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1 **Tropical Waves are key drivers of Extreme Precipitation Events in the Central Sahel**

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7

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9 **Key Points:**

10

- 11 • Tropical waves are key to build the atmospheric environment conducive to an extreme  
12 precipitation event
- 13 • Equatorial Rossby waves appear as a new driver of extreme rainfall in the Central Sahel  
14 when combined with African Easterly Waves
- 15 • The combination of African Easterly Wave with an equatorial Rossby Wave and / or  
16 Kelvin wave, increase the probability of extreme rainfall

17

18

19

20 **Abstract**

21 Extreme precipitation events (EPE) are often associated with severe floods and significant  
22 damages in Central Sahel. To better understand their formation and improve their forecasts, we  
23 investigate the sub-seasonal drivers of EPEs. A composite analysis reveals that moist, cyclonic  
24 and upper-level divergence anomalies are found on average as a result of several tropical waves.  
25 The equatorial Rossby wave (ER) dominates at large scale providing a moist and convectively-  
26 active anomaly over the northern Sahel together with a smaller-scale African Easterly Wave  
27 (AEW). The Madden-Julian Oscillation provides upper-level divergence anomalies and a Kelvin  
28 wave increases convection during the EPE. Statistics show the prevalence of AEW and  
29 emphasize ER as a key driver of EPE. The co-occurrences of several tropical waves, especially  
30 those involving AEW, ER and Kelvin waves, increase the probability of EPE. Monitoring these  
31 tropical waves combinations could improve EPEs forecasts.

32

33 **Plain Language Summary**

34

35 The drivers of extreme precipitation events (EPE) over the Central Sahel are studied at  
36 subseasonal scales. A statistical approach is adopted to build an average extreme rainfall event.  
37 EPEs occur within a large-scale moist anomaly, an upper-level divergence, and at shorter scales  
38 an intense vortex. These features are provided by multiple tropical meteorological systems,  
39 called tropical waves, that have typical spatio-temporal scales greater than that of a convective  
40 storm. The four tropical waves studied here contribute to this favorable environment. However  
41 two of them – an Equatorial Rossby wave, rather slow, and an African Easterly Wave (more  
42 rapid) - explain the largest part of the favorable conditions leading to an EPE. Statistics show  
43 that a single intense AEW or the combination of multiple tropical waves increases the probability  
44 of EPE. Monitoring these tropical waves combinations could improve EPEs forecasts.

45 **1 Introduction**

46       Mesoscale convective systems provide most of the rainfall over the Central Sahel during  
47 the monsoon season (Mathon et al. 2002). The most intense of them produce very large amounts  
48 of precipitation in a short period of time (typically one day or less), leading to Extreme  
49 Precipitation Events (EPEs) that frequently result in severe socioeconomic damages (Di  
50 Baldassarre et al. 2010; Descroix et al. 2018). Though, EPEs remain a phenomenon difficult to  
51 anticipate as indicated by the poor capacity of current numerical weather prediction models in  
52 quantitatively forecasting rainfall (Vogel et al. 2018). A better understanding of their driving  
53 mechanisms, from days to weeks before the EPE, may help inform and develop relevant early  
54 warning systems by effectively indicating on potential large-scale precursors.

55       On subseasonal timescales (typically between 2 and 90 days), tropical waves might  
56 stand as possible precursors for EPE given their recognized role in modulating convection and  
57 rainfall in the tropics and West Africa (Kiladis et al. 2009, Schluter et al. 2019). However, little  
58 is known about their role in the occurrence of EPEs. The objective of the present study is to  
59 determine to what extent tropical waves drive the occurrence of EPEs.

60       The Madden-Julian Oscillation (MJO) is one of the subseasonal drivers of Sahelian  
61 rainfall that has received the greatest interest. EPEs are more likely during its low-level westerly  
62 phase (Sossa et al. 2017) or during its upper-level divergent phase (Schreck 2021). Aside from  
63 these studies, the understanding of Sahelian EPEs at subseasonal scale relies on the findings  
64 from very few case studies. They emphasize the importance of a humid environment with

65 vertically-integrated water vapor contents (precipitable water hereafter) greater than 45-50 mm  
66 and of an intense synoptic disturbance such as an African Easterly Wave (AEW –Lafore et al.  
67 2017, Maranan et al. 2019, Vizy and Cook 2022, Taylor et al. 2017). Other than the individual  
68 effect of tropical waves, the co-occurrence of several convectively-coupled waves has been  
69 observed during the record-breaking EPE that occurred on September 1<sup>st</sup> 2009 in Ouagadougou,  
70 Burkina Faso (Lafore et al. 2017). An active MJO and an equatorial Rossby wave (ER) were  
71 active at the time of the EPE together with a Kelvin wave and an intense AEW, well-marked in  
72 humidity and vorticity. There is however no study about the frequency of such a configuration in  
73 the occurrence of EPEs.

74         The present work investigates the subseasonal atmospheric conditions associated with  
75 Sahelian EPEs and assesses the contribution of tropical waves to their occurrence from a  
76 statistical point of view.

## 77 **2 Data and methods**

78

### 79 2.1 Definition and detection of EPEs

80         EPEs are defined here as events for which the 1°x1° daily rainfall exceeds the 99<sup>th</sup> all-day  
81 percentile. For their detection, we rely on a 142 rain-gauge rather dense network covering  
82 Burkina Faso over the 1995-2016 period without missing data (Sanogo et al. 2022). This dataset  
83 is preferred to any currently available gridded precipitation product given their difficulty in  
84 reproducing high rain rates (Satgé et al. 2020, Sanogo et al. 2022), thereby leading to numerous

85 false detections. Following Sanogo et al. (2022), the daily rainfall measurements from rain  
86 gauges are aggregated at the scale of  $1^\circ \times 1^\circ$  pixels, considering only pixels that have a minimum  
87 of five rain gauges (15  $1^\circ \times 1^\circ$  pixels in total). The 99<sup>th</sup> all-day percentiles of these 15 time series  
88 range between 20 and 32 mm d<sup>-1</sup> (see Text S1 and Figure S1 in Supporting Information – SI – for  
89 further details).

90

## 91 2.2 Datasets for characterizing the EPE large-scale environment

92 The atmospheric state associated with EPEs is documented based on the daily /  $0.75^\circ \times$   
93  $0.75^\circ$  ERA Interim reanalysis data (Dee et al. 2011). Following previous studies on tropical  
94 waves (e.g., Schlueter et al. 2019, Wheeler et Kiladis 1999), the daily  $2.5^\circ \times 2.5^\circ$  Outgoing Long-  
95 wave Radiation (OLR) from National Oceanic and Atmospheric Administration (NOAA,  
96 Liebmann and Smith 1996) is used to detect and characterize convectively-coupled waves and  
97 the convective activity at large scale.

98 The large-scale spatial distribution of the precipitation field is also qualitatively  
99 characterized with CHIRPS precipitation daily data (Funk et al. 2015) provided at a  $1^\circ \times 1^\circ$   
100 resolution by Roca et al. (2019). Similar results are found with other rainfall gridded products  
101 (not shown).

## 102 2.3 Tropical wave analysis

103 For a given parameter  $X$ , we compute the difference between its raw daily data  
104 and a smoothed daily climatology, in which only the first four harmonics are retained  
105 (Lafore et al. 2017, Roundy and Franck 2004). The resulting anomaly is detrended on a  
106 90-day window centered on the EPE occurrence to only retain the intraseasonal part of  
107 the signal.

108 The contribution of four tropical waves – the MJO, ER, Kelvin wave and AEW – to the  
109 intraseasonal anomaly  $X^*$  is quantified for several atmospheric fields using wave-number-  
110 frequency filtering, following Wheeler and Kiladis (1999) and Roundy and Franck (2004). The  
111 filtering process allows writing  $X^*$  as  $X^* = X^{\text{MJO}} + X^{\text{ER}} + X^{\text{Kelvin}} + X^{\text{AEW}} + \text{residual}$ , where the right-  
112 hand side terms are the wave-filtered contributions and a residual term of weak magnitude given  
113 the prevalence of the four waves considered here over West Africa). The filtering domains used  
114 for each tropical wave are standard (see Text S2 and Figure S2 in SI) and allows to isolate their  
115 signal without any overlap among them.

116 The filtering domain for theoretical shallow water waves are set up using equivalent  
117 depths between 12 and 90 m to identify the lower and upper bounds for the dispersion curves.  
118 The filtering domains used here are broadly similar to Schreck et al. (2012). The Kelvin wave  
119 domain is given by wave-number  $k$  and period  $T$  in  $[1,14]$ ;  $[2.5-17.5 \text{ days}]$ . The periods  
120 considered for Equatorial Rossby waves (ER) are  $[10-48 \text{ days}]$  following Wheeler and Kiladis  
121 (1999). The MJO contribution is extracted from a domain encompassing periods from 30 to 96  
122 days and wave-numbers 0 to 9. The (AEW) domain includes westward-propagating signals with



123 wave-numbers -20 to -8 and periods between 2 and 10 days. Previous studies indicated a possible  
124 overlap between AEW and Mixed-Rossby Gravity waves (MRG) domains (Schlueter et al.  
125 2019), such that the contribution of MRG are not considered here. . The other tropical waves  
126 considered here have well-separated filtering domains avoiding any overlap between MJO, ER,  
127 Kelvin wave and AEW.

128 The wavenumber–frequency filtering is applied to different parameters – OLR,  
129 precipitable water, velocity potential, vorticity and wind – to account for the different signatures  
130 of tropical waves in the atmosphere with a specific attention on OLR, as a measure of the  
131 convectively-coupled nature of the waves.

#### 132 2.4 EPE attribution to tropical waves

133 Inspired by similar work on tropical cyclones (Landu et al. 2020, Chen and Chou 2014,  
134 Schreck et al. 2011, 2012, Feng et al. 2023), EPEs are attributed to a given convectively-active  
135 wave depending on the magnitude of its wave-filtered anomaly. Convectively-active waves are  
136 first detected when the wave-filtered OLR anomaly averaged over a  $5^\circ$  box centered at the EPE  
137 location is greater than half of the box-averaged standard deviation following previous studies by  
138 Landu et al. (2020), Chen and Chou (2014) and Feng et al. (2023). The leading contribution of  
139 tropical waves to EPEs and their modulations of the EPE probability remain similar for  
140 thresholds of -0.3 and -1 standard deviation (see Text S4 and Figure S3 in SI for details).

141 The contribution of each tropical wave and of multiple waves combinations are  
142 determined. As we consider four tropical waves, 16 combinations of active tropical waves are  
143 possible: four with one active wave only, six combining two waves, four combining three waves, one

144 combining the four waves and a last category with no active wave (NONE). Each day or each  
145 EPE is attributed to a unique tropical wave combination.

146 We then quantify the modulation of the EPE occurrence by each wave combination by  
147 the change in EPE frequency of occurrence (Xavier et al. 2015, Guigma et al. 2021). It is given  
148 by the relationship  $\Delta P_{\text{wave}}^{\text{EPE}} = (P_{\text{wave}}^{\text{EPE}} - P_{\text{all-day}}^{\text{EPE}}) / P_{\text{all-day}}^{\text{EPE}} * 100$  where  $P_{\text{wave}}^{\text{EPE}}$  is the probability  
149 of EPE occurrence during a given tropical wave combination. It is given by the number of EPEs  
150 during which the given tropical wave combination occurs divided by the total number of days  
151 during which this combination is observed in the climatology, regardless of EPEs.  $P_{\text{all-day}}^{\text{EPE}}$  is the  
152 probability of EPE occurrence computed for all days from the climatology and corresponds to  
153 0.01 given EPE definition (days with precipitation exceeding the 99<sup>th</sup> all-day percentile). Results  
154 from the attribution of EPE to tropical waves are tested following a bootstrap procedure at the 95  
155 % confidence level (details in Text S4 and Figure S3 in SI).

156

## 157 2.5 Composite

158 Once the dates of EPE occurrence are obtained, the atmospheric fields are aligned in time  
159 and space (latitude and longitude) relative to the time and location of each EPE, providing the  
160 basis for an EPE composite analysis (i.e. "average EPE"). DAY 0 refers to the day of occurrence  
161 of the composite EPE and its composite location is set to the average EPE location [2°W, 12.5  
162 °N]. Only values of the composite passing a two-tailed test at the 95 % confidence level are  
163 displayed in the results presented here (see Text S4 in SI for further details).

164

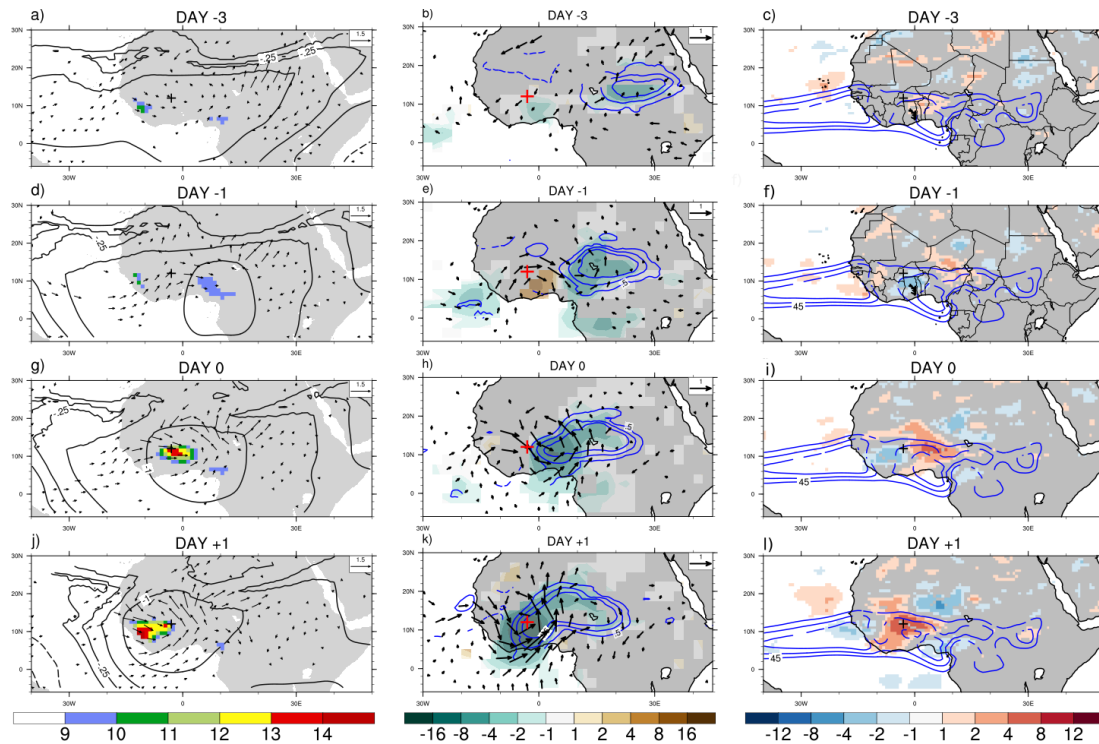
165 **3 Results**

166

## 167 3.1 Atmospheric conditions leading to EPEs

168

169 Figure 1 shows the composite state of the atmosphere during the days surrounding the  
170 composite EPE. The precipitation associated with EPE is initiated  $\sim 10^\circ$  further to the east at  
171 DAY-1 (Fig. 1d). It then moves westward to reach the EPE location at DAY 0 with a value  
172 greater than  $15 \text{ mm d}^{-1}$  in CHIRPS data (Fig. 1d-g-j). It occurs within an upper-level large-scale  
173 divergence anomaly, developing several days before the EPE (Fig1. a-j), and a low-level  
174 cyclonic vortex that forms near DAY 0, which induces north-westerly wind anomalies to the  
175 west of Burkina Faso (Fig. 1g). The EPE is associated with a large-scale humid and  
176 convectively-active anomaly ( $> 3000 \text{ km}$ ) arriving from the north-eastern part of the Sahel (Fig.1  
177 b-e-h-k). A synoptic vortex of smaller scale ( $< 1000 \text{ km}$ ) develops to the west of the moist  
178 anomaly at DAY-1 before increasing at DAY 0 and DAY+1. A noticeable convective anomaly is  
179 also found in the Atlantic Ocean at DAY-3 moving westward near the Guinea Coast at DAY-1  
180 and around the EPE location at DAY 0. The cyclonic anomaly is also visible, on average, over  
181 the 925-600-hPa layer to the east of the mean EPE location (Fig. 1c-f-i), indicating a deep and  
182 barotropic vortex. It is associated with a high precipitable water value, up to  $47 \text{ mm}$  ( $\sim 70\%$   
183 column relative humidity, not shown).



184

185

186 **Figure 1** : Left column: EPE composite mean of the 925-hPa horizontal wind anomalies  
 187 (vectors), 200-hPa negative (divergent) velocity potential anomalies (one contour every  $0.2 \times 10^6$   
 188  $\text{m}^2\text{s}^{-1}$ ) and CHIRPS raw precipitation (shading,  $\text{m d}^{-1}$ ). Lags are expressed in days relative to the  
 189 occurrence of the composite EPE. Latitude and longitude are relative to the EPE mean location  
 190 indicated by the black cross. Middle column: same as left column except for OLR anomalies  
 191 (shading,  $\text{W m}^{-2}$ ), precipitable water anomalies (one contour every  $0.5 \text{ kg m}^{-2}$ ) and 925-600  
 192 hPa layer-averaged wind (vectors,  $\text{m s}^{-1}$ ). Right column: same as left column except for 925-600-  
 193 hPa mean relative vorticity anomalies (shading,  $\text{s}^{-1}$ ) and raw precipitable water (contour every  
 194  $2.5 \text{ kg m}^{-2}$  from  $45 \text{ kg m}^{-2}$ ). Only statistically significant values at the 95 % confidence level are  
 195 displayed.

196

197

198 The average conditions emphasized by the composite consists in the co-occurrence of a multi-  
199 scale pattern. They confirm and extend previous results from the literature based on case studies  
200 (Lafore et al. 2017, Maranan et al. 2019) by pointing out the significance of a synoptic scale  
201 vortex (~1000 km) and a larger-scale moist anomaly (> 3 000 km) during EPEs.

202

### 203 3.2 Contribution of tropical waves to the EPE large-scale environment

204 To further understand the origin of such an atmospheric environment, the intraseasonal  
205 anomalies of OLR, precipitable water and winds are split into contributions from individual  
206 tropical waves (Fig. 2). The large-scale moist and convective envelope results from an ER visible  
207 at DAY-1 near 15°E-15°N that slowly propagates westward. It is associated with a large-scale  
208 cyclonic circulation to the west of the moist anomaly resulting in westerlies at the EPE location,  
209 which increases the southwesterly monsoon flow. The synoptic cyclonic vortex is the signature  
210 of an AEW that develops at DAY-1 with a convectively-active phase at 10°E and a convectively-  
211 suppressed phase at the EPE location. Finally, a convectively-coupled Kelvin wave signal  
212 propagates eastward with a peak of convective activity slightly west of the EPE location at DAY  
213 0. It provides westerly wind anomalies.

214

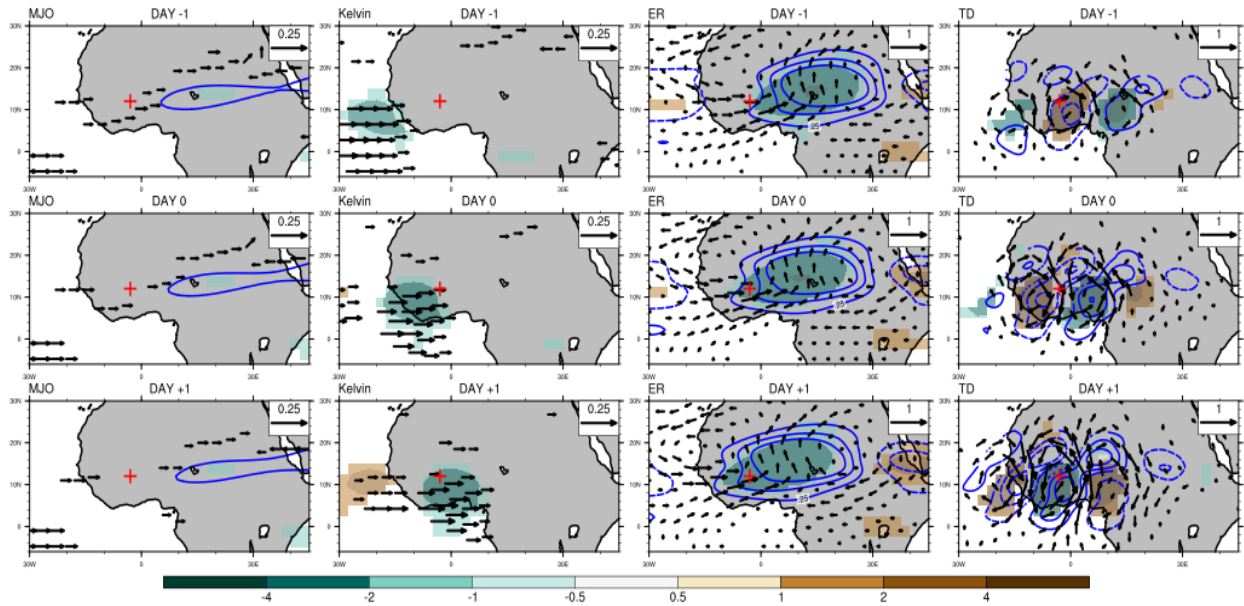
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221

222 **Figure 2** : Contributions of tropical waves to the EPE composite mean based on wavenumber-  
 223 frequency-filtered OLR anomalies (shading,  $\text{W m}^{-2}$ ), precipitable water anomalies (blue contours,  
 224 one contour every  $0.25 \text{ kg m}^{-2}$ ) and 925-600 hPa layer-averaged wind (vectors,  $\text{m s}^{-1}$ ), for the  
 225 Madden-Julian Oscillation (MJO, first column), Kelvin wave (KW, second column), Equatorial  
 226 Rossby wave (ER, third column) and African Easterly Waves (AEW, last column). Lags are  
 227 expressed in days relative to the composite EPE. The red cross indicates the average location of  
 228 the composite EPE. Only statistically significant values at the 95 % confidence level are  
 229 displayed.

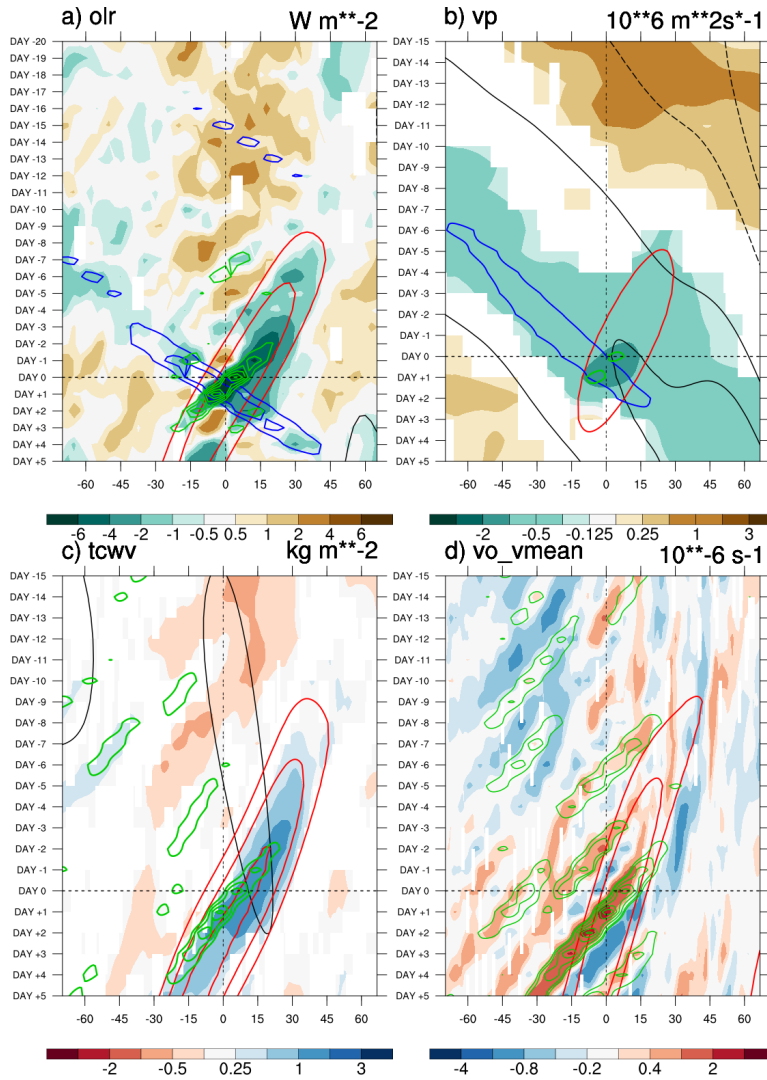
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231

232           The phasing of different waves is further documented using hovmoller diagrams centered  
233 around the EPE location (Fig. 3). The ER and AEW are the major contributors to the large-scale  
234 envelope of negative OLR anomalies (shading, Fig. 4a). The ER (red contour) is key to  
235 strengthen deep convection 5 to 10 days prior to the EPE. It is clearly seen in the unfiltered  
236 intraseasonal anomaly (shading). The Kelvin wave (blue) is also an important contributor at a  
237 shorter scale. It is visible three days in advance over the Atlantic Ocean and enhances convection  
238 to the west of the EPE at DAY 0. The signature of the MJO is weak for OLR and is better  
239 detected on velocity potential (Fig. 3b). A large-scale upper-level divergence anomaly prevails  
240 over the Sahel with a dominant contribution from the MJO and to a lesser extent the ER and the  
241 Kelvin wave (Fig. 3b). The evolution of precipitable water and vorticity intraseasonal anomalies  
242 are similar (Fig. 3c,d) and indicate that the moist cyclonic anomaly coming from the east is  
243 associated with an ER signal at large scale (red contours) and an intense AEW at shorter scale  
244 (green contours).

245           To summarize, the anomalous mean conditions associated with EPEs result from the co-  
246 occurrence of several tropical waves with a group of westward propagating convectively-coupled  
247 waves, well-marked in vorticity and humidity (ER and AEW) crossing a second group of  
248 eastward propagating waves (MJO and Kelvin wave) well-marked in upper-level divergence.

249



250

251 **Figure 3** : (a) Lag - longitude hovmoller diagram of the composite anomalies of OLR ( $W m^{-2}$   
 252 shading) averaged between  $-2.5^{\circ}$  to  $+2.5^{\circ}$  N relative to the EPE location. The contours indicate  
 253 the wavenumber-frequency-filtered OLR anomalies of the tropical waves (contours every  $1 W$   
 254  $m^{-2}$ ): the MJO (black), Equatorial Rossby wave (red), Kelvin waves (blue) and AEWs (green).  
 255 Only the convectively-active component of the waves is shown (negative OLR anomalies only).  
 256 DAY 0 corresponds to the day of occurrence of EPE and longitudes are relative to the mean EPE  
 257 location. (b), (c) and (d) same as (a) except for 200-hPa velocity potential ( $m^2 s^{-1}$ , one contour  
 258 every  $-1.25 \times 10^5 m^2 s^{-1}$ ), precipitable water ( $kg m^{-2}$ , contour every  $0.2 kg m^{-2}$ ) and 925-650 hPa



259 mean relative vorticity ( $s^{-1}$ , contour every  $0.25 \times 10^{-6} s^{-1}$ ), respectively. Only statistically  
260 significant values at the 95 % confidence level are displayed.

261

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262

### 263 3.3 Co-occurrence of tropical waves during EPEs

264 Figure 4a shows the total contribution of each tropical wave to the occurrence of EPEs.

265 The AEWs are the leading drivers for EPE with broadly half the EPEs associated with an AEW.

266 The contributions of ER and Kelvin waves are also statistically significant and are active in more

267 than 35% of EPE. It confirms their leading role as drivers of EPEs. The contributions of the

268 MJO although not statistically significant, represents more than 20 of EPEs, suggesting that the

269 four waves are frequent enough to co-occur.

270 Figure 4b refines this view by displaying the percentage of EPEs attributed to each

271 possible combination of waves. The x-axis indicates the 16 possible combinations of active

272 tropical waves. The first four bars (red) indicate that a single active AEW has the greatest

273 contribution among the single-wave category (16%). The total contribution of the single wave

274 category accounts for 39.3 % of EPEs leaving 44.7% of them attributed to the combination of

275 multiple tropical waves. Only 16% of EPEs are not associated with any wave. Statistically

276 significant contributions are found for the combinations ER+AEW and AEW+Kelvin wave

277 (yellow bars), ER+Kelvin+AEW (blue) and MJO+Kelvin+AEW. Finally, 1.5% of EPEs occur

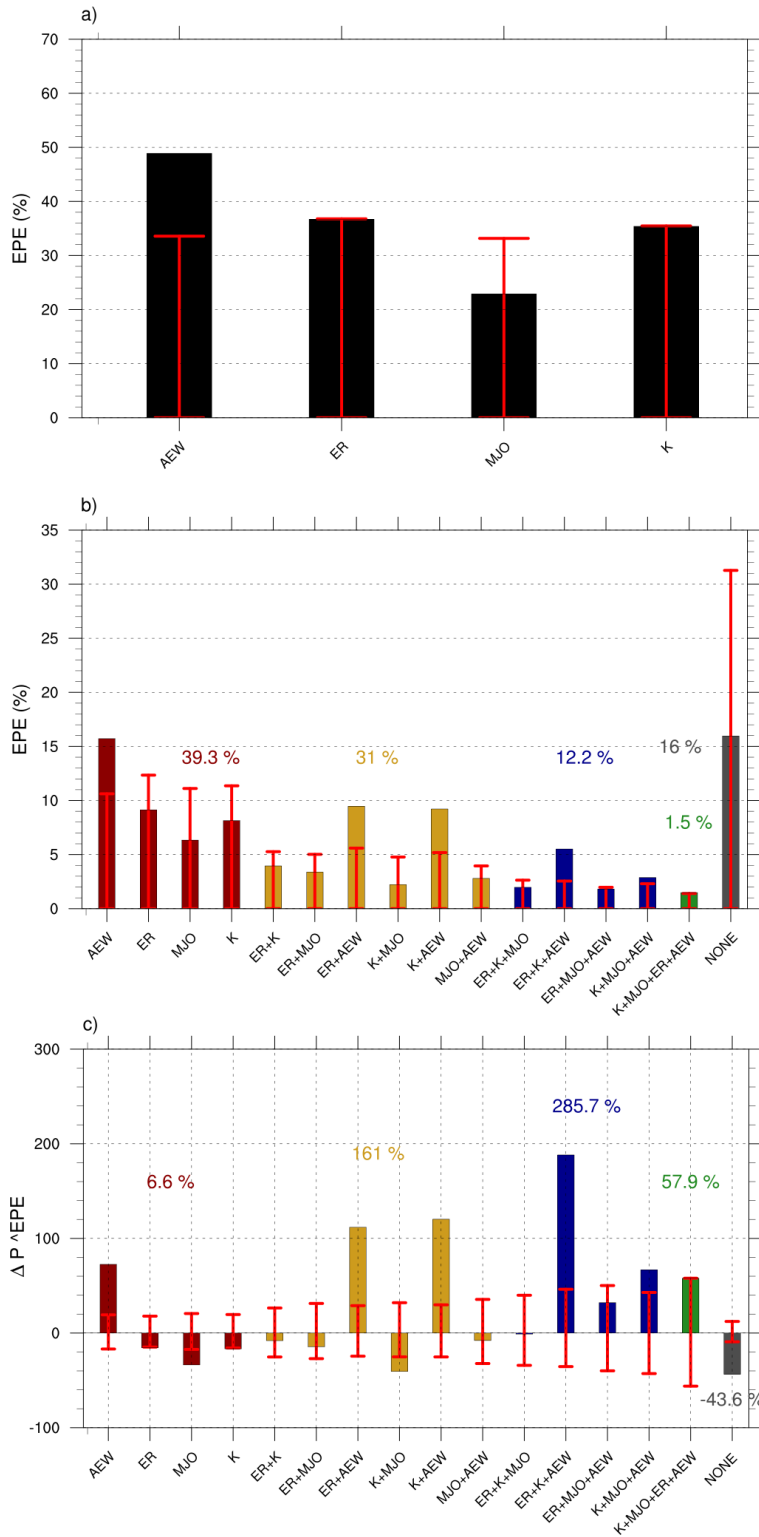
278 within a combination of the four tropical waves (green).

279           Figure 4c further assesses the modulation of the EPE frequency of occurrence by each  
280 wave combination compared to the wave climatological occurrence. Four combinations of  
281 active tropical waves clearly emerge, all including the combination of an AEW, an ER and / or a  
282 Kelvin wave. The wave combination ER+Kelvin+AEW shows the most significant increase  
283 indicating that combining westerly and easterly tropical waves clearly favors the EPE  
284 occurrence. In contrast the occurrence of a single intense AEW is the only one-wave  
285 configuration that increases EPE probability. The combinations of waves identified here as key  
286 modulators of EPE occurrence are not sensitive to an increase or decrease in the threshold for a  
287 convectively-active wave detection indicating that our results are robust Only the contribution of  
288 the AEW-alone configuration increases with the threshold while the contributions of the four-  
289 wave combination is slightly reduced (see text S4 and Figure S3 in SI).

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299 **Figure 4:** Percentage of EPE attributed to (a) each tropical wave and (b) to each configuration  
300 of tropical waves (single waves and combinations of waves). (c) Percentage change in EPE  
301 frequency of occurrence for a given wave configuration ( $\Delta P^{\text{EPE}}$ ). In (b) and (c), colored bars  
302 indicate configurations with a single active wave (red), with exactly two active waves (yellow),  
303 with exactly three active waves (blue), with four active waves (green) and no active wave (none,  
304 gray). The colored percentages indicate the total contribution or percentage of change of each  
305 wave configuration. The red vertical lines indicate the 95 % significance level.

306

307

#### 308 **4 Conclusions**

309

310 This study demonstrates that the atmospheric environment of EPEs occurring over  
311 Burkina Faso, and most probably over Central Sahel, consists, on average, in a large-scale moist  
312 envelope propagating westward and an upper-level divergence anomaly, in which an intense  
313 cyclonic vortex generates northerlies at the EPE location. It confirms and extends previous  
314 results based on case studies (Lafore et al. 2017, Engel et al. 2017). The role of tropical waves  
315 was then investigated. To our knowledge, it is the first study that provides statistical evidence on

316 the role of tropical waves in EPE occurrence, in particular the role of tropical wave co-  
317 occurrence.

318 The contribution of tropical waves can be summarized as follows:

- 319 • The equatorial Rossby wave is the dominant driver at large scale of the convective, moist  
320 anomalies developing over the eastern Sahel 5 days prior to the EPEs. Previous studies  
321 investigated the role of ER wave only on precipitation subseasonal variability over West  
322 Africa (Mounier et al. 2008, Janicot et al. 2010, Roehrig et al. 2011) but to our  
323 knowledge, the leading role of ER waves in Sahelian EPE occurrence is a new finding.
- 324 • AEW have a major contribution to EPE. A strong AEW, which frequently develops  
325 within an ER envelope, generates a deep moist cyclonic vortex.
- 326 • The MJO provides upper-level divergence and favors convection over the Central and  
327 Eastern Sahel during the week before EPE occurrence, in agreement with previous  
328 studies (Schreck 2021, Sossa et al. 2017).
- 329 • A Kelvin wave increases convection, the low-level westerlies and upper-level divergence  
330 at the time of EPE.

331

332 Statistics conditional to the occurrence of EPEs show that the AEW and ER are the most  
333 frequent tropical waves associated with EPEs. The wave configurations increasing the EPE  
334 frequency of occurrence are the single AEW and the combinations of an AEW with an ER and /  
335 or a Kelvin wave. This emphasizes the importance of tropical wave co-occurrence for EPEs. The

336 physical processes involved in such configurations and the way they contribute to the occurrence  
337 of an EPE should be addressed in the future.

338         This study has strong implications for anticipating EPE at subseasonal scale, since large-  
339 scale tropical waves have significant predictability at lead time beyond a few days. A better  
340 predictability of EPE over the Central Sahel might thus be gained by monitoring their  
341 propagation and their potentiality to occur in combination with an AEW. It can provide guidance  
342 for analyzing forecasts and help weather forecasters to issue early warnings of high-impact  
343 weather systems in the Central Sahel. This in turn would allow better preparedness for and  
344 response to EPEs, reducing risk of injuries, damages and economical loss.

345

#### 346 Acknowledgments

347 We thank K. Schreck and the anonymous reviewer for the constructive feedback on the  
348 manuscript during the review process.

349

#### 350 Data Availability Statement

351 All data used in this manuscript are publicly available. NOAA Interpolated Outgoing Longwave  
352 Radiation (OLR) data provided by the NOAA PSL, Boulder, Colorado, USA, from their website  
353 at <https://psl.noaa.gov/data/gridded/data.olrcdr.interp.html> . The EPE dates for the 15°x1° pixels used  
354 in this study for compositing are available at <https://doi.org/10.5281/zenodo.7764390>.

355 ERA Interim reanalysis data is accessible at ECMWF website  
356 <https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-interim>. CHIRPS data can be  
357 obtained at <https://doi.org/10.14768/06337394-73A9-407C-9997-0E380DAC5598>.

358

359

360

361

## 362 **References**

363

364 Chen, G., and C. Chou, 2014: Joint Contribution of Multiple Equatorial Waves to Tropical

365 Cyclogenesis over the Western North Pacific. *Mon. Wea. Rev.*, **142**, 79–93,

366 <https://doi.org/10.1175/MWR-D-13-00207.1>.

367 Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U.,

368 Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L.,

369 Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy,

370 S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally,

371 A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato,

372 C., Thépaut, J.-N. and Vitart, F. (2011), The ERA-Interim reanalysis: configuration and

373 performance of the data assimilation system. *Q.J.R. Meteorol. Soc.*, 137: 553-597.

374 <https://doi.org/10.1002/qj.828>

375

376

377 Descroix, L., and Coauthors, 2018: Evolution of surface hydrology in the Sahelo-Sudanian Strip:  
378 An updated review. *Water*, 10, 748, <https://doi.org/10.3390/w10060748>.

379

380 Di Baldassarre, G. D., A. Montanari, H. Lins, D. Koutsoyiannis, L. Brandimarte, and G. Blöschl,  
381 2010: Flood fatalities in Africa: From diagnosis to mitigation. *Geophys. Res. Lett.*, 37, L22402,  
382 <https://doi.org/10.1029/2010GL045467>.

383

384 Engel, T., A. Fink, P. Knippertz Extreme Flooding in the West African Cities of Dakar and  
385 Ouagadougou – Atmospheric Dynamics and Implications for Flood Risk Assessments, vol. 19  
386 (2017), p. 11983

387

388 Funk, C., Peterson, P., Landsfeld, M. *et al.* The climate hazards infrared precipitation with  
389 stations—a new environmental record for monitoring extremes. *Sci Data* 2, 150066 (2015).  
390 <https://doi.org/10.1038/sdata.2015.66>

391

392 Feng, X., Yang, GY., Hodges, K.I. *et al.* Equatorial waves as useful precursors to tropical  
393 cyclone occurrence and intensification. *Nat Commun* 14, 511 (2023).  
394 <https://doi.org/10.1038/s41467-023-36055-5>

395



396

397 Guigma, K.H., Guichard, F., Todd, M. *et al.* Atmospheric tropical modes are important drivers of  
398 Sahelian springtime heatwaves. *Clim Dyn* **56**, 1967–1987 (2021). [https://doi-](https://doi-org.insu.bib.cnrs.fr/10.1007/s00382-020-05569-9)  
399 [org.insu.bib.cnrs.fr/10.1007/s00382-020-05569-9](https://doi-org.insu.bib.cnrs.fr/10.1007/s00382-020-05569-9)

400

401 Janicot, S., F. Mounier, S. Gervois, B. Sultan, and G. N. Kiladis, 2010: The Dynamics of the  
402 West African Monsoon. Part V: The Detection and Role of the Dominant Modes of Convectively  
403 Coupled Equatorial Rossby Waves. *J. Climate*, **23**, 4005-4024,  
404 <https://doi.org/10.1175/2010JCLI3221.1>.

405

406 Kiladis G, Wheeler M, Haertel P, Straub K, Roundy P. 2009. Convectively coupled equatorial  
407 waves. *Rev. Geophys.* **47**: RG2003, DOI:10.1029/2008RG000266.

408

409 Lafore, J.-P., Beucher F., Peyrillé P., N. Chapelon, D. Bouniol, G. Caniaux, F. Favot A multi-  
410 scale analysis of the extreme rain event of Ouagadougou in 2009, *Q. J. R. Meteorol. Soc.*, **143**  
411 (2017), pp. 3094-3109

412

413 Landu, K., Goyal, R. & Keshav, B.S. Role of multiple equatorial waves on cyclogenesis over  
414 Bay of Bengal. *Clim Dyn* **54**, 2287–2296 (2020). <https://doi.org/10.1007/s00382-019-05112-5>

415

416 Liebmann B, and C.A. Smith 1996. Description of a complete (interpolated) outgoing longwave  
417 radiation dataset. *Bull. Am. Meteorol. Soc.* 77: 1275–1277

418

419

420 Maranan, M., Fink, A. H., Knippertz, P., Francis, S. D., Akpo, A. B., Jegede, G., & Yorke, C.

421 (2019). Interactions between Convection and a Moist Vortex Associated with an Extreme

422 Rainfall Event over Southern West Africa, *Monthly Weather Review*, 147(7), 2309-2328.

423 Retrieved Oct 6, 2022, from <https://journals.ametsoc.org/view/journals/mwre/147/7/mwr-d-18->

424 [0396.1.xml](https://journals.ametsoc.org/view/journals/mwre/147/7/mwr-d-18-0396.1.xml)

425

426 Mathon, V., H. Laurent, and T. Lebel, 2002: Mesoscale convective system rainfall in the Sahel.

427 *J. Appl. Meteor. Climatol.*, 41, 1081–1092, [https://doi.org/10.1175/1520-0450\(2002\)041,1081:](https://doi.org/10.1175/1520-0450(2002)041,1081:)

428 MCSRIT.2.0.CO;2.

429

430 Mounier, F., S. Janicot, and G. N. Kiladis, 2008: The West African monsoon dynamics. Part III:

431 The quasi-biweekly zonal dipole. *J. Climate*, 21, 1911-1928,

432 <https://doi.org/10.1175/2007JCLI1706.1>.

433

434

435

436 Roehrig, R., F. Chauvin, and J. Lafore, 2011: 10–25-Day Intraseasonal Variability of Convection  
437 over the Sahel: A Role of the Saharan Heat Low and Midlatitudes. *J. Climate*, **24**, 5863–5878,  
438 <https://doi.org/10.1175/2011JCLI3960.1>.

439

440 Roundy P. E. and W.M. Frank, 2004. A climatology of waves in the equatorial region. *J. Atmos.*  
441 *Sci.* 61: 2105–2132.

442

443 Roca, R., Alexander, L. V., Potter, G., Bador, M., Jucá, R., Contractor, S., Bosilovich, M. G.,  
444 and Cloché, S.: FROGS: a daily  $1^\circ \times 1^\circ$  gridded precipitation database of rain gauge, satellite  
445 and reanalysis products, *Earth Syst. Sci. Data*, 11, 1017-1035, [https://doi.org/10.5194/essd-11-](https://doi.org/10.5194/essd-11-1017-2019)  
446 [1017-2019](https://doi.org/10.5194/essd-11-1017-2019), **2019**.

447

448 Sanogo, S., Peyrillé, P., Roehrig, R., Guichard, F., & Ouedraogo, O. (2022). Extreme  
449 Precipitating Events in Satellite and Rain Gauge Products over the Sahel, *Journal of Climate*,  
450 35(6), 1915-1938. Retrieved Oct 6, 2022, from  
451 <https://journals.ametsoc.org/view/journals/clim/35/6/JCLI-D-21-0390.1.xml>

452

453 Satgé, F., D. Defrance, B. Sultan, M.-P. Bonnet, F. Seyler, N. Rouché, F. Pierron, and J.-E.  
454 Paturel, 2020: Evaluation of 23 gridded precipitation datasets across West Africa. *J. Hydrol.*,  
455 581, 124412, <https://doi.org/10.1016/j.jhydrol.2019.124412>.

456

457 Schlueter, A., Fink, A. H., Knippertz, P., & Vogel, P. (2019). A Systematic Comparison of  
458 Tropical Waves over Northern Africa. Part I: Influence on Rainfall, *Journal of Climate*, 32(5),  
459 1501-1523. Retrieved Oct 6, 2022, from  
460 <https://journals.ametsoc.org/view/journals/clim/32/5/jcli-d-18-0173.1.xml>

461  
462 Schreck, C. J., J. Molinari, and K. I. Mohr, 2011: Attributing tropical cyclogenesis to equatorial  
463 waves in the western North Pacific. *J. Atmos. Sci.*, 68, 195-209,  
464 <https://doi.org/10.1175/2010JAS3396.1>.

465  
466 Schreck, C. J., J. Molinari, and A. Ayyer, 2012: A global view of equatorial waves and tropical  
467 cyclogenesis. *Mon. Wea. Rev.*, 140, 774-788, <https://doi.org/10.1175/MWR-D-11-00110.1>.

468  
469 Schreck, C. J., III. (2021). Global survey of the MJO and extreme precipitation. *Geophysical*  
470 *Research Letters*, 48, e2021GL094691. <https://doi.org/10.1029/2021GL094691>

471  
472 Sossa, A., Liebmann, B., Bladé, I., Allured, D., Hendon, H. H., Peterson, P., & Hoell, A. (2017).  
473 Statistical Connection between the Madden–Julian Oscillation and Large Daily Precipitation  
474 Events in West Africa, *Journal of Climate*, 30(6), 1999-2010. Retrieved Oct 6, 2022, from  
475 <https://journals.ametsoc.org/view/journals/clim/30/6/jcli-d-16-0144.1.xml>

476  
477 Taylor, C., Belušić, D., Guichard, F. *et al.* Frequency of extreme Sahelian storms tripled since  
478 1982 in satellite observations. *Nature* 544, 475–478 (2017). <https://doi.org/10.1038/nature22069>

479

480

481 Vizy, E.K., Cook, K.H. Distribution of extreme rainfall events and their environmental controls  
482 in the West African Sahel and Soudan. *Clim Dyn* 59, 997–1026 (2022).

483 <https://doi.org/10.1007/s00382-022-06171-x>

484

485 Vogel, P., Knippertz, P., Fink, A. H., Schlueter, A., and Gneiting, T. (2018). Skill of Global Raw  
486 and Postprocessed Ensemble Predictions of Rainfall over Northern Tropical Africa. *Weather and*  
487 *Forecasting* 33, 2, 369-388, available from:<https://doi.org/10.1175/WAF-D-17-0127.1>

488

489 Wheeler, M. and G. N. Kiladis, 1999. Convectively coupled equatorial waves: Analysis of  
490 clouds and temperature in the wavenumber–frequency domain. *J. Atmos. Sci.* 56: 374–399,  
491 [https://doi.org/10.1175/1520-0469\(1999\)056<0374:CCEWAO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1999)056<0374:CCEWAO>2.0.CO;2).

492

493 Xavier, P., Rahmat, R., Cheong, W. K., and Wallace, E. (2014), Influence of Madden-Julian  
494 Oscillation on Southeast Asia rainfall extremes: Observations and predictability, *Geophys. Res.*  
495 *Lett.*, 41, 4406–4412, doi:[10.1002/2014GL060241](https://doi.org/10.1002/2014GL060241).

496

497 **References From the Supporting Information**

498

499

500 Gosset, M., M. Alcoba, R. Roca, S. Cloché, and G. Urbani, 2018: Evaluation of TAPEER daily  
501 estimates and other GPM-era products against dense gauge networks in West Africa, analysing  
502 ground reference uncertainty. *Quart. J. Roy. Meteor. Soc.*, 144 (Suppl. 1), 255–269,  
503 <https://doi.org/10.1002/qj.3335>

504

505 Schreck, C. J., III. (2015). Kelvin Waves and Tropical Cyclogenesis: A Global Survey, *Monthly*  
506 *Weather Review*, 143(10), 3996-4011. Retrieved Feb 28, 2023, from  
507 <https://journals.ametsoc.org/view/journals/mwre/143/10/mwr-d-15-0111.1.xml>

508

509 [Straub, K. H., and G. N. Kiladis, 2002: Observations of a convectively coupled Kelvin wave in](#)  
510 [the eastern Pacific ITCZ. \*J. Atmos. Sci.\*, \*\*59\*\*, 30–53.](#)

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*[Geophysical Research Letters]*

Supporting Information for

**Tropical Waves are key drivers of Extreme Precipitation Events in the Central  
Sahel**

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## **Contents of this file**

Texts S1 to S4  
Figures S1 to S3

## **Introduction**

The supplementary information presents details on the rain-gauge dataset used to detect Extreme Precipitating Events (EPE – Text S1 and Fig. S1), on the identification of tropical waves (Text S2 and Fig. S2), the inference of statistical significance for EPE composites and EPE attribution to tropical wave configurations (Text S3), and the sensitivity of EPE wave attribution to the threshold used to detect tropical waves (Text S4 and Fig. S3).



### **Text S1: Rain-gauge based precipitation dataset over Burkina Faso.**

The dataset used to detect extreme precipitation event is built from 142 rain-gauge stations covering most of Burkina Faso (Fig. S1, see also Sanogo et al. 2022). They provide daily accumulated precipitation summaries over the period 1995–2016. Considering a  $1^\circ \times 1^\circ$  resolution grid covering Burkina Faso (Fig. S1), the rain-gauge network often exhibits more than five stations within each  $1^\circ \times 1^\circ$  pixel. The densest pixel encompasses 15 stations. Following Gosset et al. (2018), we only considered  $1^\circ \times 1^\circ$  pixels that contain at least five stations, and thus ensure a proper estimate of precipitation characteristics at this scale. The daily  $1^\circ \times 1^\circ$  rain-gauge-based precipitation dataset over Burkina Faso is derived as the arithmetic mean of the rainfall records from all the stations encompassed within each  $1^\circ \times 1^\circ$  pixel. Based on this gridded dataset, the 99<sup>th</sup> all-day percentile is used as a rainfall threshold to detect EPEs. Figure S1 shows that it ranges between 20 to 32 mm d<sup>-1</sup>, broadly equivalent to rainfall events of 50 mm at the station scale (not shown).

### **Text S2: Tropical waves identifications.**

The domains for filtering tropical waves are illustrated with Figure S2, which shows the normalized wavenumber-frequency spectrum for OLR in the 15°S- 15°N band.

It is obtained as in Wheeler and Kiladis (1999) by dividing the OLR spectrum by a red noise estimate of the background spectrum, regardless of equatorial symmetry (Roundy and Frank 2004, Straub and Kiladis 2002). Spectral peaks of energy appear where enhanced variability of OLR emerges from the background noise. Filtering domains for tropical waves are derived from this spectrum to enclose the spectral peaks of energy associated with the different waves and are indicated by the solid polygons in Figures S2. Although slight variations of the filtering domains can be found among various authors, results presented here are insensitive to reasonable variations in the filtering domains.

**Text S3: Statistical significance of EPE composites and attribution to tropical wave configurations.**

The statistical significance of the EPE composite mean is assessed against the null hypothesis that the composite anomalies are obtained because of random variability. We use a bootstrap approach similar to Schreck (2015). The null hypothesis is tested by generating a series of 500 random samples of the same size as our EPE ensemble. Each sample is built as follows:

1. An EPE is randomly selected from the EPE dataset with replacement. We select the day and month from this EPE but randomly select a year from a different EPE without replacement.

2. We then randomly select another EPE case from the EPE dataset with replacement and use its latitude / longitude to build the composite.
3. These steps are repeated to generate a sample of the same size as the initial EPE composite dataset.

A given parameter is then averaged among this "null" sample to obtain a composite mean. The whole procedure is repeated 500 times to produce an ensemble of 500 null composite means obtained from random variability. At each data point, the statistical significance of the EPE composite mean is evaluated against the null composite mean by using a two-tailed test at the 95% confidence level. The EPE composite mean is considered statistically significant when it is either greater than the 97.5<sup>th</sup> percentile or lesser than the 2.5<sup>th</sup> percentile of the null composite mean. Only values passing this test are displayed and analyzed.

The statistical significance of the percentage of EPE attributed to tropical waves and of the corresponding change in EPE probability are tested against the null hypothesis that they could have arisen from random variability. The percentage of days from the climatology during which a given wave or wave combination is active is first computed for all pixels using the criterion of attribution based on box-averaged wave-filtered OLR (not shown). For a given wave or wave combination that is active during N days of the all-pixel climatology, 500 random samples of the same size N are generated from the climatology. The corresponding precipitation and the 99<sup>th</sup> percentile are used to determine the number of EPEs associated to each of the 500 samples, which form a null distribution

that is associated with random variability. The random change in EPE probability is also deduced for each sample.

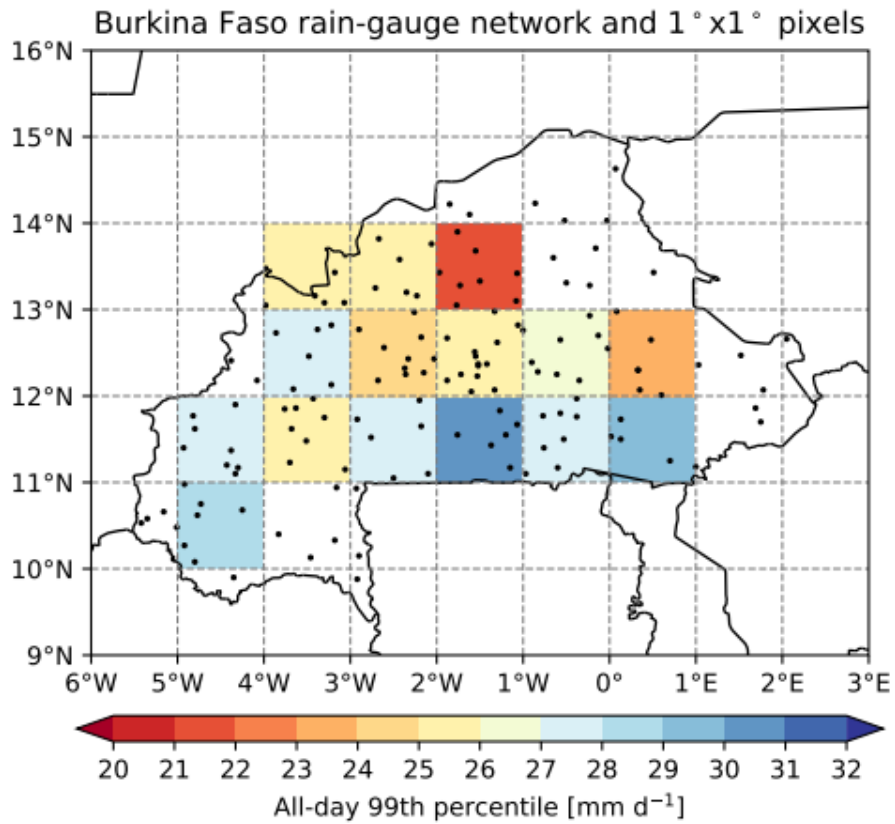
The percentage of EPEs attributed to a given combination is considered statistically significant at the 95% level when it is greater than the 95<sup>th</sup> percentile of this random distribution. The change in EPE probability for a given wave combination is considered statistically significant at the 95 % confidence level when its either larger than the 97.5<sup>th</sup> percentile or smaller than the 2.5<sup>th</sup> percentile of the corresponding null distribution.

**Text S4: Sensitivity of EPE attribution to the threshold used for tropical wave detection.**

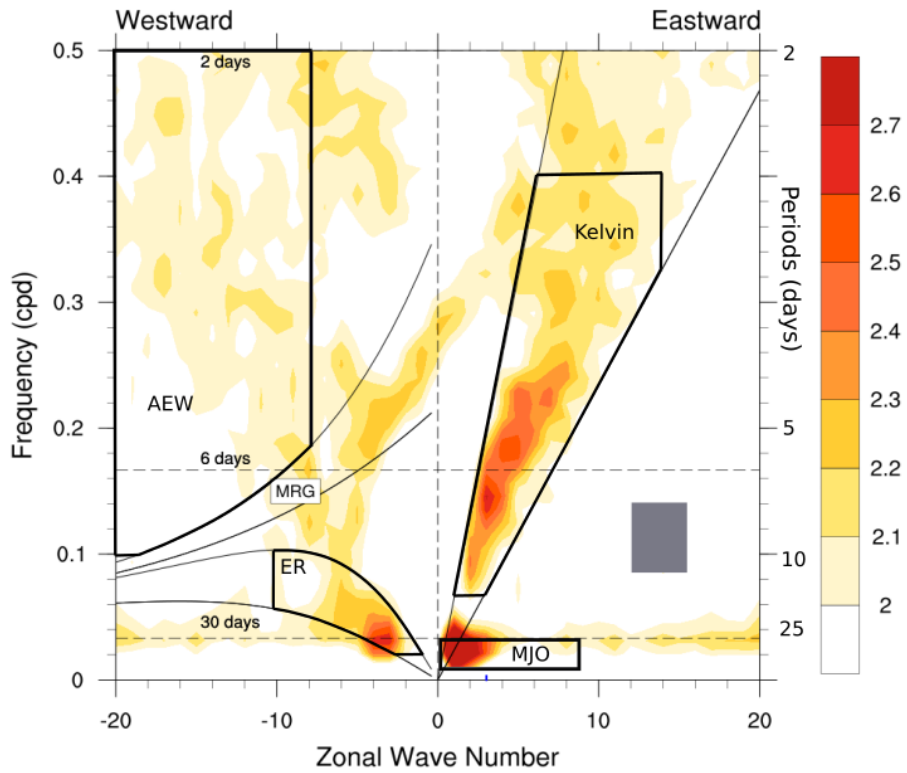
The threshold to detect any convectively-active tropical wave is discussed here. A threshold of -0.5 box-averaged standard deviation of wave-filtered OLR anomaly is used to identify whether a given tropical wave is convectively-active or not. The sensitivity of our results to this threshold is presented in Figure S3 which is the same as Figure 4 presented in the article except for thresholds of -0.3 and -1 standard deviations. In the main manuscript, we aligned with the somewhat arbitrary threshold of -0.5 which is often used in the literature seeking to attribute tropical cyclones to tropical waves (Chen and Chou 2014, Landu et al. 2020, Feng et al. 2023). Raw thresholds on OLR wave-filtered anomalies have also been tested for wave detection, leading to the similar conclusions (not shown).

Figures S3a,b show that AEW, ER and Kelvin waves remain the leading tropical waves contributing to EPE occurrence with decreasing contribution when the detection

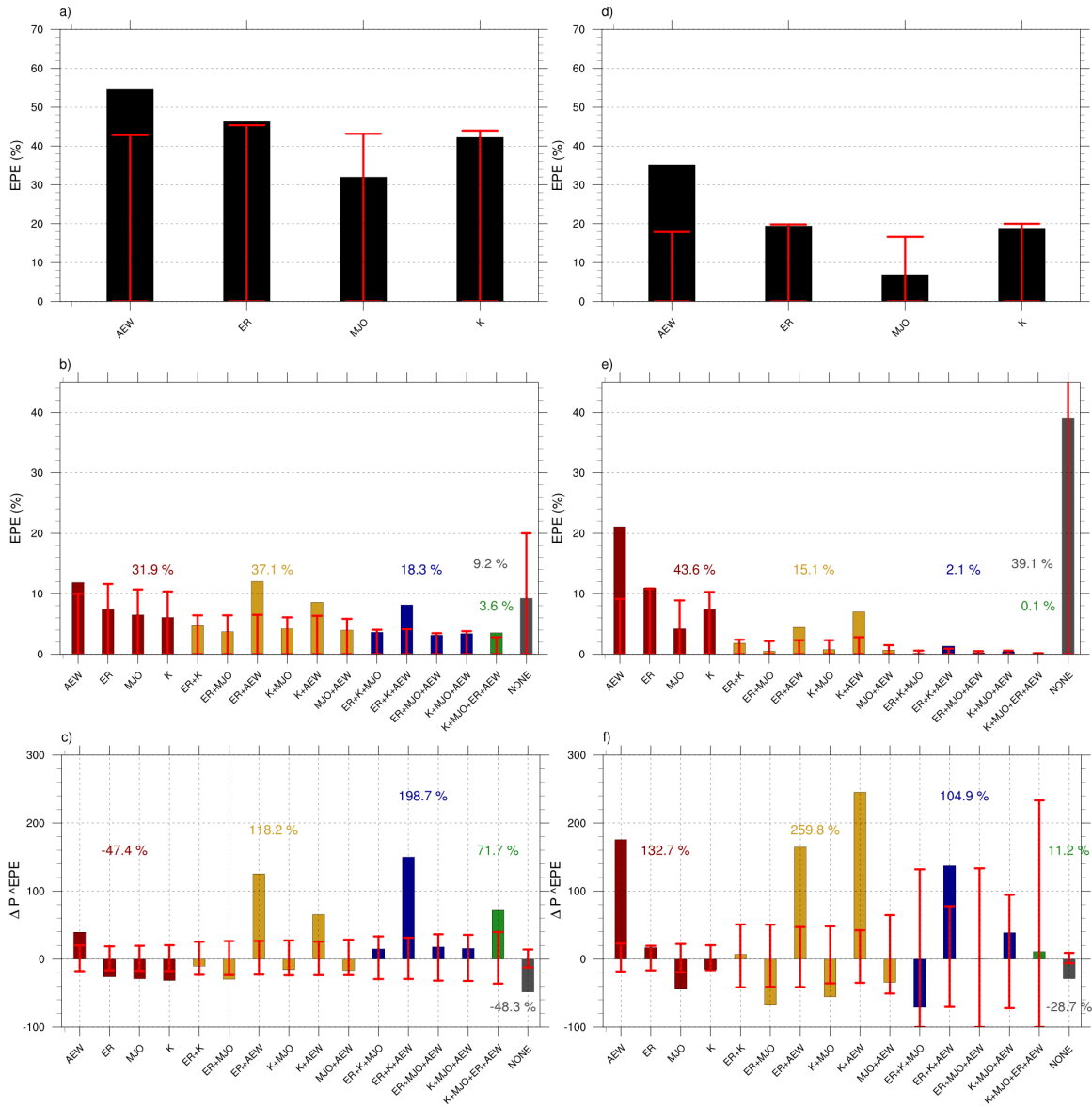
threshold is increased. The statistical significance of the Kelvin waves is slightly below the 95% confidence level compared to results presented in Figure 4. It is expected that the increase (decrease) of the detection threshold should yield a reduction (increase) of attributed EPEs as the number of detected waves diminishes. When a threshold of -0.3 standard deviation is used, the wave combinations that have the greatest contribution to EPEs and the largest modulation of EPE probability are similar to those obtained with a threshold of -0.5 standard deviation: single AEW, ER+AEW, K+AEW, ER+K+AEW and MJO+K+ER+AEW (Fig. S3b,c). The contribution of the combination of four waves is increased with a more significant change in EPE probability while the combination of K+MJO+AEW falls under the threshold of statistical significance. For a threshold of -1 standard deviation, multiple wave combinations become less likely (Fig. S3e). Although the key combinations for EPE occurrence remain qualitatively similar, the single (intense) AEW configuration now dominates as well as the contribution of single ERs (Fig. S3e). The percentage change in EPE probability remains however close to the one presented in the manuscript with the same key wave combinations with the largest modulations. The main change is a strongest effect of single AEW and a weaker effect of the four-wave combination.



**Figure S1:** Spatial distribution of the rain gauges used in the study (dots) and 99<sup>th</sup> all-day percentile of precipitation (mm d<sup>-1</sup>, shading). The 99<sup>th</sup> percentile is computed for 1°x1° pixels over the [1996-2015] period (adapted from Sanogo et al. 2022).



**Figure S2:** Normalized wavenumber-frequency spectrum of NOAA Interpolated daily OLR from 1996 to 2016, between 15° S and 15°N, and without equatorial symmetry consideration. The bold solid polygons indicate domains for the filtering of MJO, Kelvin wave, ER and AEW. The thin solid lines indicate the dispersion curve for the equivalent depths of 12 and 90 m. The gray rectangle hides an artificial peak generated by aliasing from the satellite swath path size and frequency (see Wheeler and Kiladis 1999 and Roundy and Franck 2004).



**Figure S3:** Percentages of EPEs attributed to (a) each tropical wave, (b) to each combination of tropical waves and (c) percentage change in EPE frequency of occurrence for a given wave combination obtained using a threshold of -0.3 standard deviation to detect active tropical waves. (d, e, f) same as (a, b, c) except a threshold of -1 standard



deviation threshold is used to detect active tropical waves. The red vertical lines indicate the interval below the 95 % significance level.