The characterization of the variability of the wet season over Central America

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Abstract

Central America exhibits a distinct seasonal cycle of rainfall, which is objectively defined as having an onset date and a demise date of the wet season on the first and the last day of the year when its daily rainfall exceeds and falls below the annual mean rainfall climatology. This is defined at the granularity of the rainfall analysis dataset. Additionally, the methodology diagnoses the onset/demise dates of the wet season from an ensemble of 1000 members per season by perturbing the original timeseries to obtain robust probabilistic estimates. We show that both onset and demise date variations have a bearing on the seasonal length and seasonal rainfall anomaly but impact them independently of each other. We demonstrate that a seasonal outlook based solely on the onset date variations has useful prediction skills that portend for real-time monitoring of the onset date of the wet season.

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The characterization of the variability of the wet season over Central America

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Key points

1. The variability of the length of the season has a significant influence on the seasonal rain of the wet season over Central America.
2. The onset date variations influence the length and seasonal rainfall anomalies significantly over Central America.
3. The probabilistic skill for the outlook of the wet season over Central America from monitoring the onset date of the season is promising.

Abstract

Central America exhibits a distinct seasonal cycle of rainfall, which is objectively defined as having an onset date and a demise date of the wet season on the first and the last day of the year when its daily rainfall exceeds and falls below the annual mean rainfall climatology. This is defined at the granularity of the rainfall analysis dataset. Additionally, the methodology diagnoses the onset/demise dates of the wet season from an ensemble of 1000 members per season by perturbing the original timeseries to obtain robust probabilistic estimates. We show that both onset and demise date variations have a bearing on the seasonal length and seasonal rainfall anomaly but impact them independently of each other. We demonstrate that a seasonal outlook based solely on the onset date variations has useful prediction skills that portend for real-time monitoring of the onset date of the wet season.

Plain Language Summary

The onset date and demise date of the wet season in Central America are defined every year, precisely to a specific date from our proposed definition of it. This is possible because the region exhibits a strong seasonality of the rainfall. As a result, the year-to-year (interannual) variation of the seasonal rainfall during the wet season is also determined by the variations in the length of the season that are usually overlooked in fixed calendar seasons. We define the onset or demise date of the wet season as the first or the last day of the year when the daily rain rate exceeds or falls below the annual mean climatological rainfall, respectively. We also find that both onset and demise date variations, independently influence the length and total seasonal rainfall of the wet season. Consequently, we use the diagnosed onset date to provide an outlook of the forthcoming wet season, which is shown to be an effective predictor with significant useful seasonal prediction skills.

1 Introduction

The isthmus of Central America comprising Belize, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama has a distinct seasonal cycle of rainfall and a well-recognized monsoon system that serves as a bridge for a unified view of the North and the South American Monsoon systems (Vera et al. 2006). The seasonality of rainfall is vital for the economy of the region (Alfaro 2014). However, the seasonal evolution of rainfall over Central America is rather heterogeneous given the region's complex geography (e.g., a narrow isthmus oriented northwest-southeast direction, surrounded by relatively warm oceans), topography, and in the vicinity of oceanic Inter Tropical Convergence Zone (ITCZ). For example, the region's complex topography in the narrow isthmus and its interaction with the seasonally varying easterly trade winds gives rise to a differing seasonal precipitation cycle between its Pacific and Caribbean slopes (Magana et al. 1999; Alfaro 2002; Taylor and Alfaro 2005; Amador et al. 2006). Furthermore, the north-south contrast in the rainy seasons from Panama to Belize is also distinct owing partly to the movement and extent of the ITCZ and its associated circulations and the strength and extent of the subtropical highs in the Pacific and the Atlantic Oceans. Additionally, the variability of the regional climate system forced by external factors like ENSO, tropical North Atlantic SSTs, and internal chaotic variations make anticipating or forecasting the seasonal hydroclimate over the region a challenging task (Alfaro et al. 2017; Kowal et al. 2023).

In this paper, we offer a simple but effective way to provide an outlook for the forthcoming wet season from just monitoring the evolution of the rainfall in the region around the time of the onset of the wet season. The proposed methodology has been successfully implemented over other regions like India (Bhardwaj and Misra 2019), northern Australia (Uehling et al. 2020; Misra et al. 2023), and Florida (Misra et al. 2022). But unlike some of these other expansive monsoonal regions, the Central American region as mentioned earlier has complex evolution of the wet seasons that evolve zonally and meridionally giving rise to mesoscale gradients of rainfall. Therefore, understanding this complex evolution in an objective manner and then leveraging the discerned local relationships to extend the limits of seasonal predictability is of interest.

2 Datasets and Methodology

The primary dataset used in this study is the daily rainfall, which is obtained from the Integrated Multi-Satellite Retrievals for Global Precipitation Mission version 6 (IMERG; Huffman et al. 2019). The IMERG rainfall analysis is made available at 0.1° grid spacing at half-hourly temporal resolution from June 2000 to the present. The IMERG data also includes the rainfall analysis that is labeled early, late, and final run products which have a latency of ~ 4-h, 12-h, and 3.5 months, respectively. The latency of these products is dictated by the time taken for data ingestion, pre-processing the use of the kinds of satellite radiances collected by the Global Precipitation Mission (GPM), the adopted analysis technique, and the availability and use of the atmospheric reanalysis products for the release of the final gridded rainfall product. Since the methodology introduced in this study to diagnose the evolution of the wet season is also being adapted for real-time monitoring of the season, we chose to use the 12-h latency (late) product of IMERG. For this study, we have computed the daily average of 12-h latency IMERG product from its half-hourly interval.

The methodology adopted in this study to diagnose the onset and demise of the wet season has been widely used for many of the tropical regions that show strong seasonality of rainfall (Liebmann and Marengo 2001; Misra and DiNapoli 2014; Dunning et al. 2016; Uehling and Misra 2020). Essentially, this methodology diagnoses the first and the last day of the year when the daily rain rate exceeds the corresponding climatological annual mean rainfall as the onset and the demise of the wet season. This is achieved by isolating inflection points on the daily cumulative anomaly curve of the rainfall (Fig. S1; Liebmann and Marengo 2001). This methodology is effective only where there is a strong seasonality of rainfall (Fig. S2). It should be noted that our methodology ignores the mid-summer drought phenomenon in the region which gives rise to the bimodal peak of rainfall in the region (Fig. S2). Although significant importance is attached separately to the variations of the primary peak (May-June) and secondary maximum (September-October) of rainfall (Magana et al. 1999; Alfaro et al. 2017), there is still significant rainfall during the July-August period of the "canicular" (> 5 mm day^{-1}; Fig. S2) to broadly include it as part of the wet season. Additionally, given the uncertainty of observations, analysis techniques, and discretization of the rainfall data, Misra et al. (2023) introduced perturbations of the timeseries to obtain a robust ensemble of onset and demise dates from a given daily timeseries of rainfall. Furthermore, obtaining such an ensemble of onset/demise dates also precludes their "definitive" diagnosis from excessive bearing of isolated synoptic or sub-synoptic rain-bearing systems, which may be unconnected to the large-scale seasonality of the rainfall. In a region like Central America, this may be particularly relevant where there is abundance of mesoscale convective systems (Liu and Zipser 2013, 2015). Following Misra et al. (2023), the perturbations to the timeseries are generated by shuffling the original daily timeseries of rainfall on the timescale of 6 days (representing synoptic scales) with rain rates of some randomly chosen days being replaced by rain rates occurring within the sequence of ± 3 days of the chosen date. We generate 1000 such perturbed timeseries per year per grid point. The time series plot for a sample year and for a sample grid point over Nicaragua with its perturbed 1001 timeseries (including the original timeseries) are shown in Fig. S3. The onset and demise of the wet season are computed at every grid point of the IMERG product (at its 0.1° grid resolution) for all 1001 ensemble members across Central America for the period of the dataset (2001-2022).

3 Results

a) Climatology

Figs. 1a-d shows the climatology of the onset, demise, length, and seasonal rainfall of the wet season. Since an ensemble of 1001 members is generated from the methodology, we have used the median value of the diagnosed onset, demise, length, and seasonal rain for each wet season to compute this climatology to avoid the influence of outliers. In Fig. 1a we observe that the onset date is generally earlier on the Pacific coast than on the Atlantic coast. Furthermore, the earliest onset dates appear in Panama, and onset dates gradually occur later in the year as we proceed further north. However, this progression is not uniform with parts of the Pacific coast of Costa Rica, Nicaragua, and El Salvador displaying later onset dates compared to parts of Honduras and Guatemala. The west-to-east progression of the onset date of the wet season is however more uniform across Central America (Fig. 1a).

Similarly, the demise date shows a meridional and a zonal gradient in Fig. 1b. For example, the later demise dates in Panama and Costa Rica to the rest of Central America are apparent. Furthermore, the Atlantic coast of Central America displays a later demise date than the Pacific coast, with areas between the coasts in Nicaragua, Honduras, and Guatemala showing some of the earliest demise dates of the wet season (Fig. 1b).

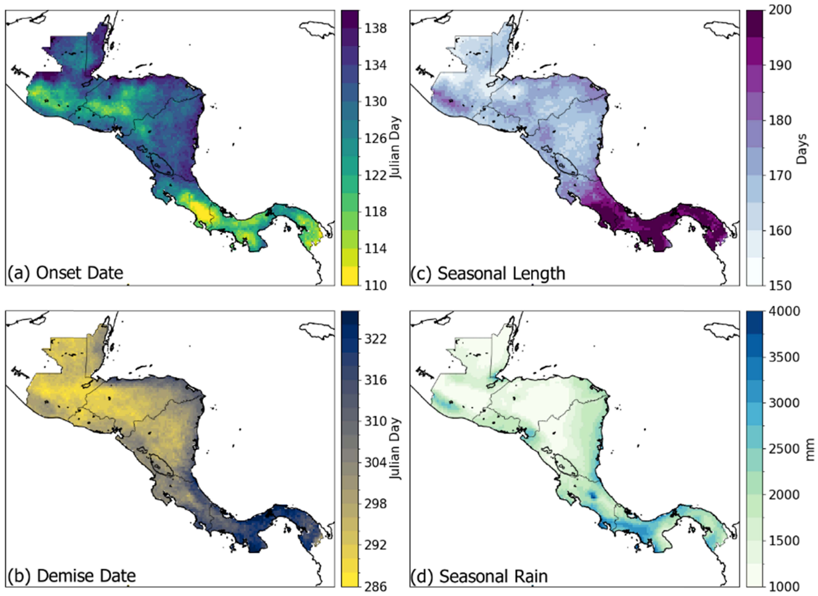

Figure 1: The 22-year (2001-2022) climatological median (a) onset date (Julian Day), (b) demise date (Julian Day), (c) seasonal length (days), and (d) seasonal rain from 12h latency IMERG product.

Consequently, the length of the wet season is the longest in Panama and parts of Costa Rica from a relatively earlier and a later onset and demise date of the wet season, respectively (Fig. 1c). Climatologically, some of the shortest wet season is in Belize and the interiors of Guatemala, Honduras, and Nicaragua (Fig. 1c). It is this spatial variation of the length of the season that is often missed when wet seasons are fixed to calendar months across Central America.

The corresponding climatological seasonal mean rainfall, accumulated from the day of the onset to the day of the demise of the wet season is shown in Fig. 1d. Generally, longer seasons correspond to higher seasonal rain in Panama and Costa Rica. However, the correspondence between the length of the season (Fig. 1c) and the seasonal rain (Fig. 1d) is not so obvious with parts of Panama and Costa Rica displaying far less seasonal rain and is comparable to other northern parts of Central America despite its comparatively longer length of the wet season. This implies that the daily rain rates in the wet season are relatively weaker in some of these regions in Panama and Costa Rica. We also observe that the interiors of Nicaragua, Honduras, and Guatemala besides Belize receive some of the lowest seasonal rain in the wet season compared to other parts of Central America.

b) Interannual variability

The four variables shown in Fig. 1 display considerable variability as noted by their standard deviation (Fig. S4). Furthermore, the standard deviation exhibits strong spatial gradients in the variations of the onset date, demise date, length, and seasonal rain of the wet season (Fig. S4). Therefore, understanding the variations in the length of the season and their implication on the seasonal rain of the wet season on local or small spatial scales is important. In Fig. 2a we show the correlations of the median onset date (diagnosed from the 1001 ensemble members) with the corresponding median seasonal length of the wet season. The correlations are significantly large and negative except near the Atlantic coast of Nicaragua and Honduras (Fig. 2a). The negative correlations in Fig. 2a suggest that an early or a later onset date of the wet season is associated with longer or shorter wet season, respectively. Furthermore, in Fig. 2b we show the correlations of the onset date with the corresponding seasonal rainfall anomaly of the wet season, which yet again highlights the importance of the onset date variations. The regions of Central America that exhibit statistically significant correlations in Fig. 2b suggest that an early or a later onset is associated with a wetter or drier wet season, respectively. However, the statistically significant correlations between the onset and the demise dates are isolated and rare (Fig. 2c). This implies that the influence of the onset date variations on the length and the seasonal rain of the wet season is relatively independent of the influence of the demise date variations. In summary, Fig. 2 suggests that monitoring the onset date of the wet season has the benefit of providing an outlook of the forthcoming length and seasonal rainfall anomaly of the wet season over most of Central America.

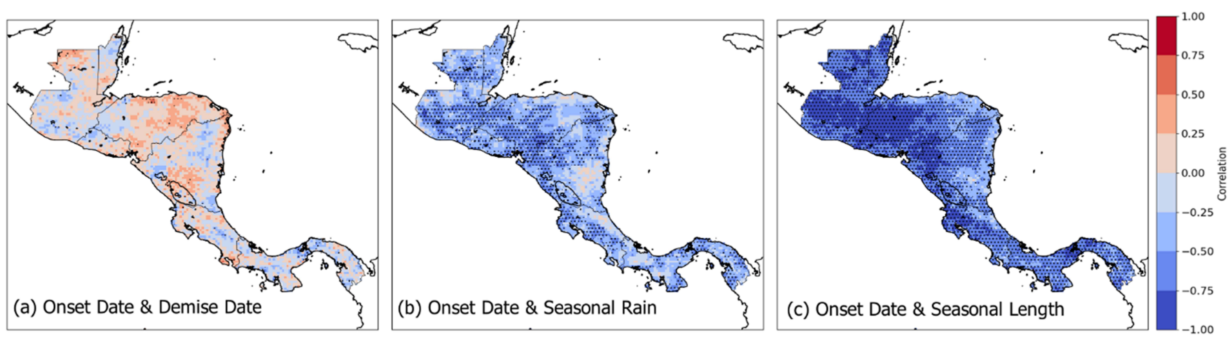

Figure 2: The correlations of the onset date with anomalies of (a) demise date (b) length, and (c) seasonal rain. The statistically significant values at a 5% significance level according to the t-test are stippled.

Similarly, the correlations of the demise date variations with the corresponding anomalies of the length of the wet season are shown in Fig. 3a. In comparing Fig. 3a with Fig. 2a, we notice that there is significant overlap in the regions where demise and onset date variations affect the seasonal length. However, more subtly, we find that in some of the regions along the Atlantic coasts of

Nicaragua and Honduras, the demise date variations have a significant correlation with length of the wet season (Fig. 3a) compared to the insignificant correlations between the onset date and length of the wet season in Fig. 2a. In contrast, the correlations between the onset date and the seasonal length are relatively significant in western Honduras (Fig. 2a) while the correlations between demise date and length of the season are weak (Fig. 3a). But given that in many of these regions the co-variability between onset and demise dates are weak (Fig. 2c), their corresponding influence on the seasonal length and seasonal rain are independent of each other. The statistically significant positive correlations in Fig. 3a suggest that early or later demise of the wet season is associated with shorter or longer length of the wet season, respectively.

Likewise, the positive correlations of demise date with seasonal rain over Panama, Costa Rica, parts of the Atlantic coast of Nicaragua and Honduras, and Belize suggest that early or later demise is associated with drier or wetter wet seasons, respectively (Fig. 3b). It is apparent comparing Figs. 3b and 2b, that the regions of overlap with significant correlations are relatively small. For example, the correlations in Fig. 2b over interior Honduras, Guatemala, and the west coast of Nicaragua are strong while it is weak in Fig. 3b, suggesting that variations in onset and demise date complement each other in associating with corresponding changes in the seasonal rainfall. However, unlike onset date variations which offer the luxury to foretell the evolution of the forthcoming wet season the demise date variations can only posteriorly explain the seasonal rainfall anomalies of the wet season. Nonetheless, the seasonal length anomalies have a widespread and significant relationship with seasonal rain of the wet season across Central America (Fig. 3c). There are some exceptions where the length of the season variation does not covary significantly with seasonal rain (Fig. 3c). For example, in the region bordering between Costa Rica and Nicaragua, parts of Atlantic coasts of Nicaragua and Honduras, and some parts of Guatemala where neither the onset date (Fig. 2b) nor the demise date (Fig. 3b) variations have a significant influence on the seasonal rain.

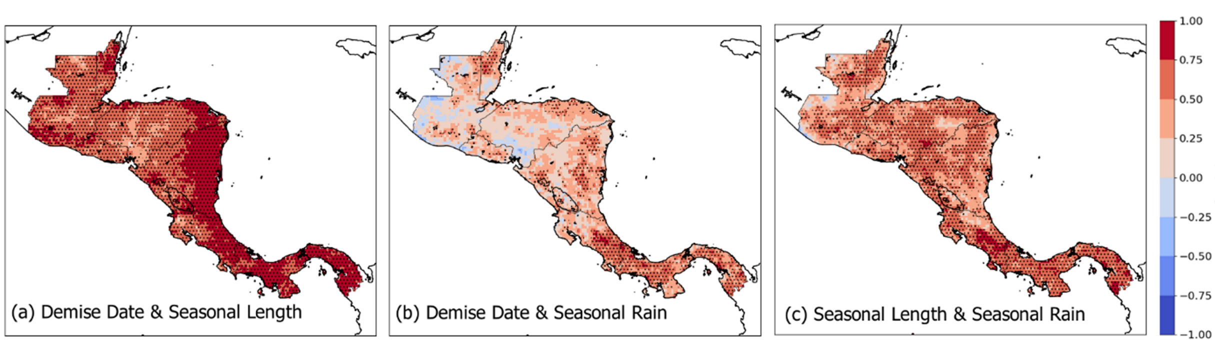

Figure 3: The correlations of the demise date with anomalies of (a) length and (b) seasonal rain of the wet season. (c) The correlations of the seasonal length with corresponding seasonal rainfall anomalies of the wet season. The statistically significant values at a 5% significance level according to the t-test are stippled.

The correlations in Figs. 2a and b and in Figs. 3a and b assume significance in the fact that other potential external forcings like the ENSO variability, the tropical northeast Pacific, and the tropical Atlantic warm pool variations have comparatively far less bearing on the seasonal variations of the wet season of Central America (Figs. S5-S7). In other words, the correlations in Figs. 2 and 3 reflect the local relationships that dictate the seasonal evolution of the wet season over Central America, which are not necessarily dictated by large-scale climate variations.

c) Real-time monitoring

Given the comparatively weak external forcing of large-scale climate variability on the wet season variations of Central America (Fig. S5-S7), the relationship between the onset date and the seasonal length and seasonal rain could be exploited for real-time monitoring and outlook of the evolution of the forthcoming wet season. In Fig. 4 we show the area under the Relative Operating Characteristic (ROC) curve for the outlook of seasonal length and seasonal rainfall anomalies based on anomalous early and late-onset seasons. The Area under the ROC curve (AROC) measures the probabilistic skill of the outlook, which is obtained from the 1001-member ensemble of the adopted methodology. The outlook at a given grid point in the domain is considered useful if its corresponding AROC curve is (≥ 0.5; Narotsky and Misra 2021). The anomalous onset dates, length of the season, and seasonal rain are considered when they are not in the middle but extreme terciles. In Fig. 4a, we find that the outlook of a long wet season from early onset has a very high area under the ROC, well over 0.5 across Central America, with rare exceptions in pockets over Costa Rica and along the Atlantic coasts of Nicaragua and Honduras. Similarly, the outlook of the short wet season from the late onset is also promising (Fig. 4b). There are however slightly more widespread regions of low skill scores (< 0.5 area under ROC curve) along the Atlantic coasts of Nicaragua and Honduras (Fig. 4b) compared to outlook from early onset seasons (Fig. 4a). In contrast the skills along the northwestern part of Central America in Fig. 4b are much higher and widespread than in Fig. 4a.

The outlook of the wetter season in early onset seasons also shows considerable probabilistic skill with widespread areas across Central America exhibiting areas under ROC curve

≥ 0.5 (Fig. 4c). From Belize to Panama and in all the intervening countries in between, there are significant regions with the area under ROC curve ≥ 0.5 (Fig. 4c). However, there are also larger pockets of regions with weaker to no probabilistic skill (Fig. 4c) compared to the length of the season (Fig. 4a). Similarly, the outlook of the drier wet season from the late onset of the season also shows widespread probabilistic skill across Central America (Fig. 4d). In fact, the magnitude of the area under the ROC curve in Fig. 4d is slightly higher than in Fig. 4c, suggesting that likelihood of drier season from the later onset of the season has higher probability of validating than the likelihood of wetter season from earlier onset, especially over western Honduras, El Salvador, parts of Guatemala and Belize.

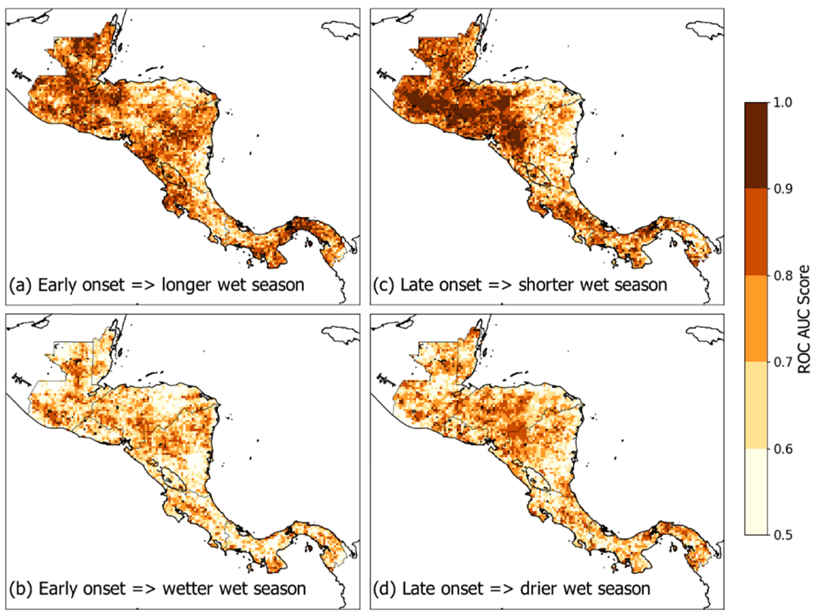

Figure 4: The area under the Relative Operating Characteristic (ROC) curve for the outlook of a) a longer wet season based on early onset, b) a wetter wet season based on early onset, c) a shorter wet season based on later onset, and d) drier wet season based on later onset of the wet season. Only regions with an area under the ROC curve ≥ 0.5, which signifies probabilistic skill that is better than random forecast are shaded.

4 Conclusions

Central America with its complex geography of an isthmus, steep orography, and diverse vegetation features offers a stiff challenge to predict its hydroclimate at all spatial and temporal scales. As shown earlier in this study, the influence of external forcings such as ENSO, tropical northeastern Pacific, and the tropical Atlantic warm pool variations have a very modest bearing on the seasonal variations of the wet season over Central America. Therefore, numerical climate models will require a large ensemble of integrations to discern the internal variations at relatively high resolutions to resolve the impacts of steep gradients of orography, neighboring upper ocean processes, and air-sea interactions on the regional climate, while also having a reasonably low bias to produce useful seasonal climate forecasts.

We introduce a robust and objective way of defining the onset and the demise of the wet season from observed daily timeseries of rainfall. The proposed methodology includes the variations in the length of the season in accounting for the variability of the wet season that is otherwise ignored in the fixed calendar month definitions of the season. We show that the variations in onset and demise dates of the wet season over Central America influence the length and the seasonal rainfall variations of the wet season significantly. Furthermore, the impact of onset and demise date variations on the corresponding seasonal length and seasonal rainfall is found to be relatively independent of each other. With the availability of high-resolution rainfall data like IMERG, the proposed methodology can easily and effectively be adapted for real-time monitoring of the evolution of the wet season over this region.

This study offers a very simple but effective tool to provide an outlook of the forthcoming wet season by simply monitoring the realization of the onset date of the wet season. The methodology, by way of generating an ensemble of estimates of onset and demise dates, allows for the generation of a probabilistic outlook of the wet season. We show that across most of the region in Central America, an early or later onset date of the wet season is closely associated with the longer and wetter or shorter and drier seasonal length and rainfall anomaly of the wet season, respectively. The probabilistic skill scores of such an outlook also support the effectiveness of this local teleconnection. Therefore, the proposed monitoring of the local onset of the wet season would be beneficial in the presence of stiff challenges in seasonal prediction by numerical climate models for the region.

Acknowledgments

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Data availability statement

The IMERG rainfall from NASA was obtained from https://gpm1.gesdisc.eosdis.nasa.gov/data/GPM_L3/GPM_3IMERGDL.06/. All the figures were generated by using python (Van Rossum and Drake, 2009).

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