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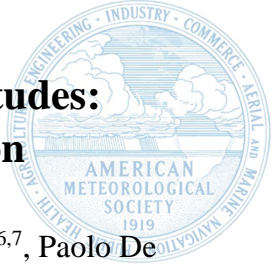
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# Compound climate events and extremes in the mid-latitudes: dynamics, simulation and statistical characterisation

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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:** 7<sup>th</sup> – 9<sup>th</sup> September 2020

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

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

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

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

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

52

53

#### 54 **Day 1: Drivers of Multivariate Compound Events**

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

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

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

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

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

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

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

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## 111 **Day 2: Spatially or Temporally Compounding Events**

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

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

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

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

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

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

147

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

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

153 Flavio Pons opened the day by presenting a novel bias correction approach for snowfall in climate  
154 models. Accurate estimation of snowfall is crucial to correctly describing compound  
155 hydrometeorological events in winter, such as rain-on-snow episodes, yet climate models often  
156 display large biases in this respect (Frei *et al.*, 2018). Flavio argued that, by combining breakpoint  
157 search algorithms with cubic spline logit-linear regression outputs, it is possible to improve on past  
158 bias-correction methods for snowfall by relying only on temperature and precipitation data. The  
159 method provided encouraging results when applied to the ERA5 reanalysis data (Hersbach *et al.*,  
160 2020) and to a high-resolution numerical climate simulation over Europe, and offers a feasible  
161 approach to reconstruct snowfall without requiring multivariate or conditional bias correction, nor  
162 stochastic generation of unobserved events.

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



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

175 The difficulty of modelling compound extremes, and more broadly low-probability events, was  
176 also the topic of Pascal Yiou's presentation. Pascal presented a methodology combining importance  
177 sampling – often used in statistical mechanics – with a stochastic weather generator based on  
178 circulation analogues. This allows to simulate physically plausible, but unprecedented, long-lasting  
179 events such as warm or wet seasons (Yiou and Jézéquel, 2020). In this context, analogues are days  
180 displaying similar large-scale atmospheric states over a chosen geographical domain. The  
181 methodology was then applied to simulate temporally compounding warm winters and wet springs  
182 in France. These events have a major detrimental effect on French wheat production: in 2016, a  
183 record-low yield was reported due to warm winter temperatures followed by heavy precipitation in  
184 May. The stochastic importance sampling tool shows that the present-day climatic conditions in  
185 principle allow for a compound warm winter – wet spring event even more devastating than that of  
186 2016 (Pfleiderer *et al.*, *in review*). This type of approach thus allows investigating the properties of  
187 unprecedented events linked to the large-scale atmospheric circulation.

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

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

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## 202 **Future Perspectives and Challenges in the Field**

203 The results presented during the workshop highlighted the breadth of climate drivers and hazards  
204 falling under the umbrella term *compound events*, even when focussing on the mid-latitudes. At the  
205 same time, the presentations underscored some pivotal ideas – both theoretical and methodological –  
206 that may be leveraged as unifying paradigms for advancing our understanding of the topic. Recurrent  
207 planetary-scale atmospheric anomalies, such as those associated with planetary wave-patterns and the  
208 closely-related storm-track variability, provide an effective lens for interpreting different categories  
209 of compound events, from multivariate extremes such as wet and windy episodes (e.g. Messori *et al.*,  
210 2019; De Luca *et al.*, 2020a) to spatially compounding heatwaves (e.g. Kornhuber *et al.*, 2019; 2020)  
211 to compound long-lasting anomalies (Yiou and Jézéquel, 2020). Persistence was also highlighted as  
212 an overarching concept relevant to a diverse set of compound events. Often, multivariate or spatially  
213 compounding extremes are associated with unusually persistent large-scale atmospheric anomalies.  
214 Similarly, persistent structures can be key for driving temporally compounding events. The workshop  
215 also pointed to the added value of cross-pollination with tools drawn from other fields of science,  
216 such as dynamical systems theory, statistical physics or information theory. These tools provide, for  
217 example, a means of simulating unprecedented compound events (Yiou and Jézéquel, 2020) or  
218 evaluating the ability of climate models to reproduce compound extremes (Zscheischler *et al.*, *in*  
219 *review*). They also provide a framework to diagnose the role of changes in atmospheric dynamics in  
220 modulating the frequency of occurrence and physical properties of hazardous extremes in future  
221 climates (Faranda *et al.*, 2020). These advances do not preclude the relevance of more conventional  
222 analyses based on atmospheric dynamics, and indeed partly rely on the latter through, for example,  
223 the calculation of circulation analogues for compound events.

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

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

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

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

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

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

268

269

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273 physical meeting have taken place.

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275

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