Evaluation of ENACTS-Rwanda: A new multi-decade, high-resolution rainfall and temperature data set—Climatology

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There were a large number of active meteorological stations in Rwanda prior to the mid-1990s and since around 2010. However, from around the time of the Rwandan genocide in 1994 throughout the late 2000s, the number of active stations was greatly reduced. To address temporal and spatial gaps in meteorological observation in several African nations (including Rwanda), the ENACTS (Enhancing National Climate Services) initiative reconstructs rainfall and temperature data by combining station data with satellite rainfall estimates, and with reanalysis products for temperature. Bias correction factors are applied to the satellite and reanalysis data and the merged final product is spatiotemporally complete from the early 1980s to the present at a high spatial resolution (4–5 km). This paper offers the first analysis of Rwanda’s climatology using this new ENACTS data set for 1981–2016.

The temperature and rainfall climatology of Rwanda are analysed at both annual and seasonal timescales as are the climatological influences of topography and regional winds. Climatology maps of mean rainfall intensity, rainy day, 5-day dry spell and extreme rain day (20+mm) frequency are shown, and spatial pattern correlations are analysed.

The rainfall climatology of Rwanda exhibits a clear seasonal bimodality typical of the East Africa region. Topography has a significant effect with the more mountainous, higher-elevation western part of the country being consistently cooler and wetter than the lower, flatter eastern region. Southeasterly winds tend to prevail over Rwanda, but in some seasons, the climatological winds weaken and shift direction. While spatial patterns of rainy day and dry spell frequency are consistent with the spatial patterns of the seasonal rainfall total, climatologically drier regions have a higher mean rainfall intensity on rainy days. This analysis demonstrates the value of the ENACTS product and illustrates climatological patterns in Rwanda over the last 30 years.

KEYWORDS
climatology, ENACTS, satellite-station data, rainfall, rwanda

1 | INTRODUCTION

Situated in East Africa, just south of the equator and bordered by Uganda, Tanzania, the Democratic Republic of Congo (DRC) and Burundi, Rwanda is the most densely populated nation on the African mainland with a population in excess of 12 million inhabitants and an area of 26,340 km². Rwanda is known as “Pays des mille collines” (the country of a thousand hills) and its mountainous topography creates a wide diversity of climatological and ecological environments, from the lush cloud forests of the mountainous west to semi-arid savannahs in the eastern lowlands.
1.1  |  Rainfall climatology

On seasonal timescales, rainfall in tropical East Africa (within about 10° of the equator) is typically bimodal in most regional environments from humid uplands to arid lowlands. However, the timing of the bimodality depends on latitude and the annual evolution of the Intertropical Convergence Zone (ITCZ; Nicholson, 2000; Siebert, 2014). Locations close to the equator tend to have two rainy seasons in March–May (the “long rains”) and September–December (the “short rains”), while locations further from the equator have climates closer to a unimodal rainfall pattern.

Locations a little north of the equator tend to have a longer dry period during the boreal winter and receive comparatively little rain from December to February while having a shorter and/or less dry period during the boreal summer (June–August). Locations a little south of the equator (including Rwanda) tend to have a longer dry period during the austral winter with comparatively little rain from June to August while having a shorter and/or less dry period during the austral summer (December–February) (Nicholson, 2000).

For Rwanda specifically, one study of historical station rain gauge data (up to the early 1990s) found that a little over 40% of the annual rainfall occurred in the March–May season, between 30 and 40% occurred in the September–December season, and about 15–20% occurred in January and February with June–August typically having only about 5% of the annual rain (Muhire et al., 2015). One study found that the pluviometric coefficient (ratio of monthly rainfall to annual rainfall) is more spatially heterogeneous across the country in February and October than in other months, potentially suggesting a role of additional sources of moisture (e.g., advection from the Congo and/or Atlantic). At other times of year, the pluviometric coefficient is more homogenous.

There has been regional hydro-climatic variability on multi-decadal timescales (Ilunga and Muhire, 2010; Mbungu et al., 2012; Muhire et al., 2015; Muhire and Ahmed, 2015a). On shorter, inter-annual timescales, the El Nino–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) play a significant role in the rainfall patterns of Rwanda in particular and East Africa more generally (Ropelewski and Halpert, 1987; Saji and Yamagata, 2003; Ilunga and Muhire, 2010; Muhire et al., 2015; Ndomeni et al., 2018).

1.2  |  Temperature climatology

While many prior studies of Rwanda’s climate have tended to focus more on precipitation than temperature, several published studies show that temperatures in Rwanda tend to be very stable throughout the year and topography is the dominant control on temperature within the country. One study of multiple stations from 1961 to 1992 shows that mean annual temperatures are above 20 °C in most regions below 1,500 m elevation (in much of the eastern Province, Kigali and parts of the western province near the shoreline of Lake Kivu and in the southwest lowland valley of the Rusizi River). In the central plateau region and along much of the Nile-Congo divide where elevations range from 1,500 to 3,000 m, mean annual temperatures are between 15 and 20 °C. In the high elevations of the Virunga Mountains of the northwest, the mean temperature is below 15 °C (Safari, 2012; Muhire and Ahmed, 2015b).

1.3  |  Data constraints

There were a large number of active meteorological stations in Rwanda prior to the mid-1990s and since around 2010. However, from around the time of the Rwandan genocide in 1994 throughout the late 2000s, the number of active stations was greatly reduced. In light of the spatial heterogeneity of this landscape and the severe data gaps, there is a great need for improved spatiotemporal climatological and meteorological information to inform climate services and related decision making. Understanding the patterns of the rainy seasons is critical for Rwanda, in which over 80% of the total population are engaged in agriculture. The sector meets 90% of the national food needs and generates more than 70% of the country’s export revenues (World Bank, CIAT, 2015). To this end, this paper offers a detailed climatological analysis of Rwanda using the new Enhancing National Climate Services (ENACTS) data set that covers the period from 1981 to the present, along with an assessment of the interaction between regional winds, topography and precipitation. Additionally, this paper illustrates the potential added value of using ENACTS data over other high-resolution data sets with fewer meteorological stations and discusses the ENACTS methodology.

1.4  |  The roles of topography and regional winds

Figure 1a,b shows the topography of the region around Rwanda and Rwanda in particular. Figure 1a clearly illustrates a number of dramatic topographic features of the Albertine Rift Valley near the border of DRC and the neighbouring countries to the east: including high mountain ranges in eastern DRC, western Uganda, western Rwanda and western Burundi and depressions of the African Great Lakes (Tanganyika, Kivu, Albert and Edward). Figure 1b shows the topography of Rwanda in finer detail with Lake Kivu on the border with DRC, the Virunga Mountains in the northwest, Nile-Congo divide in the west and the lowlands of the eastern and south central regions. Figure 1b also denotes the locations of four cities in Rwanda, the climate of which will be explored further in Figure 3.

Several prior studies of Rwandan climate subdivide the nation into four physiographic regions: the area near Lake Kivu (entirely in the western province), the Nile-Congo divide (mostly in the western and northern provinces), the plateau region (including much of Kigali, much of the southern province and parts of the northern province) and the eastern lowlands (including most of the eastern province and parts of Kigali) (Ilunga et al., 2004; Ilunga and Muhire, 2010; Muhire and Ahmed, 2015b).
2010; Muhire et al., 2015). The eastern lowland region is the driest and warmest (and topographically lowest) region of the country. The mountainous region along the Nile-Congo divide is the wettest and coldest (and topographically highest) region of the country and includes the volcanic peaks of the Virunga Mountains of the northwest and the high elevations of the Nyungwe rainforest in the southwest. The region around Lake Kivu and the plateau region to the east of the Nile-Congo divide are at intermediate elevation, temperature and precipitation levels (Henninger, 2013). An example of such regional climate classification is shown in Figure 2.

Figure 3 shows climographs of monthly average rainfall and maximum and minimum temperature for four locations based on the ENACTS data: Kigali, Musanze, Kibuye and Kayonza—representative locations of the plateau, mountain, lake region and eastern lowlands, respectively. The rainfall peaks in April with a secondary peak in November for each location and is lowest in July for each location. The temperatures are quite stable through the year in each location. Elevation clearly has a significant impact on both temperature and rainfall with the higher-elevation locations being cooler and wetter than the lower elevation locations.

While this division of the country into four physiographic regions has some appeal, recent research suggests that the boundaries of some of these regions may have changed over time. After analysing climatic data from 1996 to 2011 as compared to data from the mid to late 20th century, Henninger (2013) concludes that some of the parts of northern Congo-Nile divide that were previously considered to have a mountain/alpine climate type had developed characteristics closer to those of the plateau region in the recent past. This inference may be suggestive of a climate change signal.

In addition to its effects on the mean climatology, topography can also play an important role in shaping the spatial distribution of rainfall and flooding risks in Rwanda under certain meteorological conditions. One study that modelled two historical heavy rainfall events in both the March–May and September–December seasons using the Weather, Research and Forecasting (WRF) model found that reducing the model topography by half could considerably alter the spatial pattern and degree of heavy rainfall during extreme event periods (Ntwali et al., 2016). The WRF simulations with reduced topography not only produced less total rainfall, but also a significantly reduced rain shadow effect (Ntwali et al., 2016).

The dynamics of rainfall over Rwanda are also influenced by larger-scale high-pressure centres: the Mascarene, St. Helena, Azores and Arabian. The Mascarene high influences the advection of moisture and path of storm systems into East Africa from the Indian Ocean while the St. Helena high influences the advection of moisture and path of storm systems into the southwest and central Africa from the Atlantic. The Azores and Arabian high-pressure systems have somewhat more remote influences on the positioning and persistence of high-pressure systems which can influence regional droughts (Muhire et al., 2015). During much of the year, the majority of rainfall in Rwanda comes primarily from the Intertropical Convergence Zone (ITCZ), Indian Ocean/Lake Victoria and storms influenced by the Mascarene high (Ilunga et al., 2004).

In this study of Rwanda, the year is divided into the January–February intermediate rainfall season (in Kinyarwanda, Uru-garyi), the March–May wet season (in Kinyarwanda, Itumba), the June–August dry season (in Kinyarwanda, Impeshyi) and the September–December wet season (in Kinyarwanda, Umuhindo). While these season lengths are unequal, this choice of season selection was made to be consistent with the climatology and agricultural practices of the nation. While sowing and harvest date for different crops vary by cultivar
and region, this seasonal division of the year is most in line with the more extensive harvests in December and May.

This general pattern is illustrated in Figure 4 with precipitation data taken from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and 850 hPa wind climatologies taken from the European Center for Medium Range Weather Forecasting Interim ReAnalysis (ERA-Interim).

In this study domain, during the January–February season, the heaviest precipitation is south of Rwanda in Tanzania and DRC, while during the June–August season the peak rainfall is north of the equator in northern Uganda and DRC. During the March–May and September–December seasons, the peak rainfall is centred closer to the equator and includes Rwanda. On an even larger scale, heavy precipitation in January–February extends further south (towards and including Mozambique and Madagascar), whereas during June–August heavy precipitation extends further north (towards and including Ethiopia).

The wind pattern shown here exhibits strong southeasterly flow during JJA, slightly weaker, primarily easterly flow (with a southerly component) during MAM, weak winds across much of the region in JF and convergent easterlies in SOND. The strong southeasterly flow during JJA is associated with the northwards migration of the ITCZ and the intensification of high-pressure systems in the Southern Hemisphere. The ITCZ is typically in a more equatorial position during the MAM and SOND seasons, although the southerly winds during MAM suggest a northwards displacement of the zone of convergence. The observed winds are not symmetric about the equator but are strongly influenced by the sea surface temperature gradient of the Indian Ocean and land–sea heating contrasts between the Indian Ocean and the African mainland.

In the rainfall maps, there are semi-persistent wet regions in the east central DRC highlands and over Lake Victoria (centred on the equator around 32.5°E), consistent with the expected impacts of orographic lifting and lake effect precipitation, respectively. The weak wind climatology over Rwanda in most seasons may be partly product of a disruptive influence of the topography on the mean wind field while also reflecting the equatorial doldrums and larger-scale patterns of atmospheric convergence. The MAM and SOND rains are strongly influenced by the near-equatorial positioning of the ITCZ and while the majority of moisture flux into Rwanda...
comes from the Indian Ocean from the (south) east, there is some moisture advection from the DRC between January and May (Muhire et al., 2015). While this moisture advection from the DRC is not explicitly visible in the mean wind fields shown in Figure 4a,b, episodic westerly wind anomalies and storms that convey moisture from the Congo air mass into Rwanda are counterbalanced by weak prevailing easterlies.

1.5 Objectives of study

In addition to the foregoing discussion of past literature on Rwanda’s climate and the roles of topography and regional wind dynamics in shaping Rwanda’s climate, this study has several objectives. Sections 2 and 3 illustrate the methods by which the ENACTS data is produced and make an argument for why it is a preferable product to other observational products in this context. Section 4 includes a detailed climatological analysis of rainfall, rainy day frequency, 5-day dry spell frequency, mean rainfall intensity, extreme rainfall frequency, temperature and diurnal temperature contrast. Furthermore, the spatial pattern correlations between the rainfall variables are explored.

2 DATA

The data used in this study are from the Enhancing National Climate Services (ENACTS) initiative, which strives to improve availability of climate data in areas with sparse or no observation network (Dinku et al., 2014; 2016; 2017). This is accomplished by blending quality-controlled station observations with satellite rainfall estimates (for rainfall) or climate model reanalysis proxies (for temperature) (Dinku et al., 2014; 2017).

While the station observations are provided by the Rwanda Meteorological Agency, the satellite data are from the Tropical Applications of Meteorology using SATellite data and ground based observations (TAMSAT) project (Maidment et al., 2014; Tarnavsky et al., 2014). The TAMSAT algorithms use cold cloud duration readings from satellites to estimate surface rainfall (Maidment et al., 2017). Reanalysis products systematically combine station observations with climate model forecasts using data assimilation techniques and climate models (Kalnay et al., 1996). For the Rwanda ENACTS data, the temperature estimate reanalysis data are taken from the Japanese 55-year reanalysis project (JRA55) at a 50 km resolution. The raw observational data underpinning the JRA55 reanalysis is taken mostly from European Reanalysis (ERA-40). Several bias correction and quality control techniques are applied and the data assimilation time step is 6 hr (Kobayashi et al., 2015).

The main advantages of the satellite and climate model reanalysis products are that they (a) offer spatially complete data; (b) are freely available; (c) have relatively long time series (over 30 years for satellite rainfall products and over
50 years for reanalysis products). However, these products are not as accurate as the station observations. Therefore, in the ENACTS process, station observations are used to evaluate and correct the error bias in the spatially complete products, which in turn are used to fill spatial and temporal gaps in station observations. The mean bias errors vary seasonally but are temporally constant throughout the 1981–2016 period. The approach thus combines the spatial information from the proxies with the accuracy from point station measurements. The spatial resolution of ENACTS is the same as for the satellite rainfall estimates from TAMSAT and is 0.0375° (~4 km). For the temperature products, the resolution is the same as the reanalysis data and is slightly coarser at 0.05° (~5 km). While other high-resolution blended station-satellite rainfall data sets exist (e.g., Climate Hazards Group InfraRed Precipitation with Station data [CHIRPS]) (Funk et al., 2015) and are often used for forecasting activities in Africa (Kipkogezi et al., 2017), the ENACTS approach also specifically engages the National Meteorology Agencies of participating countries and uses considerably more stations than does CHIRPS or any other blended product (Dinku et al., 2018). ENACTS rainfall data for Rwanda exist from 1981 to present and ENACTS temperature data exist from the 1960s to the present (Dinku et al., 2017). The ENACTS data are produced at two temporal resolutions: daily and dekad. In section 4 of this study, the temperature and rainfall climatologies are aggregated from the dekad data and the rainy-day frequency, dry spell frequency and extreme rain frequency climatologies are aggregated from the daily data.

The number of regularly reporting meteorological stations in Rwanda declined abruptly during the civil war and genocide of the mid-1990s and remained very low until about 2010, when Meteo-Rwanda was able to significantly increase capacity and bring the number of active meteorological stations back to levels comparable to pre-1994. The ENACTS approach fills this temporal data gap to help provide more robust information for climate services for the...
nation. This data gap and the efforts to address this data gap have been covered in public media (Aizenman, 2016; Fiondella, 2016). Figure 5 shows the number of reporting meteorological stations over time in Rwanda.

While other studies have examined Rwanda’s climate in the past using station data up to the early 1990s (as described in section 1.1), this is the first study to include a climatological analysis of the more recent post-war period using the ENACTS product for Rwanda.

3 METHODS

3.1 Generating climate time series

In the standard ENACTS approach, the approach for generating rainfall time series involves the following steps:

1. Use the available data from 1981 to 1993 and 2010 to 2016 to calculate climatological bias adjustments factors for each Julian day or dekad.
2. Interpolate the adjustment factors via inverse distance weighting to the required grid points.
3. Apply the adjustment factors to all satellite time series from 1981 to present.
4. Combine the bias-adjusted satellite rainfall estimates with station data for each day/dekad of every year. This is done via regression kriging.
5. Combine output from the last merging with station (also via regression kriging), this time at shorter radius of influence. This is done to accommodate the different station densities over the different parts of the country and the complex topography (Dinku et al., 2014; 2017).

Step 3 above generates the most temporally consistent time series. The product in step 5 is the best product in terms of quality, but might have some inhomogeneities because of the varying number of stations used. The quality of generated time series will therefore be very good for the years with station coverage, and will be close to or the same as product 3 for the years with few or no station observations. Thus, this product may not be used for applications such as climate trend analysis. However, it provides good data for users interested in rainfall values for the years with good station coverage. More information on the methodology behind and limitations of the Rwanda ENACTS product is also available publicly on the Météo-Rwanda maproom webpage.

There are no satellite temperature estimates going back 30 years. Thus, reanalysis data was used as a proxy for temperature. The following steps were used to reconstruct the temperature time series:

1. Downscale reanalysis data from 50 to 5 km. This was accomplished by calculating the atmospheric lapse rate in the reanalysis data at the coarse resolution and using high-resolution elevation data to refine the temperature estimation at that higher resolution (Dinku et al., 2014; 2017).
2. Use the data from 1981 to 1990 and 2010 to 2016 to calculate bias adjustments factors for each Julian day/dekad.
3. Interpolate the adjustment factors via inverse distance weighting.
4. Apply the adjustment factors to all downscaled reanalysis data from 1981 to 2016.

FIGURE 5  Average number of reporting meteorological stations in Rwanda over time (1981–2016). Note the significant decline in 1994, coincident with the genocide and the subsequent re-emergence of station coverage around 2010 (source: Dinku et al., 2016)
5. Combine the bias-adjusted satellite rainfall estimates with station data for each day/decadal of every year (via regression kriging) (Dinku et al., 2014; 2017).

Again, step 3 above generates the most temporally consistent time series, while the product in step 5 is the best product in terms of quality, but would have some inhomogeneities.

3.2 | Comparison with other similar satellite rainfall products

It would be impossible to compare the ENACTS data with other satellite products because ENACTS makes use of all available stations data. It would be possible to withhold some stations for use as independent validation. However, that will not represent the actual ENACTS data. A qualitative comparison is provided in Figure 6 for one particular day (December 13, 1992) to give the reader an idea of the characteristics of ENACTS data relative to other similar products. Figure 6 compares station measurements and ENACTS data with latest version of the TAMSAT product (TAMSAT3) and CHIRPS at daily timescale.

As Figure 6 displays, TAMSAT 3 does not pick up much of the rainfall observed over the country on that day and while CHIRPS provides information at a high resolution, most of the small-scale variations are missing. ENACTS provides much better and more accurate spatial coverage.

3.3 | Monthly cross validation

Cross validation of monthly total rainfall between the station data and the ENACTS would be another approach to evaluate the quality of the ENACTS data. However, this is also challenging because of the number of steps involved in generating the ENACTS products. The two figures below (Figures 7 and 8) show monthly cross validation results for the MAM season, but only for one-step merging (combining the satellite estimate with station only once and without bias removal).

This will not represent the quality of the actual ENACTS data, but may provide insight. As ENACTS data exist for several African countries, other validation studies that have explored statistical metrics such as mean absolute error, Heidke skill score, probability of detection, bias, false alarm ratio and efficiency for ENACTS in Tanzania, Kenya and Ethiopia (Dinku et al., 2018).

Figure 7 shows the correlation coefficient between the station rainfall readings and satellite rainfall estimates. Most of the correlation values exceed 0.8 and for almost all stations, the correlation values exceed 0.5.

Figure 8 shows the bias score for the stations included in the Rwanda ENACTS product as a quotient of the satellite rainfall estimate divided by the station rainfall reading. Most of the satellite readings are within 20% of the station readings.

Table 1 describes 11 stations that are used for both CHIRPS and ENACTS and the correlations and quotient biases between those station readings and the gridded products for CHIRPS and ENACTS; calculated for March, April and May rainfall totals for 1981–1993.

The average correlation between the stations and the ENACTS data is 0.86, whereas the average correlation with the CHIRPS data is 0.75. The quotient biases for CHIRPS also tend to represent slightly greater deviations from the station values than is the case for the ENACTS data.

3.4 | Climatological analysis methods

In this study, rainfall, temperature, rainy day frequency (greater than 1 mm/day), dry spell frequency (5 days or longer with no rain), mean rainfall intensity (quotient of rainfall total divided by number of rainy days) and extreme rain frequency (greater than 20 mm/day) from the ENACTS data set are presented at annual and seasonal aggregations. With the ENACTS data, the mean values are calculated and mapped in section 4. All figures in section 4 are based on a recent version (version 4) of the ENACTS data which includes 1981–present.

Historically, most assessments of climatology are based on 30 year windows which are updated at the beginning of each decade (e.g., 1971–2000, 1981–2010) (World Meteorological Organization, 2011). In the case of Rwanda, with its significant hiatus of station coverage from the mid-1990s to around 2010, this approach is not as constructive, because doing so leaves out the more recent period (since 2010) during which the number of meteorological stations significantly increased. For this reason, the window of
climatological averaging used in this paper is 1987–2016. Figures 9–15 are all based on this period.

While the Rwanda ENACTS data exists for the domain from 28 to 31°E and from 1 to 3°S, all of the stations used to inform the data are within the national borders of Rwanda. For this reason, in all the following map figures, the regions of the neighbouring countries of Democratic Republic of Congo, Burundi, Uganda and Tanzania have been masked out.

4 | RESULTS

4.1 | Rainfall

Figure 9 shows the mean annual rainfall and seasonal rainfall over Rwanda. The spatial pattern of rainfall described in other prior literature (as discussed in section 1.1) is clearly visible here in all the subpanels (drier east, wetter climatology in the mountainous west). Figure 9a,d shows the climatological mean rainfall for four seasons (JF, MAM, JJA and SOND, respectively) with MAM and SOND being wet seasons, JF being an intermediate season and JJA being dry, while Figure 9e shows the annual climatological mean rainfall. While the general spatial pattern is fairly consistent in each season, it is worth noting that in the JF season, the southwest corner of the country is the wettest region and the entire northern region is comparatively dry, whereas during other times of the year, the northwest is comparatively wetter. In JJA in particular, only a small region in the northwest receives more than 100 mm. These north–south asymmetries in JF and JJA are broadly consistent with the positioning of the ITCZ south of the equator in JF and north of the equator in JJA.

The results in Figure 9 are broadly consistent with a similar analysis constructed using CHIRPS data (not shown), while the ENACTS data exhibit more fine-scale detail.

| Station | Latitude | Longitude | Elevation (m) | ENACTS correlation | CHIRPS correlation | ENACTS bias | CHIRPS bias |
|---------|----------|-----------|--------------|--------------------|--------------------|-------------|-------------|
| Kamembe | −2.46    | 28.91     | 1,588        | 0.93               | 0.79               | 0.91        | 1.09        |
| Kibungo | −2.18    | 30.52     | 1,657        | 0.81               | 0.73               | 0.95        | 0.9         |
| Byimana | −2.14    | 29.74     | 1,828        | 0.88               | 0.78               | 1.04        | 1.05        |
| Rubengera | −2.07   | 29.41     | 1,589        | 0.79               | 0.74               | 1.16        | 1.19        |
| Kigali   | −1.97    | 30.13     | 1,495        | 0.84               | 0.46               | 0.96        | 0.95        |
| Gitega   | −1.96    | 30.06     | 1,523        | 0.97               | 0.91               | 1           | 1           |
| Kawangire | −1.82   | 30.45     | 1,526        | 0.86               | 0.77               | 0.97        | 1.1         |
| Gisenyi  | −1.68    | 29.26     | 1,552        | 0.87               | 0.69               | 1.02        | 0.93        |
| Byumba   | −1.59    | 30.05     | 2,189        | 0.92               | 0.76               | 0.93        | 0.8         |
| Busogo   | −1.55    | 29.55     | 2,201        | 0.75               | 0.72               | 1.14        | 1.39        |
| Ruhengeri | −1.50   | 29.63     | 1,855        | 0.79               | 0.86               | 1.01        | 1.03        |

Note. The analysis is calculated on the basis of the monthly rainfall totals for March–May 1981–1993.
4.2 | Rainy day/dry spell frequency

For agricultural, water management and other applications, the quantity of seasonal rainfall is not the only important quantity. The timing and frequency of rain events and dry spells is also play a critical role in important agricultural decision-making such as the time of sowing and harvest (Ilunga et al., 2008). This section explores the climatological frequency of rainy days and dry spells. In addition to the importance of rainy day frequency for agricultural decision making, scientific research has shown that the frequency of rainy days within a season may be a more predictable variable than the total seasonal rainfall in many locations throughout the tropics (Moron et al., 2007) and has also been shown to potentially be a more predictable variable for Rwanda (Siebert et al., 2017). Figures 10a,e show the climatological frequency of rainy days (with >1 mm rainfall) during the JF, MAM, JJA, SOND and annual seasons, respectively.

Similar patterns are seen in Figures 10 as were seen in Figures 9 so that higher climatological rainfall amounts tend to reflect more rainy days. The largest number of rainy days is during MAM and SOND, with fewer in JF and very few in JJA. The eastern part of the country experiences fewer rainy days than does the western part in every season. In the JF season, the rainy day frequency is highest in the southwest, whereas in the JJA season, it is highest in the northwest. During the MAM and SOND seasons, both the northwest and southwest are regions prone to many rainy days. Since the seasons have different lengths, the colour bars of Figure 10 are adjusted to reflect the different season lengths.

Dry spell frequency is an important variable for agricultural cultivation as well. Some work is underway through international partnership to explore methods of integrating early season dry spell risk into a dynamic onset date definition and integrating daily seasonal water stress into an analysis of crop water requirement satisfaction (Siebert et al., 2017).

Figure 11a,c shows the climatological average frequency of 5 day or longer dry spells during the JF, MAM and SOND seasons, respectively.

Since the three seasons shown in Figure 11a,c have different lengths, the colour bars are adjusted to reflect that difference in the season length. The JJA season is omitted from the figure here because it is a dry season during which most parts of the country do not receive more than a few days of rain during the whole season and most regions have dry spells much longer than 5 days during this time. Since there is limited, if any, agricultural cultivation during this season, the
metrics of rainy day frequency and dry spell frequency have less salience for application during this period. Although an exceptionally dry JJA season may affect soil moisture conditions at the beginning of the SOND season in less direct ways; an exceptionally hot, dry JJA (Impe-shyi) may limit soil water conditions more than usual in advance of the first rains of SOND (Umuhindo). Excessive drought can also influence the characteristics of soil and impact the runoff coefficient.

The spatial patterns shown in Figure 11 are mostly the opposite of those shown in Figures 9 and 10: the eastern part of the country is more prone to dry spell risk than the western part of the country. Following from Figures 9a and 10a, we see that in Figure 11a, the dry spell risk during January–February is particularly suppressed in the southwest region, while in the MAM season and SOND season (Figure 11b, c, respectively), both the southwest and northwest regions show low dry spell frequency.

4.3 | Rainfall intensity and extremes

While the timing, frequency and total quantity of rainfall in a season do have important implications for seasonal agriculture and for other sectors, rainfall intensity is another important consideration. Intense rainfall events can cause landslides, mudslides and significant erosion particularly in the steep, mountainous terrain of western Rwanda. This can threaten lives, human structures and agricultural productivity. Intense rainfall events, especially in quick succession can also cause persistent flooding; damaging or waterlogging crops, and potentially create more suitable environments for pests and disease. To address the issue of rainfall intensity, two statistics are shown in this section in Figures 12 and 13. Figure 12a–c shows the climatological mean intensity of rainfall in the JF, MAM and SOND seasons. The values for Figures 12 are calculated simply by dividing the seasonal total rainfall (Figure 9) by the number of rain days in the season (Figure 10).

Figure 12 shows an interesting result. In all three seasons shown, the mean rainfall intensity is higher in the (climatologically drier) east than in the west. This implies that the east–west gradient of rainy day frequency is greater than the east–west gradient of seasonal rainfall. In the SOND season, the pattern is more complex with areas of elevated mean rainfall intensity in the east and in the
western part of the southern province (in the eastern foothills of the Nile-Congo divide). Figure 13a–c shows the frequency of extreme rainy days (20+mm) in the same three seasons.

In addition to the figures shown here, the JJA season was also analysed with regard to both mean rainfall intensity and the frequency of extreme rainfall events. The frequency of extreme rainfall events was very low during the JJA season, but the mean rainfall intensity on rainy days was actually higher than during the wetter seasons, suggesting that when rainfall occurs during JJA, relatively light rainfall events are quite rare. However, as the rainfall intensity during JJA is less important for agriculture, livelihood and hazard risk than the rainfall intensity during the other seasons, that analysis is not shown here.

Figure 13 shows that the region with the highest frequency of 20mm+rainfall events is in the southwestern part of the southern province near Nyungwe cloud forest. In the JF season (Figure 13a), the frequency of extreme rainfall is generally suppressed in the northern and eastern regions of the country. In the MAM and SOND seasons, the north/south asymmetry is not as pronounced, a relatively high frequency of extreme events extends towards the eastern part of the country and the pattern does not seem as tightly coupled to topography.

These results suggest an interesting narrative. While Figures 9–11 portray a fairly self-consistent picture between
seasonal rainfall, rainy day frequency and dry spell frequency. Figure 12 suggests that in the drier regions of Rwanda, the mean rainfall intensity on rainy days is higher. This finding is different from another study of rainfall amount frequency and intensity in Senegal that found a positive correlation between total rainfall amount and rainfall intensity (Moron et al., 2006). Figure 13 shows that in absolute frequency of heavy rainfall days, the cloud forests of the southwest have the highest frequency, despite the higher mean intensity in the east. This logically implies that relatively light rainfall events are more commonplace in the western part of the country in both absolute terms and as a fraction of the total number of rainy days. This may have interesting dynamical implications: more convective instability and more regional moisture flux may be necessary in order to trigger rainfall in the relatively flatter, lower east. In the mountainous west, the interaction of air parcels with high topography may more easily bring an air parcel above the lifting condensation level, but in many cases (of lighter precipitation), less total moisture is entrained in the system. It may also be that a larger fraction of the rainfall in the west is from stratiform clouds.

4.4 | Spatial pattern correlations

The results shown in sections 4.1–4.3 suggest certain patterns of spatial correlation between the different studied variables: seasonal rainfall total, rainy day frequency, dry spell frequency, mean rainfall intensity and extreme rainfall intensity. Standardized spatial anomaly values are calculated for each gridbox of each climatological map shown in sections 4.1–4.3 and correlations are established between the different permutations of the variables for each season. Significance of these correlation values was then evaluated using a two-sided t test. The correlation results of this spatial pattern correlation analysis are shown in Table 2 for the JF, MAM and SOND seasons.

While the total number of spatial observations in the ENACTS-Rwanda data is large (\(N = 66 \times 52 = 3,432\) grid-boxes), spatial autocorrelation is likely to significantly reduce the number of degrees of freedom. While the spatial autocorrelation matrix was not explicitly calculated, the maximum radius was assumed to be half the maximum diagonal distance between southwest and northeast corners of the domain. This creates a lower bound of DOF~40 (Bretherton et al., 1999).

The rainfall/rainy day frequency, dry spell frequency/mean rainfall intensity and extreme event frequency/mean rainfall intensity have statistically significant positive correlations for all seasons. The dry spell frequency/extreme event frequency correlation is also positive for all seasons, although the correlation is notably weaker in JF. The rainfall/dry spell frequency, rainfall/mean rainfall intensity and rainy day frequency/mean rainfall intensity all have statistically significant negative correlations for all seasons. The rainy day frequency/dry spell frequency correlation is almost perfectly negative, suggesting a near perfect inverse relationship. The rainy day frequency/extreme event frequency has a negative correlation for all seasons, although the correlation strength is not significant for JF. The results are mixed for the rainfall/extreme event frequency, with JF having a positive correlation, and MAM and SOND having weak positive and negative correlations, respectively.

4.5 | Temperature

The ENACTS data also includes maximum and minimum temperature metrics. Climatological temperatures are very consistent across the different seasons of the year and the
intra-annual variability is also small. The spatial variability in temperature is controlled largely by elevation with higher elevations being climatologically cooler.

Figure 14a,b shows the average annual daily high temperature or Tmax and average annual daily low temperature or Tmin in °C. Both figures have a similar pattern with the highlands of the north, southwest and the Nile-Congo divide are comparatively cool, the lowland regions of the south and east are comparatively warm and the very topographically high volcanic peak region (known as the Virunga Mountains) of the northwest is the coolest region. The lowlands of the south-central region have an average Tmax close to 30 °C and an average Tmin of around 15 °C, while the high peaks of the northwest have an average Tmax below 15 °C and an average Tmin below 7 °C. Occasionally, on the very highest peak of the country, Mt. Karisimbi (elevation

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**Table 2** Spatial pattern correlations of the correlations of the different precipitation variables analysed in sections 4.1–4.3 for the JF, MAM and SOND seasons

|                         | JF      | MAM    | SOND   |
|-------------------------|---------|--------|--------|
| Rainfall/rainy day freq  | 0.849   | 0.790  | 0.864  |
| Rainfall/dry spell freq  | −0.803  | −0.754 | −0.831 |
| Rainfall/extreme event freq | 0.411  | 0.026  | −0.109 |
| Rainfall/mean rainfall intensity | −0.321 | −0.384 | −0.558 |
| Rainy day freq/dry spell freq | −0.979 | −0.985 | −0.987 |
| Rainy day freq/extreme event freq | −0.045 | −0.477 | −0.518 |
| Rainy day freq/mean rainfall intensity | −0.736 | −0.834 | −0.863 |
| Dry spell freq/extreme event freq | 0.070  | 0.479  | 0.531  |
| Dry spell freq/mean rainfall intensity | 0.731  | 0.853  | 0.875  |
| Extreme event freq/mean rainfall intensity | 0.539  | 0.662  | 0.679  |

*Note. A two-sided t test indicates that the values in bold italicize are significant at the 0.05 level, assuming 40 degrees of freedom.*
~4,500 m), temperatures can fall below freezing and snow can fall.

Variability of cloud cover, radiation and local thermodynamics can influence diurnal temperature range from one season and one location to another. Figure 15a,d shows the climatological difference between Tmax and Tmin in the four seasons JF, MAM, JJA and SOND, respectively. Nuanced differences in diurnal temperature range may have a subtle effect on soil moisture and/or for pest habitats (such as suitability for malaria transmitting mosquitoes).

We see in each figure that the smallest diurnal temperature range is in the north/northeast, while the largest diurnal temperature range is in the south—in particular the south centre and a region in the southwest near Lake Kivu. We also see that the diurnal temperature range is smallest in MAM and largest in JJA. This is expected, as more cloud cover during the rainy season generally implies a reduced radiative heating/cooling and a reduced diurnal temperature range and while MAM is the wettest season, JJA is the driest and sunniest season.

5 DISCUSSION/CONCLUSIONS

The foregoing analysis shows that this high-resolution climate data set ENACTS (at daily and dekadal time resolutions) provides a promising new tool for climate analysis for Rwanda, in part because of the high spatial resolution and temporal completeness and in part because of the integration of a larger number of meteorological station data than other similar blended products. The ENACTS product is created by a multi-step process of merging station data with satellite and reanalysis data for rainfall and temperature, respectively. Bias correction is applied in the process, the gridded and station data are merged via regression kriging and the final ENACTS product offers high correlation and limited bias with respect to the underlying station readings.

The influence of larger-scale atmospheric dynamics and topography have also been examined in this study and while topography acts as a significant control on both rainfall and temperature, large-scale regional atmospheric dynamics can have a significant impact at a local level. The seasonal movement of the ITCZ acts as a primary driver of the timing of the wet and dry seasons. While the predominant winds are from the east/southeast for much of the year, intermittent westerly winds and moisture advection from the Congo air mass (particularly from January to May) produces a more complex dynamic.

Patterns in the climatological rainfall, rainy day and dry spell frequency and temperature have been analysed for the period 1987–2016. The mountainous western region of the country is cooler and wetter than the lowlands of the east and south centre. Spatial patterns of rainfall climatology are fairly consistent across the seasons, but the MAM season is the wettest, SOND is slightly drier, the JJA season is the driest season and JF season has intermediate rainfall. In the JF season, the heaviest rainfall (and the largest number of rainy days) is in the southwest, but in other seasons, the northwest is comparably wet and rainy. In the JJA season, only the northwestern region of the country receives more than 100 mm.

In general, the spatial pattern of average rainy day frequency tends to mimic the spatial pattern of total rainfall with a higher frequency of rainy days in the west than in the east. Furthermore, subtle geographic seasonal differences in the rainy day frequency also mirror the seasonal differences in total rainfall (higher rainy day frequency in the southwest during JF and higher rainy day frequency in the northwest during JJA).

There is an elevated dry spell risk in the east and a suppressed dry spell risk in the west for each season. Furthermore, there is greater dry spell frequency suppression in the southwest than in the northwest during JF, while the same contrast is not visible in MAM or SOND.

Mean rainfall intensity (on the days with rain) is actually greater in the comparatively drier eastern region of the country than in the comparatively wetter western part of the county. However, the region most prone to 20mm+rainfall events in each season is near Nyungwe cloud forest in the southwestern region. Patterns of mean intensity and 20mm+frequency seem less in line with the seasonal patterns of the other rainfall variables explored and seem less tightly coupled to topographic influences.

Spatial pattern correlation analysis shows that while the rainfall and rainy day frequency are positively correlated to each other, the dry spell frequency, mean rainfall intensity and extreme event frequency tend to be positively correlated to each other. These pattern correlations have intriguing implications about the spatial and temporal distribution of rainfall events of different sizes and the dynamic factors that lead to those differences. This analysis suggests a greater E-W gradient of rainy day frequency than seasonal rainfall and a larger proportion of light rainfall events in western Rwanda than in eastern Rwanda, even though western Rwanda is more prone to a larger absolute number of extreme events. This may also imply nuanced differences in atmospheric dynamics and cloud types in different regions within the country.

Both Tmax and Tmin show the warmest average values in the lowlands of the south and east and the coldest values in the highest mountains of the northwest. Generally cooler values persist in the northern province and along the Nile-Congo divide. The coldest region of the country is in the volcanic peak region (Virunga Mountains) in the northwest.

The average diurnal temperature range tends to be greatest in the south and at lower altitude parts of the southwest in all seasons, while the average diurnal temperature range tends to be smallest in the north/northeast in all seasons. The diurnal temperature range is greatest during JJA and smallest
during MAM, as is expected from the difference in cloud cover and radiative heating/cooling between those two seasons.

The ENACTS data set is shown here to provide valuable insights into the climate of Rwanda from the early 1980s to the present. This helps to compensate for the significant decline in meteorological station data coverage from the mid-1990s to around 2010.

ENACTS-Rwanda is an ongoing collaboration between Columbia University's International Research Institute for Climate and Society and Météo-Rwanda. There have already been multiple training and collaboration efforts between the institutions to build on, improve and mainstream the use of the data set (delCorral, 2016; Dinku and delCorral, 2016; Faniriantsoa, 2017). There has also been an effort underway during the last few years to bring the ENACTS data into application for the USAID sponsored Climate Change and Food Security (CCAFS) initiative in Rwanda (Nsengiyumva et al., 2016; Kagabo et al., 2017). In addition to these climatological studies here, these data have also been used in conjunction with sea surface temperature (SST) data and global climate modelling (GCM) outputs, to hone and inform seasonal forecasts and to build user oriented digital maprooms for visualizing these forecasts (Siebert et al., 2017).

While this paper has illustrated the potential added value of the ENACTS data set, there are several caveats to be considered. The bias correction methods described assume a degree of temporal stationarity, which could be assessed by examining different adjustment coefficients for the pre-and post-gap years (1981–1993, 2010–2016). The significant decline in the number of reporting meteorological stations in the 1990s and 2000s led to discontinuities in the level of calibration of the ENACTS data during those periods which have an impact on the quantification of trends and variability of the ENACTS data (Greatrex, 2017).

A forthcoming companion paper will explore the variability and trends of these same variables over a similar time frame using data that is more temporally consistent. In addition to this companion study in development, further exploration of the role of ENSO and IOD in seasonal predictability and comparison of the forecast skill of ENACTS to other products (such as CHIRPS) would be beneficial future research steps. As part of the aforementioned CCAFS project, ENACTS data will also serve as a focal point for future forecasts of variables critical to agriculture and other societal applications.

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REFERENCES

Aizenman, N. (2016) Turns out you do need a weatherman to know which way the wind blew. National Public Radio/WNYC, May 2016.

Bretherton, C., Widmann, N., Dymnikov, V., Wallace, J. and Blade, I. (1999) The effective number of spatial degrees of freedom of a time-varying field. Journal of Climate, 12, 1990–2009.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaerts, A.C.M., van de Berg, L., Ballot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Holm, E.V., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J.-N. and Vitart, F. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137, 553–597. https://doi.org/10.1002/qj.828.

Dinku, T. and delCorral, J. (2016) Training program on ENACTS climate time series, data library and maprooms, Kigali, Rwanda, December 2015. Copenhagen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). CCAFS workshop report. Available at: www.ccafs.cgiar.org [Accessed March 2018].

Dinku, T., Haillemariam, K., Maidment, R., Tarnavsky, E. and Connor, S. (2014) Combined use of satellite estimates and rain gauge observations to generate high-quality historical rainfall time series over Ethiopia. International Journal of Climatology, 34, 2489–2504.

Dinku, T., Cousin, R., Corral, J.D., Ceccato, P., Thomson, M., Faniriantsoa, R., Khomyakov, I. and Vadillo, A. (2016) The ENACTS approach: transforming climate services in Africa one country at a time. World policy paper.

Dinku, T., Thomson, M., Cousin, R., delCorral, J., Ceccato, P., Hansen, J. and Connor, S. (2017) Enhancing National Climate Services (ENACTS) for development in Africa. Climate and Development, 10, 664–672. https://doi.org/10.1080/17565529.2017.1405784.

Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadaïn, H. and Ceccato, P. (2018) Validation of the CHIRPS satellite rainfall estimates over eastern Africa. Advances in Remote Sensing of Rainfall and Snowfall, 144, 292–312. https://doi.org/10.1002/qj.3244.

Faniriantsoa, R. (2017) Training on IRI climate data tools and developing a method for integrating climate data in Kigali, Rwanda. Wageningen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). CCAFS workshop report. Available at: www.ccafs.cgiar.org [Accessed March 2018].
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