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More variable tropical climates have a slower demographic growth

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1 ABSTRACT : The amplitude of observed rainfall variations in the world is analysed using station
2 data for the twentieth century. Rather than the classical approach based on the coefficient of
3 variation, a polynomial fit is developed which is more relevant to semi-arid climates. The results
4 singularise the tropical and subtropical regions, whose amplitude of interannual rainfall
5 variability is larger than that of the extra-tropical regions, for a given mean rainfall value.
6 However, the tropical belt also shows large contrasts between highly variable climates,
7 corresponding mainly with regions where the sea-surface temperature forcing is strongest, and
8 more steady climates.

9 A separate analysis documents the relationship between the amplitude of rainfall variations and
10 human demography. Population densities do not show any systematic decline with increasing
11 variability. However, in the tropics, there is often a coincidence between reduced demographic
12 growth and high rainfall variability. This smaller demographic growth is suggested to result from
13 both reduced natural growth (especially enhanced mortality) and out-migration from regions
14 affected by strong rainfall variations, as evidenced from a number of African cases studies. On
15 the contrary, tropical regions with a fast growing population have on the average a lower rainfall
16 variability.

17 KEY WORDS : Precipitation, Variability, Demographic growth, Population density

1. INTRODUCTION

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Climate variations around the mean are unequal around the world. Some regions are known to be repeatedly affected by climatic hazards which have devastating impacts on the local population and economy. In some cases the damaging effects of climatic hazards can be attributed to a high vulnerability of the local communities. In other cases, it is the intensity of the climatic event itself which accounts for much of the devastation, which can be extensive even in areas having a high level of preparedness. Tropical cyclones and droughts provide numerous examples illustrating both situations. However, in several instances, and in the long run, it is difficult to assess the respective parts played by vulnerability and hazards characteristics or repetitiveness in the variable impacts of climate variability. For instance, while the direct consequences of a single powerful climatic event over a given area are fairly easy to assess, it is much more tricky to have both a global and a long-term view of the relationship between year-to-year climate fluctuations and human societies (Ribot et al. 1996, Wisner et al. 2003). In one of the few studies available, Brown & Lall (2006) found a statistically significant relationship between greater rainfall variability (especially intra-annual) and lower per capita Gross Domestic Product, in a comparison taking into account 163 countries over the period 1979-2004.

Comparing the amplitude of climate variability around the world is partly marred by an unsuitable quantification of the latter. Rainfall, in particular, is a difficult variable due to the fact that it has a skewed statistical distribution, with numerous records of nil precipitation in drylands, and sometimes in wetter areas, depending on the timescale. Yet, in much of the tropics and subtropics, its variability strongly impacts on human communities. A spatial comparison of rainfall variability, for instance using a most standard criterion, the coefficient of variability (CV), is biased by this statistical distribution issue. A first objective of this contribution is therefore to document spatial patterns in the amplitude of rainfall variations, by considering an alternative definition of interannual rainfall variability. Conrad (1941) and Nicholls (1988) calculated relative variability as the mean of the absolute deviations from the long-term mean. This definition, like the coefficient of variation (Nicholls & Wong 1990), tends to make drier stations display a higher variability. Dewar & Wallis (1999) further analysed the patterns of rainfall variability, using as the measure of variability the 0.1 quantile (QU10), or the proportion of mean annual rainfall expected in the driest year in 10. A nonlinear regression was fitted to the relationship between QU10 and mean annual rainfall. They found strong spatial contrasts between coherent regions of high and low rainfall variability. However, their analysis was restricted to the tropics and near tropics. We therefore extend their results to the global scale,

1 using a rainfall variability index based on standard-deviation, at both annual and monthly time-
2 scales.

3 It is a delicate task to assess how regional differences in the level of rainfall variability impact on
4 societies. These impacts actually take many different forms, and depend on the economic
5 activities, incomes, technical knowledge, and coping mechanisms developed by these societies.
6 Since developing countries are predominantly in the tropics, and rainwater availability is a major
7 climatic constraint in the tropics, we hypothesize that the rainfall amplitude / human activities
8 relationship is more prevalent in this zone than elsewhere. To verify this assumption, this study
9 focuses on demography. The aim is to assess whether either population densities or demographic
10 growth around the world have any relationship with the above defined rainfall variability index.

11 Le Blanc & Perez (2007) noted that in sub-saharan Africa mean annual rainfall and human
12 density are strongly correlated below 900 mm of annual rainfall. They suggested that the
13 variability of rainfall was also a critical determinant of local carrying capacities, but they did not
14 test this hypothesis. Small & Cohen (2004) found that the global distribution of population is
15 much more dependent on physiographic (altitude, distance to water bodies) than on climatic
16 parameters, although population densities tend to peak at intermediate (around 1000 mm) annual
17 precipitation amounts, and in highly seasonal (e.g., monsoonal) precipitation regimes. Again,
18 they did not consider population change. This aspect is however dealt with in regional case
19 studies analysing the demographic impacts of individual climatic hazards. In connection with
20 flooding, Bangladesh in 1974 lost about 2% of its population to famine (Caldwell & Caldwell
21 1992 ; Devereux 2002). Even more pronounced mortality rates (about 7 times higher than in
22 Bangladesh) were found during the 1984-85 drought-related famine in northern Ethiopia (Kidane
23 1989). Demographic behaviours of Ethiopian rural communities have also been affected by
24 environmental stress and food insecurity, with an increase in out-migration and a reduction in
25 fertility (Ezra 2001). Many regional case-studies suggest that out-migration is a frequent outcome
26 of major climatic events, especially long-lasting droughts (Teklu et al. 1991, Magalhaes 1993,
27 Finan & Nelson 2001, Haug 2002, Henry et al. 2003, Weiss 2003). However, authors insist on the
28 diversity of situations in the relationship between drought and migration (Findley 1994, Pedersen
29 1995, Retaillé 1995). There are in fact very few studies dealing with the possible relationship
30 between population dynamics and climate variability at global scale. Based on global gridded
31 population maps, Milesi et al. (2005) noted that population growth between 1982 and 1998 was
32 strong in water-limited areas (most tropical regions). They also found significant correlations
33 between El-Niño-Southern-Oscillation (ENSO), the leading mode of interannual climate

1 variability around the globe, and terrestrial net primary production over 63% of the world's
2 vegetated surface, mainly in tropical and subtropical areas. However, possible associations
3 between population growth and ENSO variability were not explicitly addressed. Afifi & Warner
4 (2008) found a statistically significant relationship between environmental degradation and out-
5 migration, based on a selection of countries, though their study did not consider climate
6 variability indicators as such.

7 At continental and global scales, it is therefore unknown whether there is any discernable effect
8 of climate variability on human occupation and dynamics, a question which the present study
9 seeks to address, by considering the mean amplitude of rainfall variations. After presenting the
10 data (section 2), a rainfall variability index is defined and analysed in section 3. A diagnostic on
11 the probable causes of the spatial discrepancies in the amplitude of rainfall variability is also
12 provided. Section 4 then deals with the potential relationships between rainfall variability and
13 demography.

14 2. DATA

15 The rainfall data used in this study originate from the Global Historical Climate Network
16 (GHCN, Peterson & Vose 2001). Over 12,300 stations have been extracted, with monthly
17 precipitation time-series of various lengths, encompassing the period 1901-2005. It was not
18 possible to use a fixed period of time for all stations, given the poor data availability during either
19 the first or the second half of the twentieth century for several parts of the world. A minimum
20 period of time of 40 years has been retained (no prior estimation of missing values), and the long-
21 term monthly and annual means and standard-deviations have been computed. A 40-yr period
22 was judged as sufficient to reflect reasonably well both decadal and year-to-year variability. Note
23 that it is preferable to use station (point) data and not grid-point (areal) averages. Spatial averages
24 tend to reduce the amplitude of interannual variations when they mix stations having contrasted
25 time-evolutions, unless the amplitude is rescaled to that of the individual stations (Osborn &
26 Hulme 1997 ; Brohan et al 2006).

27 The population data set used in the second part of the study is the Gridded Population of the
28 World, Version 3 (GPWv3), which originates from Columbia University (CIESIN 2005).
29 Gridded population density values are available at a 0.25° latitude and longitude resolution for
30 the years 1990 and 2000. Population growth rates between the two years have also been
31 computed. Their accuracy depends on the availability of regular census data. This data set has

1 already been used in previous studies dedicated to the relationship between climate patterns and
2 human densities (e.g., Le Blanc & Perez 2007).

3 Due to data availability, there is an apparent mismatch between the periods used for assessing
4 rainfall variability (40 year periods within the years 1901 to 2005) and demographic growth
5 (1990 to 2000). However, the aim is not to study the impact of individual climatic events on
6 demographics for a given year. Instead, it is to assess how large the standard climate variability at
7 different locations is and whether it is matched by spatial variations in population densities and
8 general population growth. Additionally, it was verified that the amplitude of interannual
9 variability during 1990-2000, at the stations having data for this decade, was not strongly
10 different from that computed from long term time-series.

11 3. A RAINFALL VARIABILITY INDEX : DEFINITION AND SPATIAL PATTERNS

12 3.1. An indicator of rainfall variability

13 A common indicator of the amplitude of interannual climate variability is the coefficient of
14 variation (CV), which is defined as the ratio between the standard-deviation and the mean
15 (Longley 1952). Apart from the fact that it cannot be applied to some climate variables like
16 temperature, its use for zero-bounded climate variables, like precipitation amounts, is
17 questionable. The problem arises when working at short time-scales (daily to monthly), or even at
18 annual time-scales in semi-arid environments. When the time-series is skewed towards zero, the
19 CV draws towards very high values as a result of the division by a very small mean.

20 Therefore, for an adequate comparison of stations (or seasons), an alternative indicator of
21 precipitation variability should be looked for. Fig. 1 shows the standard-deviations of annual
22 rainfall, with respect to the mean, at the 12,335 GHCN stations across the world. It is evident
23 that there is a strong relationship between standard-deviations and means. However, the
24 relationship is not fully linear (below a mean annual rainfall of about 500 mm, the scatter-plot
25 tends to be slightly curved), and the plot is offset with respect to zero standard-deviation. There is
26 also a considerable scatter, which indicates that for a given mean, precipitation variations can be
27 either high or low. For instance, both Copenhagen (Denmark) and Penedencias (north-eastern
28 Brazil) have a mean annual rainfall close to 600 mm. The climate of Penedencias is however thrice
29 as variable as that of Copenhagen, the two stations having standard-deviations at 94 and 301 mm,
30 respectively.

1 A second-order polynomial best fit was thus empirically adjusted to the scatter-plot. The equation
2 is in the form :

$$3 \quad \sigma_e = a_1 x^{k_1} + a_2 x^{k_2} + a_3,$$

4 with σ_e the estimated standard-deviation, x the mean, and a_1 , a_2 , a_3 , k_1 , k_2 empirically fitted
5 coefficients. Best fit coefficients were set to 0.0013, 1.52, -2.16, 1.43 and 0.71 for a_1 , a_2 , a_3 , k_1 ,
6 k_2 , respectively. The polynomial power curve is fairly linear for the wettest stations, and
7 curvilinear for drier environments (Fig. 1). It is shown that the coefficient of variation (as
8 exemplified by the 0.4 CV line on Fig. 1, above which are located all low-rainfall stations)
9 systematically overestimates rainfall variability under dry conditions. The polynomial fit is more
10 efficient at differentiating highly/ weakly variable stations.

11 In a second step, we define the rainfall amplitude index (RAI) as the ratio between the actual
12 standard-deviation at each station and the theoretical value σ_e obtained from the empirical best fit.
13 Thus, a RAI of one at a given station means that the rainfall variability at this station is close to
14 average.

15 **3.2. Patterns of rainfall variability**

16 To depict the spatial patterns of rainfall variability, the network of stations has been first divided
17 into tropical (23°S-23°N) and extra-tropical subgroups. For each subgroup, and for successive
18 classes of mean annual rainfall, the standard-deviation is shown on Fig.1 for tropical stations as
19 red dots and line, and for extra-tropical stations as black dots and line. There is a gap between the
20 two subgroups, particularly under semi-arid and sub-humid environments (about 250 to 1000
21 mm). In this range, tropical stations display much larger interannual rainfall variability than their
22 extra-tropical counterparts. For a given mean rainfall amount, the standard-deviation is 25 to 50%
23 higher in the tropics than in the extra-tropics. A first possible explanation for this difference could
24 be that extra-tropical stations tend to have rainfall scattered over the year, hence a greater chance
25 to compensate a high rainfall amount by a lower one a few months later. Reciprocally, in much of
26 the tropics rainfall is concentrated over a well-defined (and sometimes short) rainy season (Mc
27 Gregor & Nieuwolt, 1998). To test whether this hypothesis could explain the higher variability of
28 the tropics, a good way is to consider interannual variability on a monthly basis.

29 The same scatter-plot as in Fig.1 is thus shown for monthly instead of annual rainfall amounts
30 (Fig.2). For mean rainfall between 25 and 125 mm, there is still a discernible difference between
31 tropical and extra-tropical stations. Variability in the extra-tropics tends to be much lower. The

1 reverse is found above 200 mm, but the difference between the two sets of stations is not
2 significant. This is a demonstration that the larger interannual variations of annual rainfall in the
3 tropics are not an artefact caused by a greater seasonal concentration.

4 In order to better apprehend the spatial patterns of rainfall variability, the RAI for annual rainfall
5 has been mapped (Fig.3). Besides the overall lower precipitation variability which is
6 characteristic of the middle and high latitudes, the map reveals large contrasts within the tropical
7 zone. Tropical drylands generally display relatively high rainfall variability. However, these areas
8 are not as uniform as the image conveyed by maps of the coefficient of variation, which
9 exaggerate rainfall variability in drylands. Interannual variability is high in Somalia, Australia
10 and North-West India, but moderate in parts of the central Sahel. This is contrary to general belief
11 but in accordance with Le Houérou (2006), who noted that Sahelian precipitation is less variable
12 than that of the East African drylands.

13 An example of the unequal level of rainfall variability is provided by the comparison of 3 stations
14 belonging to the African drylands (Fig.4). Hombori (Mali), Garissa (Kenya) and Okahandja
15 (Namibia) have a mean annual rainfall between 342-376 mm over the period 1951-2000.
16 However, their RAI are markedly different. Hombori (RAI = 1.0), in the west African Sahel is by
17 far the station exhibiting the most reliable rains. Garissa and Okahandja (RAI= 1.6 at both
18 stations) have experienced annual rainfall in excess of 600 mm in 7 and 2 occasions, respectively,
19 while at Hombori this amount was never reached during the same 50 years. Similarly, rainfall
20 below 120 mm has been recorded at least twice in the two former stations, but never at Hombori.
21 Though crops in the Sahel have been impacted by drier conditions starting from the 1970s, it
22 should not be forgotten that rain fed agriculture is commonly practised in the region even at
23 relatively low mean annual rainfall amounts, whereas other parts of the tropics (including East
24 Africa) with similar mean annual rainfall do not generally bear crops (Ellis & Galvin 1994, Le
25 Houérou 2006). This is partly because of the rainfall concentration over a few months, and also
26 because of a lower interannual variability of the rains. A comparison of monthly rainfall
27 variability between Eastern and Sahelian Africa confirms that above a mean rainfall of 50 mm
28 there are much larger interannual variations in Eastern Africa (Fig.5). Ellis & Galvin (1994)
29 noted that this higher rainfall variability in East Africa induces non-equilibrium ecosystem
30 dynamics, which make unsuitable some concepts of agricultural and natural-resource
31 management. Additionally, it increases the risk of crop losses, and therefore restricts the area
32 devoted to rain fed agriculture.

1 Reciprocally, wetter climates do not always have the regularity suggested by CV maps. For
2 instance, parts of southern Indonesia, southern Mozambique and the central Pacific islands
3 exhibit quite large interannual rainfall variations. On the contrary, apart from most of the extra-
4 tropics, some tropical regions like southern China, the Congo Basin and much of the Amazon
5 Basin display low RAI values (Fig.3).

6 On the whole, these patterns closely resemble those found by Dewar & Wallis (1999). They
7 noted that the geographical patterning of rainfall variability for the region they studied (30°S-
8 30°N) was far from random. They found that oceanic islands have a strong tendency toward high
9 variability. As displayed in the present study (Fig.3), they also noted, like Conrad (1941), that
10 most high variability regions are located near coasts, and continental interiors tend to be areas of
11 reduced variability. This is evident in Africa, including in the Sahelian belt (see the difference
12 between coastal Senegal / Mauritania and inland stations in Mali, Niger or Chad, at the same
13 latitude). The delineation of the extra-tropical regions having a lower rainfall variability is also
14 consistent with Nicholls & Wong (1990) who noted a decrease of rainfall variability with
15 latitude.

16 A thorough explanation of the causes of these spatial patterns in climate variability is not the
17 topic of this study. However, we postulate that the sensitivity to sea-surface temperature
18 variations plays a major role. Regions with a higher interannual variability are often those where
19 large-scale ocean-atmospheric modes of climatic variability have the strongest impact. In
20 particular, El-Niño-Southern-Oscillation (ENSO) is known to strongly affect rainfall amounts
21 over parts of Indonesia, Australia and in some Pacific islands (Ropelewski & Halpert, 1987). The
22 latter are shown to exhibit abnormally high interannual variability of its precipitation. The ENSO
23 influence is combined to that of Walker-type, large-scale circulation anomalies across the Indian
24 Ocean to explain the large rainfall variability also experienced in East Africa (Philippon et al
25 2002, Hastenrath & Polzin, 2003, Black et al 2003). By contrast, precipitation over the Congo
26 Basin is known to be quite insensitive to global SSTs in general, and ENSO in particular
27 (Camberlin et al 2001, Friederichs & Paeth 2006). Nicholls & Wong (1990) demonstrated that
28 low latitude stations display a greater rainfall variability when they have a strong relationship
29 with ENSO. Peel et al. (2002) found that the coefficient of variation of annual precipitation was
30 5-25% higher in “ENSO” than in “non-ENSO” zones, after having stratified the stations
31 according to Köppen climate types. Koster et al. (2000) published maps of the rainfall variance
32 explained by SST variability, based on ensemble simulations performed on the NASA Goddard
33 Earth Observing System-Climate atmospheric model. There are coincidences with Fig.3 (e.g.,

1 strong SST forcing and high rainfall variability in the Brazilian Nordeste and Western Sahel), but
2 some areas known from the observation to be strongly affected by SST variations, such as East
3 Africa, were not identified as such in Koster et al. (2000) simulations, probably due to model
4 deficiencies.

5 On the whole, there is strong indication that sensitivity to SST variability explains much of the
6 spatial inequalities in rainfall variability. In extra-tropical regions, the weaker SST forcing
7 reduces the seasonal persistence of monthly rainfall anomalies, hence a damped interannual
8 variability compared to those regions whose climate is influenced by highly persistent modes of
9 variability, such as ENSO. Other factors may also contribute to the spatial discrepancies. For
10 instance, some regions with relatively high rainfall variability, without necessarily being
11 drylands, are those affected by tropical cyclones, such as part of the Caribbean, southern
12 Mozambique, Viet Nam and part of the Philippines. However, not all cyclonic areas are affected,
13 and the effect is smaller than that associated with the SST control on rainfall. Contrary to higher
14 latitude regions, where « oceanic » climates tend to have a dampening role on rainfall variations,
15 the ocean impact in the low latitudes (either direct or indirect) is in the direction of enhanced
16 rainfall variability.

17 4. RELATIONSHIP WITH DEMOGRAPHIC VARIABLES

18 4.1. Population density

19 Possible effects of rainfall variability on demography are now considered. It is first questioned
20 whether higher climate variability is detrimental to human occupation. Though the above African
21 examples suggest a potential incidence of rainfall variability on land use and farming systems, it
22 remains to be assessed whether population densities are impacted at global scale. Gridded
23 population densities for the year 2000, at a 0.25° latitude and longitude resolution, are extracted
24 from the Columbia University GPWv3 data set. RAI is plotted for different classes of population
25 density (Fig.6). Although rainfall variability tends to be slightly higher in tropical areas with a
26 low population density, on the whole the relationship between density and variability is not
27 significant, either for the tropics or the extra-tropics. This is still true when the data are stratified
28 according to the mean annual rainfall (not shown). Some relatively dry areas experiencing a high
29 variability (Fig.2) show either high (Brazil Nordeste, north-western India) or low (Somalia,
30 Namibia) population densities. Reciprocally, there is a higher rainfall variability in Java than in
31 Thailand and south-western China, whereas all these areas are densely settled.

1 The absence of any relationship between population densities and precipitation variability, at
2 global scale, can be interpreted in two different ways :

3 (i) there is an actual disconnection between the two features, which means that in high
4 variability areas societies often successfully adapted to these more risky environments.
5 Strategies aiming at reducing the impact of precipitation variability, such as irrigation,
6 mixed cropping, may be able to feed a larger number of people, while even in “low risk”
7 areas extensive land management systems only tolerate low densities. For instance, agrarian
8 societies in northern Peru have in the past developed social and technological responses to
9 environmental uncertainty (Dillehay & Kolata 2004).

10 (ii) the impact of rainfall variability on human densities is found at regional level only, and is
11 masked out by other factors at global scale. In insular Southeast Asia and the western
12 Pacific, Dewar (2003) noted that from west to east, in conjunction with increasing
13 interannual rainfall variability, subsistence systems shift from grain crops to root and tree
14 crops. He suggested that this variability limited the suitability of annual crops and increased
15 dependence on long-lived plants. We can add that annual crops both require and permit
16 higher population densities, thus the associated west to east decreasing population density
17 gradient amplifies the west to east increasing variability gradient. In Africa, there are
18 contrasted subsistence systems between the East and West African drylands. As depicted
19 above, at similar mean annual precipitation amounts, crops are much less common in East
20 Africa, where pastoral, lower density communities prevail. This contrast reflects the greater
21 (smaller) intra-annual and interannual rainfall variations of East (West) Africa (Ellis &
22 Galvin 1994). Elsewhere, however, there are numerous examples of relatively high human
23 densities in otherwise high-variability areas, such as Northeast Brazil, parts of India,
24 whereas several low-variability areas, especially in the Amazonian and Congo rainforest,
25 have very low densities. This may overshadow any regional relationships between human
26 density and rainfall variability.

27 These results on rainfall variability do not imply that human population distribution is
28 disconnected from rainfall. Consistent with Small & Cohen (2004), global maps of mean annual
29 rainfall and population densities show that below a certain amount the joint decrease of
30 population densities and precipitation is a recurrent feature around the globe, except in a few
31 cases where exogenous rivers provide water resources in otherwise dry environments. This
32 pattern is particularly obvious in sub-saharan Africa (Le Blanc & Perez 2007). Although in some
33 regions (e.g., western Pacific, African drylands) rainfall variability may play a significant part in

1 the contrasted human densities, it is believed that in the long run (present-day densities result
2 from demographic dynamics integrated over a long period of time) and at global scale other
3 factors (natural, political, historical, socio-economic...) are overwhelming.

4 **4.2. Demographic growth**

5 A similar analysis is carried out by considering recent population dynamics (1990-2000 growth
6 rates; Fig.7). It is found that in the tropics, the regions where the demographic growth is small, or
7 even negative, often display high interannual rainfall variability (red dots and line on Fig.7).
8 Though there is some uncertainty about the precision of the population data, the fact that a similar
9 pattern is found for each continent (colour dashed lines on Fig.7 depict tropical Africa, tropical
10 Asia and tropical America) is an indication that this result is relatively robust. Several high
11 variability regions, such as Northeast Brazil, Mauritania, Somalia, actually display a demographic
12 growth slower than that of the other tropical regions. Between 1991 and 2000, the four Brazilian
13 northeastern states of Paraiba, Rio Grande do Norte, Pernambuco and Alagoas had a 11%
14 population growth while in the rest of Brazil it was 16%. In Mauritania, annual rural growth rates
15 between 1970 and 1990 have been as low as 0.9%, compared to a West African average of over
16 2%, based on data from the United Nations Urbanization Prospects (United Nations 2007). High
17 rainfall variability sometimes combines with political instability to generate low population
18 growth rates, as in Timor and Somalia.

19 These slower growth rates may be attributed to two potential factors: a lower natural growth
20 (especially due to a higher mortality) and/or out-migration. The data used in this study do not
21 enable to distinguish between these two causes. However there is evidence from previous studies
22 that both factors may contribute.

23 Mortality associated with climatic catastrophes like droughts and tropical cyclones is a recurrent
24 feature in low-income countries (Kidane 1989, Devereux 2002, Shultz et al 2005), though in the
25 last decades national and international responses to humanitarian crises tended to reduce
26 fatalities. Evidence has also been provided of fertility decrease as a consequence of drought in
27 Mali (Pedersen, 1995) and Ethiopia (Ezra, 2001). The increase in mortality is relatively short-
28 lived, with no real confirmation of long-term effects (Alderman et al 2006, Song 2009). However,
29 recurrent rainfall deficits may affect the natural growth, especially through malnutrition which
30 has a direct death toll (50% of infant deaths worldwide are attributable to malnutrition) or
31 increases the risk of fatal outcome of severe diseases (Ehrhardt et al 2006). Similarly climate
32 variability associated with ENSO is known to result in epidemics in several parts of the tropics

1 (Patz et al. 2005). As shown above and discussed in Nicholls & Wong (1990), climate variability
2 is higher in regions impacted by ENSO. It is therefore conceivable that regions displaying a
3 higher probability of rainfall exceeding certain thresholds (as in part of the tropics), and where
4 the population is more vulnerable (as in many developing countries, Hunter 2005), experience
5 reduced natural demographic growth rates.

6 The other factor accounting for the relationship between rainfall variability and population is
7 migration. It is suggested that a greater climatic risk triggers out-migration, mainly at times when
8 a given climate hazard (such as a drought) exceeds the coping range. Demographic data analysed
9 by Ezra (2001), for Ethiopia, and Henry et al. (2003), for Burkina Faso, demonstrate a connection
10 between out-migration and the occurrence and repetition of droughts. This process applies to
11 several parts of West Africa (Lalou 1996, Mounkaila 2004, Faure 2005). In some cases like
12 Ethiopia, migration from regions with unreliable rainfall has been organised or even forced
13 (Comenetz & Caviedes 2002). At the scale of sub-Saharan Africa as a whole, it was shown that
14 the interannual variations of the rains between 1981 and 2002 were very significantly correlated
15 with civil conflict onset (Hendrix & Glaser 2007). The net result is cross-border refugee flows,
16 for which it is difficult to separate climatic and political motivations. However, climate migrants
17 generally move domestically rather than internationally (Afifi & Warner 2008, Brown 2008).

18 Migration triggered by adverse climatic events may not necessarily be reflected in the data
19 analysed in this study, since in some regions it may mostly be a rural-urban migration, therefore
20 undetectable from aggregated district or regional statistics such as those used above. The fact that
21 the relationship between demographic growth and rainfall variability is detected even with no
22 prior separation of rural and urban populations gives further credit to the hypothesis of an
23 incidence of rainfall variability on population growth.

24 Of course the lower growth / higher variability relationship should not be considered as a
25 deterministic one, and there are a number of departures to this trend, climate being in many
26 instances a minor trigger of population dynamics. In India for instance, the north-westward
27 gradient to higher rainfall variability (Fig. 3) is not paralleled by a decrease of the demographic
28 growth rate, the smallest population growth rates being actually found in the south. A variety of
29 reasons explain this pattern (female education, health improvements etc...). In the north, in
30 addition to the higher natural growth rates which explain the strong population rise, the low
31 rainfall reliability may have been partly compensated by the development of irrigation schemes.
32 This has limited out-migration, or even encouraged in-migration, as in Haryana and Punjab. More
33 generally, with respect to migrations, environment is never the single factor which pushes people

1 to migrate , except in some critical situations (Auclair et al 2001). Even disasters do not always
2 trigger migrations (e.g., Findley 1994, Pedersen 1995, Paul 2005). Therefore, a large rainfall
3 variability does not necessarily mean a slower demographic growth.

4 It is also assumed that climate variability does not lead to migration or demographic changes in a
5 linear way (Kniveton et al 2008). A study carried out in Burkina Faso shows that the interaction
6 between the long-term average climate conditions (mean annual rainfall) and yearly variations
7 needs to be considered in order to best understand the relationship between rainfall and child
8 mortality (Dos Santos & Henry 2008). In the drier parts of this country, child mortality tends to
9 increase when less than 85% of the normal amount of rain falls during the year, in conjunction
10 with malnutrition and income reduction. By contrast, the risk of child mortality is increased in the
11 wettest rainfall region (more than 900 mm) when the rains are more abundant, possibly as a result
12 of the development of vector-borne diseases (Dos Santos & Henry 2008).

13 Somehow, the latter study also points to the fact that the effect of rainfall variability is not
14 restricted to dry environments. The measure of rainfall variability used in the present study is
15 actually independent from the mean rainfall amount, thus suggesting that the relationship with
16 population growth encompasses both dry and wet contexts. Fig.7 provides evidence that, on
17 average in the tropical zone, slow growth areas tend to have a high rainfall variability. Although
18 caution needs to be exerted when discussing the impact of climate variability on population, the
19 above literature review supports this evidence. Two features are likely to explain the absence in
20 the extra-tropics of such a negative relationship between rainfall variability and population
21 variation : (i) the extra-tropics are dominated by developed countries which are less dependant on
22 agriculture and are less vulnerable to crop failures, as they have adequate resources and
23 infrastructure to cope with the effects of rainfall variability ; (ii) rainfall variability itself is lower
24 than in the Tropics, and does not show as large spatial contrasts as in the Tropics.

25 As part of the questioning on human-induced climate change, resulting from enhanced
26 greenhouse gases concentrations, there is concern about a possible increase of climate variability
27 in the coming decades. Räisänen (2002) showed that at global-scale, simulated rainfall variability
28 in the event of doubled CO₂ concentrations would generally change in proportion of mean
29 rainfall. Some cases of rising variability, in areas expected to get stable or even decreasing
30 rainfall amounts, are nevertheless projected, as in many subtropical regions and in tropical South
31 America. An increased variability is a subject of concern for tropical areas where vulnerability to
32 natural hazards is often high, as suggested by the above noted relationship between demographic
33 growth and precipitation variability. Vulnerability itself is not a once-for-all fixed entity (Ribot et

1 al 1996). It adjusts to the socio-economic background, as exemplified by some Masai groups in
2 East Africa, whose high initial resilience tends to regress (Galvin et al. 2004). By contrast we
3 may expect resilience to increase where, for example, reliable seasonal climate forecasts become
4 available, and appropriate preventive action is taken.

5 5. CONCLUSION

6 Using long-term precipitation series, this study demonstrates that the tropics, on average, show
7 larger rainfall interannual variations than the extra-tropics, for similar mean rainfall amounts. The
8 difference is particularly noticeable in semi-arid to sub-humid environments (mean annual
9 rainfall between 250 and 1000 mm). However, the tropics also display strong contrasts. The
10 largest amplitude in interannual rainfall variations tends to be found in regions where rainfall is
11 highly dependant on large-scale sea-surface temperature variations. This includes several semi-
12 arid monsoon regions, as well as regions most affected by shifts in Walker-type circulation, in the
13 Pacific and Indian Ocean regions. Inland regions generally display a weaker interannual
14 variability.

15 Though population densities do not show any systematic relationship with rainfall variability, it is
16 found that demographic growth rates in the recent decades have some connection with the
17 amplitude of rainfall variations. This feature is found for the tropics as a whole and for each
18 continent individually, but it does not apply to the extra-tropics. Regions showing larger
19 interannual rainfall variability tend to have lower demographic growth rates between 1990 and
20 2000. The relationship between climate variability and demography is suggested to illustrate the
21 combined effect of changes in natural demographic growth (especially enhanced mortality) and
22 out-migration from the regions affected by recurrent precipitation hazards such as droughts or
23 floods. Though out-migration does not necessarily arise as a result of adverse climatic events,
24 these results tend to show that at global scale the net effect of tropical climate variability on
25 population growth takes the form of a distinctive signal. This provides further significance to the
26 affirmation by Hulme et al. (1999) that in the future a valid assessment of climate-change impacts
27 needs to incorporate the combined effects of human-induced climate change and natural climate
28 variability.

29

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FIGURES CAPTIONS

Fig.1 : Interannual variability of annual precipitation, for 12335 stations extracted from the GHCN data base (Peterson & Vose 2001). Standard-deviations and mean annual rainfall are computed for stations having at least 40 years of complete data between 1901 and 2005. For reference, the green line corresponds to a coefficient of variation of 0.4. The upper red solid line is the median for tropical stations (23°S - 23°N) ; the lower black solid line is the median for all other stations. Vertical bars are the interquartile range of the standard-deviation for successive bins of mean annual rainfall. The double thin line shows the polynomial fit used for the computation of the RAI.

Fig.2 : same as Fig.1, but for monthly rainfall.

Fig.3 : Relative Amplitude Index (RAI) of the interannual variability of annual rainfall amounts.

Fig.4 : Frequency distribution of annual rainfall amounts (1951-2000) at three semi-arid African locations : Hombori (Mali, mean rainfall 376 mm) ; Okahandja (Namibia, 342 mm) ; Garissa (Kenya, 370 mm).

Fig.5 : same as Fig.2, but for all the stations from East Africa (5°N - 5°S , 35 - 45°E) and the Sahel (11 - 19°N , 20°W - 20°E).

Fig.6 : Relationship between population density (2000) and the rainfall amplitude index (RAI). The squares correspond to the mean values obtained for successive density classes. Empty (filled) symbols correspond to extra-tropical (tropical) locations.

Fig.7 : Relationship between annual population growth rate (1990-2000) and the rainfall amplitude index (RAI). The squares correspond to the mean values obtained for successive growth rates classes. Black (empty) symbols, and the double line, correspond to extra-tropical locations. Red symbols correspond to tropical locations. The dashed lines correspond to tropical Latin America, tropical Africa and tropical Asia / Pacific islands.

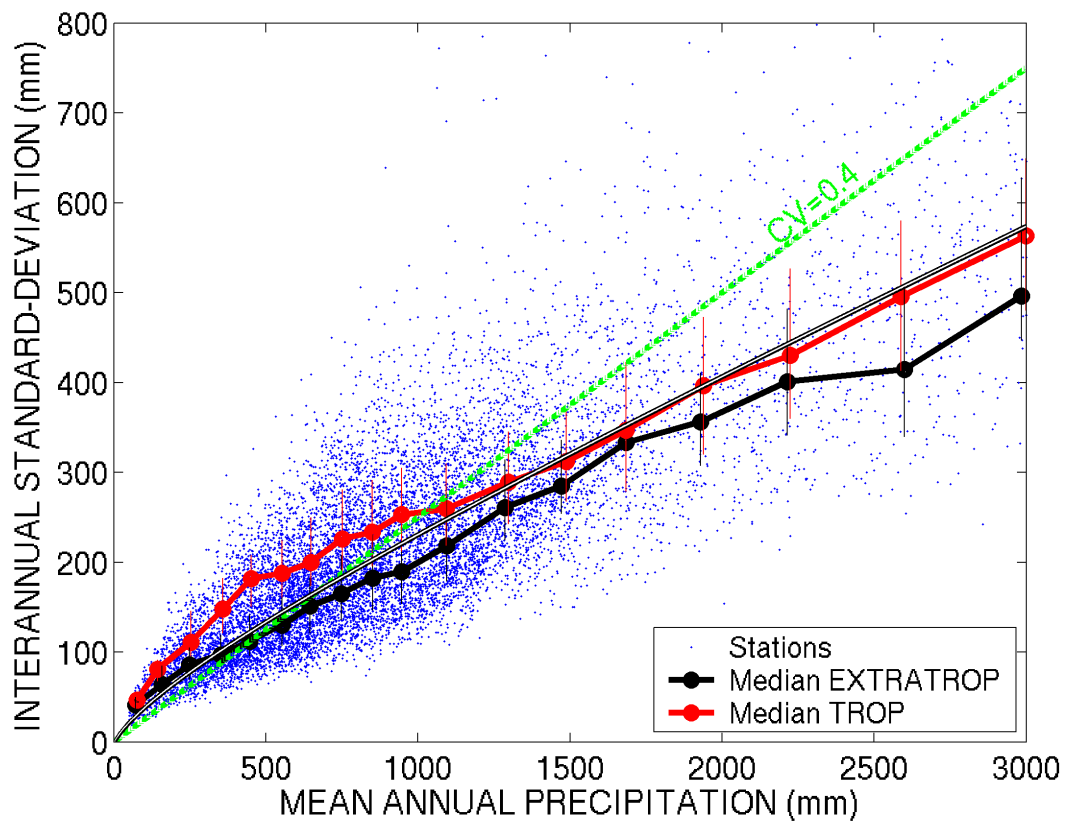


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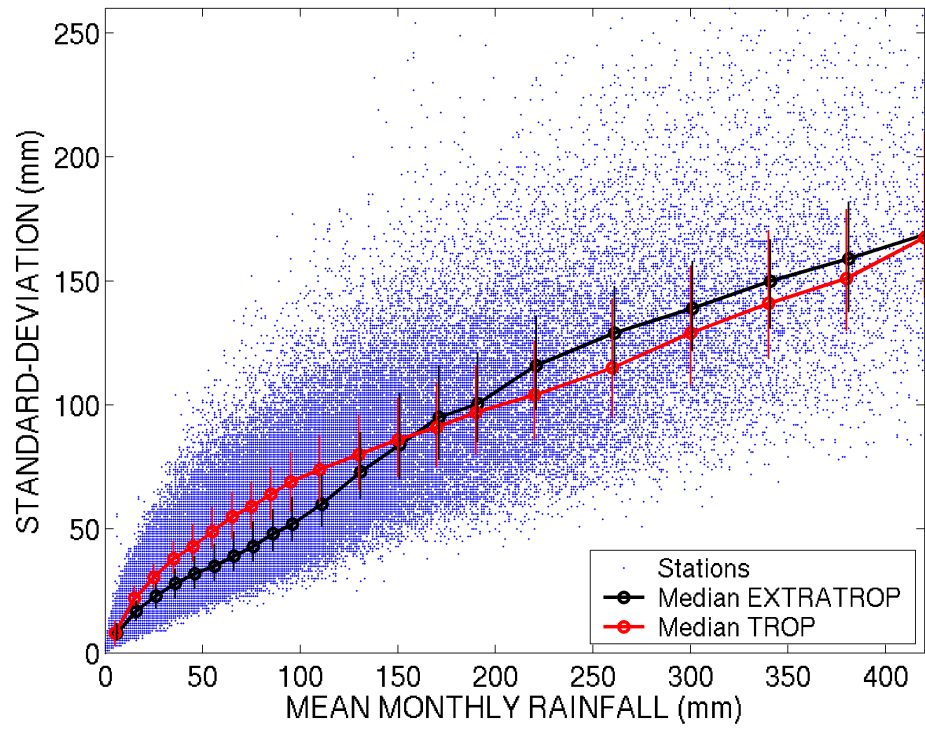


Fig.2 : same as figure 1, but for monthly rainfall.

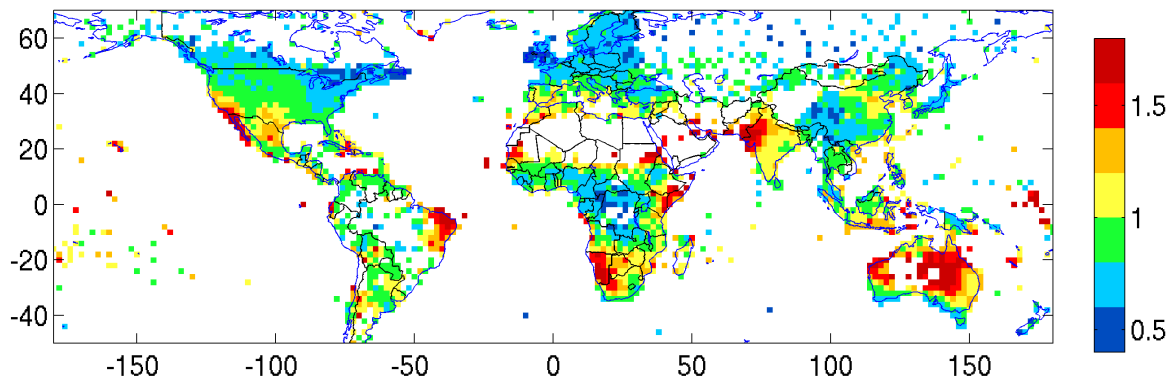


Fig.3 : Relative Amplitude Index (RAI) of the interannual variability of annual rainfall amounts.

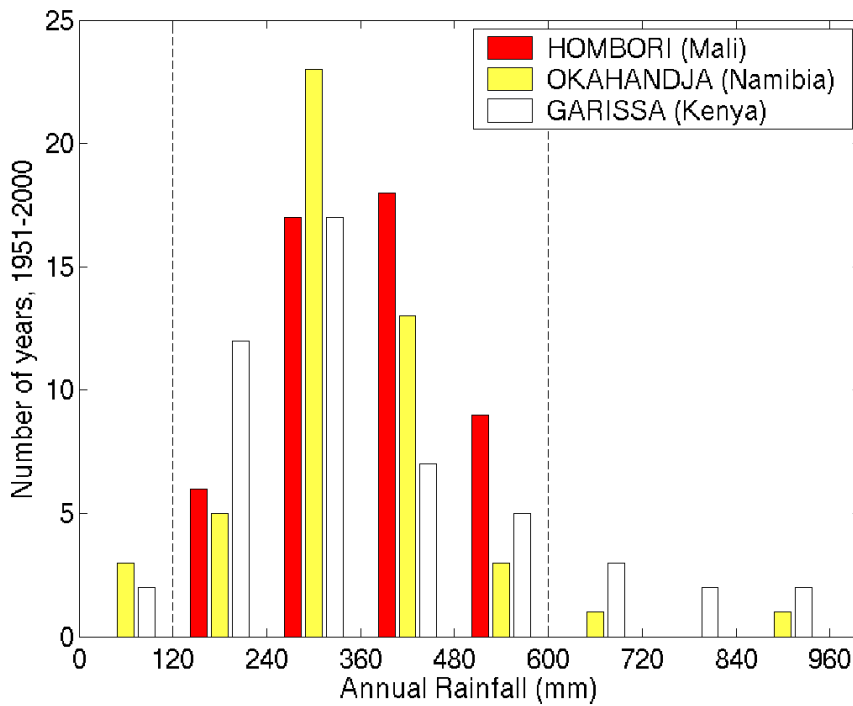


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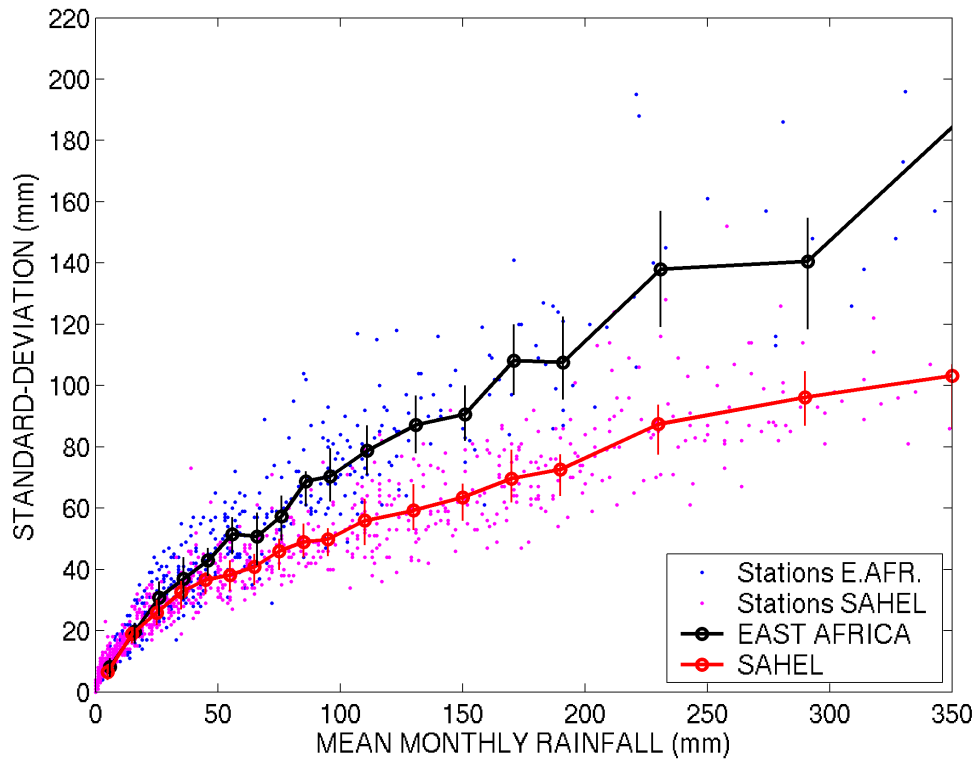


Fig.5 : same as figure 2, but for all the stations from East Africa (5°N - 5°S , 35 - 45°E) and the Sahel (11 - 19°N , 20°W - 20°E).

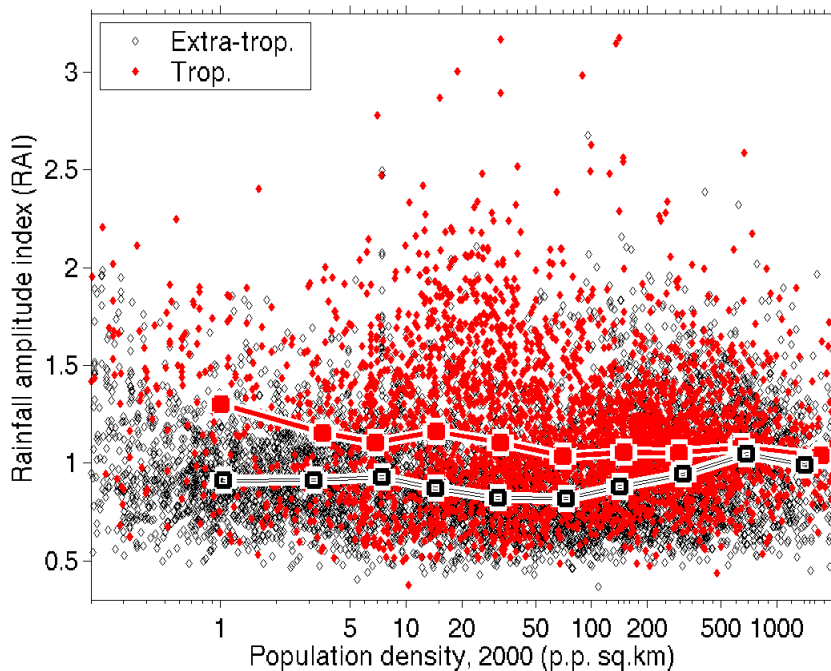


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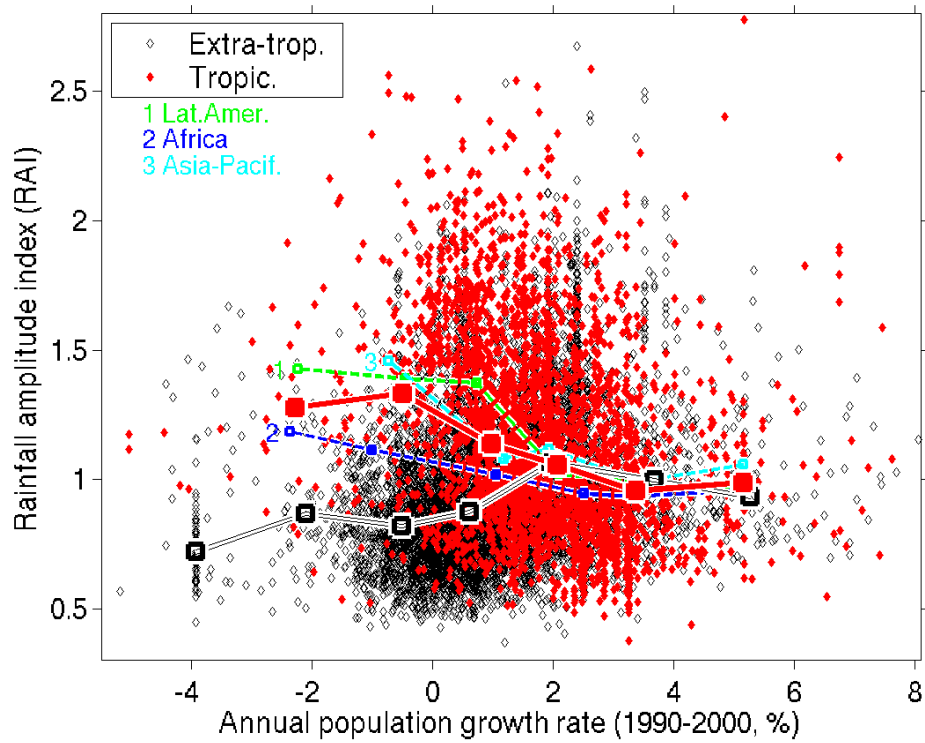


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