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# Challenges in attributing the 2022 Australian rain bombs to climate change

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## Abstract

In February and March 2022, the eastern coast of Australia recorded unprecedented amount of precipitation with extended floods and damages to properties amounting at least to AUD 2.3 billions. In this paper we use both reanalysis and observations to perform a statistical and dynamical attribution of this precipitation event to climate change. We define 1948-1977 as the counterfactual period and 1990-2019 as the factual one. The statistical attribution is based on fitting the generalized extreme value distribution for 3-days precipitation annual maxima for the two periods, while the dynamical attribution aims at looking at the recurrence properties of sea-level pressure and geopotential height patterns in both periods. We find that the dynamics of the event consists in an unprecedented combination of several factors: a tropical atmospheric river, the presence of the Coral low and a blocking anticyclone offshore Eastern Australia. Our main finding is that no clear attribution statements can be made, because of its unprecedented

nature, the lack of long high quality available data and the dependence of the results on the La Nina phase of El Nino Southern Oscillation.

**Keywords:** Climate Change, Extreme Precipitation, Attribution, Australia

## 1 Introduction

In the latest IPCC report (Masson-Delmotte et al, 2021), researchers confirm the role that human activity plays in the climate upheavals of recent decades. The scientists also hypothesize possible future scenarios and confirm the role of climate change on the frequency and intensity of extreme weather events that we experience today. The IPCC scientists warn in particular about the effects that climate change is having on the water cycle. Studies have shown that rising temperatures are leading to more intense rainfall, flooding but also to more severe droughts (Cook et al, 2018) in some regions of the world. The distribution, frequency and intensity of precipitations are changing significantly across the globe, especially in subtropical regions accustomed to monsoons (Douvillle et al, 2021). In the 21st century, coastal areas are already experiencing and will increasingly experience flooding due to heavy precipitation and sea level rise (Wilby and Keenan, 2012). Flooding from rising seas, which was only occasional a few decades ago, could occur every year by the end of the century (Hirabayashi et al, 2013).

Australian average temperatures have risen by 1.44°C since 1910, according to the recent study by Grainger et al (2022), who recall the proximity of the actual values to that of the Paris climate agreement, whose aim is to contain the rise in temperatures to 1.5°C compared to the pre-industrial era. The oceans surrounding the continent have also warmed by an average of one degree over the same period, leading to acidification and more frequent marine heat waves. Half of the corals in Australia's Great Barrier Reef have died since 1995 because of this rise in water temperature (Wolff et al, 2018; Holland et al, 2020). Few studies predict that sea levels will rise in line with international forecasts while tropical cyclones will be more intense (Church et al, 2006; Woodruff et al, 2013; Church et al, 2017). Other authors have also pointed out that rainfall has decreased in southwestern Australia as well as in the fire-ravaged southeast, even as it is more in the north, which has been hit by major floods and destructive cyclones in recent years (Dey et al, 2019; Abram et al, 2021).

If climate change projections for Australia are worrying, the country is already experiencing severe extreme weather events. Indeed, climate change has already taken its toll on Australia (Head et al, 2014; Abram et al, 2021; Canadell et al, 2021), which has been hit by fires, drought and intense cyclones. In 2019-2020 the country was already ravaged by wildfires of exceptional proportions after experiencing the hottest and driest year on record (Borchers Arriagada et al, 2020; Jetten et al, 2021). The fires destroyed

73 an area almost the size of the United Kingdom, killed several people and killed  
74 or displaced nearly three billion animals, costing the Australian economy about  
75 7 billion AUD (Filkov et al, 2020). In the current 2022 year, both high and low  
76 temperature records have been broken in Australia. On one hand, the 13/01  
77 The coastal town of Onslow reached an unprecedented 50.7°C, the warmest  
78 temperature ever recorded in Australia for sixty-two years (The Guardian,  
79 2022). On the other hand, on the 02/06, at the Thredbo Top weather station  
80 the temperature reached -6.9°C and historic snowfalls for this time of year (The  
81 New Daily, 2022). Future projections of climate-related disasters for the coastal  
82 areas as well as the vast island-continent report an increasing risk of extreme  
83 events capable of heavily damaging natural ecosystems and impact health and  
84 agriculture (Hobday et al, 2018; Dey et al, 2019; Ukkola et al, 2020).

85 Here we will focus on the extreme precipitation event which occurred from  
86 the last week of February to mid-March 2022, in the eastern coast of Aus-  
87 tralia. 345mm of rain were recorded at Brisbane on the 28th of February. The  
88 precipitations met soils already close to saturation from the recent rains in  
89 the end of 2021. This led to severe and enduring floodings during the month  
90 of March. This event caused 22 recorded casualties, rendered uninhabitable  
91 25,000 homes and businesses, forced 200,000 people to evacuate and produced  
92 massive power and transports outages for a total of 2.32 billion AUD of dam-  
93 age (Foreign Policy, 2022). We will attribute this event to climate change using  
94 dynamical systems theory to target the concurrent atmospheric circulation  
95 patterns and search for pattern recurrences in the far (1948-1977) and recent  
96 past (1990-2019). Our working hypothesis is that the far past acts as a coun-  
97 terfactual world where the Earth climate was not influenced by anthropogenic  
98 forcing when compared to the recent past (the factual world). Additionally,  
99 we assume that 30 years is a long enough period to average out the interan-  
100 nual variability of the atmospheric motions (as that caused, for example, by  
101 El-Niño - Southern Oscillation). Finally we verify that these events produce  
102 similar impacts on the targeted regions.

103 The paper is organized as follows: section 2 describes the data and methods  
104 used in this study. This is followed by the presentation of the meteorology of  
105 the event (Section 3) and by the results (Section 4) providing both a statistical  
106 a dynamical attribution analysis. We conclude with a discussion and perspectives  
107 in Section 5.

## 108 2 Data and Methods

### 109 2.1 Data

110 In order to detect significant changes in the circulation associated with Aus-  
111 tralian Rain bombs, we use daily sea level pressure (*slp*), 500hPa geopotential  
112 height (*z*500) and 2m air temperature (*t*2m) data from the NCEP/NCAR  
113 reanalysis (Kalnay et al, 1996) over the period 01/01/1948 – 31/03/2022. The  
114 data has a horizontal resolution of  $2.5^\circ \times 2.5^\circ$ .

115 The precipitation data are taken from the high resolution daily rainfall  
 116 gridded datasets of the Bureau of Meteorology of Australia. The data has a  
 117 horizontal resolution of  $0.05^\circ \times 0.05^\circ$ . Daily precipitation data from the Alderley  
 118 station, close to Brisbane, is also used solely. For the ENSO index, we used  
 119 the Nino3.4 detrended index.

## 120 2.2 Methods

121 Extreme Value Theory (EVT) has been introduced in the study of climate  
 122 a decade ago (Freitas et al, 2008) and has gained a considerable amount of  
 123 attention in both the applied mathematics and the climate science commu-  
 124 nities (Lucarini et al, 2012, 2016; Faranda et al, 2019). It allows to compute  
 125 recurrence times statistics for climatic systems, but also provides important  
 126 information on the stability and the predictability of a particular climatic state.  
 127 This information is contained in indicators that can be estimated via EVT-  
 128 based methods, namely the instantaneous dimension  $D$  and the persistence  $\Theta$ .  
 129 The concept of instantaneous dimension is intuitive: for an atmospheric state  
 130  $\zeta$ , e.g. a daily map of sea-level pressure on a given region, the instantaneous  
 131 dimension  $D(\zeta)$  measures the density of similar configurations. This implies  
 132 that  $D$  can be related to both entropy and trajectory predictability. The sta-  
 133 bility of the state  $\zeta$  is measured by  $\Theta(\zeta)$  defined as the average persistence time  
 134 of trajectories around  $\zeta$ . If  $\zeta$  is a fixed point of the dynamics,  $\Theta(\zeta) \rightarrow \infty$ . For  
 135 a trajectory immediately leaving the neighbourhood of  $\Theta = 1$ . In general, the  
 136 more persistent the configuration, the more the system states will resemble  $\zeta$ .

137 We can apply this framework to the study of weather extremes to study  
 138 anthropogenic-driven climate change of weather patterns (Faranda et al, 2020).  
 139 For each of the events, we identify the day where the largest impacts are  
 140 detected. We then perform a visual inspection of the concurrent weather pat-  
 141 tern. In most of the cases, we are interested in a synoptic object, i.e. a cyclone  
 142 or anticyclone or a couple of these structures. During this identification, we  
 143 select a region (a longitude/latitude box) that fits the synoptic map that we  
 144 want to examine.

145 Once fixed the day of interest  $\zeta$  we scan all the 3-days rolling averaged  
 146 sea-level pressure  $slp$  and 500hPa geopotential  $z500$  maps in two periods: 1948-  
 147 1977 (counterfactual world) and 1990-2019 (factual world). For both periods  
 148 we select the best 35 analogues (quantile 0.997) as the  $slp$  and  $z500$  maps  
 149 minimizing the pointwise euclidean distance with respect to the target  $\zeta$ . The  
 150 choice of a 30 years period for the factual and counterfactual periods ensures  
 151 having a large statistical sample of  $slp$  and  $z500$  maps to select authentic ana-  
 152 logues and to satisfy both the assumptions of stationarity of the climate with  
 153 respect to anthropogenic climate change while averaging over the interannual  
 154 and interdecadal natural variability of the atmospheric circulation. Indeed, we  
 155 have verified that the results do not depend sensibly on the choice of the num-  
 156 ber of analogues provided that we extract between 25 and 50 analog maps.  
 157 Once obtained the two sets of analogues for the factual and counterfactual  
 158 periods, we average them out to search for significant differences  $\Delta slp$  and

159  $\Delta z500$ . To determine significant changes, we apply a Welch's t-test (Welch,  
160 1947) with different variance at each grid point. We mark as significant only  
161 grid point changes for which the  $p$ -value of the test is below 0.05. Conditioning  
162 to the dates determined for  $slp$  or  $z500$  maps, we also study the associated 2  
163 meters temperatures  $t2m$  and total precipitation maps  $tp$ . The Welch's t-test  
164 procedure is repeated on these ensembles to identify significant changes.

165 Using the framework of dynamical systems described above, we then intro-  
166 duce few metrics to determine the recurrences properties of the map in the  
167 counterfactual and factual world. This means that the metrics introduced  
168 below are computed twice with respect to the analogues obtained in the two  
169 periods.

- 170 • **Analog Quality  $Q$ :** we can study the typicality of  $\zeta$  by comparing the  
171 euclidean distance of  $\zeta$  from its analogues with the distances of the analogues  
172 from their own analogues. If the value of  $Q$  belongs to the same distribution  
173 of the values of  $Q$  analogues, then typicality is ensured and attribution of  
174  $\zeta$  can be performed. If instead the  $Q$  for the chosen day is larger than that  
175 of the analog days, then this is an unprecedented  $slp$  or  $z500$  configuration  
176 and the results for attribution must be taken more carefully. A difference  
177 in  $Q$  between the counterfactual and factual periods indicate a change in  
178 typicality of the event due to climate change.
- 179 • **Predictability Index  $D$ :** we can compute the above defined dimension  $D$  of  
180 the event  $\zeta$  in both the periods to detect a climate-change induced shift in  
181 predictability. Indeed,  $D$  is a proxy for the number of degrees of freedom  
182 of the map, meaning that the higher the dimension the more unpredictable  
183 the next  $slp$  or  $z500$  maps will be. If the dimension  $D$  of the chosen day is  
184 higher or lower than that of the analogues, then the day will be less or more  
185 predictable than its closest dynamical situations.
- 186 • **Persistence Index  $\Theta$ :** another information derived from the dynamical sys-  
187 tems theory is the persistence of a given configuration. The persistence  
188 counts for how many days we are likely to observe a map that is an analogs  
189 of the one considered. Once again we will compute  $\Theta$  for the two different  
190 periods and using the analogs as well to detect shifts from the factual to the  
191 counterfactual worlds.
- 192 • **Seasonality of Analog:** we can also simply count the number of analogs in  
193 each month to detect whether a given circulation shifts towards earlier or  
194 later months. This can have strong thermodynamic implications.

195 For more information, please refer to (Faranda et al, 2022).

196 We also provide results of the attribution conditional not on the past and  
197 present climate, but on the El-Niño - Southern Oscillation (ENSO) mode.  
198 ENSO is known to be a major factor in the variability of tropical and subtrop-  
199 ical regions around the Pacific and likely played a role in the February 2022  
200 event for which the mode was strongly negative. Therefore, we decided to run  
201 the attribution analysis conditional on the Nino3.4 index being above the 75%

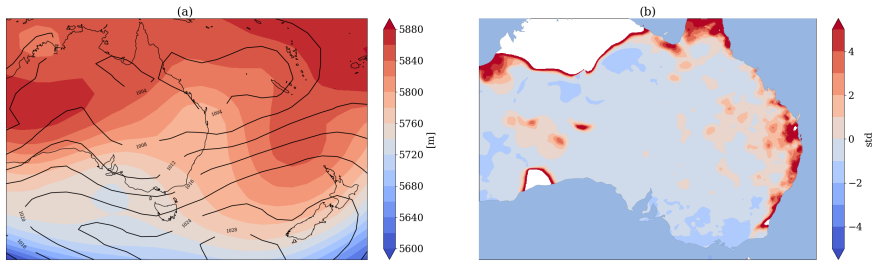
202 quantile (ENSO+) and below the 25% quantile (ENSO-) for the period 1948-  
203 2019. Analogues are then computed in those two pools of data using either  
204 3-days rolling averaged *slp* or *z500* maps.

### 205 **3 Meteorology and Impacts for the Australian** 206 **rain bombs**

207 In order to explain the rain bomb event, we identified two main ingredients: i)  
208 an atmospheric river, formed north the continent around the 22nd of Febru-  
209 ary, in the upper atmosphere – between eight and 10 kilometres up –, moved  
210 from the ocean to the south reaching the continent and producing a contin-  
211 uous flux of precipitation originating from the tropics, ii) a dipolar structure  
212 consisting of a low pressure system in the coral Sea and a blocking anticyclone  
213 further east. The combination of these elements allowed to transport moist  
214 air from the tropics to the Coral sea and then condense the moisture that has  
215 then fallen as rain thanks to the low pressure, and winds pushing rain over  
216 Queensland’s south east. Precipitation was further enhanced by orographic  
217 effects. At an even larger scale, the phenomena were embedded in a strong La  
218 Nina phase, which induces additional air moisture in the south west Pacific  
219 and wind circulation patterns that could have played a role in the intensity of  
220 the event.

221 Preliminary results of the University of Melbourne reported by national and  
222 international newspapers (see, e.g. [The Guardian \(2022\)](#)) showed that on the  
223 26th and 27th of February, the two days with heaviest rain, 16 times the water  
224 held by Sydney harbour (500 bn liters) flowed in the atmospheric river above  
225 Queensland. Indeed during those days rainfall of over 400 millimetres was  
226 recorded across the greater Brisbane area, summing up, for the 28th February  
227 to a total of 676.8 millimetres of rainfall, the largest three, and seven, day total  
228 ever recorded in Brisbane. Another record breaking amount of rainfall was  
229 recorded in Mount Glorious which received rainfall in excess of 1770 millimetres  
230 in the week until 28th of February. More than 30 locations across the south-  
231 east recorded rainfall in excess of 1000 millimetres, resulting in the floods being  
232 more intense than that of 1974. The unprecedented flooding that raised many  
233 rivers above record highs moved south, leaving towns underwater. The area  
234 of Sydney was more affected on the 3rd and the 8th of March with the city’s  
235 chief reservoir, spilling at a rate in excess of 70 gigalitres a day on 3 March.  
236 Residents in parts of western Sydney were told to evacuate for the second year  
237 in a row as the city’s Warragamba Dam overflowed. But the system stalled  
238 before it passed over Sydney.

239 Damage from floods is only partially estimated at this stage, but is expected  
240 to reach almost AUD 2.3 billion ([Foreign Policy, 2022](#)), an estimate that  
241 exceeds that of the Insurance Council of Australia, which also summed-up the  
242 cost of claims from the disaster to AUD 1.45 billion ([ClimateCouncilAustralia,](#)  
243 [2022](#)). This is somehow a lower bound as the estimates are expected to grow.



**Fig. 1 Description of the rain bomb event.** (a) Geopotential height at 500hPa (colors) and sea level pressure (contours) averaged over the 26th, 27th and 28th of February 2022. (b) Standardized anomaly of cumulated precipitation for the period 20th February - 20th March with respect to the 1990-2019 period. Regions in white correspond to standardized anomaly above 15 standard deviations.

244 Figure 1 (a) presents the synoptic situation averaged over the 26th, 27th  
 245 and 28th of February over the region. We see the dipole structure with an  
 246 upper level low pressure system centered above the Brisbane region and a high  
 247 pressure system over the Coral sea. Figure 1 (b) presents the standardized  
 248 anomaly of cumulated precipitations for a one month period (20/02-20/03)  
 249 with respect to the 1990-2019 period. The Eastern coast of Australia saw  
 250 extremely strong precipitations, with many locations exceeding 5 standard  
 251 deviation anomalies with respect to climatology.

## 252 4 Results

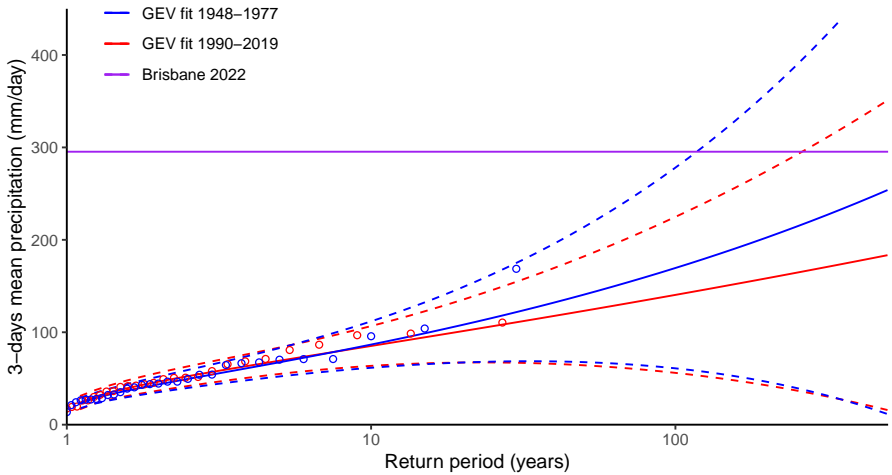
### 253 4.1 Statistical attribution

254 To assess the change of probability of the event to climate change, we use the  
 255 rapid statistical attribution method described in 2. We fit the 3-days rolling  
 256 average precipitation yearly maxima in Alderley station to a Generalized  
 257 Extreme Value (GEV) law for the factual and counterfactual periods.

258 Figure 2 shows the resulting GEV fit. In both the factual and counterfactual  
 259 worlds the event of April 2022 was highly exceptional, with return periods of  
 260 more than a thousand years. For high return periods, return levels are slightly  
 261 higher in the counterfactual period, due to the January 1974 precipitation  
 262 event that led to historical floods in Brisbane. However, the 95% confidence  
 263 intervals are too wide to conclude to any detectable effect of climate change  
 264 with this method.

265 Figure 3 shows the same analysis applied to the ENSO mode, using ENSO+  
 266 as a factual period and ENSO- as a counterfactual period. Results show a  
 267 much stronger effect of the la Niña phase (ENSO-) on precipitation rates in  
 268 the Eastern Australian coast. The 2022 26th to 28th February event is very  
 269 highly improbable during ENSO+ mode - with a return period of over 400  
 270 years taking into account the 95% confidence interval - whereas it has a return  
 271 period of 120 years according to the best estimation in ENSO- mode. This





**Fig. 2** Fit of the annual maximum of 3-days precipitation running means at Alderley station to a GEV in the factual and counterfactual periods. Gumbel plot of the GEV fit over 1948-1977 (blue lines with 95% uncertainty estimates), and 1992-2021 (red lines) using the maximum likelihood estimation. The purple line shows the value of intensity of the observed event at Alderley station in 2022.

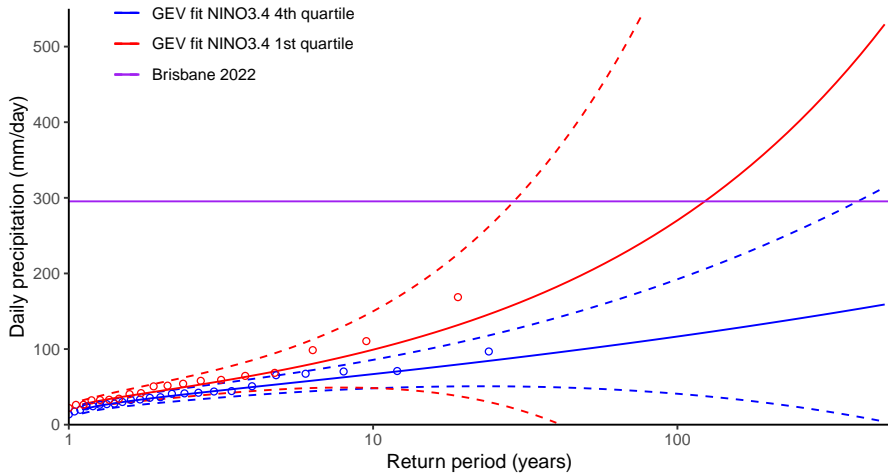
272 is consistent with the influence of the strong la Niña phase currently ongoing  
 273 on the intensity of the 2022 event suggested in 3. We however underline that  
 274 the wide confidence intervals prevent again to obtain statistical significant  
 275 differences at least at the 95% level chosen as a reference in this study.

## 276 4.2 Dynamical attribution

277 To identify the dynamical and thermodynamic factors which may have played  
 278 a role in the intensity of the event, we ran the dynamical attribution framework  
 279 presented previously.

280 Figures 4 and 5 present the results using respectively *slp* and *z500* analogues.  
 281 These figures display the *slp/z500* (a-d), *t2m* (e-h) and *prate* (i-l)  
 282 maps and, from left to right, the maps of the event (a,e,i), the composites of  
 283 counterfactual (b,f,j) and factual (c,g,k) analogs and the difference between  
 284 the factual and counterfactual analogs (d,h,l) where hashed-filled areas show  
 285 significant differences. Distributions of additional metrics comparing the  
 286 counterfactual and factual periods, namely analogs quality, predictability,  
 287 persistence and distribution by season are shown in panels m-p, respectively.

288 For the *slp* analogues, we firstly notice that the analogues quality is not  
 289 good and therefore results must be interpreted carefully (panel (m)). In the  
 290 factual period, there is a signal of intensified high-pressures over New Zealand,  
 291 which may be related to the stronger advection of moist air from the Coral  
 292 sea. When we look at the precipitation difference map (Fig. 4 (l)), there are  
 293 indeed stronger precipitations on the Eastern coast of Australia in the factual

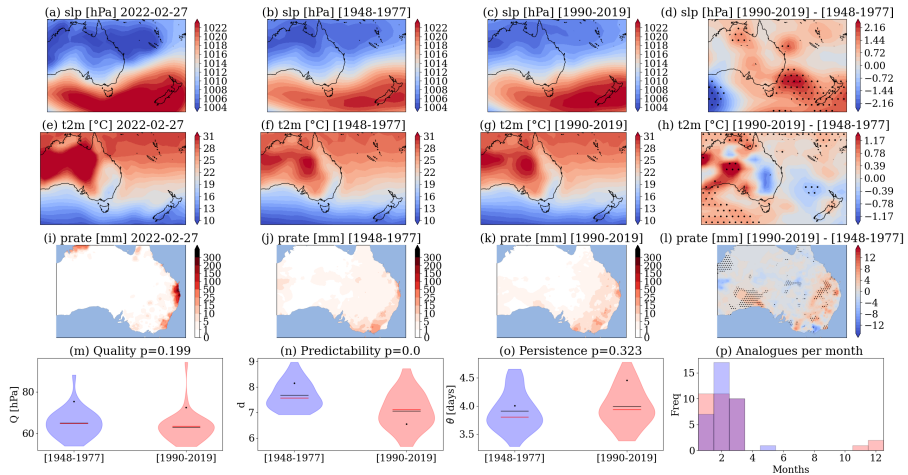


**Fig. 3** Fit of the annual maximum of 3-days precipitation running means at Alderley station to a GEV, depending on El Niño 3.4 detrended index. Gumbel plot of the GEV fit over years in the 1st quartile (red lines) and 4th quartile (blue lines) of NINO3.4 index average over JFM from 1944 to 2021, with 95% uncertainty estimates. The purple line shows the value of intensity of the observed event at Alderley station in 2022.

294 period but only few regions are significantly different than the counterfactual  
 295 period and do not fully correspond to the regions where the precipitations  
 296 are maximum during the February 2022 event. There is moreover no strong  
 297 thermodynamic signal as depicted in panel (h) using 2m air temperature which  
 298 does not display significant differences between the factual and counterfactual  
 299 periods on the Eastern coast and in the Coral sea. However, panel (o) and (p)  
 300 show that the predictability is lower and the persistence is higher in the factual  
 301 period. The event is particularly persistent compared to its analogues in the  
 302 factual period which may explain the intensity of the event.

303 This results are confirmed when using the  $z500$  analogues (Fig. 5), which  
 304 are better as shown in panel (m). The factual period displays stronger high  
 305  $z500$  over the northern region but also almost no significant thermodynamic  
 306 signal (panel (h)). The low predictability (panel (n)) but high persistence  
 307 (panel (p)) of the event is also noticed using  $z500$  analogues. When it comes to  
 308 precipitations, even though they are stronger during the factual period (panel  
 309 (l)), this difference is not significant.

310 These results are coherent with the statistical attribution in so far as the  
 311 thermodynamic signal associated with climate change is weak. There is how-  
 312 ever a noticeable dynamical signal in the two periods as represented in the  $slp$   
 313 and  $z500$  analogues difference maps. One may indeed notice that ENSO, which  
 314 is the major driver of variability in the region, was in a strong and persistent  
 315 La Nina phase during the event, which is not fully represented using analogues  
 316 (see figure 6). We therefore decided to run the same dynamical attribution



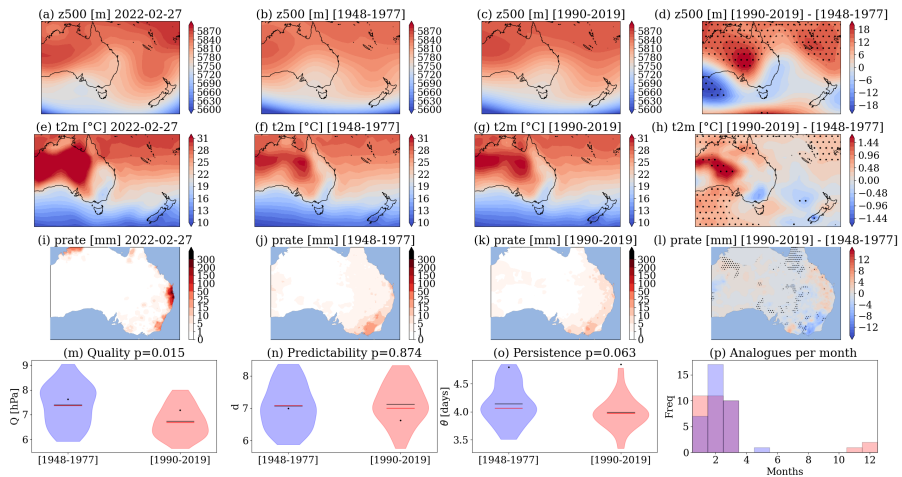
**Fig. 4** Dynamical attribution using *slp* analogues for the Australian rain bomb on 27-02-2022. 3-days rolling mean sea-level pressure *slp* (a), 2-meter temperatures *t2m* (e) and total precipitation *prate* (i) centered on the 27-02-2022. Average of the 35 sea-level pressure analogs found for the counterfactual [1948-1977] (b) and factual [1990-2019] (c) periods and corresponding 2-meter temperatures (f,g) and daily precipitation rate (j,k).  $\Delta slp$  (d),  $\Delta t2m$  (h) and  $\Delta prate$  (i) between factual and counterfactual periods: hashed-filled areas show significant differences. Violin plots for counterfactual (blue) and factual (red) periods for the Analogs Quality  $Q$  (m) the Predictability index  $D$  (n), the Persistence index  $\theta$  (o) and the distribution of analogs in each month (p). Values for the selected day are marked by a black dot.

317 analysis using the Nino3.4 index to define counterfactual (ENSO-) and factual  
 318 (ENSO+) periods.

319 The results of this analysis are presented in figures 7 and 8 using respec-  
 320 tively *slp* and *z500* analogues. On the dynamical side, there is a significant  
 321 stronger upper level low during ENSO- phase (Fig. 8 panel (d)) analogues.  
 322 Using both analogues, the thermodynamic signal is much stronger during  
 323 ENSO+ events, which may explain the absence of signal when doing the analy-  
 324 sis during past and present periods: the natural variability is stronger than the  
 325 climate change signal on this region. When it comes to precipitations, there is  
 326 a strong positive signal on the Eastern coast and Brisbane regions during La  
 327 Nina phases using *slp* analogues but the quality of analogues is low and these  
 328 results are not significant using *z500* analogues.

## 329 5 Conclusions

330 In this paper we have performed a statistical and dynamical attribution of the  
 331 Australian rain bomb event of February 2022. We have used both reanalyses  
 332 and historical records of daily precipitations in the past (1948-1977, coun-  
 333 terfactual) and present (1990-2019, factual) periods. From a statistical point  
 334 of view, this extreme precipitation event was unprecedented in the Brisbane

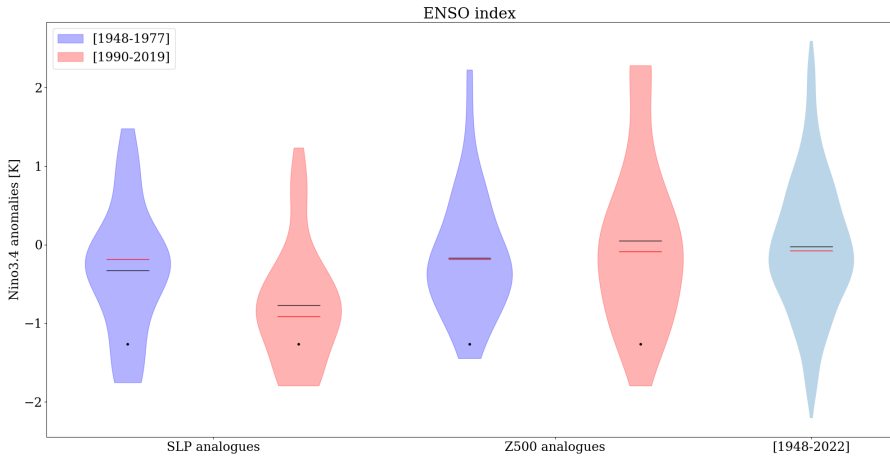


**Fig. 5** Dynamical attribution using  $z500$  analogues for the Australian rain bomb on 27-02-2022. 3-days rolling mean 500hPa geopotential height  $z500$  (a), 2-meter temperatures  $t2m$  (e) and total precipitation  $prate$  (i) centered on the 27-02-2022. Average of the 35 500hPa geopotential height analogs found for the counterfactual [1948-1977] (b) and factual [1990-2019] (c) periods and corresponding 2-meter temperatures (f,g) and daily precipitation rate (j,k).  $\Delta z500$  (d),  $\Delta t2m$  (h) and  $\Delta prate$  (i) between factual and counterfactual periods: hashed-filled areas show significant differences. Violin plots for counterfactual (blue) and factual (red) periods for the Analogs Quality  $Q$  (m) the Predictability index  $D$  (n), the Persistence index  $\theta$  (o) and the distribution of analogs in each month (p). Values for the selected day are marked by a black dot.

335 region and very intense with regards to historical records in the broader East-  
 336 ern coast of Australia. The statistical attribution suggests that this event has  
 337 a low probability to happen both in the past and present climate (less than  
 338 one in a century). There is no clear signal of a climate change influence (high  
 339 uncertainty) which translates in a low evidence for the attribution of this event  
 340 to climate change.

341 The dynamical attribution, performed using the method of analogues cir-  
 342 culation patterns proposed in Faranda et al (2022) to those observed during  
 343 the events suggest the exceptional characteristics of the event which appears  
 344 to be unprecedented in both the factual and counterfactual distributions of  
 345 weather patterns: it has arisen as the combination of ingredients: the tropical  
 346 moisture was deflected to the subtropics, collected and lifted by a low pressure  
 347 system blocked by an high pressure offshore the Coral sea. This combination  
 348 created an atmospheric river capable of transporting several gigaliters of water  
 349 towards the Queensland and the South West of the continent. Finally, La Niña  
 350 phase of the El-Niño-Southern-Oscillation likely played a significant role in the  
 351 intensity of the event.

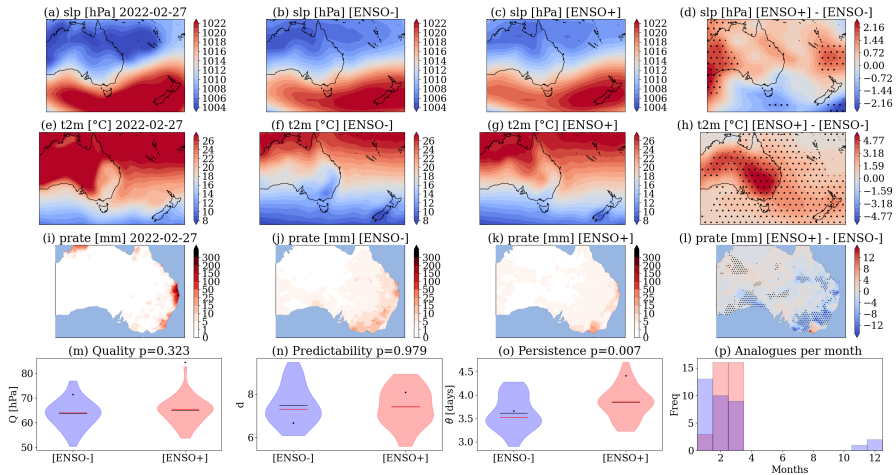
352 The main limitation of this study is that we do not use climate models:  
 353 the rationale for doing so comes from the evidence that both large, regional



**Fig. 6 Distribution of ENSO index between factual and counterfactual periods for the two types of analogues.** Blue (resp. red) violin plots represent the distribution of the ENSO index for the analogues in the counterfactual (resp. factual) period. The red (resp. black) line depicts the median (resp. mean) of the distribution. The black dot corresponds to the value of the ENSO index during the February 2022 event. The last violin plot depicts the distribution of the ENSO index for all dates between 1948 and 2019.

354 and local phenomena contributed to this event. In order to perform an attri-  
 355 bution study based on models, we would need a large ensemble of convection  
 356 permitting models resolving at least the region shown in Fig. 1, with specific  
 357 runs capable to evaluate also the contribution of la Nina to the event. Even  
 358 with such models, the detailed physics of the precipitation could still depend  
 359 on the microphysics introduced in the model as shown by Ban et al (2021).  
 360 A further limitation of this study is the use of factual and counterfactual peri-  
 361 ods consisting of only 30 years. While we could in principle consider the whole  
 362 period twice, as in the protocol described by Philip et al (2020), we cannot  
 363 here use the implicit assumption of stationarity of the variability of the rain-  
 364 fall extremes that is underlying the protocol. While this is a limitation on the  
 365 available data, it is a fair way to account for the variability of extremes, allow-  
 366 ing for a larger uncertainty and a conservative estimates on the role of climate  
 367 change to triggering this event.

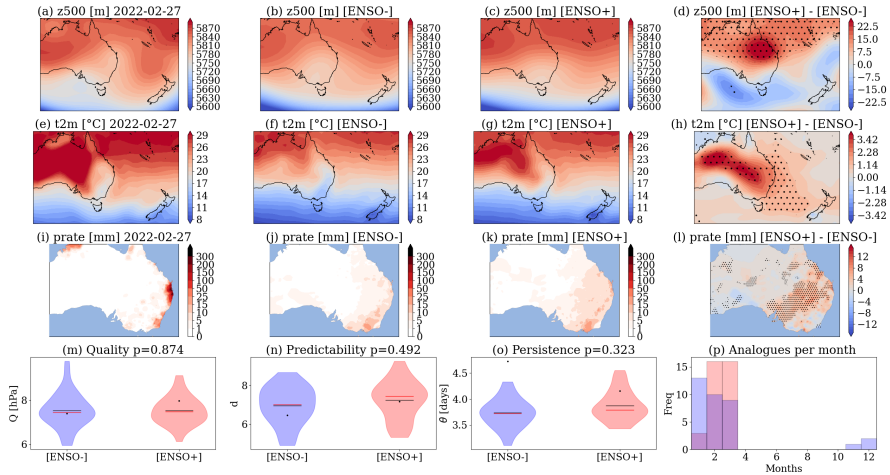
368 To frame our results in a more general framework, we observe that they  
 369 are in line with what the IPCC report AR6, WG1, Chapter 11.4, states about  
 370 rainfall over the region, namely that “Available evidence has not shown an  
 371 increase or a decrease in heavy precipitation over Australasia as a whole  
 372 (medium confidence), but heavy precipitation tends to increase over North-  
 373 ern Australia (particularly the north-west) and decrease over the eastern and  
 374 southern regions.” (Seneviratne et al, 2021) . We however observe that the  
 375 compounding dynamical elements driving this event are also observed in a  
 376 series of unprecedented extreme weather events occurred in the last few years,  
 377 including the 2021 Canada heat dome, the Antarctica atmospheric rivers, the



**Fig. 7** Dynamical attribution using *slp* analogues for the Australian rain bomb on 27-02-2022 relative to the ENSO index. 3-days rolling mean 500hPa geopotential height  $z500$  (a), 2-meter temperatures  $t2m$  (e) and total precipitation  $prate$  (i) centered on the 27-02-2022. Average of the 35 sea-level pressure analogs found for the counterfactual [ENSO-] (b) and factual [ENSO+] (c) periods and corresponding 2-meter temperatures (f,g) and daily precipitation rate (j,k).  $\Delta z500$  (d),  $\Delta t2m$  (h) and  $\Delta prate$  (i) between factual and counterfactual periods: hashed-filled areas show significant differences. Violin plots for counterfactual (blue) and factual (red) periods for the Analogs Quality  $Q$  (m) the Predictability index  $D$  (n), the Persistence index  $\theta$  (o) and the distribution of analogs in each month (p). Values for the selected day are marked by a black dot.

378 2022 Indian, Chinese, Western European and North American heatwaves. Such  
 379 series of record breaking events raise the question of the emergence of new phe-  
 380 nomena linked to global warming, a field to explore statistically, e.g. by using  
 381 the concept of time of emergence introduced in Hawkins and Sutton (2012)  
 382 and dynamically, e.g. by looking the possible presence of tipping elements in  
 383 the climate system (Lenton et al, 2008).

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**Fig. 8** Dynamical attribution using  $z500$  analogues for the Australian rain bomb on 27-02-2022 relative to the ENSO index. 3-days rolling mean 500hPa geopotential height  $z500$  (a), 2-meter temperatures  $t2m$  (e) and total precipitation  $prate$  (i) centered on the 27-02-2022. Average of the 35 500hPa geopotential height analogs found for the counterfactual [ENSO-] (b) and factual [ENSO+] (c) periods and corresponding 2-meter temperatures (f,g) and daily precipitation rate (j,k).  $\Delta z500$  (d),  $\Delta t2m$  (h) and  $\Delta prate$  (i) between factual and counterfactual periods: hashed-filled areas show significant differences. Violin plots for counterfactual (blue) and factual (red) periods for the Analogs Quality  $Q$  (m) the Predictability index  $D$  (n), the Persistence index  $\theta$  (o) and the distribution of analogs in each month (p). Values for the selected day are marked by a black dot.

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- 401 • Availability of data and materials: NCEP data are available on the  
 402 NOAA website at <https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html>. Rainfall data over Australia are available at the National Computa-  
 403 tional Infrastructure (NCI) THREDDS server at <https://dapds00.nci.org.au/thredds/catalog/zv2/agcd/v1/precip/total/r005/01day/catalog.html>.
- 404 • Code availability: The main results of this work were obtained using Python.  
 405 The scripts are available upon request.
- 406 • Authors’ contributions: CC, NM and RN performed the analysis. DF  
 407 designed the analyses. All authors participated to the manuscript prepara-  
 408 tion and writing.  
 409  
 410



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