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Assessment of Precipitation and Evapotranspiration in an Urban Area Using Remote Sensing Products (CHIRP, CMORPH, and SSEBop): The Case of the Metropolitan Region of Belem, Amazon

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Abstract: The aim of this study was to assess precipitation (P) and actual evapotranspiration (ET) by analyzing data from in situ stations compared with remote sensing products. Climate Hazards Center InfraRed Precipitation (CHIRP) and Climate Prediction Center morphing technique (CMORPH) were used for P and Operational Simplified Surface Energy Balance (SSEBop) was used for ET. The P in situ data for six stations were also compared to a reference station in the city. ET was analyzed for a single in situ station. The region chosen for this study was the Metropolitan Area of Belem (MAB), close to the estuary of the Amazon River and the mouth of the Tocantins River. Belem is the rainiest state capital in Brazil, which causes a myriad of challenges for the local population. The assessment was performed using the statistical metrics root-mean-square error (RMSE), normalized root-mean-square error (NRMSE), mean bias error (MBE), coefficient of determination (R2), regression slope, and Nash–Sutcliffe coefficient (NS). For the reference station, the automatic and conventional CHIRP and CMORPH results, in mm/month, were as follows: automatic CHIRP: RMSE = 93.3, NRMSE = 0.32, MBE = −33.54, R2 = 0.7048, Slope = 0.945, NS = 0.5668; CMORPH: RMSE = 195.93, NRMSE = 0.37, MBE = −52.86, R2 = 0.6731, Slope = 0.93, NS = 0.4344; conventional station CHIRP: RMSE = 94.87, NRMSE = 0.32, MBE = −33.54, R2 = 0.7048, Slope = 0.945, NS = 0.5668; CMORPH: RMSE = 105.58, NRMSE = 0.38, MBE = −59.46 R2 = 0.7728, Slope = 1.007, NS = 0.4308. In the MAB region, ET ranges on average between 83 mm/month in the Amazonian summer and 112 mm/month in the Amazonian winter. This work concludes that, although CMORPH has a coarser resolution than CHIRP for the MAB at a monthly resolution, both remote sensing products were reliable. SSEBop also showed acceptable performance. For analyses of the consistency of precipitation time series, these products could provide more accurate information. The present study validates P and ET from remote sensing products with station data in the rain-dominated urban MAB.

Keywords: Amazon; Metropolitan Area of Belem; precipitation by remote sensing products

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1. Introduction

The Amazon is the ideal and largest natural environment in which to perform geophysical science studies. Studies in the Amazon have helped determine its influence on the continental climatology and different characteristics of the hydrologic cycle. Therefore, the Amazon is of great interest to the scientific community [1–3], providing a thorough understanding of water and heat exchanges. Most studies focus on a global perspective, in which the Amazon has a macro-scale influence [3,4], but the Amazon also has an enormous influence on South America's climate [3]; part of the continental precipitation comes from Amazon evapotranspiration, creating a positive feedback loop in the forest [4]. The Amazon also plays a key socio-economic role in the region. Moisture from the Amazon is transported from the forest areas to the main economic regions in the southwest and central parts of South America, preventing the desertification process common to these latitudes around the world [3,5–7]. On a micro-scale, urban areas are studied in relative isolation within their country's context. In Brazil, urban areas are of national interest because of the effects of extreme climatological events on society. Metropolitan areas in the Amazon region are facing more frequent extreme events such as droughts and floods.

This study analyzes the precipitation (P) and actual evapotranspiration (ET) fluxes in the Metropolitan Area of Belem (MAB) within the regional and continental context of the Amazon. P and ET in situ data are assessed and compared to those from remote sensing products. P is obtained from the Climate Hazards Group InfraRed Precipitation (CHIRP) and Climate Prediction Center Morphing Technique (CMORPH) datasets. ET is obtained from the Operational Simplified Surface Energy Balance (SSEBop) product. The MAB was chosen due to its proximity to the estuary of the Amazon River and the mouth of the Tocantins River. The MAB is uniquely relevant because it is the rainiest region in Brazil. Moreover, in the past 20 years, precipitation in the MAB has increased, resulting in the intensification of extreme events [5]. There have been no prior studies on the MAB characterizing ET using solely remote sensing data from SSEBop, a global product that has been influential in studies on other parts of the Amazon.

In the socio-economic context, the MAB is the second-largest metropolitan region in the Amazon. Approximately 2.5 million people live in the area, with an average Human Development Index (HDI) of 0.727, one of the lowest in Brazil [6]. Changes in extreme events are additional challenges to the local communities; their characterization could help to identify adaptation mechanisms that can prevent further negative impacts on local communities.

As the rainiest region in Brazil, the MAB receives a mean annual precipitation of ~2800 mm [7]. Commerce in the Amazon relies mainly on rivers for the transportation of goods and people. This dependence on rivers concerns commerce participants, especially with regard to large cargo boats and transport containers [8]. Furthermore, there is the concern of overflow and flooding inside the MAB region. Lastly, intense precipitation, or lack thereof, for long periods compromises all mobility in the MAB region, while also exacerbating disease occurrence in the wet season [9].

The MAB is located in the eastern part of the Amazon, closer to the Atlantic Ocean, but its climatology is influenced by large-scale atmospheric factors, including those in the Pacific Ocean. The climatology of the MAB is heavily influenced by the surface temperature (SST) of the Atlantic Ocean in its equatorial part [10], the South Atlantic convergence zone (SACZ), the Intertropical Convergence Zone (ITCZ), the El Nino Southern Oscillation (ENSO) [3,11,12], the winds blowing from the sea, and the micro-climate of the area [13,14]. Two general seasons are identified in the MAB region: the wettest season and the wet season. The wettest season starts around December and finishes in May/June, while precipitation is lower during the other season from June to December, with more convection precipitation. Precipitation decreases in this latter season, but it is not low enough to be considered a dry season. There is still a considerable amount of precipitation, characterized by short, intense periods during the day. Thus, locals consider "winter" December to May/June as the wettest season and "summer" June to December as the wet season.

The position of the MAB near the mouth of the Amazon River makes it an ideal place to study the interaction of P and ET fluxes in an urban area within the context of a large-scale ecosystem. The present study focuses on the assessment of P and ET measurements from in situ stations and remote sensing products, which had been unavailable in the contemporaneous literature, especially for large urban areas with high precipitation such as the MAB. The MAB is a heterogeneous environment with a complex mosaic of land use. There are parts that remain protected forest, transitions from forest to cerrado, and urban areas with tall buildings in between houses and farms. This work examines remote sensing data for an urban area in a region prone to floods, high precipitation, and the intensification of extreme events, in the tropics near the equator.

2. Materials and Methods

2.1. Site Description

The MAB is part of the state of Pará, Brazil, and is almost on the equator—only 1 degree below it. Belem is the capital of Pará. The total area of the MAB is 4,876,121 km^2 [15] and includes the cities of Belem, Ananindeua, Benevides, Castanhal, Marituba, Santa Bárbara do Pará, Santa Izabel do Pará, and Castanhal. The most populous cities in the region are Belem (~2.4 million), Ananindeua (540,410), and Marituba (131,500). The MAB has a dense hydrography with small rivers, channels, and creeks within the city, surrounded by the mouths of the rivers Guama, Moju, Acara, and Tocantins, and part of the mouth of the Amazon (Figure 1).

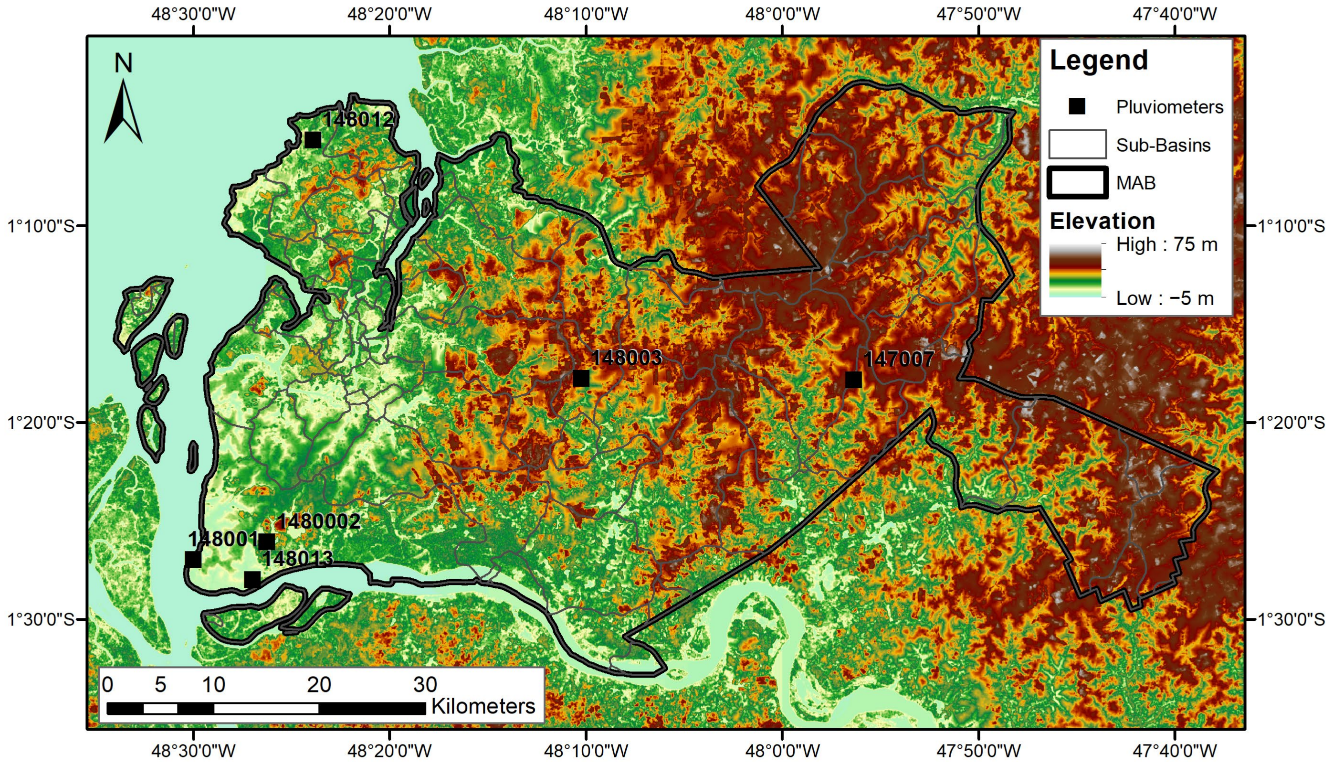

Figure 1. Metropolitan Area of Belem (MAB), sub-basins and hypsometry.

Although it is 200 km from the Atlantic Ocean, the MAB is considered a coastal area. This transition zone of forests, cerrado, and coastal types is unique in Brazil. There is dense forest bordered by replaced forest. In the Amazon Basin, the flatness of the region and the low slope of such a large area mean that it is almost considered continental, with the river basin alone being the same size as Australia (~6,000,000 km^2). The MAB also has a low elevation; in the wet season, combined with tidal forces, spring tides ("marés sizígias"), and intense precipitation, this can be problematic, especially for Belem and Ananindeua.

2.2. Location of Stations, Pluviometers and Data Loggers

The majority of the precipitation stations, the pluviometers, and the data loggers are concentrated in Belem. Figure 1 shows the MAB, its elevation, the sub-basins, and the locations of the pluviometers used in this study. The reference station used is coded 00148002 by the National Water Agency (ANA)—hidroweb.ana.gov.br/ (accessed on 15 June 2020). This station is operated by the National Institute of Meteorology (INMET)—https://portal.inmet.gov.br/ (accessed on 17 June 2020), with code A201/82191 from the World Meteorological Organization (WMO) and is both conventional and automatic. The conventional station is equipped with a pluviometer; every day, around 07:00, the precipitation for the day is manually collected. This provides 1-day precipitation data, not 24 h data. In contrast, precipitation data can be collected remotely from the automatic station and sent to satellite, Wi-Fi, mobile, or saved in a data logger. The automatic station uses electronic devices. Usually, these pluviometers are tipping buckets. The set-up of the time between registered measurements depends on the user and the purpose of the data. The automatic pluviometer that was used from INMET records the precipitation every hour, even if it does not rain. The reference station 00148002 is the only site with ET data available for this study in the MAB region. The locations of the stations used in this study and the sub-catchments are shown in Figure 2. The drainage of the MAB, surrounding tributaries, and rivers form the Baia do Guajara.

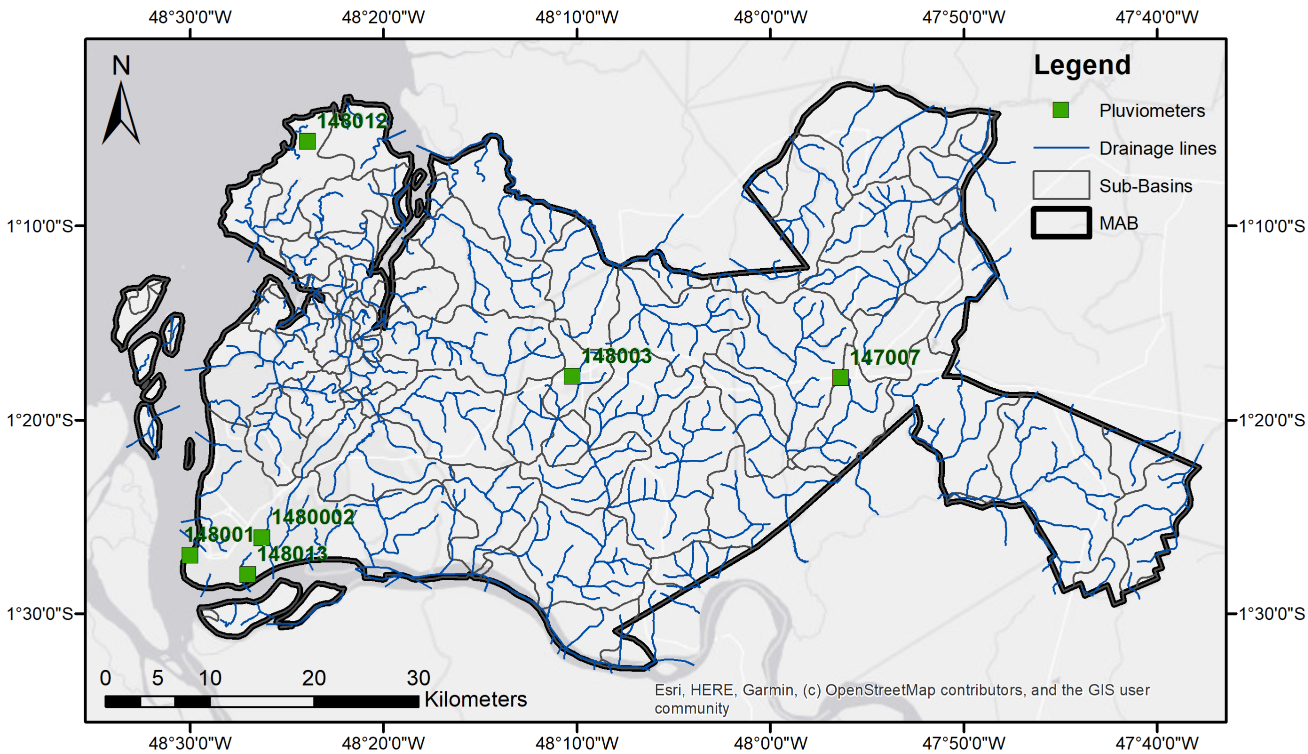

Figure 2. Map of the localization of the stations, hydrography, and sub-basins.

The drainage data were obtained from ANA, in which a high density of rivers and creeks are present. Moving further west, the altitude increases sharply (Figure 3).

Station 00148002 was considered the reference station due to its records length reliability. These records include information on interstate and international data transfers and share critical hydrological events, water balances and availability, long-term changes and trends [12], water quality, and the regulation of water resources [11]. In addition to being a complete station, there is a proper observer at the location, recording three readings per day at 09:00, 12:00, and 18:00, Brazilian time (−3 UTC), in addition to the automatic data logger.

The support station readings are recorded by an observer between 07:00 and 08:00 daily. It is recommended that the readings be recorded at 07:00, but there is a time lag due to variability in the coordination and logistics of the local personnel. They register the daily rain in a pluviometer booklet, which is collected every three months by SGB or uploaded to social media as a mobile picture. After an initial quality control and quality assurance process, the records are included in the central database at ANA.

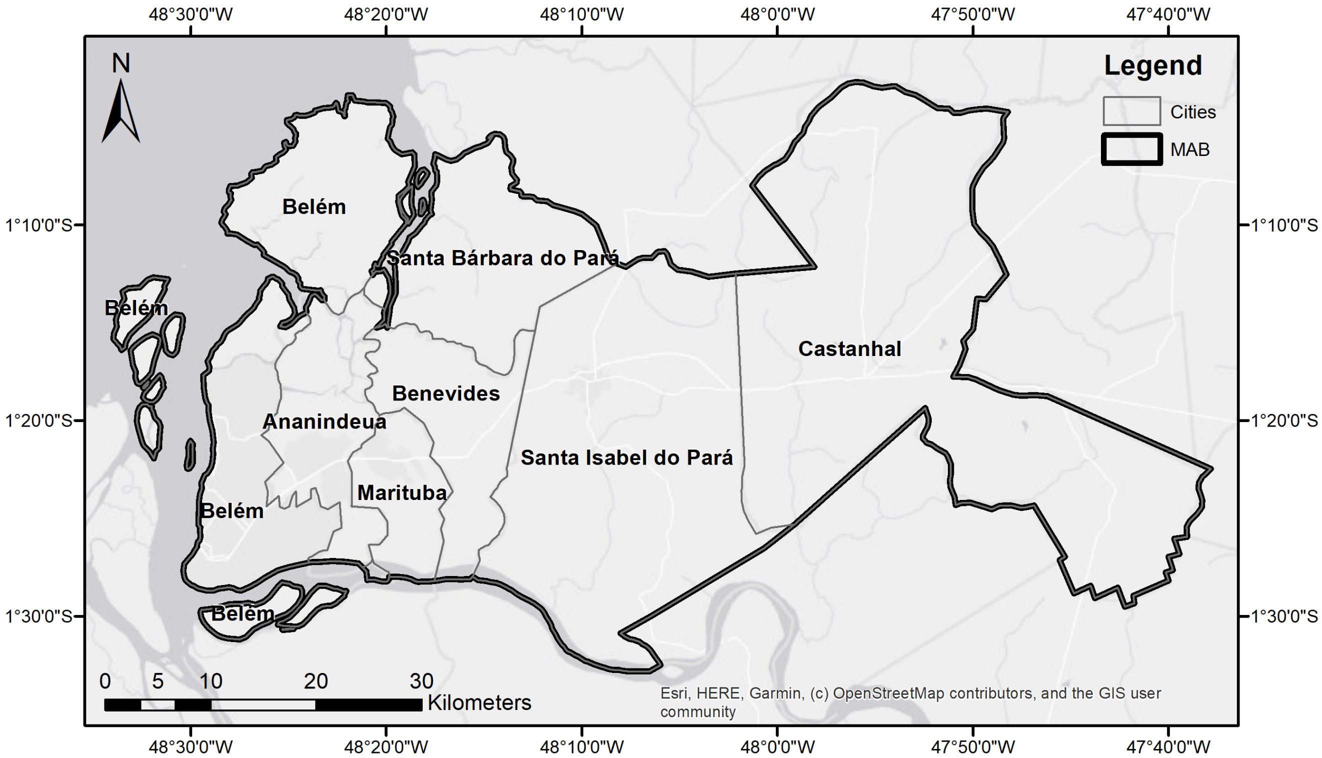

Figure 3. Map of cities in the MAB, with the capital Belem.

There are also long-term time series from in situ conventional stations (pluviometers) to be compared with data from the automatic and conventional reference station.

Table 1 shows the codes and names of the stations, their latitude and longitude, and the period compared to the satellite products.

Table 1. The in situ stations used for analyses with CMORPH and CHIRP for P and SSEBop for ET.

Code	Name	Latitude	Longitude	Variable	Start	End
00147007	Castanhal	−1.2975	−47.9394	P	January 1981	December 2020
00148001	Belem EMBRAPA IPAGRO	−1.4500	−48.5000	P	January 2000	December 2013
00148002	BELEM INMET	−1.4350	−48.4378	P	January 2003	December 2018
				ET	January 2011	December 2020
00148003	Santa Isabel do Para	−1.2964	−48.1708	P	January 1981	December 2020
00148012	Mosqueiro	−1.0942	−48.3986	P	January 1984	December 2020

Actual evapotranspiration (ET) is measured at station 00148002 following the FAO 56 guidelines [13]. The equipment at site 00148002 measures precipitation, net radiation, soil moisture at four different depths, wind speed, wind direction, and evaporation from an evapometric pan. The land cover at the site is trimmed grass; ET is calculated using the Penman–Monteith equation [13].

2.3. Data Analysis

The data analysis objective is to calculate the difference and bias between the in situ stations and remote sensing products through statistical metrics at different time intervals. Conventional observations and hourly automatic data from station 00148002 for the same period were used. The data were aggregated into daily, monthly, and annual time steps. The data from the other stations were obtained, analyzed, and aggregated to evaluate their concordance with the reference station data.

Table 2 provides a summary of the satellite products that were compared with the stations. However, CMORPH has a coarse resolution of ~25 km, and a square root of ~5 km.

Table 2. Overview of global-scale satellite-based products. The column "gauge" indicates whether a product is calibrated against ground data; N indicates no.

Product	Main Principal Data	Resolution	Spatial Coverage	Minimum Time-Step Interval	Producer
CMORPH	Microwave estimates (DMSP F-13, 14, and 15 (SSM/I); NOAA-15, 16, 17, and 18 (AMSU-B); AMSR-E; and TRMM (TMI)), IR motion vectors	0.25°	50° N–S	3 h	NOAA/CPC
CHIRP	Microwave estimates (TMPA, TRMM, 3B42-RT/3B42/2B31, CHPclim, CMORPH)	0.05°	50° N–S	daily	Climate Hazards Group (CHG)

Improvements have been made in the performance of the satellite products, which have become better and more reliable since 3B42 and 3B43 [12,16]. Additionally, pluviometers are used for correction, such as for CHIRPS [17–19]. Complementary analysis methods can include pluviometers, satellite products [17], and modeling. We opted for the first two options.

For the automatic station 00148002, 11.3% of the daily data were registered as "NaN" values. On the other hand, the conventional station had only one gap in 2017.

Table 3 presents the number of precipitation days and the seasonality of the rainfall in Belem. These data are representative as the reference station is located in this city. As the objective of this work was to check complementary information and assess it, we opted to not fill the gaps in the records.

With this amount and number of days of precipitation, and as there is no correction in the remote sensing products, we opted to use the following statistical metrics to ensure confidence in the analyses. The metrics used to evaluate the models were the root-mean-square error (*RMSE*) (Equation (1)), the normalized root-mean-square error (*NRMSE*) (Equation (2)), the mean bias error (*MBE*) (Equation (3)), the coefficient of determination (R^2) (Equation (4)), the *slope* (Equation (5)), and the Nash–Sutcliffe (*NS*) coefficient (Equation (6)).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(station_i - model_i)^2}{n}} \quad (1)$$

$$NRMSE = \frac{RMSE}{\mu_{station}} \quad (2)$$

$$MBE = \frac{1}{n}\sum_{i=i}^{n}(model_i - station_i) \quad (3)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(station_i - (slope \cdot model_i + intercept))^2}{\sum_{i=1}^{n}(model_i - \mu_{model})^2} \quad (4)$$

$$slope = \frac{\sum_{i=1}^{n} station_i \cdot model_i}{\sum_{i=1}^{n} model_i^2} \quad (5)$$

$$NS = 1 - \frac{\sum_{i=1}^{n}(station_i - model_i)^2}{\sum_{i=1}^{n}(station_i - \mu_{station})^2} \quad (6)$$

where $station_i$, $model_i$ are the measurements from the station or the remote sensing model, respectively, for the ith month or year, μ is the mean, the *slope* and *intercept* are the parameters from the linear regression, and n is the number of available measurements. Equation (1) assesses the square root of the errors to avoid the positive and negative deviations from canceling each other out. Equation (2) aids in the comparison of RMSE values by normalizing them to the coefficient of variance. Equation (3) indicates the estimation of the model. Equation (4) calculates the coefficient of determination, which describes the model fitting with a value between 0 and 1; here, 1 indicates perfect relevance, which is rare. Equation (5) gives the steepness of the line, which indicates whether the model is over- or underestimating the values. In Equation (6), the Nash–Sutcliffe coefficient is obtained by dividing the variance into the time series.

In addition, the stations were assessed via traditional methods, such as double mass analysis, to review the data consistency.

Table 3. The number of rainy days and the seasonality of precipitation in Belem from 2000 to 2019.

Number of Days with Rain (NDR)													
Year	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**NDR**
2000	28	27	29	30	27	21	25	24	22	24	10	23	290
2001	29	27	29	29	26	25	21	11	20	20	20	20	277
2002	29	26	28	26	27	26	18	15	13	23	20	26	277
2003	24	23	27	25	24	23	14	16	18	18	19	25	256
2004	22	28	30	27	24	20	22	22	26	18	13	19	271
2005	25	28	29	26	29	19	15	13	19	14	18	25	260
2006	26	25	31	29	31	20	14	19	15	15	21	26	272
2007	28	27	29	27	27	24	21	15	19	22	14	27	280
2008	29	27	28	27	23	22	16	8	17	13	12	20	242
2009	29	28	29	25	28	23	16	14	18	15	9	25	259
2010	26	25	27	28	26	19	17	15	15	14	17	21	250
2011	27	25	29	25	26	19	19	21	13	17	16	22	259
2012	27	29	31	26	23	27	24	15	17	12	10	25	266
2013	28	27	29	28	28	22	3	17	18	20	22	23	265
2014	26	27	29	30	27	22	21	14	18	13	0	20	247
2015	29	25	27	28	28		24	10	15	13	12	25	
2016	26	29	30	25	23	24	21	15	13				
2017						20	9	16	13	20	15	23	
2018	28	26	28	29	29	12	17	19	13	17	22	29	269
2019	29	24	29	26	26	19							
Mean	26	26	28	26	25	20	18	15	17	15	14	21	252

3. Results

The statistical metrics and plots between the station data and remote sensing products are presented for precipitation (Section 3.1) and evapotranspiration (Section 3.2). Section 3.1 *Precipitation* firstly presents the statistical metrics between the station data and both remote sensing products (CHIRP and CMORPH) at monthly and annual time intervals (Figure 4). Secondly, the analysis and metrics for the pluviometric reference station (00147002) are presented (Figure 5). Thereafter, the statistical metrics and scatter plots for the conventional station are shown at daily (Figure 6), monthly (Figure 7), and annual (Figure 8) time intervals; the time-series plots are also shown for daily (Figure 9) and monthly (Figure 10) time intervals. Lastly, the inter-daily precipitation is assessed at the conventional station site (Figure 11). A summary of the statistical metrics for the precipitation analysis is given in Appendix A.

Section 3.2*Evapotranspiration* first shows a comparison of the mean and maximum ET time series in the MAB using SSEBop (Figures 12 and 13). Then, the inter-annual range of ET in the MAB using SSEBop is presented (Figure 14). Lastly, the SSEBop data are compared against the station measurements at site 00148002, through time-series plots (Figure 15) and the analysis of the inter-annual ET range (Figure 16).

3.1. Precipitation

This study uses visualization and metrics to compare the support stations to the reference station. Methods, such as double mass, show simple concordance between the precipitation data in the surroundings. In this section, we present plots for each selected in situ station validated against CMORPH and CHIRP. The metrics are shown in each figure and in Table 3. The main type of precipitation is convection rainfall, and as observed in Table 3, rain occurs almost every day in the region.

The models vs. stations are analyzed for each month and year in the scatter plots; a closer inspection, per day, was available for 00148002, but this is not a reasonable increment to consider. It is shown for further improvements.

Using many metrics is important to properly discuss and evaluate ~5 and ~25 km pixels versus a single station in a metropolitan region, with buildings, urban heat, and local temperature differences, where there is mostly convection precipitation. The convection resolution can be captured by the whole area, but not always by the pluviometer.

Figure 4 shows the monthly and yearly plots for the support stations (00147007, 00148001, 00148003, and 00148012). The monthly results are better, while the yearly data are too scattered. The metrics for the monthly remote sensing products show better performance and are quite similar. CHIRP and CMORPH alone, without station correction, show good results for the monthly analyses. Station 00148001 from EMBRAPA gave the best fit, even though it had fewer records due to its shorter period of available records. CHIRP presented better results than CMORPH.

The tipping bucket pluviometers performed similarly across the support stations, as shown in Figure 3. The stations 00148001 (EMBRAPA) and 00148002 (INMET) are alike in their results, forming one of the better-correlating pairs of stations. The results are good, and CHIRP presented better outcomes than CMORPH. The monthly data are acceptable, but the yearly data are inferior.

The conventional pluviometer has a superior outcome and fewer unsatisfactory data records compared to CHIRP and CMORPH. Unlike the daily data from the pluviometer, the remote sensing products did not capture the day-by-day precipitation, as shown in Figure 6.

Figure 7 presents the metrics and a comparison with the conventional station for CHIRP and CMORPH, as shown in Figures 4–6. The results are satisfactory and suitable for unique precipitation remote sensing products. The MAB is prone to convective precipitation throughout the year. However, when the daily results shown in Figure 6 are accumulated on a monthly basis, the precipitation is better captured and registered. This is in contrast with the daily and yearly values shown in Figure 8.

The daily time series in Figure 16 seems to have an outlier in 2005, but this precipitation was the highest rainfall ever recorded in Belem. It was between 24 and 25 April 2005, and 200.8 mm was observed (hidroweb.ana.gov.br (accessed on 14 June 2020)).

The precipitation in the MAB is convection rainfall, but it is consistent. The precipitation is almost considered continuous, with water pouring down throughout the day.

In the monthly time series, a tiny decrease was observed across the months. The small slope of −0.0006 is in contrast to that in Figure 10, which shows yearly data.

The ENSO system plays a huge role with the SACZ and wind blowing from the sea into the MAB [12]. These driving forces influence climatic events for the whole Amazon. However, in Belem, which is closer to the sea, the effect of the winds is captured. The ENSO system depends on events in the Pacific Ocean. El Nino results in less precipitation in the Amazon, while La Niña results in more precipitation. The intensity of the ENSO influences results in greater extremes and intensification. The yearly data show the contrast with Figure 10. In 2017/2018, the total amount of rainfall was 3800 mm/year.

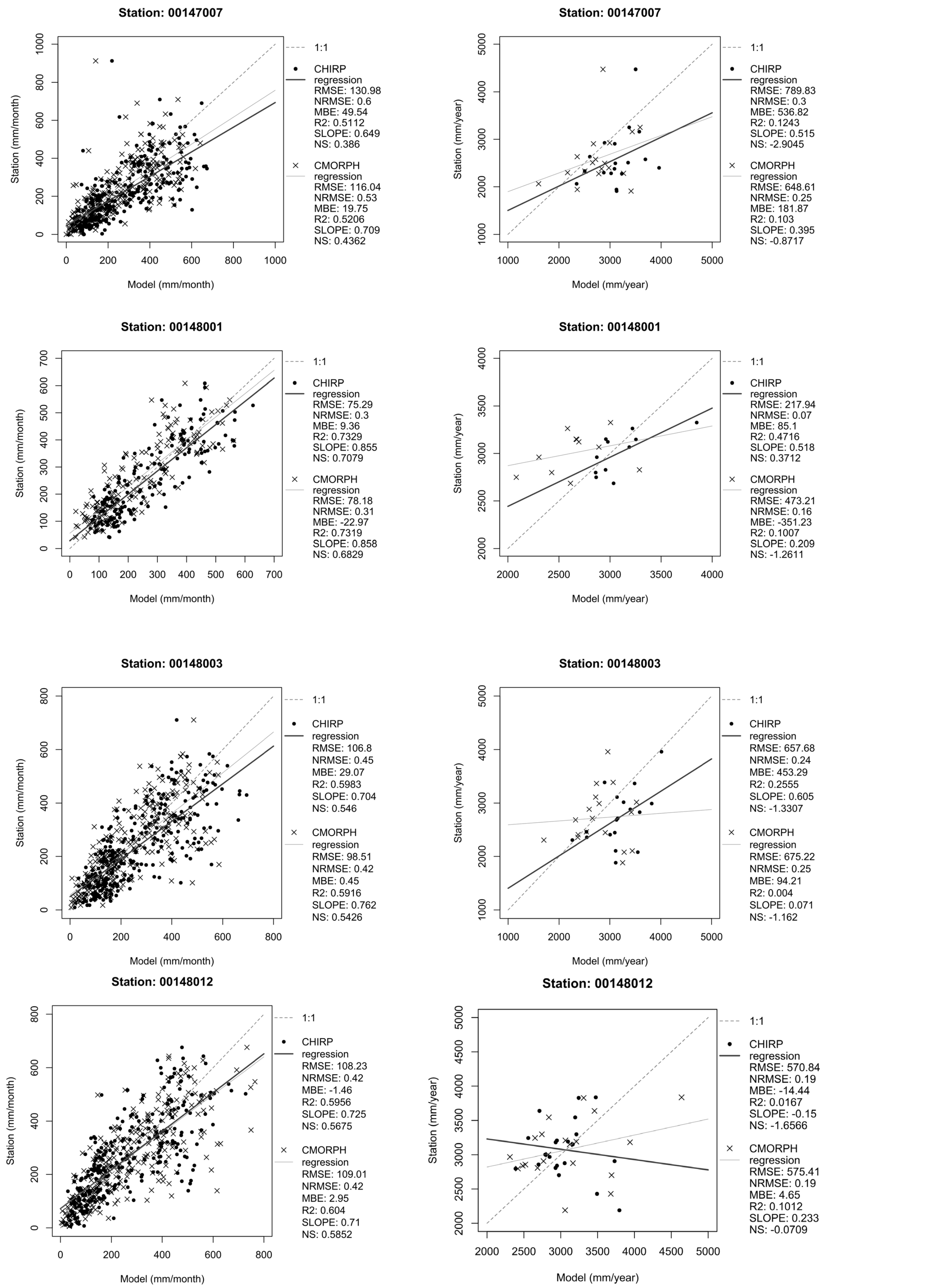

Figure 4. Monthly and yearly data from all pluviometers at the support stations: 00147007, 00148001, 00148003, and 00148012.

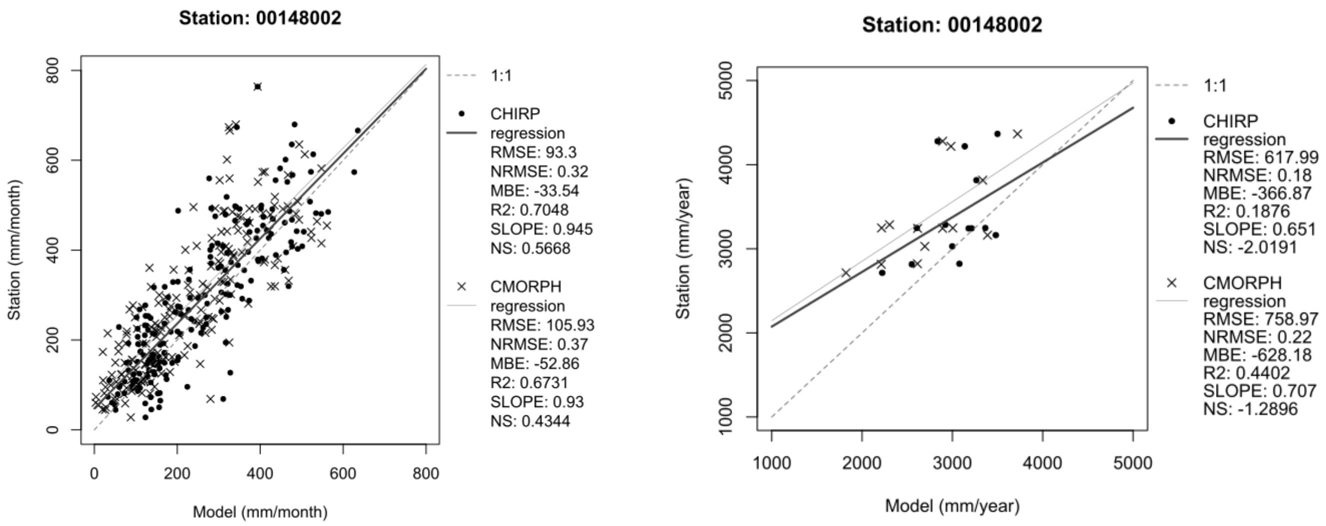

Figure 5. Monthly and yearly automatic pluviometer data for reference station 00147002.

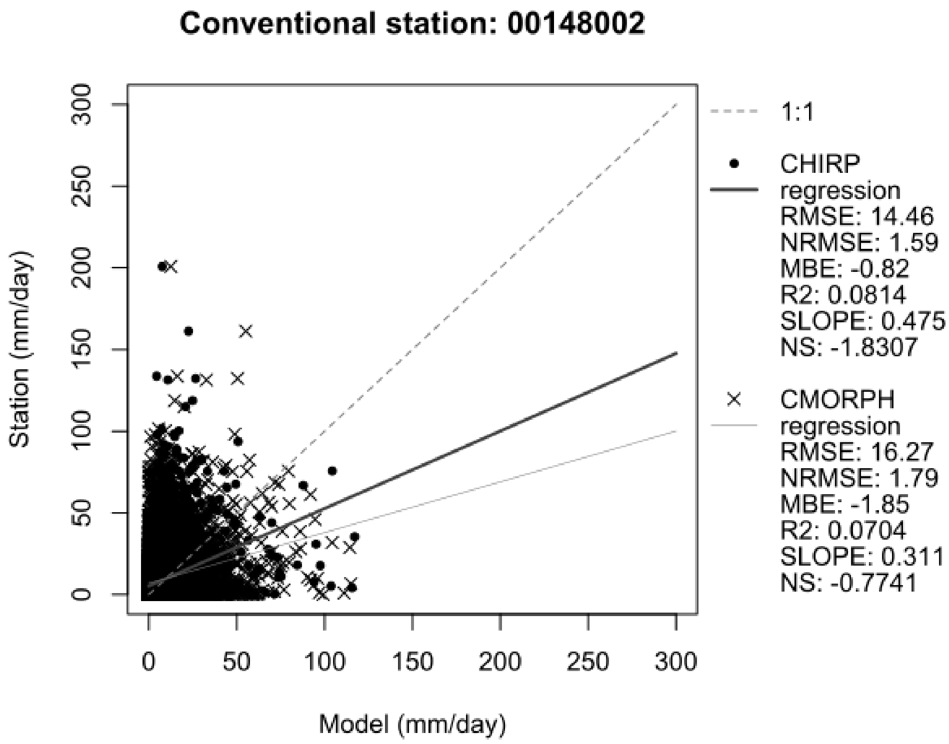

Figure 6. Daily data from station 00148012 from 2003 to 2020.

When the precipitation from the automatic station 0148002 is divided into hourly values, the rainiest hours are 15:00 and 16:00. The precipitation starts smoothly around 13:00, increases until 16:00, and then decreases around 21:00, in Figure 11.

The averages for 15:00 and 16:00 are almost the same, and the box plot also shows this equivalence. However, at 16:00, the maximum value is higher; the rainiest hour also occurs at 16:00, with more than 60 mm/hour.

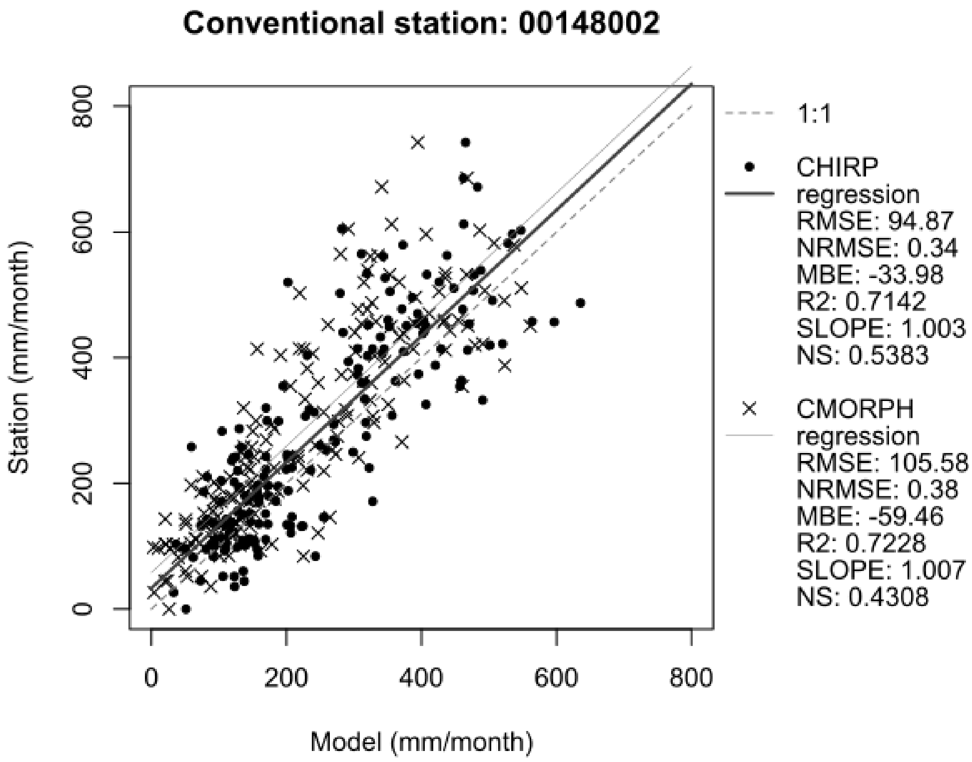

Figure 7. Monthly data from station 00148012 from 2003 to 2020.

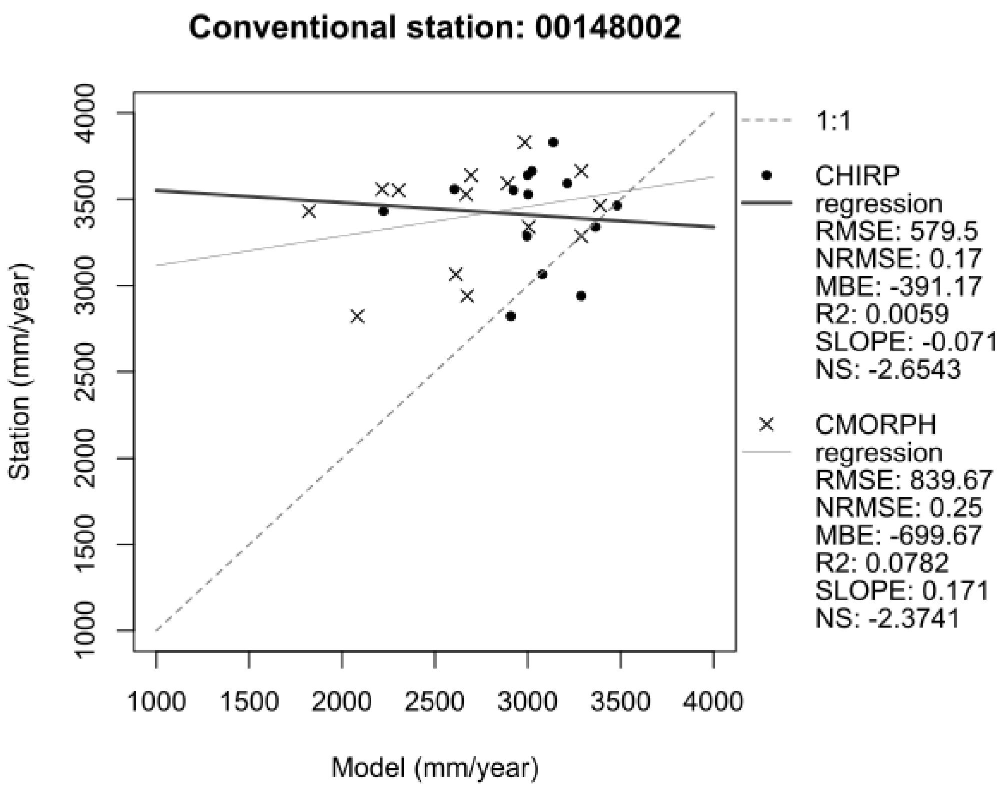

Figure 8. Yearly data from station 00148012 from 2003 to 2020.

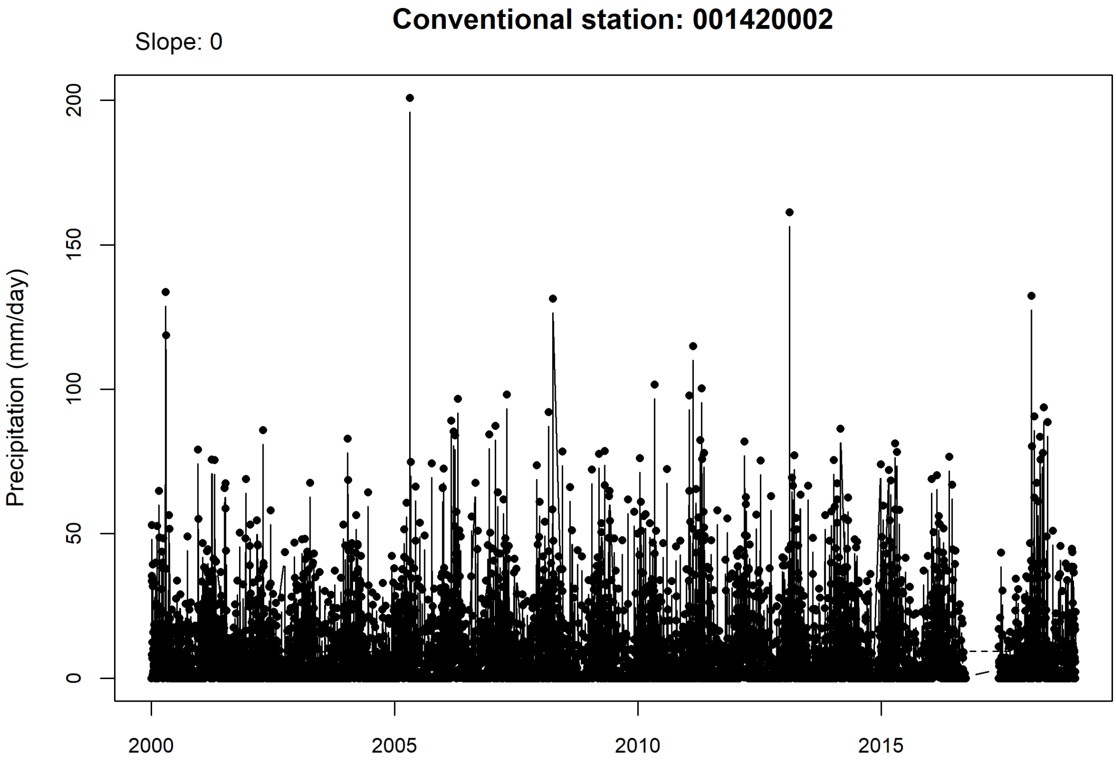

Figure 9. Daily time series from 00148002/INMET.

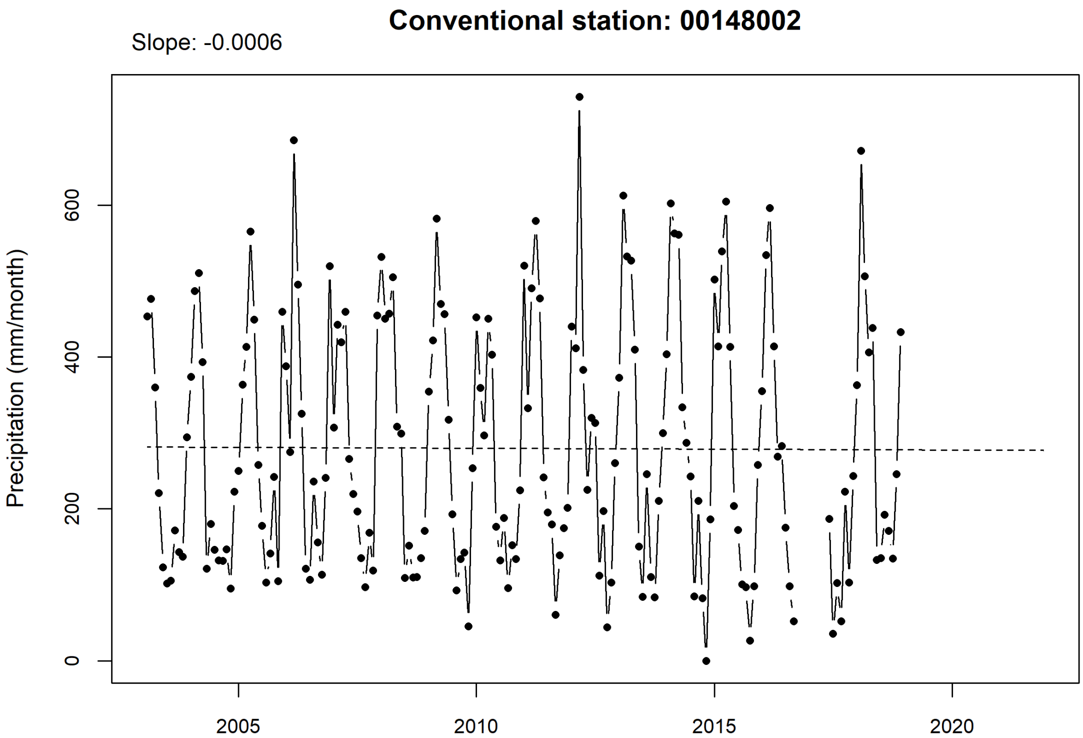

Figure 10. Monthly time series from 00148002/INMET.

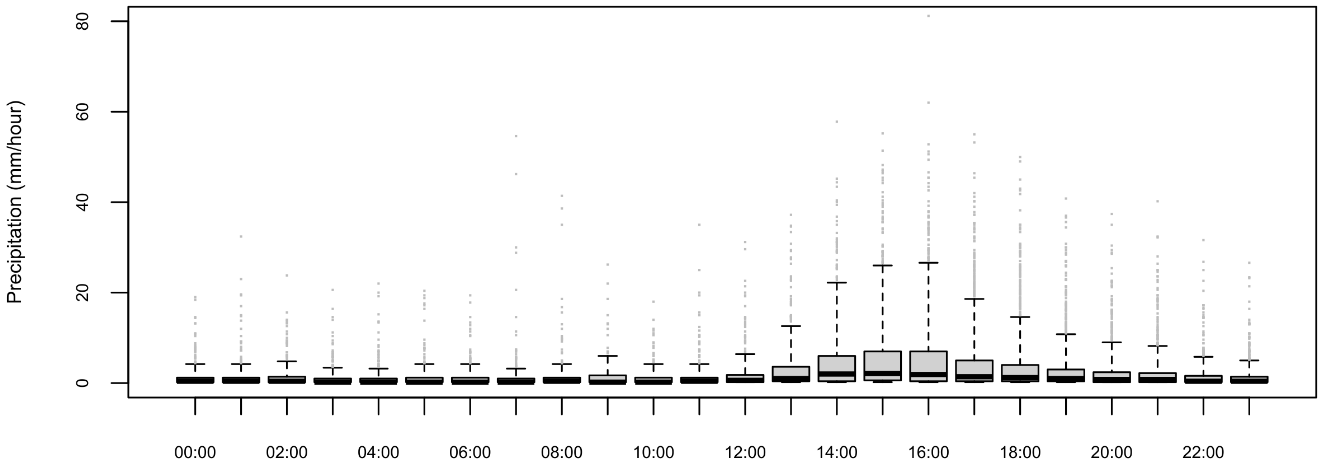

Figure 11. Box plot of hourly precipitation from 2003 to 2020 for the conventional station 00148002.

3.2. Evapotranspiration

SSBEop was used to analyze the evapotranspiration (ET) (https://earlywarning.usgs.gov/fews/ (last accessed on 19 August 2023). SSEBop is provided by USGS, as detailed in Table 4, and was created by Gabriel Senay [16,18,19]. SSEBop is ready to use, and version 5 contains data from 2003 up to 2019. Its use was validated with flux towers in the Amazon by Paca et al. [20] with suitable results. ET in situ data from the 0148002 station were used, with a temporal extent from January 2020 to December 2020.

Table 4. Overview of the global-scale satellite-based product SSEBop.

Product	Spatial Resolution	Temporal Resolution	Version	Latitudes	Ongoing Product until Present	Main Data Input
SSEBop	0.01°	Monthly	5	90° N–90° S	Yes	TIR/VIIRS

Table 4 shows the monthly ET at 0.01°~1 km spatial resolution, which was considered acceptable for this work to evaluate ET for the MAB.

Figure 12 presents analyses of the maximum ET compared to the mean ET in the MAB region. The maximum values probably occur closer to the shores of the MAB, in the city of Belem, where the landscape is flat. The average values show the same pattern as the maximum values.

The pattern of the average ET values in the MAB is coherent with that of the values in the greater Amazon [17,20]. There is a low spike in 2010, which can be considered an error after closer analyses; the values otherwise range between 70 and 120 mm/month, as shown in Figure 13.

The overview of all the mean ET values over the MAB shows a pattern similar to that for precipitation in Figure 14, starting in December/January and ending in May/June. When precipitation is occurring, the vegetation releases less ET. During the season with less rain, there is greater ET.

The mean annual and monthly evapotranspiration values are similar for SSEBop and the in situ data at site 00148002. The mean annual evapotranspiration between 2011 and 2020 is 852.7 mm for SSEBop and 852.2 mm for the station. The mean monthly ET for the same period is virtually the same (71 mm) for both datasets. Nevertheless, ET from SSEBop has a higher amplitude than the ET data from the station (Figure 15) at a monthly time interval. In addition, there is a likely phase shift between the two datasets.

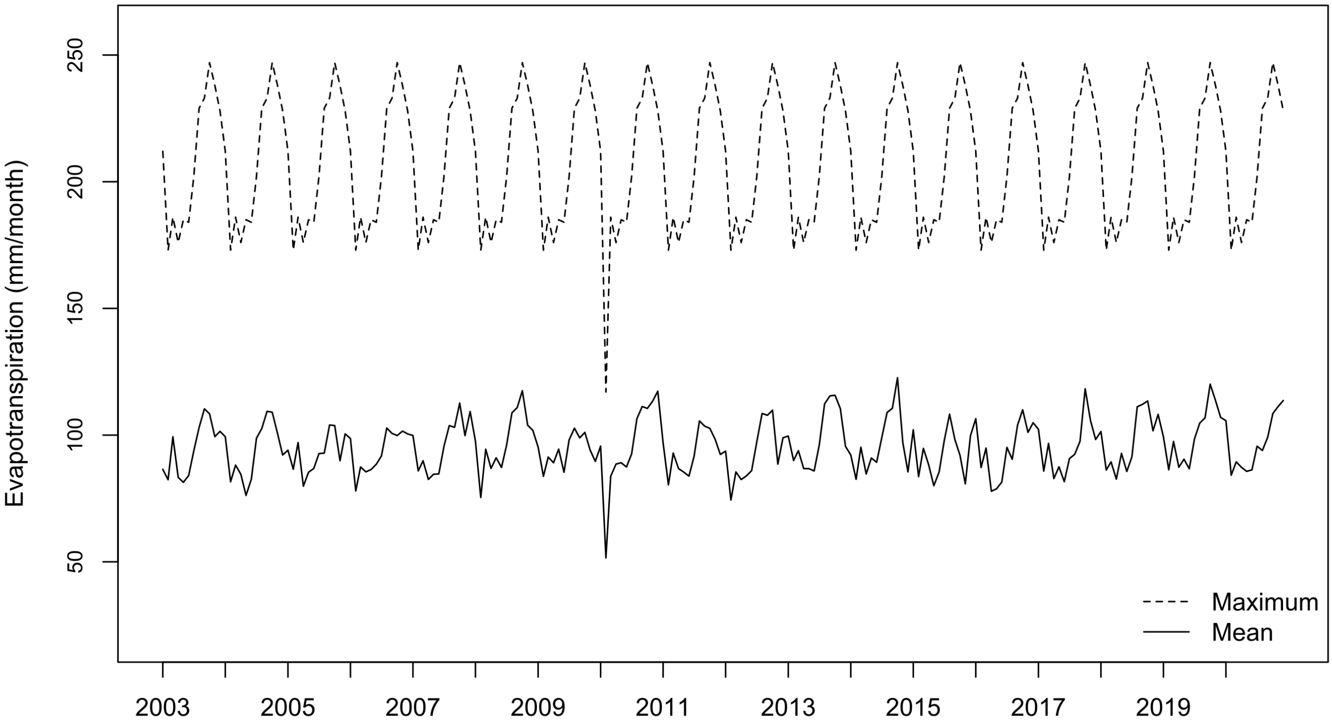

Figure 12. The maximum and mean ET in the MAB region from SSEBop.

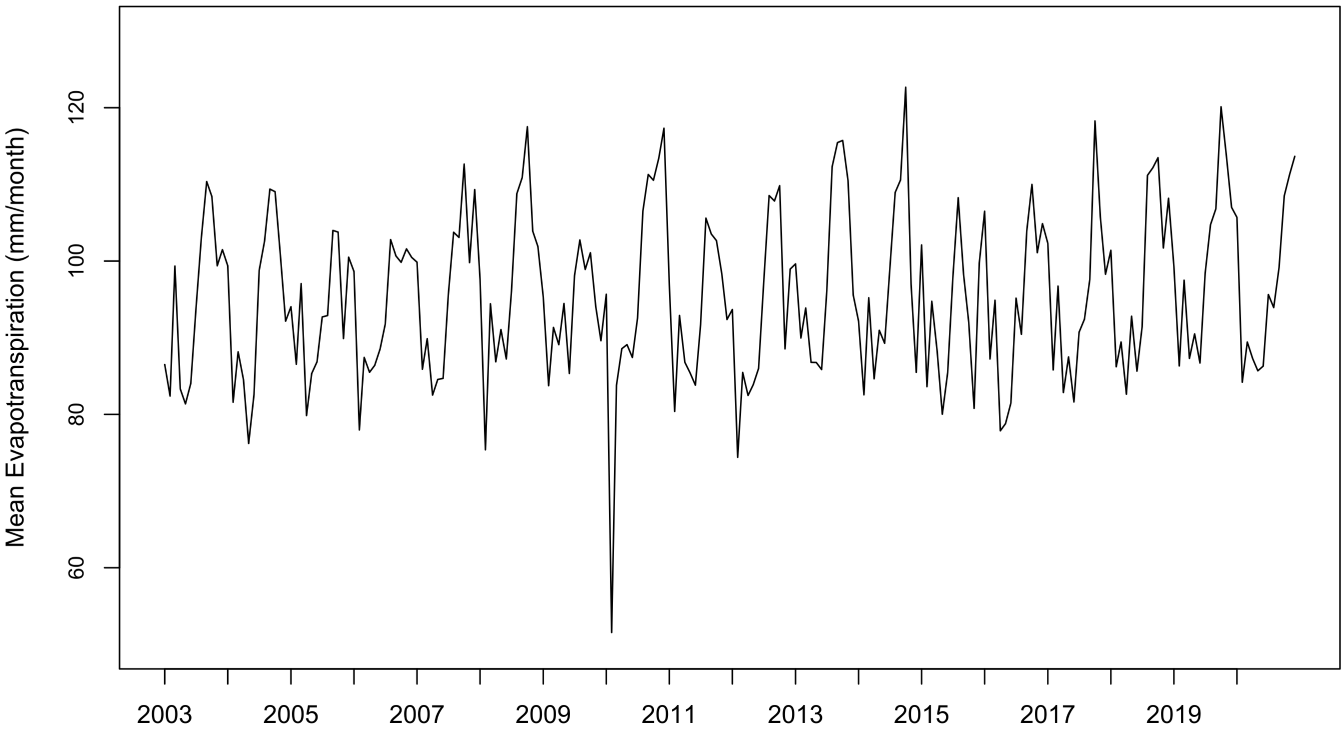

Figure 13. Mean ET values in the MAB obtained from SSEBop.

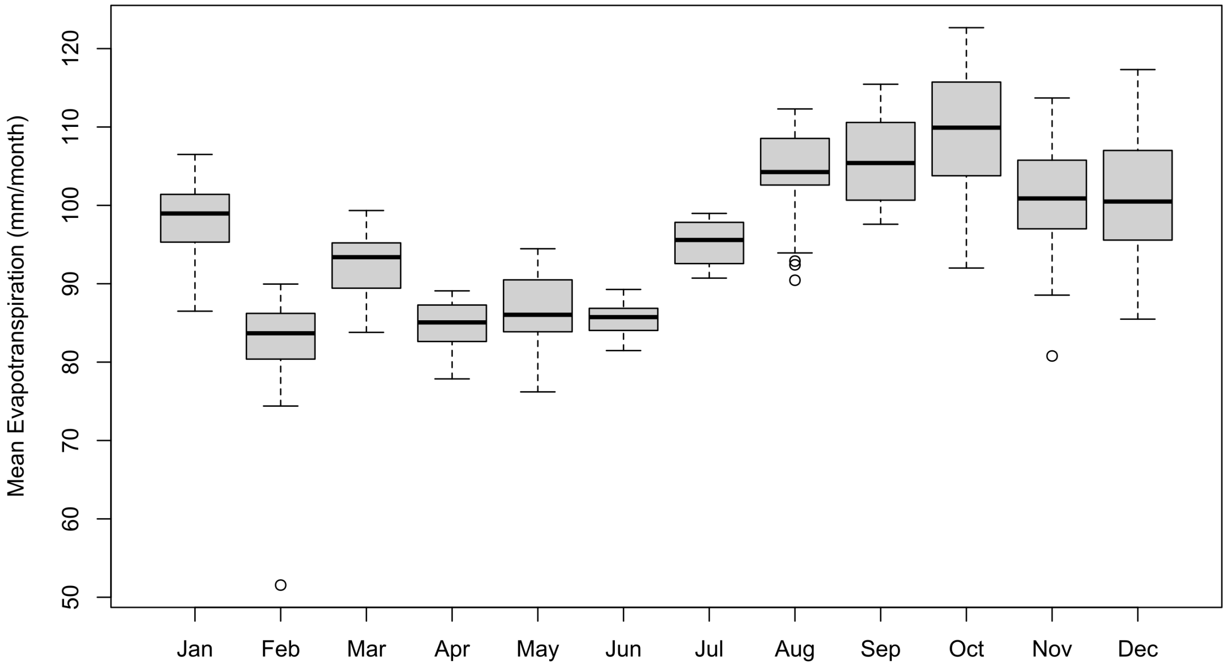

Figure 14. Box plot showing the inter-annual ET range in the MAB using SSEBop.

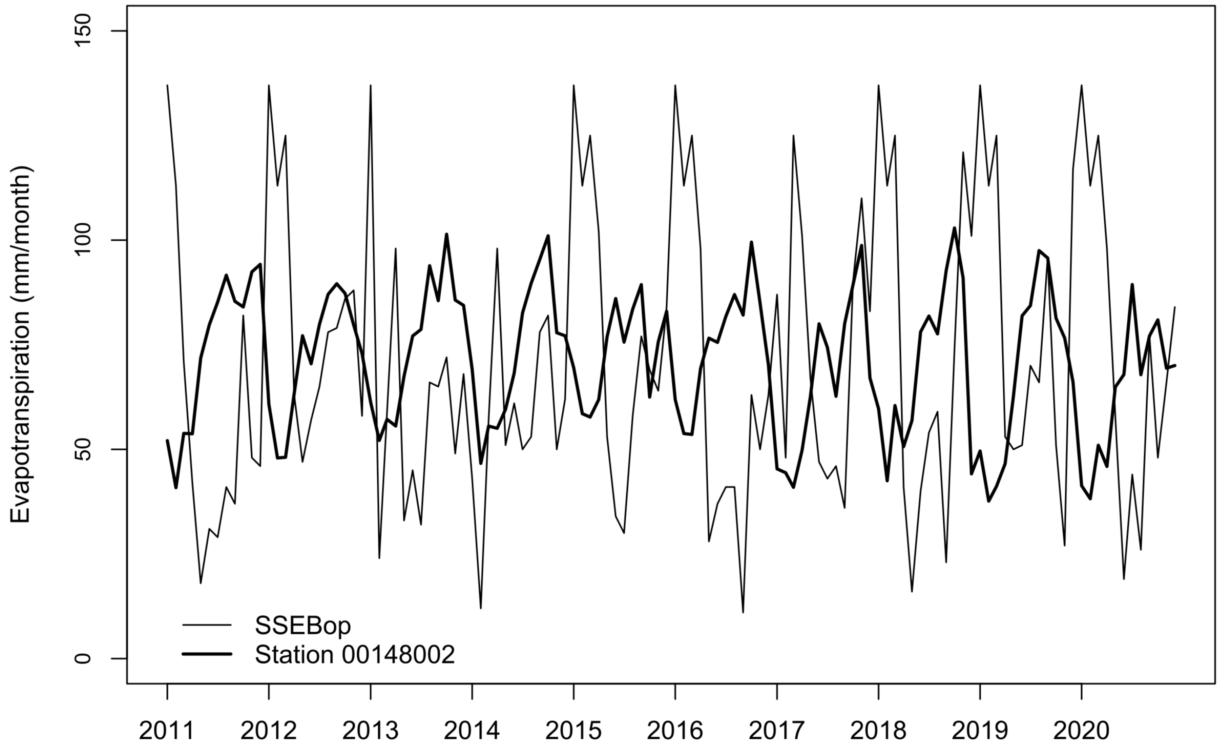

Figure 15. Evapotranspiration at site 00148002 from SSEBop and in situ measurements.

Figure 16 shows the inter-annual variation in ET for SSEBop and in situ data at the site 00148002 for the period between 2011 and 2020. The station data follow the same pattern as the one for the mean MAB region. The station shows more consistency in the results throughout the years while SSEBop has a larger variation due to its higher frequency in the ET signal. Furthermore, the difference between both datasets varies at each season of the year. The NRMSE for the wettest season (December–May) is 0.88 which is more than double the 0.40 in the wet season (June–November).

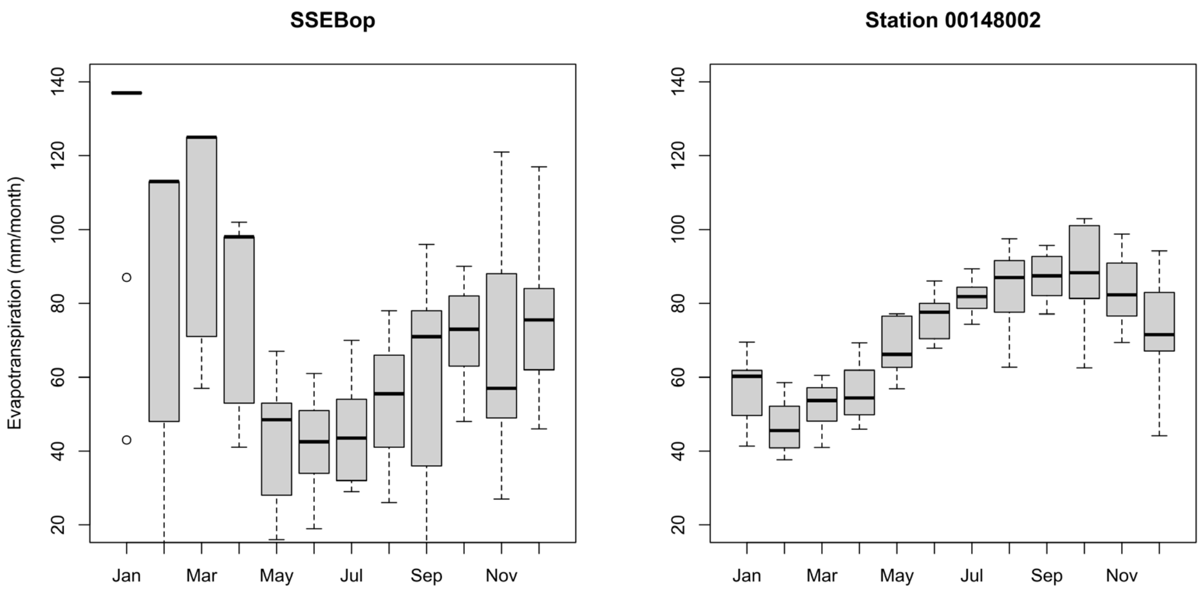

Figure 16. Inter-annual variability of evapotranspiration in the Metropolitan Area of Belem (MAB) from SSEBop and station data at site 00148002.

4. Discussion

The Metropolitan Area of Belem has two divisible parts—the west is flatter and the east is higher. However, the remote sensing products CHIRP and CMORPH showed similar precipitation. The lower resolution of CMORPH, at approximately 25 km, could not explain the whole precipitation of the region. CHIRP, with a finer resolution of around 5 km, showed better results. Despite the fact that both showed similar results in the analyses and metrics, CHIRP developed a better performance than CMORPH.

The conventional station used as the reference station showed poor results at the daily and yearly scales, as did the support stations. However, at a monthly temporal resolution, CHIRP showed a slight increase in model overestimation, with a slope of 1003. CMORPH showed a slight underestimation. Both coefficients of determination were approximately 0.72, which is very promising for solely remote sensing products. The Nash–Sutcliffe efficiency for CHIRP was equal to 0.53, and that for CMORPH was equal to 0.43. This is reasonable, sitting midway between 0 (low fit) and 1 (best fit), and it is in accordance with the other metrics. The RMSE was scattered, with the upper part more out of line than the lower part, beginning at 400 mm/month.

The station 00148002 (INMET) time series showed consistency during the period of study. Even the daily and monthly scales showed standard variation. The slope was −0.0006, showing a slight underestimation and a decrease, which indicates an increment or decline in the precipitation. The average precipitation was 75 mm/day and 280 mm/month. Five unusually high periods of precipitation were registered, but none of them are outliers—they really did occur. The period of 24/25 April 2005 was the rainiest, with 200.7 mm/day recorded.

However, the results from the automatic station (the tipping bucket pluviometer) were the worst compared to those from the station with an observer who manually collects the data four times a day. This could be due to a lack of calibration of the equipment or the high temperature of Belem, which is located just −1 degree in latitude relative to the equator. The results from the automatic station began to scatter at 200/month, with both slopes underestimating the time series at 0.7. The coefficient of determination was middling, at around 0.6. The NSE was equivalent.

It was hypothesized that it would rain more at night, when people do not observe precipitation but the equipment records it. The true precipitation ended up aligning with the common knowledge of the local population, with the precipitation being strong between 14:00 and 18:00, and the rainiest hour at 16:00, for the whole period of records.

It is worthwhile to mention that the best support station was station 00148001 (EMBRAPA). At the monthly scale, the model NSE was around 0.7, showing a good fit, with a high slope of approximately 0.8 underestimating the precipitation, and a coefficient of determination of 0.73 for CHIRP and CMORPH. The other stations showed lesser, medium values. Station 00148003 (Santa Isabel do Pará) showed the second-best agreement with station 00148002.

Unfortunately, for all stations, CHIRP and CMORPH performed poorly in all annual analyses, and for the reference station in daily analyses. This is a relevant aspect to consider.

The results were smaller than those for 00148001 (EMBRAPA), with the advantage of being more distant than 00148002 INMET. For consistent data, this is a valuable station due to the separation in between.

The evapotranspiration was more consistent, but there were outliers such as 0 and 287 mm/month in the maximum and minimum. This is why we opted for a closer inspection of the maximum and the mean. The average values were consistent with the area and also at site 00148002. The comparison between SSEBop and the station data at site 001148002 was performed using a single pixel. The results suggest that taking an average between surrounding pixels (e.g., for the MAB region) can improve the ET inter-annual signal, reducing the difference in estimation between datasets. ET from SSEBop was consistent between 2002 and 2020, except for 2010 which can be considered an outlier. The variation in the mean ET data between 77 mm/month and 120 mm/month was expected in the analyses for the study area. The maximum recorded was 180 mm/month.

The box plot of the average ET shows the buffer effect on vegetation: in the rainy season, less ET is released, while in the drier season, more ET is delivered. The median is also in agreement with the precipitation period. The highest ET occurs in September to November, with the highest in October. This is the same as the precipitation. The lowest median was in the interval of February to May.

CHIRPS uses the CHIRP methodology but is corrected with station data. CHIRPS [21] has shown better performance and has been well implemented in many studies by the scientific community. CMORPH is also broadly used and is analyzed for comparison with CHIRP. Both CHIRP and CMORPH can be used as a starting point for research, or even as a complete basis, such as with CMORPH. CHIRP uses solely remote sensing, and CHIRPS is corrected with the precipitation station bias. That is why when CHIRPS is compared to the precipitation stations, it fit almost the same [22].

This study on the MAB also relates to the environment and sanitation; according to Sistema Nacional de Informações sobre Saneamento (SNIS), 81.2% of the population go without sewage collection (2021), and 35.4% of the population do not have access to water (https://www.painelsaneamento.org.br/localidade/index?id=151 (accessed on 15 June 2020)). If sewage is not collected properly, the water flows straight into the drainage system, creating temporary puddles that may be small or huge. Most of the diffuse and point sewage flows into the drainage system. Because the sewage system is inefficient, and because there is only a small percentage of the city with a proper sewer system, pollution from the water after precipitation flows to channels and is dissipated in the Baia do Guajara.

The performance of remote sensing products at short time intervals such as daily data is considerably inferior compared to larger time intervals. This difference in performance might be due to phase shifts in the remote sensing products, capturing the correct events but with a lag in the temporal dimension. Future research studies or remote sensing products can improve the temporal component, allowing the use of remote sensing products for characterizing the environmental processes of high intensity and short duration.

Among the United Nations' (UN) 17 Sustainable Development Goals (SDGs), this study embraces, in order, SDGs 6, 3, 11, and 13 (https://sdgs.un.org/goals (accessed on 15 June 2020)). The amount of water that enters as precipitation is the major input in the water balance, and assessing the consistency of these data, complimentary to remote sensing products, addresses SDG 6. As the sewage system is inefficient, the drainage system is overloaded and sewage flows into the rivers without any treatment, relating to SDG 13.

Given the impact on the large proportion of poor inhabitants (40.6%), and the GINI index of 0.43, contributing to SDG 3 could help mitigate this disparity (https://cidades.ibge.gov.br/brasil/pa/belem/pesquisa/36/30246?indicador=30246 (accessed on 15 June 2020)).

Science integrated with government and NGOs could also improve the welfare of the MAB toward meeting SDG 11. However, communication and a relationship between these are not yet mature.

5. Conclusions

The present study had the objective to analyze the performance of remote sensing products to estimate precipitation (P) and evapotranspiration (ET) in an urban area with high and stable precipitation. This study compared CHIRP and CMORPH data for P and SSEBop for ET in the Metropolitan Area of Belem (MAB). The MAB is heavily prone to rain throughout the year, especially from December to June and slightly less from June to December. Precipitation is highly likely every day around 15:00 to 19:00 (Figure 11). The precipitation remote sensing products CHIRP and CMORPH captured the pattern of the precipitation. Overall, CHIRP and CMORPH are both in agreement with the station data and with previous studies [12], with an overall bias for overestimating precipitation (Figure 5). In general, precipitation was overestimated for larger precipitation values and slightly underestimated at smaller precipitation values at a monthly time interval.

ET had larger differences between SSEBop and the station measurements at the only available site with data (site 00148002). The differences between SSEBop and the station data are likely due the heterogeneous environment of the urban region and a likely phase shift (Figure 15) between SSEBop and the station measurements. These results are in agreement with previous studies [17,20]. The inter-annual variability of ET in the MAB (Figure 16) was consistent in the station data and had a larger variation in SSEBop. Especially in the period between December and June, that corresponds to the wettest season in the region. SSEBop can still be used to characterize ET in the MAB but the implementation of bias and phase correction processes are recommended. Further studies can also include other ET products such as SEBAL [23].

The MAB is also susceptible to flooding due to the low elevation of the terrain, the landscape, and the ceaseless precipitation. Precipitation events of high magnitude and short duration such as the ones causing floods are challenging to estimate with the remote sensing products analyzed. Extreme events such as floods should be considered in further studies using datasets that combined remote sensing and in situ measurements to reduce bias and improve estimations.

Overall, using solely remote sensing products showed acceptable results for replicating P and ET estimates at monthly and yearly time intervals. CHIRP performed to some degree better than CMORPH at all stations. It should be noted that CHIRP does not use in situ data correction, such as CHIRPS. The addition of station data to bias correct remote sensing products remarkably improves the results [12] but the assessment of the performance without correction by station data as presented in this study is recommended. Station data measurements are sparse and limited. Areas without local measurements rely on the underlying bias and error of uncorrected remote sensing products.

A tripod of (1) station data, (2) remote sensing products, and (3) modeling is recommended for the estimation and validation of hydrological variables such as precipitation and evapotranspiration. Each part of the tripod complements and overlaps with the others, improving the overall knowledge of the environment.

As part of one of the components of the Sustainable Development Goals (SDGs), this study falls within SDG 6. The input precipitation and output ET were assessed to provide valuable information to the society, scientific community, agriculture, cattle, environmental NGOs, and other actors who use these datasets.

Author Contributions: Conceptualization V.H.d.M.P. and G.E.E.-D.; methodology V.H.d.M.P.; software development G.E.E.-D. and V.H.d.M.P.; formal analysis and investigation V.H.d.M.P., E.B.d.S., J.C.B.Q. and G.E.E.-D.; writing—original draft preparation V.H.d.M.P.; review and editing E.B.d.S., J.C.B.Q. and G.E.E.-D. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: https://www.snirh.gov.br/hydroweb/apresentacao, https://www.chc.ucsb.edu/data/chirps, and https://earlywarning.usgs.gov/ssebop (accessed on 16 September 2023).

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Statistical metrics evaluating precipitation between station data and remote sensing products (CHIRP and CMORPH).

Station/Time Interval	Statistical Metric	CHIRP	CMORPH
00147007			
Metrics in mm/month	RMSE	130.98	116.04
	NRMSE	0.6	0.53
	MBE	49.54	19.75
	R2	0.5112	0.5206
	SLOPE	0.649	0.709
	NS	0.386	0.4362
Metrics in mm/year	RMSE	789.83	648.61
	NRMSE	0.3	0.25
	MBE	536.82	181.87
	R2	0.1243	0.103
	SLOPE	0.515	0.395
	NS	−2.9045	−0.8717
00148001			
Metrics in mm/month	RMSE	75.29	78.18
	NRMSE	0.3	0.31
	MBE	9.36	−22.97
	R2	0.7329	0.7319
	SLOPE	0.855	0.858
	NS	0.7079	0.6829
Metrics in mm/year	RMSE	217.94	473.21
	NRMSE	0.07	0.16
	MBE	85.1	−351.23
	R2	0.4716	0.1007
	SLOPE	0.518	0.209
	NS	0.3712	−1.2611
00148003			
Metrics in mm/month	RMSE	106.8	98.51
	NRMSE	0.45	0.42
	MBE	29.07	0.45
	R2	0.5983	0.5916
	SLOPE	0.704	0.762
	NS	0.546	0.5426

Table A1. *Cont.*

Station/Time Interval	Statistical Metric	CHIRP	CMORPH
Metrics in mm/year	RMSE	657.22	675.22
	NRMSE	0.24	0.25
	MBE	453.29	94.21
	R2	0.2555	0.004
	SLOPE	0.605	0.071
	NS	−1.3307	−1.162
00148012—Automatic station			
Metrics in mm/month	RMSE	93.3	105.93
	NRMSE	0.32	0.37
	MBE	−33.54	−52.86
	R2	0.7048	0.06731
	SLOPE	0.945	0.93
	NS	0.5668	0.4344
Metrics in mm/year	RMSE	617.99	758.97
	NRMSE	0.18	0.22
	MBE	−366.87	−628.18
	R2	0.1876	0.4402
	SLOPE	0.651	0.707
	NS	−2.0191	−1.2896
00148012—Conventional station			
Metrics in mm/day	RMSE	14.46	16.27
	NRMSE	1.59	1.79
	MBE	−0.82	−1.85
	R2	0.0814	0.0704
	SLOPE	0.475	0.311
	NS	−1.8307	−0.7741
Metrics in mm/month	RMSE	94.87	105.58
	NRMSE	0.34	0.38
	MBE	−33.98	−59.46
	R2	0.7142	0.7228
	SLOPE	1.003	1.007
	NS	0.5383	0.4308
Metrics in mm/year	RMSE	579.5	839.67
	NRMSE	0.17	0.25
	MBE	−391.17	−699.67
	R2	0.0059	0.0782
	SLOPE	−0.071	0.171
	NS	−2.6543	−2.3741

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