A simple set of indices describing the Tropical Rain Belt over central and southern Africa

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Abstract
Understanding the variability of the Tropical Rain Belt (TRB) in Africa is a challenging task due to complex interactions among global, regional and local drivers of rainfall. A simple method that provides a set of three indices describing large-scale spatial–temporal characteristics of the TRB over central and southern Africa is introduced. The method is based on approximation of a meridional cross-section of monthly mean precipitation by the Gaussian function. The three parameters of the Gaussian function correspond to the three TRB indices, namely: intensity, location and width. It is shown how the TRB indices can be used for describing the climatology of the TRB, for estimating observational uncertainties, and for evaluating the ERA-Interim and ERA5 reanalyses against observations. Simplicity and flexibility of the method allow using the TRB indices for a wide range of applications, including evaluation of climate models and assessment of projected climate change in tropical rainfall.

Keywords
Africa, climate, index, proxy, rain belt, variability

1 INTRODUCTION

The Intertropical Convergence Zone (ITCZ) is a prominent feature of the tropical weather and climate and commonly associated with the Tropical Rain Belt (TRB) formed by convective activity (Krishnamurti et al., 2013). Although the TRB does not always spatially coincide with the ITCZ over land (Nicholson, 2009; Žagar et al., 2011), at global scale they are tightly coupled and follow the seasonal progression of the Sun. At regional scale, the seasonal progression of the ITCZ and TRB can be modulated by smaller-scale processes making their regional behaviour much more complex than an idealised seasonal progression. A typical example of such regional modulation is the abrupt northward shift of the West African monsoon rainfall in late June (Sultan and Janicot, 2000).

Rainfall, brought by the seasonal migration of the TRB, is the main source of water for many sectors of economy and human well-being in Africa (e.g., rain-fed agriculture and rural/urban water supply). Seasonal amount of rainfall in Africa undergoes large interannual, decadal and multi-decadal variability that has a strong impact on water availability at regional scale: for example, a dry period around 1980s in the Sahel (Nicholson, 2013; Nicholson et al., 2018) and increasing frequency of droughts in the recent years in eastern Africa (Masih et al., 2014). Understanding drivers of rainfall variability in Africa and assessing their possible future changes under global warming can be facilitated by proxies describing temporal–spatial characteristics of the ITCZ and/or TRB.

A number of such proxies, of different levels of complexity, have already been developed and are based on:
outgoing longwave radiation (Shangcheng, 1987), highly reflective clouds (Waliser and Gautier, 1993), low level wind convergence (Zagar et al., 2011; Berry and Reeder, 2014) and precipitation (Zhang, 2001; Nikulin et al., 2012; Adam et al., 2016). However, not all of them can easily and consistently be applied to different datasets as observations, reanalyses and climate models. The simplest proxies are based on precipitation, as this variable is widely available across different datasets and directly related to the TRB in contrast to, for example, low-level wind convergence. Simple one-dimensional proxies usually provide latitude of maximum of zonally- or regionally-averaged precipitation in the tropics (Zagar et al., 2011) while more complex two-dimensional ones also include longitudinal position of the TRB over a region (Nikulin et al., 2012). The latter approximates the position and width of the TRB over Africa by calculating the geographical position of maximum precipitation in the centre of the rain belt and the 1 mm·day⁻¹ mean intensities on either flank of this maximum. Continuing work on characteristics of the TRB, we present a simple set of three one-dimensional indices, based on monthly mean precipitation, describing location, intensity and width of the TRB over central and southern Africa.

2 | DATA

We use in our analysis three common gauge-based precipitation gridded datasets at 0.5° horizontal resolution. They include: (a) the Global Precipitation Climatology Centre, GPCC, version 8 (Schneider et al., 2014), (b) the Climate Research Unit Time-Series, CRU, version 4.01 (Harris et al., 2014), and (c) University of Delaware, UDEL, version 5.01 (Legates and Willmott, 1990). Precipitation from the two latest European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses—ERA-Interim (Dee et al., 2011) and ERA5 (Hoffmann et al., 2019) are also included for evaluation.

3 | METHOD

To estimate the TRB indices, we first calculate a meridional cross-section of monthly mean precipitation averaged over 20°–30°E and then the Gaussian function is fitted to the cross-section. Selection of the 20°–30°E belt is justified by the longest meridional extension of the cross-section over the African continent and by the availability of the gauge-based gridded data sets over land only. However, the width and position of the belt is flexible and can be adjusted accordingly to any region of interest. The nonlinear least-square optimization algorithm is used to fit the Gaussian function to the cross-section. For each month, the three parameters of the Gaussian function correspond to intensity, location and width of the tropical rain belt over central and southern Africa.

4 | RESULTS

First of all, we evaluate how good the Gaussian function is for describing the meridional cross-section of the TRB over central and southern Africa. Taking into account the seasonal migration of the TRB during the year, we select the 35°S–25°N latitudinal range of the cross-section for fitting the Gaussian function (larger box in Figure 1a and e). The coefficient of determination ($R^2$) is used as a measure of the goodness of fit. The annual cycle of the $R^2$ coefficient (Figure 1a, green) shows that the best fit is found from May to September (climatology is about 0.95) with the smallest interannual variability in this period. The worst fit (climatology around 0.85) occurs in March–April and October–November when the interannual spread also reaches its maximum. In a few individual months, the $R^2$ values can drop to 0.6, indicating that the Gaussian function is not always a good approximation of the meridional cross-section of the TRB.

To investigate what can lead to lower values of the $R^2$ coefficient, Figure 1b–d shows the meridional cross-section of the TRB and its Gaussian fit when the worst fit was found for 3 months: November, January and July. In contrast to months with the best fit when the meridional cross-section of precipitation has an almost perfect Gaussian shape ($R^2$ is above 0.95, not shown), the lowest $R^2$ values are associated with a more complex shape of the cross-section. In January 1995 (Figure 1b, $R^2$ is 0.71) the Gaussian fit cannot describe a sharp maximum at about 13°S and the second maximum at the southern flank of the TRB. The lowest $R^2$ value (0.6) is found in November 1996 (Figure 1d) when the cross-section has double maxima between 10°S and the Equator and the southernmost maximum near 35°S has almost the same magnitude as the double maxima near the Equator. In July 1983 (Figure 1c), a maximum at the southern flank does not impact the description of the TRB by the Gaussian function even if the $R^2$ coefficient decreases to 0.8. For all three cases, there is an additional maximum in precipitation south of 20°S in contrast to the best-fit months when both flanks of the TBR smoothly approach zero (not shown). In austral summer (Figure 1b and d) the southern flank of the TRB over southern Africa is not a direct extension of the ITCZ-related precipitation but rather represents precipitation related to the South Indian Convergence Zone (SICZ). The SICZ-related precipitation is generated by synoptic-scale Tropical
Temperate Troughs (TTTs; e.g., Washington and Todd, 1999) originated in the sub-tropics, merging with the TRB in its southernmost position. However, it is not clear what leads to a similar situation (maximum in precipitation south of 20°S) during the austral winter, July 1983 (Figure 1c). It is not surprising that the Gaussian function cannot accurately approximate such complex shapes of the meridional cross-section of precipitation. We need to note that a clear separation of the SICZ-related precipitation in the south and the ITCZ-related one in the north is not straightforward.

In order to isolate the precipitation maximum south of 20°S, we also test the Gaussian fit to the 25°S–25°N range of the 20°–30°E GPCC rainfall cross-section for 1981–2010. Climatological annual cycle of $R^2$ is represented by thick lines, individual years by small dots and statistics by whisker boxes. (b–d) The GPCC rainfall cross-section (red dots) and its Gaussian fits for 3 months with the worst fit over 35°S–25°N. The TRB intensity (Int), location (Loc) and width (Wid) for 35°S–25°N are shown in upper-left corners (green) and for 25°S–25°N in upper-right corners (blue). The goodness of fit is shown in parentheses ($R^2$).

The Gaussian fit to 25°S–25°N shows a flatter annual cycle with higher values and reduced interannual variability all year round. These improvements are especially noticeable from October to April—the period when $R^2$ has the lowest values and largest interannual variability if the 35°S–25°N range is used. The 25°S–25°N approach much better captures the shape of the meridional cross-section of precipitation in the tropics in January 1995 (Figure 1b) and in November 1996 (Figure 1d) than 35°S–25°N. Ignoring precipitation south of 25°S quite expectedly leads to much higher values of $R^2$: 0.89 vs 0.71 in January 1995 and 0.9 vs 0.6 in November 1996. Using 25°S–25°N instead of 35°S–25°N has no impact on the Gaussian fit in July 1983 (Figure 1c): the intensity, location and width are the same for both latitudinal ranges. An interesting detail is that even if in July 1983 both ranges result in the same Gaussian fit, the $R^2$ coefficient is higher for 25°S–25°N (0.95 vs
This shows that higher values of the coefficient of determination not always indicate a better fit. In general, we conclude that the Gaussian function is a good approximation of the meridional rainfall cross-section over Africa and choosing the 25°S–25°N latitudinal belt instead of 35°S–25°N provides a better fit. We also found that all subsequent results are not very sensitive to the latitudinal range chosen. Taking 25°S–25°N leads to a slightly higher intensity, more northward position and smaller width of the TRB during November–March compared to 35°S–25°N. Moreover, the TRB indices for the two latitudinal ranges are highly correlated: 0.98 for the intensity, 0.99 for the location and 0.95 for the width.

Additionally, it is found that months with the lowest values of $R^2$ are sensitive to the choice of observational datasets. Applying the same methodology to other gridded precipitation products such as CRU and UDEL (not shown) brings different months with the lowest $R^2$ values. This difference across the datasets simply indicates observational uncertainties for individual months.

Figure 2 shows the annual cycle of the three TRB indices estimated for the GPCC dataset. The climatological mean of the TRB intensity varies from about 6 up to 7.5 mm day$^{-1}$ with the lowest values in June. The TRB intensity in individual months has a wider range from about 5 up to 10 mm day$^{-1}$ indicating large interannual variability. The TRB climatological location, as expected, has a pronounced annual cycle reaching 11–12°S in January and about 7°N in July. The smallest interannual variability is found in boreal summer and the largest one in boreal winter. The climatology for the third index describing the TRB width has maximum values (about 11–12°) in boreal winter while minimum (7°) occurs in June. The annual cycle of the interannual variability of the TRB width is similar to one of the TRB location: variability is larger in boreal winter and smaller in boreal summer.

![Figure 2](attachment:image.jpg)

**FIGURE 2** Tropical Rain Belt Indices (GPCC) estimated over central and southern Africa for 1981–2010: (a) intensity, (b) location and (c) width. Climatological annual cycle is represented by red line, individual years by dots and statistics by whisker boxes.

![Figure 3](attachment:image.jpg)

**FIGURE 3** Scatter plots for the TRB indices: (a) intensity and location, (b) intensity and width and (c) location and width. July–September months are represented by red dots, December–February by blue dots and other months by green ones. Correlation coefficient for each pair of the TRB indices (Corr) is shown on top of subplots (0.1 is statistically significant at the 0.05 significance level).
Relationship among the three indices, separated to July–September (JAS), December–February (DJF) and the rest of the year is shown in Figure 3. The JAS and DJF seasons are selected as examples when the TRB is in its northernmost and southernmost position. The intensity and location indices are slightly dependent of each other (Figure 3a), the linear correlation coefficient ($k$) between them is statistically significant but not high ($-0.35$). Similarly, no strong relationship ($k = 0.22$) is found between the intensity and width indices (Figure 3b). However, a strong dependence is found for the location and width indices with $k$ equals $-0.75$ (Figure 3c). The TRB has a pronounced tendency to be wider when located more southward and narrower when located more northward.

The three TRB indices describe large-scale features of the rain belt. Figure 4 shows how the large-scale indices are related to local rainfall correlating the indices with precipitation at each grid box for JAS and DJF. In JAS, the intensity index has a relatively small area with significant correlation concentrated in South Sudan and the Central African Republic (Figure 4f). Smaller patches of significant correlation are scattered across western and eastern Africa without a systematic pattern. In DJF, the intensity index significantly correlates with local rainfall over Zambia and the southern part of the Democratic Republic of Congo (Figure 4b). The location index shows a belt of the positive correlation stretching from western Africa to the Red Sea coast with a pronounced maximum over the eastern part of Chad and the western part of Sudan (Figure 4g). A more northerly position of the TRB is associated with more rainfall over a large region between about 7° and 15°N. The TRB location is strongly negatively correlated with local rainfall over almost all southern Africa in DJF (Figure 4c). The negative correlation is simply explained by negative latitudes south of the Equator. A more southerly position of the TRB results in more rainfall over the entire region. The width index behaves similar to the location one. In JAS, a wider TRB is associated with more rainfall in the Sahel/Sahara region (Figure 4h) while a wider TRB in DJF is associated with more rainfall in southern Africa (Figure 4d). These correlation patterns are in line with the results shown in Figure 3 where relationship between the location and width indices is very pronounced.

A practical example on how the TRB indices can be used for assessment of observational uncertainties is shown in Figure 5 presenting the climatological annual cycle for the three gauge-based observational datasets and ERA-Interim and ERA5 reanalyses. The gauge-based datasets have in general good agreement on the TRB intensity (Figure 5a).
CPCC and UDEL show similar annual cycle with some difference in magnitude for the April–August period while CRU has more contrasting differences with respect to GPCC and UDEL in individual months. The shape of the annual cycle for ERAINT is similar to the observations but the TRB intensity is strongly overestimated all year round. Too intense precipitation in Africa is a well-known feature of the ERA-Interim reanalysis (Dee et al., 2011; Nikulin et al., 2012) and the TRB intensity serves as a simple diagnostic to detail this feature. The ERA5 shows good agreement with the observations from May to August but overestimates the TRB intensity from September to April. The gauge-based observational datasets agree well on the TRB location all year round (Figure 5b). In its turn ERAINT is consistent with the observations from May to October while during November–March the TRB in ERAINT does not propagate far enough south. This bias in the TRB location has completely disappeared in ERA5 which is in very good agreement with the observations. Both ERAINT and ERA5 represent well the TRB width, being within the observational uncertainties (Figure 5c). This evaluation example shows how simple it is to assess the ability of the two reanalyses to represent the TRB by applying the three TRB indices.

5 | CONCLUSIONS

We present a simple methodology to describe temporal–spatial characteristics of the Tropical Rain Belt over central and southern Africa. Fitting the Gaussian function to a meridional cross-section (20°–30°E) of monthly mean precipitation provides three parameters of the Gaussian distribution that represent, respectively, intensity, location and width of the TRB. An issue in our approach is the separation of the TRB related to ITCZ and precipitation related to SICZ in southern Africa as both can overlap. If maximum extension of the rainfall climatology (35°S–25°N) is used to estimate the TRB indices, the second SICZ-related maximum in precipitation south of 20°S leads to a worse fit. Our results show that selecting the 25°S–25°N latitudinal range instead of the 35°S–25°N one in general provides a better fit while the TRB indices for both latitudinal ranges are still highly correlated. If we use the 25°S–25°N latitudinal belt the Gaussian function is a good fit to the meridional cross-section of monthly mean precipitation, even if the fit is not perfect in a few individual months. Additionally, the goodness of fit for these months depends on observational datasets revealing the well-known problem with quality of gridded precipitation products in Africa, related to low density of the observational network. We also present a number of examples on practical use of the TRB indices: (a) describing the TRB climatology based on the GPCC dataset, (b) comparing the three observational datasets (GPCC, CRU and UDEL) and (c) evaluating the TRB characteristics in the ERA-Interim and ERA5 reanalyses.

The advantage of the methodology proposed is its simplicity and flexibility. The 20°–30°E cross-section is selected to cover most of the African continent in the north–south direction. However, the same methodology can be applied to other regions in the tropics. The main criterion here is approximately the Gaussian shape of a meridional cross-section of precipitation. If necessary, the methodology can be tuned to more complex shapes of meridional cross-sections of precipitation taking another function than the Gaussian one, for example in case of the double ITCZ. In addition, the methodology can be applied to the precipitation climatology instead of

FIGURE 5  Climatological annual cycle of the TRB indices for GPCC (blue), CRU (green), UDEL (red), ERAINT (black) and ERA5 (dark orange)
monthly means that also helps to reduce noise, although provides less details (e.g., no interannual variability). The TRB indices have already been used to describe climate process chains (Daron et al., 2019) and to assess the co-behaviour of climate processes over southern Africa (Quagraine et al., 2019).

The inclusion of this simple diagnostic in the Earth System Model eValuation Tool—ESMValTool (Eyring et al., 2016) and Regional Climate Model Evaluation System—RCMES (Lee et al., 2018) will be very useful for intercomparison of the rainfall variability over different TRB regions in the CMIP6 and CORDEX models. Practical application of the TRB indices can be very wide and includes (a) describing precipitation climatologies in the tropics and sub-tropics, (b) estimating observational uncertainties, (c) evaluating global and regional climate models and (d) assessing projected changes in tropical precipitation.

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