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Compound climate events and extremes in the mid-latitudes

What: The workshop, conducted virtually due to travel restrictions related to COVID-19, gathered scientists from six countries and focussed on the mechanistic understanding, statistical characterisation and modelling of societally-relevant compound climate events and extremes in the mid-latitudes. These ranged from co-occurring hot–humid or wet–windy extremes, to spatially compounding wet and dry extremes, to temporally compounding hot–wet events and more. The aim was to bring together selected experts studying a diverse range of compound climate events and extremes to present their ongoing work and outline challenges and future developments in this societally-relevant field of research.

When: 7th – 9th September 2020

Where: Held digitally, hosted from Uppsala University, Uppsala, Sweden

Compound climate events result from the combination of multiple drivers and/or hazards, which collectively lead to a socio-economic and/or environmental risk (e.g. Zscheischler *et al.*, 2018). The term *compound extreme* refers to the specific case where several or all of the compounding elements are themselves extreme events. A univariate perspective hampers the process understanding of climate events and extremes, and may ultimately lead to an underestimation of the associated risk (Zscheischler *et al.*, 2020). At the same time, a multivariate perspective brings its own unique challenges, both conceptual and methodological. Multivariate statistical models are typically complex and data-intensive (e.g. Bevacqua *et al.*, 2017), yet compound events are by definition less sampled than their univariate counterparts. This is particularly evident for studies on compound extremes, which often rely on very limited datasets. Process studies face analogous challenges, since the components of a compound event may be controlled by one or a multitude of drivers.

The workshop on "Compound climate events and extremes in the mid-latitudes" was convened to outline promising ongoing and future research developments in this field and foster discussions on

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cross-disciplinary methodological approaches. A specific focus was to delineate challenges hindering our understanding of compound events, which may require a concerted community effort to be overcome.

We summarize the workshop's outcomes around the following themes: drivers of multivariate compound events, spatially and temporally compounding events and novel cross-disciplinary methodologies for the study of compound events. We conclude by reporting the challenges and future perspectives in the field, issued from roundtable discussions that closed each of the three days of the workshop.

Day 1: Drivers of Multivariate Compound Events

Multivariate compound climate events are the archetype of a compound event, and occur when relevant climate drivers and/or hazards co-occur in the same geographical region.

Rodrigo Caballero and Colin Raymond opened the workshop with a discussion of concurrent hot–humid extremes. These are understood to drive heat stress extremes, often diagnosed through wet-bulb temperature, with potentially lethal effects on humans (Sherwood and Huber, 2010). A comprehensive understanding of hot–humid extremes requires complementary approaches, embracing global-scale statistical analyses and process-oriented studies at the regional-to-local scale. Colin highlighted strong observed trends in combined hot–humid extremes at the global scale, driven by warming air and sea-surface temperatures (Raymond *et al.*, 2020). The balance between temperature and moisture contributions to hot–humid extremes results from processes that affect water vapour and atmospheric stability – for example, surface radiative heating, evapotranspiration and deep convection. However, the lack of detailed and comprehensive datasets at process-relevant timescales (~hourly), as well as regional geographic and meteorological variations, remain outstanding challenges. At the regional scale, a notable hot–humid hotspot is Pakistan's Indus Valley. Rodrigo explained that events in the region are driven by advection of moist air masses from the

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Arabian Sea onto land, where they are further heated and moistened through surface fluxes as they pass over the highly-irrigated Indus Valley region (Monteiro and Caballero, 2019). A comprehensive evaluation of current and future hot–humid extremes thus requires both full- complexity global climate models and high- resolution regional simulations, able to resolve small-scale processes such as land surface evaporation.

The focus next shifted to the role of moist oceanic air masses – and more broadly storm-track activity – in favouring compound coastal flooding from co-occurring extreme precipitation and storm surge. Emanuele Bevacqua analysed the co-occurrence probability of these two meteorological drivers in the present climate and in a future scenario under high anthropogenic greenhouse gas emissions. Storm-track variability explains to a large extent the spatial variation of the co-occurrence probability. In a future warmer climate, a combination of thermodynamic and dynamic atmospheric changes will likely increase the occurrence of compound flooding, particularly in the mid-latitudes (Bevacqua *et al.*, 2020a, b). These findings indicate that the detected changes should be considered in future risk assessments, as they may aggravate the hazard caused by mean sea-level rise.

Storm track variability also modulates other mid-latitude compound events, in both summer and winter. Summer can see persistent hot–dry or cold–wet weather, with significant impacts on agriculture, health, the energy sector and the environment. In Europe, such summer weather anomalies are associated with specific states of jet-stream, *i.e.* respectively the dominance of blocked flows or a persistent zonal jet. Dim Coumou presented a dynamical systems perspective on the topic, which supports Lorenz' hypothesis that summer climate is largely intransitive (Lorenz, 1990) and suggests that persistent blocked or zonal states may be characterized by long memory (~40 days) and governed by different attractors. If intransitivity were indeed a fundamental property of summer atmospheric dynamics, this would have major implications for predictability on meteorological to interannual timescales. However, there are still critical gaps in our knowledge of the dynamics underlying jet-stream variability in the summer season. This is a pressing issue, as the summer season

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is when the bulk of the agricultural production takes place, and thus present and future climate risks are likely most severe in this season.

In winter, storm track variability modulates concurrent wet–windy and hot–windy extremes in Europe (e.g. Messori *et al.*, 2019; De Luca *et al.*, 2020a). Gabriele Messori discussed the causal chain leading to these extremes. The simultaneous occurrence of anti-cyclonic planetary wave-breaking to the south of the North Atlantic jet-stream and cyclonic wave-breaking to the north of the jet-stream leads to a very zonal and intense large-scale flow. This, in turn, favours a heightened frequency of explosive cyclones in the Atlantic basin and destructive windstorms over Western and Continental Europe (Messori and Caballero, 2015). A zonal, intense jet also leads to heavy precipitation, associated with the Atlantic cyclones, and favours the penetration of warm, moist airmasses deep into the European continent. The above process chain is recovered when studying multidecadal or longer variability in long climate model integrations (Messori *et al.*, 2019). This has important implications for the interpretation of dynamical changes in climate projections and their relevance for high-impact compound climate extremes in Europe.

Day 2: Spatially or Temporally Compounding Events

Spatially compounding climate events occur when multiple locations are affected by climate hazards within a short time-window. Temporally compounding events result from a temporal sequence of hazards at a given geographical location (Zscheischler *et al.*, 2020).

Kai Kornhuber opened the day with an analysis of concurrent summertime heatwaves across different Northern Hemisphere breadbasket regions. This co-occurrence can be ascribed to amplified planetary waves, which induce large meanders in the jet-stream in turn favouring the spatial compounding of the heatwaves. Specifically, planetary waves with zonal wavenumbers 5 and 7 are recurrent in summer, and have a favoured phase position, making them very effective drivers of synchronised regional heatwaves (Kornhuber *et al.*, 2020). While no scientific consensus on future

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changes in these wave-patterns has been established so far, their impacts are expected to become more severe due to thermodynamic factors alone, possibly enhancing crop production volatility and imperilling global food security.

Food security was also one of the motivations underlying Paolo De Luca's study of co-occurring wet and dry extreme events on a global scale (De Luca *et al.*, 2020b). Paolo highlighted periods in the observational record when large parts of the global land surface were simultaneously affected by flooding and drought, and then proceeded to evaluate the correlations between these extremes and leading modes of climate variability. The El Niño–Southern Oscillation, Pacific Decadal Oscillation, and Atlantic Multidecadal Oscillation show regionally significant correlations with wet and dry extremes, highlighting how their interplay may lead to extensive co-occurrence episodes. This result puts the spotlight on global multi-hazard maps as a key tool to evaluate worst-case hydrological scenarios.

Large-scale variability patterns were also highlighted by Kunhui Ye as key to the spatial compounding of extremes. Kunhui discussed the large-scale dynamics underlying the Warm Arctic – Cold Eurasia (WACE) pattern observed in recent decades, and highlighted two wintertime circulation modes of variability. Decadal trends in these modes explain a large part of the observed WACE pattern and additionally lead to a heightened frequency of temperature extremes over Northern Europe and Northern Eurasia (Ye and Messori, 2020).

The focus next shifted to temporally compounding events. Olivia Martius revisited several methods that have been proposed to characterize and quantify temporal (serial) clustering – including the index of dispersion, Ripley's K and the Cox Regression – with a specific focus on the serial clustering of heavy precipitation. The latter has implications on seasonal-to-yearly timescales for insurance contracts and the broader economy (Priestley *et al.*, 2018), and on sub-seasonal time-scales for flooding (Barton *et al.*, 2016). Olivia highlighted how most of the available statistical approaches quantify the significance of serial clustering and allow to include covariates, but are unable to identify specific clustering episodes and require a predefined event set.

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Day 3: Cross-disciplinary Methodologies for the Study of Compound Events

The final day of the workshop was dedicated to methodological innovations for the study of compound climate events and extremes, with a focus on cross-pollination from fields beyond climate science.

Flavio Pons opened the day by presenting a novel bias correction approach for snowfall in climate models. Accurate estimation of snowfall is crucial to correctly describing compound hydrometeorological events in winter, such as rain-on-snow episodes, yet climate models often display large biases in this respect (Frei *et al.*, 2018). Flavio argued that, by combining breakpoint search algorithms with cubic spline logit-linear regression outputs, it is possible to improve on past bias-correction methods for snowfall by relying only on temperature and precipitation data. The method provided encouraging results when applied to the ERA5 reanalysis data (Hersbach *et al.*, 2020) and to a high-resolution numerical climate simulation over Europe, and offers a feasible approach to reconstruct snowfall without requiring multivariate or conditional bias correction, nor stochastic generation of unobserved events.

The issue of model biases, and of how to evaluate the ability of climate models to simulate compound events, is indeed crucial to gaining a robust understanding of the latter. Compound extremes are particularly challenging in this respect, since many commonly used model evaluation metrics for multivariate distributions, such as correlation coefficients, are not suitable for isolating extreme occurrences. Jakob Zscheischler proposed a new metric, based on the Kullback–Leibler divergence concept from information theory, that measures whether the tails of different bivariate distributions show a similar dependence structure. Such metric was then used to compare compound precipitation and wind extremes in the Alpine region across different datasets (Zscheischler *et al.*, *in review*). Boundary conditions appear to be a key factor in correctly modelling compound extremes, while external forcings are a second-order effect. The proposed metric allows to evaluate climate

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model simulations with respect to compound extremes, and to outline key requirements for future model development.

The difficulty of modelling compound extremes, and more broadly low-probability events, was also the topic of Pascal Yiou's presentation. Pascal presented a methodology combining importance sampling – often used in statistical mechanics – with a stochastic weather generator based on circulation analogues. This allows to simulate physically plausible, but unprecedented, long-lasting events such as warm or wet seasons (Yiou and Jézéquel, 2020). In this context, analogues are days displaying similar large-scale atmospheric states over a chosen geographical domain. The methodology was then applied to simulate temporally compounding warm winters and wet springs in France. These events have a major detrimental effect on French wheat production: in 2016, a record-low yield was reported due to warm winter temperatures followed by heavy precipitation in May. The stochastic importance sampling tool shows that the present-day climatic conditions in principle allow for a compound warm winter – wet spring event even more devastating than that of 2016 (Pfleiderer *et al.*, *in review*). This type of approach thus allows investigating the properties of unprecedented events linked to the large-scale atmospheric circulation.

Closely related to the study of unprecedented compound events is the question of how anthropogenic emissions may impact hazardous climate events. This is often studied under the assumption that the atmospheric circulation associated to such events is not itself affected by climate change. However, the compound events paradigm demands for new methodologies in this respect. Davide Faranda presented an approach grounded in dynamical systems theory, that allows diagnosing the role of the atmospheric circulation during hazardous extreme events (Faranda *et al.*, 2017). The approach is based on embedding the circulation patterns observed during selected extremes into historical climate simulations and future projections. When applied to the latter, it highlights major changes in the probability, predictability and persistence of large-scale atmospheric patterns leading to hazardous extremes such as European heatwaves and cold spells (Faranda *et al.*, 2020).

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These results highlight that dynamical changes in the atmosphere must be taken into account when performing attribution studies for compound events.

Future Perspectives and Challenges in the Field

The results presented during the workshop highlighted the breadth of climate drivers and hazards falling under the umbrella term *compound events*, even when focussing on the mid-latitudes. At the same time, the presentations underscored some pivotal ideas – both theoretical and methodological – that may be leveraged as unifying paradigms for advancing our understanding of the topic. Recurrent planetary-scale atmospheric anomalies, such as those associated with planetary wave-patterns and the closely-related storm-track variability, provide an effective lens for interpreting different categories of compound events, from multivariate extremes such as wet and windy episodes (e.g. Messori *et al.*, 2019; De Luca *et al.*, 2020a) to spatially compounding heatwaves (e.g. Kornhuber *et al.*, 2019; 2020) to compound long-lasting anomalies (Yiou and Jézéquel, 2020). Persistence was also highlighted as an overarching concept relevant to a diverse set of compound events. Often, multivariate or spatially compounding extremes are associated with unusually persistent large-scale atmospheric anomalies. Similarly, persistent structures can be key for driving temporally compounding events. The workshop also pointed to the added value of cross-pollination with tools drawn from other fields of science, such as dynamical systems theory, statistical physics or information theory. These tools provide, for example, a means of simulating unprecedented compound events (Yiou and Jézéquel, 2020) or evaluating the ability of climate models to reproduce compound extremes (Zscheischler *et al.*, *in review*). They also provide a framework to diagnose the role of changes in atmospheric dynamics in modulating the frequency of occurrence and physical properties of hazardous extremes in future climates (Faranda *et al.*, 2020). These advances do not preclude the relevance of more conventional analyses based on atmospheric dynamics, and indeed partly rely on the latter through, for example, the calculation of circulation analogues for compound events.

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During the daily roundtable discussions, the workshop participants also distilled some outstanding challenges faced by the compound climate events community. These pertain to both the seamless integration of the different perspectives discussed above and to longer-standing interpretational issues in atmospheric dynamics. A first, fundamental challenge is to develop a clear terminology to distinguish between different compound events and extremes. A decisive step in this direction was recently made with the publication of a compound events typology (Zscheischler *et al.*, 2020), but a continued collective effort by the community is needed in this respect.

A similar problem extends to the integration of perspectives issued from different fields of science, where the same term may be used with different meanings. *Persistence* is emblematic in this respect: on the one hand, it was identified as a concept of relevance to a broad range of compound events; on the other hand, discussions on persistence highlighted how the meaning of the term is highly context-specific. In dynamical systems theory, persistence relates to how long the system being studied resides in a given neighbourhood in an appropriately defined phase-space (e.g. Faranda *et al.*, 2017). In the atmospheric sciences, persistence is used very broadly: from the number of consecutive days the atmosphere spends within a given cluster of large-scale configurations (often referred to as *weather regimes*), to the duration of propagating structures, such as planetary wave-patterns. Each definition has advantages and shortcomings, and reflects different aspects of the evolution of a given system. A concerted effort is required to compare and reconcile the different viewpoints and identify those most relevant to specific classes of compound events.

Other challenges reflect long-standing open questions within the atmospheric sciences. The continuum of spatial and temporal scales within the climate system complicates separating the drivers of specific compound events. For example, the interplay between planetary waves and storm track variability often results in a chicken-and-egg problem of what drives what. Similarly, energy transfers across scales – resulting in direct and inverse turbulent energy cascades – are key for triggering atmospheric waves, yet they can be complex to diagnose and quantify (e.g. Faranda *et al.*, 2018). These challenges feed into the broader difficulty of understanding the role of atmospheric dynamics

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in climate change (Shepherd, 2014), and particularly in modulating the frequency and nature of future compound events.

Finally, a challenge unique to this year – albeit common to all fields of research – was the need to hold a virtual meeting. On the one hand, this enabled the participation of colleagues who may have been unable to travel to a physical meeting even under normal circumstances. On the other hand, it required a careful tailoring of the workshop's format to enable effective discussions and brainstorming. For example, a deliberate choice was made to reduce the audience to a minimum, and to shorten the time allotted to individual presentations. While the informal and often extremely useful "coffee-break interactions" are difficult to reproduce in a virtual setting, the authors of this report were overall satisfied with the ease and quality of the virtual discussions.

In summary, the workshop's outcomes motivate a cautious optimism and the view that neither the scientific nor the logistic challenges facing research on compound events are unsurmountable. For example, dynamical systems theory and statistical physics can help to diagnose how future changes in atmospheric dynamics may affect compound events. Similarly, a joint application of different concepts of persistence to temporally compounding precipitation extremes was discussed during the workshop, and no *a priori* major theoretical or technical hindrances were identified. Ultimately, the workshop helped to identify and describe key challenges in the study of compound climate events and extremes, which is an important first step towards developing concerted initiatives to tackle them.

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