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Mediterranean Extreme Precipitation: Amplification by Warmer Sea Surface Temperatures in a Kilometer-Scale Regional Model

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Abstract

We employ convection-permitting regional climate modeling to analyze the intense Mediterranean Heavy Precipitation Event (HPE) in October 2020 in the south-eastern French Alps and north-western Italian Alps regions, post passage of extra-tropical storm Alex. Exploring the event's sensitivity to warmer sea surface temperatures (SSTs), we conduct modeling experiments for September-October 2020 in western Europe. An ensemble-based approach is adopted to comprehensively assess local uncertainties purely driven by internal variability.

Using the CNRM-AROME model, we accurately reproduce the HPE and precursor storm Alex characteristics, including the observed sequence of extreme events and related regional to local impacts. Sensitivity experiments are then conducted with idealized and uniform 2K warming and cooling patterns added to the SSTs over the entire domain and the Mediterranean Sea solely, all other forcings kept identical and representative of the 2020 observed conditions.

SST warming intensifies the HPE's extremeness and accumulated precipitation amounts over the Alps. This is accompanied by a shift of the most intense precipitation eastward. In contrast, the strengthening of storm Alex with SST warming has limited impact on the Mediterranean HPE. Our findings underscore the crucial role of Mediterranean warming, enhancing moisture and instability upstream, and fostering deep atmospheric convection over the mountainous coastal region. A plausible worst-case scenario testing warmer SSTs in 2022 on HPE and storm Alex suggests milder precipitation-related impacts in the French Alpes-Maritimes region but increased damage in Italy.

Keywords

Heavy precipitation events; intensification of extreme precipitation; sensitivity to sea surface temperature; kilometer-scale regional climate modeling; convection-permitting modeling

50

51 **1. Introduction**

52 On the 1st of October 2020, the intense extra-tropical storm Alex hit the north-west
53 coasts of France, bringing heavy rainfall, and causing flooding and damage to the electricity
54 network (Kreitz, 2021). Very intense wind gusts of remarkable intensity for this time of year
55 were recorded. Around the low-pressure system centered at the tip of Brittany, a rapid
56 southerly flow of warm and moist air triggered a very wet disturbance over a large part of
57 eastern France.

58 Local strengthening of convective precipitation due to orographic lifting and low-level
59 wind convergences, along with slow-evolving large-scale situation, led to record-breaking
60 rainfall amounts over the 2nd and the 3rd of October in south-eastern French Alps and north-
61 western Italian Alps regions. More than 600mm in 24 hours and 90mm in 1 hour were
62 recorded in the French Alpes-Maritimes region (Chochon et al., 2021; Kreitz, 2021; Payrastre
63 et al., 2022). In France, this Heavy Precipitation Event (HPE) caused severe flooding and
64 landslides, killing at least 10 people, and leaving hundreds of people homeless (Météo-
65 France, 2021). It accounted for an economic loss of approximately 1 billion euros in damage.
66 Several villages in the French Vésudie and Roya valleys have been isolated and without
67 drinking water for several months due to the destruction of roads, bridges, and tunnels.

68

69 The synoptic situation of this event is typical of those observed during Mediterranean
70 HPEs (Ducrocq et al., 2008; Khodayar et al., 2016; Nuissier et al., 2008): a quasi-stationary
71 atmospheric system is associated with a low-level moist flow toward the coast, with a
72 supply in water by evaporation of the autumnal warm Mediterranean sea surface
73 temperatures (SSTs) and from remote tropical sources (Duffourg & Ducrocq, 2013; Krichak
74 et al., 2015). Along the land coastline, heavy precipitation is triggered by local reinforcement
75 of convective precipitation by orographic lifting, and lifting induced by low-level wind
76 convergence and cold pools (Bresson et al., 2012; Ducrocq et al., 2008).

77 Although this mountainous Mediterranean region has experienced other damaging HPEs
78 in the past, the intensity of the 2020 HPE is exceptional (Payrastre et al., 2022). Rainfall
79 accumulations were exceptional while maximum hourly rates and discharge rates were
80 intense yet not record-breaking for the region (Payrastre et al., 2022). This observed
81 extreme event will serve as a crucial benchmark for studying natural hydrometeorological
82 hazards and their evolution in the context of climate change.

83 The high-impact HPE of October 2-3 is the focus of this study. We take a stronger
84 emphasis on the south-eastern French region of Alpes-Maritimes than the north-western
85 Italian Alps due to availability of high spatial and temporal resolution observations limited to
86 France.

87

88 Contextualizing this event within the framework of ongoing regional climate change is
89 essential for a comprehensive understanding of its distinct characteristics and exceptional
90 nature. Over mainland France, surface air temperatures in 2020 were estimated +1.66 °C
91 [1.41-1.90 °C] warmer with respect to the 1900-1930 period and the projected rise is of +3.8
92 °C [2.9-4.8 °C] by 2100 in an intermediate scenario of emission, and up to +6.7 °C [5.2- 8.2
93 °C] in a very high emission scenario (Ribes et al., 2022). As for extreme precipitation,
94 changes have been detected in the observations, with an increase in the frequency and
95 intensity of extreme precipitation events in the French Mediterranean region (Ribes et al.,
96 2019). SSTs in the Mediterranean basin are also rising (Simon et al., 2023) and it has been

97 shown that warmer SSTs can significantly intensify extreme precipitation in autumn in the
98 western Mediterranean basin (González-Alemán et al., 2023). Furthermore, a non-linear
99 relationship between SST warming and the intensification of precipitation extremes have
100 been found in the Black Sea coastal region (Meredith et al., 2015).

101 Hence, it is essential to assess the effects of contemporary and future climate change on
102 high-impact extreme precipitation events such as the HPE observed in October 2-3, 2020.
103 Here, we assess how idealized warm SSTs contribute to the extremeness of this observed
104 HPE. We further explore the sensitivity to SSTs by investigating a plausible worst-case
105 scenario where the timeline of extreme events would occur under year 2022 warmer
106 Mediterranean SST conditions.

107
108 We utilize convection-permitting regional climate modeling with a spatial resolution of
109 2.5 km to achieve realistic simulation of atmospheric deep convection and its associated
110 triggering processes. Short-duration simulations covering September-October 2020 in
111 western Europe are conducted, employing an ensemble-based approach to thoroughly
112 assess local uncertainties purely driven by internal variability.

113 Kilometer-scale modeling has demonstrated improvements in representing hourly
114 precipitation and extremes compared to conventional regional climate models with
115 parametrized convection (Ban et al., 2021; Berthou et al., 2020a; Lucas-Picher et al., 2023;
116 Pichelli et al., 2021). We carry out modeling experiments with the CNRM-AROME model that
117 has been shown to correctly reproduce the frequency and intensity of HPEs compared to
118 observations (Caillaud et al., 2021; Fumière et al., 2020). Additionally, it compares
119 reasonably well with other CP-RCMs over Europe (Caillaud et al., n.d.; Coppola et al., 2020).

120
121 In section 2, we introduce the model, simulation set-up, ensemble-based simulation,
122 description of the modelling experiments, observations, and the general framework of
123 analysis used in this study. Results are then presented in three subsections: section 3a
124 focuses on the simulation of the observed extreme event, section 3b assesses the impact of
125 warmer SSTs on the simulated event, and section 3c explore the worst-case scenario.
126 Finally, a discussion of our results is provided in section 4 followed by concluding remarks in
127 section 5.

130 2. Data and Methods

132 2.1. Data

133 Hourly precipitation observations at very high spatial resolution (1 km) are taken
134 from the COMEPHORE dataset developed by Météo-France (Fumière et al., 2020). This
135 blended product combines *in situ* data (~4000 and ~1200 rain gauges with a daily and hourly
136 timestep, respectively) and local radar reflectivities (5 minutes timestep) (see Appendix A of
137 Caillaud et al. (2021) for more details). It covers mainland France and Corsica, from 1997 to
138 2022. COMEPHORE observations have been regridded to the CNRM-AROME curvilinear grid
139 of 2.5 km using a second-order conservative scheme.

140 Hourly precipitation data is also taken from the ERA5 reanalysis, on its native spatial
141 resolution of 25 km (Hersbach et al., 2020). The objective is not to directly compare
142 precipitation intensity between CNRM-AROME and ERA5 considering their differences in
143 spatial resolution and representation of convective processes (parameterized in ERA5).

144 Instead, the timeline of the events from the passage of storm Alex to the onset of the
145 Mediterranean HPE and related impacts with regards to precipitation are compared.

146

147 Pseudo-observations of orography at ~90m spatial resolution are taken from the
148 Shuttle Radar Topography Mission database (<https://srtm.csi.cgiar.org/>) (Jarvis et al., 2008).

149

150 2.2. The convection-permitting regional climate model CNRM-AROME

151 CNRM-AROME is an area limited atmospheric model. It is based on the current French
152 numerical weather prediction (NWP) system AROME used since 2008 operationally by
153 Météo-France and that has been continuously improved over the years to gain in accuracy
154 of prediction for extreme precipitation events and HPEs particularly (Brousseau et al., 2016;
155 Seity et al., 2011).

156 CNRM-AROME can be considered as the climate counterpart to the NWP model AROME.
157 They share the same physics and non-hydrostatic dynamical core. Apart from the use of
158 data assimilation in the case of the NWP model, the two models differ mainly in their
159 resolution and a wider relaxation zone for CNRM-AROME, for a stronger constrain from the
160 driving data within the inner model (see (Caillaud et al., 2021) for more details). In addition,
161 the NWP model AROME has been proven to accurately forecast both the extra-tropical
162 storm ALEX and the HPE of October 2-3 in the French Alpes-Maritimes region a day before
163 the event (Chochon et al., 2021). For all these reasons, CNRM-AROME is considered a good
164 candidate for the simulation of this observed extreme precipitation event.

165

166 The advection scheme is semi-Lagrangian and the time discretization is semi-implicit.
167 The bi-spectral dynamical core is non-hydrostatic, which, along with the km-scale modeling,
168 allows the explicit simulation of the deep atmospheric convection, whereas shallow
169 convection at the sub-grid scale still requires to be parameterized.

170 The physiographic contrasts (land, urban, sea and inland waters) are finely described
171 (1km; ECOCLIMAP database; (Masson et al., 2003)) using four tiles per grid cells. Soil-
172 atmosphere interactions are resolved by the SURFEX V8 model (Le Moigne et al., 2020;
173 Masson et al., 2013). The version of CNRM-AROME used in this study is cycle46t1,
174 succeeding version cycle41t1 previously evaluated specifically for Mediterranean HPEs
175 (Caillaud et al., 2021) and for north-western Europe regional climate (Lucas-Picher et al.,
176 2023). The main differences between these two versions are: the implementation of a
177 correction for diurnal convection under low forcing conditions, a novel oceanic flux scheme
178 (ECUME V6;(Belamari & Pirani, 2007)), and updated land surface model SURFEX (version 8).
179 Overall, these two versions are very close, and we therefore refer to Table 2 of (Caillaud et
180 al., 2021) and (Lucas-Picher et al., 2023) for technical details on the model and physical
181 parameterizations.

182

183 2.3. Simulation set-up

184 The simulation domain covers western Europe centered over France (Figure 1a). It has a
185 spatial resolution of 2.5 km, with a conformal-Lambert projection, and 60 vertical levels with
186 hybrid coordinates levels (from 10m to ~1hPa). Out of the 60 levels, 21 are under 2000m
187 and the lower troposphere is hence finely represented in CNRM-AROME. The timestep of
188 CNRM-AROME is 60 seconds.

189

190 Lateral Boundary Conditions (LBCs) are imposed every hour and are derived from the
191 ERA5 reanalysis (Hersbach et al., 2020). For more details on the relaxation zone and more
192 generally on how LBCs forcings are imposed within this spectral model, please refer to
193 (Caillaud et al., 2021; Lucas-Picher et al., 2023).

194 For availability reason, the LBCs forcing data from ERA5 were taken at a lower
195 resolution (50km) than its native resolution. In our configuration, this leads with a resolution
196 jump of a factor 20 between the driving data and the inner model. We acknowledge this
197 resolution jump by considering a spatial spin-up, i.e. we exclude the edges of our
198 simulations from our analyses. This allows small scales features to fully develop away from
199 the LBCs. Following the guidelines of (Matte et al., 2017) and previous studies (Berthou et
200 al., 2020b; Caillaud et al., 2021; Fumière et al., 2020), we consider a spatial spin-up of 120
201 grid cells width. Analyses performed in this study always exclude these border areas too
202 close to the LBCs (see Figure 1a and note that simulated data used on Figure 3 and 4 is
203 masked according to the observational coverage which excludes grid cells within the spatial-
204 spin up area except for a few points at the north tip of France).

205
206 SSTs are also derived from ERA5 and are imposed monthly, using 3-month centered
207 mean. Hence, SSTs forcings in September and October consist of the August-September-
208 October (ASO) and September-October-November (SON) mean, respectively.

209
210 Except for water vapor that is directly simulated by the model, greenhouse gases
211 concentrations of year 2020 are taken from the Representative Concentration Pathways 4.5
212 (RCP4.5)(van Vuuren et al., 2011) for CO₂, N₂O, CH₄, CFC11 and CFC12. Aerosols are taken
213 from a blended product of remote sensed and simulated data (Nabat et al., 2013), providing
214 evolutive bidimensional distributions of dust, sea salt, sulfates, and organic and black carbon
215 aerosols.

216

217 2.4. Description of the modeling experiments

218 We carry out five 20-member ensembles of 2-month simulations starting on
219 September 1st up to October 31st, 2020. All the simulations of an ensemble share the same
220 initial conditions, which consist of the first LBC given to the entire domain for the
221 atmosphere. All 20 ensemble members also have identical lateral and surface conditions. A
222 very small random offset ($\sim 10^{-4}$ ppm) is added to the initial CO₂ concentration to each
223 ensemble member (as in (Bador et al., 2017)), which is enough to generate differences
224 across the simulations thanks to simulated internal variability within CNRM-AROME.

225

226 The *CTRL* experiment is the reference simulation, i.e. SSTs imposed as forcings are
227 those of year 2020 from the ERA5 reanalysis. Then, to assess the role of warmer (and
228 cooler) SSTs on the Mediterranean HPE of October 2-3, we conduct 4 different sensitivity
229 tests by modifying the SSTs but keeping the initial, lateral, and surface conditions consistent
230 and representative of September-October 2020.

231 A theoretical and spatially homogeneous pattern of +2°C/-2°C warming/cooling is
232 added on the SSTs of 2020 over the whole domain (*SST+2K* and *SST-2K* experiments,
233 respectively). These sensitivity tests are further complemented by another experiment
234 where we add the +2°C warming pattern but restricted to a Mediterranean box [3°W-
235 12.2°W;38°N-44.5°N] (*SST_MED+2K* experiment; see box on Figure 2).

236 We realize another experiment where SSTs of 2022 are used as surface forcings
237 instead of those of 2020 (*SST2022* experiment). The motivation behind this is that SSTs
238 during summer 2022 were anomalously hot (between +1.3 °C and 2.6 °C compared to 1982–
239 2011; Guinaldo et al., 2023) due to record-breaking marine heatwaves during summer in the
240 Mediterranean basin (González-Alemán et al., 2023; Guinaldo et al., 2023) that led to
241 warmer SSTs in fall 2022 compared to 2020 (Supplementary Figure 1). Years 2020 and 2022
242 are sufficiently close in time so that we can assume the observed extreme rainfall event of
243 2020 could have occurred in 2022, and that warming trends are of reasonable similarity
244 between these two years. This last modeling experiments thus allows exploring the
245 plausible worst-case scenario of the observed extreme events in 2020 (i.e. its synoptic
246 conditions) occurring only two years later in 2020 under warmer SSTs conditions.

247

248 According to ERA5 reanalysis data, the 2020 seasonal mean ASO and SON SSTs over
249 the whole domain are very close to the 1993-2022 climatology (Figure 2, first column). SSTs
250 are much warmer in 2022 (González-Alemán et al., 2023), with anomalies higher than 2°C in
251 the Mediterranean basin (Figure 2, second column). These 2022 SST anomalies in the center
252 of the Mediterranean box are close but slightly lower than the theoretical *SST+2K* ones,
253 whereas in the Atlantic Ocean for instance, SSTs in 2022 are generally cooler (at least 1°C)
254 than the idealized *SST+2K* (Figure 2, third column). Finally, *SST-2K* temperatures are much
255 cooler than the 1993-2022 climatology (between -0.5°C and -2.5; Figure 2, last column).

256

257 2.5. General framework of analysis

258 The majority of the analyses are performed over three different domains: the entire
259 domain (Figure 2a), an intermediate domain covering the western Alps ([5°W-10°W;43.5°N-
260 47.5°N], larger box on Figure 2a), and a smaller region centered over the French Alpes-
261 Maritimes region that was heavily impacted by the 2020 Mediterranean HPE (6.6°W-
262 8°W;43.5°N-44.6°N, smaller box in Figure 2a). Comparisons between the observations and
263 the model are limited by the spatial coverage of COMEPHORE (France and Corsica Island;
264 Figure 3).

265 Throughout this work, emphasis is given on the 5-day window centered on October 2
266 (i.e. September 30 to October 4), especially when focusing on the evolution of precipitation
267 at the hourly scale. This time window also captures the Alex storm hitting the coast of
268 France on October 1.

269

270

271 3. Results

272

273 3.1. Simulation of the observed extreme precipitation event

274 In this section, we demonstrate that the *CTRL* ensemble of CNRM-AROME simulates
275 reasonably well the observed Mediterranean HPE of October 2-3. Our primary objective
276 here is not to strive for the most realistic simulation of the observed event, a goal that could
277 have been pursued through spatial resolution refinement and additional model tuning.
278 Instead, we aim to replicate the general features of the HPE and the sequence of the
279 precipitation events that unfolded in the first days of October 2020, along with the full
280 distribution of outcomes due to internal variability.

281

282 First, we show that the ERA5 reanalysis captures well the sequence and the
283 exceptional intensity of the observed extreme precipitation event (Figure 3, first two
284 columns). Hence, using ERA5 as forcings to CNRM-AROME is relevant for the purpose of this
285 study.

286 Extra-tropical storm Alex hits Brittany on October 1, bringing heavy rainfall over this
287 area and the western part of France more generally (Figure 3, left). The Mediterranean HPE
288 in the south-eastern French Alps and north-western Italian Alps then occurs on October 2
289 with intense precipitation recorded. The peak of the event is at 20:00 GMT +1 in ERA5 and
290 18:00 GMT +1 in COMEPHORE in the evening of October 2, showing a reasonable alignment
291 between the two.

292 In addition, both the reanalysis and observations indicate relatively similar level
293 exceedances for the HPE intensity based on their respective 5-day climatology (September
294 30 to October 4; 1993-2022 for ERA5, 1997-2022 for COMEPHORE): hourly precipitation
295 rates exceed approximately 5 times the climatological values across their respective full
296 domain, around 10 times for an intermediate domain representative of the eastern Alps
297 region, and roughly 50 times for the core region of the French Alpes-Maritimes region
298 (which extends over Italy in ERA5; Figure 3 first two columns).

299
300 Then, we evaluate precipitation simulated by the CP-RCM CNRM-AROME. On
301 average over the observational domain (France and Corsica), the evolution of hourly
302 precipitation from September 30 to October 4 compares well between COMEPHORE
303 observations and the *CTRL* ensemble mean (Figure 3b,c).

304 Focusing on the French Alpes-Maritimes region affected by the intense
305 Mediterranean HPE, we find that COMEPHORE presents four organized bands of heavy
306 rainfall tilted along the south-west to north-east direction. These “rainfall corridors” are
307 mainly located over the valleys (Figure 1, top; Figure 3, second column). Locally, several
308 valleys are oriented along the axis of the low-level flow, causing air parcels to lift abruptly
309 when encountering pronounced contrasts in terrain. Hence, orographic lifting, coupled with
310 the stationary nature of the triggering zones, resulted in convective cells consistently
311 forming in nearly the same locations, where significant accumulations of precipitation were
312 observed (Chochon et al., 2021; Kreitz, 2021).

313 These rainfall bands are not found in the *CTRL* ensemble mean (Figure 3, third
314 column). Valleys are represented in CNRM-AROME, but the orography contrasts appear
315 smoother compared to observations (Figure 1), potentially contributing to certain simulated
316 precipitation biases. CNRM-AROME tends to precipitate over larger areas in the south-east
317 of France and the core region of the Alpes-Maritimes. It also underestimates the highest
318 intensities when compared to the observations (Figure 3e,f and 3h,i). At the center of the
319 observed heavy rainfall bands, where intensities are the highest, hourly precipitation
320 accumulated over the 24-hour window that best captures the Mediterranean HPE (i.e.
321 October 2 at 5am to October 3 at 4am) exceed 500 mm in the observations, contrasting
322 with 350 mm in CNRM-AROME.

323 Hence, on average over the French Alpes-Maritimes region, hourly precipitation
324 rates compare relatively well between the observations and CNRM-AROME. This hides a
325 compensatory effect, where the model captures a larger area impacted by heavy rainfall,
326 but the observations exhibit higher intensities (Figure 3 and Supplementary Figure 2 for
327 maps of bias). The model’s overestimation of the area affected by intense hourly rainfall
328 leads to higher peak intensities in the precipitation distribution compared to the

329 observations averaged over the intermediate domain of the western Alps and the French
330 Alpes-Maritimes region (Figure 3).

331

332 We further evaluate simulated precipitation with regards to hourly precipitation
333 extremes. Daily maximum values of hourly precipitation over the 2-month duration of the
334 *CTRL* simulation are compared to the observations, on average over the three domains
335 (Figure 4). October 2 exhibits the highest values in both the model and the observations, for
336 the three different domains but the smaller domain of the French Alpes-Maritimes region
337 more particularly. Daily maximum of hourly precipitation on October 2 is therefore taken as
338 an indicator of extremeness of the observed Mediterranean HPE and is further investigated
339 throughout this work.

340 As previously noted, we find higher intensities during the HPE when spatially
341 averaged in *CTRL* ensemble mean compared to the observations, for the three regions
342 considered. This pattern is consistently replicated in all 20 members of *CTRL*, which exhibit a
343 relatively uniform simulation of the hourly evolution of spatially averaged precipitation
344 (Supplementary Figures 2). None of the ensemble members can reproduce the observed
345 rainy bands and the observed pronounced spatial contrast in accumulated precipitation
346 amounts (Supplementary Figure 3).

347

348 Interestingly, the largest spread in average precipitation among the 20 members of
349 *CTRL* is not found on October 2 despite the HPE occurrence (Figure 4), which tends to
350 indicate a strong dynamical control by the synoptic situation. Throughout the simulation,
351 bursts of simulated internal variability occur on specific days (e.g., September 19-24), while
352 on other days, inter-member differences are limited (e.g. October 25 has larger
353 precipitation than September 19-24 yet smaller inter-member differences; Figure 4). These
354 bursts of simulated internal variability are also evident at the hourly scale during the HPE
355 (Supplementary Figure 2). Similar to the daily scale, the highest inter-member differences
356 do not coincide with the peak of the event but rather with its onset. Overall, all 20 members
357 of *CTRL* compare reasonably well with the observations over the 2-month simulation period
358 concerning daily maxima of hourly rainfall (Figure 4). All members replicate the observed
359 Mediterranean HPE with a similar pattern (Supplementary Figures 2 and 3), although some
360 inter-member differences capturing some stochasticity.

361 We argue that the ensemble-based simulation is important for case studies of
362 extreme precipitation to fully capture an event, including the most extreme rainfall
363 intensities that can be reached locally. These stochastic differences purely driven by internal
364 variability lead to different impacts locally, justifying the need to fully consider them in our
365 simulations. Indeed, the km-scale modelling allows the production of relevant local climate
366 information, which should always be associated with its relevant uncertainties.

367 This is demonstrated using the maximum values of hourly precipitation on October 2
368 as a measure of extremeness that we compare along the different realizations of the *CTRL*
369 ensemble. Inter-member spread is the highest over the ocean and in the eastern part of
370 simulation domain (Figure 5b,c). Focusing regionally on the intermediate domain of the
371 western Alps, it becomes evident that each of the 20 members exhibits slightly different
372 spatial distributions of the extreme rainfall cells (Figure 5d-w). Particularly in Italy, the
373 highest intensities can be found further eastward or northward according to the members.

374

375

3.2. Impact of 2°C warmer and cooler SSTs on the simulated extreme precipitation event

In this section, we explore the sensitivity of extreme precipitation to different SST conditions. Taking the *CTRL* ensemble as the reference, we assess the response of hourly precipitation in the modelling experiments where SSTs forcing conditions are modified using idealized patterns of uniform 2K warming and cooling. A plausible worst-case scenario with the observed SSTs of 2022 and related response in extreme precipitation will be discussed in the next section.

First, we explore the role of SSTs on the extremeness of precipitation throughout the 2-month duration of the simulations. On average over the entire domain, daily maxima of hourly precipitation generally respond as follow: 2K cooler SSTs lead to lower intensities (*SST-2K* experiment; blue line; Figure 6a) compared to *CTRL* (black line), and 2K warmer SSTs lead to higher intensities (*SST+2K* experiment; red line). The response in *SST_MED+2K* experiment (purple line; Figure 6) shows a similar pattern with higher intensities compared to *CTRL*. However, this intensification is more moderate than in *SST+2K*. This response to warmer and cooler SSTs is less clear when averaging over the intermediate and smaller regions (Figure 6b,c). This can be expected, as thermodynamic control exerts less influence on smaller scales, whereas, conversely, dynamical processes impose stronger constraints on precipitation (Emori & Brown, 2005; Pfahl et al., 2017).

This simple extremeness measure clearly shows that hourly precipitation on October 2 can be intensified by warmer SSTs (Figure 6). We further explore the changes in the spatial distribution of hourly precipitation maxima on that day corresponding to the peak of the Mediterranean HPE in the French Alpes-Maritimes region. Locally, hourly precipitation rates higher than 60 mm are found in the *CTRL* multi-member mean, and up to 80 mm across the different ensemble members (Figure 7a versus 7b).

Warming SSTs by 2K over the entire domain leads to an eastward shift of the most intense daily maxima of hourly precipitation, with values exceeding 50 mm displaced from the French Alpes-Maritimes region towards Italy (Figure 7c; see also Supplementary Figure 4c). Interestingly, our sensitivity modeling experiments demonstrate that the warming in the western Mediterranean basin is primarily responsible for this eastward shift (Figure 7d). Indeed, the spatial differences between *SST+2K* and *CTRL*, and those between *SST_MED+2K* and *CTRL* are rather similar in the multi-member mean. This shows that the 2020 Mediterranean HPE is highly sensitive to regional SSTs. In contrast, cooling SSTs by 2K over the entire domain leads to a decrease in the area affected by heavy precipitation compared to *CTRL* and lower intensities of daily maxima (Figure 7f), except for the north-western corner of Italy, where maxima are more intense in *SST-2K* (Supplementary Figure 4f).

Generally, a similar response is found for the evolution of hourly precipitation on average over the entire domain: warmer SSTs lead to an intensification of precipitation throughout the HPE duration, whereas cooler SSTs lead to a decrease in intensity (Figure 8a). Over the intermediate domain of the western Alps, the response of hourly precipitation to SSTs is very similar but the HPE tends to be shifted in time by a couple of hours in the *SST-2K* ensemble. Overall, the hourly evolution of average precipitation compares well between the *SST+2K* and *SST_MED+2K*, especially during the HPE and over the Alps region. This once again emphasizes that the HPE intensity is sensitive to regional SSTs.

423 Over the smaller domain of the French Alpes-Maritimes region, it is harder to
424 extract general conclusions on the sensitivity of hourly precipitation to warmer and cooler
425 SSTs (Figure 8c). The initiation of the HPE in the early hours of October 2 experiences a
426 delayed onset by a few hours under warmer SSTs compared to colder SSTs. Hourly
427 precipitation rates tend to be higher in *SST_MED+2K* compared to *SST+2K* but not
428 consistently throughout the HPE. In addition, hourly precipitation averaged over this smaller
429 domain does not consistently exhibit an intensification with warmer SSTs compared to *CTRL*.
430 This contrasts with the general increase on average over the larger domain where the
431 thermodynamic control is stronger. The interpretation of the response to SST warming is
432 here limited by the blending of spatially contrasting responses explored hereafter.

433 The spatial distribution of accumulated precipitation over the 24h hours period that
434 best represents the duration of the HPE (grey shading on Figure 8) depicts a similar
435 eastward shift of the precipitation areas with warmer SSTs (Figure 9; see also
436 Supplementary Figure 5). This aligns with the changes in daily maxima of hourly
437 precipitation (Figure 7). We note once again that SST warming solely in the western
438 Mediterranean basin leads to a very similar response in accumulated precipitation (Figure
439 9b,c). However, the decrease in intensity over the French Alpes-Maritimes region is slightly
440 smaller in *SST_MED+2K* compared to *SST+2K*, while the intensification is more pronounced
441 in *SST_MED+2K* in Italy (Figure 9b,c). The impact of cooler SSTs on accumulated
442 precipitation amounts is also in general agreement with results on daily maxima of hourly
443 precipitation (Figure 9e). A decrease in intensity is found in the area with the highest rainfall
444 *CTRL*, while an intensification occurs in the north-wester corner of the Italian Alps (Figure
445 9e).

446
447 One strength of our modeling study lies in our ability to simulate the entire sequence
448 of events that led to the occurrence of the Mediterranean HPE in the south-eastern French
449 Alps and the north-western Italian Alps on October 2-3, covering a substantial geographic
450 domain. This allows to assess the impact of warmer (and cooler) SSTs on the extra-tropical
451 storm Alex, how this can further induce modifications on the synoptic forcings responsible
452 for the onset of the HPE, and the consequences at the local scale of the French Alpes-
453 Maritimes region. Our focus hereafter is on the 24h period that best captures the HPE, from
454 October 2 at 5am to October 3 at 4am (grey shadings on Figures 3 and 8).

455 In the *CTRL* ensemble, we find that low pressures associated with the extra-tropical
456 storm Alex are located at the west tip of France (Britany region), with minimum values of
457 980.5 hPa in the core of the system (Figure 10a). Around the low pressures, strong onshore
458 winds bring maximum near-surface wind speed of gusts exceeding 150 km/h over the west
459 coast of France and Britany (i.e. maximum values over the 24h period and across the 20
460 members; Figure 11a). The location of storm Alex over Britany induces a south-eastern flow
461 in eastern side of the western Mediterranean basin, a rapid southern flow in the center of
462 the basin, and a south-western flow on the western side. These low-level flows are heading
463 towards the orographic barrier of the southern French and Italian Alps (Figure 10a).

464 Warming SSTs of 2K over the entire simulation domain leads to lower minimal values
465 of sea level pressure at the center of the low-pressure system (978.8 hPa in *SST+2K*; Figure
466 10b) whereas SST cooling results in higher values (980.6 hPa in *SST-2K*; Figure 10e).
467 Moreover, warmer SSTs contribute to an expanded spatial extent of low sea-level pressures,
468 while cooler SSTs result in a reduction. Over the west coast of France, this has a clear impact
469 on wind gusts with amplification and attenuation depending on the positive or negative SST

470 anomalies (Figure 11b,e). Overall, we find that warming (cooling) the SST consistently leads
471 to a negative (positive) response in sea level pressure, over both the Atlantic Ocean and the
472 Mediterranean Sea (Supplementary Figure 6).

473 Focusing on the *SST_MED+2K* ensemble, we find that the spatial extent of the low-
474 pressure system and the maximum wind gust intensities generally resemble those in *CTRL*
475 (Figure 10c and Figure 11c). This alignment is anticipated, considering that SSTs remain
476 unaltered over the Atlantic Ocean in this modeling experiment. Interestingly, patterns of sea
477 level pressure change compare well between *SST+2K* and *SST_MED+2K* in the western
478 Mediterranean Sea region. This indicates that changes in the characteristics of extra-tropical
479 storm Alex have limited impact on the changes in regional atmospheric circulation over the
480 Mediterranean Sea. These changes are primarily controlled by the response to regional sea
481 surface warming.

482 In both *SST+2K* and *SST_MED+2K* experiments, a negative response in sea level
483 pressure leads to wind anomalies circumventing the north of Corsica (Supplementary Figure
484 6b,c). This results in a tilting of the atmospheric flow in the eastern side of the simulated
485 Mediterranean domain, with a direction that becomes less southerly and more south-
486 southeasterly oriented. Meanwhile, in the western side, the low-level flow weakens and
487 penetrates less deeply inland into Italy compared to *CTRL* (Figure 10 and Supplementary
488 Figure 6).

489

490 Finally, we investigate the mechanisms responsible for the changes in accumulated
491 precipitation with warmer (and colder) SSTs over the south-eastern French Alps and north-
492 western Italian Alps over the 24h period of the Mediterranean HPE (Figure 12, first row).

493 Regionally, warmer SSTs lead to heating in the near-surface troposphere (Figure 12,
494 second line). In turn, an increase in specific humidity is associated with the surface heating
495 (Figure 12, third row). Changes in moisture convergence across the different modeling
496 experiments helps understanding some of the changes in accumulated precipitation.
497 Indeed, in *SST+2K*, moister air is advected further eastward to the French Alpes-Maritime
498 region. Similarly, in Italy, weakened atmospheric flow with increased moisture leads to higher
499 accumulations eastward (i.e. upstream) to the region the most affected in *CTRL* (Figure 12,
500 first row). In contrast, the cold SST experiment is associated with decreased moisture
501 converging onshore and generally lower accumulations in precipitation, except for north-
502 western Italy, where stronger westward winds bring moist air closer to the Alps with locally
503 an intensification of rainfall.

504 These thermodynamic changes alone cannot fully explain the overall precipitation
505 changes during the HPE. Thermodynamical changes are intertwined with dynamic changes,
506 and while considering them separately has its limitations, it helps gaining a more
507 comprehensive understanding of the effects induced by warming the SSTs. Generally,
508 warmer SSTs lead to larger CAPE values and thus to increased lower tropospheric instability
509 which is advected onshore (Figure 13, first row). Upstream instability is carried inland and is
510 a favoring factor to trigger deep atmospheric convection. Higher in the troposphere (at 700
511 hPa), vertical velocities are enhanced east of the French Alpes-Maritimes region where
512 rainfall accumulation is higher in *SST+2K* (Figure 13, second row). In addition, an increase in
513 relative humidity is found in areas where the atmospheric conditions were not already
514 saturated in *CTRL* (Figure 13, third row). These dynamical changes are all ingredients to
515 enhance deep atmospheric convection, and indeed, precipitable water is increased where
516 instability and moisture increases are collocating (Figure 13, fourth row).

517 We note once again that the thermodynamic and dynamic changes are generally
518 similar in the *SST_MED+2K* and *SST+2K* experiments (Figures 12 and 13). This highlights
519 again that the regional warming of SSTs has a crucial role on the 2020 Mediterranean HPE in
520 amplifying the precipitation-related impacts and driving local changes.

521
522

523 3.3. Plausible worst-case scenario of the extreme precipitation event 524 occurring in 2022 under warmer SSTs

525

526 The sensitivity of simulated extreme precipitation to SSTs is further assessed through
527 a plausible worst-case scenario. We investigate how the observed Mediterranean HPE in
528 2020 could have been different had it occurred two years later, in 2022, under warmer SSTs
529 conditions (Figure 2 and section 2.4). To that end, we explore the response of extreme
530 precipitation in the *SST2022* ensemble and compare it to that of the *CTRL* experiment.
531 Results are then contextualized with the idealized modeling experiments *SST+2K* and
532 *SST_MED+2K*.

533

534 On average over the entire domain and over the duration of the simulations, daily
535 maxima of hourly precipitation in *SSTs_2022* exhibit greater intensities compared to *CTRL*
536 (green and black lines, respectively; Figure 6a). Daily maxima in *SSTs_2022* are generally
537 close to those in *SST_MED+2K* (purple line) and generally less intense than in *SST+2K* (red
538 line). In 2022, ASO and SON mean SST patterns closely resembles those idealized in *SST+2K*
539 over the western Mediterranean basin (Figure 2). In contrast, over the Atlantic Ocean, SSTs
540 in 2022 are not as anomalously warm and therefore differ from those of *SST+2K*.
541 Thermodynamic consideration can thus broadly explain why, over the scale of the entire
542 domain, the intensification of extreme precipitation with warmer SSTs of 2022 somehow
543 sits in between the responses of *SST+2K* and *SST_MED+2K*. At the hourly scale throughout
544 the Mediterranean HPE event, similar thermodynamically-driven responses are found with
545 precipitation rates averaged over both the entire and intermediate domains of similar
546 intensities between the *SST+2K*, *SST_MED+2K* and *SST2022* ensembles (Figure 8a,b).

547 Focusing on the Mediterranean HPE over the smaller region of the French Alpes-
548 Maritimes, we find a similar response in *SST2022* compared to *SST+2K* and *SST_MED+2K*
549 with lower daily maxima values than in *CTRL* on days 2, 3 and 4 of October (Figure 6c).
550 Firstly, this reaffirms the high sensitivity of extreme precipitation in this region to regional
551 SSTs. Then, it indicates that if storm Alex had occurred two years later, the precipitation-
552 related impacts in the French Alpes-Maritimes region would have been less severe than
553 those experienced in 2020. Indeed, the warmer SSTs of 2022 in the western Mediterranean
554 basin leads to an eastward shift of the rainfall patterns. This shift is found in both the daily
555 maxima of hourly precipitation on October 2 (Figure 7e and Supplementary Figure 4e) and
556 the increased accumulations of precipitation (Figure 9e and Supplementary Figure 5e). In
557 contrast, the HPE impacts would have been much more severe in Italy.

558

559 The influence of the 2022 warmer SSTs on the extra-tropical storm Alex somehow
560 resembles a dimmed version of the response in *SST+2K*. This aligns with expectations,
561 considering the relatively small SST anomalies in 2022 compared to 2020 in the Atlantic
562 Ocean. A small expansion of the low-pressure system is found along with a small decrease in

563 minimum pressure (Figure 10d and Supplementary Figure 6d). Similarly, we find minimal
564 impact on the maximum wind gust speeds along the western France coastline (Figure 11d).

565 Previous results from *SST+2K* and *SST_MED+2K* showed that changes in
566 characteristics of storm Alex have a limited role on the Mediterranean HPE. This is
567 confirmed with *SSTs_2022*. The response of the regional atmospheric circulation in the
568 western Mediterranean basin resembles those in *SST_MED+2K*, albeit with slightly smaller
569 intensity (Figure 10d and Supplementary Figure 6d). In response to warmer SST conditions
570 in 2022, and compared to *CTRL*, a negative sea level pressure pattern leads to wind
571 anomalies and a tilting of the low-level flow heading to the French Alpes-Maritimes region
572 according to a south to south-easterly direction.

573 The thermodynamic and dynamic changes in *SST2022* are generally like those in
574 *SST_MED+2K*, albeit with slightly lower intensities (Figures 12 and 13). Across the French
575 Alpes-Maritimes region, these changes in thermodynamics and dynamics can generally
576 explain the local precipitation response during the HPE. While instability is increased
577 upstream, changes in moisture convergence between *SST2022* and *CTRL* primarily account
578 for the decrease in extreme precipitation intensity in the French Alpes-Maritimes region.
579 Conversely, on the other side of the Alps in Italy, changes in low-level flow, along with
580 increased instability and moisture, contribute to more intense extreme precipitation.

581

582

583 4. Discussion

584 Hourly precipitation rates and accumulated amounts during the Mediterranean HPE
585 simulated by CNRM-AROME compare reasonably well with high-quality observations in the
586 French Alpes-Maritimes region. The main biases of the model lie in an underestimation of
587 the spatial contrasts of the heavy rainfall distribution, and in an underestimation of the
588 highest intensity, which has been previously documented in the literature (Caillaud et al.,
589 2021; Fumière et al., 2020). Part of this bias may be attributed to the orography in CNRM-
590 AROME, which cannot fully capture the complex spatial contrasts of this mountainous
591 region at the 2.5 km resolution. However, this likely does not account for the entire bias.

592 Convective precipitation extremes are difficult to model. Furthermore, other limitations
593 tied to the model's performance may also contribute to these difficulties. Substantial
594 advancements have been made in recent years with convection-permitting regional climate
595 models (CP-RCMs), particularly for hourly precipitation and extremes, compared to
596 conventional regional climate models (Ban et al., 2021; Berthou et al., 2020b; Lucas-Picher
597 et al., 2008; Prein et al., 2015). While CP-RCMs currently appear as our best tool to study
598 extreme precipitation at fine spatial and temporal climate scales, ongoing model
599 developments are essential to address the increasing demand for relevant local climate
600 change information.

601 The ensemble-based modeling approach allows to assess the full range of outcomes due
602 to internal variability, which is highly relevant to gain a better understanding of climate
603 change impacts locally. In this study, we realized 20 simulations for each modeling
604 experiments. All ensemble members reproduce similarly the overall sequence of observed
605 events as they have identical large-scale forcings. However, we highlight variations locally
606 among the ensemble members for the highest rainfall amounts locally and for the maximum
607 near-surface wind speeds. We argue that the ensemble-based approach is important when
608 modeling extreme events, and extreme precipitation more particularly. Impact sectors
609 increasingly rely on the km-scale modeling to produce local climate information. This should

610 always be accompanied by the comprehensive description of the uncertainties, including
611 those associated with internal variability.

612
613

614 Our findings consistently highlight the potential enhancement of warmer autumnal SSTs
615 on the intensity of heavy precipitation events (HPEs) in the Mediterranean region. This is in
616 line with previous studies that emphasize the crucial role of pre-event SST conditions in
617 driving the intensity of such events (Berthou et al., 2014; Lebeaupin et al., 2006; Meredith et
618 al., 2015; Rainaud et al., 2017). The onshore advection of moist and unstable air, essential
619 for fueling convective systems during HPEs, is intricately tied to the pivotal role played by
620 air-sea interactions in the Mediterranean Sea. These interactions contribute significantly by
621 supplying moisture and heat to the lower atmospheric layers (Lebeaupin Brossier et al.,
622 2008; Rainaud et al., 2017).

623 While investigating the impact of the air-sea interactions on the 2020 HPE case could
624 offer valuable insights, existing studies suggest that coupled ocean-atmosphere modeling
625 might yield significant improvements. Based on simulations involving three HPEs with
626 consideration of coupling through air-sea interface fluxes, an oceanic response with a SST
627 cooling under the low-level jet was identified (Lebeaupin et al., 2006). However, minimal
628 impact was found on the 24-hour lead time forecast of heavy precipitation. The main
629 explanation lies in the intensity of the low-level jet that leads to a forcing from the
630 atmosphere onto the ocean during an HPE. Furthermore, the Mediterranean Sea is not the
631 only source of moisture for feeding the convective systems. Moisture exported from the
632 Atlantic and the Tropics contributes significantly to the amount of water vapor to supply the
633 convection (Duffourg & Ducrocq, 2011, 2013). Our simulation domain does not encompass
634 these moisture sources, preventing an exploration of their potential influence.

635
636

637 **5. Conclusions**

638 Using convection-permitting climate modeling with a spatial resolution of 2.5 km, we
639 conduct short ensembles of 20 simulations over a period of 2 months. These simulations
640 accurately reproduce the extra-tropical storm Alex, which initiated the development of large
641 scale conditions favorable to the onset of an intense Mediterranean Heavy Precipitation
642 Event (HPE). Low-level wind convergence and orographic lifting from the advection of moist
643 and unstable air to the Alps triggered deep atmospheric convection and precipitation of rare
644 intensity on the early days of October 2020 in the south-eastern French Alps and the north-
645 western Italian Alps. Modeling this sequence of extreme events is a challenge. In this study,
646 we show that the convection-permitting regional climate model (CP-RCM) CNRM-AROME
647 can successfully reproduce such high-impact extreme precipitation events over a substantial
648 domain.

649 Our main objective is to examine the role of warmer (and colder) sea surface
650 temperatures (SSTs) in influencing the HPE intensity. We focus primarily on the effects on
651 precipitation and in the French Alpes-Maritimes region that was severely affected by this
652 event. We carry out three modeling sensitivity experiments, testing different SST conditions.
653 First, idealized patterns of uniform 2K warming and cooling are applied to the 2020 SSTs
654 over the entire domain of simulation. The influence of regional SSTs is further tested by
655 adding 2K to the SSTs over a Mediterranean box solely.

656 Generally, at the scale of the simulation domain, warmer SSTs lead to an
657 intensification of precipitation. Daily maximum values of hourly precipitation and
658 accumulations over the course of the HPE are consistently higher under warmer SSTs
659 conditions. The response to SST warming is more contrasted locally, which can be explained
660 by a lesser influence of the thermodynamic change and, conversely, a stronger influence of
661 the dynamic changes at finer spatial and temporal scales (Emori & Brown, 2005; Pfahl et al.,
662 2017).

663 A key finding from our study is that the extremeness of the 2020 Mediterranean HPE
664 can be intensified with warmer SST conditions in the western Mediterranean Sea.
665 Extremeness is here measured by the daily maximum values of hourly precipitation on the
666 day that received the highest rainfall. Our results indicate that the region characterized by
667 daily maxima exceeding 60mm (in the ensemble mean) expands in simulations with warmer
668 SSTs. The potential for precipitation amplification has also been demonstrated in the case of
669 the 2012 Krymsk event, highlighting the influence of Black Sea surface temperatures
670 (Meredith et al., 2015).

671 An additional finding is that the region affected by the most intense hourly
672 precipitation rates are shifted eastward. This pattern is also depicted in the changes in
673 accumulated hourly rainfall during the Mediterranean HPE. Interestingly, the eastward shift
674 of precipitation is highly consistent in the modeling experiment with warmer SSTs imposed
675 over the entire oceanic domain and the experiment where warming is confined solely to the
676 Mediterranean region. This emphasizes the sensitivity of the 2020 Mediterranean HPE to
677 regional sea surface conditions.

678
679 Over the Atlantic Ocean, SST warming leads to the deepening of the extra-tropical
680 storm Alex and the expansion of the low pressures, in agreement with (Ginesta et al., 2023).
681 Along the western coasts of France, wind gusts are intensified, and strong winds are
682 simulated extending further south than under the SSTs conditions of 2020. While this storm
683 is responsible for the development of the synoptic conditions leading to the Mediterranean
684 HPE, our findings indicate that changes in storm Alex have limited effects on the changes in
685 regional atmospheric circulation in the Mediterranean basin. Indeed, the regional response
686 of the atmospheric circulation during the HPE is relatively similar between the simulations
687 where warmer SSTs are imposed over the entire domain and over the Mediterranean region
688 solely.

689 In the western Mediterranean Sea, warmer SSTs modify the low-level flow. The
690 eastern part of the flow directed toward the French Alpes-Maritimes region tilts in a
691 south/south-east direction under warmer SSTs, while the western part of flow weakens in
692 intensity over inland Italy. In the lower troposphere, surface heating is associated with an
693 increase in humidity and instability upstream, which is transported inland to the natural
694 barriers of the Alps, where orographic lifting occurs. Deep atmospheric convection is
695 enhanced in the modeling experiments with warmer SSTs. Overall, consideration of the
696 thermodynamic and dynamic changes in our modeling experiments help understanding the
697 intensification in precipitation and the eastward shift of the highest precipitation amounts
698 with SST warming.

699
700 Finally, we explore a plausible worst-case scenario and investigate how the observed
701 2020 Mediterranean HPE could have been different had it occurred 2 years later, in 2022,
702 where warmer SSTs conditions were recorded in the western Mediterranean Sea.

703 This worst-case scenario simulation confirms the high sensitivity of the 2020
704 Mediterranean HPE to regional SSTs. Furthermore, it suggests that had the extra-tropical
705 storm Alex occurred two years later, the precipitation-related impacts in the French Alpes-
706 Maritimes region might have been less severe than those experienced in 2020, owing to an
707 eastward shift of precipitation. Conversely, in Italy, the potential for more significant
708 damage would likely have increased.

709
710 Our findings demonstrate the need to further explore the effects of climate changes
711 on extreme precipitation events in the Mediterranean region. The convection-permitting
712 regional climate modeling appear adapted for the event-based analysis of extreme
713 precipitation and should be further developed to explore the impacts of the future changes
714 in the mean atmospheric circulation on extreme precipitation events locally.

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907 **Statements & Declarations**

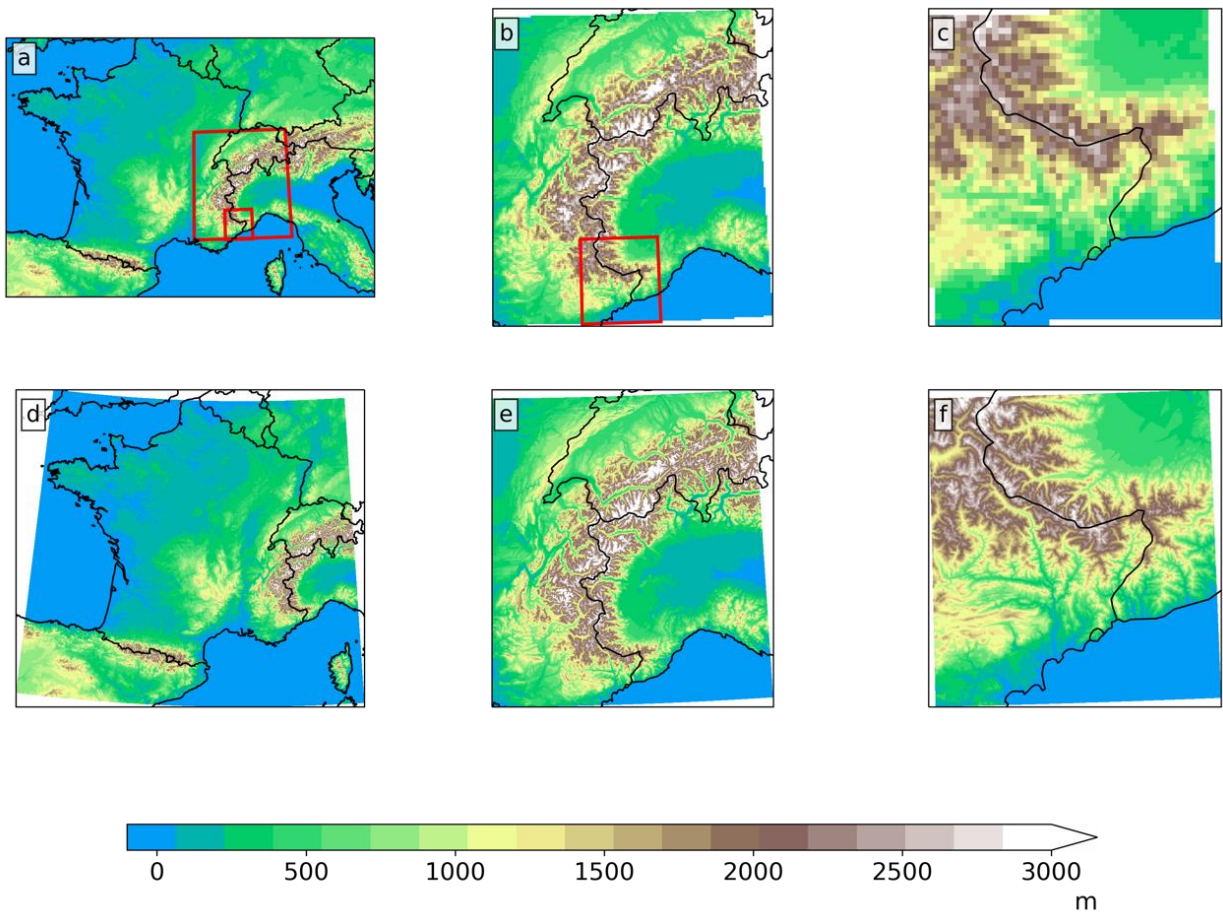
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911 **Competing interests.** The authors declare they have no financial interests.

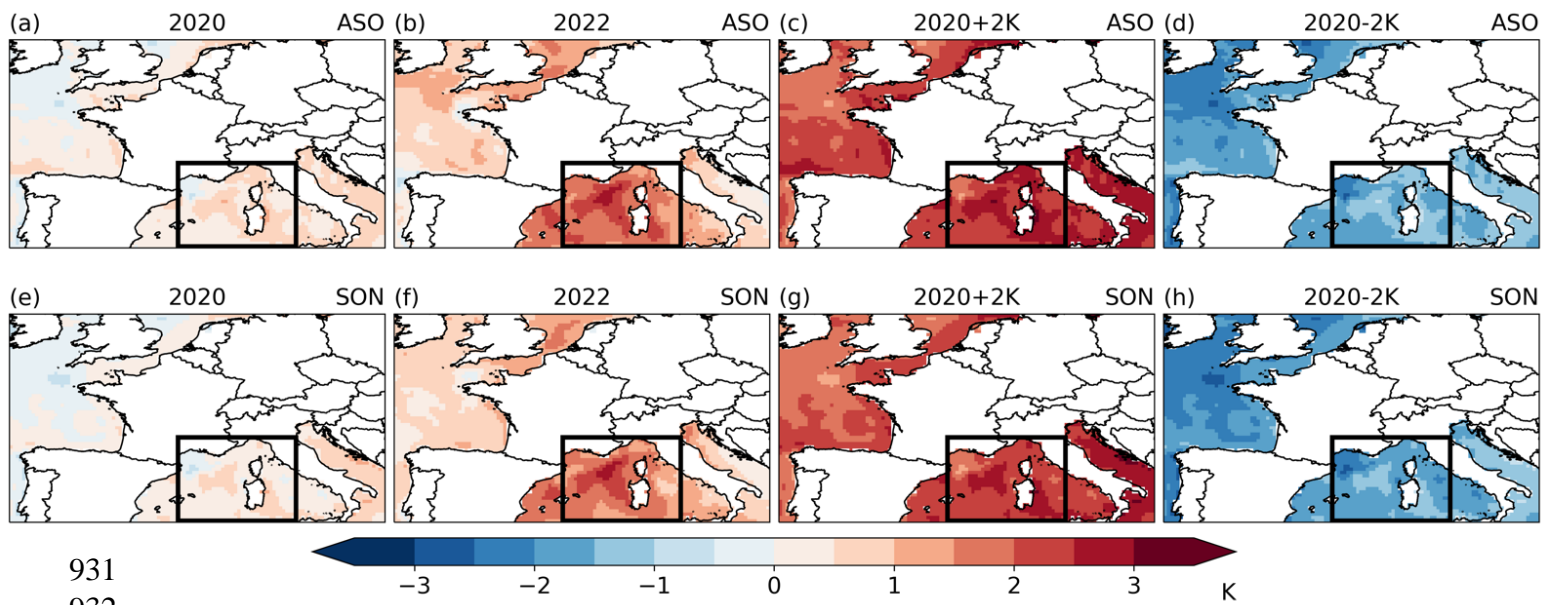
912 **Author contributions.** All authors contributed to the study conception and design. Material
913 preparation, data collection and analysis were performed by MB, with the help of MPM, CC,
914 and AA to carry out the simulations with CNRM-AROME. JB, LT and CC helped designing the
915 modeling experiments and contributed to the interpretation of the results. The first draft of
916 the manuscript was written by MB and all authors commented on previous versions of the
917 manuscript. All authors read and approved the final manuscript.

918 **Data availability.** The simulations produced for this research can be made available from
919 the corresponding author on reasonable request. The COMEPHORE observations will be
920 made freely available from the Meteo-France institute throughout the year 2024.

921 **Figures**
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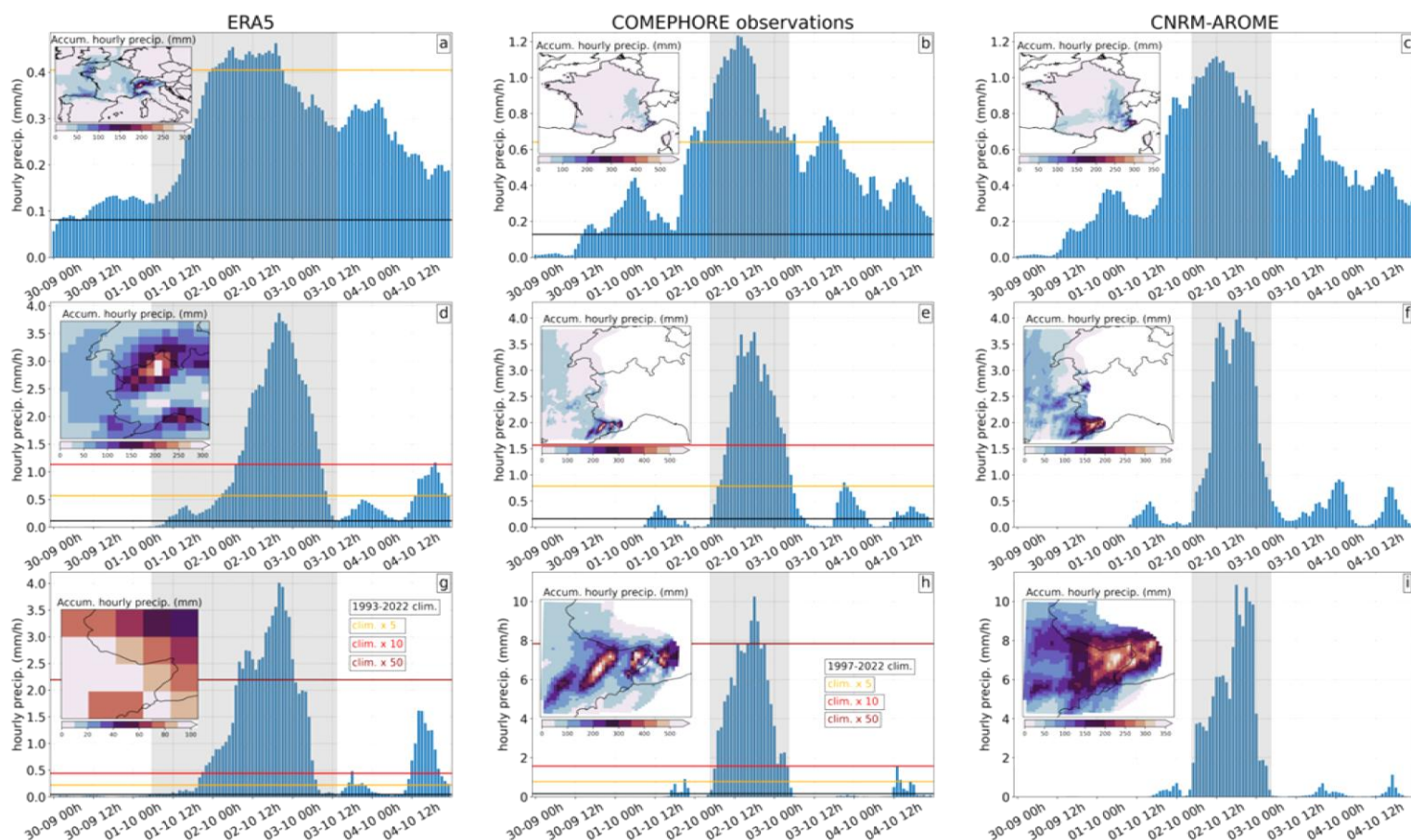


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924 **Figure 1:** Orography (in m) in CNRM-AROME (top) and in pseudo-observations (bottom)
925 over the three domains used in this study: the entire domain (left), an intermediate domain
926 covering the western Alps (middle), and a smaller region centered over the French Alpes-
927 Maritimes region (right). The intermediate and smaller region are also indicated by the red
928 boxes on panels (a) and (b).
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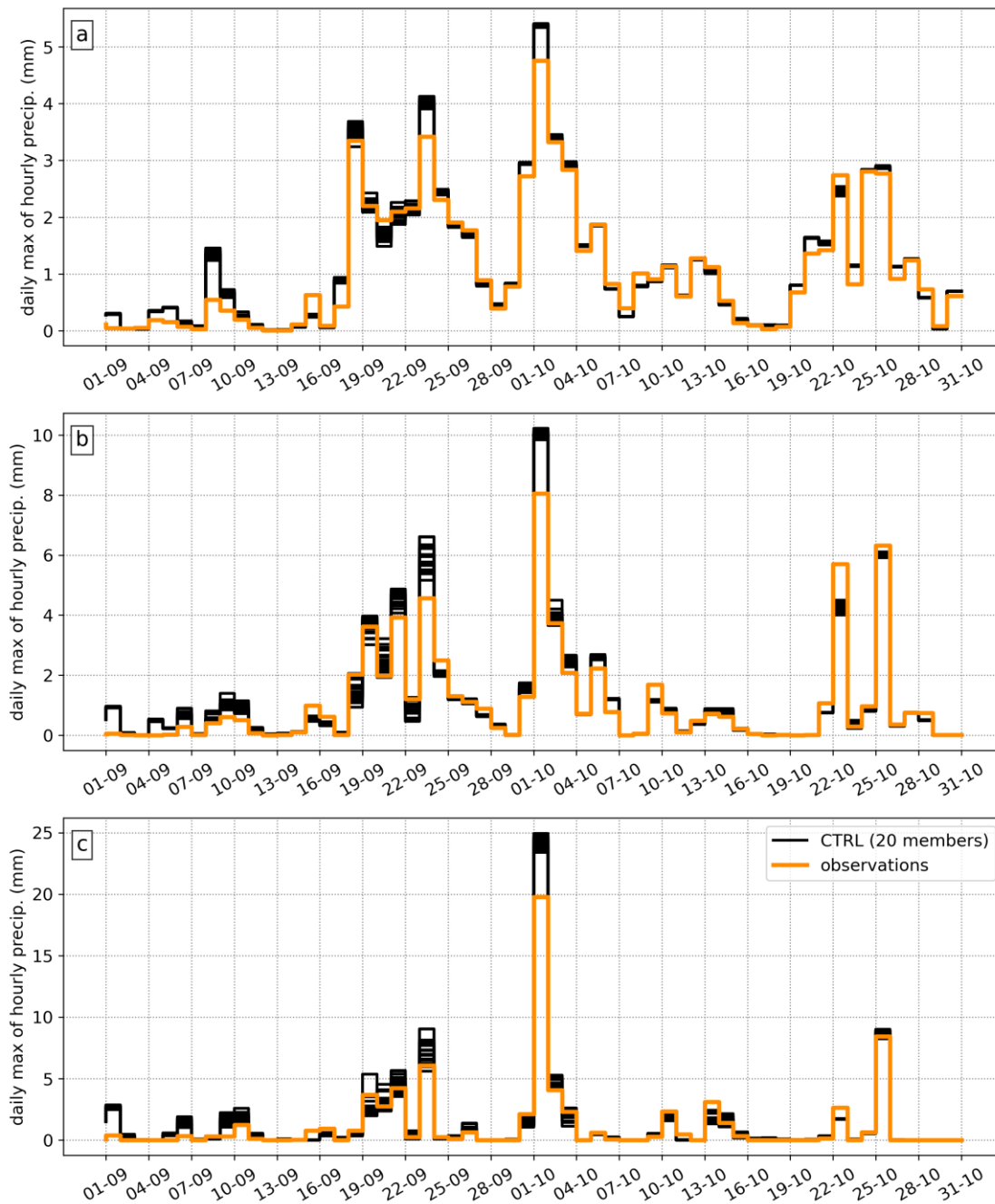


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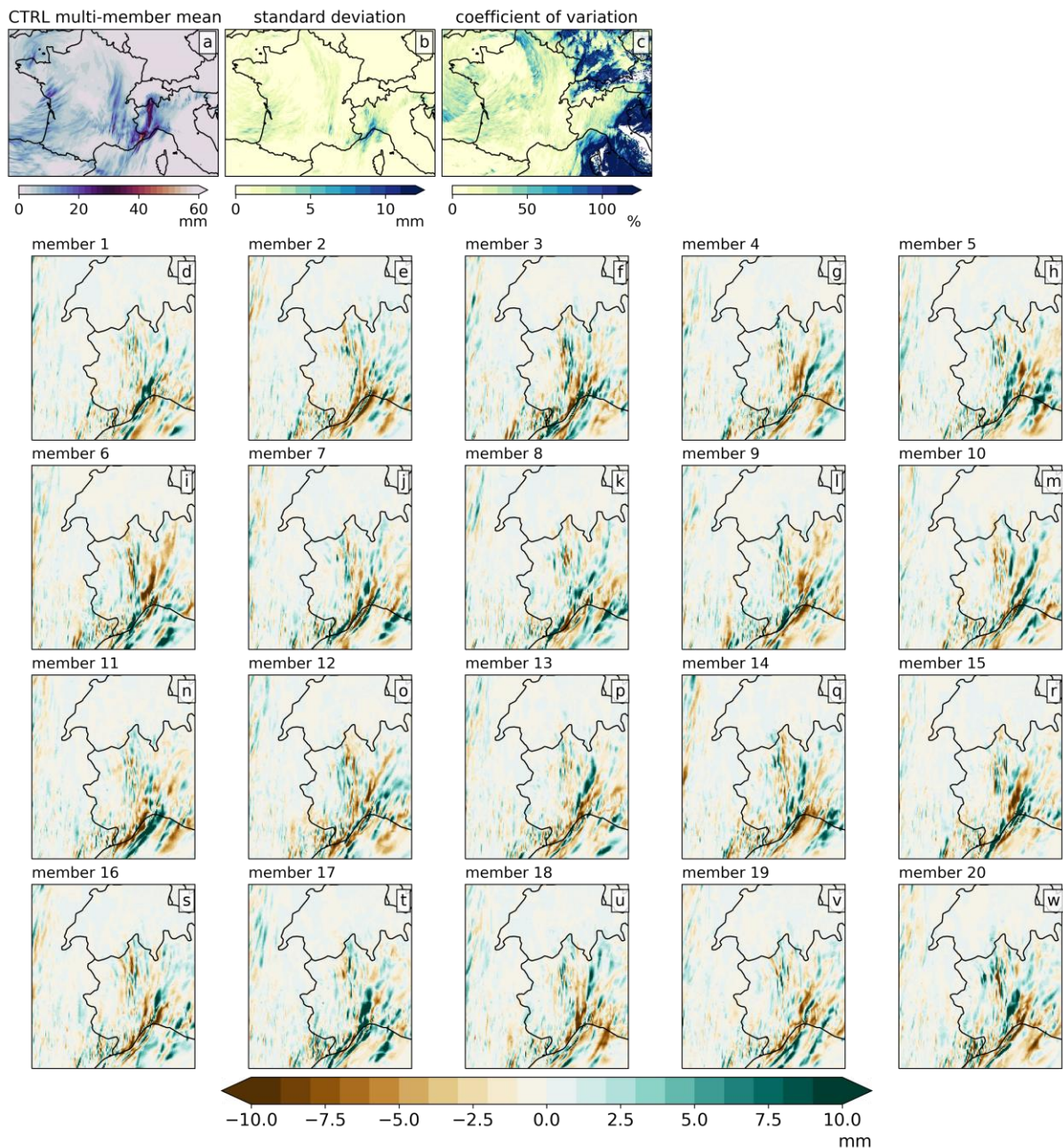
Figure 2: Mean August-September-October (ASO; top) and September-October-November (SON; bottom) sea surface temperature anomalies (in K) to the 1993-2022 climatology in the ERA5 reanalysis for the years 2020 (a,e), 2022 (b,d), and for the idealized anomalies of the year 2020 with the addition of uniform 2K warming (c,g) and cooling (d,h).



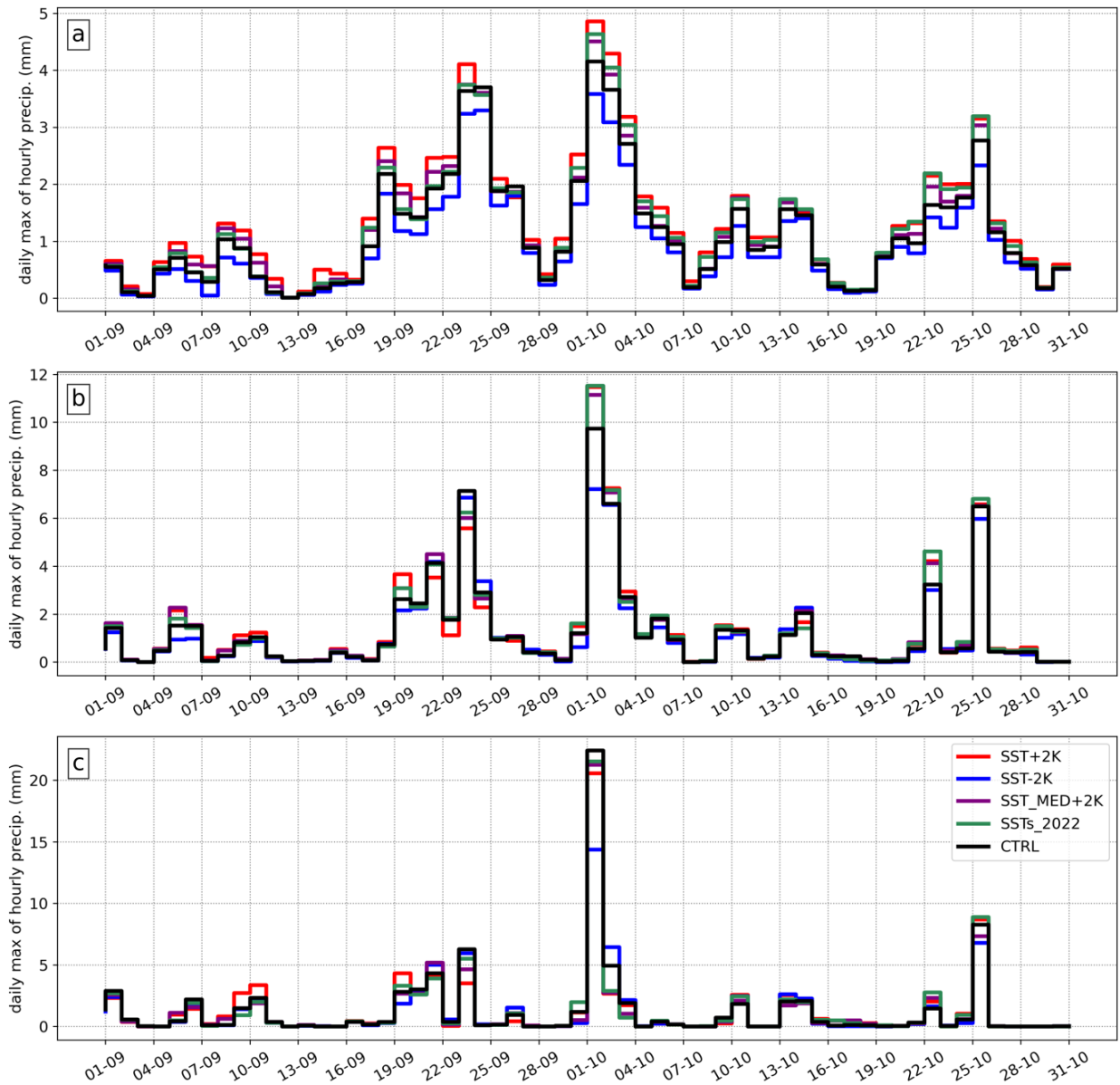
939 **Figure 3:** Hourly evolution of precipitation (in mm) averaged over the domains depicted in
 940 the inserted maps on each individual panels, from September 30 to October 4, 2020, in (left)
 941 the ERA5 reanalysis, (middle) the COMEPHORE observations, and (right) the *CTRL* ensemble
 942 mean of the CNRM-AROME model. Inserted maps show the accumulated hourly
 943 precipitation over the time window indicated by the grey shading on each individual panel.
 944 The three domains (per row) correspond to the different domains investigated in this study
 945 (see section 2.5). ERA5 data is at the native 25 km resolution, while COMEPHORE and
 946 CNRM-AROME data are at a resolution of 2.5 km, and the spatial coverage is constrained to
 947 match those of the observations.. Horizontal colored lines for ERA5 and COMEPHORE data
 948 represent exceeding levels (see inserted legends) of precipitation intensity relative to their
 949 5-day climatology (September 30 to October 4; 1993-2022 period for ERA5 and 1997-2020
 950 period for COMEPHORE).



951
 952 **Figure 4:** Observed (orange) and simulated (black; in the 20 members of the CTRL ensemble)
 953 daily maxima of hourly precipitation (in mm) averaged over (a) the entire domain, (b) the
 954 intermediate domain of the western Alps, and (c) the smaller region of the French Alpes-
 955 Maritimes. The COMEPHORE observations and CNRM-AROME data are at a resolution of 2.5
 956 km, and the spatial coverage is constrained to match those of the observations.

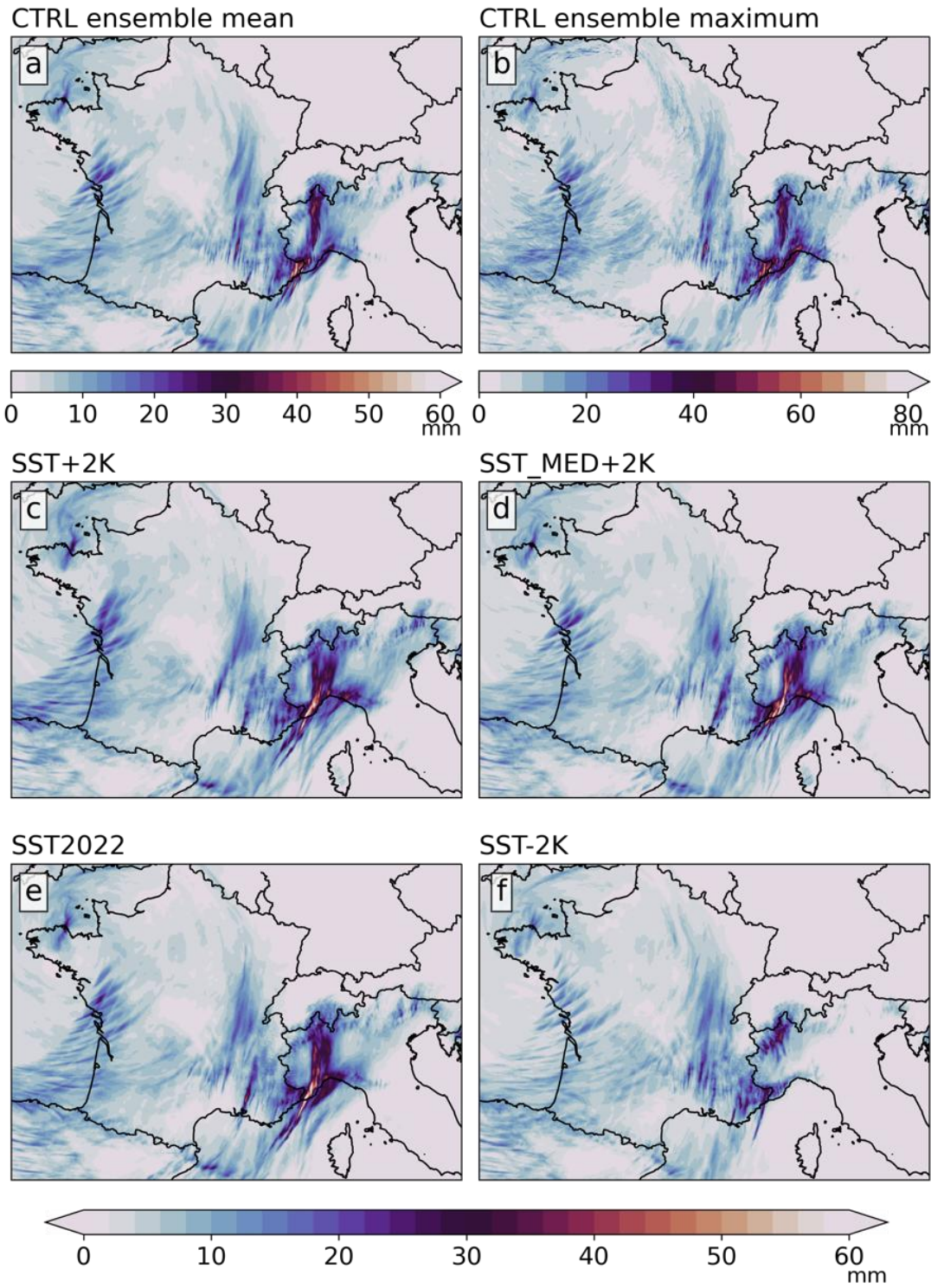


957
 958 **Figure 5:** Maximum of hourly precipitation on October 2 in the *CTRL* multi-member mean (a;
 959 in mm) and its corresponding standard deviation (b; in mm) and coefficient of variation (c;
 960 standard deviation normalized by the climatology, in %). Panels d-w show the difference to
 961 the *CTRL* ensemble mean for each of the 20 members of the *CTRL* experiment (in mm).



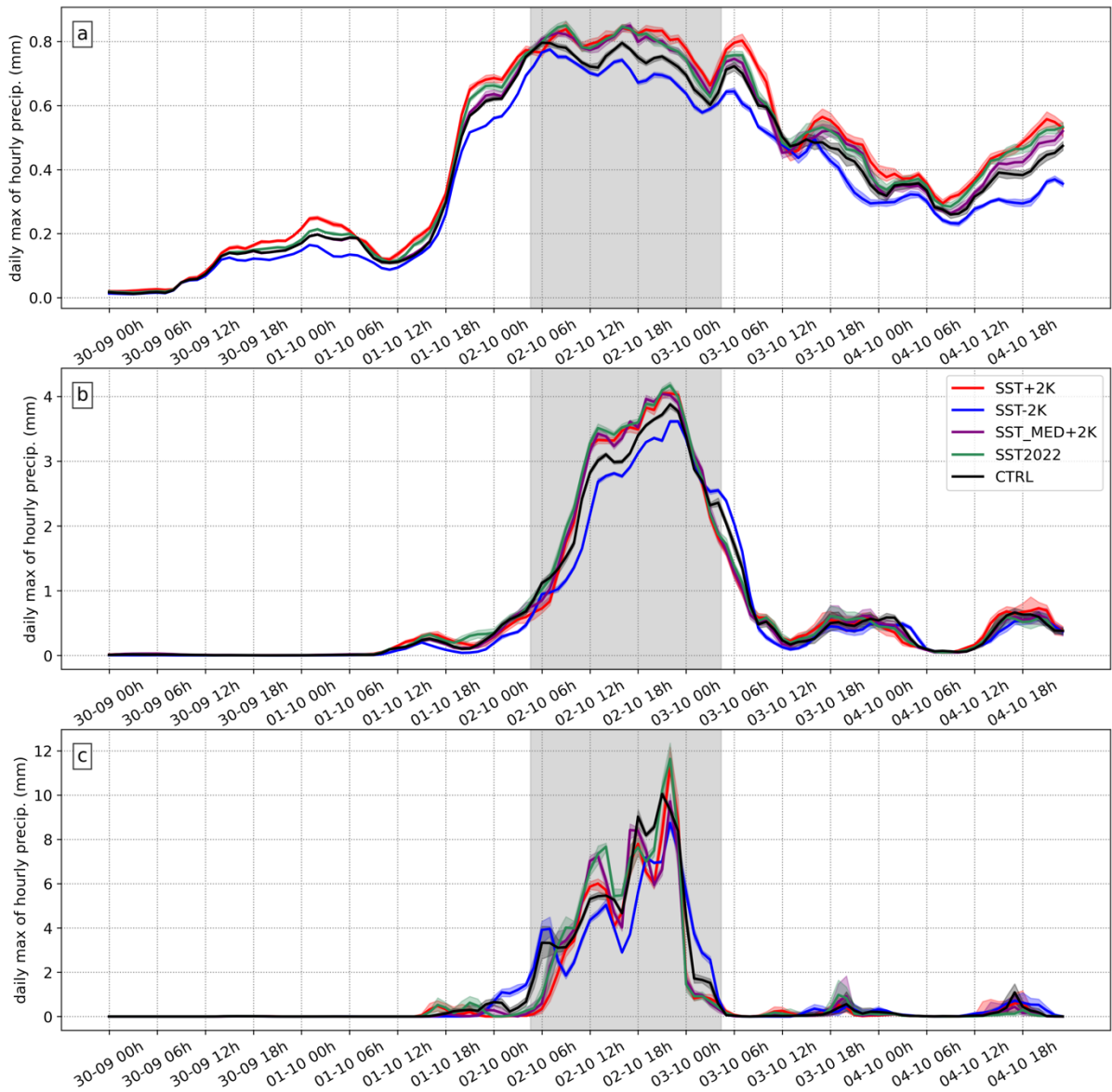
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Figure 6: Daily maxima of hourly precipitation (in mm) in the ensemble mean of the different modeling experiments (see inserted legend) averaged over (a) the entire domain, (b) the intermediate domain of the western Alps, and (c) the smaller region of the French Alps-Maritimes.



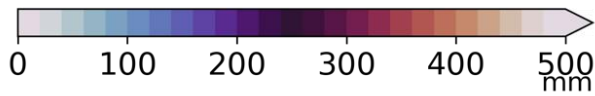
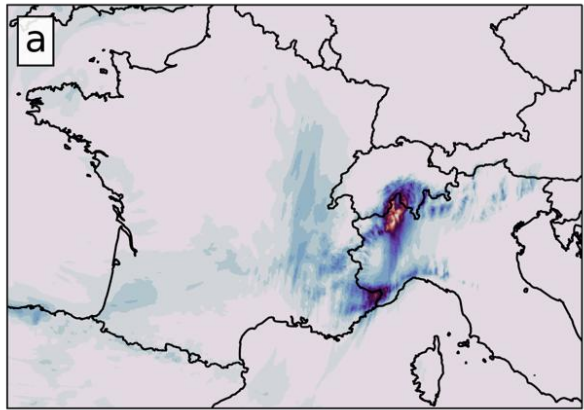
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Figure 7: Maximum of hourly precipitation (in mm) on October 2 in the ensemble mean of the following modeling experiments: (a) CTRL, (c) SST+2K, (d) SST_MED+2K, (e) SST2022, and (f) SST-2K. Panel (b) displays the maximum value (in mm) across the 20 members of CTRL.

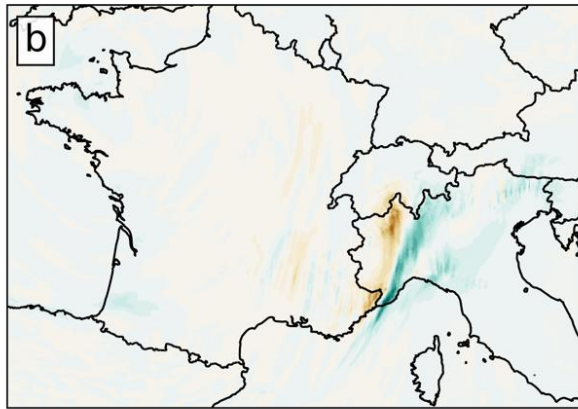


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 972 **Figure 8:** Hourly evolution of precipitation (in mm) over the 5-day period from September
 973 30 to October 4, 2020, averaged over (a) the entire domain, (b) the intermediate domain of
 974 the western Alps, and (c) the smaller region of the French Alpes-Maritimes. The five
 975 modeling experiments conducted with CNRM-AROME are shown using the color-code
 976 provided in the inserted legend. For each experiment, the ensemble mean is represented by
 977 the thick line, and the respective shading indicates the minimum-maximum range across the
 978 20 members. The grey shading corresponds the 24-hour time window that best captures the
 979 2020 Mediterranean HPE and is used in Figures 9 to 13.

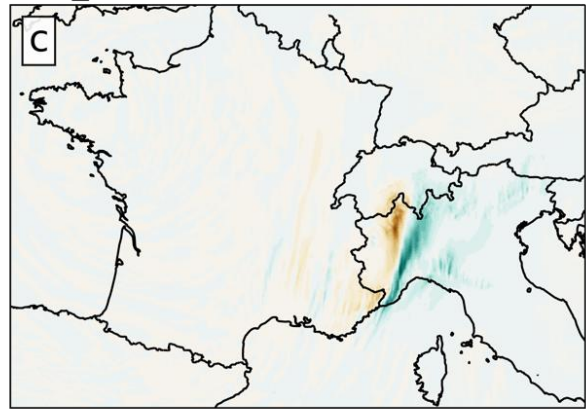
CTRL



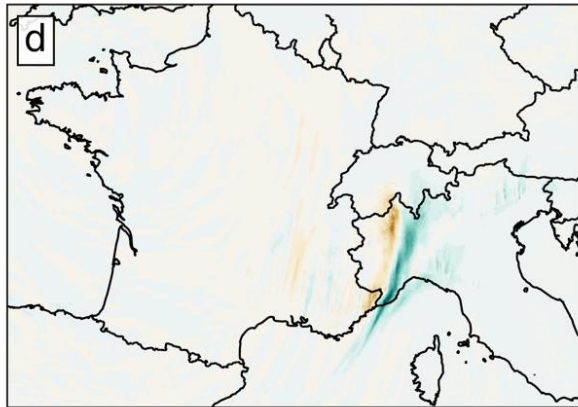
SST+2K - CTRL



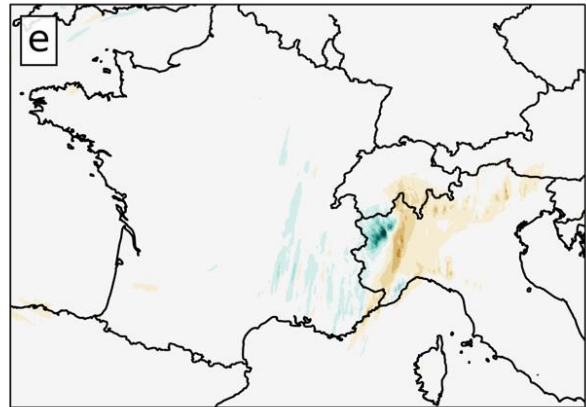
SST_MED+2K - CTRL



SST2022 - CTRL



SST-2K - CTRL



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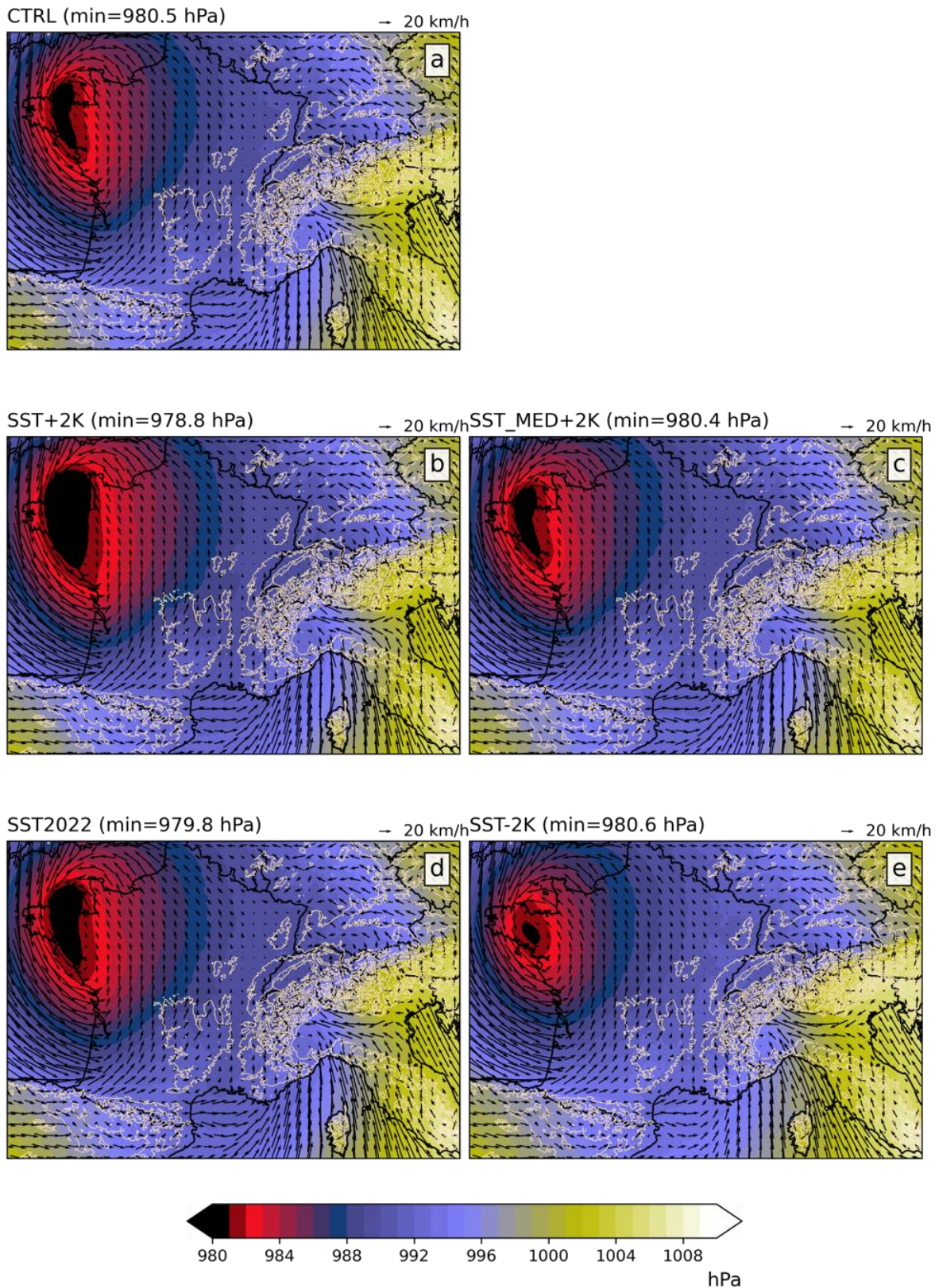
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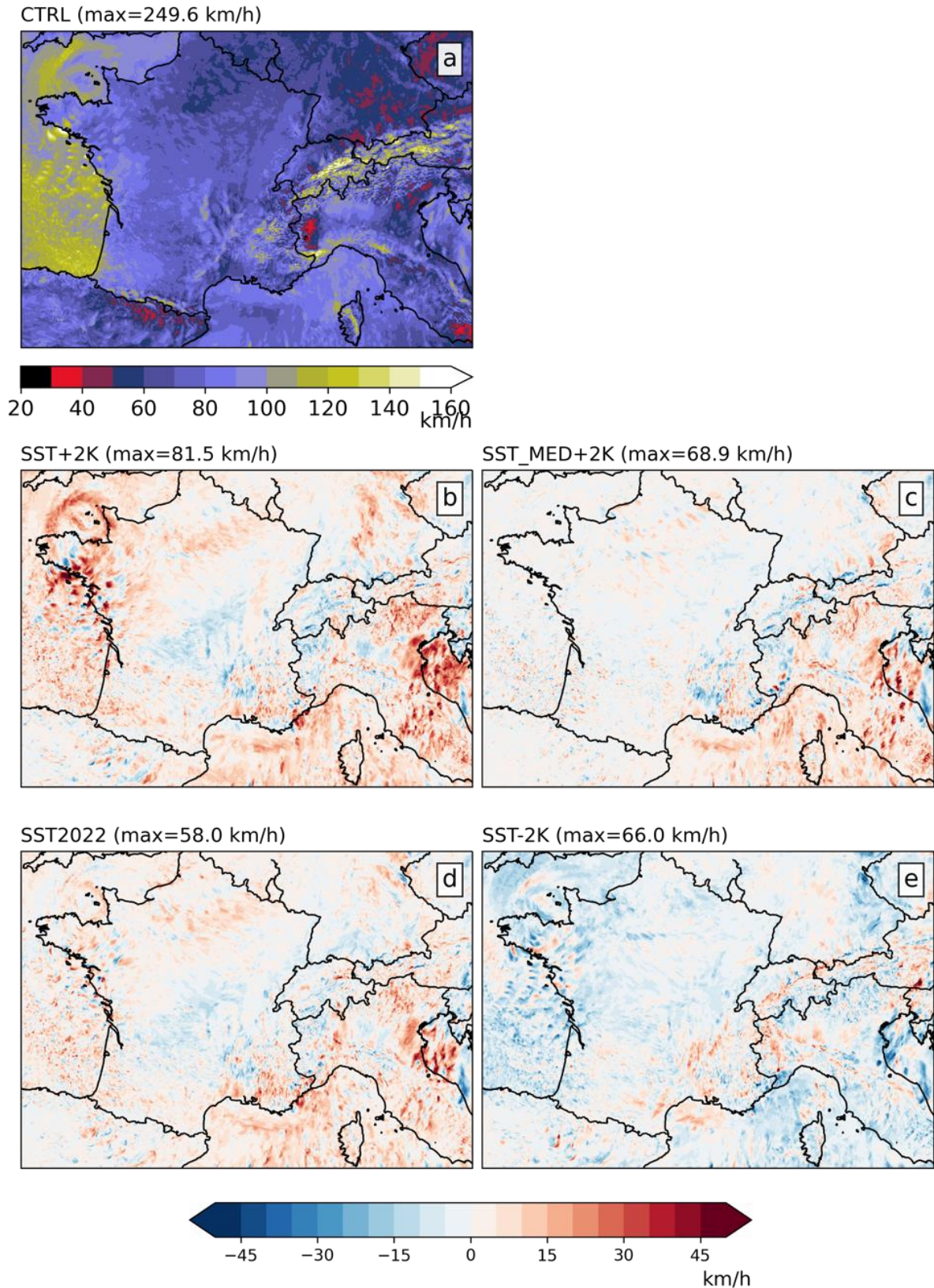
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Figure 9: Accumulated precipitation (in mm) over the 24-hour period that best captures the 2020 Mediterranean HPE (refer to grey shading in Figure 8) in (a) the *CTRL* ensemble mean, and the difference to the *CTRL* ensemble mean for the (b) *SST+2K*, (c) *SST_MED+2K*, (d) *SST2022* and (e) *SST-2K* ensemble mean.



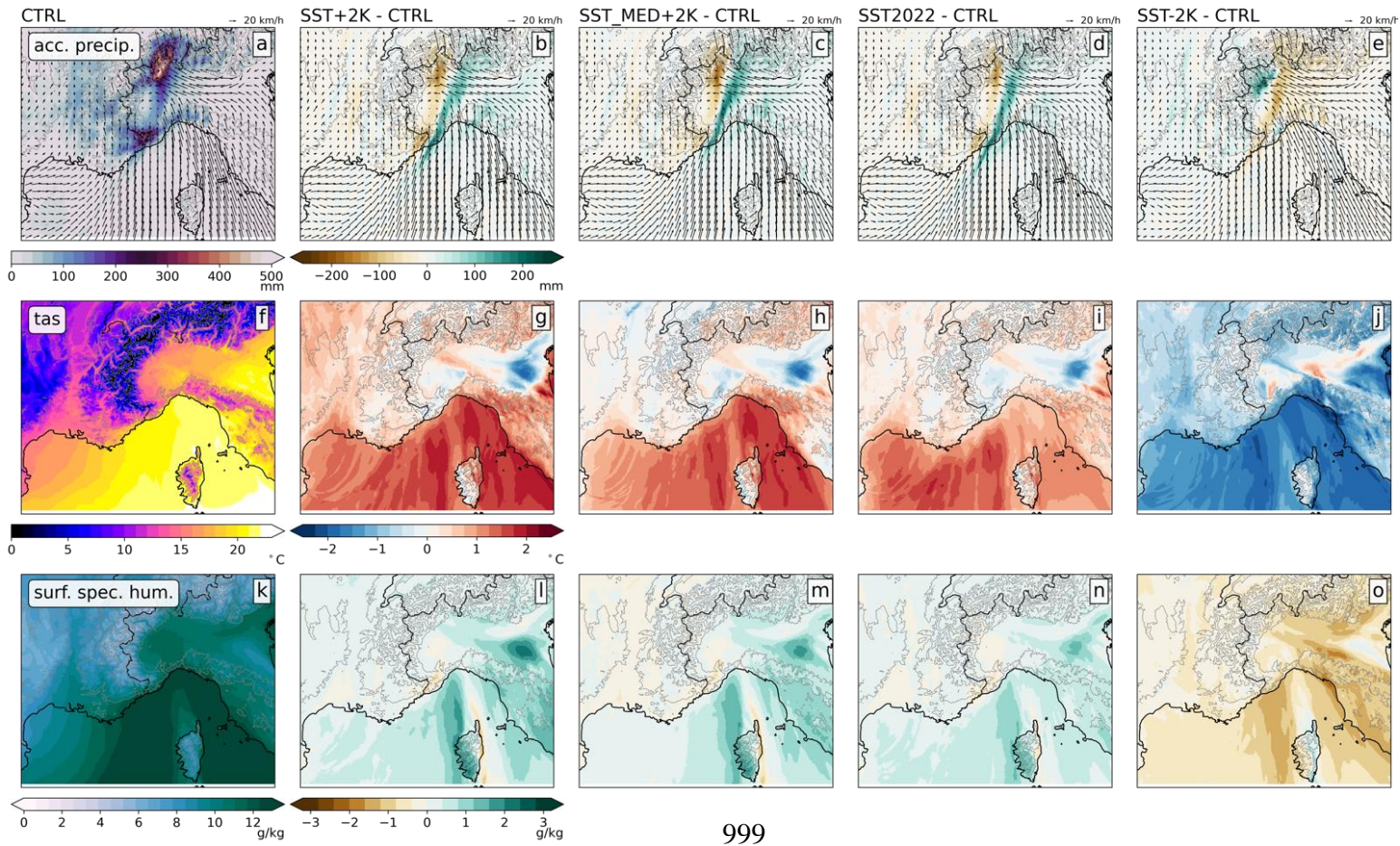
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 986 **Figure 10:** Mean sea level pressure (contours; in hPa) and surface winds (vectors; in km/h)
 987 over the 24-hour period that best captures the 2020 Mediterranean HPE (refer to grey
 988 shading in Figure 8) in the ensemble mean of the (a) *CTRL*, (b) *SST+2K*, (c) *SST_MED+2K*, (d)
 989 *SST2022*, and (e) *SST-2K* experiment. The minimum sea level pressure value over the domain
 990 is indicated at the top of each panel. Orography is represented by the white contours at the
 991 500, 1500, and 2500 m levels.



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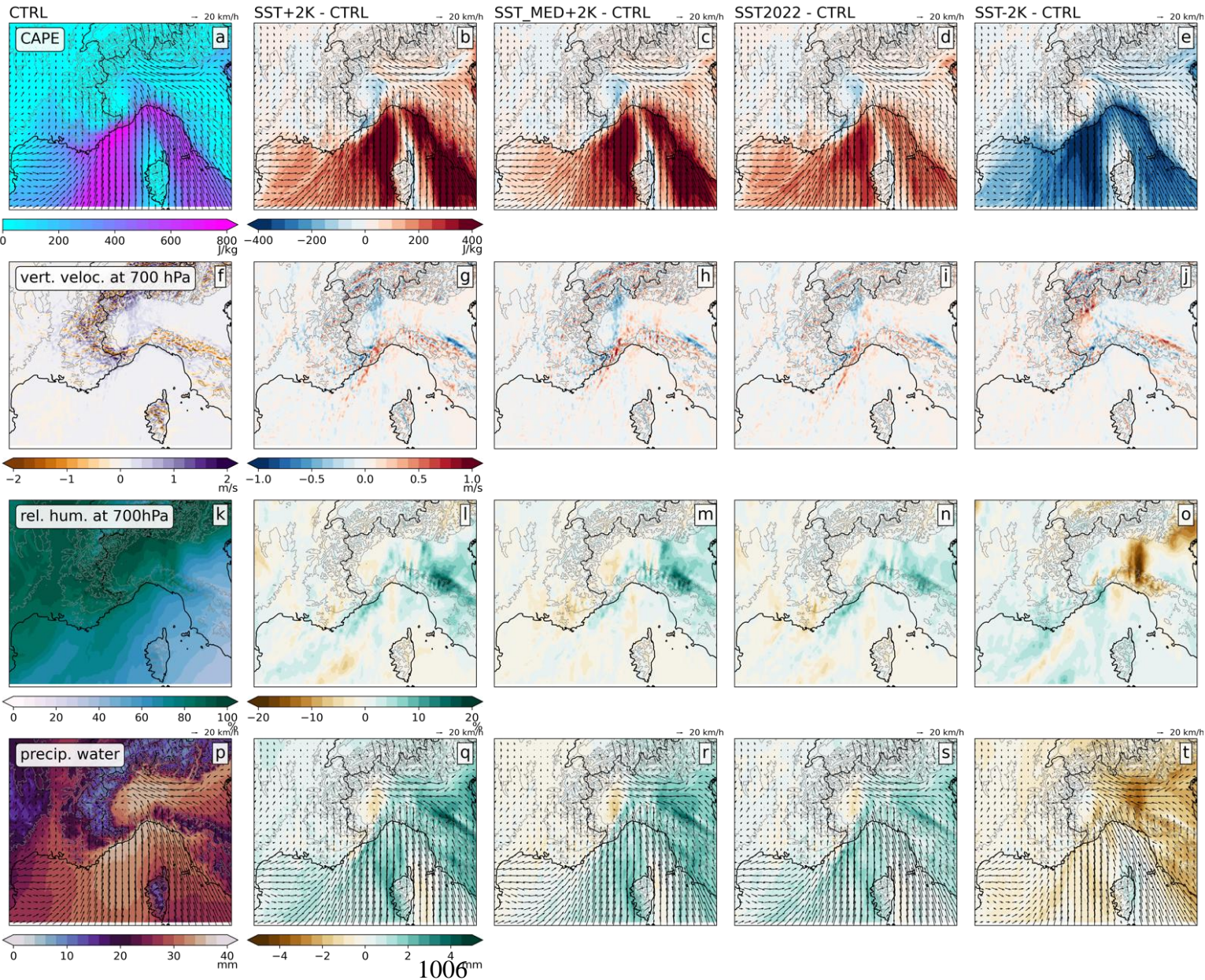
Figure 11: Mean daily maximum near-surface wind speed of gust (in km/h) over the 24-hour period that best captures the 2020 Mediterranean HPE (refer to grey shading in Figure 8) in (a) the *CTRL* ensemble mean, and the difference to the *CTRL* ensemble mean for the (b) *SST+2K*, (c) *SST_MED+2K*, (d) *SST2022* and (e) *SST-2K* ensemble mean. The maximum value over the domain is indicated at the top of each panel.

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1000 **Figure 12:** Mean accumulated precipitation (contours; in mm) and surface winds (vectors; in
 1001 km/h) (first row), surface air temperature (in °C; second row), and surface specific humidity
 1002 (in g/kg; third row) over the 24-hour period that best captures the 2020 Mediterranean HPE
 1003 (refer to grey shading in Figure 8) in (a,f,k) the *CTRL* ensemble mean, and the difference to
 1004 the *CTRL* ensemble mean for the (b,g,l) *SST+2K*, (c,h,m) *SST_MED+2K*, (d,l,n) *SST2022* and
 1005 (e,j,o) *SST-2K* ensemble mean.



1007 **Figure 13:** Mean CAPE (contours; in J/kg) and surface winds (vectors; in km/h) (first row),
 1008 vertical velocity at 700 hPa (in m/s; second row), relative humidity at 700 hPa (in %; third
 1009 row), and precipitable water (contours; in mm) and surface winds (vectors; in km/h) (fourth
 1010 row) over the 24-hour period that best captures the 2020 Mediterranean HPE (refer to grey
 1011 shading in Figure 8) in (a,f,k,p) the *CTRL* ensemble mean, and the difference to the *CTRL*
 1012 ensemble mean for the (b,g,l,q) *SST+2K*, (c,h,m,r) *SST_MED+2K*, (d,l,n,s) *SST2022* and (e,j,o,t)
 1013 *SST-2K* ensemble mean.