonal flow across the North Pacific. Two clusters are of particular interest due to their strong relationship with phases of the El Nino/Southern Oscillation (ENSO). Cluster 3, characterized by a strong ridge in the Bering Sea, most frequently occurs during La Niña and Neutral ENSO years and is associated with the highest cluster-average precipitation across California. Cluster 4, characterized by a zonal elongation of lower geopotential heights across the Pacific basin and an extended North Pacific Jet, most frequently occurs during El Niño years and is associated with lower cluster-average precipitation across California but a longer AR family duration. This study advances the understanding of the large-scale environments and underlying physical drivers associated with AR families—with the ultimate aim of supporting near-real time predictability applications.

187 Gabriele Hegerl

Learning from an old catastrophic compound event: the US dustbowl heat and drought

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Learning from a past catastrophic compound event: the US dustbowl heat and drought
Record-breaking summer heat waves were experienced across the contiguous United States during the decade-long ‘‘Dust Bowl’’ drought in the 1930s. Across the historical record, heat waves in the Great Plains occur earlier, and are more severe if following dry springs, highlighting the importance of land surface feedbacks. Climate model simulations suggest that the dustbowl heat waves were forced by anomalous sea surface temperatures in the Atlantic particularly, which favour drier spring conditions. Atmospheric model simulations show that human-induced deterioration of vegetation can sharply amplify heatwaves. Similar heatwaves would have been slightly less warm without greenhouse gas forcing at the time, and the return period of a rare heat wave summer (as observed in 1936) would be much reduced at the present time due to greenhouse warming. The drought and heat of the 1930s Dust Bowl contributed to the socio-economic and ecological disaster over North America's Great Plains over that period, highlighted by Steinbecks ‘Grapes of Wrath’. It highlights the danger that naturally occurring compound events, amplified by vegetation feedbacks, can create very extreme events and tipping points in a warmer world.

188 Theodore Shepherd

Storyline approach to compound weather and climate events

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In principle, every extreme event is unique. This presents a dilemma. We either embrace the singular nature of the event and take something of a 'case study' approach, or we aggregate over similar events and take a statistical approach. The problem with the latter is that since different 'similar' events will be different in important ways (they are not iid), aggregation may destroy what we are most trying to understand. This dichotomy is found across all areas of science. For extreme weather and climate events, the dichotomy is especially pronounced when it comes to compound events. I here discuss the 'storyline' approach to event characterization, which has emerged in recent years as a way of following the first of these two pathways, and how it may be reconciled with the statistical approach through the mathematical framework of causal networks.

189 Linda van Garderen

A Methodology for Attributing the Role of Climate Change in Extreme Events: A Global Spectrally Nudged Storyline

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Extreme weather events are associated with unusual dynamical conditions, yet the signal-to-noise ratio of the dynamical aspects of climate change that are relevant to extremes appears to be small, and the nature of the change can be highly uncertain. On the other hand, the thermodynamic aspects of climate change are already largely apparent from observations, and are far more certain since they are anchored in agreed-upon physical understanding. The storyline method of extreme event attribution, which has been gaining traction in recent years, quantitatively estimates the magnitude of thermodynamic aspects of climate change, given the dynamical conditions. There are different ways of imposing the dynamical conditions. Here we present and evaluate a method where the dynamical conditions are enforced through global spectral nudging towards reanalysis data of the large-scale vorticity and divergence in the free atmosphere, leaving the lower atmosphere free to respond. We simulate the historical extreme weather event twice: first in the world as we know it, with the events occurring on a background of a changing climate, and second in a ‘counterfactual’ world, where the background is held fixed over the past century. We describe the methodology in detail, and present results for the European 2003 heatwave and the Russian 2010 heatwave as a proof of concept. These show that the conditional attribution can be performed with a high signal-to-noise ratio on daily timescales and at local spatial scales. Our methodology is thus potentially highly useful for realistic stress testing of resilience strategies for climate impacts, when coupled to an impact model.

Sequential Humid Heat and Heavy Precipitation Events

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Focusing primarily on the U.S. and other relatively data-rich regions, we assess whether warm-season extreme precipitation events (at hourly and/or daily timescales) tend to be immediately preceded by humid heat extremes--as defined by wet bulb temperature--at similar timescales. We also assess high dry bulb temperatures as a predictor of extreme precipitation. We link our results to driving mechanisms and diagnostics, such as sea surface temperature anomalies and moisture convergence, respectively. We may also flip the sequences, investigating how extreme precipitation events modify wet bulb temperatures across different timescales and contexts.

191 Danielle Touma

Changes in risk of extreme rainfall over burned areas in California

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An extreme rainfall (ER) event on a recently burned area (BA) can multiply damages to natural and human systems through flash floods, debris flows and mudslides. One example are the destructive mudslides that occurred in Southern California during a brief but severe storm over the burned area of the 2017 Thomas Fire, leading to 21 deaths and over $200M in damages. Anthropogenic forcing is expected to drive increases in wildfire risk and amplify extreme wet events, possibly increasing the risk of concurrent BA-ER events. First, we examine the characteristics of observed precipitation over recent BA's in California and identify the characteristics of ER events over these areas. We then examine extreme sub-daily and daily precipitation in the 40-member CESM Large Ensemble (LE) experiment over the same observed burned areas in 20th and 21st centuries. This allows us to isolate the possible impacts of precipitation trends and variability on the risk of compound BA-ER events. Next, we quantify historic and future extreme fire weather risk in the CESM-LE experiments in order to examine the projected role of BA trends in driving changes in compound BA-ER events. Moreover, we investigate the atmospheric dynamics and land processes that create conditions that underlie temporally compounding BA-ER events on multiple time scales. Our analysis will provide insight to adaptation efforts focused on preventing devastating impacts in wildfire-prone regions.

foreSIGHT: An R-package to evaluate system performance under hydroclimate variability and change

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The performance of water resources and environmental systems is affected by changes in hydro-climatic variables. Adaptive planning to sustain system performance under changes in hydro-climatic conditions requires consideration of alternate system management or design options. Scenario-neutral climate impact assessment of the system facilitates such an analysis. The assessment involves the generation of stochastic time series with targeted changes in hydro-climatic attributes for evaluation of system performance under a range of conditions. Effective implementation of a scenario-neutral climate impact assessment relies on the integration of multiple modelling components - generation of perturbed hydroclimate time series that can rigorously ‘stress-test’ a system, simulation of system performance, and visualisation of the performance space to interpret the results. The simulation and visualization demands are significant and preclude the wide-scale adoption of scenario-neutral approaches. Here we present an R-package, foreSIGHT (Systems Insights from the Generation of Hydroclimate Time series), for scenario neutral climate impact assessment. foreSIGHT can be used to assess the current system performance and compare alternate system management or design options for adaptive planning. The package is developed for ease of use with sensible default stochastic model and optimisation settings, and at the same time, offers customisation options for advanced users. The internal structure of the package supports its use in both serial and parallel computing environments. It is envisaged that foreSIGHT would develop as a community software that offers a platform for the implementation of advances in stochastic hydroclimatic simulation methods and optimisation approaches for scenario neutral climate impact assessment.

193 Dirk Eilander

A nested model framework for compound flooding: A case study based on hurricane Idai

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Many delta areas in the world are densely populated and have large exposure. These areas are prone to fluvial, pluvial and coastal flooding. However, current large-scale flood risk assessments consider these different flood drivers to be independent, which might result in an under- or overestimation of the total flood risk. Hurricane Idai in March 2019 is a recent example of a flood event where the combination of these drivers led to extensive flooding and large impacts: over $1 billion worth of infrastructure, more than 100,000 houses damaged or destroyed and over 1000 people killed in Mozambique, Zimbabwe and Malawi combined. These so-called compound flood events, where multiple drivers combine to increase the flood impact, may occur even with non-extreme sea water levels and/or discharges, but from the interplay between both. For instance, these could occur in situations where: high sea water levels propagate up a river pushing up water levels in the river; the drainage of high river discharge or abundant rainfall is limited by elevated sea water levels; or rainfall on top of coastal or fluvial flooding.

Compared to univariate flood risk assessments, compound flood risk assessments add new requirements to a modelling framework. The framework should capture large-scale processes that trigger surge or peak discharges as well as small scale hydrodynamic processes that are important for simulating interactions between drivers and flood dynamics. At the same time, it should be computationally efficient to be able to scale to large spatial domains and to many events or scenarios. The latter is important to capture many plausible combinations of flood drivers and allow for scenario analysis. We suggest a new ‘nested’ modelling framework to meet these requirements.

The framework consists of a large-scale hydrological and a large-scale tide and surge model, which are coupled through a large-scale 1D river routing model, with local nested 2D hydrodynamic models. Based on the large-scale models riverine and near shore water levels are simulated and flood events are detected. For these events, the nested 2D hydrodynamic model is initialized to simulate flooding. In this way the expensive detailed hydrodynamic computations are limited to events and to areas where these are required. All model parameters and schematizations are based on globally available data, making the framework particularly useful in areas where local models and data are not available and to yield globally consistent results.

In this contribution we will present the framework and results for a case study of hurricane Idai. Eventually, the modeling framework will be extended to simulate both the hazard and impact of a range of scenarios in order to determine compound flood risk and the effectiveness of flood risk reduction measures for compound flood events.

194 Anais Couasnon

The impact of compound flood events in Ho Chi Minh City

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Ho Chi Minh City (HCMC), a low elevation coastal megacity with a large concentration of assets, is threatened by multiple flood perils such as high tide events, monsoonal rains and storm surge from tropical cyclones and monsoonal winds. Until now, state-of-the-art flood risk estimates for the city were calculated by considering simplified temporal interactions of pluvial and coastal flood drivers.

In this work, we study these interactions and their impact on annual average losses. We extract the date of the year from reported pluvial and coastal floods in the city between 2009 and 2017 and link them with observed time series of daily rainfall and storm surge. Using circular statistics, we find a strong seasonality in both types of floods, driven by the seasonality of rainfall and sea levels. Extreme rainfall events dominantly occur within the monsoon season between May to November while high sea level peaks occur between October until March. This means that while yearly maxima are unlikely to co-occur, this is not the case of monthly maxima in October and November.

We develop a risk framework that can include compound flood events during this secondary flood season by combining a hydrodynamic model, a damage model and the monthly joint distribution of rainfall and sea level. Instead of modelling the inland water depth for each stochastic event, we limit computational time by selecting combinations within the multivariate space of rainfall, tide and storm surge extremes. Finally, we estimate and compare the yearly flood risk with and without the inclusion of secondary flood events. This analysis therefore suggests to include compound flood events and temporal dynamics of flood drivers when calculating flood risk.

195 Ana Maria Vicedo Cabrera

Clarifying the role of humidity on the effect of heat on health: an epidemiological perspective

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Current literature on the role of humidity on the heat-health effects is full of contradictive findings. While experimentalevidence from physiological models strongly suggests that high moisture exacerbates heat stress, epidemiological studies published so far failed to find clear conclusions on the potential interactive effects between heat and humidity. Indeed, recent epidemiological assessments found that the effect of humidity, on top of dry air temperature, on health is small or even negligible. This is the reason why, although the direct impact of heat on health has been extensively assessed, most of these studies relied on the sole effect of high temperatures and disregarded the contribution of humidity to the observed impacts. Understanding the role of humidity on the association between heat and adverse health outcomes is relevant for (1) quantification of reliable projections of temperature-related health impact under climate change scenarios that would account for trajectories of both weather variables, (2) implementation of improved heat-health warning systems that more accurately forecast short-term peaks in mortality and morbidity, (3) design of public health measures and/or adaptation strategies targeted to individuals more susceptible to heat stress. The present contribution will aim to provide an overview on current literature on the topic, discuss on the potential reasons for these contradicting findings and propose alternative methods and approaches to clarify the role of humidity in heat-health assessments.

197 Alexandre Tuel

Subseasonal temporal clustering of extreme precipitation – a global perspective

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Several precipitation extremes that occur in a short time span can have major impacts on human societies, by causing for instance extreme flood conditions that persist over a week or longer. Subseasonal temporal clustering of precipitation extremes has already attracted attention, but most studies have focused on catchment or regional scales. Thus, we know little about its spatial and seasonal distribution. Here, we combine statistical and event-based metrics to assess the degree to which precipitation extremes tend to cluster on subseasonal time-scale in observation, reanalysis and model-based datasets. We find that, at the global scale, subseasonal temporal clustering is largely concentrated in the equatorial band, but is also significant seasonally in certain mid-latitude regions. CMIP6 models are able to reasonably reproduce clustering patterns found in ERA5 and GPCP. Our findings pave the way for a better understanding of the physical drivers behind temporal clustering.

198 Yannick Barton

On the temporal clustering of European extreme precipitation events and its relationship to large-scale atmospheric drivers

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Extreme precipitation events that occur in close succession can have important societal and economic repercussions. Few studies have investigated the link between large-scale atmospheric drivers and temporal clustering of extreme precipitation events on a sub-seasonal scale. Here we use 40 years of reanalysis data (ERA-5) to investigate the link between possibly influential atmospheric variables and the temporal clustering of catchment-averaged extreme rainfall events in Europe. We define extreme events as exceedances above the 99th percentile and runs of consecutive days are declustered. We then explicitly model the seasonal rate of extreme occurrences using penalized cubic splines. The smoothed seasonal rate of extremes is then used to (i) infer the significance of subseasonal clustering and (ii) serves as the baseline rate for the subsequent modelling step. We use a Poisson Generalized Additive Model (GAM) to model the relationship between the temporal clustering and predictor variables, such as the North Atlantic Oscillation, the Arctic Oscillation, atmospheric blocks and the R-metric.

199 David N. Bresch

Compounding Impacts - the Resilient Adaptation Strategy Imperative

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Climate change is a fact and adaptation to a changing environment therefore a necessity. Adaptation is ultimately local, yet similar challenges pose themselves to decision-makers all across the globe and on all levels. The Economics of Climate Adaptation (ECA) methodology established an economic framework to fully integrate risk and reward perspectives of different stakeholders, underpinned by the CLIMADA impact modelling platform, designed to enable risk assessment and options appraisal in a modular form and occasionally bespoke fashion yet with high reusability of common functionalities to foster usage in interdisciplinary studies and international collaboration. The cascade of uncertainty progressing from different socio-economic development pathways, their translation into forcing scenarios driving global climate models being regionalized and translated into local socio-economic impacts is further broadened by compound causation and cascading consequences of severe impact events. To strengthen the adaptive capacity of socio-economic systems in this context, we propose to test adaptation options for robustness against a wide range of possible outcomes in order to provide the fact base to develop resilient adaptation strategies.

A Systems Dependency Perspective for Individual, Compound and Systemic Risks: An Application to Australian Wildfire Risk

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The recent unprecedented Australian wildfires have shown that new approaches for the assessment and management of such risks are needed. We suggest that dependencies may act as the guiding principle not only for assessing wildfire risks but also for evaluating risk management options. The two most extreme cases within such a system state approach would be independence and full dependency with a continuous scale between them. Such a perspective enables an integration of risk management strategies within a coherent framework across geographical and governance scales. In that regard we argue that focusing on spatial and tail dependencies will be crucial to dealing with wildfire risk in the future.

201 Jonathan Robert Buzan

Moist Heat Stress on a Hotter Earth

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As Earth overheats—potentially to conditions warmer than during the three million years over which modern humans evolved—suffering from heat stress will become widespread. Fundamental questions about humans' thermal tolerance limits are critical. However, understanding heat stress requires linking a network of disciplines together, from human health and evolutionary theory to planetary atmospheres. The implications of heat stress are equally interdisciplinary, requiring engineering, social, and political decision making over the next century. What the underlying atmospheric drivers of heat stress—temperature, moisture, and radiation—remain poorly understood. Here we focus on moist heat stress, describing the theoretical framework that enables robust prediction of averaged properties of moist heat stress extremes and their spatial distribution in the future. We also draw some implications for human and natural systems from this framework.

Main Points:

Moist heat stress affects societies and we summarize the drivers of moist heat stress and assess future global impacts.

Moist heat stress pattern scaling of extremes in temperature and humidity together allows for research on future heatwaves, infrastructure planning, and economic productivity.

202 Sidharth Sivaraj

Constraining the occurrence probability of hot and dry summers in CMIP5 models using an observational constraint on the dependence between temperature and precipitation

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Compound weather and climate events can be understood as combinations of multiple climate drivers (and/or hazards) that contribute to societal or environmental risk. To date, there is little knowledge on how well climate models represent the dependence between drivers of compound events. In this project we study the frequency of compound hot and dry warm seasons as projected by 40 CMIP5 global climate models. Using a constraint based on the dependence between warm season temperature and precipitation, we investigate whether the likelihood of compound hot and dry warm seasons is significantly different in models that match observations well. Hot and dry warm seasons (three warmest months in the climatology) are defined as concurrent exceedance of temperature (>90 percentile) and precipitation (<10 percentile) thresholds for the historical period 1901-2000. We first examine whether models are able to capture the linear correlation between temperature and precipitation in the observation. Overall, models project a strongly increased frequency of compound hot and dry warm seasons for the future (2000-2100) compared to the historical period (1901-2000) based on a high-emission scenario. The constrained model ensemble projects a higher frequency of compound hot and dry warm seasons on average compared to the full ensemble both in the historical as well as the future period. However, lack of stations, in particular in the southern hemisphere, make it difficult to constrain models in these regions. In the next step, we will constrain the dependence based on the empirical copula between temperature and precipitation, which is more flexible in capturing non-linearities in the dependence structure.