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1 Major role of water bodies on diurnal precipitation regimes in eastern Africa

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22 **Abstract**

23 Mean diurnal rainfall regimes over Eastern Africa (also referred to as the Greater Horn of Africa) are
24 studied based on 3-hourly data from the TRMM 3B42 data set, averaged over a 17-yr period (1998-
25 2014). The consistency with long-term mean raingauge data, available for partly independent periods,
26 varies from good (Sudan, Ethiopia, Eritrea, Somalia) to very good (Kenya, Tanzania, Uganda). Over sea
27 (Indian Ocean and Red Sea), the diurnal rainfall distribution is quite uniform; however, a morning peak
28 dominates and there is evidence of offshore phase propagation south of the equator. Over land, both
29 rainfall frequency and rainfall amounts show a dominant afternoon maximum (1500 to 1800 East
30 African Time). However many inland regions show a delayed rainfall maximum (evening, nighttime or
31 morning). The evening to nighttime maximum found over some land areas is associated with a phase
32 propagation from areas showing an afternoon peak. This occurs west of high ground areas (Sudan and
33 parts of the Great Lakes region) and in belts parallel to the seashores (Eritrea, northeastern Ethiopia,
34 Somalia and eastern Kenya). The latter provide indirect evidence that sea breeze effects can be
35 detected at unexpectedly great distances from the coast (up to 300-400 km) in parts of eastern Africa.
36 A remarkable ring of early afternoon (1500) maxima is found around most lakes, although some east-
37 west asymmetries occur. Over the lakes, a morning or late night maximum is mostly found. It is
38 generally inversely related to the distance to the shorelines for the larger lakes, but over the mid-size
39 lakes it is replaced by or competes with a late afternoon to evening maximum.

40 Key words

41 Horn of Africa, East Africa, Lake Victoria, Indian Ocean, rainfall, diurnal cycle, sea breeze, lakes

42

43 **1. Introduction**

44 The spatial distribution of rainfall over Eastern Africa is inherently complex. It is strongly controlled by
45 terrain (Ethiopian and Kenya Highlands, East African Rift system) and water bodies (Indian Ocean and
46 Red Sea to the east, and many lakes, including Lake Victoria, the world's second largest lake). These
47 features interact with large-scale wind flows, resulting in local convergence / divergence and upslope
48 / downslope circulation, all playing a major role on rainfall patterns (Beltrando, 1990 ; Mukabana and
49 Pielke, 1996 ; Nicholson and Yin, 2002 ; Thiery et al., 2015 ; Cattani et al., 2016). These topographical
50 features also influence the diurnal rainfall distribution, yet to date no comprehensive study has ever
51 been carried out on this aspect for Eastern Africa as a whole.

52

53 In the tropics, land masses generally exhibit a strong afternoon maximum, associated with convection
54 generated by daytime land surface heating (e.g., Meisner and Arkin, 1987 ; Yang and Slingo, 2001).
55 Tropical oceans show more uniform diurnal rainfall distributions, although a nighttime or morning
56 maximum often prevails (Hendon and Woodberry, 1993; Janowiak et al., 1994). Dai (2001) noted that
57 over the tropical oceans, showery precipitation is most frequent from midnight to 0400 local solar time
58 (LST), and maritime thunderstorms around midnight. Yang and Smith (2006) and Yang et al. (2008)
59 noted that oceanic rainfall in convergence zones often shows a secondary late afternoon maximum
60 besides the dominant late evening to early morning maximum. Nesbitt and Zipser (2003) noticed that
61 over sea the morning maximum is due to more frequent mesoscale convective systems (MCS), whereas
62 over land the MCS diurnal cycles vary significantly depending on environmental conditions. Non-MCS
63 convection results in an afternoon peak, often triggered by relief. Over neighboring plains the
64 afternoon maximum is not always prominent due to possible slope breezes and late drifts of major
65 convective cells born over the highlands (Shinoda et al. 1999 ; Laing et al. 2008 ; Yaodong et al., 2008).
66 Funatsu et al. (2012) observed that southern Amazonia convection is maximal near 1500 local time
67 and minimal around 0700, with few significant differences between forested and deforested areas.
68 Kikuchi and Wang (2008), distinguished three tropical diurnal cycle regimes. Both the oceanic regimes
69 (small amplitude and early morning peak around 0600-0900 LST) and the continental regimes (large
70 amplitude, afternoon peak around 1500-1800 LST) show little spatial phase propagation. By contrast
71 the coastal regime shows a large amplitude and phase propagation of about 10 m.s^{-1} , both inland and
72 offshore.

73

74 Regional and local studies on diurnal rainfall regimes over eastern Africa are few. Over Eastern
75 Equatorial Africa, the only studies specifically dedicated to diurnal rainfall distribution were those by
76 Tomsett (1975) and Asnani and Kinuthia (1979), using in situ rainfall records. They distinguished ten
77 different diurnal patterns, strongly determined by the interaction between the synoptic scale flow and
78 the mesoscale circulation induced by orography, like along the eastern slopes of the East African
79 highlands and around Lake Victoria. The original diurnal regimes of Lake Victoria were actually noticed
80 earlier by Flohn and Fraedrich (1966), who found that due to diverging lake breezes, the lake was
81 cloudless at daytime, while the convergence of nocturnal land breezes accounted for a late night to
82 early morning maximum in thunderstorm activity over the lake, slightly shifted westward by the large-
83 scale easterlies. Analysis of cold cloud occurrences for 1983-1990 period confirmed the morning
84 maximum of convective activity over Lake Victoria (Ba and Nicholson, 1998), in agreement with in-situ
85 lakeshore rainfall data (Datta, 1981). An afternoon maximum is evident east of the lake.

86 Over Kenya, numerical simulations (Mukabana and Pielke, 1996) showed that differential heating and
87 cooling of the terrestrial surface at day- and night-time between elevated and lowland areas, and
88 between land and water bodies resulted in extensive breeze systems, contributing to rainfall regimes
89 variations. Laing et al. (2011) noted that in equatorial Africa many MCSs form in the afternoon and
90 move westward from the East African mountains. They also noted that along the Indian Ocean, a line
91 of high cold cloud parallels the coast between 1400 and 1500 LST and moves inland in the evening.
92 They attributed this pattern to land-ocean temperature contrast and associated breezes, but since it
93 was at the margin of their study area it was not further analyzed. Along the Tanzania coast, Sumner
94 (1982, 1984) documented the diurnal variations of breeze systems and their interaction with the
95 monsoon. He found a late morning to early afternoon peak, shifted to the early morning during the
96 northerly monsoon. Similar morning maxima are found on the Kenya coast (Okoola, 1978 ; Camberlin
97 and Planchon, 1997).

98 In the northern part of Eastern Africa, diurnal rainfall variations are very imperfectly known, except for
99 some studies of specific locations within the Ethiopian Highlands. Pedgley (1971) found a pronounced
100 afternoon maximum both at Asmara in Eritrea (over 30% of rainfall occurrence from 1500 to 1800 local
101 time) and Addis-Ababa in Ethiopia (where the rains are however more scattered across the day). The
102 afternoon maximum also predominates further west over much of Sudan (Pedgley, 1969). However,
103 in eastern Sudan, rainfall occurrence often peaks later at night or early morning, with a secondary
104 maximum in the afternoon. Pedgley (1969) hypothesized that this could either be due to increased
105 convergence within the Intertropical Convergence Zone (ITCZ), as a result of stronger nocturnal winds,
106 or a relative afternoon subsidence over the Sudan plains connected to the strong convective activity
107 over the nearby Ethiopian Highlands. The night maximum would therefore result from the westward
108 drift of convective cells, embedded in the upper-tropospheric easterlies. In the Upper Blue Nile basin
109 in Ethiopia, Haile et al. (2013) and Rientjes et al. (2013) compared hourly rainfall variations from
110 CMORPH and TRMM satellite estimates to automatic weather stations for the year 2007. Both the
111 rainfall occurrence and conditional mean rain rate were highest between 1500 and 1800 LST.
112 Exceptions were found, especially in the Lake Tana Basin where a midnight and early morning
113 maximum occurs. About 70% of the variance in the spatial distribution of nocturnal rainfall is explained
114 by the distance to the center of Lake Tana (Haile et al., 2009).

115 Between the global or continental scale studies and the fragmentary ones carried out at local scale,
116 there is a definitive lack of any study on diurnal rainfall regimes for the whole Eastern Africa. Yet, the
117 complex patterns of land, sea, lakes and relief found across Eastern Africa (Fig.1) introduce many
118 discontinuities in the land surface which generate daytime temperature gradients modulating
119 atmospheric circulation and convective activity. In particular, it is unknown whether the morphology

120 of the coasts (bordered by mountain ranges along the Red Sea and Gulf of Aden, and by extensive
121 plains south of Cape Guardafui) influences diurnal rainfall regimes.

122 The objective of this study is therefore to provide a broad-scale mapping of diurnal rainfall variations
123 over Eastern Africa, also referred to as the Greater Horn of Africa (GHA). Rainfall regimes from satellite
124 estimates are compared to in situ data of rainfall occurrence and rainfall amounts. Emphasis is put on
125 the potential role played by water bodies (sea and lakes), both locally and remotely through sea/lake
126 breezes. The study also explores diurnal phase propagation based on mean rainfall patterns. Section 2
127 presents the data (satellite estimates and in situ records) and the methods used to describe the diurnal
128 cycles. Section 3 shows the general patterns of the diurnal peak rainfall (sections 3.1 and 3.2), then the
129 specific contribution of water bodies (section 3.3). A discussion is provided in section 4.

130 **2. Data and methods**

131 The study makes use of the 3-hourly TRMM Multi-satellite Precipitation Analysis (TMPA) 3B42 rainfall
132 data base (Huffman et al., 2007), version 7, at a 0.25° resolution. TMPA 3B42 (hereafter TRMM) is a
133 multi-satellite product, incorporating microwave and infrared precipitation estimates, calibrated with
134 monthly raingauge data, developed by the Mesoscale Atmospheric Processes Laboratory at NASA
135 Goddard Space Flight Center. Version 7 improves upon previous versions of TRMM rainfall estimates
136 by incorporating additional microwave and infrared data, revising the relationship between radar
137 reflectivity and rainfall rates, the detection of surface clutter over high ground, and the use of better
138 reference data bases for the passive microwave algorithm and the bias corrections (Huffman and
139 Bolvin, 2013 ; Zulkafli et al., 2014).

140

141 Data are extracted for the period 1998-2014 and for the region from 28°E to 52°E and 12°S to 23°N
142 (Fig.1). This covers the GHA, including Djibouti, Eritrea, Ethiopia, Somalia, Kenya, Uganda, Rwanda,
143 Burundi, Tanzania, much of Sudan and South Sudan. 17-yr averages of 3-hr rainfall amounts and 3-hr
144 rainfall occurrences are computed. The whole year is considered in the computation, since seasonal
145 variations in diurnal rainfall phases are quite small (see supporting information S1 and S2).

146

147 TRMM data have been shown to reproduce quite efficiently observed spatial patterns and diurnal
148 variations of rainfall in several parts of the tropics. For Western Africa, Pfeifroth et al. (2016) found
149 that TRMM 3B42 rainfall estimates well captured the observed diurnal cycles of precipitation and their
150 variability, with a slight delay (up to 2 hours) of evening peak precipitation. For Eastern Africa, TRMM
151 3B42 was found to perform very well in reproducing rainfall patterns (Cattani et al., 2016). With

152 regards to the diurnal cycles, a validation has been made only over the Lake Victoria and upper Blue
153 Nile areas, where a good agreement exists with ground observations (Haile et al., 2013).

154

155 Comparisons are made with early published data of in situ mean hourly rainfall occurrence in Sudan,
156 Eritrea and Ethiopia (Pedgley 1969 and 1971), mainly for the period 1951-1966. Three-hour station
157 data from these studies are resampled to match the TRMM time sampling. For Kenya, Uganda and
158 Tanzania, mean percentage hourly distribution of rainfall amounts at a number of stations are
159 obtained from Tomsett (1975), averaged over 6 to 26 years, mostly in the 1950s and 1960s. For
160 northern Somalia, hourly rainfall data are collected from 5 automatic weather stations set up as part
161 of the Somalia Water and Land Information Management (SWALIM) project. They cover 2 to 5 years
162 within the period 2008-2015. Three-hour averages of rainfall amounts matching the TRMM time
163 sampling are computed for the Kenya, Tanzania, Uganda and Somalia stations.

164

165 All times are expressed in East African Time (EAT, i.e. GMT+3). In the notations below, 0300 refer to
166 the 3-hr period from 0130 to 0430 EAT, 0600 to the period from 0430 to 0730, and so on. Phase
167 variations are investigated by mapping the timing of precipitation maximum and by showing time-
168 space plots of 3-hr frequencies of rainfall occurrences or 3-hr mean rainfall amounts. A comparison
169 between mean diurnal rainfall regimes for land and lake areas is done to infer the influence of the
170 latter on rainfall distribution, and its dependence to the size of the lakes. Additionally, composite
171 diurnal rainfall regimes are plotted as a function of the distance to the coastline to detect propagative
172 features possibly associated with sea breezes.

173

174 **3. Results**

175 **3.1 Diurnal rainfall phases**

176 The diurnal rainfall patterns are first documented by plotting the 3-hr period during which the rainfall
177 is most frequent (as a number of observations with rainfall of at least 1 mm) (Fig.2a) and the 3-hr
178 period which records the highest mean rainfall amounts (Fig.2b). The two maps are quite similar, hence
179 they will not be discussed separately.

180 Over land, diurnal rainfall regimes show a dominant peak in the early or late afternoon (1500 or 1800
181 EAT), suggesting an effect of daytime convection as over many other tropical land areas. The early
182 afternoon maximum is mostly found (1) in a narrow belt along the coast (up to about 100 km inland,
183 suggesting a relationship with sea breezes, see below), (2) close to some lake shores (e.g., in the
184 periphery of lake Tanganyika), (3) in inland depressions far from the coast (e.g., in a crescent south of
185 the Ethiopian Highlands) and (4) marginally over isolated mountain peaks. The late afternoon

186 maximum is more widespread. For the region as a whole, 41.5% of the land grid-points show a
187 maximum rainfall occurrence at 1800 EAT (Fig.2, central histogram). Over the Indian Ocean, an early
188 morning peak generally prevails (often at 0600), but the amplitude of the diurnal cycle is much smaller
189 than inland (coefficient of variation around 2-6%, as against 7-15% over most land areas, see also
190 supporting information S3).

191 However, there are 3 main discrepancies from this general pattern:

192 (i) Large inland areas, at some distance from the coast, exhibit a nighttime maximum (red to dark blue
193 colours on Fig.2). Mainly located in lowland areas or gently sloping plateaus, they include northern
194 Sudan, northeastern Ethiopia, parts of inland Somalia and east-central Kenya.

195 (ii) A few inland areas, like over the ocean, display a late night / early morning maximum (0600 to
196 0900): some areas southwest of the Ethiopian Highlands, Lake Victoria and Lake Tanganyika. Other
197 lakes often singularize by their regimes, with an evening or nighttime peak. An asymmetry is also
198 obvious between lakeshores, especially for Lake Victoria where an afternoon peak dominates along
199 the eastern shores, shifting to a morning one on the western shores (see also Lake Tanganyika and
200 Lake Turkana).

201 (iii) Over sea surfaces, the early morning peak is often delayed to 0900 or 1200 close to the coast (Red
202 Sea and Gulf of Aden, Tanzania and Kenya coasts), although caution should be exerted over coastal
203 areas due to the fact that TRMM rainfall estimates use different algorithms over land and sea
204 (McCollum and Ferraro, 2005), and the diurnal amplitude is small over the ocean. Further offshore,
205 the area 200-600 km off the Tanzania coast is an exception by showing an afternoon maximum.

206 Interestingly, there are several instances of apparent long-distance phase propagations of the diurnal
207 signal from the coastlines (arrows on Fig.2). A westward propagation (arrow A) is evident from the
208 Eritrean coast to northern Sudan (early afternoon maximum along the coast, shifting to 1800 west of
209 the highlands), then to the night over the Nile plains, (over a distance of about 400-600 km). Similar
210 shifts from 1500 to 0300 occur:

211 - southwestward from the Red Sea coast in eastern Eritrea to central Ethiopia, over about 500 km
212 across the Afar depression (arrow B);

213 - in Somalia and Kenya both southward from the Gulf of Aden (arrow C) and northwestward from
214 the Indian Ocean coast (arrows D & E), over distances of 300 to 500 km.

215 Less clear phase propagation can be found further inland, mainly from east to west, e.g. from central
216 Ethiopia to South-Eastern Sudan (arrow F), or from the Western Kenya Highlands to Lake Victoria and

217 then Rwanda (arrow G). Note that over the southern part of the Indian Ocean sector there is an
218 apparent propagation of the rainfall phase both offshore and onshore.

219 A zoom on 3 regions (northwestern GHA, Equatorial GHA, and Somalia) enables a comparison with in
220 situ data and a preliminary discussion of possible mechanisms. Note that the spatial sampling of in situ
221 data is not fully satisfactory, with more stations in regions showing an afternoon peak. In northwestern
222 GHA (western Ethiopia, Eritrea, Nile plains, Fig.3), there is a fair agreement between in situ records of
223 the time of most frequent rainfall occurrence published by Pedgley (1969 and 1971 ; blue lines on side
224 panels) and TRMM data (bars). Correlations between in-situ data and TRMM are statistically significant
225 ($P=0.95$) at 56% of the stations, excluding En-Nahud and Kosti where the diurnal cycle is quite flat. An
226 afternoon maximum dominates, especially over the Ethiopian and Eritrean highlands, generally
227 peaking at 1800 or sometimes earlier (Asmara and Addis-Ababa, panels 10-11). Valleys make an
228 exception (e.g. along the Blue Nile from Lake Tana, where the phase is often delayed to 2100). This
229 likely reflects the development of daytime convective cells over elevated ground and their later shift
230 to the valleys, as noted by Rientjes et al. (2013). A conspicuous feature is that the maximum rainfall
231 occurrence is delayed to the night over much of the northern Sudan plains (e.g. Khartoum, panel 1), in
232 agreement with Pedgley (1969). The apparent propagation suggests a westward drift of the MCS
233 developed from daytime convection over the Eritrean and Ethiopian highlands, as a result of the upper-
234 tropospheric summer easterlies (see supporting information S4). This is also found further south,
235 although the night maximum is often masked out by the afternoon peak which becomes dominant in
236 the Nile plains south of 12°N. At Kosti (13°N, panel 4) there is a double peak where the afternoon
237 maximum is not strong enough to override the nighttime maximum. Dots on figure 3 show a secondary
238 afternoon maximum over much of the northern plains, suggesting daytime convection combined to
239 MCS drifts from the highlands. This propagative signal can actually be tracked back to the Red Sea
240 coast, with an early maximum (1500) possibly associated with the sea breeze front.

241 Over equatorial GHA (Fig.4), where the pattern of terrain and waterbodies is very complex, TRMM
242 mean 3-hr percentage rainfall amounts are in excellent agreement with in situ data from Tomsett
243 (1975) although the periods for calculating the mean regimes are completely different. Correlations
244 between in-situ data and TRMM are statistically significant ($P=0.95$) at all the 18 stations (average
245 correlation: 0.91). A late afternoon maximum (1800) again dominates over land. This 3-hr period often
246 accounts for a very large proportion of the daily rainfall amounts, exceeding 35% in pixels with a plus
247 sign on figure 4 (e.g., Kisumu, panel 5). The peak rainfall is found earlier (1500) at the periphery (mainly
248 to the west) of water bodies, including both the Indian Ocean (in a 100 to 150-km wide inland corridor)
249 and many of the lakes, for instance to the west of lakes Victoria, Albert, Edward and Malawi/Nyassa,
250 and all around Lake Tanganyika. The early afternoon peak is also found in northern Kenya (except over

251 Lake Turkana) and over or slightly west of high ground areas, e.g. above 1400 m in Tanzania and near
252 Mt Kenya (Nanyuki, panel 12). The location of these early afternoon rainfall maxima suggests an
253 interaction between topography and the mid-tropospheric easterly flow, dominant during the main
254 rainy seasons (March-May and October-December, see supporting information S4). However, in two
255 types of regions the afternoon maximum does not prevail:

256 (i) Over the water bodies themselves (lakes, Indian Ocean in a 150-km wide alongshore corridor), early
257 morning maxima dominate (0600 or 0900). Along the coastline and some western lakeshores the peak
258 is often delayed to 1200, like in Malindi, Mombasa and Dar-es-Salaam (panels 15, 17, 18). Reciprocally,
259 the peak occurs earlier (0300) over the eastern part of Lake Victoria, southeastern part of Lake
260 Tanganyika and northeastern parts of Lake Malawi/Nyassa.

261 (ii) A few inland areas display evening or nighttime maxima. This is most obvious across eastern Kenya,
262 showing belts parallel to the Indian Ocean where the rainfall phase is gradually delayed as the distance
263 from the ocean increases. This pattern is absent further south in Tanzania. More scattered evening
264 peak areas are found in central Tanzania and northern Uganda (Lake Kyoga area south of Gulu, panel
265 2). They are mainly located in depressions or to the east of mountain ranges. It is suggested that
266 daytime convection is detracted by nearby ascending slope breezes, and that the maximum results
267 from the advection of convective systems developed in the afternoon further east.

268 Finally, figure 5 provides a zoom on the Somalia peninsula. There is a fair agreement between TRMM
269 and the SWALIM automatic in situ rainfall recordings (side panels), with an average correlation of 0.77
270 (significant at $P=0.95$) when we exclude Galcaio (panel 5) where the in-situ record is very short (2 years)
271 and the rainfall very low (150 mm.yr^{-1}). The resulting diurnal pattern is quite simple: an early afternoon
272 maximum prevails alongshore, in a 100 to 150-km wide strip. Further inland the phase shifts to the
273 late afternoon (e.g. at Borama, Hargeisa and Burao, panels 1-3), then to the evening and the night as
274 ones moves away from the coast. A broad area of early morning peak (0300) is found in Ogaden
275 (eastern Ethiopia) and southern Somaliland, and the maximum is even found as late as 0600 near 6°N -
276 44°E , 450km from the coast. The pattern, more or less parallel to the coasts, suggests that the diurnal
277 cycle could be controlled by a propagation of sea breeze fronts from both the Gulf of Aden, in the
278 north, and the Indian Ocean in the east. The inland nighttime maximum often cohabits with an
279 afternoon one, weak (Garowe, panel 4) or occasionally stronger like further south (5°N - 44°N).

280 **3.2 Maps and cross-sections of 3-hour rainfall occurrence**

281 In order to better show the distribution of rainfall within the day, 3-hourly maps of mean rainfall
282 occurrence have been plotted (Fig.6). Rainfall occurrence is at its lowest at noon. It strongly increases
283 at 1500 EAT. The areas of most frequent rainfall occurrence are clearly co-located with the main

284 mountain ranges, suggesting their role on daytime convection. At 1800 convective cells become bigger
285 and/or drift (in slightly different directions depending on the large-scale flow), with rainfall occurrence
286 exceeding 15-20% over highland areas. Later in the evening (2100) and at night (2400 and 0300), the
287 areas of high rainfall occurrence generally shift westwards and gradually decay. The wet area in the
288 southwestern Ethiopian Highlands makes an exception for it is still very active at night, though also
289 showing a westward drift towards the nearby plains in the following morning. Lowlands are quite dry,
290 except in southern Tanzania, South Sudan and at a small distance of the coast in Kenya and southern
291 Somalia. A line of medium rainfall occurrence (5 to 9%) parallel to the east African coast actually
292 develops at 1200 and moves inland during the afternoon and evening, gradually decaying. The main
293 lakes, especially Lake Victoria, show a markedly different cycle. They are generally rain-free in the
294 afternoon, but a strong maximum develops in the second part of the night and the morning. Over the
295 Indian Ocean, there is much less diurnal variation than over land. However, rainfall occurrence
296 generally peaks in the morning as discussed above, with a secondary maximum off the coasts of Kenya
297 and Tanzania around 1500.

298 As a way to mask out spatial variations in mean rainfall amounts (e.g. between the drier lowlands and
299 wetter highlands), figure 7 displays rainfall occurrences for each 3-hr period as a percentage of all local
300 rainfall occurrences. This better shows the generalized pattern of propagative rainfall lines from the
301 Indian Ocean and Red Sea coasts (at 1200) to the interior. This apparent propagation can be tracked
302 till 0300-0600 in some inland areas of Kenya and Somalia, and from the Red Sea towards the Nile Valley
303 in northern Sudan. Propagation is also evident over Lake Victoria from the eastern to the western shore
304 from 0300 to 1200.

305 Two time-longitude plots are drawn to further analyze the propagative patterns and their relationship
306 with terrain.

307 The first plot (1.5°S, Fig.8), between the Indian Ocean and the Western Rift Valley, emphasizes the
308 contrast between the uniform distribution of rainfall occurrence over the ocean and that found over
309 land areas and Lake Victoria. Areas over and to the west of the highest ground (Western Rift, 29.5°E,
310 and Western Kenya Highlands, 35.5°E) display the characteristic afternoon rainfall maximum. Evidence
311 of downwind (westward) propagation is found. Afternoon maxima (slightly earlier) are also found west
312 of Lake Victoria (31°E) and near the Indian Ocean coast (41°E), from where the phase is similarly
313 delayed as one moves westwards, generating a nighttime maximum near 38°E. However it appears
314 that this maximum results from an (apparent) propagation from both the east (Indian Ocean coast)
315 and the west (Central Kenya highlands). Different phase speeds on either side of 39°E also suggest
316 different mechanisms, possibly sea breeze front displacement to the east and convective cells

317 movement to the west (see discussion below). The morning maximum of Lake Victoria (32°E) is
318 distinctive. In this sector, a westward drift is also conspicuous, possibly in continuity with the
319 convective systems developed in the Western Kenya Highlands in the afternoon, drifting westward and
320 then reactivating over Lake Victoria in the early morning. Some systems might even propagate further
321 west over the Western Rift Highlands where daytime convection may rejuvenate them. However, the
322 different apparent phase speeds (4.1 and 9.9 m.s⁻¹ respectively) suggest different mechanisms, or
323 propagations in different directions.

324 The second plot (15°N, Fig.9) depicts the Red Sea- Eritrea- Sudan area, again with strong evidence of
325 the effect of relief on rainfall timing. Highlands on both sides of the Red Sea (over 2000 m in Eritrea
326 and Yemen) display an overwhelming afternoon maximum (1500 to 1800 EAT), with no rain at all
327 between 0300 and 1200. The later maximum on the Yemenite side (1800 as against 1500 for the
328 African side) could be due to a later exposition to the sun's rays, delaying slope breezes, or to different
329 interactions between breezes and mid-tropospheric winds. Convective systems developed over Eritrea
330 clearly shift westward (at about 10 m.s⁻¹), resulting in a strong maximum around midnight at 36°E on
331 the foothills. Further west, the nighttime maximum is still obvious, but a large share of rainfall occurs
332 at other times of the day, and there is no more evidence of a propagation, suggesting other
333 mechanisms are at work. In sharp contrast with the highlands, the (dry) Red Sea shows a weak double
334 peak regime, with morning rainfall typical of many maritime areas, and an evening peak likely resulting
335 from the drift of systems developed in the highlands. For the Yemen highlands, rain structures
336 propagate both westward and eastward.

337 **3.3 Role of waterbodies on land diurnal rainfall regimes**

338 A closer attention is paid to the role of water bodies (first maritime areas, then lakes) on the diurnal
339 rainfall distribution, both over these surfaces and over the nearby land areas. Figure 10 shows the
340 mean frequency of 3-hr rainfall occurrence (relative to the local total rainfall occurrence) over the
341 continent, as a function of the distance to the nearest maritime coastline, all latitudes combined from
342 12°S to 23°N. Two diurnal cycles are displayed for legibility, and three months are retained in addition
343 to the yearly average to detect possible seasonal changes. For all plots, a remarkable pattern is shown
344 where, starting from the vicinity of the coast, rainfall occurrence is low before 1000 EAT, then rapidly
345 reaches a mid-afternoon maximum (1500) followed by an almost as rapid decrease (rainfall occurrence
346 <12% well before 2100). A similar pattern is found further inland, but with a gradual delay such that
347 the maximum occurs at 1800 at 50-150 km from the coast, 2400 at 250-300 km, 0300 at around 300-
348 400 km, and is still faintly visible at 0600 beyond 400 km from the coast. The switch to drier conditions
349 later in the day is very clear, with a constant propagation rate (7-8 m.s⁻¹) in April and October, the main

350 rainy seasons in Somalia and Kenya, from the coast to at least 300 km inland. Beyond 250-300 km from
351 the coast, in April and October, the nighttime maximum resulting from this propagative feature
352 coexists with a local afternoon maximum (1500-1800), which becomes dominant beyond about 400
353 km. This pattern evidently points to two different mechanisms accounting for diurnal rainfall
354 variations: local convection driven by daytime surface heating, and rainfall activity along the sea breeze
355 front, whose inland penetration can be associated with the sharp late afternoon rainfall decrease close
356 to the coast, then gradually later inland. If the propagative pattern shown on figure 10 can be
357 interpreted as a result of sea breeze penetration, it points to a very deep (and unexpected) effect
358 inland (see discussion in section 4).

359 The analysis now considers inland water bodies. East African lakes of different sizes have been
360 selected, ranging from 230 km² for Lake Manyara to 68 800 km² for Lake Victoria (Fig.11). Their mean
361 diurnal regimes (in mm.hr⁻¹, bars on the left panels) are plotted individually and as an average for all
362 East African lake pixels (bottom right panel). In the computations, mixed land-lake pixels (at least 25%
363 of water) have been included. For the largest lakes the computation has also been done for the full
364 lake pixels (>75% water). However, the results being similar for the two thresholds (Fig.11), the regimes
365 will not be discussed separately. A morning maximum is obvious for the largest lakes only (Victoria,
366 Tanganyika, both at 0900). Over the northern part of lake Malawi (Nyassa), it is slightly earlier (0300
367 to 0600), as for other elongated, narrow Rift lakes such as Rukwa and Albert (see discussion below).
368 For the smaller lakes, an afternoon maximum appears, giving double-peak regimes (Eyasi, Manyara,
369 Ziway, Abaya, and even the larger Lake Turkana) or almost single-peak regimes (Edward, Tana, Kyoga,
370 Kivu). In these cases, the afternoon maximum is late compared to other inland areas, or even shifted
371 to the evening (e.g., Lake Kyoga). The spatial average, dominated by the Great Lakes (especially Lake
372 Victoria) confirms the inverted patterns between land and lake regimes, with the dominating morning
373 maximum for lakes contrasting with the afternoon one for land (dashed line with squares).

374 Since the lake size seems to matter, lake pixels are now stratified according to their distance to the
375 nearest lakeshore (Fig.12). 3-hr rainfall amounts for sea and land pixels are also plotted for
376 comparison. At 0300, there is little effect of the distance to the lakeshore. The contrast with the land
377 pixels is small as well. At 0600, while rainfall decreases over the land, it strongly increases over the
378 lakes at more than 80 km from the lakeshores. The gradient further increases at 0900, and is still strong
379 at 1200. A dramatic change occurs at 1500: while rainfall away from the shores collapses, it increases
380 over land. Areas close to lakeshores start to be affected by the rainfall increase from 1800. This pattern
381 persists in the early night, gradually weakening. These results, especially the quick transition between
382 1200 and 1500, suggest that local circulations, whose strength and extent are related to the lake size,
383 are instrumental in shaping the diurnal regimes over the lakes. While the cooler surface of the lakes is

384 detrimental to convection during the day, the drift of systems generated over nearby land areas can
385 explain the frequent early evening maximum on the shores (cf. also figures 2-3). As discussed above,
386 given the east-west asymmetries related to interactions between breezes and synoptic-scale winds,
387 this analysis could be further refined by separating eastern and western lakeshores.

388 On the whole, evidence is found of two types of lake regimes: a late afternoon regime, associated with
389 the propagation of convective systems from non-lake areas, mostly over small lakes and lakeshores,
390 and a late night to morning regime, restricted to the larger lakes, associated with a nighttime
391 convergence and uplift over the lake surface.

392 **4. Discussion**

393 TRMM 3-hourly data show that GHA land areas, as in most other tropical regions, generally exhibit a
394 clear afternoon maximum (at 1500 or 1800 EAT), explained by the predominant convective rains and
395 their initiation by daytime surface heating.

396 However, it is noteworthy that extensive areas depart from this pattern. Although some of these
397 peculiar features have been shown in earlier studies based on a few station records, several new
398 patterns are revealed and are now discussed for a more complete interpretation.

399 *(1) Role of the sea-land interface on diurnal rainfall regimes*

400 One of the key findings is the major role of the sea-land interface as a determinant to diurnal rainfall
401 variations in the GHA, not only along the coast but at a long distance from it. This is evident in the
402 gradual delay in the rainfall maximum from the early afternoon to the evening and sometimes the
403 night hours as one moves inland. It is suggested to reflect the inland progression of the sea breeze and
404 associated convective activity along the breeze front, as documented before in other tropical regions
405 (Carbone et al., 2000 ; Mori et al., 2004 ; Zhou and Wang, 2006 ; Kikuchi and Wang, 2008). This feature
406 has never been shown earlier for the GHA, for which little information is available on sea breezes and
407 their role on rainfall regimes. Previous studies point to a morning precipitation maximum at coastal
408 stations of Kenya and Tanzania (Asnani and Kinuthia, 1979 ; Sumner, 1984 ; Camberlin and Planchon,
409 1997). Our study shows that the coastal morning peak quickly shifts to an early afternoon peak a few
410 kilometers inland. The morning peak is generally attributed to the onset of the sea breeze. Then its
411 subsequent penetration over the continent, as the land surface heats up, results in progressively later
412 rainfall peaks. The orientation of the coastline with respect to dominant winds is important (Sumner,
413 1982). The inland propagation along much of the Tanzanian coast, where the winds often parallel the
414 coast (supporting information S4), is limited to the afternoon hours (Fig.2). Further north in Kenya and

415 Somalia, where winds during the rainy seasons are onshore and orthogonal to the coastline, the phase
416 propagation extends further inland into the night, suggesting a deeper sea breeze penetration.

417 In the Red Sea area, previous studies on sea breezes are even scantier. In summer along the Sudanese
418 coast, WRF simulations show an afternoon sea breeze of 3-8 m.s⁻¹, replaced at night by a land breeze
419 (Davis et al., 2015). Our results indicate that the sea breeze penetration is likely to explain the
420 progressive delay in the rainfall phase from the coastline to the interior in the Afar region, and south
421 of the Gulf of Aden. Further north in northern Eritrea and Sudan, it is uneasy to separate the westward
422 drift of afternoon convective storms initiated over the highlands, from the effect of the sea breeze
423 penetration (similarly westwards).

424 The rainfall phase propagation from the coast raises the question of the maximum inland extent of sea
425 breezes in the GHA. In Kenya, Nganga and Masumba (1988) detect them 120 km away from the coast.
426 Our study suggests that their penetration reach 300-500 km from the coast in Eritrea, the Afar region,
427 Somalia and eastern Kenya. This is not at odds with numerical and observational results over various
428 tropical regions. In the Guianas and around the Amazon delta, the sea breeze penetrates up to at least
429 100 km inland (Snow 1976; Molion 1987). In north-eastern Brazil, sea-breeze fronts identified by
430 remote sensing at the warmest time of the day penetrate up to 100 km inland during the late dry
431 season, because of high land-sea temperature differences (Planchon et al., 2006). In Saudi Arabia, the
432 strong desert heating results in a deep inland penetration of the sea breeze of over 225 km (Steedman
433 and Ashour, 1976). Sea breeze penetrations of 250 km were reported in Pakistan (Holmes, 1972), and
434 of over 200 km in flat areas of Australia (Physick and Smith, 1985 ; Planchon, 1995), with possible
435 penetrations of up to 500 km (Clarke, 1984 ; Garratt and Physick, 1985). South of the Persian Gulf, Zhu
436 and Atkinson (2004) obtained a simulated penetration of over 250 km. Over Sumatra Island, Mori et
437 al. (2004), using TRMM data, found both offshore and onshore propagations of diurnal rainfall phases.
438 The onshore propagation, substantiated by upper-air dynamics, can be tracked over 400 km, with a
439 peak rainfall at 1500 LST near the coast, gradually delayed to 0600 in the east.

440 Several factors support a deep inland penetration of sea breezes in the GHA: (i) the low latitude, which
441 restricts wind deviation due to the Coriolis force ; (ii) the relatively flat surfaces, at least over southern
442 Somalia, eastern Kenya and the Afar depression; and (iii) the strong sea-land temperature contrast :
443 maximum temperatures over northeastern Kenya are in the range of 33-37°C during the rainy seasons,
444 while the coastal Indian Ocean reaches 27-29°C. A land-sea temperature gradient over 5°C is required
445 for a deep sea breeze penetration (Miller et al. 2003). The smaller effect of the Coriolis force makes
446 this threshold even lower (4°C) in the tropics (Okoola 1978; Cautenet and Rosset 1989), as against 6°C
447 at higher latitudes. The deep inland phase propagation is also suggested to result from both advection

448 processes due to large-scale circulation and mesoscale gravity currents (Clarke, 1984) generating a new
449 convergence ahead of the initial cloud system.

450 Over the open sea bordering East Africa, while the diurnal distribution of the rains is more uniform,
451 there is evidence of offshore propagation. This is mostly south of the equator, with a 50-km wide
452 coastal belt showing a morning peak (0900) then a mid-afternoon peak (1500) further offshore, as
453 plausibly related to land breezes then gravity waves propagation. We hypothesize that the better
454 developed offshore propagation south of 3°S results from both the warmer sea surface temperatures
455 and the direction of the prevailing winds, crossing the seashore at a small angle. Further north off the
456 Southern Somalian coast, the predominantly onshore winds during the rainy seasons (supporting
457 information S4, March-May and October-December) are detrimental to land breezes. Offshore phase
458 propagations were found in many tropical regions, including Indonesia (Mori et al., 2004 , Teo et al.
459 2011) the Bay of Bengal, Central America and West Africa (Yang and Slingo, 2001 ; Biasutti et al. 2012).

460 *(2) Other nighttime inland maxima*

461 Many nighttime maxima can be related to rainfall systems associated with sea breeze propagation, as
462 discussed above, but some cases exist of other mechanisms. Instances of a nighttime maximum have
463 been found in other inland tropical regions, such as southwestern Amazonia (Rickenbach, 2004), the
464 Himalaya (Sahany et al., 2010) and the Khorat Plateau in Thailand (Takahashi et al., 2010). In the
465 Amazonian case, a post-midnight secondary maximum was attributed to nocturnal convective events,
466 many of which are traced to squall lines propagating westward thousands of kilometers from their
467 origin, i.e. the sea breeze front developed in northeast Brazil (Kousky, 1980; Garstang et al., 1994 ;
468 Machado et al., 2014). The late night/early morning peak over the Himalaya foothills was suggested to
469 be associated with the convergence of katabatic winds and the southwesterly monsoon (Sahany et al.,
470 2010). We consider that these two mechanisms also operate in the GHA.

471

472 Nighttime maxima observed in northern and central Sudan clearly result from the westward shift of
473 MCS generated over the Ethiopian and Eritrean Highlands. This was suggested by El-Fandy (1949) and
474 Pedgley (1969), then confirmed by Desbois et al. (1988). South Sudan is similarly affected, but in-situ
475 convective systems also develop which result in a dominant afternoon rainfall peak (section 3.1). Laing
476 et al. (2008) actually found that the lee of the Ethiopian Highlands, east of 31°E, was the birthplace for
477 25% of cold cloud streaks occurring over Northern tropical Africa between 5 and 15°N. A nighttime to
478 early morning maximum is also found over southeastern Sudan, northwestern Kenya (around Lake
479 Turkana) and nearby Ethiopia. It results either from the drift of MCS generated over the Southern

480 Ethiopian Highlands (as suggested by the phase propagation from the north-east) or from the
481 nighttime convergence of katabatic flows from the Ethiopian and Kenya-Uganda Highlands.

482

483 Further south, Asnani and Kinuthia (1979) found that stations on the eastern slopes of the Kenya and
484 Tanzania Highlands, like Nairobi, had a nighttime maximum, instead of the usual late afternoon one as
485 expected inland. As discussed above, this nighttime maximum may partly be related to convective
486 systems generated along the sea breeze front and later advected further inland. However, Asnani and
487 Kinuthia (1979) suggested that it was rather a result of the downslope flow opposed to the easterly
488 tradewinds. It is safe to consider that the two mechanisms either combine (convergence between
489 katabatic winds and the easterly flow, possibly reinforced by the sea breeze) or operate at different
490 times to explain the nighttime maximum. The January pattern (Fig.S2a), in which southern Kenya
491 shows a discontinuity between the diurnal phase associated with a propagation from the coast, and
492 the nighttime maximum northeast of Mt Kilimanjaro and southeast of Mt Kenya, actually suggests that
493 katabatic winds are an important player.

494

495 *(3) Role of inland water bodies and lake breezes*

496 The largest East African lake, Lake Victoria, is known for its specific diurnal cycle of precipitation (Flohn
497 and Fraedrich, 1966 ; Datta, 1981 ; Ba and Nicholson, 1998 ; Nicholson and Yin, 2002). Nicholson and
498 Yin (2002) found similarities over Lake Tanganyika. TMPA 3B42 data confirmed a strong morning peak
499 over these two lakes. Several other large- and medium-size lakes in the region exhibit a nighttime or
500 morning maximum. Numerical climate modeling of the East African Great Lakes region (Thiery et al.,
501 2015) found precipitation occurring mostly at night and morning hours over the lakes (0300-1200 EAT),
502 in agreement with our results. However, the precipitation maximum they found for the surrounding
503 land, around local noon (1000-1500) is too early and fits neither TRMM nor in-situ observations.

504

505 Except for the smallest lakes, the share of morning and late night rainfall is proportional to the distance
506 from the lakeshores, a feature consistent with observations by Haile et al. (2009) for Lake Tana
507 (Ethiopia). The lake surface remains cool in the afternoon while convection develops over the heated
508 surrounding land areas. The lake breeze which develops results in subsidence over the lake, thus
509 promoting dry conditions. This has been well shown for Lake Victoria (Flohn and Fraedrich, 1966;
510 Anyah et al., 2006; Thiery et al. 2015), but it may also apply to large lakes such as Lake Tanganyika over
511 which strong diurnal wind changes are found. However, Lake Tanganyika being a Rift lake, about half
512 of its diurnal wind variation is due to slope breezes, and one quarter is strictly due to the thermal lake
513 effect (lake breeze) (Savijärvi, 1997). East of Lake Victoria, strong interactions exist with the slope

514 winds of the nearby highlands (Kayiranga, 1991; Anyah et al., 2006; Thiery et al. 2015). West of the
515 lake, the afternoon lake breeze also combines with slope winds (Dhonneur, 1985) to explain the mid-
516 afternoon maximum, then the late afternoon peak further west, as the breeze front shifts westward,
517 aided by the large-scale easterlies. A similar combination occurs in the Spanish eastern Pyrenees (Llasat
518 and Puigcerver, 1997) where combined sea and slope breezes enhance convection. The late night /
519 early morning rainfall maximum is explained by the instability over the relatively warm lake, enhanced
520 by the converging land breezes.

521

522 Over small-size lakes, such a convergence may be too weak to generate a rainfall peak. The diurnal
523 regime is therefore characterized by an evening maximum resulting from the drift of convective
524 systems generated over the nearby land areas. Crosman and Horel (2010) noted that while lake
525 breezes associated with large lakes ($d > 100$ km) have similar characteristics to sea breezes, this does
526 not apply to small water bodies due in part to shoreline curvature effects. A bimodal regime, including
527 both a morning peak and an afternoon peak, was found over several relatively small east African lakes
528 (e.g., Abaya, Ziway, Eyasi, Manyara, which cover between 250 and 1150 km²). This sharp morning
529 maximum, given the small size of these lakes, is puzzling. Although Tian and Peters-Lidard (2007) in
530 the USA reported systematically-positive errors in TRMM 3B42 (version 6) over inland water bodies,
531 this was not confirmed by Paiva et al. (2011) for Amazonia where relatively small water bodies (rivers)
532 exhibit specific diurnal regimes (lowest rainfall during the afternoon, highest at night and early
533 morning), opposite to those of land areas. Medium-size lakes such as Malawi, Rukwa and Albert show
534 a nighttime (0300 EAT) maximum (Fig. 11). Their small width, compared to Lake Victoria and
535 Tanganyika where the maximum occurs at 0900, makes the nighttime convergence of land breezes
536 less durable, with a faster cooling of the lake surface than over bigger lakes.

537

538 As a result of the dominant easterly winds over much of the Great Lakes region, a notable feature is
539 the asymmetrical pattern of the phase of diurnal rainfall regimes around the main water bodies. The
540 nighttime-morning maximum is deflected westwards of the lake surface. This is conspicuous for Lake
541 Victoria (Anyah et al., 2006) but it is also visible over Lake Tanganyika, Rukwa, Malawi, Albert and
542 Turkana (Fig.2). For Lake Tanganyika, late night to early morning convection is frequent along the
543 western lakeshore (Nicholson and Yin, 2002).

544

545 **5. Conclusion**

546

547 This study highlighted the potential of 3-hourly rainfall estimates from the TRMM 3B42 product, which
548 compare favorably with independent in-situ data, to document the patterns of diurnal precipitation

549 variations in eastern Africa. Maps of the diurnal rainfall phase based on 17-yr (1998-2014) averages
550 show evidence of an important spatial complexity strongly controlled by geographical features
551 (orography and water bodies), with relatively little seasonal changes. Besides a confirmation of the
552 role of relief and Lake Victoria on diurnal regimes, the study provided for the first time evidence of a
553 strong diurnal modulation of the rains in areas never investigated before, such as Somalia and the
554 eastern part of Ethiopia.

555

556 Over the region as a whole, 70% of the annual rainfall amount falls between 1330 and 0130 over land
557 areas (lake surfaces excluded). Land surfaces display an overwhelming afternoon maximum, with a late
558 afternoon peak (1800 EAT) at 41.5% of the pixels. The phase occurs slightly earlier (1500) along land
559 strips (about 100-km wide) bordering most of the Indian Ocean coast as well as many of the Great
560 Lakes, as shown by rings of mid-afternoon maxima around most water bodies. This suggests a key role
561 of the daytime sea and lake breezes in controlling convection over these regions. Reciprocally, the
562 phase is delayed to the evening or even nighttime hours in some regions further inland such as eastern
563 Ethiopia, northeastern Kenya, the Afar depression and the northern Nile plains. The gradual delay in
564 the rainfall phase from the coast to the hinterland, most developed in lowland areas, sometimes at
565 unexpectedly long distances from the coast (300-500 km), is likely associated with sea breeze
566 propagation combined, in some regions, with downslope winds. Propagating mesoscale systems
567 developed over high ground areas during the afternoon, also account for the late (nighttime) maximum
568 found in a few parts of the GHA, like northern Sudan.

569

570 The diurnal rainfall distribution over the Indian Ocean and the Red Sea is much more uniform.
571 However, a morning peak dominates close to the coast (and at some coastal locations), especially
572 south of the equator. Phase propagation is evident south of 3°S, resulting in a weak afternoon
573 maximum further offshore. Lakes themselves demarcate from land surfaces by their diurnal regimes.
574 The larger ones (Victoria, Tanganyika, Malawi/Nyassa) show a dominant late night / early morning
575 maximum, more evident as the distance to the lakeshore increases. It was shown in previous studies
576 to be related to nighttime convergence of land breezes over the relatively warm lake surfaces, possibly
577 aided by downslope breezes. It is found that smaller lakes also display specific diurnal regimes: a
578 morning peak frequently combines with a late afternoon one resulting from the propagation of
579 convective cells generated over the surrounding warmer land areas. Further work, considering the
580 actual propagation of cloud systems or the use of limited area climate modelling, is required to fully
581 assess the mechanisms explaining the phase shifts in diurnal precipitation regimes from the coastlines
582 or the highlands and the interaction between sea-land-lake breezes and the large-scale winds.

583

584 **Acknowledgements**

585 This article is dedicated to the memories of Raphael Okoola (1943-2016) and Gérard Beltrando (1956-
586 2016) for their contributions on the climates of East Africa.

587

588 **Supporting information**

589 Appendix S1: Seasonal variations of diurnal rainfall phases

590 Figure S2: Diurnal phase of peak rainfall in Eastern Africa for the months of January, April, July and
591 October. Areas left blank are those where mean rainfall is less than $0.02 \text{ mm}\cdot\text{hr}^{-1}$ (about $15 \text{ mm}\cdot\text{mth}^{-1}$)
592 or where the maximum 3-hr rainfall does not exceed 17% of the monthly total. Solid lines: 1000 (white)
593 and 2200 m (grey) elevation contours

594 Figure S3: Percentage rainfall occurrence during the wettest 3-hr period.

595 Figure S4: Seasonal wind flows over Eastern Africa : meridional cross-section of 500 hPa wind
596 direction (arrows pointing to the left denote easterly winds) and wind speed, along 35.25°E (a) and
597 44.25°E (b), and 925hPa streamlines for March-May (c), June-September (d) and October-December
598 (e).

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775 Figure Captions

776 Figure 1: Location map and relief of Eastern Africa (elevation in meters). 1: Lake Albert ; 2 : Lake
777 Kyoga ; 3 : Lake Edward

778 Figure 2: 3-hour period during which precipitation is (a) most frequent and (b) most abundant,
779 TRMM data (1998-2014, whole year). 3 EAT stands for the period between 0130 and 0430 East
780 African Time. Arrows show the most apparent phase propagations (see text). Solid lines: 1000 (white)
781 and 2200 m (grey) elevation contours. Areas where mean rainfall frequency does not exceed 0.5% in
782 any 3-hr period (a) or mean annual rainfall is below 80 mm (b) are left blank. Central histogram:
783 percentage of grid-points as a function of the 3-hour period during which rainfall is most frequent (in
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785 Figure 3: Same as Fig.2a but for the region covering Sudan, South Sudan, western Ethiopia and
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787 m contour lines. Side panels: percentage of all local rainfall occurrences in each 3-hour period at the
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798 for the period 2008-2015 depending on stations (only 2 years are available for Burao and Galcaio).

799 Figure 6: Raw rainfall occurrence for each 3-hour period, all months together (average for 1998-
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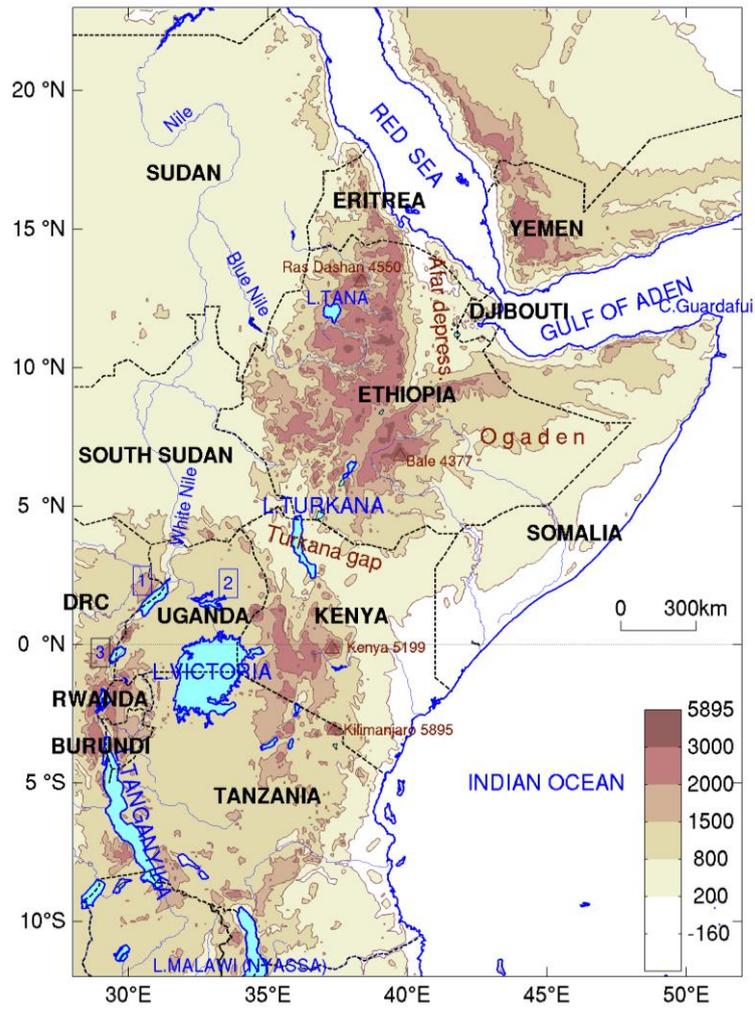
804 Figure 8: Time-longitude plot of diurnal rainfall occurrence along 1.5°S. Top : elevation cross-section.
805 Bottom : percentage of local rainfall occurrence during each 3-hr period. For convenience, two
806 consecutive diurnal cycles are plotted. Heavy grey lines show approximate propagation and
807 corresponding speeds.

808 Figure 9: Time-longitude plot of diurnal rainfall occurrence along 15°N. Top : elevation cross-section.
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810 consecutive diurnal cycles are plotted.

811 Figure 10: Distribution of rainfall in each 3-hr period (percentage of total rainfall occurrences at each
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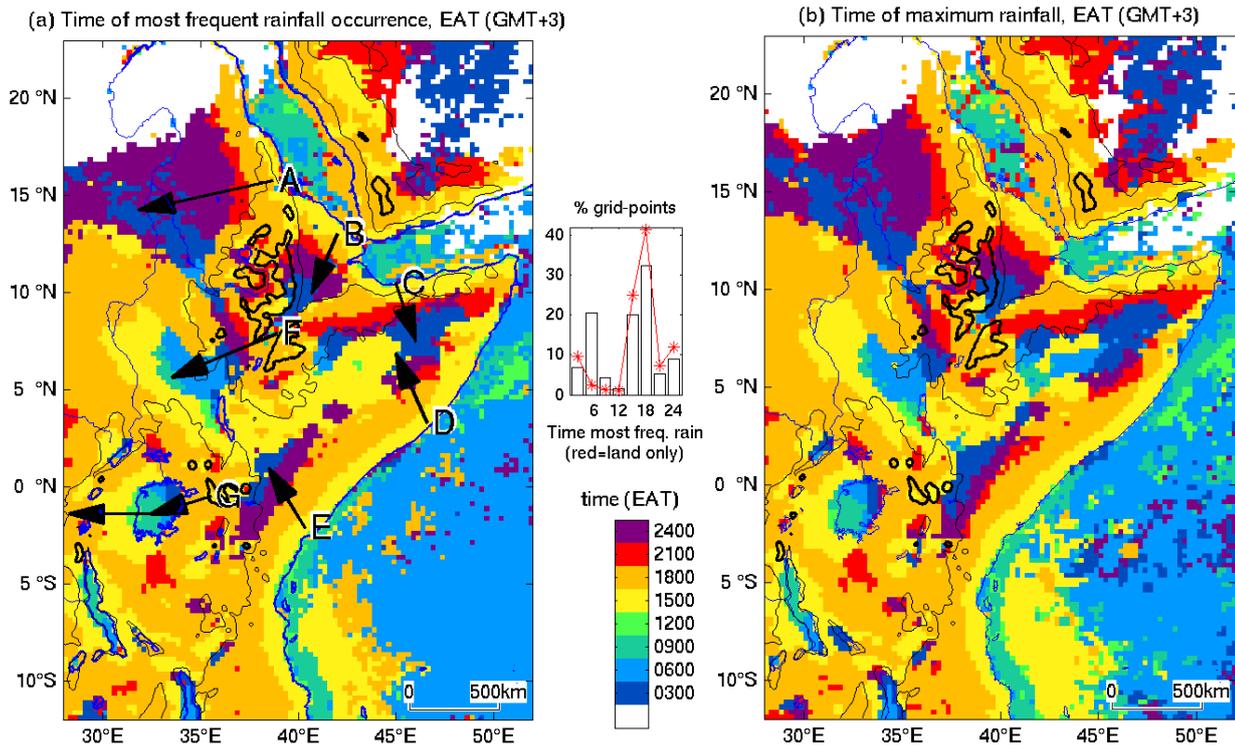
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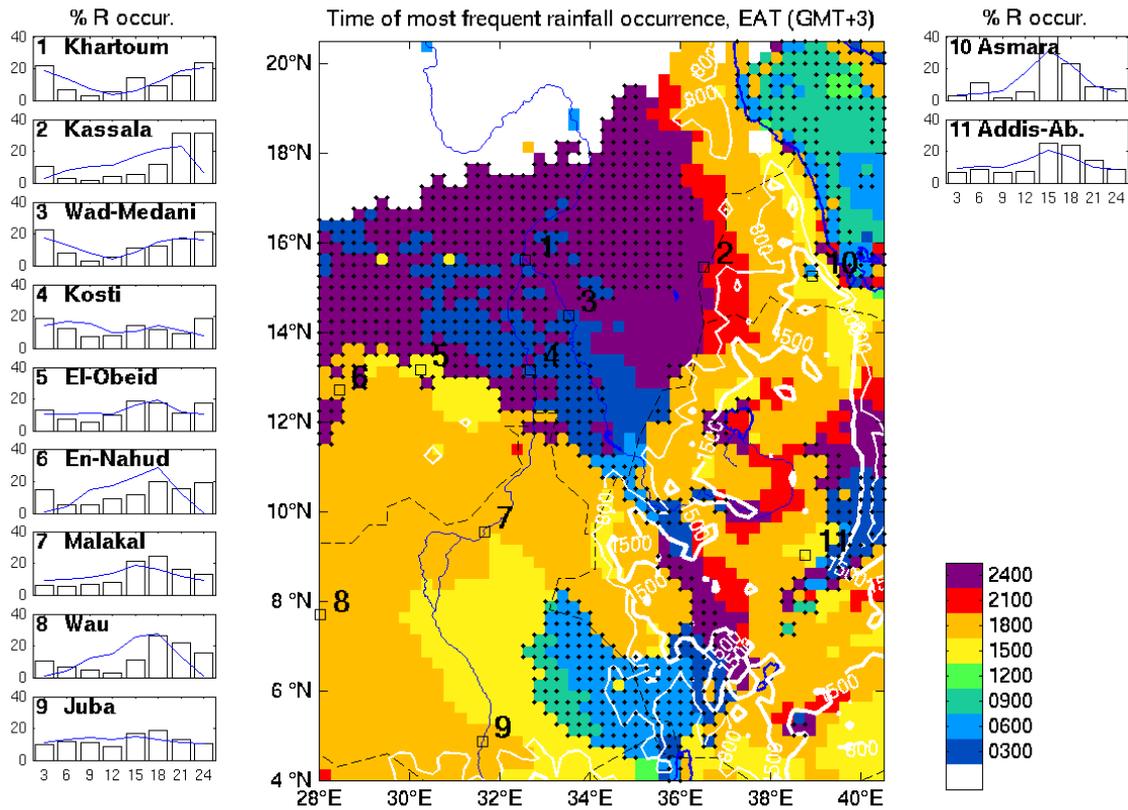


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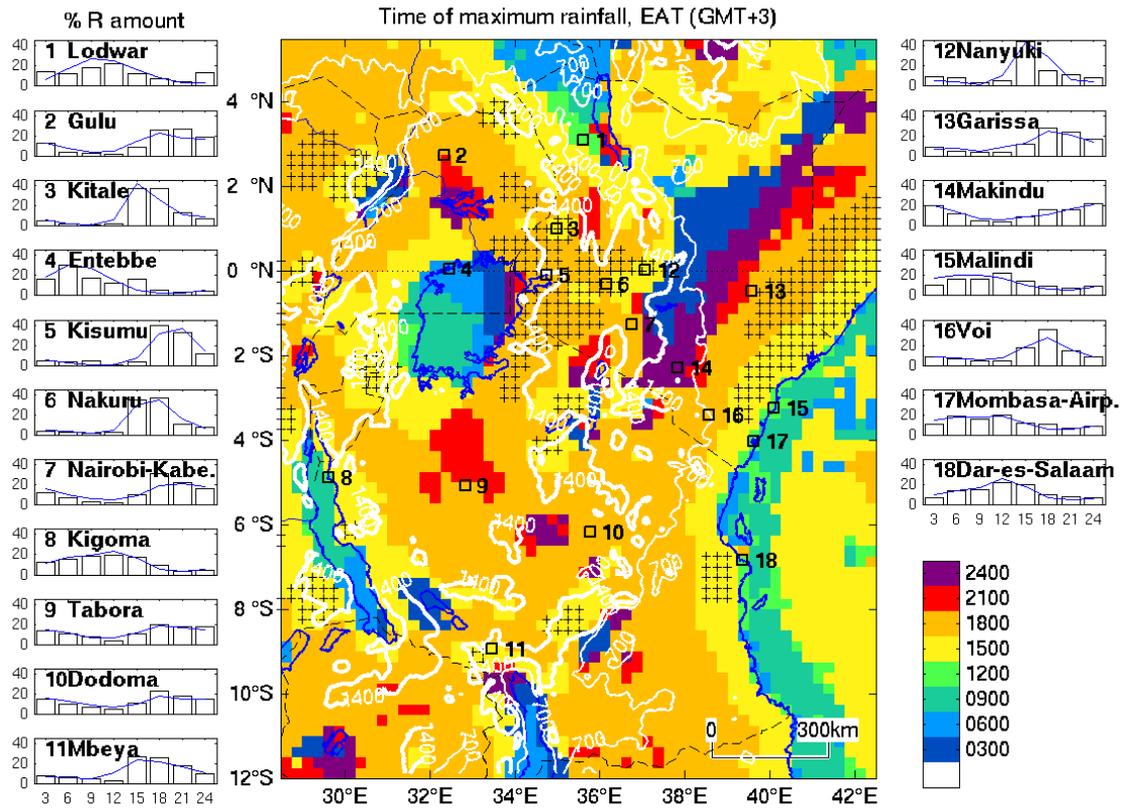
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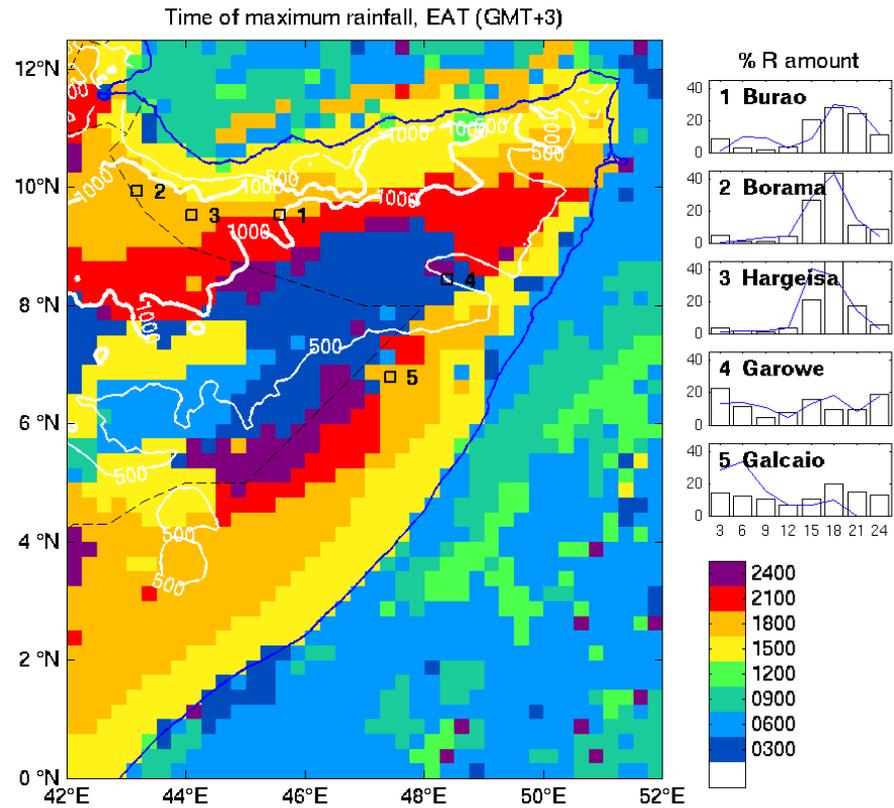
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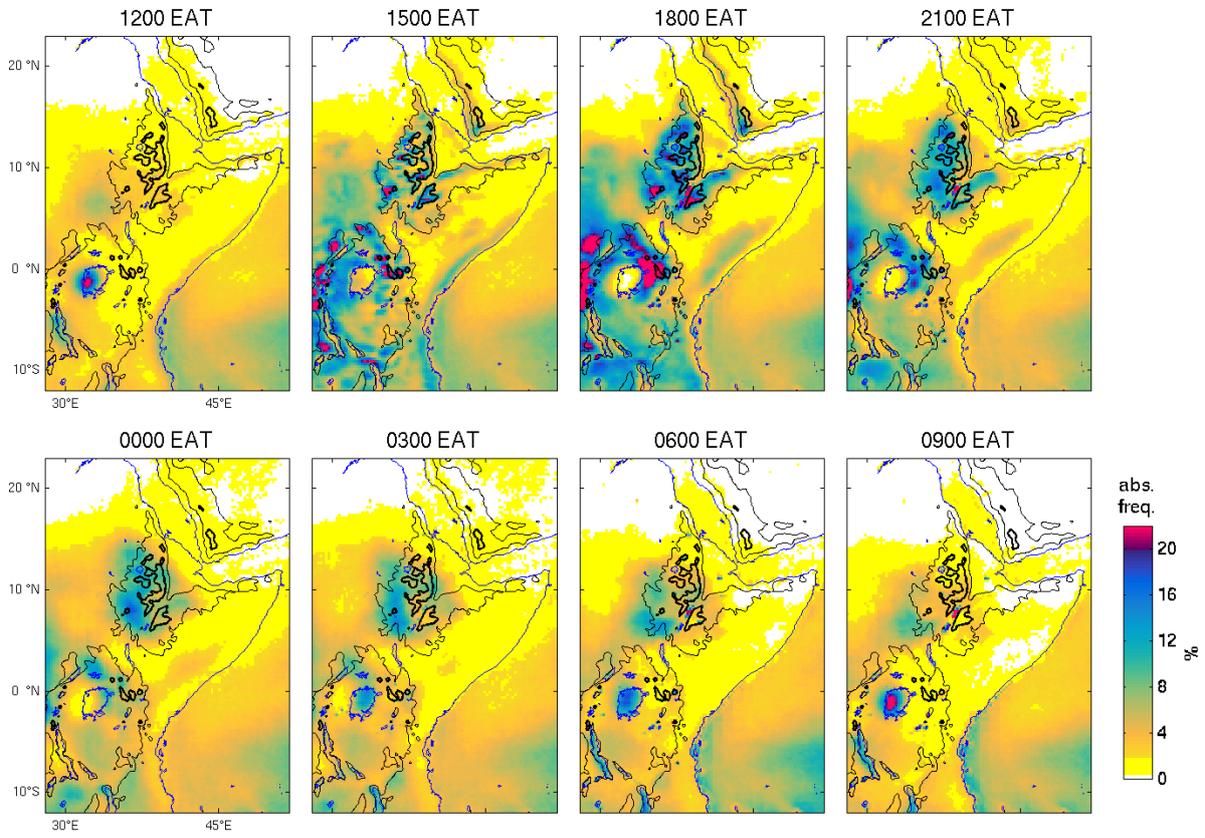
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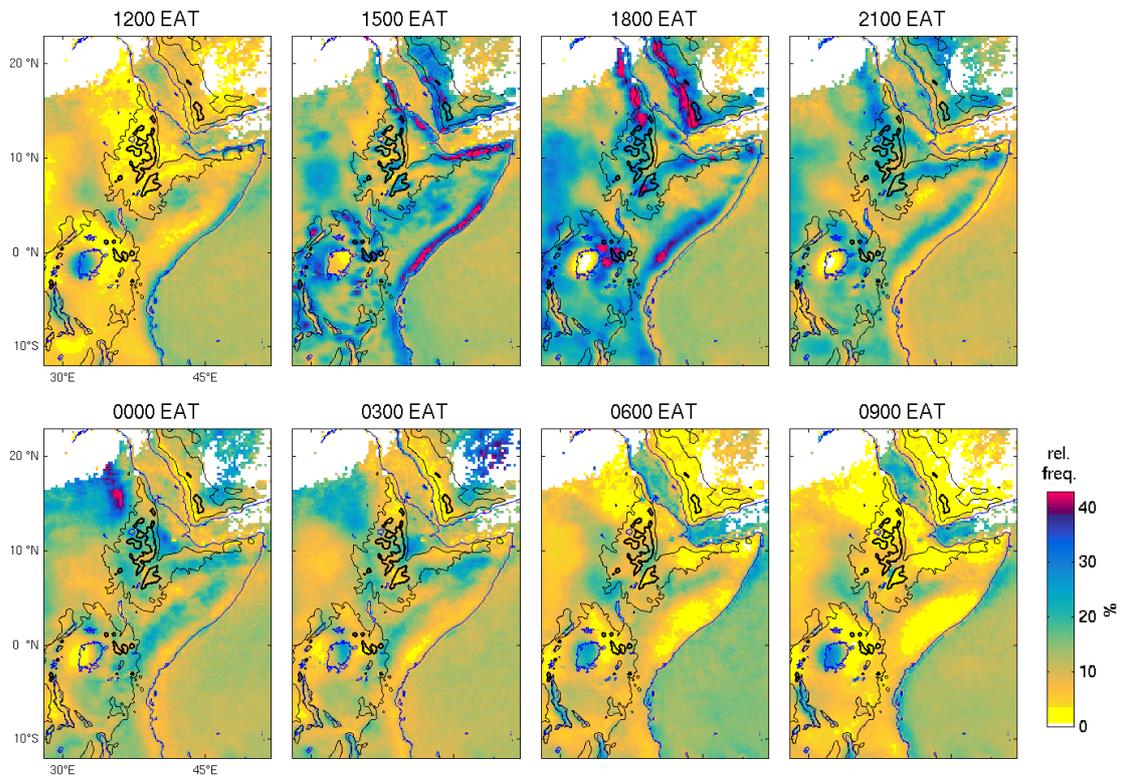
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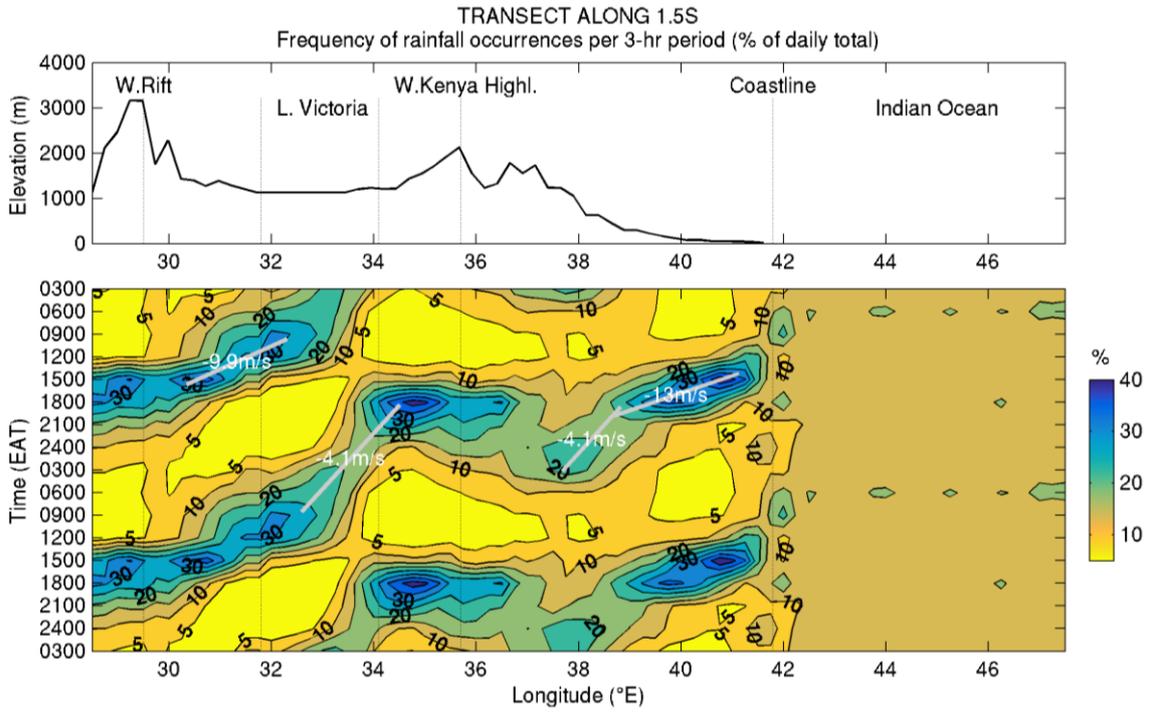
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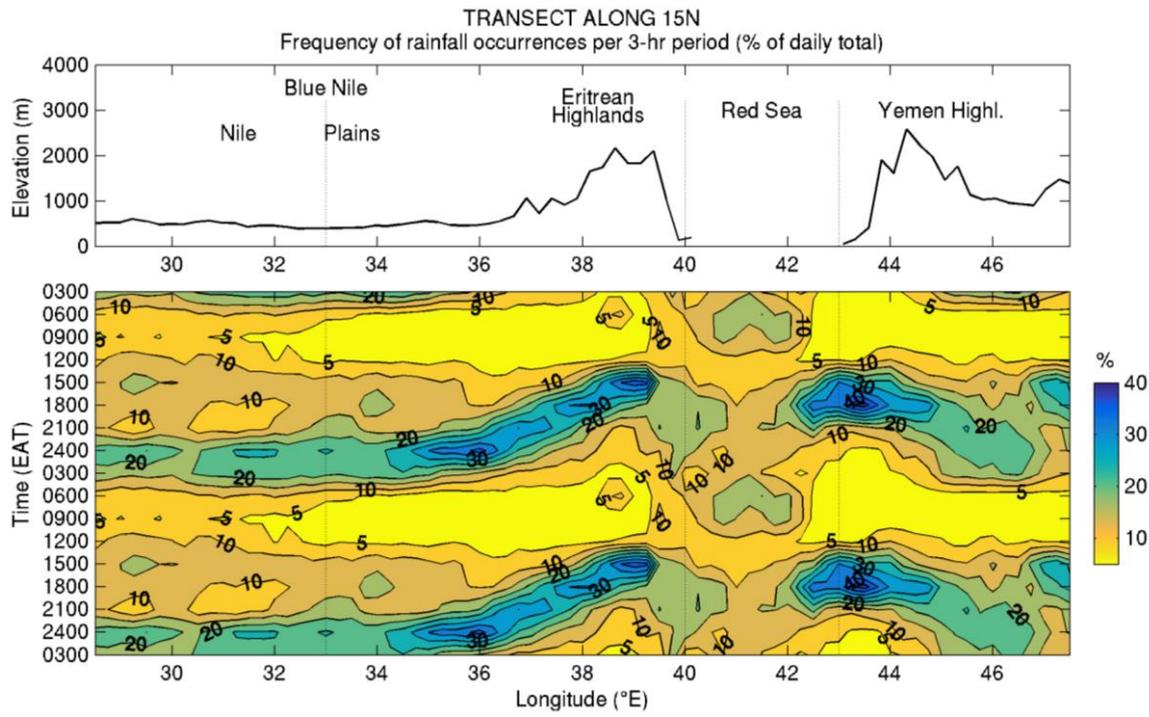


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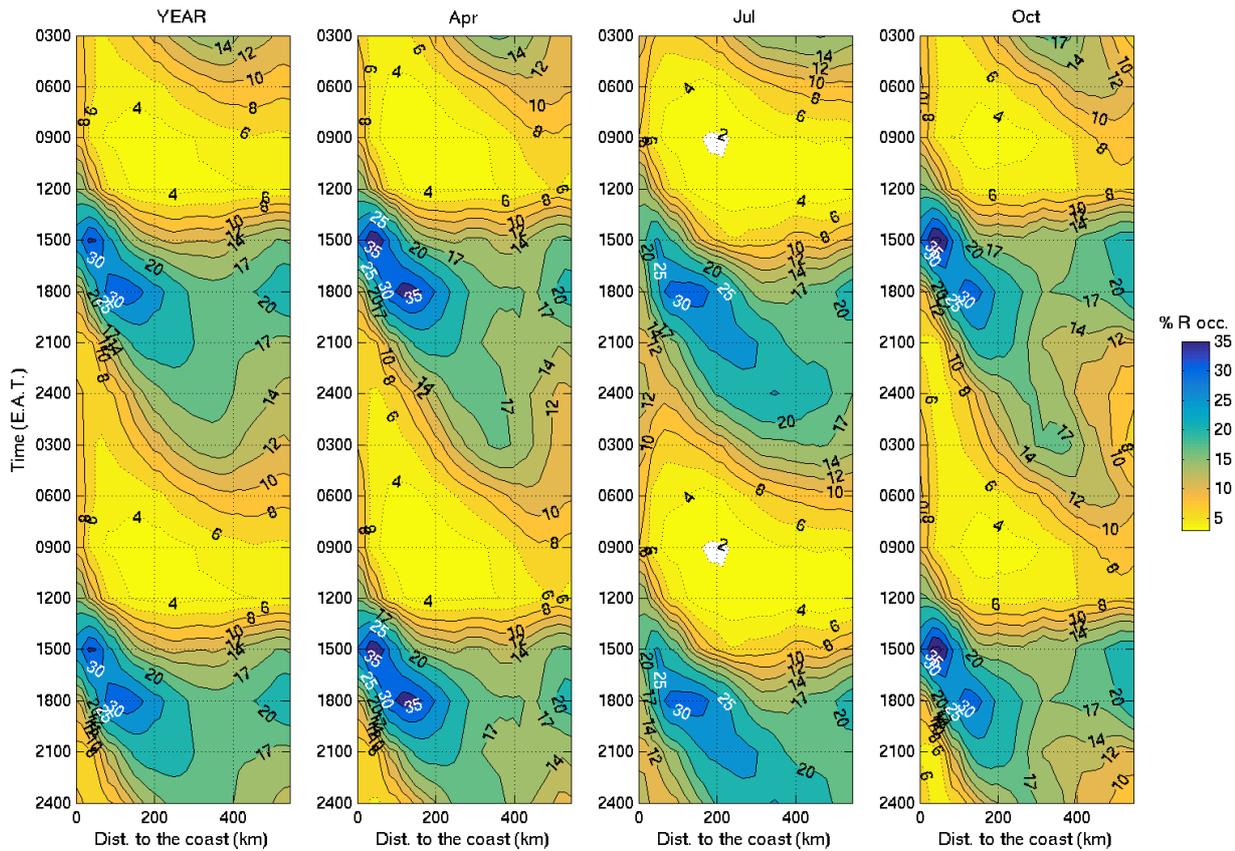




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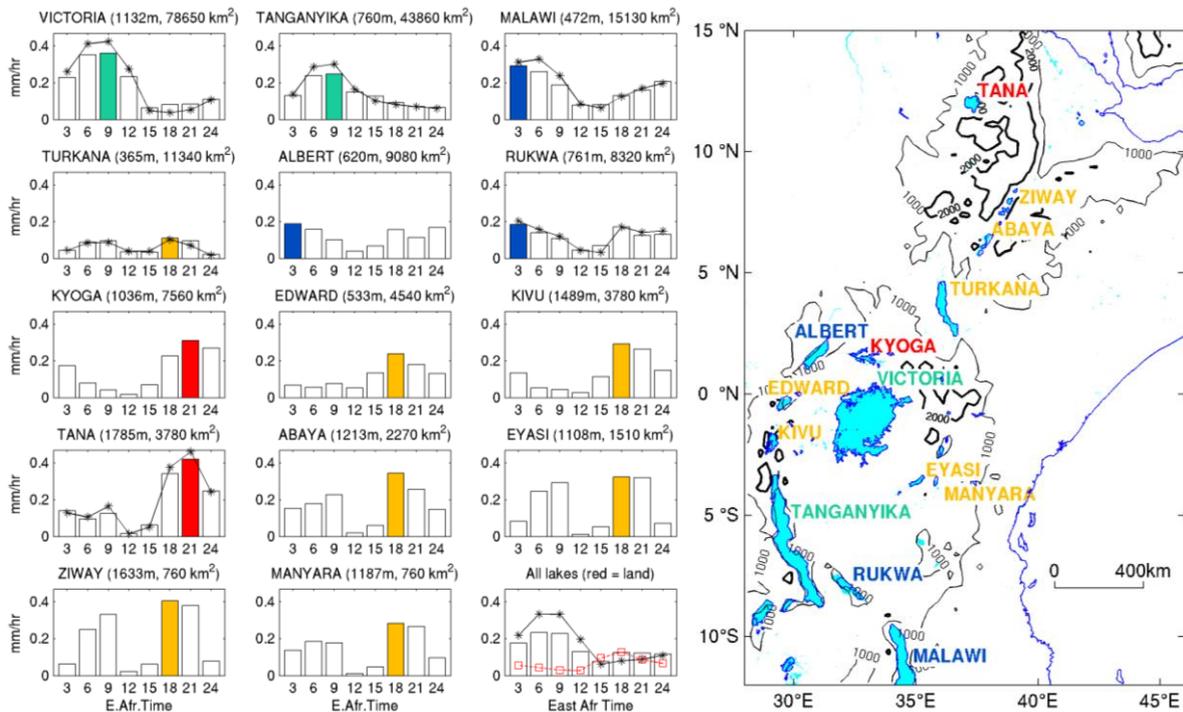
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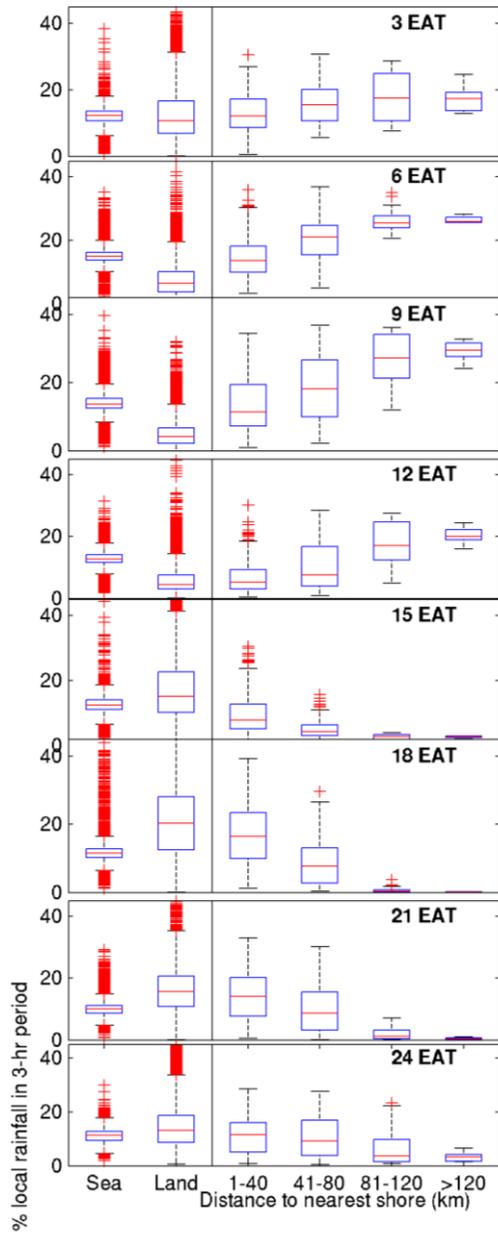
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