



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

Gabriele Messori, Emanuele Bevacqua, Rodrigo Caballero, Dim Coumou, Paolo de Luca, Davide Faranda, Kai Kornhuber, Olivia Martius, Flavio Pons, Colin Raymond, et al.

► To cite this version:

Gabriele Messori, Emanuele Bevacqua, Rodrigo Caballero, Dim Coumou, Paolo de Luca, et al.. Compound climate events and extremes in the mid-latitudes: dynamics, simulation and statistical characterisation. Bulletin of the American Meteorological Society, 2021, 102 (4), pp.E774-E781. 10.1175/bams-d-20-0289.1 . hal-03193711

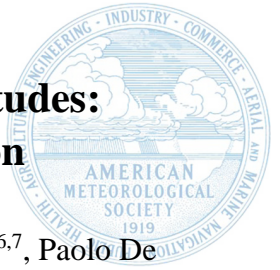
HAL Id: hal-03193711

<https://hal.science/hal-03193711>

Submitted on 9 Apr 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



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

Gabriele Messori^{1,2,3,4,*}, Emanuele Bevacqua⁵, Rodrigo Caballero^{3,4}, Dim Coumou^{6,7}, Paolo De Luca⁶, Davide Faranda^{8,9,10}, Kai Kornhuber^{11,12}, Olivia Martius^{13,14}, Flavio Pons⁸, Colin Raymond¹⁵, Kunhui Ye¹, Pascal Yiou⁸, Jakob Zscheischler^{14,16,17}

¹Department of Earth Sciences, Uppsala University, Uppsala, Sweden.

²Centre of Natural Hazards and Disaster Science (CNDS), Uppsala, Sweden.

³Department of Meteorology, Stockholm University, Stockholm Sweden.

⁴Bolin Centre for Climate Research, Stockholm University, Stockholm Sweden.

⁵Department of Meteorology, University of Reading, Reading, United Kingdom.

⁶Department of Water and Climate Risk, Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, the Netherlands.

⁷Royal Netherlands Meteorological Institute (KNMI), De Bilt, the Netherlands.

⁸Laboratoire des Sciences du Climat et de l'Environnement (LSCE), UMR8212, CNRS-CEA-UVSQ, Université Paris Saclay, IPSL, Gif-sur-Yvette, France.

⁹LMD – École Normale Supérieure, Paris, France.

¹⁰London Mathematical Laboratory, London, United Kingdom.

¹¹Earth Institute, Columbia University, New York, United States.

¹²Lamont-Doherty Earth Observatory, Columbia University, New York, United States.

¹³Institute of Geography, University of Bern, Bern, Switzerland.

¹⁴Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

¹⁵Jet Propulsion Laboratory/California Institute of Technology, Pasadena, United States.

¹⁶Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland

¹⁷Department for Computational Hydrosystems, Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany.

* Corresponding author: gabriele.messori@geo.uu.se

Early Online Release: This preliminary version has been accepted for publication in *Bulletin of the American Meteorological Society*, may be fully cited, and has been assigned DOI 10.1175/BAMS-D-20-0289.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

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

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

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

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

148

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.

200

201

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

270 **Acknowledgements**

271 The workshop was convened by G. Messori, and was held virtually due to the COVID-19 pandemic.
272 However, the Stockholm International Meteorological Institute had made funding available should a
273 physical meeting have taken place.

274

275

276

277 **References**

- 278 Barton, Y., P. Giannakaki, H. von Waldow, C. Chevalier, S. Pfahl, and O. Martius (2016). Clustering
279 of Regional-Scale Extreme Precipitation Events in Southern Switzerland. *Mon. Wea. Rev.*, **144**, 347-
280 369.
- 281 Bevacqua, E., Maraun, D., Hobæk Haff, I., Widmann, M., and Vrac, M. (2017). Multivariate
282 statistical modelling of compound events via pair-copula constructions: analysis of floods in Ravenna
283 (Italy), *Hydrol. Earth Syst. Sci.*, **21**, 2701–2723.
- 284 Bevacqua, E., Vousdoukas, M. I., Zappa, G., Hodges, K., Shepherd, T. G., Maraun, D., Mentaschi,
285 L., and Feyen, L. (2020a). More meteorological events that drive compound coastal flooding are
286 projected under climate change. *Communications Earth & Environment*, *in press*.
- 287 Bevacqua, E., Vousdoukas, M. I., Shepherd, T. G., and Vrac, M. (2020b). Brief communication: The
288 role of using precipitation or river discharge data when assessing global coastal compound flooding.
289 *Nat. Hazards Earth Syst. Sci.*, **20**, 1765–1782.
- 290 De Luca, P., Messori, G., Pons, F.M.E., Faranda, D. (2020a) Dynamical systems theory sheds new
291 light on compound climate extremes in Europe and Eastern North America. *Q. J. R. Meteorol.*
292 *Soc.*, **146**: 1636– 1650.
- 293 De Luca, P., Messori, G., Wilby, R. L., Mazzoleni, M., and Di Baldassarre, G. (2020b). Concurrent
294 wet and dry hydrological extremes at the global scale. *Earth Syst. Dynam.*, **11**, 251–266.
- 295 Faranda, D., Messori, G., Yiou, P. (2017). Dynamical proxies of north atlantic predictability and
296 extremes. *Sci. Rep.*, **7**, 41278.
- 297 Faranda, D., Lembo, V., Iyer, M., Kuzzay, D., Chibbaro, S., Daviaud, F. and Dubrulle, B. (2018).
298 Computation and characterization of local subfilter-scale energy transfers in atmospheric flows. *J.*
299 *Atmos. Sci.*, **75**(7).
- 300 Faranda, D., Vrac, M., Yiou, P., Jézéquel, A., & Thao, S. (2020). Changes in future synoptic
301 circulation patterns: Consequences for extreme event attribution. *Geophys. Res. Lett.*, **47**,
302 e2020GL088002.
- 303 Frei, P., Kotlarski, S., Liniger, M. A., & Schar, C. (2018). Future snowfall in the Alps: projections
304 based on the EURO-CORDEX regional climate models. *The Cryosphere*, **12**(1), 1-24.
- 305 Hersbach, H., B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C.
306 Peubey, R. Radu, and D. Schepers. (2020). The ERA5 global reanalysis. *Quart. J. Roy. Met. Soc.* **146**,
307 730: 1999-2049.
- 308 Kornhuber, K., Osprey, S., Coumou, D., Petri, S., Petoukhov, V., Rahmstorf, S., & Gray, L. (2019).
309 Extreme weather events in early summer 2018 connected by a recurrent hemispheric wave-7 pattern.
310 *Env. Res. Lett.*, **14**(5), 054002.
- 311
312 Kornhuber, K., Coumou, D., Vogel, E., Lesk, C., Donges, J. F., Lehmann, J., & Horton, R. M. (2020).
313 Amplified Rossby waves enhance risk of concurrent heatwaves in major breadbasket regions. *Nature*
314 *Clim. Change*, **10**(1), 48-53.
- 315 Lorenz, E. N. (1990). Can chaos and intransitivity lead to interannual variability? *Tellus A*, **42**(3),
316 378-389.
- 317 Messori, G., and Caballero, R. (2015). On double Rossby wave breaking in the North Atlantic. *J.*
318 *Geophys. Res. Atmos.*, **120**, 11,129– 11,150.

319 Messori, G., Davini, P., Alvarez-Castro, M.C. *et al.* (2019) On the low-frequency variability of
320 wintertime Euro-Atlantic planetary wave-breaking. *Clim. Dyn.*, **52**, 2431–2450.

321 Monteiro, J. M. and Caballero, R. (2019). Characterization of extreme wet- bulb temperature events
322 in Southern Pakistan. *Geophys. Res. Lett.*, **46**:10659–10668.

323 Pfleiderer, P., Jézéquel, A., Legrand, J., Legrix, N., Markantonis, I., Vignotto, E., and Yiou, P.
324 Simulating compound weather extremes responsible for critical crop failure with stochastic weather
325 generators. *Earth Syst. Dynam. Discuss.*, *in review*.

326 Priestley, M. D. K., Dacre, H. F., Shaffrey, L. C., Hodges, K. I. and Pinto, J. G. (2018). The role of
327 serial European windstorm clustering for extreme seasonal losses as determined from multi-
328 centennial simulations of high resolution global climate model data. *Nat. Haz. Earth Sys. Sci.*, **18**,
329 2991–3006.

330 Raymond, C., Matthews, T., Horton, R. M. (2020). The emergence of heat and humidity too severe
331 for human tolerance. *Sci. Adv.*, **6**(19), eaaw1838.

332 Shepherd, T. G. (2014). Atmospheric circulation as a source of uncertainty in climate change
333 projections. *Nature Geosci.*, **7**(10), 703–708.

334 Sherwood, S. C. and Huber, M. (2010). An adaptability limit to climate change due to heat stress.
335 *Proc. Natl. Acad. Sci. USA*, **107**:9552–9555.

336 Ye, K., Messori, G. (2020). Two Leading Modes of Wintertime Atmospheric Circulation Drive the
337 Recent Warm Arctic–Cold Eurasia Temperature Pattern. *J. Clim.*, **33**(13), 5565–5587.

338 Yiou, P. and Jézéquel, A. (2020). Simulation of extreme heat waves with empirical importance
339 sampling. *Geosci. Model Dev.*, **13**, 763–781.

340 Zscheischler, J., S. Westra, B. J. J. M. van den Hurk, S. I. Seneviratne, P. J. Ward, A. Pitman, A.
341 AghaKouchak, D. N. Bresch, M. Leonard, T. Wahl, and X. Zhang (2018). Future climate risk from
342 compound events. *Nature Climate Change*, **8**, 469–477.

343 Zscheischler, J., Martius, O., Westra, S. *et al.* (2020). A typology of compound weather and climate
344 events. *Nat. Rev. Earth Environ.*, **1**, 333–347.

345 Zscheischler, J., Naveau, P., Martius, O., Engelke, S., and Raible, C. C. (2020). Evaluating the
346 dependence structure of compound precipitation and wind speed extremes. *Earth Syst. Dynam.*
347 *Discuss.*, *in review*.