END OF STUDIES INTERNSHIP REPORT
ÉCOLE NATIONALE DE LA MÉTÉOROLOGIE

Nino Guida

MULTI–SCALE ANALYSIS OF EXTREME RAINFALLS IN SEYCHELLES

SUPERVISED BY

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—ABSTRACT—

The main island of the Seychelles archipelago – Mahé – is frequently affected by thunderstorms and heavy rainfalls, causing damages such as landslides or floods. The most intense of them result in Extreme Precipitation Events (EPEs) which consist in large amounts of precipitation in a short period of time. These episodes are hardly predictable for the Seychelles Meteorological Authority (SMA) as they are still hardly documented. The variability of the equatorial climate that prevails over the Seychelles is affected by multiple drivers covering a range of time and spatial scales going from the interannual scale (> 1 year) with the modes of variability of sea surface temperature (SST) or the modulation of the ITCZ location, but also down to the subseasonal scale (2–90 days) with atmospheric equatorial waves. The resulting variability can have significant repercussions over rainfall.

This study firstly draws the climatology of the EPEs in Seychelles, based on the analysis of the 24hr rainfall amounts (1979–2023) for 13 different rain gauges. A high interannual variability is observed with 6 EPEs per year on average, with a standard deviation of 3 events per year. A clear seasonal cycle is observed, following the Monsoon cycle with the trimester December–January–February recording half of the EPEs observed over the 44 seasons studied. Then, hourly rainfall data enables us to figure out that the extreme rainfalls mainly last from a few hours to half a day.

We then focus on the links between the extreme rainfalls and large–scale drivers. The tropical storms/cyclones activity is not a major driver of the extreme rainfalls over the Seychelles, as very few of them are concurrent with EPEs. However, a count of the number of EPEs per type of SST mode event (positive, neutral or negative) shows that the Indian Ocean Dipole (IOD) positive phase and the El Niño events strongly favor the occurrence of EPEs in the Seychelles. The contribution of the convectively–coupled equatorial waves (CCEWs) is highlighted with Outgoing Longwave Radiation (OLR) and Precipitable Water (PW) wave–filtered data. The CCEWs play a major role as more than half of the events observed are associated with the presence of one or two waves in an active phase over Mahé area during the heavy rainfall occurrence.

Key words : **extreme rainfalls**, **sea surface temperature**, **atmospheric waves**, **precipitable water**, **outgoing longwave radiation**, **modulation**.

—ACKNOWLEDGMENTS —

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I must mention that other people – from Météo–France or the Lacy – contributed to this study. These people also deserve to be thanked for their remarks and advice that helped me to structure my work and my study.

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—INTRODUCTION —

The Seychelles archipelago is composed of more than hundred islands, dispatched over the western equatorial Indian Ocean (WEIO). Among these islands, few are inhabited and the human activity is primarily concentrated on Mahé (~70 000 hab.), located at 55.5°E and 4.5°S. The equatorial climate of this area is characterized by a wet and hot season, followed by a cooler and dryer period. Frequently, thunderstorms and heavy rainfalls affect the island of Mahé, causing damages such as landslides or floods (*Disaster risk profile of the Republic of Seychelles, 2016*). These episodes of extreme rainfalls are hardly predictable for the Seychelles Meteorological Authority (SMA) as they are still poorly documented, and with the absence of high–resolution weather models. Alternatives to global model forecasting have been experimented at the start of this century (*Rainfall forecasting in tropical–equatorial environments : a case study of the Seychelles zone*, Pezzoli & Franza, 2003) with promising results but being insufficient for a good anticipation of extreme precipitation events (EPEs). The complex topography and the small spatial extension of the islands also explain the difficulty of forecasting these events and their consequences. Despite the existence of the SMA for decades now, the data treatment and analysis over the meteorological measurements in Seychelles is still very limited and very few studies have examined this subject yet. Previously, researchers have shown the correlation between sea surface temperature (SST) anomalies and the rainfalls in the WEIO. For instance, the Indian Ocean Dipole (IOD) has been found to be responsible for about 20% of the precipitation variability in the Seychelles (*The influence of the Indian Ocean Dipole Mode on precipitation over the Seychelles*, Aurelie P. Harou & al. 2006). In 2019, Jean Roman Sambenoun published his research paper (*Spatial and temporal rainfall variability and its influence in Seychelles*), presenting the rainfall characteristics over Mahé from 1979 to 2019. His research focuses on the annual rainfalls and shows a high variability at multiple scales, with evidence of correlation between different SST indexes and the annual rainfall observed on Mahé.

Recently, the SMA and the DIROI (Direction Interrégionale pour l'Océan Indien) of Météo–France worked together as part of the PISSARO project (Prévisions Intra–Saisonnières à Saisonnières avec AROme), with the aim of improving the rainfall forecasts in the Indian Ocean. The subject of this internship was proposed by the climate division of the DIROI, in partnership with the SMA, with the will to help the SMA enhancing its knowledge on the EPEs and finding new approaches for their characterization and their forecasting.

Little was known about the features and drivers of precipitation over Seychelles before this study. The first step of the internship was to statistically analyze the rainfall data provided by the SMA, and draw characteristics of EPEs in the Seychelles. The first part of this document is dedicated to this work, beginning with a presentation of the data and methods used for selecting

EPEs and highlighting their characteristics (distribution, climatology, duration, intensity, ...). This first section also develops the interest of studying the large-scale drivers that are SST modes and atmospheric waves. Then the second one presents the method and the results about the EPEs modulation by SST indexes as El Niño Southern Oscillation (ENSO) for example. Finally, the last part shows the major role played by the atmospheric waves in the occurrence of EPEs in Seychelles using ERAI reanalysis data from 1980 to 2016, applying methods already used for heavy rainfalls predictability analysis over Central Africa (*Tropical waves are key drivers of extreme precipitation events in the Central Sahel*, Peyrillé & al (2023)). The last part concludes and gives perspectives for future works and the forecasting of EPEs in Seychelles.

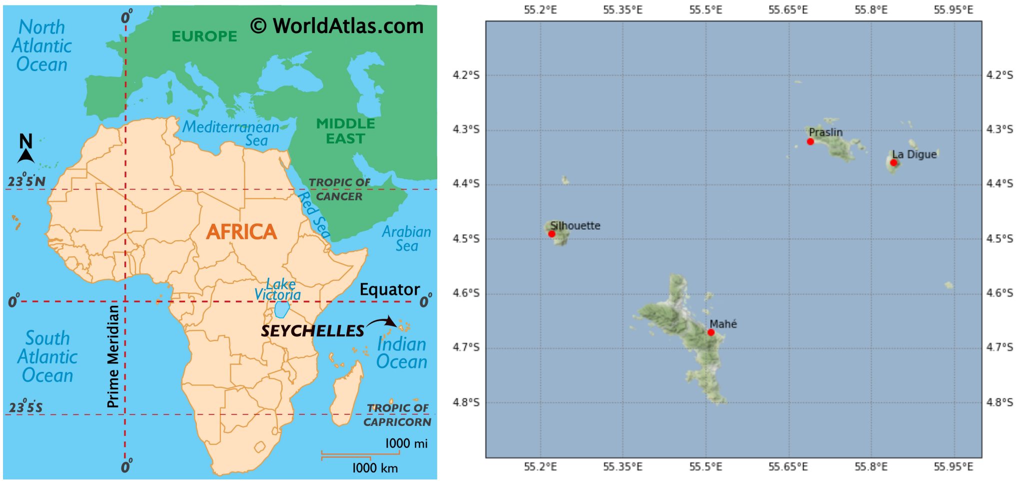


Figure 1 : the Seychelles is an archipelago of theWEIO, with most of the population and activity concentrated in Mahé and the island around (Silhouette, Praslin and La Digue).

—Extreme rainfall events climatology and characteristics—

Incharge of weather forecasting and observation in the Seychelles, the SMA has implemented rain gauges at various places in the archipelago, some of them being in place for more than 40 years. These data represent a huge source of information about the rainfalls pattern and climatology. However, very few statistics have been made and the notion of extreme rainfalls is still mainly based on the damages observed and not on statistical thresholds rigorously calculated.

This first part is dedicated to the description and the analysis of the rainfall data provided by the SMA, on which all the following works and results are based. We start with the characteristics of our dataset, then we will present some preliminary results obtained about the precipitation climatology, these results being important for understanding the complexity and the variability in the precipitation distribution.

Data available and climatology

Over the years, the weather observations network developed in Seychelles, and the initial dataset given by the SMA is composed of daily rainfall amounts for 40 rain gauges, but many of them were implemented recently, after 2016. As recommended by the World Meteorological Organization (WMO), establishing relevant climatological statistics requires a sufficient time period, with 30 years being the reference adopted by many weather services like Météo–France. For that reason, we only selected the station having measured daily rainfalls since 1979, in order to have a dataset compatible with a climatological study. 13 stations remain from the 40 initially contained in the dataset, with 12 of them being on the main island of Mahé, and 1 being located about 50km north–eastward Mahé, on Praslin island.

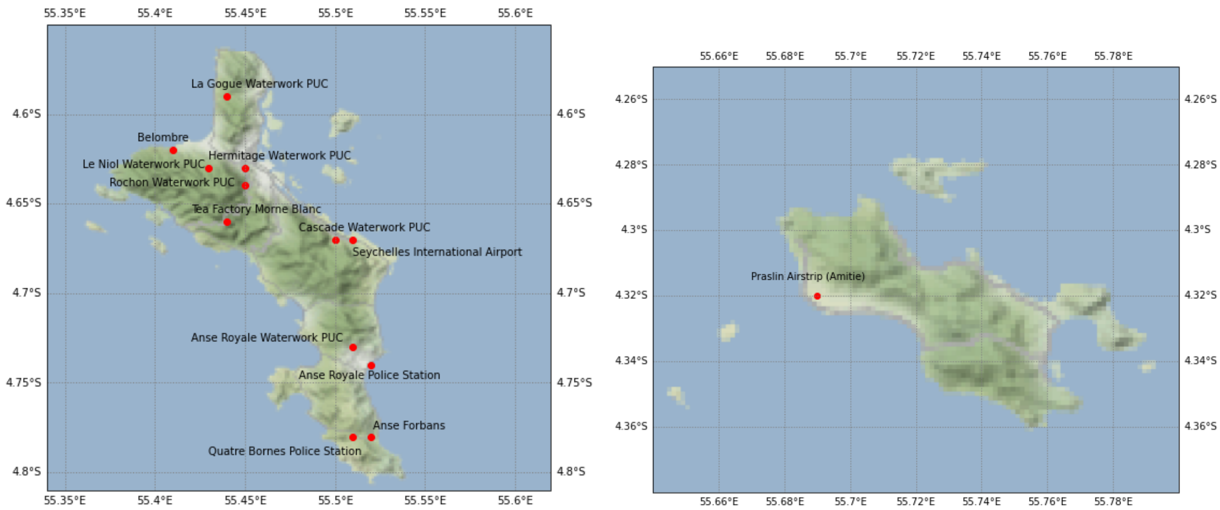


Figure 2 : our dataset is composed of 13 rain gauges, with daily rainfalls from January 1979 to March 2023.

As shown by the previous map, the rain gauges are quite evenly distributed on Mahé island, the Praslin airport station will be useful for studying the large–scale events concerning Mahé and Praslin at the same time. It will be also interesting to compare the climatologies of these two islands. A weather observation dataset of 44 years is hardly complete, and our data unfortunately present also missing values. It is important to look precisely at the ratio of missing values and their distribution, as all the rest of the study will be based on these data. Only one station (Tea Factory Morne Blanc) has an elevated number of missing data, with 19.1% of daily rainfall amounts missing for the 1979–March 2023 period. For the other 12 stations, the ratio of missing data is very low (<3%) and confirms that this dataset is a strong base for further analysis.

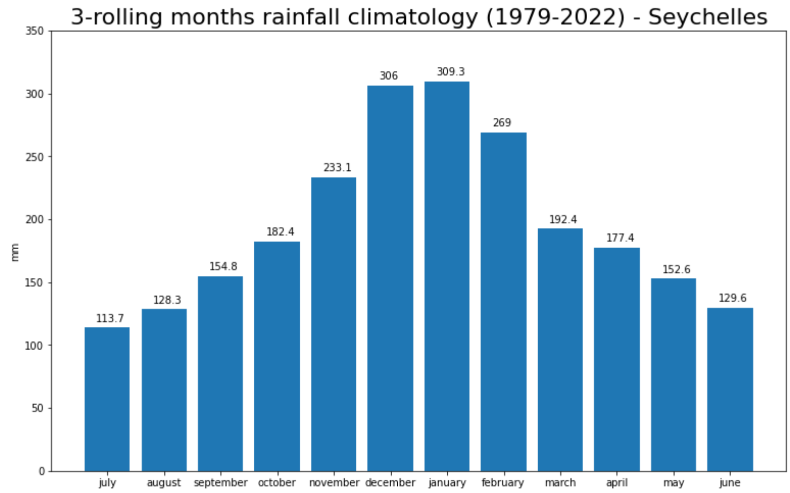


Figure 3 : Monthly rainfall climatology (mm) averaged on the 13 stations and the 44 years of data. The annual mean rainfall amount is 2349mm.

These data give a quick overview of the annual cycle of rainfall around Mahé. The annual variability cycle is well identified with the rainy season peaking from November to February, and the driest part of the year between May and August. Figure 4 sums up the annual mean rainfall amount for every station. An important spatial variability is observed. If the global average over the 13 stations is about 2350mm, the southern part of Mahé has lower annual precipitation (~1700–2100mm) meanwhile the northern and more mountainous part of the island presents higher values (2700–3100mm).

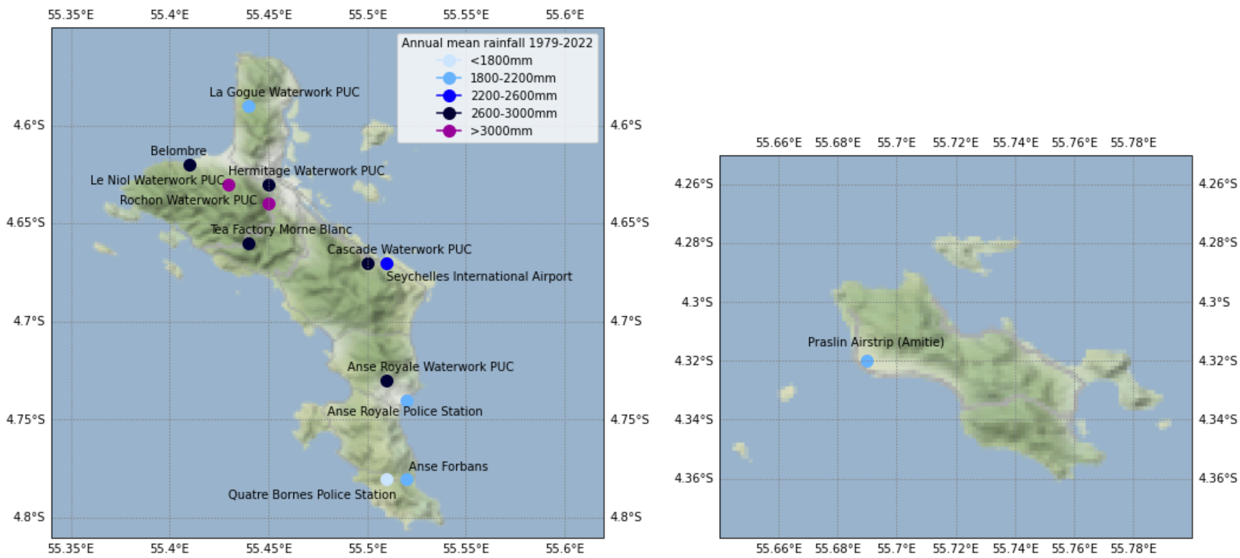


Figure 4 : Spatial variability of the annual mean rainfall amount.

This first part was dedicated to the presentation of the data available. The results presented in the rest of the manuscript are based on the 24hr rainfall amounts for the 13 stations presented above. For better coherence with the seasonal cycle of rainfall, we will not refer to calendar years (from January to December), but we will use a 12–month period, centered on the rainy season peak (December). For instance, the 2021 season corresponds to the June 2021–July 2022 period. In addition to the daily measurements, hourly data are also available but for only one station : the Seychelles International Airport (SIA). These data cover the January 1979–March 2023 period, and will be used later for further examinations of the EPEs characteristics.

Definition of an extreme precipitation event (EPE)

With the aim of characterizing and studying the previsibility of EPEs in Seychelles, a first step is to define a criterion to select EPEs. With no data treatment having been done on 24hr rainfalls data in Seychelles before this study, we had no values or thresholds to refer to. There are several approaches for characterizing the upper/lower ranges of a distribution (return time level, percentiles, probabilistic thresholds...), and our definition of an extreme precipitation event will be based on the exceedance of percentiles of the 24hr rainfalls distribution. For instance, the 99th percentile (p99) corresponds to a value that is overtaken once every 100 days on average when calculated for all days of the climatology (all–day percentile hereinafter). The aim of this study is not to look at every convective rainfall event that can affect Mahé island very temporarily or locally, but to have an overview of the large–scale EPEs in Seychelles, for which an anticipation can be expected from large–scale weather conditions. Thus, our selection is based on extreme rainfalls at various places at the same time. We define an EPE based on all–day percentile as follows :

- at least 3 stations exceed their all–day percentile 95 (p95) at the same time
- at least 1 of these station exceeds its all–day 99th percentile

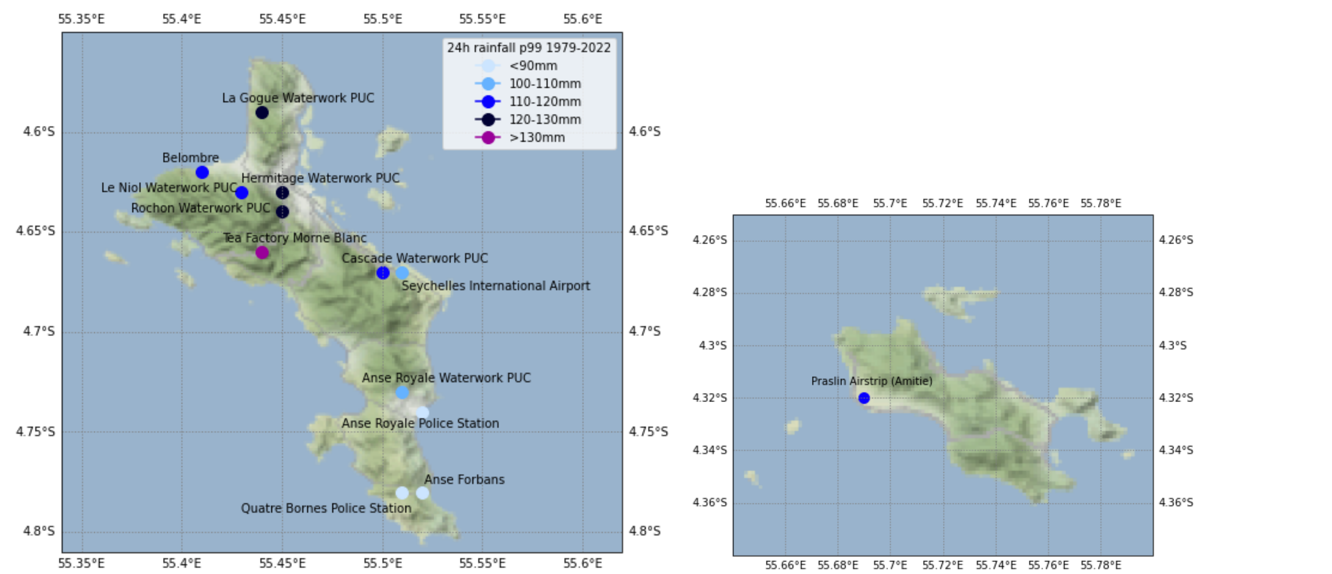


Figure 5 : Map of the 99th all–day percentile (mm) values of the 1979–2022 distribution for the 13 stations.

As for the annual rainfall amounts, the p99 presents a high variability, mostly between the north and the south of Mahé. These thresholds give a first idea of the intensity that heavy rainfalls can have, with values of 110–120mm/24hr being statistically reached about 3 times a year. Return–time thresholds have also been calculated and are available in annex 1. For every station, 5–years and 10–years return time thresholds obtained with the DCSC (Direction du Climat et Services Climatiques) service of Météo–France are significantly higher than the p99 we use for the EPEs detection (often 40 mm to 60 mm higher). The EPEs also present a wide range of intensity, with p95/p99 detection thresholds being about 90 to 140mm in 24hr, but some events have seen rain gauges measuring up to 250–300mm (annex 1).

Climatology of the extreme precipitation events

The criteria defined previously give us a selection of 254 EPEs from January 1979 to March 2023 (5.8 events per season on average). These EPEs present a high interannual variability, with a standard deviation of 3 EPEs per season.. Hardly any trend can be figured out from this distribution : a slight decrease of the number of EPEs per season can be identified, but with no statistical significance (very low r^2 value for a linear regression). The monthly distribution of the EPEs shows, with no surprise, that the rainy season (November–February) corresponds to the peak of EPEs occurrences, but also that these heavy rainfalls can occur outside the rainy season.

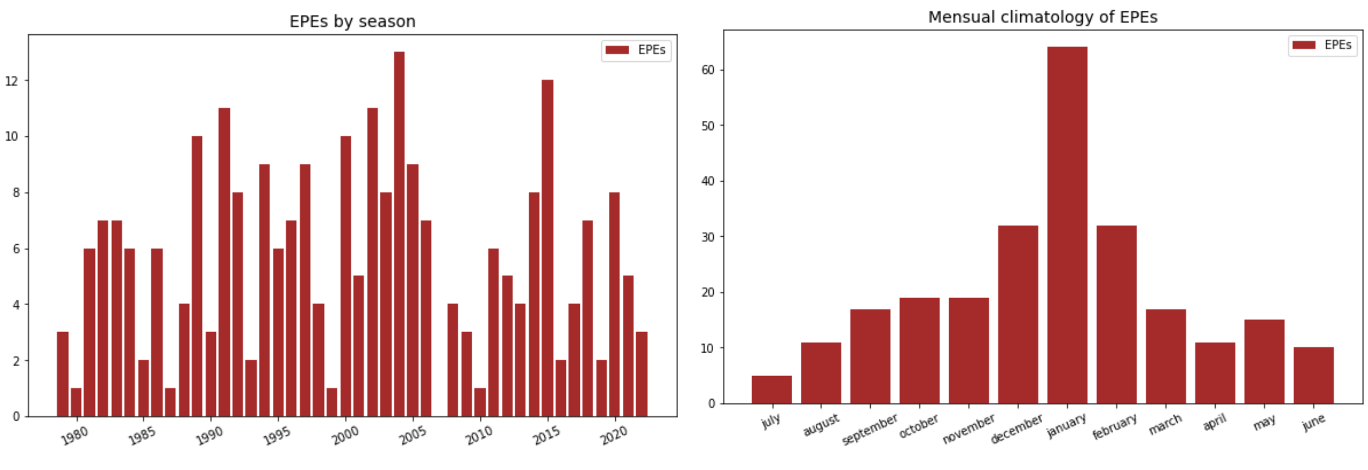


Figure 6 : Interannual (Left) and annual (Right) evolution of EPEs.

The number of EPEs per station enables identifying 2 clusters on Mahé : the northern stations, and the southern ones. The annual rainfall climatology has shown that the north part of the island is the rainiest one, and this is also visible with the number of EPEs per station. The next figure presents the monthly percentages of EPEs concerning the northern part or the southern part of the island (at least one station of the north/south part of Mahé is concerned). Several patterns are identifiable. First, the EPEs concerning Praslin seem to be quite similar to the ones affecting the southern stations of Mahé, as the trends for these two groups are similar. Next, even if it confirms that the northern stations experienced more numerous EPEs, the balance between the north and the south is not constant all–over the season. Indeed, the gap is the highest during the rainy season, when the north–west Monsoon is well established. And we can observe a higher part of the EPEs affecting the southern stations starting in March, when the southeasterly winds begin to prevail in Seychelles.

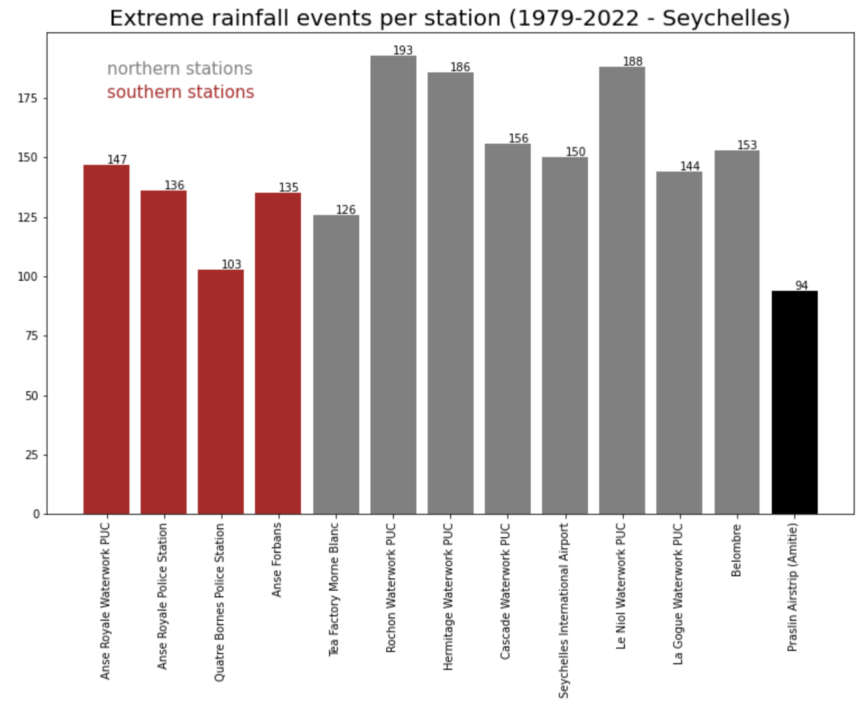


Figure 7 : Number of EPEs per station in the northen part of the island (gray) and southern part of the island (red) , for instance, among the 254 EPEs of the 1979–2022 period, there are 139 EPEs concerning the SIA station (its p95 or p99 is exceeded).

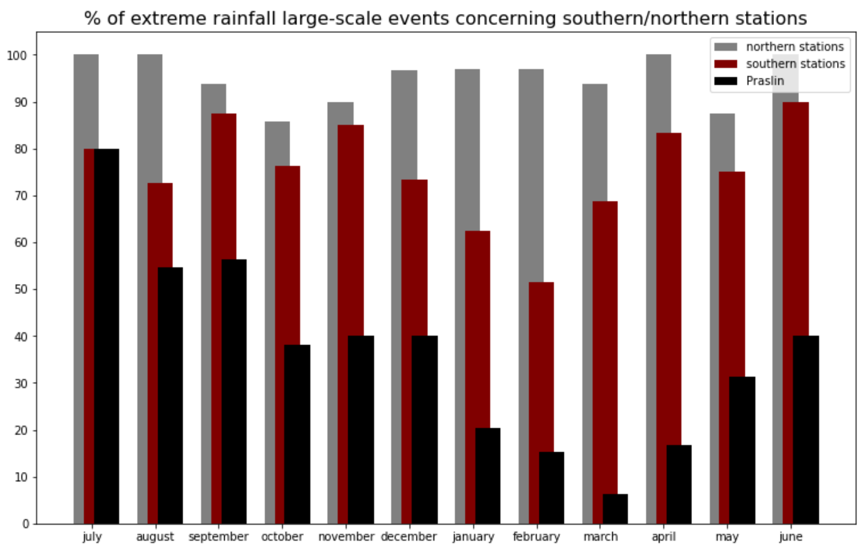


Figure 8 : Annual cycle of the percentage of the EPEs affecting each station group for the northern stations (gray), southern stations (red) and Praslin (black).

Hourly analysis at the Seychelles International Airport

As mentioned in the part dedicated to the data description, we dispose of hourly data for the Seychelles International Airport (SIA). Even if we do not have data for all the stations included in the study, an analysis of the SIA hourly data allows to highlight characteristics of the EPEs at time–scales shorter than the day. The duration and the time of the day of the most intense rainfall that compose the daily EPE are of particular interest. We considered the EPEs days previously identified (the SMA considers that the precipitations of a day D is the cumulative rainfalls from 7am the day D0 to 7am the day D+1), and analyzed the frequency of various hourly thresholds during those 24 hours.

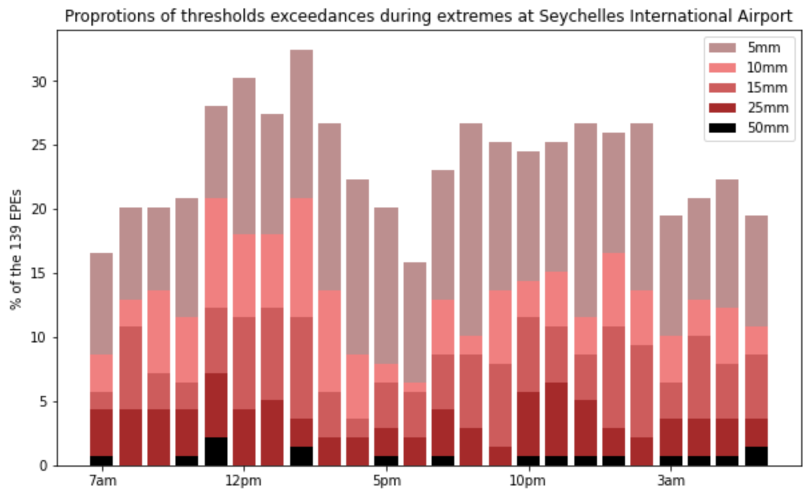


Figure 9 : Frequency of occurrence of hourly rainfalls for thresholds ranging from 5 mm to 50 mm (colors) during the SIA EPEs. Hours are in local time.

EPEs are characterized by two peaks of intensity : a first one around 12pm, which can be related to the typical diurnal cycle of convection, and a second one at night. Discussion with the SMA forecasters brought interesting propositions for explaining this second peak : during the dry season, the south–easterly wind blows on the eastern coast of Mahé, on which the SIA is located. At night, the night breeze goes down the mountains (cooler air is heavier and creates a downward flow) and converges with the south–easterly winds on the coast. This convergence zone is usually observed around midnight and responsible for cloud formation and even precipitations. The hourly rainfalls amount (averaged on the EPEs dates) profile is available in annex 2 and presents a similar trend.

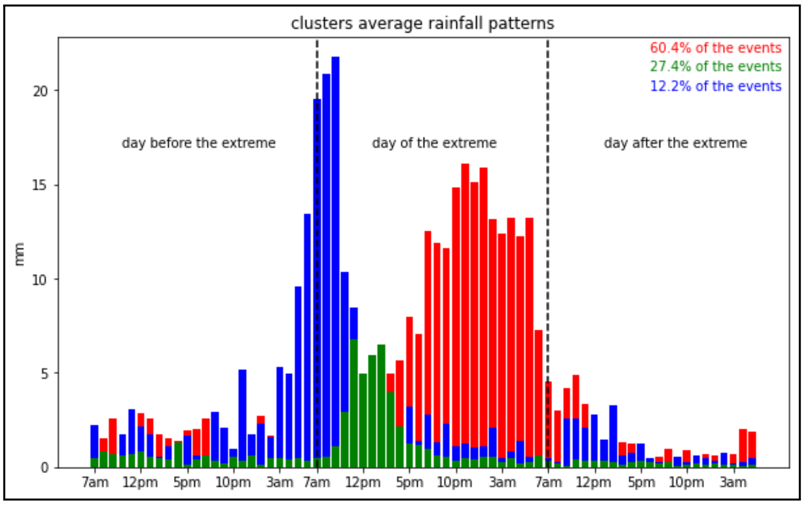


Figure 10 : Composite mean diurnal cycle of hourly rainfall during the SIA EPEs for the three clusters obtained from k-means.

A k-means clustering method on the average hourly rainfalls during EPEs enables us to visualize different categories of events. At the SIA, the EPEs generated by the convergence of the night breeze and the south-easterly winds are the most numerous, as it concerns about 60% of the 139 EPEs, which is not very surprising as the SIA is located on the eastern coast. The rainfalls occuring in the morning at the SIA are heavier but also rarer.

Extreme precipitation events related variability analysis

The EPEs detection showed a high variability in their distribution at different scales. In order to quantify the different scales involved in the EPEs modulation, we use the Outgoing Longwave Radiation (OLR) parameter, which is a parameter commonly used to describe the large-scale evolution of convection. Negative OLR anomalies correspond to high and cold cloud tops (deep convection).

A first view of the time scale involved in the occurrence of EPEs is given with the time filtering of OLR in various bands (Fig. 11). We define a low-pass filter to retain the interannual variations of OLR with periods T > 1 year and a band-pass filter with period 2 < T < 90 days, allowing to select the subseasonal part of OLR variations. The latter filter encompasses the signature of atmospheric waves – which are key drivers of the convection and rainfall variability in equatorial climate (Kiladis & al. (2009)). On the interannual-filtered OLR anomaly, we can identify a signal due to the largest atmospheric drivers that are the SST modes that will be studied in the next section, with a pattern typical of El Niño scheme being recognizable (negative OLR anomaly associated to convection over the central equatorial Pacific and a dry anomaly on the Maritime Continent), as well as a positive IOD with a zonal dipole of OLR anomaly in the Indian Ocean. The 2-90 days filtered OLR reveals the influence of a simple atmospheric pattern with an isolated peak of convection localized near Seychelle. This anomaly is larger than a convective system and points out that a large–scale signature is observed at the time of EPE, likely associated with the passing of atmospheric waves.

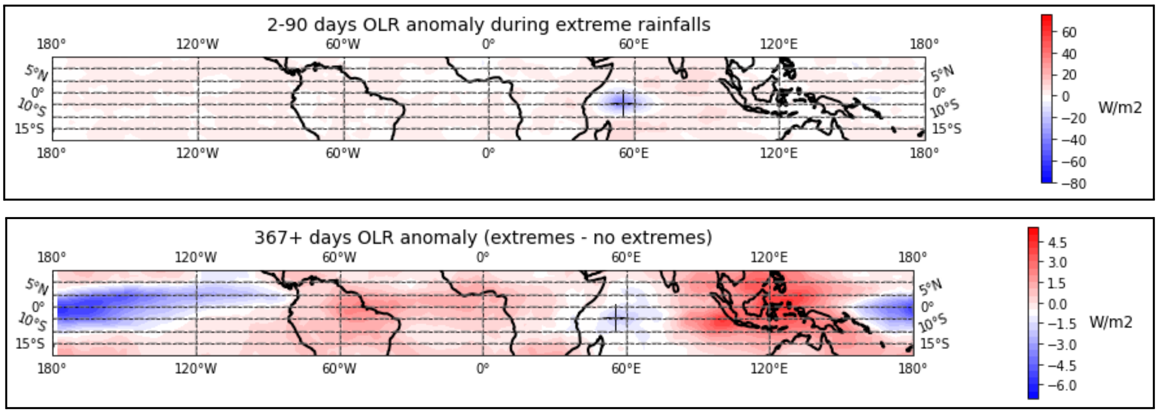


Figure 11 : Anomalies of OLR filtered (2–90 days on top and interannual on bottom), averaged on the days of EPEs. The color–bars are different for the two maps.

The overall analysis of Figure 11 shows that the mean atmospheric conditions of EPE involve the subseasonal scale for a large part, which is embedded within an interannual mode of variability that also favors convection in the WEIO. This analysis led us to prospect the EPEs modulation by different atmospheric and oceanic drivers : SST modes and atmospheric waves. Also, tropical cyclones and their consequences are a major concern in the Indian Ocean. The rainfalls associated can be very intense and we cannot omit these phenomena in our research. The next part explores the link between the cyclonic activity in the Indian Ocean and the EPEs in Seychelles.

Tropical cyclones contribution

The Indian Ocean is regularly impacted by tropical systems (TS). Tropical cyclones are associated with deep convection, not only on its main core but also in the spiral bands, that can extend over hundreds of kilometers from the cyclone center. The Seychelles archipelago, and especially Mahé, is not used to facing direct impacts from tropical storms or cyclones, as they usually develop and circulate further south. However, because of their large extension and their strength, tropical systems usually influence the circulation at different levels of the atmosphere and around thousands of kilometers away from their position. This section analyzes the possible link between the occurrence of EPEs and the presence of TS near the island of Mahé. Inspired by previous work made by Erwan Cornillaut (Météo–France, DESR/CNRM/GMME) for his thesis about the extreme precipitations in the overseas countries and territories, we will use the IBTrACS data (International Best Track Archive for Climate Stewardship) and only consider the TS within

2000 km from Mahé with an intensity above or equal to the tropical storm stage (sustained winds > 63 kph).

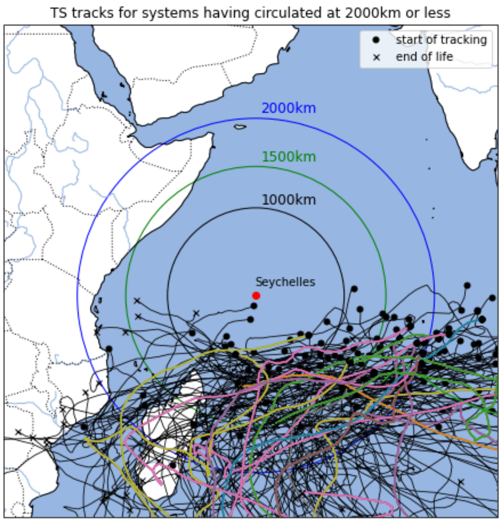


Figure 12 : Tracks for TS having circulated within 2000 km from Mahé between 1979 and 2022, with the co–occurring EPEs in color.

From January 1979 to December 2022, 156 TS circulated at 2000 km or less from Mahé, with only 19 (13%) being associated with an EPE. It appears that it is very rare that TS come close to Mahé, with only 22 systems in 43 years having passed within 1000 km from Mahé. It is even rarer that these phenomena can be associated with the occurrence of EPEs in Mahé, as only 21 (8%) of the EPEs are concurrent with the presence of a TS at 2000 km or less. Moreover, we can observe that, in accordance with the TS climatology, the systems causing heavy rainfalls circulate south–east or south of the archipelago. We also noticed that the EPEs occurred when the systems still have a zonal or quasi zonal trajectories, moving westward (map with the locations of the systems when the EPEs occurred in annex 3).

The IBTrACS data combined with the daily rainfall data of the SMA allowed us to estimate the proportion of EPEs being caused by the proximity of a TS. Very few cases were found, with less than 10% of the EPEs of the 44 seasons studied being associated with a TS, and 13% of the systems having passed within 2000 km from Mahé responsible for heavy rainfalls. These results show that, despite the strength of such phenomena, tropical cyclones do not have a major contribution to the number of EPEs.

To sum up, the statistical analysis of the daily rainfall data highlighted the characteristics of the EPEs from the diurnal scale up to the seasonal scale. These events logically follow the seasonal cycle with a peak of occurrence during the rainy season. Despite the heavy rainfalls they can provoke, tropical cyclones are not a major driver of EPEs in Seychelles, especially because very few of them circulate within 2000 km from Mahé. However, the high variability observed, particularly at the interannual scale, justifies the study of the EPEs modulation by oceanic/atmospheric drivers that will be detailed in the next sections.

—Extreme rainfall episodes modulation by SST index—

Introduction and methods

As mentioned in the introduction, previous works studied the possibility of correlating SST indexes associated to known coupled modes of variability such as ENSO to the precipitation variability in the WEIO. Aurelie P. Harou and al. (2006) established that about 20% of the precipitation variability in Seychelles can be explained by the fluctuations of the SST anomalies dipole observed between the western and the eastern parts of the Indian Ocean. This part documents the link between three different SST indexes summarizing the evolution (phase and intensity) of three of the main oceanic modes of variability (IOD, ENSO, Subtropical Indian Dipole (SIOD)) and the EPEs variability. SST index data come from the NOAA and Météo–France (DIROI/EC). Our method consists in a counting of the number of EPEs by SST index phase (positive, neutral or negative). The discrimination of the type of SST index event is based on the SST index distribution. For a given index, we calculated the first and the third quartile (noted q25 and q75) of its whole distribution and established that positive (negative) events correspond to values higher (lower) than the q75 (q25). It is important to take into account that the IOD and SIOD usually peak at some times of the season. Thus, for a better characterization of the positive and negative events, we averaged the monthly indexes on chosen periods. For the IOD, we use the July–December period (noted JASOND). For the SIOD, the October–March period (noted ONDJFM) appeared to be the most relevant one. For the ENSO, we used the annual averaged index, as this mode mainly evolves along greater time periods. We firstly studied the EPEs modulation by each SST index taken on their own, at annual and then monthly scales. Then we built composites considering the combined configurations of these three SST indexes as it better represents the oceanic and atmospheric situation at a seasonal scale than looking at one SST index.

Indian Ocean Dipole influence

Identified at the end of the 90s, the IOD is an oscillation of the SST in the Equatorial Indian Ocean, with 2 regions forming a dipole, being alternatively warmer or cooler. The positive phase (IOD+) occurs when the SST of the western area is higher than the SST of the eastern part of the basin. The negative phase (IOD–) is the exact opposite, meanwhile the neutral phase is established when no significant differences are observed between the two areas.

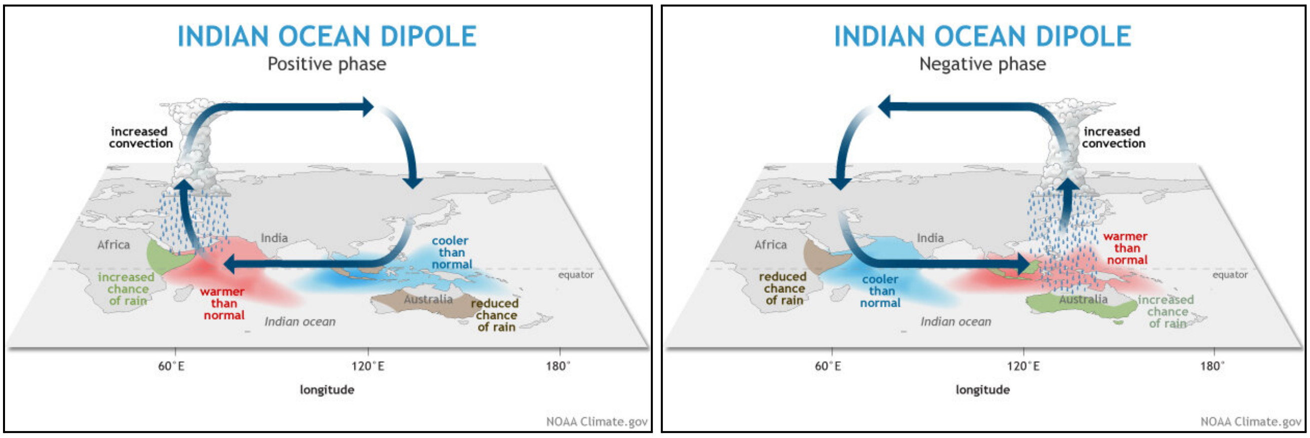


Figure 13 : Indian Ocean Dipole simplified view for positive phase (left) and negative phase (right). Blue/red shading indicates positive/ negative SST anomaly. © NOAA.

As shown in Figure 13, a IOD+ event corresponds to a positive precipitation anomaly over the WEIO, and so in the Seychelles, as the warmer SST implies enhanced atmospheric convection conditions. According to this scheme, we can expect the IOD+ to favor the EPEs in comparison with the IOD– phase, which implies a dry anomaly in the WEIO. A first evidence of a positive modulation of the number of EPEs per season by the IOD+ events is that among the 10 seasons classified as positive IOD phases, we observe 75 EPEs, meanwhile only 52 EPEs occurred during the 13 seasons identified as negative IOD phases. The IOD– years account for 4 EPEs on average, while the IOD+ years account for 7.5 events on average. These values stand out from the global average of 5.8 EPEs per season and confirm the IOD scheme. Nevertheless, neutral IOD phases (q25<IOD index<q75) present a high variability with numbers of EPEs per season ranging from 0 to 13.

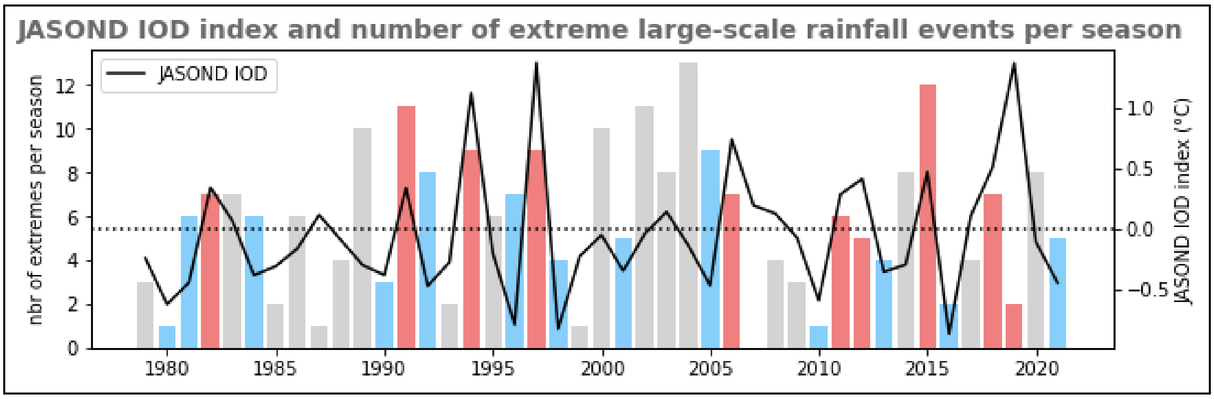


Figure 14 : Interannual variation of the IOD phase (solid line) and of the number of EPEs per season (colored bars). Red (blue) bars indicate the number of EPE in positive (negative) IOD phases. Gray bars correspond to neutral SIOD events.

For assessing the modulation of each phase at the intraseasonal scale, we compare averaged numbers of EPEs by month by type of IOD event. Figure 14 shows the mensual averaged number of EPEs for the IOD+, IOD– and neutral the global average (all years). The IOD+ contribution prevails during the first half of the season, with a clear positive modulation of the EPEs between September and November. The negative phase contribution dominates the core and the end of the rainy season, and is still prevailing for the rest of the season, but the different contributions are close from March to June.

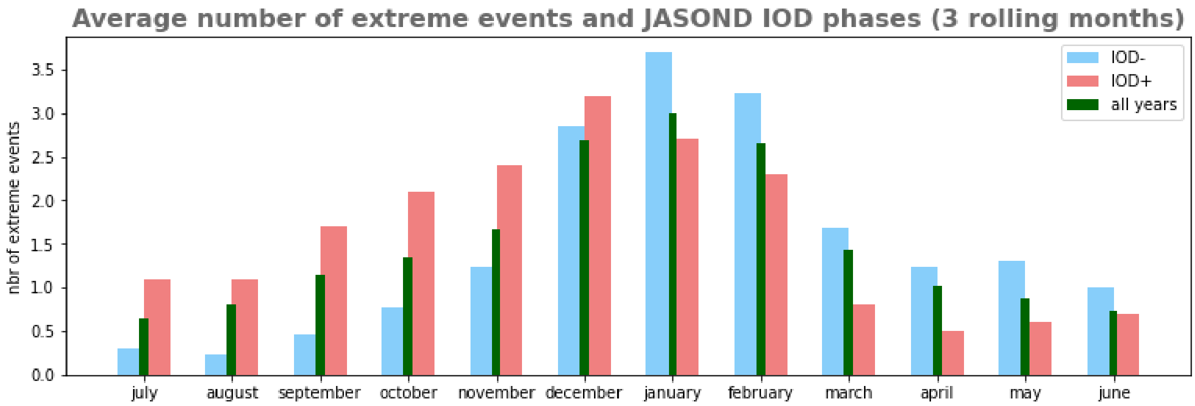


Figure 15 : Averaged numbers of EPEs observed per month during positive IOD (red) and negative IOD (blue) based on the value of IOD index during JASOND, and during the whole period of study (in green).

Previous works have already established that the positive IOD events are associated with positive rainfalls anomalies in the Seychelles. Our results demonstrate that this trend is also valid for the extreme events : austral summer with IOD+ favors – at a seasonal scale – more EPEs than average in the 1979–2022 period. However, the subseasonal analysis showed a more complex signal, with IOD– events also favoring more EPEs than average during the second half of the season.

Subtropical Indian Ocean Dipole influence

The SIOD is an analogue of the IOD, featuring the SST oscillation in the subtropical part of the basin. Positive SIOD configuration corresponds to warmer SST over the southwestern Indian Ocean, at the south–east of Madagascar and the Mascarenes, and cooler SST further east, at the east of Australia and south of the maritime continent. SIOD configuration is known for influencing the Mascarene High and so the intensity and the direction of the wind circulation over the basin. Its influence can modulate the northwestern Monsoon that affects Seychelles during the rainy season. During SIOD+ events, the Mascarene high is – on average – stronger, leading to a southeastern surface wind anomaly over the center of the basin. It results in the weakening of the northwestern Monsoon flux that brings moisture, precipitable water and favors the precipitations in Seychelles. SIOD– events are associated with a shift of the Mascarene High to the south. This configuration, on the opposite of the SIOD+, favors a strong northwestern Monsoon over the WEIO.

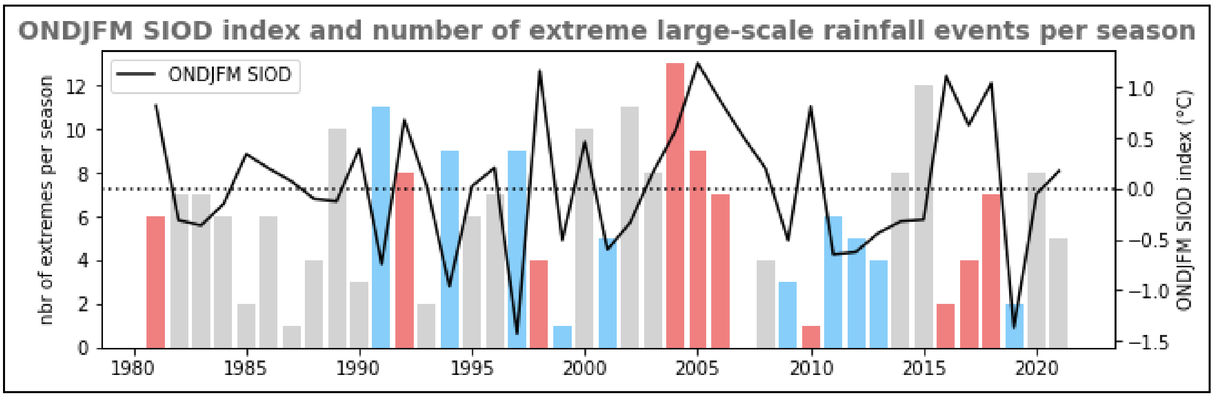


Figure 16: Interannual variations of SIOD index (solid line) and of the number of EPEs per season (colored bars) with the positive (negative) SIOD phases in red (blue).

Both SIOD+ and SIOD– were observed 10 seasons from 1981 to 2021 (period for which we dispose of SIOD index data), with respectively 6.1 and 5.5 EPEs per season on average. Out of the 10 SIOD+ events, 6 corresponds to years with more EPEs than average, and among the 10 SIOD–, only 4 corresponds to more EPEs than on average. The variability of the EPEs in each type of SIOD event is even more important than for the IOD, but a slight positive (negative) modulation by the SIOD+ (SIOD–) is identified. The monthly analysis confirms this result. The gap between these three configurations is still small throughout the season, but during the rainy season, the SIOD+ phase contribution is a little bit higher than the global average and the negative phase contribution. This signal extends after the rainy season, all along the second half of the season.

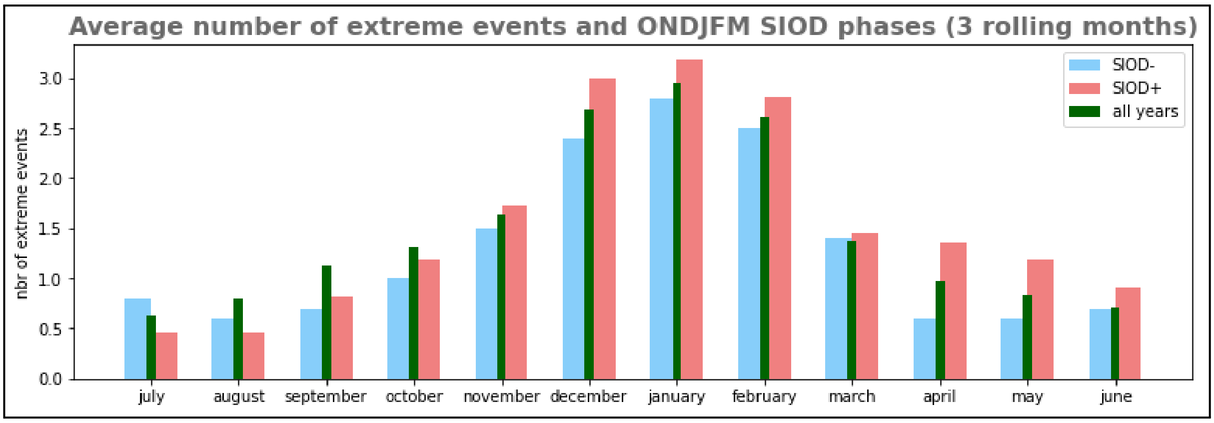


Figure 17 : Averaged numbers of EPEs observed per month, classified using the type of SIOD phase, and the global average (in green).

The SIOD data combined with the EPEs identified from the daily rainfall data of the SMA shows that no obvious modulation by the SIOD taken on its own can be highlighted. In the second half of the season, the positive phase seems to favor the EPEs, but not significantly.

El Niño Southern Oscillation influence

The last SST mode studied is the most famous one. Many researches and studies have already been done on the ENSO and its influences, with planetary scale teleconnections identified. Same methods are once again applied on the 1979–2022 ENSO index provided by the NOAA.

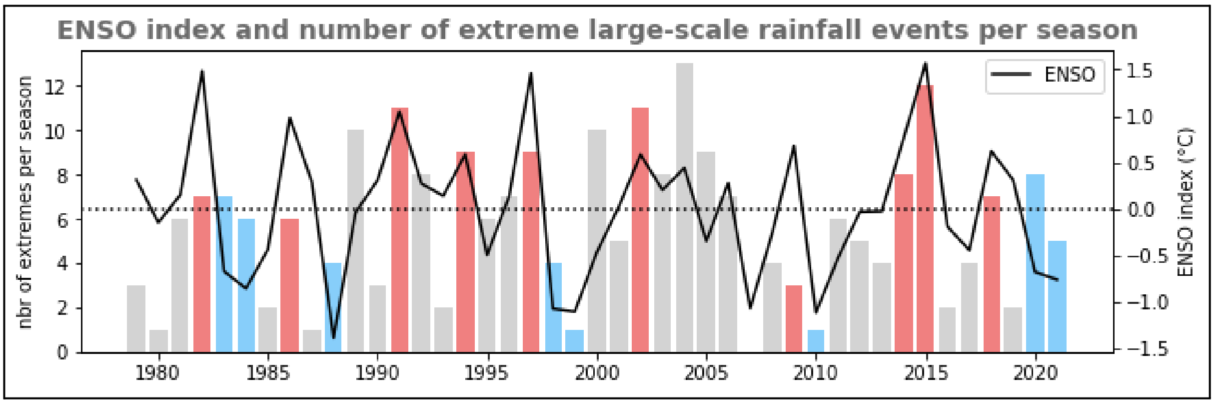


Figure 18: Interannual variations of ENSO index (°C , solid line) and of the number of EPEs per season during positive (negative) ENSO phases in red (blue).

The ENSO+ (El Niño) and the ENSO– (La Niña) categories account respectively for 8.3 and 4.5 EPEs per season on average. The modulation of the heavy rainfall episodes in the Seychelles by the ENSO seems to be well established. We confirm this assessment with the fact that 100 EPEs out of the 254 (39.4%) occurred when the monthly ENSO index was in the last quartile of its distribution, meanwhile only 71 (27.9%) occurred with an ENSO index in its first quartile.

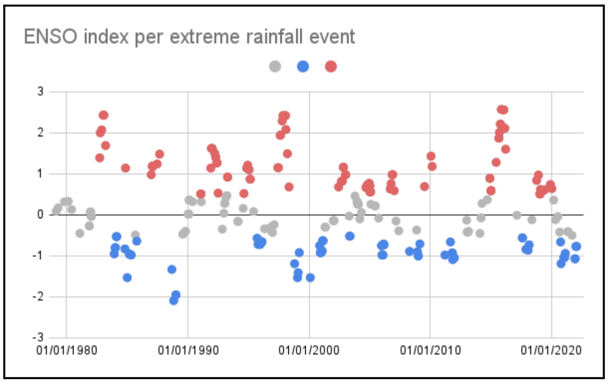


Figure 19 : ENSO index distribution during the 254 EPEs of the 1979–2022 period. Values above the 3rd quartile (+0.49°C) are colored in red, and the ones below the 1st one (–0.52°C) are in blue.

At the seasonal scale, the observation is in accordance with the previous result. The ENSO+ contribution largely dominates during the first half of the season, but decreases slightly then. Figure 20 shows that the positive and negative ENSO events have respectively higher and lower averaged numbers of EPEs per 3–rolling months from July to December. The difference between the global average and the negative phase one is not very large, but the positive modulation of the EPEs in the early part of the season is clearly identifiable. For the rest of the season, La Niña and El Niño do not distinguish themselves from the global average.

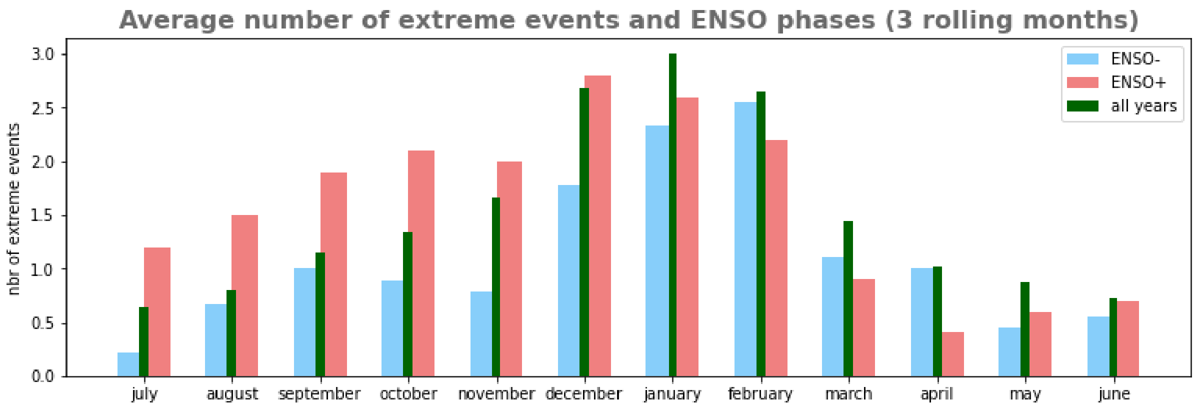


Figure 20 : averaged numbers of EPEs observed per month, classified using the type of ENSO phase, and the global average (in green).

The El Niño event clearly favors the occurrence of extreme rainfall episodes in the Seychelles, with almost 40% of the 1979–2022 events being concurrent with a ENSO index above its 3rd quartile value. At a subseasonal scale, this predominance of the positive ENSO phase during EPEs is only observed during the first half of the season. From January to June, hardly any phase stands out from the other and the global average.

Composites of the SST index

We studied the possible influence of three major oceanic drivers, highlighting the positive or negative modulation of the EPEs they can imply. However, a realistic seasonal categorisation cannot be done that way. Indeed, teleconnexions also exist between the different SST modes. This section presents the composites obtained by classifying each season according to the triplet of the three SST indexes. This classification enables counting every season once and only once. For each category obtained, we count the average number of EPEs per season and compare it to the global average in order to identify anomalies. Some configurations (as ENSO–/IOD–/SIOD– for instance) never happened between 1981 and 2021, and many categories have very few years in it. However, 41 seasons is still a long time–period, and we can affirm that the configurations that never happened during these 41 years are not likely to happen in the future either. The first two categories at the top of the next graph (ENSO−/IOD−/SIOD+ and ENSO+/IOD+/SIOD−) are considered as cannonic configurations that are regularly observed. The result concerning these two configurations is very interesting as their anomalies are completely opposed (−60% and +60%). We can also notice that the positive (or neutral) phases of the ENSO and the IOD appear in most of the categories having a positive anomaly higher than +25%, meanwhile their negative phases are never present in the categories with anomalies lower than −25%. The ENSO− appears in three of the five categories with the most important negative anomalies, confirming the results mentioned previously about ENSO. For the SIOD, the observation is more balanced as its three phases appear in categories with very different anomalies.

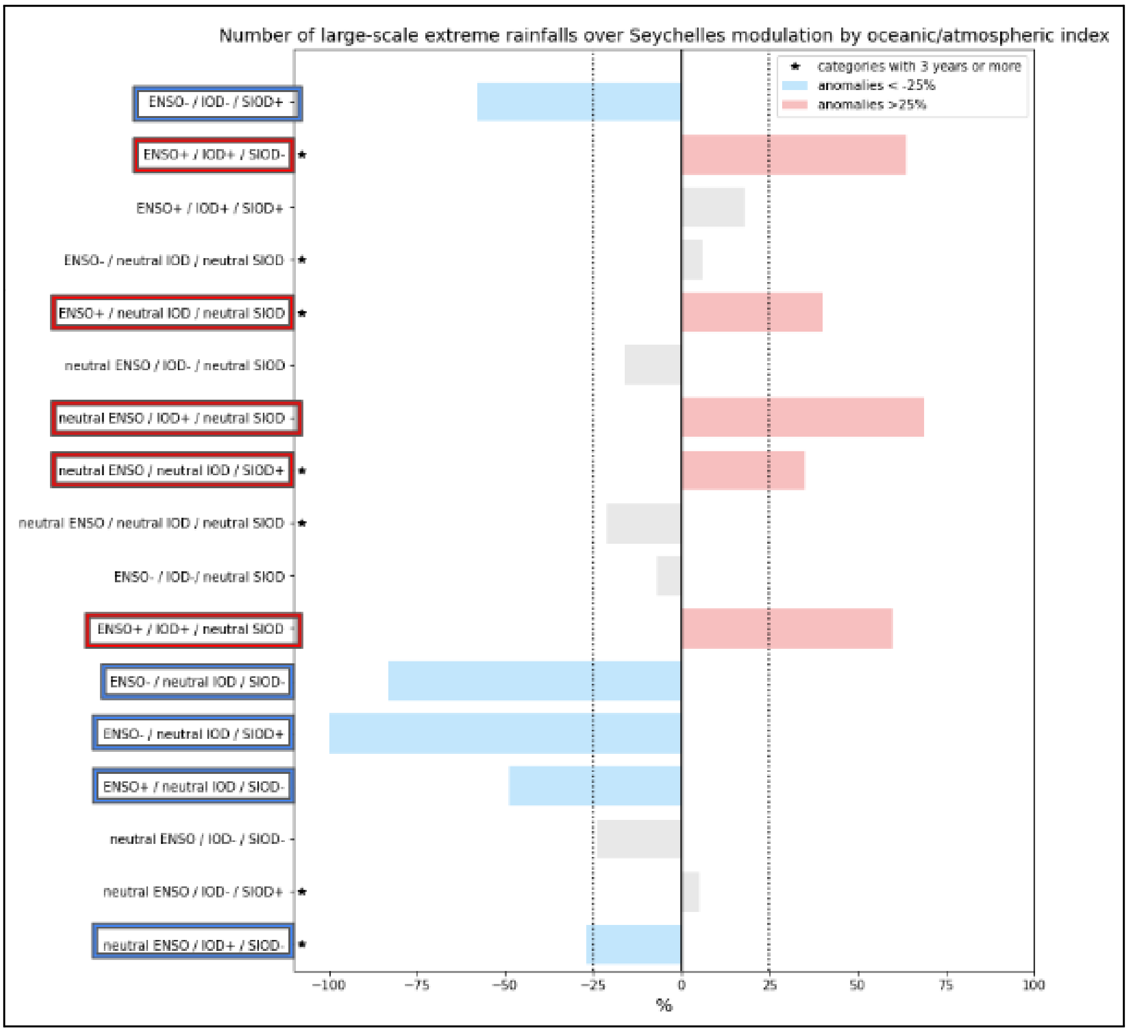


Figure 21 : anomaly (in %) of the number of EPEs in Seychelles per season depending on the ENSO/IOD/SIOD configuration.

The study of the SST mode impacts on the EPEs gave interesting results even if the evidence of significant modulations are not always found. Mainly, the positive ENSO and IOD events clearly favor seasons with more EPEs than average, with a stronger signal in the first half of the season. As for the result about the EPEs modulation by the SIOD, it is difficult to conclude about this SST mode, as both its negative and positive phases appear in the configurations having important positive and negative modulation. In any case, the composites enable a better overview and a more realistic study of the EPEs modulation, as these SST modes are also closely linked to each–others.

—Atmospheric waves contribution—

Introduction

Atmospheric waves are key elements of the equatorial climate. These perturbations of the atmospheric parameters (precipitable water, cloudiness, wind force and direction, ...) can boost or inhibit convection at large–scale and can be responsible for important weather variability in time and space (Kiladis & al. (2009)). The atmospheric wave influence on the extreme precipitations have already been highlighted for the Sahel (*Tropical Waves are key drivers of Extreme Precipitation Events in the Central Sahel*, by Philippe Peyrillé & al.(2023)), and a similar investigation and methods will be applied here for the Seychelles. Throughout our study, we designate convectively–coupled equatorial waves (CCEWs) the atmospheric waves that can amplify the convective activity in the near–equatorial band. Different CCEWs known for modulating convection and rainfalls will be named and detailed further. As shown previously, an analysis of the OLR variability in the Seychelles area at different time scales confirms the usefulness of a focus on the atmospheric waves. Our CCEWs contribution to EPEs assessment is based on OLR and Precipitable Water (PW) filtered data, using the ERAI reanalysis, on a 2.5°x2.5° grid. The method for the obtention of these data is detailed in the next section.

Methods for time filtering and wavenumber–frequency filtering

Digital filters are used to isolate the specific contribution of a given frequency and / or a given spatial scale. The anomaly of a parameter X (OLR or Precipitable Water), X^*, is first determined as the difference between a given day and the corresponding day averaged over the daily annual climatology. In order to separate the time scales as a first analysis, the OLR anomaly is filtered with a Lanczos filter with a low–pass filtering allowing it to retain periods greater than a year. It is indicated as interannual–filtered OLR. A bandpass filter is also applied to select the subseasonal variations of OLR with period 2 days $< T <$ 90 days, which is referred to as subseasonal–filtered OLR. In order to select the contribution of a given CCEW to the anomaly X^* we use the wavenumber–frequency filtering as defined by Roundy and Franck (2004) and Wheeler and Kiladis (1999). The anomaly X^* is processed with a Fast Fourier Transform in time and longitude to analyze the data in the spectral wavenumber – frequency space. Figure 22 shows the resulting normalized spectrum on which peaks of energy emerge across the subseasonal time scale from high frequency (few days on top of the figure) to a few weeks or month (bottom of the figure). These peaks of energy are associated with different CCEWs. For long periods, the Madden Julian Oscillation (MJO) is found for eastward propagation (k>0) and periods between 30 and 90 days. Equatorial Rossby waves (ER) are for periods between 10 and 48 days and a westward propagation (negative wavenumber). At synoptic scale, the Kelvin wave is found for periods between 14 and 2.5 days with eastward propagation. On the westward propagation, the Mixed Rossby Gravity wave (MRG) and the easterly wave (EW) or Tropical Disturbance (TD) explain most of the signal at synoptic scale. The wave–number filtering consists in selecting appropriate filtering domains from the equatorial wave theory by imposing equivalent depths between 12 and 90 m to determine the corresponding CCEW dispersion curves (solid polygons). For the MJO and EW, which do not have analytical solutions, the filtering domain is designed to capture the corresponding peak of energy. The inverse FFT is then computed to rebuild the signal which allows writing $X^{*}{\sim}X^{*}_{MJO}{+}X^{*}_{ER}{+}X^{*}_{K}{+}X^{*}_{MRG}{+}X^{*}_{EW}$.

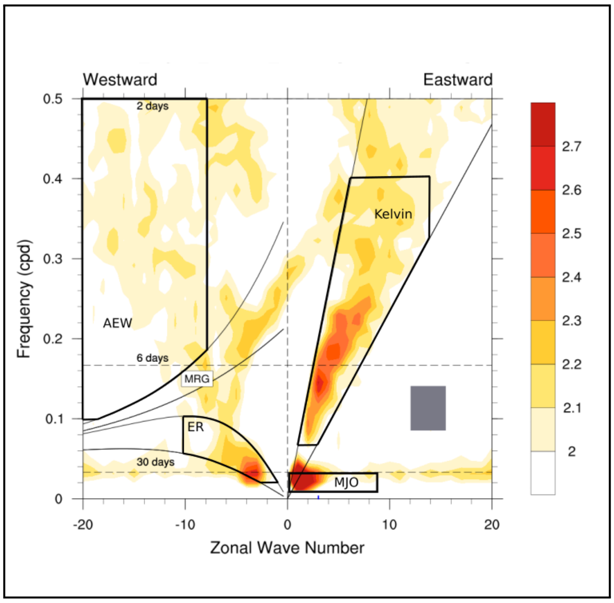
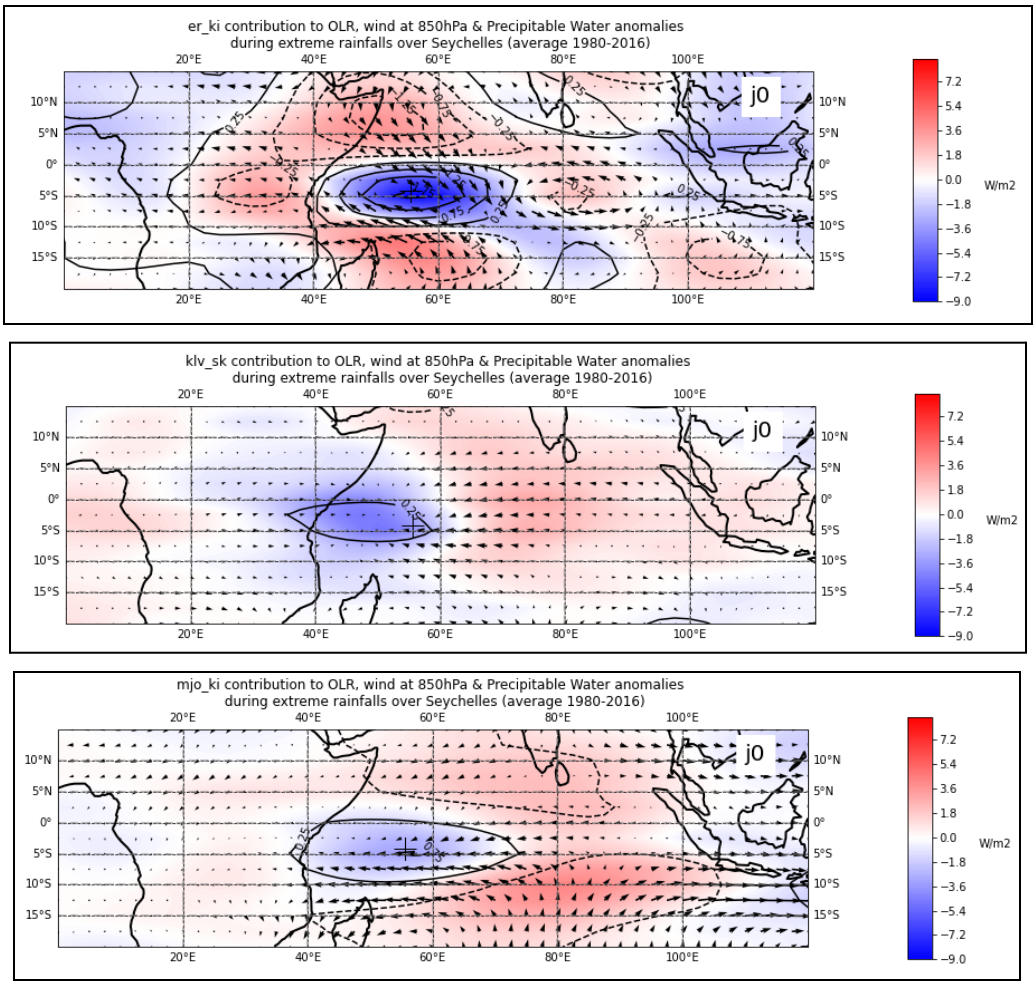


Figure 22 : Normalized power spectrum of OLR (shaded) averaged over [15°S–15°N] for July 1996–2015. source : Peyrillé & al. (2023) The solid polygons indicate the filtering domains used in the study.

Results

Maps showing the average contributions of CCEWs to OLR, PW and wind at 850hPa anomalies during EPEs reveal that, on average, Equatorial Rossby waves are responsible for the greater anomalies, with about contributions of about $-9W/m^2$ to the OLR anomaly and +1.75mm to the PW anomaly (Fig. 23). The anomalies of the other CCEWs are weaker, which can be the result of less frequent and / or less intense waves. Note that the size of the pattern of negative OLR associated with ER is close to the one presented in the subseasonal–filtered OLR. For most of the CCEWs, we can observe that, during the heavy rainfalls, Mahé is located in the core of the convective anomaly (center and maximum of the negative OLR anomaly and positive PW anomaly). However, for the Kelvin wave, the EPEs seem to occur in the front–head of the wave envelope, in the anomalous low–level convergence area. Same observation is done for the MJO, with the EPEs occurring – on average – in the eastern wind anomaly, which is not common. For EW and MRG, the spatial structures are smaller than for the other CCEWS, and so naturally their impact will be less extended in time on a fixed location.

The same maps have been produced for 4 consecutive days, from day–3 to day+1 by reference to the day of the EPEs which are available in annex and enable a visualization of the development and the arrival of the wave structure before the occurrence of an EPE.



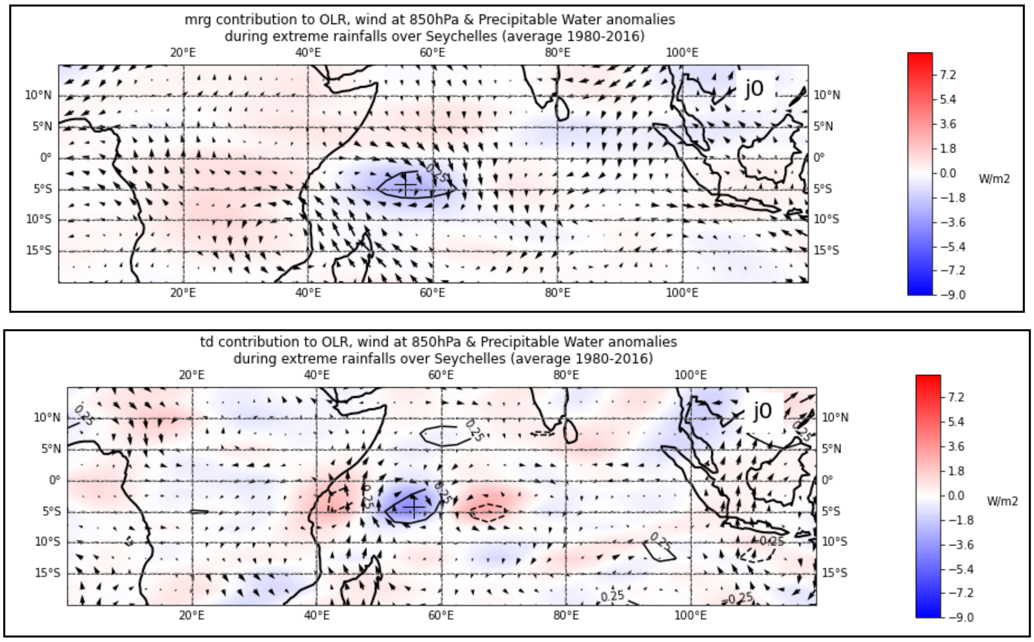


Figure 23 : atmospheric waves contributions to OLR, PW and Wind850 anomalies during extreme rainfalls over Seychelles. PW anomalies in contour (a contour every 0.5mm), OLR anomalies in colors and winds anomalies in arrows.

Peyrillé& al. (2023) demonstrate that various CCEWs configurations were responsible for most of the EPEs observed in Sahel. We drew inspiration from this study to identify and quantify which CCEWs were the most associated with EPEs in Seychelles. The detection of active waves during EPE highlights that – for both of the parameters used as convections proxy – about half of the EPEs are associated with the presence of 1 or 2 convectively active CCEWs around Mahé. With the OLR, the single MJO, Kelvin and ER stand out with more than 20% of the EPEs being associated with the presence of one of these waves as the only one active. Another important result is that the NONE category (no active waves detected) only accounts for less than 15% of the cases. This information shows all the interest of studying the CCEWs contributions to EPEs, as more than 75% of them are situations where at least one atmospheric wave was in an active phase in the Seychelles area. The 2–wave categories do not show any preferred combination more favorable to EPEs except for Kelvin+MJO and ER+MRG. The 3–wave combination of interest is KElvin + MRG + TD.

With PW, the results (available in annex 5) show the contribution of CCEWs influencing humidity close to the equator. The MJO and MRG waves are now predominant in the 1 active wave configuration, meanwhile ER are less likely because the typical pattern of moist anomaly is off the equator. This difference shows that the humidification during EPE is done by a single MJO or MRG most frequently but also by combination involving an ER, a MRG and a EW. A noticeable combination is Kelvin+MRG+EW which shows the greatest contribution in the 3–wave categories both in PW and OLR.

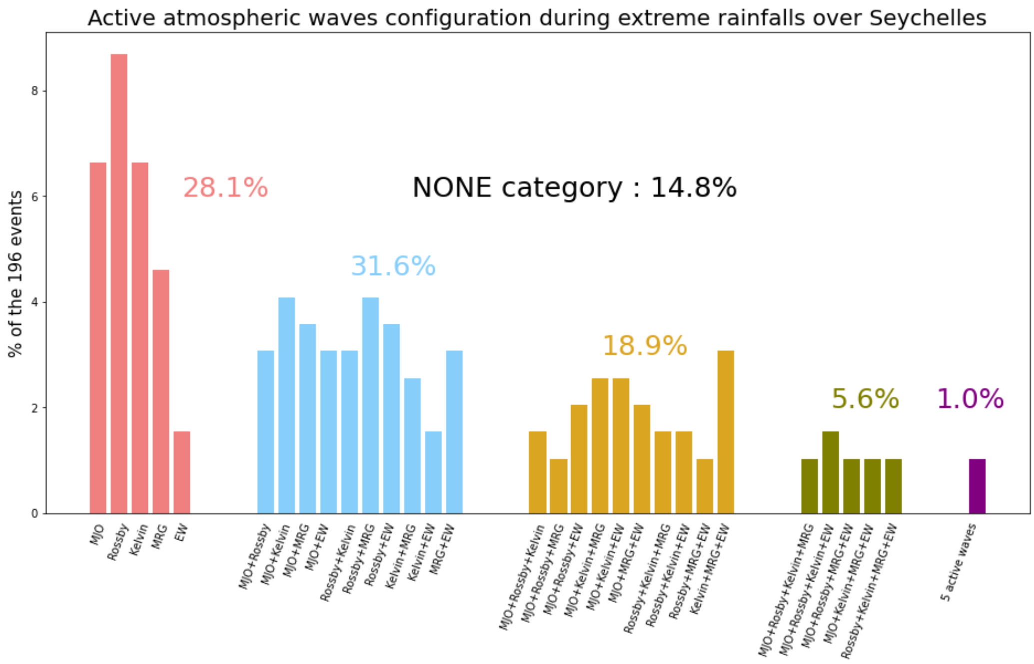


Figure 24 : Percentage of EPEs attributed to different configurations of convectively active CCEWS identified with an OLR attribution criterion.

In conclusion, CCEWs contributions to EPEs analysis reveals that about 75% of the days of extreme rainfalls in Seychelles correspond to the presence of one active CCEW or more. In more detail, about 50% of the cases corresponds to the presence of one or two active waves, with the Rossby+Kelvin and Rossby+MRG being relevant configurations to monitor for forecasters as these configurations stand out from the other ones. The Kelvin+MRG+EW is also noticeable, with its frequency being quite clearly higher than the frequencies of the other trios. The first section of this focus on the CCEWs showed the global OLR, PW and wind at 850hPa anomalies and structures during EPEs, highlighting for instance that Kelvin waves used to cause heavy rainfalls in its front–end and not in the central core of the wave envelope.

—Conclusion and perspectives—

Combining the daily rainfall data of the SMA and statistical methods (percentiles, return–time level), this study enabled the identification of extreme precipitation that occurred between 1979 and 2023 in Seychelles. The analysis of these episodes, named EPEs, draws their climatology and their characteristics, which are totally new information about this topic. If they mainly follow the global rainfall cycle, with a peak of occurrences between December and February, these extreme episodes can also happen outside the rainy season. Their variability is high and at multiple scales. For instance the mean conditions associated with EPEs involve the interannual scale driven by the SST modes of variability with period > 1 year and the subseasonal scale (< 90 days), with a strong signal at the latter scale associated with CCEW. Our study draws a more precise

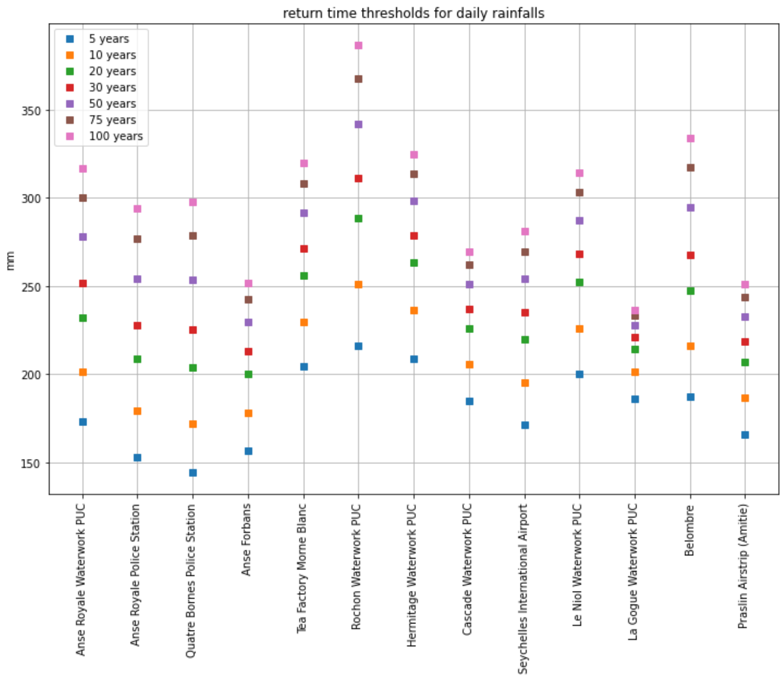
picture of the influence of SST modes, as seasons with more EPEs than average are often associated with ENSO+ and IOD+ events. At the seasonal scale, the signal is more complex, with for instance the IOD– accounting for more EPEs than IOD+ in the second half of the season, which is the contrary of the IOD modulation observed in the first half of the season.
At subseasonal scale, the focus has been given to the CCEWS as they stand as drivers of the precipitation variability in the tropics. It is also shown in the Seychelles a large majority of EPEs (85%) are associated with active CCEWS near Seychelles 15%). About 50% of the cases identified for the 1980–2016 period are linked to the presence of 1 or 2 active waves. Unfortunately, we did not apply statistical significance tests over our results and a further step will be to assess if the results are really significant. Nonetheless, these results give already good perspectives for improving the EPEs predictability. Indeed, with the absence of a high resolution model for the Seychelles area, finding links between EPEs and larger phenomena that have greater predictability is a key step. At a seasonal scale, the SST mode watch can lead to a first estimation : will the next season involve more or less EPEs than average ? Then, the atmospheric waves forecasts that are for instance available with the products of MISVA (Monitoring and forecast of IntraSeasonal Variability over Africa, https://misva.aeris-data.fr/), can alert about some days or a week that are at risk for the occurrence of heavy rainfalls if one or several CCEWs are expected to travel around Seychelles.

—Annex—

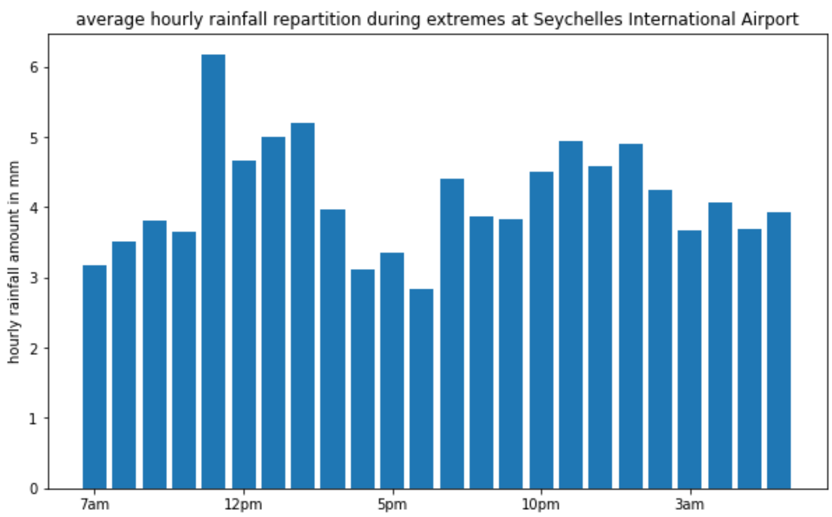
1) Percentiles, return time levels and records

Station	**24hr p95/p99**	**Highest 24hr rainfall observed (date)**
Anse Royale Waterwork PUC	58.2mm/104.3mm	220.5mm (15/08/1997)
Anse Royale Police Station	55.5mm/95.0mm	260mm (05/01/1983)
Quatre Bornes Police Station	52.5mm/89.6mm	198mm (16/08/1997)
Anse Forbans	54.4mm/99.4mm	216.5mm (15/08/1997)
Tea Factory Morne Blanc	80.9mm/141.6mm	191.5mm (04/11/1996)
Rochon Waterwork PUC	68mm/122.1mm	295.8mm (03/02/1984)
Hermitage Waterwork PUC	67mm/125.0mm	288.2mm (27/01/1987)
Cascade Waterwork PUC	65mm/115.0mm	242mm (21/05/1990)
Seychelles International Airport	58.5mm/106.3mm	239.8mm (15/08/1997)
Le Niol Waterwork PUC	65.1mm/117.8mm	286.6mm (21/05/1990)
La Gogue Waterwork PUC	64.7mm/124.5mm	240mm (30/01/1991)

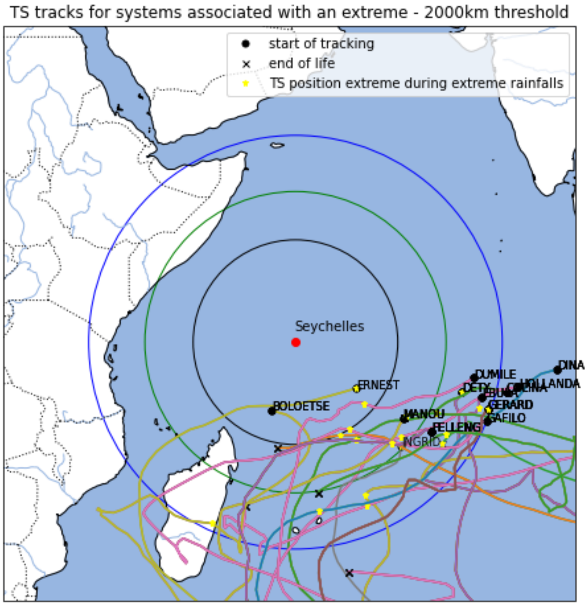
Belombre	70.5mm/115.0mm	247.5mm (30/01/1991)
Praslin Airstrip (Amitie)	58.1mm/105.2mm	229mm (16/08/1997)



2) Hourly rainfalls profile during EPEs at the SIA

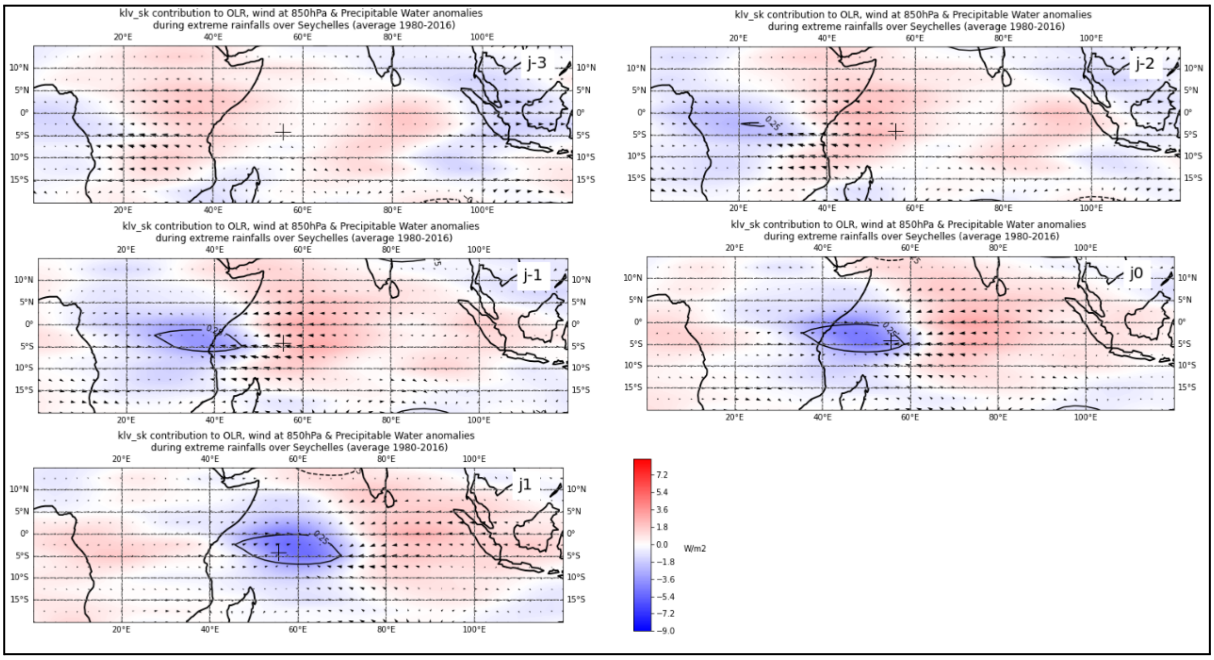


3) Tropical storms/cyclones positions when EPEs occurred

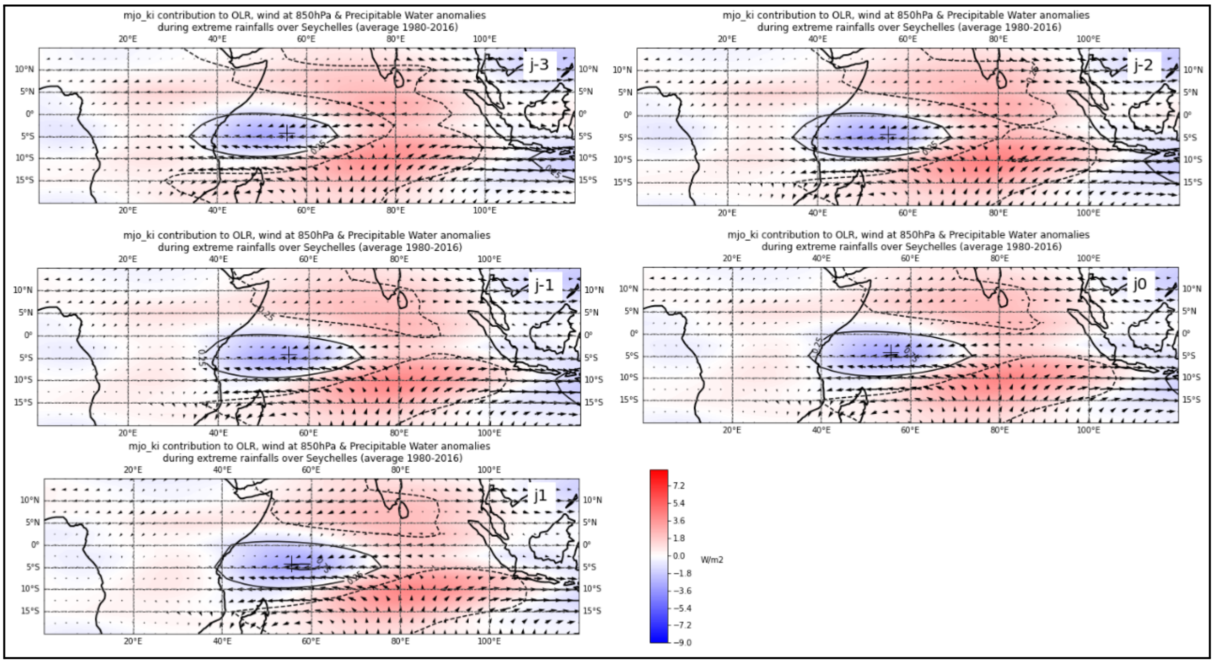


4) Time series of anomaly contributions of CCEWS

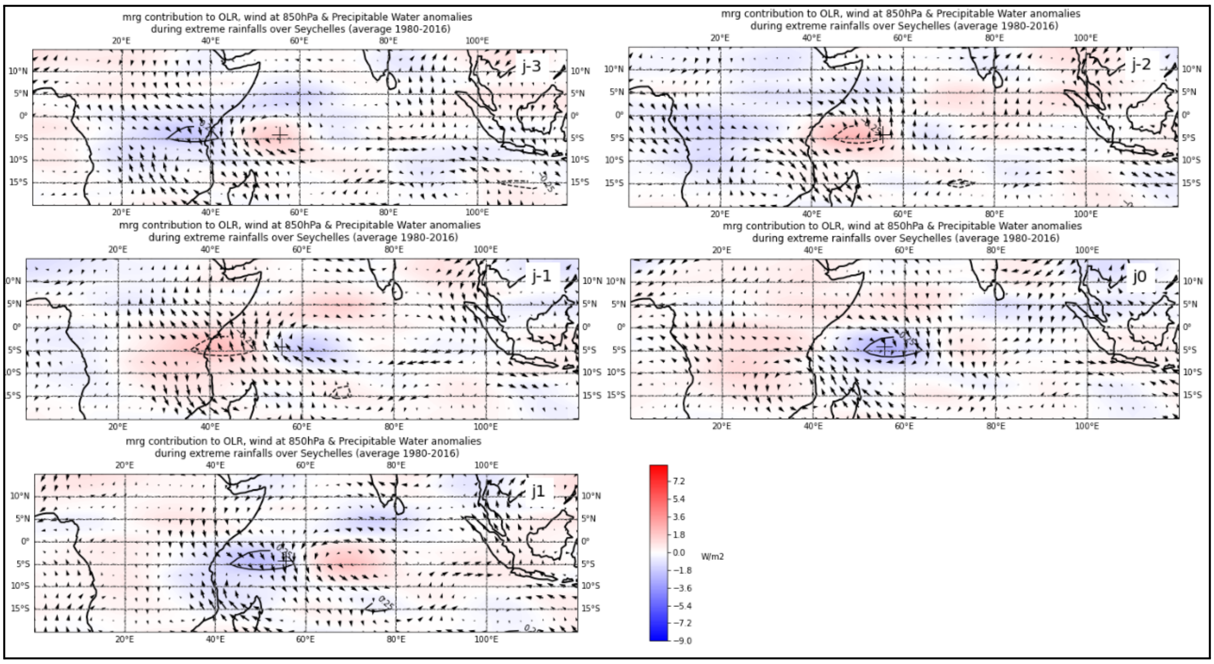
Kelvin wave



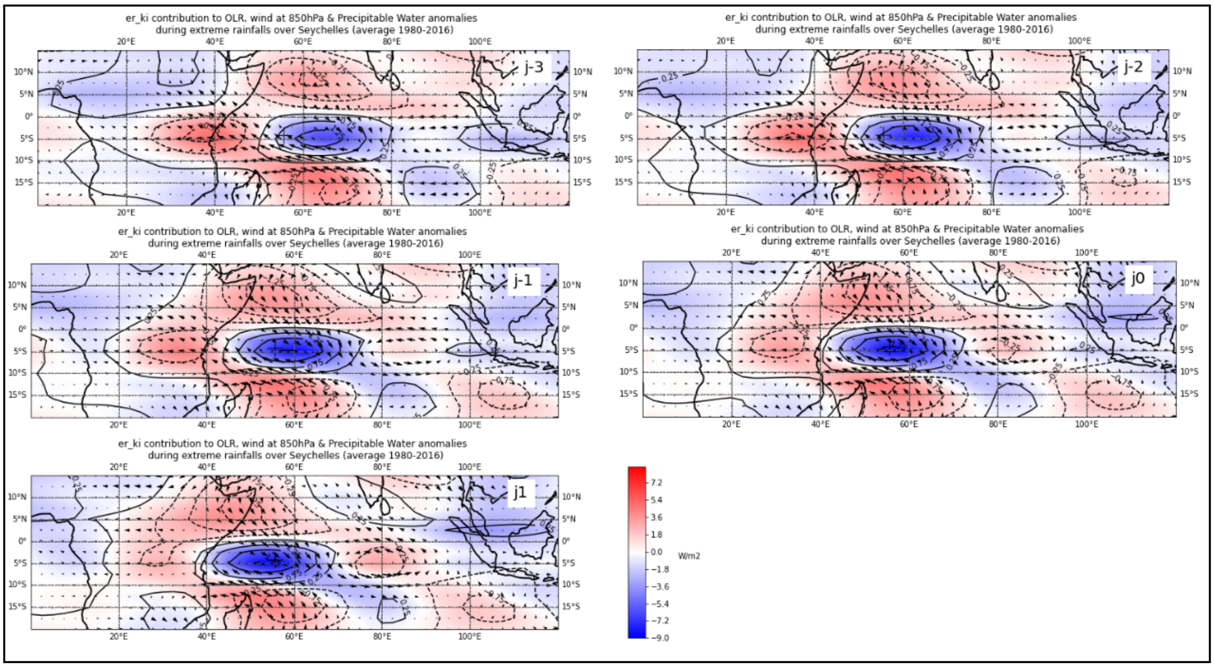
MJO


mjo_ki contribution to OLR, wind at 850hPa & Precipitable Water anomalies
during extreme rainfalls over Seychelles (average 1980-2016)
j-3
j-2
j-1
j0
j1
W/m2

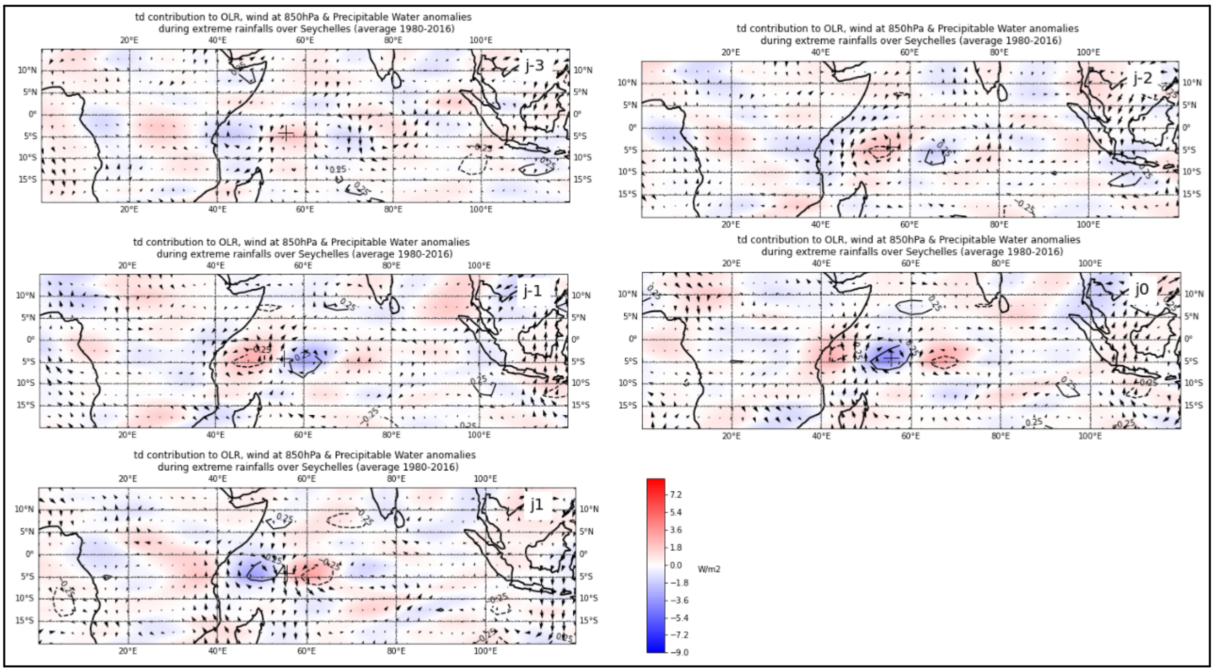
MRG


mrg contribution to OLR, wind at 850hPa & Precipitable Water anomalies
during extreme rainfalls over Seychelles (average 1980-2016)
j-3
j-2
j-1
j0
j1
W/m2

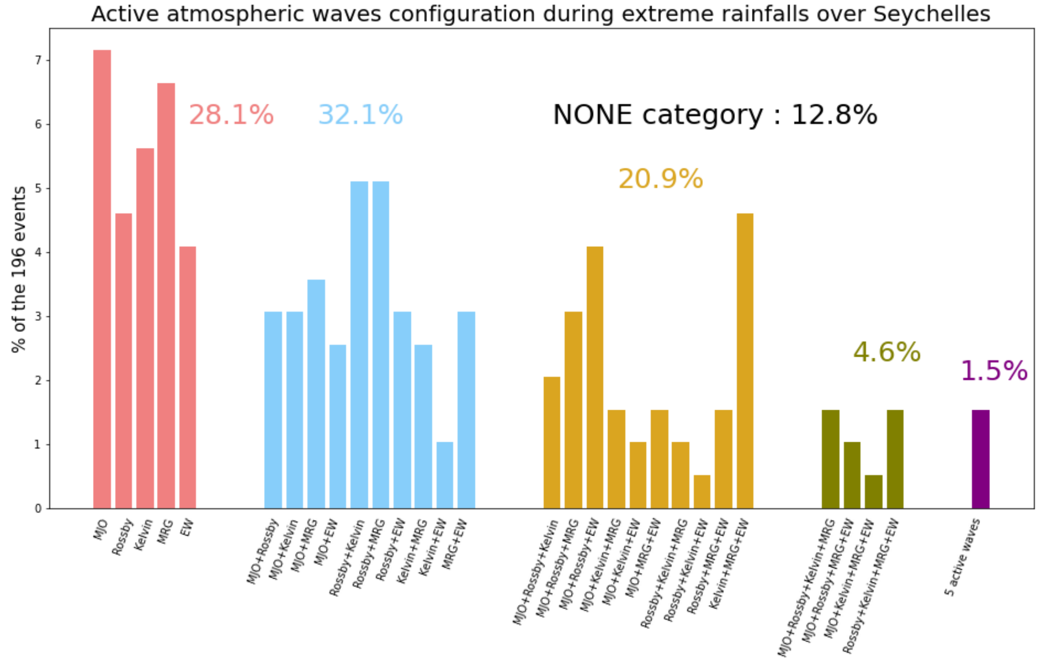
Equatorial–Rossby



Easterly waves



5) CCEWs contribution to EPEs obtained with PW detection



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