Factors Affecting Precipitation over Western Puerto Rico during the NASA 2021 CPEX-AW Project

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ABSTRACT

Afternoon precipitation typically occurs over western Puerto Rico throughout the year, but its duration and intensity can vary significantly on a daily basis. Much research has been done to analyze the different local processes that lead to afternoon rainfall, such as the sea breeze, a thermal low and two counteracting gyres in the northwestern and southwestern parts of the island. However, it is not fully understood how the combination of these factors results in a higher or lower amount of precipitation. This study uses a set of 30 weather balloons that were launched during the NASA 2021 Convective Processes Experiment - Aerosols Winds project, two buoys and an Aerosol Robotic Network station to investigate the variations in the atmospheric conditions present during the late morning hours, right before convection develops in the early afternoon. We consider the role of sea breeze, the Saharan dust, the Convective Available Potential Energy, Convective Inhibition and the Precipitable Water obtained with the weather balloons as drivers for the diurnal precipitation. Results suggest that high rainfall was observed when most of the aforementioned factors were favorable for rainfall, but if only one factor was unfavorable, less rainfall was observed. We also find that the higher amount of Saharan dust increases the convective inhibition and reduces the convergence between the north and south coasts. This suggests that the lower amount of Saharan dust has three contributions to enhance rainfall over western Puerto Rico: higher precipitable water, lower convective inhibition, and a stronger north-south convergence. The convective inhibition had the highest correlation with afternoon rainfall.

1. Introduction

This project aims to better understand the behavior of the afternoon rains in Puerto Rico and improve short-term forecasts across islands like Puerto Rico. In the absence of synoptic forcing, most of the rainfall that falls in Puerto Rico occur over the western half of the island due to the combination of diurnal processes in combination with the local orography of the island. A secondary maximum is observed over the El Yunque National Forest which consist of an isolated but steep mountain located in the north-eastern Puerto Rico (Figure 1). Thus, afternoon precipitation in Puerto Rico is a very important but complex process that have been studied for several decades (Riehl 1947; Carter and Elsner 1996; Jury et al. 2009; Villamil-Otero et al. 2015). To achieve our goal, we compared the observed precipitation over western Puerto Rico with different atmospheric quantities obtained from 30 weather balloons launched in Mayagüez, Puerto Rico during the NASA's Convective Processes Experiment - Aerosols and Wind project (2021 CPEX-AW), conducted between August and September 2021. The studied quantities are the Convective Available Potential Energy (CAPE), Convective Inhibition (CIN) and the Precipitable Water (PWAT) Beside these quantities, we also considered the Saharan dust levels that tend to reduce the rainfall (Mote et al. 2017). Finally, we also considered the convergence between the north and south coast to evaluate the sea breeze in the western parts of the north and south coast. The objective of this study is to examine if these factors act as drivers of the rains that we usually see during the afternoons.

Puerto Rico is an island in the northeastern Caribbean with approximate dimensions of 70km × 180km with a mountain ridge oriented from east to west with heights

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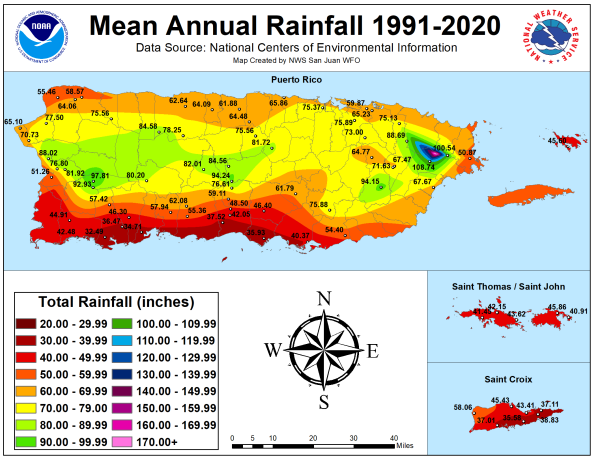

FIG. 1. Mean annual rainfall in Puerto Rico based on the latest 30-year period covered by the official U.S. Climate Normals (1991-2020). Source: NWS San Juan

greater than 600m and a highest point a little higher than 1,300m (Figure 2). The island is under easterly winds about 80% of the time and is surrounded by warm water, with the Caribbean Sea to the south and the Atlantic Ocean to the north, with sea surface temperatures between 28.0 and 29.5°C surrounding the island in August and September 2021. Thus, it is known that the air mass is thermodynamically driven and convective, with a thermal low and a cyclonic gyre in the northwest and an anticyclonic gyre in the southwest corner of the island developing as the morning progresses, as described by Jury et al. (2009), which favors the formation of a sea breeze which penetrates through the west coast. It has also been shown that when sea breeze penetrates inland, it causes convergence with the antecedent flow (Atkins and Wakimoto 1997). In this case, the antecedent flow is a turbulent wake cast caused by the mountain ridge, which in turn can enhance the rainfall in western Puerto Rico during the afternoon hours (Jury and Chiao 2013). Besides these locally induced processes, larger scale Saharan air layers (SAL events) often affect the island during the summer and have a suppressive effect on rainfall (Mote et al. 2017; Wong et al. 2009).

With all these processes being present on most days, we analyzed the existing environmental conditions in western Puerto Rico right before most of the diurnal precipitation begins to develop. Our primary focus is to compare and analyze the differences in atmospheric conditions in the late morning hours to understand why some days are rainier than other. We hypothesize that a stronger sea breeze, stronger convergence between the north and the south coast, higher instability, higher moisture, and lower Saharan dust levels will lead to increased precipitation across western Puerto Rico.

TABLE 1. The 29 weather balloons launched during the NASA 2021 CPEX-AW project.

Date	Quantity	Hours of launches (AST)
Aug 24	2	0615, 1406
Aug 26	4	0810, 1147, 1449, 1759
Sep 3	4	0930, 1157, 1515, 1739
Sep 4	2	1136, 1435
Sep 7	3	0808, 1128, 1538
Sep 8	4	0837, 1153, 1516, 1651
Sep 13	5	1052, 1315, 1431, 1711, 1832
Sep 14	5	1058, 1248, 1518, 1730, 1853

2. Data and methods

Between August and September of 2021, we had the opportunity within the NASA field project called the 2021 Convective Processes Experiment, Aerosols and Winds (CPEX-AW), in which Dr. Rosimar Rios-Berrios together with the help of several meteorology students from the University of Puerto Rico at Mayaguez Campus (UPRM) launched a total of 29 weather balloons from the roof of the UPRM Physics Department building in Mayaguez, a municipality in the center of the west coast of Puerto Rico. The goal of the field project was to study the convective processes and sea breeze in tropical regions, among other objectives. More importantly, the data obtained with the project helped to fill the gap in field data to investigate the diurnal evolution of the atmosphere over the west coast of Puerto Rico. The launching site is shown in Figure 2 and the specific coordinates are 18.210845°N and -67.138973°W. The radiosonde system sent back data every second (except for some occasional seconds), which provides a very high-resolution vertical profiles in the areas it sampled, including data such as temperature, dew point and wind speed and direction. The 29 weather balloons were launched over eight non-consecutive days, as shown on table 1.

We can quickly notice that the launches were at different times on some of the days, so inter-comparisons between observations from different days can be a bit challenging. To solve that, we used the soundings launched between 1000 and 1200 LST to be the representative soundings for the late morning hours. Since we wanted to study the pre-existing conditions during the late morning hours before most convection activity develop and we do not have sounding data within that time frame for August 24, we disregarded that day for our sounding analysis.

Taking advantage of the available sounding parameters, we examined different moisture and instability indices such as the CAPE, CIN and PWAT. For the CAPE and CIN, the values were obtained using the surface-based, mixed-layer (lowest 100hPa of the sounding) and the most unstable parcel.

One of the factors that we investigate is the role of the sea breeze in the afternoon rainfall (from 1200-1800

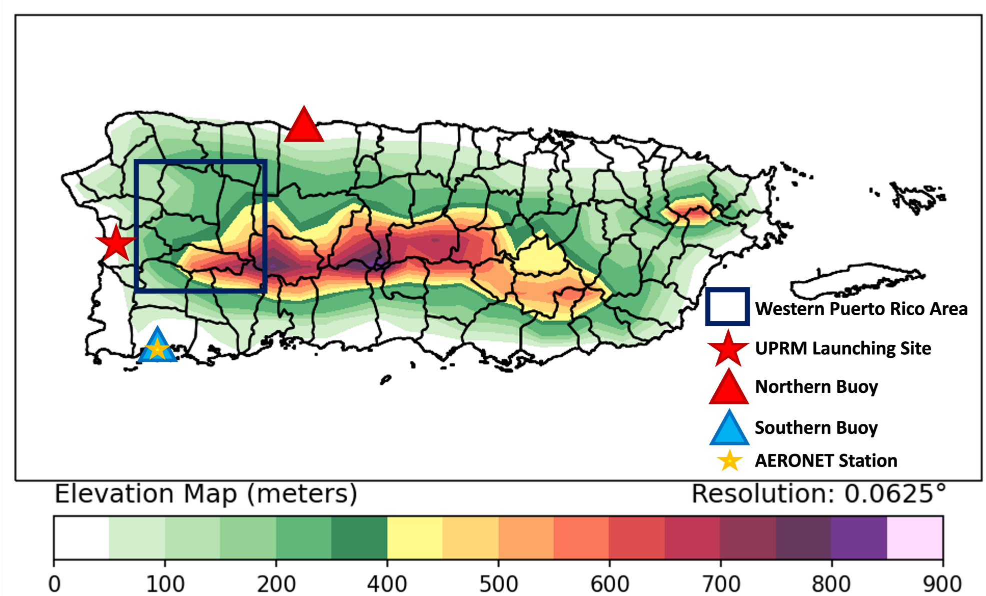

FIG. 2. Topography of Puerto Rico. The western Puerto Rico area, the location of the NASA 2021 CPEX-AW weather balloon launching site, the AERONET station and the two stations used for this project are also shown.

AST) over western Puerto Rico. Therefore, we first had to identify on which of these eight days we had a sea breeze developing over Mayaguez. To do this, we used a combination of the available weather balloon data and the MGZP4 weather station which is located a few meters from the coast near the Bay of Mayaguez (specific coordinates: 18.218ºN 67.159ºW). After identifying the sea breeze days, we estimated their strength using the average surface-950 hPa zonal wind, obtained from weather balloons launched during the late morning hours. The 950 hPa pressure level (which was approximately 500m above the launch site) was chosen because the westerly winds associated with the sea breeze reached heights below that level most of the days in the late morning, except on September 3rd where a strong sea breeze formed reaching a height of about 925 hPa (aproximately 740m above the launch site).

After getting the late morning sea breeze strength, we calculated their correlation coefficients with the afternoon rainfall to see how closely the strength of the sea breeze was related with the observed afternoon rainfall. We also evaluated the strength of the sea breeze along with other indices obtained from the late morning soundings to see if a combination of two or more variables better explained the resulting afternoon rainfall.

The rainfall data came from the NCEP Stage IV system, which provides estimated hourly precipitation data for the entire island. We averaged the rainfall observed in western Puerto Rico between 1200 and 1800 AST, and the resulting value was the value used for that afternoon. Here, we defined western Puerto Rico as the region between 18.1–18.4°N and 67.1–66.8°W, which is shown in Figure 2.

We also used a station from the Aerosol Robotic Network (AERONET) located near La Parguera in Lajas, Puerto Rico, a municipality in the southwest part of the island, to investigate the Saharan dust. We used the average daily 490 nm aerosol optical depth (AOD) concentration values instead of the instantaneous values to avoid the random variations that the instrument records sometimes, especially since as of the time this research project was made the data was still in the 1.5 level, meaning that the data is cloud cleared and quality controls have been applied but may not have final calibration applied. The 490 nm wavelength was chosen because the station did not measure data between the more commonly used 500-600 nm wavelength range for SAL events.

Finally, we also used a set of two buoys weather stations located along the coast close to the region of interest, one in the north and one in the south, to estimate the north-south convergence (N-S convergence) caused by the thermal low and the two gyres described by Jury et al. (2009). To do that, we calculated the average difference in the meridional wind between the southern and northern stations measured during the late morning hours. The two stations used are AROP4 located in the coast north of the Arecibo municipality and the MGIP4 located near Isla Magueyes just south of Lajas municipality. Their respective locations are shown in Figure 2.

3. Results

With many variables to consider (sea breeze strength, CAPE, CIN, PWAT, AOD and the N-S convergence), we created a few plots containing 3 or 4 variables in each to

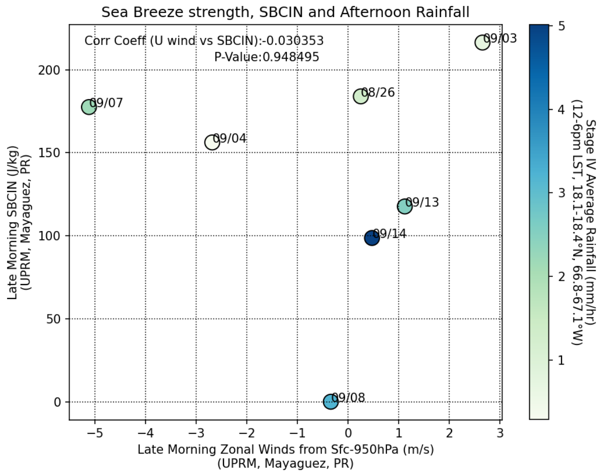

FIG. 3. Late morning surface-based CIN compared with the zonal wind averaged from surface to 950 hPa using the late morning sounding data, and the average afternoon rainfall values over western Puerto Rico.

investigate which ones seem to explain the afternoon rainfall behavior, or if it is a combination. Correlation coefficients were computed, and the most significant results are shown in the following subsections of this report.

a. Role of the western Sea Breeze

The strength of the sea breeze in the west coast of Puerto Rico had the lowest coefficient correlation of all the variables, with a value of -0.03 and a P-value of 0.95. The higher rainfall values were observed when the average surface to 950 hPa zonal wind was around 0 m/s, and lower as wind speed increased either as easterlies or westerlies dominated (Figure 3). A sea breeze was present during the late morning hours on 4 of the 7 days, while the other 3 days had easterly winds dominating the wind flow. However, when considering only the days with westerlies, as the CIN decreased, higher rainfall was observed. This may imply that a combination of favorable factors may be producing higher rainfall and that sea breeze alone is not a strong factor to cause higher or lower rainfall.

b. Parcel method selection

First, we needed to know which parcel method had the highest correlation with observed precipitation to be able to analyze the two instability indices. We obtained the observed CAPE and CIN using the surface-based, mixed-layer and most-unstable parcel. The surface-based parcel shows the CAPE and CIN values assuming that the parcel is being lifted from the surface, and therefore the temperature trajectory of the parcel will start from the surface temperature. The mixed-layer parcel shows the mean CAPE and CIN considering the average conditions of temperature and dew point from the first 100 hPa of the sounding. Finally, the most-unstable parcel shows the CAPE and CIN from the most unstable parcel of air found within the first 300 hPa of the sounding.

TABLE 2. Correlation values of the late morning surface-based, mixed-layer and most unstable parcel CAPE and CIN with observed afternoon rainfall over western Puerto Rico.

Surface-based CAPE	0.37
Mixed-layer CAPE	0.02
Most-unstable CAPE	0.03
Surface-based CIN	-0.64
Mixed-layer CIN	-0.29
Most-unstable CIN	-0.08

After getting the three CAPE and CIN values, we computed their respective correlations with the afternoon rainfall to see which parcel method seems to have the strongest relationship with observed rainfall. The correlations are shown in Table 2.

The surface-based CAPE and CIN showed the highest correlations, and therefore, we assumed that parcels in that region start their upward motion from the surface around that time. In fact, this makes sense as Jury and Chiao (2013) found that thermal forcing from the surface may be playing a more important role in convection rather than the leeward side confluence zone, at least for the two cases that they studied. Therefore, only the surface-based CAPE and CIN indices will be considered for the purpose of this research.

c. Role of the Saharan dust

The Lajas AERONET station reported data during 40 of the 61-day period from August to September of 2021 for which we had rainfall data available from the Stage IV. A plot of the AOD values and afternoon rainfall over western Puerto Rico is shown on Figure 4. All of the 40 days showed AOD values greater than 0.05.

There is a noticeable negative correlation between the AOD and the afternoon rainfall over western Puerto Rico, when there is more Saharan dust there is less rainfall, with a correlation coefficient of -0.56 and a P-value near 0.00. A total of 13 of the 40 days had moderate to high concentrations of Saharan dust with AOD values exceeding 0.30, including one of the launching days. Those 13 days showed average afternoon rainfall less than 2.0 mm. However, the rainfall values show a significant spread that becomes wider as the AOD values decrease, with some days having nearly 0 mm and some others over 3.0 mm, but never 0 mm, as occurred on some days with AOD values greater than 0.30.

The rainfall spread that occurs as the AOD values decrease means that when there is less Saharan dust, other variables may be controlling the amounts of rain, and, therefore, other variables must be taken into account. Fortunately, as Figure 4 shows, almost every launching date coincided with the most interesting part of the graph where

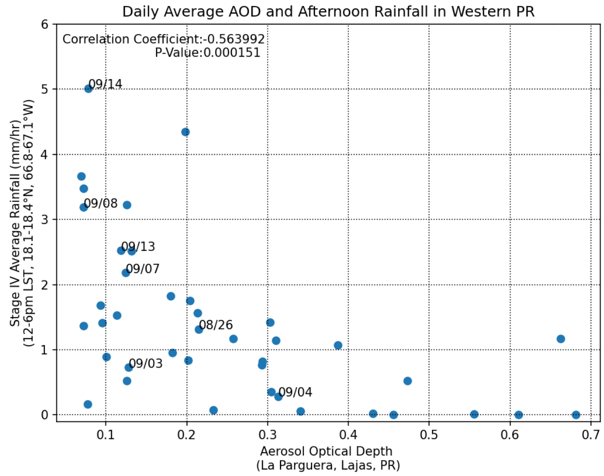

FIG. 4. Daily average AOD values compared with the average afternoon rainfall over western Puerto Rico. The labeled markers represent the days where weather balloons were launched during the late morning hours at UPRM.

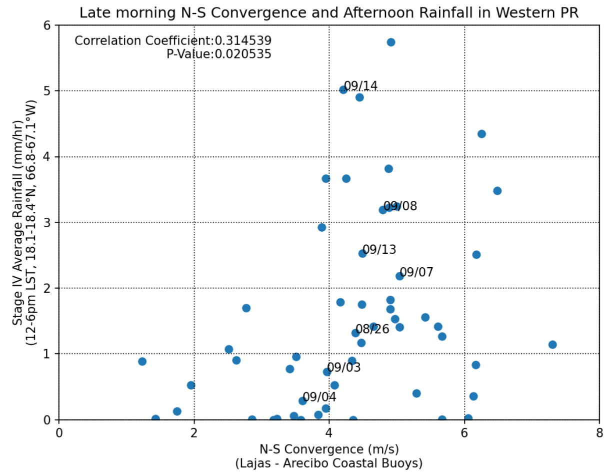

FIG. 5. Late morning average N-S convergence values compared with the average afternoon rainfall over western Puerto Rico.

the large rainfall spread exists as the AOD values decreased. Therefore, the sounding data obtained during the NASA's 2021 CPEX-AW project provided very valuable and useful information as to why some days were rainier than the others.

d. Role of the N-S convergence

The Arecibo buoy reported data all the 61 days, but the Lajas buoy failed 7 days. Since both are needed to compute the north to south convergence, only the 54 days that both were working were used. The resulting value was used to estimate the strength of the northern and southern sea breeze, particularly in the western parts of the north and south coasts that is closer to our area of interest. Figure 5 shows the computed N-S convergence (i.e., difference in meridional wind) for those days along with the observed average afternoon rainfall.

There is a positive correlation with a coefficient value of 0.31 and P-value of 0.02. It is important to note that all the N-S convergence values were positive with values greater than 1.0 m/s, meaning that everyday during the late morning hours featured a convergence process in the western portion of the north and south coast as there was never any divergence. There is also a general trend that when there was less convergence, the afternoon rainfall decreased, but as the convergence increased, a large spread in the afternoon rainfall values appeared.

We also examined the late morning N-S convergence along with the daily average AOD values and afternoon rainfall. A total of 37 of the 61 days had both N-S convergence and AOD data, and the resulting plot is shown on Figure 6. Interestingly, a decrease in the N-S convergence was observed as the AOD increased. This particular finding is something that can be studied in future works and it may be caused by less surface diurnal heating as Saharan dust scatters part of the incoming shortwave radiation or other processes that may fall beyond the scope of the present research.

It is worth mentioning that we also examined the average late morning N-S convergence with afternoon rainfall, but using two stations in the north coast (AROP4 in Arecibo and XJUA in San Juan) and two in the south coast (MIGP4 in Lajas and XMRS in Guayama), which averaged the situation occurring along the entire north and south coasts instead of just considering the two westernmost buoys. The results were similar with a positive correlation coefficient of 0.39 and a P-value of 0.003. In this case, however, 21% of the days experienced divergence during the late morning hours while 79% had convergence. This occurred because the easternmost stations showed

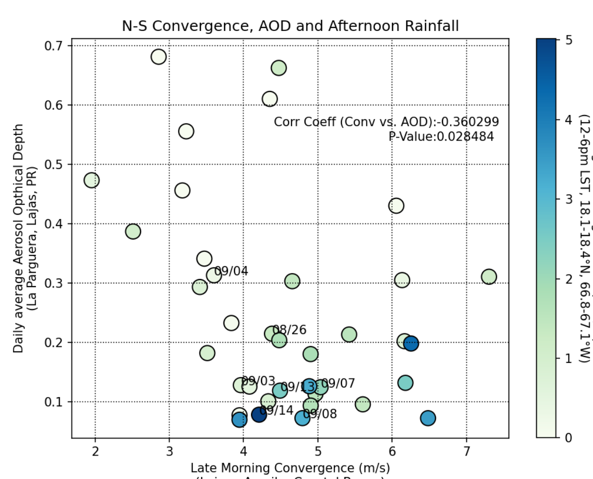

FIG. 6. Late morning average N-S convergence values compared with the daily average AOD and average afternoon rainfall values over western Puerto Rico.

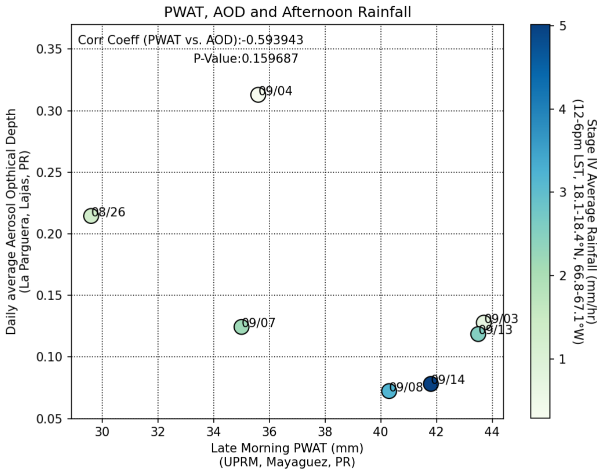

FIG. 7. Late morning PWAT compared with the daily average AOD and average afternoon rainfall values over western Puerto Rico.

strong divergent components (ie. northeasterly winds in the southeastern station and/or southeasterly winds in the northeastern station) in some of the days, more evident on Aug 08, Aug 19, Aug 23 and Sep 13.

e. The PWAT and AOD

In subsection 3c, we used the AOD as an approximation of the environmental moisture because direct measurements of precipitable water during the late morning was only available during the 7 day period of the NASA's 2021 CPEX-AW field project. Therefore, we wanted to know the relationship between the AOD and the late morning PWAT to see how useful would be to use the AOD as an approximation of the general moisture in the environment. This would be very useful since AOD is relatively easier to measure or estimate from observations and model data because the main driver of it are the large-scale SAL events that affect the region from time to time. A plot was made with the AOD and PWAT and the is shown in Figure 7.

There is a negative relationship between the PWAT and the AOD with a correlation coefficient value of -0.59 and P-value of 0.16. In general, days with the higher values of AOD and low PWAT showed less rainfall than the days with lower AOD and higher PWAT. However, a larger rainfall spread was observed in the latter case as Sep 09 had the highest PWAT value and a relatively low value of AOD and yet it was the second driest day only behind Sep 04, which had the highest AOD value of the 7 days.

The relationship of the AOD with afternoon rainfall was both higher and stronger than that of the PWAT with afternoon rainfall, with correlation coefficient and P-values of -0.56/0.0002 for 40 days of AOD data and 0.36/0.42 for 7 days of PWAT data, respectively.

f. Role of the CAPE and CIN

The surface-based CAPE and CIN (SBCAPE and SBCIN) and the PWAT and respective afternoon rainfall over western Puerto Rico are provided on Figure 8. The SBCIN is plotted in the x axis, meaning that days located more to the right had higher SBCIN wich is less favorable for rainfall. The PWAT is in the y axis, so days located higher in the plot had higher PWAT which is more favorable for rainfall. The size of the markers represent the SBCAPE, so the greater the circle, the higher and more favorable SBCAPE values for rainfall were observed. Finally, the colors represent the rainfall, so the darker ones mean higher rainfall was observed over western Puerto Rico that afternoon.

The correlation coefficient values for the SBCAPE with rainfall was 0.37 with P-value of 0.41 and for the SBCIN with rainfall was -0.64 with P-value of 0.12. As the SBCIN increased, the afternoon rainfall decreased, especially with SBCIN values greater than 150 J/kg. Similarly, as the PWAT increased, the rainfall also increased, except on Sep 03 when a SBCIN greater than 200 J/kg was present. On Sep 04, the highest SBCAPE of the 7 days was observed, but the rainfall was the lowest of all these days.

In general, days with low values of SBCAPE had little rainfall but days with high SBCAPE had a spread in afternoon rainfall values. Again, as the values became increasingly favorable for higher rainfall values, a spread in rainfall appeared. However, this was not the case with the SBCIN as days with low values, which are more favorable for rainfall, showed moderate to high rainfall values.

We also computed the relationship between the SBCIN and AOD to see if higher amounts of Saharan dust lead to greater CIN, and the correlation coefficient value was

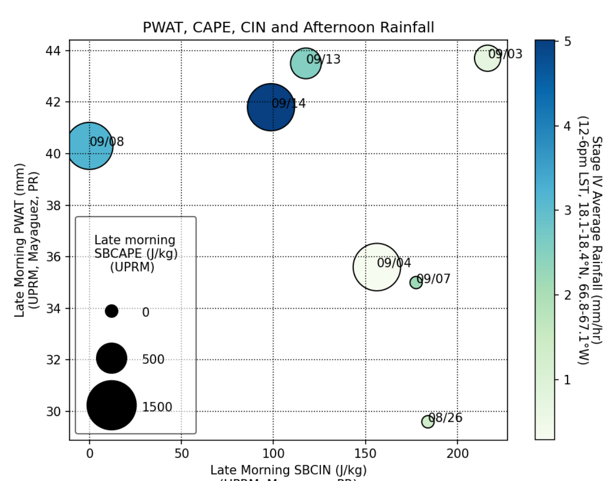

FIG. 8. Late morning surface-based CIN and CAPE compared with the late morning PWAT and average afternoon rainfall values over western Puerto Rico.

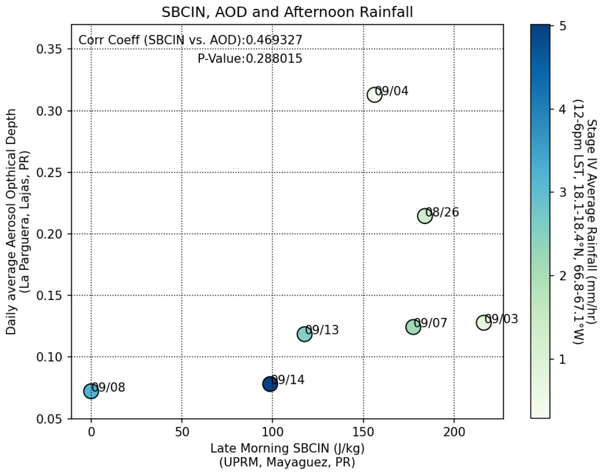

FIG. 9. Late morning SBCIN compared with the AOD and average afternoon rainfall values over western Puerto Rico.

TABLE 3. Summary for the 7 days of sounding data, from rainiest on the left to driest on the right. A "Yes" is shown if the variable was considered favorable for enhanced rainfall.

Variable	09/14	09/08	09/13	09/07	08/26	09/03	09/04
SBCIN	Yes	Yes	Yes	-	-	-	-
AOD	Yes	Yes	Yes	Yes	-	-	-
SBCAPE	Yes	Yes	Yes	-	-	-	Yes
PWAT	Yes	Yes	Yes	-	-	Yes	-
N-S Conv.	-	Yes	-	Yes	-	-	-
Sea Breeze	Yes	-	Yes	-	Yes	Yes	-

0.47 with a P-value of 0.29, as shown in Figure 9. A general positive relationship was observed between the two as lower SBCIN values did not had high AOD values and high SBCIN values did had higher AOD values than those ocurring on lower SBCIN days.

4. Discussion

The main goal of this study is to investigate the relationship between the late morning environmental conditions and the afternoon rainfall across western Puerto Rico. As we analyzed the factors individually (sea breeze strength, CAPE, CIN, PWAT, AOD and the N-S convergence), we noted that when one factor was unfavorable for higher afternoon rainfall, less rainfall was observed all days. However, as the factor becomes favorable for higher rainfall, a spread in rainfall was observed with some days having high rainfall values and some others with little to no rainfall at all. Therefore, one variable was not enough to explain the afternoon rains over western Puerto Rico. Table 3 shows a summary for each of the 7 days with sounding data during the late morning hours.

The AOD values indicate that there was always some concentrations of aerosols in the region, likely from Saharan dust. In Puerto Rico, large scale SAL arrives to the island frequently during the summer months, reaching a peak between June and July, and decreasing in late summer to early fall. Our study considered data between August and September 2021, and two weak tropical cyclones (a weak tropical storms and a tropical depression) passed close to the south of the island in early and mid August, right before a large scale SAL event entered the region. Based on our data, everyday, no matter the dominant weather phenomena, some aerosols remained suspended in the air, although some days had low amounts with AOD values around 0.10. Days with high AOD values greater than 0.30 experienced little afternoon rainfall likely because of the drying effect that SAL events tend to have but also due to increased SBCIN and weaker N-S convergence. The AOD and SBCIN values appeared to be related as SBCIN trended to increase with the AOD values. This means that when we have a moderate to strong SAL event in the area, not only the atmosphere tend to be drier, but also a warmer low level air layer with a temperature inversion strengthens a cap that the rising convection have to overcome for rainfall to start.

Another interesting finding about the AOD is that a decrease in the N-S convergence was observed as the AOD increased. Of the 13 days that experienced N-S difference in meridional wind values less that 4.0 m/s (i.e., weak convergence), 9 (near 70%) had AOD values greater than 0.20 and most of them occurred during a multi-day strong SAL event that occurred by mid-August 2021. However, their relationship is not very strong as days with moderate N-S convergence have had high values of AOD, but there was a slight trend to lower AOD as N-S convergence increased. Therefore, we had some indications that days with low AOD is associated with three other contributions for enhanced rainfall: higher moisture, stronger N-S convergence and a weaker SBCIN. And the opposite is true for reduced rainfall. With all these variables being affected by the AOD, it becomes clear why the AOD had the most coherent relationship of all the variables with the afternoon rainfall, with a coefficient of -0.56 and a P-value near 0.00. In fact, since PWAT had a lower correlation with the rainfall, the AOD values are a better predictor for afternoon rainfall, especially the more unfavorable the values become for rainfall. This is because most of the variables showed a spread in rainfall the more favorable those variables became. A summary of the correlation of all variables with afternoon rainfall is shown on Table 4.

The late morning SBCAPE values were very similar on Sep 04, Sep 08 and Sep 14 with values of 1396, 1373 and 1379 J/kg, respectively. In fact, Sep 04 had the highest SBCAPE of the 7 days, but the rainfall was the lowest of all these days. However, the highest AOD value greater than 0.30 and the lowest N-S convergence with less than 4.0 m/s were observed on that day, along with a high SBCIN of 150 J/kg. Therefore, although the SBCAPE was the highest (but still not an impressive value), it alone was not

TABLE 4. Correlation coefficient and P values of all the variables with the observed average afternoon rainfall over western Puerto Rico.

Variable	Corr. Coeff.	P-value	Days
SBCIN	-0.64	0.12	7
AOD	-0.56	0.00	40
SBCAPE	0.37	0.41	7
PWAT	0.36	0.42	7
N-S Convergence	0.31	0.02	54
Sea Breeze	0.09	0.84	7

enough to overcome the other negative factors in terms of afternoon rainfall. A few isolated but strong showers developed that afternoon possibly due to a few parcels that had enough momentum to break a strong temperature inversion that was present that day and produced a high SBCIN based on the UPRM sounding. Interesting to note, that inversion was not very evident in the morning sounding of the NOAA's NWS San Juan WFO, which launches weather balloons everyday at 0800 and 2000 LST (12Z and 00Z) from Carolina, PR, a municipality just east of the metropolitan area of San Juan, in the northeast part of the island. This could be because the SAL was probably still entering the island by that time since the AOD from the day before, but the UPRM sounding was made just after 1130 LST and no launches were made earlier to see it the inversion was present before that time.

For the other two cases with similar SBCAPE values (Sep 08 and Sep 14), an interesting behavior was observed. Besides the SBCAPE, almost all the investigated variables were more favorable on Sep 08 than those observed on Sep 14, and yet Sep 14 had a higher rainfall value. The only thing from our analysis that appeared more favorable on Sep 14 was the presence of the sea breeze over the west coast, that was absent on Sep 08. However, based on the morning's NWS discussion for Sep 14, there was tropical wave approaching the area and a westward-moving upper level trough enhancing the potential for thunderstorms. Therefore, although we had indications of favorable upper level conditions with the relatively high SBCAPE value, two possible reasons for the higher rainfall on Sep 14 are upper level divergence and/or slower steering winds. Unfortunately, we were not able to investigate these two factors or any other that may have played a role in the area.

Another thing that we wanted to investigate is the sea breeze, which was initially hypothesized to be the key factor that drives afternoon rainfall over western Puerto Rico. However, as is shown on Figure 3, sea breeze varied as it is shown by the average surface to 950 hPa zonal wind values, and not all days had a sea breeze present during the late morning. To confirm that, we examined the MGZP4 station which is at the coast of the Mayaguez Bay. About two thirds of the days between August 17 and September 30, 2021 (the time frame for which the station was working), a sea breeze developed on the west coast of Puerto Rico, with zonal winds values exceeding 1 m/s between 1100-1300 local standard time (LST), the time when the strongest sea breeze was observed on average. This coincides with the time of maximum heating, indicating that it is a thermally forced phenomenon associated with the land-sea temperature difference. So sea breeze develops most days, but with varying intensities, times and heights.

As for its relationship with rainfall, our analysis did not show a significant correlation between afternoon rainfall and the late morning surface to 950 hPa zonal winds, with a coefficient correlation of 0.09 and a P-value of 0.83. It is worse noting, however, that if we only consider the 4 days where the sea breeze was observed (Aug 26, Sep 03, Sep 13 and Sep 14), rainfall values increased as SBCIN values decreased, as shown in Figure 3. Further investigation would be needed to see if it is a real relationship and not a coincidence, but it is important to mention that a temperature inversion of different intensities and at varying heights was present during the late morning hours during all the 7 days. Therefore, if the relationship between sea breeze and SBCIN were to be true, it could mean that sea breeze and associated convergence is acting to lift air parcels in the lower levels, but as these parcels encountered the layer of temperature inversion, the weaker the inversion was, the more easier it was for the parcels to break it and reach the positive CAPE area to enhance the convective development, eventually leading to higher rainfall values. In fact, the SBCIN was the variable with the highest correlation with rainfall, as shown in Table 4, so it appears that the SBCIN is one of the main drivers for afternoon rainfall.

On Sep 03, the strongest and highest sea breeze was observed with sfc-950hPa zonal winds greater than 3.0 m/s and the top of the westerlies reached a pressure height of 925 hPa (about 0.74 km above the launch site). This day had the highest PWAT value too, so if sea breeze was really helping in the rain development, this would have been the best of the 7 days to demonstrate it. However, SBCIN had a very high value greater than 200 J/kg and two steep temperature inversions were present, one with its nose at a pressure height of 812 hPa (about 1.86 km) and the other at 550 hPa (about 5.00 km). These two inversions resulted in a relatively low SBCAPE value of 355 J/kg and may have limited the vertical updraft that the sea breeze would have given to the air parcels. All this to say that more research is needed to confirm this possible relationship.

In summary, one variable was not enough to produce higher rainfall values, but when only one variable is unfavorable, high rainfall values were not observed. However, when one variable was favorable, a spread in rainfall was observed because more variables were needed to produce the rainfall (ie. favorable AOD or PWAT combined with unfavorable SBCAPE or SBCIN always resulted in low rainfall). Therefore, a combination of favorable variables is needed to produce high rainfall values, and that trend can be identified on Table 3 that summarizes the conditions present each of the 7 days with sounding data.

5. Conclusions

We studied several factors as drivers for the rainfall observed during the afternoons over western Puerto Rico. The studied variables included the western sea breeze, sea breeze-driven N-S convergence, Saharan dust levels, CAPE, CIN and PWAT. The data collected during the NASA 2021 CPEX-AW project was very valuable to identify the different potential factors affecting the afternoon rains over western Puerto Rico, and understand how they combine to produce higher or lower rainfall.

Although we analyzed many variables as drivers for the afternoon rains, we did not consider some potential factors that could also be affecting the rainfall. Some of the factors that we did not consider for this study are the steering winds (both direction and speed), the upper-level conditions (i.e., upper level divergence), and other factors that may be influencing the rainfall over western Puerto Rico. These factors can be considered in future works.

Another possible improvement that can be done as a continuation of this research project is to consider the soundings of the NWS that are launched twice a day near the northeastern part of the island. This would be useful since the low-level winds are easterly most of the time and soundings launched there are more exposed to the synoptic air mass that will eventually move over western Puerto Rico. Another advantage is that these are launched on a daily basis, which means that much longer time periods can be analyzed. It would also be interesting to investigate the interactions that occur between the two gyres described by Jury et al. (2009) and the western sea breeze, since they may trigger a convergence process that could eventually lead to rainfall near the west coast of Puerto Rico.

Our hypothesis was correct because a combination of favorable factors caused higher afternoon precipitation over western Puerto Rico. Days with the presence of the western sea breeze during the late morning hours had higher rainfall when they were combined with other favorable factors. However, the strength of the western sea breeze did not matter much since the strongest and deepest sea breeze coincided with many unfavorable factors, which resulted in little rainfall. In general, if a single variable was very favorable for rainfall but most of the rest were unfavorable, little rainfall was observed. Even on days with several favorable factors for rainfall, a single unfavorable factor (i.e., high AOD, high SBCIN, low SBCAPE or low PWAT) can suppress rainfall.

We also found that higher Saharan dust levels reduces the afternoon rainfall not only because is associated with lower PWAT and higher SBCIN, but also a weaker N-S convergence. More research is needed to see how the Saharan dust may be affecting the N-S convergence in Puerto Rico, to see if it is related to a reduced land-sea temperature contrast caused by lower incoming short wave radiation or another process.

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