CREDDI
CENTRE DE RECHERCHE EN ECONOMIE ET
EN DROIT DU DÉVELOPPEMENT INSULAIRE

Guadeloupe in the face of climate change: the stylised facts and macroeconomic consequences

Maurice BILIONIERE

&

Alain MAURIN

Research Centre for Island Development Economics and Law
University of the French West Indies and Guiana
Fouillole Campus
Guadeloupe
Tel: 0590-48-32-77 **Fax**: 0590-48-33-05
E-mail:
maurice.bilioniere@gmail.com
alain.maurin@univ-ag.fr

July 2023

Université
des Antilles

La Guadeloupe face au changement climatique : sur les faits stylisés et les conséquences macroéconomiques

Guadeloupe in the face of climate change: the stylised facts and macroeconomic consequences

Maurice Bilionière, Alain Maurin
LEAD, UAG

Abstract:

Natural disasters have made up a large part of media headlines in recent years. These disasters are often manifested in extreme weather events and are increasingly related to the phenomenon of global warming. There are many examples from all over the world. Among the most recent, in early July 2023, from Monday 3rd to Thursday 6th, the average temperature record was broken four times on our planet, reaching the level of 17.23°C. At the end of June 2023, the city of Penticton, in central British Columbia, recorded Canada's all-time temperature record of 49.6 degrees Celsius. In this same city, during the month of December 2021, the maximum temperature was 22.5 degrees on Monday 2nd, whereas the previous absolute peak for this month was 11.2°C in 2012. In the USA, this winter warmth manifested itself in temperatures almost 20 degrees above normal in Washington, Montana, Wyoming and North Dakota. In February 2020, temperatures in Antarctica exceeded the 20°C barrier for the first time.

Going back in time just a decade, similar observations have been made. Russia in 2010 was affected by "the strongest heat wave in a thousand years," according to the Manager of the Russian meteorological services. In the same year, Pakistan experienced the worst floods in its history, causing several thousands of deaths and a major humanitarian crisis. In Central Europe, the floods of 2013 were described as historic with record-breaking water levels. In some cases, the increase in these large-scale phenomena calls their classification criterion into question. Indeed, since Typhoon "Haiyan" passed through the Philippines in 2013, scientists have been seriously debating adding a sixth category to the Saffir-Simpson scale, which goes up to 5. According to the Saffir-Simpson scale, a cyclone reaches its highest level with sustained winds measured at 252 km/h. However, the winds measured for Typhoon "Haiyan" reached 315 km/h, a difference of more than 60 km/h.

In developed countries and many emerging countries, the theoretical problems and practical decisions of public policies to be implemented have undoubtedly occupied the thoughts and discussion forums of researchers and decision-makers. In recent months, large countries such as China, the United States, Russia, France, India and Pakistan have shown their limitations in coping with impressive and destructive floods, severe droughts and massive forest fires. You can therefore only imagine the risks and impacts these natural shocks have on small island territories, which rank among the most vulnerable countries in the world. In a context where many scientists have tried to assess the environmental and economic consequences of global warming for developed countries, it is therefore appropriate to increase knowledge for such territories where the potential risks and impacts are still unknown and potentially more dangerous. Given the various controversies between researchers about the evidence of climate change and whether it is a series of exceptional events or a long-term persistent trend, it seems difficult to prove that climate change exists, even more so in smaller territories.

Using very long time series, in monthly data over the period January 1951 to December 2022, this article proposes a discussion and empirical study of the issue of climate change in the Caribbean with the case of Guadeloupe. First, we present the main elements of the literature on the consequences of climate change in the Caribbean. Secondly, we apply various approaches from time series statistics and econometrics to carry out different modeling exercises based on changes in two key climate monitoring components: rainfall and air temperature.

Keywords: *Climate change; Rainfall; Temperature; Time series; seasonal unit root tests; SARIMA modeling;*

Résumé :

Occupant une large part des titres traités dans l'actualité des médias depuis maintenant quelques années, les catastrophes naturelles qui se manifestent souvent par des évènements climatiques extrêmes sont de plus en plus mises en relation avec le phénomène du réchauffement climatique. Les exemples en sont légions aux quatre coins du globe. Parmi les plus récents, figurent au début du mois de juillet 2023, du lundi 3 au jeudi 6, le record de température moyenne qui a été battu à quatre reprises sur notre planète, pour atteindre le niveau 17,23 °C. La ville de Penticton, au centre de la Colombie-Britannique, a enregistré fin juin 2023 le record historique de température au Canada avec 49,6 degrés Celsius. Dans cette même ville, durant le mois de décembre 2021, la température maximale s'est établie à 22,5 degrés le lundi 2 alors le précédent pic absolu pour ce mois était de 11,2 °C en 2012. Aux États-Unis, cette chaleur hivernale s'est manifestée par des températures supérieures de presque 20 degrés à la normale dans les États de Washington, du Montana, du Wyoming et du Dakota du Nord. En février 2020, l'Antarctique a connu des températures franchissant pour la première fois la barre des 20°C.

En remontant dans le passé juste une décennie en arrière, des constats du même ordre ont apportés. La Russie en 2010 a été touchée par « une vague de chaleur la plus forte depuis mille ans » selon le responsable des services météorologiques russes. Au cours de la même année, le Pakistan a connu les pires inondations de son histoire causant plusieurs milliers de morts et une crise humanitaire majeure. En Europe centrale les inondations de 2013 furent qualifiées d'historiques avec des crues record. La multiplication de ces phénomènes de grandes ampleurs suscite dans certains cas une remise en question de leur critère de classification. En effet, depuis le passage du Typhon « Haiyan » aux îles Philippines en 2013, les scientifiques s'interrogent sérieusement sur l'ajout d'une 6ème catégorie à l'échelle de Saffir-Simpson qui en contient 5. Cette dernière considère qu'un cyclone atteint son dernier échelon à partir de vents soutenus mesurés à 252 km/h. Or, les vents mesurés pour le Typhon « Haiyan » ont atteint les 315 km/h, soit une différence de plus de 60 km/h.

Dans les pays développés et dans bon nombre de pays émergents, les problématiques théoriques et les décisions pratiques de politiques publiques à mettre en œuvre ont indiscutablement envahi les réflexions et espaces de discussions des chercheurs et des décideurs. Si de grands pays comme la Chine, les Etats-Unis, la Russie, la France, l'Inde et le Pakistan ont montré ces derniers mois toutes leurs difficultés à faire face à des inondations impressionnantes, des crues destructrices, des sécheresses sévères et des feux de forêts gigantesques, alors que dire en ce qui concerne les risques et les impacts de ces chocs naturels sur les petits territoires insulaires qui, par excellence, figurent dans le haut du classement des pays les plus vulnérables de la planète. Dans un contexte où nombre de scientifiques ont essayés d'évaluer les conséquences environnementales et économiques du réchauffement climatique pour les pays développés, il apparaît donc opportun d'enrichir les connaissances pour de tels territoires où les risques et impacts potentiels sont encore méconnus et potentiellement plus dangereux. Si l'on s'en tient aux différentes controverses entre chercheurs au sujet de la mise en évidence du changement climatique entre évènements exceptionnels ou tendance persistante qui s'inscrit dans la durée, il semble difficile de prouver son existence, à plus forte raison sur les plus petits territoires.

En recourant à des séries temporelles très longues, en données mensuelles sur la période de Janvier 1951 à décembre 2022, cet article propose une discussion et une étude empirique sur la question du changement climatique dans le cas la Guadeloupe. Dans un premier temps, nous procédons à une description de nos séries climatiques visant à identifier leurs mouvements de court terme et tendances de long terme. Dans un deuxième temps nous appliquons différentes approches de la statistique et de l'économétrie des séries temporelles pour conduire différents exercices de modélisation autour des évolutions de deux composantes clés du suivi du climat : la pluviométrie et la température de l'air.

Mots clés : *Changement climatique ; précipitation, température, Séries chronologiques, tests de racines unitaires saisonnières, modélisation SARIMA*

Summary:

Introduction

Although the Caribbean islands have varied topographical and geographical features, they share a common set of characteristics such as their small size and high economic dependence on densely populated coastal areas. These characteristics increase their vulnerability to climatic phenomena, which are a proven threat to regional development, all the more so in the context of global warming (Karmalkar et al., 2013). This phenomenon is very real, in spite of the scepticism that has surrounded it until recently (Björnberg et al., 2017). Yet natural disasters, which often take the form of extreme climatic events, have dominated media headlines for several years now, and are increasingly being linked to the phenomenon of global warming. There are many examples from all over the world. The most recent ones include the beginning of the month of July 2023, from Monday 3rd to Thursday 6th, when the average worldwide temperature reached record-breaking levels four times, going up to 17.23°C. At the end of June 2023, the city of Penticton in central British Columbia recorded the highest temperature ever in Canada, at 49.6 degrees Celsius. In the same city, during the month of December 2021, the maximum temperature was 22.5 degrees on Monday 2, whereas the previous absolute peak for this month was 11.2°C in 2012. In the United States, this winter heat was reflected in temperatures almost 20 degrees above the normal one in the states of Washington, Montana, Wyoming and North Dakota. In February 2020, temperatures in Antarctica broke the 20°C barrier for the first time.

Going back in time just a decade, observations of a similar nature were made. In 2010, Russia was hit by "the strongest heatwave for a thousand years", according to the head of the Russian meteorological services. In the same year, Pakistan experienced the worst floods in its history, causing several thousands of deaths and a major humanitarian crisis. In Central Europe, the floods of 2013 were described as historic with record-breaking water levels. In some cases, the increase in these large-scale phenomena calls their classification criterion into question. Indeed, since Typhoon "Haiyan" passed through the Philippines in 2013, scientists have been seriously debating adding a sixth category to the Saffir-Simpson scale, which goes up to 5. According to the Saffir-Simpson scale, a cyclone reaches its highest level with sustained winds measured at 252 km/h. However, the winds measured for Typhoon "Haiyan" reached 315 km/h, a difference of more than 60 km/h.

Météo-France's Arpege-Climat model predicts an average warming throughout the Caribbean region of about 1.5°C over the ocean and 2°C over land (islands and mainland) per year between recent and future decades (Berge et al., 2022). Increasingly excessive weather conditions in the Caribbean also point in this direction. According to Webster and Holland (2005), the proportion and number of Category 4 and 5 hurricanes on the Saffir-Simpson scale have almost doubled since the year 1970. According to their research, over the 5-year period from 1970 to 2004, category 4 and 5 cyclones accounted for an increasing proportion of the total number of cyclones, rising from around 18% to almost 36%. Conversely, Category 1 and Categories 2 and 3 have been on the decline. The year 2017 provided the third worst cyclone season in history in the area (Kemp-Benedict et al., 2019). Current state-of-the-art models suggest that, globally, the average intensity of storms will increase by around 5%, and that the proportion of higher intensity storms (Categories 4 and 5) will increase by 13% (Knutson et al., 2019).

In view of the main impacts mentioned within the scope of global change, such as rising sea levels, changes in marine and terrestrial biodiversity, coastal erosion or even the intensification of cyclone activity, have worrying socioeconomic implications for the Caribbean islands. In a context where a number of studies have attempted to assess the environmental and economic consequences of sustainable climate change for developed countries (Pielke, 2007; Emmanuel, 2011; Ye et al., 2019), it would seem appropriate to expand our knowledge of smaller territories where the potential risks and impacts are hypothetically more dangerous. In recent decades, numerous publications have attempted to identify the potential impacts of climate change on the Caribbean islands (Strobl, 2012; Duvat, 2015; Acevedo, 2016; Moore et al., 2017; Thomas and Banjamin, 2018; Kemp-Benedict et al., 2019; Spencer et al., 2020), but very few have attempted to determine the extent of climate change in action.

The first section of this article presents the essential elements of the literature dedicated to identifying climate change, while the second focuses specifically on its macroeconomic consequences. The third applies time series analysis approaches to various modelling exercises based on two key climate monitoring parameters: precipitation and air temperature. All in all, our study could be useful to other Caribbean islands and, more broadly, to other small island developing territories threatened by global warming.

I. Climate change in the French West Indies: a literature review of findings and issues

1.1.Stylised facts about climate change

Changes in temperature and rainfall patterns

According to forecasts by Météo-France, average temperatures in Guadeloupe have increased by almost 1.5°C over the 1965-2009 period. Using a climate modelling tool and two IPCC reference scenarios, the specialists at Météo-France have also projected how the climate in Guadeloupe will change by the year 2100. Irrespective of the scenario used, mean annual temperatures increase: up to 2.3°C for minimum temperatures and 1.9°C for maximum temperatures in the RCP 4.5 scenario, compared with 4.3°C for minimum temperatures and 3.3°C for maximum temperatures in the RCP 8.5 scenario[1].

On a finer scale, *"the GICC IMFREX[2] project revealed a trend for Guadeloupe between 1976 and 2003 of 0.36°± 0.14/decade for a 95% confidence interval. From 1954 to 2003, the trend is 0.41°± 0.06/decade for a confidence interval of 0.95%[3]"*. The IPCC's fifth report (2013) predicted an increase in the average air temperature of 1.2° over the 2016-2035 period. As part of the CA3F (Climate Change and Consequences for the French West Indies) project, which began in 2018, Météo-France has shown that day/night dry-season temperatures in the French West Indies will increase by about 1.5/1.5-2°C by the year 2055 and 2.5-3/2.5-3.5°C by the year 2080. As a result, the highest temperatures observed in Guadeloupe over the last 25 years (around 34°C in the shade during the day, 26-27°C at night) would be exceeded almost every year.

According to Figure 1, this upward trend in temperatures seems to have been a reality since the 1980s. This trajectory appears to be common to all the overseas regions, with only minor variations. In Martinique, the homogenised series showed an average increase in temperature of around 1°C over 40 years, with the highest levels of warming observed on average during the period from 1965-2005. Based on IPCC models and scenarios, regional projections have recently been produced for Martinique. Temperatures are projected to increase between 1.5 and 2.3°C (Saffache and Pelis, 2023).

With regard to precipitation, the fifth IPCC report (2013) predicts a global average increase in precipitation by the end of the 21st century. Although it is difficult to obtain a clear trend in hydrology in Guadeloupe according to the models used, average rainfall quantities could drop by 40% in February and rise by 60% in July, according to Météo-France projections based on IPCC scenarios. This double movement in the opposite direction would increase the seasonal divide in the rainfall system, with dry seasons becoming drier and wet seasons wetter. Other results obtained by the experts at Météo-France using their Arpege-Climat model corroborate this trend. In Guadeloupe, rainfall on the leeward coasts would decrease throughout the year in the dry season by the year 2055. This projected drying up is greater by 2080 (-10/-15% across the whole of Guadeloupe) than by 2055 (-5%). In the wet season, it is equivalent for both horizons (-10-15%). Widespread drying is accompanied by a decrease in the frequency of heavy rains and an increase in the frequency of droughts. The number of days with rainfall exceeding 10 mm is reduced (-2 to -7 days) during the

---

[1] The Météo-France results are presented for the RCP (Representative Concentration Pathway) 4.5 scenario, which corresponds to stable levels of CO2 emissions at a level of 660 CO2 equivalents after 2100, and the RCP 8.5 scenario, which corresponds to an increase in GHG emissions; the concentration reaches 1,370 CO2 equivalents in 2100 and continues to increase.

[2] "Management and Impacts of Climate Change" and "Impact of Anthropogenic Changes on the Frequency of Extreme Wind, Temperature and Precipitation Events".

[3] Based on the Météo-France document sent to the DIRAG in October 2009.

wet season for both time periods. On the other hand, the number of dry episodes (4 or more days without rain) will increase significantly by the year 2080 (from 58 to 61 days/year) (SDAGE, 2021).

In Martinique, average annual rainfall is expected to increase by 1.7% by the year 2030 (Dupont, 2013). In addition, according to various IPCC scenarios, it is anticipated that the average annual rainfall in Martinique will increase. Rainfall is expected to increase by 15-25% in the south and centre of the island and by -3% to +8% in the north and north Atlantic, respectively (Comité du bassin de la Martinique, 2016). Météo-France forecasts an increase of between 10% and 60% in precipitation in July and a drop in precipitation in February (between 0 and 40%) over most of the country. As a result, following the example of Guadeloupe, by 2071-2100, there could be a seasonal divide, with an increase in extremely dry seasons (January to March), particularly in the north-west region of the island, as well as an increase in extremely wet rainy seasons.

Climate change and cyclones

With regard to trends as regards certain climatic hazards, including cyclones, the fifth IPCC report admits that there could be an intensification and/or potential increase in the number of intense climatic events on a global scale. The proportion and number of Category 4 and 5 hurricanes on the Saffir-Simpson scale have almost doubled since 1970 (Webster and Holland, 2005). Over the 5-year period from 1970 to 2004, category 4 and 5 cyclones accounted for an increasing proportion of the total number of cyclones, rising from around 18% to almost 36%. On the other hand, Categories 1, 2 and 3 have been in decline during the same period. According to experts at Météo-France, for every one degree rise in sea temperature, cyclone wind speeds could increase by 3 to 5%. Scientists explain this phenomenon by the fact that, in order for a cyclone to form, the temperature needs to be at least 26.5°C over a depth of at least 60 metres. However, it is important to highlight that the uncertainties involved in modelling extreme events are very high. According to Michel Desbois, Director of research at the CNRS-Polytechnique weather laboratory, the apparent link between the formation of hurricanes and rising temperatures needs to be interpreted, since the strength and number of hurricanes vary naturally every 20-30 years.

Consequently, the conclusions of the regional projections are mitigated with regard to hurricanes. Regional projections from the “Explore 2070” project conclude that there is no trend in hurricane activity in the French West Indies. The general observation for the Atlantic basin is that there has been no significant increase in the number of cyclones due to global warming over the last 50 years. According to projections from the C3AF project, a reduction in the number of cyclones is even expected across most of the basin. However, the most intense hurricanes (Categories 4 and 5) will, on average, increase in number. Furthermore, cyclonic rainfall is also expected to increase by 5 to 15% (SDAGE, 2021).

1.2.Impact on the natural environment

Coastal erosion risks

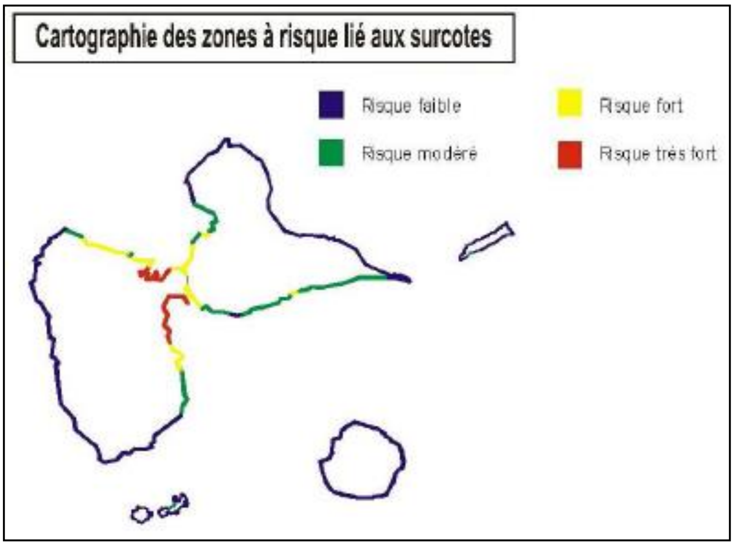
The risk of coastal erosion is twofold for the French West Indies. On the one hand, this is one of the identified consequences of climate change, which could, on the other hand, also be amplified by the intensification of hurricanes. The IPCC report (2013) predicts a rise in sea levels, all scenarios combined, of between +26 and +82 centimetres by the end of the 21st century (2081-2100), although it specifies that the uncertainty surrounding the data is very high, particularly at regional level.

Based on Météo-France research, the intensification of cyclonic phenomena is likely to result in a risk of a storm surge in the French West Indies, because when an intense hurricane approaches the coast, there is a sudden increase in the sea level. In Guadeloupe, the inland coasts are the most vulnerable, with a high or even very high risk (Figure 2). This could lead to a loss of 6 to 7% of the surface area of Guadeloupe (Duvat, 2015). The results of the C3AF project suggest that the increase in sea level will contribute to the permanent flooding of low-lying areas and to the extension of storm surges in many coastal regions with very low slopes (SDAGE, 2021). In Guadeloupe, 70% of buildings in coastal areas currently do not have a dedicated refuge floor, and in 2013, 23% of the population lived less than 10 m above sea level. The foreseeable consequences of rising water levels in Guadeloupe are as follows:

- 5% of the territory (78 km²) and 6% of the population exposed to marine submersion (23,500 inhabitants);
- 6% of buildings exposed to marine submersion (14,500 buildings/229 critical infrastructures);
- 160 km of eroding coastline by 2030 (with 7% of the coastline suffering minor erosion, 12% moderate erosion and 6% significant erosion).

The study by Schleupner (2008) on coastal erosion on the island of Martinique reports that an increase in sea level could cause premature erosion of the island's coastline, leading to a reduced number of beaches. Erosion would affect 78% of mangroves, 98% of beaches and 86% of other coastal wetlands in the event of an increase in sea level. According to the IPCC, a 38 cm rise in sea level by 2090-2100 will likely reduce the size of Martinique by about fifty square kilometres, leading to a gradual shrinking of numerous coastal communities.

Figure 2. Mapping of areas at risk from storm surges



Source: Météo-France

Threats to biodiversity

The islands of the Caribbean basin have been classified as hotspots due to their rich biodiversity. With regard to terrestrial biodiversity, no fewer than 13,000 species of vascular plants have been recorded in the Caribbean (6,500 of which are endemic to a single island), 600 species of birds (27% of which are endemic), 500 species of reptiles (94% of which are endemic) and 170 species of amphibians (all of which are endemic) (Petit and Prudent, 2008). At the level of marine biodiversity, no less than 26,000 km² of coral reefs are spread across the Caribbean islands, representing more than 10% of the world's shallow reefs. Indeed, these islands contain a third of the world's mangroves along 25% of their coastline.

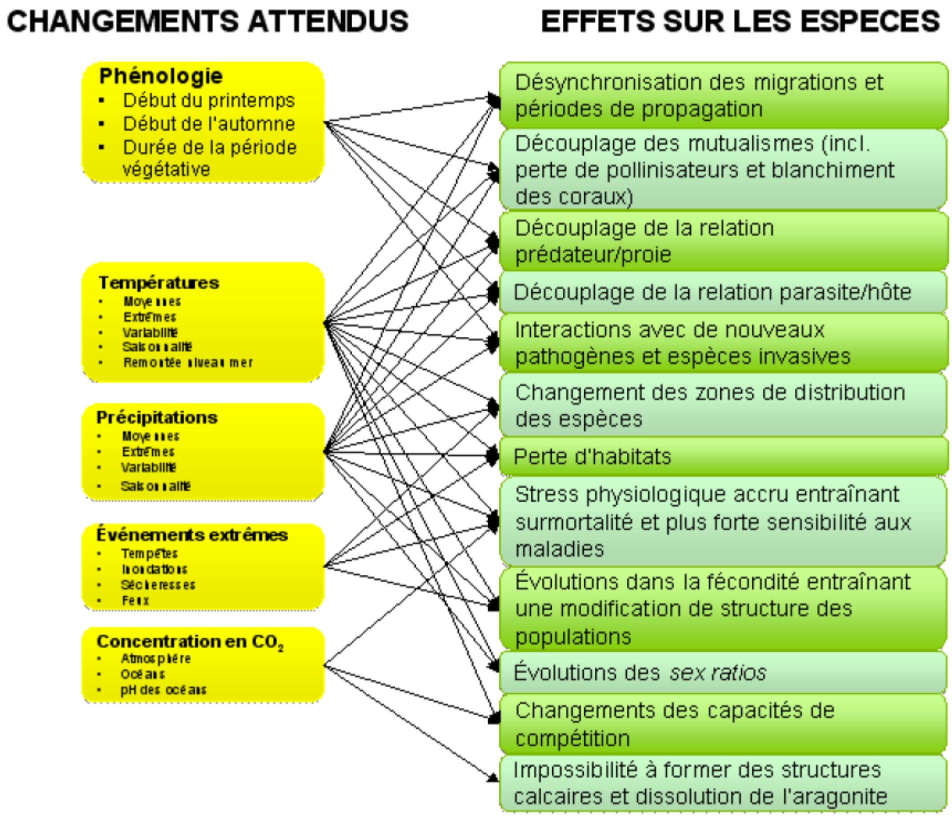
The French West Indies have an exceptional biodiversity, with climatic conditions and a specific geography that give them a highly diversified fauna and flora, as well as maritime areas of considerable wealth. In Guadeloupe, for example, mangroves and backwater swamp forests cover an area of about 7,000 hectares. Coral reefs can be found on all the islands in the archipelago. 109 species of fish have been recorded in the Grand Cul-de-sac Marin, three species of marine turtle still lay their eggs on the beaches, and 17 species of cetacean have been recorded in Guadeloupe's waters (Gargominy, 2003).

Within the context of climate change, marine biodiversity seems to be the most vulnerable to temperature increases, particularly through coral bleaching. This is a phenomenon that occurred in 2005 when, under the pressure of a heat wave, 95% of the reefs in the French West Indies were bleached. Coral is highly sensitive to temperature changes, and even a one-degree increase in temperature risks bleaching, followed by death if there is a persistent increase in temperature. After the 2005 episode, this affected 40% of corals in Guadeloupe and 13% of corals in Martinique. An increase in tropical water temperatures of 2.8°C between now and 2100, projected by the IPCC, could make bleaching episodes in 2005 more frequent: occurring every year or two between now and 2030-2050 (UNEP 2006). More generally, the effects of climate change are likely to significantly increase the damage and reduce the resilience of coral ecosystems.

Apart from coral reefs, seagrass beds are also particularly vulnerable to the effects of climate change because of their location close to the coast and in shallow water. The increasing power of climatic phenomena could exacerbate the destruction of this ecosystem. Mangroves, which play a vital role in the life cycle of a number of species such as crabs, reef fish and birds, are also likely to suffer the negative effects of climate change, particularly rising sea levels.

IPCC experts estimate that one in three plants threatened by climate change is endemic to island states, and that 23% of island bird species are equally at risk. Foden et al. (2008) summarise the various impacts attributed to climate change on species (Figure 3).

Figure 3 Potential impact of climate change on species



Source: Météo-France (Foden et al. 2008)

Increase in sea surface salinity (SSM) and ocean acidification

Based on data covering the period 1970-2003, Delcroix and Cravatte (2009) used interpolation to measure the SSM for different ocean basins. Their results show a degree of heterogeneity for the different ocean basins. The geographical distribution of high salinity averages in the Atlantic, the Pacific and the Arabian Sea is no coincidence, as these areas correspond to centres of significant high wind and evaporation with low precipitation. Of all these areas, the Atlantic Ocean has the highest salinity. Areas of low surface salinity are found mainly in cold regions, near large freshwater rivers and inter-tropical convergence zones in the Pacific and the Atlantic. These areas have the opposite characteristics of high salinity areas, i.e. heavy rainfall with low-amplitude surface winds.

With regard to the French West Indies in particular, the authors observed an upward trend in surface salinity over the last ten years around Guadeloupe (+0.025). The drop in salinity in areas of low relative salinity and the increase in areas of high relative salinity therefore reflect a strengthening of regional contrasts. To understand what these contrasts actually represent, the authors will draw on the conclusions of the work of Douville and Terray (2007) in relation to the response of the hydrological cycle to anthropogenic forcing. In their article, they conclude that wetlands could become wetter, while drylands could become even drier. Given that the territories of the West Indies are located in an area where the SSM has increased by +0.025, according to their calculations, the SSM could dry up at the same rate as the rise in temperatures. On the other hand, some specialists see ocean acidification as a major risk for coral formations. Although scientific studies are still few and far between, some conclusions point to a risk of decline in coral reefs. In the West Indies, apart from corals, all marine organisms with a calcareous skeleton are affected, such as sea urchins, families of molluscs and species of zooplankton with a calcareous envelope. If the degradation of coral reefs increases, there could be an increase in ciguatera and the mass mortality of fish in tropical regions.

II. A summary of the macroeconomic consequences of climate change

1.1. The economic risks and costs of hurricanes

There is a growing consensus in the scientific community that climate change could exacerbate certain natural disasters (Kousky, 2017). Among these disasters, hurricanes cause major damage and disrupt economic activity. Without claiming to be exhaustive, this section presents the recent literature on the economic impacts of hurricanes, highlighting the diversity of the fields studied.

Strobl (2011) analyses the impact of hurricanes that affected US coastal counties, with an impact on their economic growth rates between 1970 and 2005. To this end, he developed a destruction index based on an equation linking monetary losses due to hurricanes, local wind speed and variables characteristic of a county's exposure to risk. The econometric results suggest that a county's annual economic growth rate drops by an average of 0.45 percentage points, 28% of which is due to the departure of the wealthiest individuals from the affected counties, even when this has no effect on national macroeconomic indicators.

The work of Albalate and Padro-Rosario (2018) seeks to assess the long-term effect of a hurricane on a country's production, in this case, the impact of Hurricane Georges in 1998 on the economy of Puerto Rico. In order to do so, they use the synthetic control method, adapted for the assessment of public policies. Their results confirm the negative impact of hurricanes on a region's growth, with Hurricane Georges causing direct damage estimated at US$ 4.3 billion. They also showed that purchasing power parity in relation to GDP could have been 9% higher in 2010 if the hurricane had never hit Puerto Rico.

Using a probabilistic model, Frame et al. (2020) estimate the average cost of the damage associated with Hurricane Harvey at around US$ 90 billion. The damage caused by Hurricane Sandy, which hit the east coast of the United States in 2012, was estimated at US$ 60 billion. Strauss et al. (2021) break down these costs into the natural impacts of the hurricane and the potential influence of climate change on these impacts. They conclude that about US$ 8.1 billion of the damage caused by Hurricane Sandy is due to man-made factors.

While the various studies presented above have estimated the costs of the direct and/or indirect impacts of hurricanes, Deryugina (2017) specifically focuses on hurricane-related social budget expenditure, including disaster aid, unemployment insurance and medical benefits. Its results show that aid earmarked for hurricanes represents about US$ 155 to US$ 160 per capita per hurricane during the 1969-2012 period, while in the ten years after the hurricane, induced social spending amounts to an average of about US$ 780 to US$ 1150 per capita. In a similar field of study, Jerch et al. (2023) analyse the post-hurricane fiscal dynamics of municipalities in the United States. They can exacerbate the fiscal pressure on municipalities by reducing tax revenue and debt financing, and inhibiting their ability to make major capital investments in the decade after the hurricane. More specifically, in the decade following major hurricanes, local sources of income and expenditure drop by between 5 and 6%.

Another aspect of the literature on the impact of hurricanes refers to the displacement of people, particularly coastal populations, that can result from the increase in sea level at the time of a hurricane (Frazier et al., 2010). These studies show that natural disasters, including hurricanes, lead to long-term population migration (Deryugina et al., 2018; Boustan et al., 2020; Billings et al., 2022).

The history of the Caribbean is filled with references to the considerable loss of life and property caused by hurricanes, and some researchers have even argued that hurricanes have played an important role in the region's lack of development (Mulcahy, 2006). Over a period of 65 years (1950-2014), the total cost of the damage caused by the 148 hurricanes recorded in 20 Caribbean islands has been estimated at US$ 52 billion, an average cost of US$ 352 million per hurricane. The damage caused represents on average of 82% of the GDP of these islands (Acevedo, 2016). Strobl (2012), adopting a similar but improved methodology to that of his work applied to US counties, studies the macroeconomic impact of hurricanes on the Central American and Caribbean region. Its results show that, on average, a hurricane has led to a drop in economic growth of around 0.84 percentage points in the region. The results of the study by Bertinelli et al. (2016) estimate that it costs about US$ 8 billion for a major hurricane every 50 years in the 29 islands in the region that were included in the study. However, risks and losses are likely to vary considerably from one island to another. Moore et al. (2017) develop a general equilibrium framework for conducting an assessment of the impact of climate change and hurricane formation on the Caribbean region. Their conclusions suggest losses of between US$ 350 and 550 million a year by 2100, or around 11 to 17% of the GDP of the sample of 14 islands studied. The Category 5 hurricanes Maria and Irma ravaged numerous Caribbean islands, including Dominica, Antigua and Barbuda, Saint-Martin and Puerto Rico, causing an estimated US$ 220 billion in damage (Kemp-Benedict et al., 2019). For the islands of Saint-Martin and Saint-Barthélemy alone, the insured damage is €2 billion (Montador, 2022). It should be noted that if Hurricane Irma had passed over Guadeloupe, the cost of insured damage would have exceeded €10 billion. Furthermore, a cyclone risk study carried out in 2020, which reconstructed major events based on simulated trajectories, established average losses of €4.9 billion in Guadeloupe resulting from Category 5/5+ cyclones. The damage caused by cyclone Hugo, which devastated Guadeloupe in 1989, is estimated at 4 billion francs. The agricultural and tourism sectors suffered losses estimated at CHF 466 million and CHF 152 million respectively (Desse, 2013).

Tropical storms have caused more than US$ 800 billion in damage over the last 20 years, including US$ 58 billion in the 2018 season alone (Spencer and Strobl, 2020). From another point of view, the hurricanes are equally having an impact on the Caribbean banking sector. In the aftermath of a hurricane, the region's commercial banks were faced with an overall reduction in deposits and assets, to which they reacted by reducing the supply of loans and drawing on their liquidity. Hurricanes are associated with an increased overall bank risk, which translates to some extent into lower bank profitability (Brei et al., 2019).

1.2. The economic risks and costs associated with sargassum

Historically, Sargasso seaweed species originated in the Sargasso Sea and only a minor quantity reached certain territories in the Atlantic Ocean (Gower et al., 2013; Frazier et al., 2013). It was not until 2011 that the stranding phenomenon began to be frequent and significant for numerous territories in the Caribbean region. In the context of climate change and the eutrophication of the oceans, there will likely be more frequent and abundant strandings (Smetacek and Zingone, 2013). Currently their strandings are causing environmental, economic and health problems in the region. It is therefore necessary to collect sargassum seaweed washed up on beaches, in order to preserve the integrity of these ecosystems and reduce health risks and economic vulnerability. However, it is costly for the affected regions to clean up sargassum.

For example, the Mexican government, invested about US$ 17 million to dispose of 522,226 tonnes of sargassum in 2018, and about US$ 2.6 million to dispose of 85,000 tonnes in 2019 (Chavez et al., 2020). Also in Mexico, the cost of cleaning up the beach at Cancun has been estimated at US$ 1,000 per metre of coastline. The authorities have budgeted US$ 10 million and hired 5,000 temporary workers to clean up Mexico's Caribbean coast (Louime et al., 2017). Salter et al. (2020) reported that in 2018, hotels on Mexico's northern Caribbean coast spent between US$ 128,770 and US$ 284,830 per kilometre of coastline just on staff salaries and transporting sargassum to disposal sites. The annual cost of cleaning up sargassum in the Caribbean has been estimated at US$ 120 million by Milledge and Harvey (2016) and US$ 210 million by Davis et al. (2021).

More recent work conducted by Rodriguez-Martinez et al. (2023) analysed the costs of cleaning up sargassum for three municipalities in Mexico (Puerto Morelos, Solidaridad and Tulum) as well as five hotels between Tulum and Cancun. Overall, clean-up costs range from US$ 0.3 to US$ 1.1 million dollars per kilometre for an annual volume harvested of between 10,105 and 40,932 cubic metres per kilometre. Similarly, the estimated cost of cleaning up one cubic metre of sargassum is between US$ 19 and US$ 85. For the city of Puerto Morelos, the annual clean-up costs, based on the average unit price obtained from the hotels in this municipality and the volumes of sargassum collected monthly by 14 hotels in 2018, 2019, 2021 and 2022, have made it possible to estimate an average annual clean-up cost of US$ 1 million per kilometre. Monthly costs were estimated at between US$ 10,186 and US$ 100,446.

In Guadeloupe, quantitative data on sargassum strandings, and studies on their economic impact, are relatively recent. It did not feature in weather news until the end of the decade of 2010, as was also the case in the States and other islands of the Caribbean basin, thus it is easy to understand why indicators on the flow of Sargasso seaweed were unknown until then.
Logically, the initiative to collect them came from the Syndicat Intercommunal pour la Protection des Plages et des Sites touristiques (Intercommunal Association for the Protection of Beaches and Tourist Sites), which commissioned the Chamber of Commerce and Industry of the Islands of Guadeloupe (CCI IG) to conduct a study to measure the economic impact of the nuisance caused by sargassum seaweed on businesses located in the areas concerned. It was based on a survey of a representative sample of 424 companies during the period from 13 November to 8 December 2015.

While it is true that exercises for measurement of the macroeconomic impact are most commonly based on computable general equilibrium models and econometric methods, it should be noted that this quantitative survey approach seemed to be one of the only ones applicable, given the availability of data. When implemented rigorously, with focus on the representative nature of the sample, the quality of the questionnaire and practical data collection, quantitative surveys provide sufficiently robust results. These results, in the form of proportions verified against the sample, are generalised to all the entities in the population and calculated to work out the values of the desired impact.

As regards the impact of sargassum strandings on the coastline, the impact analysis involves identifying the changes that have occurred in the activities or habits of the various categories of stakeholders, measuring them and, ultimately, aggregating them and, where necessary, translating them into monetary estimates.

The CCI-IG study report, which was written by Mathias Bini, indicated that one in three of the companies surveyed had been affected by sargassum, and that the main material impacts were the deterioration of machinery, air conditioning systems, computer electronics and premature wear and tear on work tools. The impact on staff essentially consists of temporary closures and two positions being made redundant.
The fishing industry, one of the most vulnerable, lost an average of 22 days at sea, was negatively affected by the deterioration of its engines and the fact that it was impossible to carry out trolling.
Naturally, the tourist industry was also affected, particularly by its smell, which had a long-term impact on the number of people visiting coastal accommodation structures and restaurants.

In monetary terms, Mathias Bini provides the following summary:

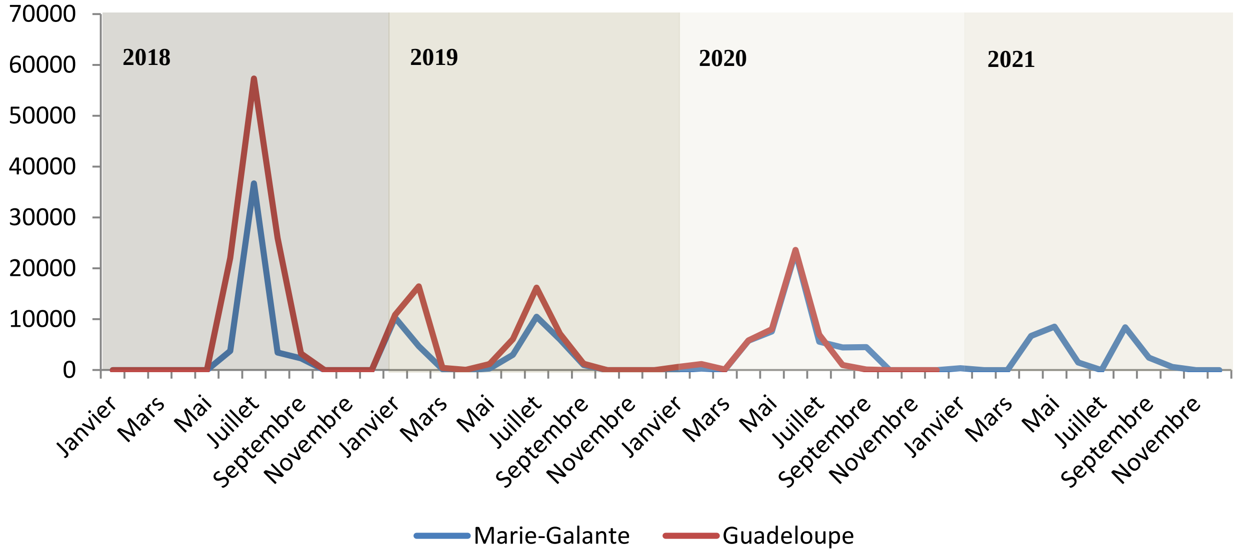
> "In the first half of 2015, the total financial impact of these nuisances was €4.9 million in lost earnings by the companies surveyed. While the range of sectors affected is quite broad, including shops, B&Bs, hotels, restaurants, fishing, pleasure boat hire, scuba diving and

> tourist vehicle hire, on average, businesses will have lost a minimum of €10,800 (fishing sailors) and a maximum of €67,200 (restaurant owners).” (Bini, 2015, page 3).

By attempting to directly analyse data on sargassum strandings and clean-up costs where they exist, it goes without saying that attempts at quantification would provide insights and results that could not be envisaged through the use of other modelling approaches.

In Guadeloupe, the government has set up a statistical monitoring system that will produce data from 2018 onwards. On the basis of observations of strandings in tonnes and volume by municipality, it is already possible to describe some specific features of the stranding phenomenon. Graph 1 shows an irregular pattern over the years. In 2018, collections took place from May to September, with a significant peak in July (57,326 m^3). The following year, in 2019, we can observe a start earlier in the year, in the months of January to September, with two peaks this time, one in February (16,431 m^3) and one in July (16,182 m^3). This trend seems to be confirmed in 2020, with a collection period extending from January to September, but with a single peak in June (23,615 m^3). As illustrated in graph 1, it is clear that no two years are alike, whether in terms of the period, the peaks observed or even the total volume collected (108,604 m^3 in 2018, 59,696 m^3 in 2019 and 47,452 m^3 in 2020). A closer look at the individual municipalities does not contradict this overall observation, although Capesterre de Marie-Galante (CMG) stands out as the most affected, accounting for about 60% of collections during the period studied (see graph 1).

Figure 4. Volumes of sargassum collected per month in Guadeloupe and Marie-Galante between 2018 and 2021



Source: PULSAR, service technique mairie CMG

Table 1 indicates the total quantities of sargassum collected in tonnes for the municipalities of the Guadeloupe islands affected by strandings between the years 2018 and 2022. This flow is notable, given that the municipality of Capesterre de Marie-Galante is the most important final destination. According to information from Météo-France, the geographical position of this municipality makes it the gateway for Sargasso to the islands of Guadeloupe. In fact, more than 50% of the data on collection for the period studied was recorded here.

Using this data and other administrative information, particularly logistical data (transport costs, distances from collection points to the recovery site and transport times), Bilionière and Lanneau (2023) estimated the costs of collecting Sargasso seaweed in Guadeloupe for various municipalities affected by strandings, based on two transport cost assumptions. Average daily costs range from €8 to €119 per tonne, based on flat-rate transport costs, and from €18 to €69, based on round-trip costs (Table 2).

Table 1. Sargassum collected by municipality between 2018 and 2022 (in tonnes)

Municipalities	Total tonnage
Anse-Bertrand	9 142
Le Moule	14 093
Petit-Canal	5 247
Le Gosier	2 746
Sainte-Anne	21 499
Saint-François	11 963
Goyave	7 658
Petit-Bourg	12 114
Capesterre Belle-Eau	12 613
Désirade	19 626
Terre-de-Bas	18 082
Terre-de-Haut	18 767
Capesterre de Marie-Galante	177 780

Source: PULSAR unit, Guadeloupe Prefecture

Figure 4. Average daily cost per tonne of sargassum (in euros)

Sites	Flat-rate costs	Cost per round
Petit-Bourg	8	18
Petit-Canal	22	25
Gosier	119	69
Sainte-Anne	11	23
Goyave	35	32
Capesterre Belle-Eau	30	29
Anse-Bertrand	27	26
Mould	27	30
Saint-François	31	29

Source: Bilionière et Lanneau (2023)

1.3. The economic risks and impacts on tourism

In 2017, the tourism industry generated an estimated US$ 57.1 billion in the Caribbean, with a projection that this would amount to US$ 83.3 billion by the year 2027 (Thompson et al., 2020). Tourism is the main driving force behind the development of a lot of Caribbean islands. Although it is flourishing, this specialisation is a source of external vulnerability. Indeed, tourism is also considered to be highly climate-sensitive, even more so in the context of climate change, which is a source of concern for Caribbean small island developing states (SIDS) (Stephenson et al., 2014). Coastal destinations such as St Lucia, the Bahamas, Jamaica and Barbados are extremely vulnerable to the direct and indirect impacts of climate change (such as storms and extreme weather events, coastal erosion, infrastructure damage, rising sea levels, flooding, water shortages and water contamination) (Spencer, 2019). In fact, small island economies specialising in tourism are significantly more physically vulnerable to climate change than other territories, and therefore present a development model with sustainability that cannot be guaranteed in the absence of mitigation and adaptation policies (Goujon and Hoarau, 2020).

Climate change is already having a negative impact on the region's tourism sector, with rising temperatures causing coral bleaching and droughts occurring more frequently, with an effect on water availability. Damage and losses caused by storms and hurricanes have also increased. In 2015, the damage caused by tropical storm Erika cost Dominique 90% of its GDP. The main tourist infrastructures, notably, seaports and airports, are threatened by a one-metre rise in sea level. The costs of rebuilding damaged infrastructure along the coast are disproportionately high for the affected areas (Layne, 2017).

In Barbados, the potential losses to the tourism industry due to climate change have been estimated at US$ 356 million under a moderate cyclone activity scenario (Moore et al., 2010). For Guadeloupe and Martinique, the losses have been estimated at €45 million and €60 million respectively by 2100, according to a pessimistic scenario of greenhouse gas increases (Dupont, 2013). In the Bahamas, the damage caused by Hurricane Matthew, which hit the island during the 2016 season, was estimated at US$ 600 million, mainly as a result of damage to tourism-related infrastructure, such as Nassau airport (Stewart and Berg, 2017). In addition, rising sea levels could result in the displacement of coastal communities, coastal erosion and loss of land, salinisation of aquifers and damage or loss of coastal resources, infrastructure, including airports, major roads, and billions of dollars of tourism superstructure for the islands of the Bahamas with little relief (Thomson and Benjamin, 2018). Rising sea levels, combined with weak (category 1), moderate (category 3) and strong (category 5) storms, could cause the destruction of 34%, 69% and 83% of tourist infrastructure (hotels and resorts) respectively. In addition to flooding, coastal erosion affects 28% of all hotels located between 0 and 50 m from the coastline, and 60% of tourist infrastructures located between 0 and 100 m from the coastline. Taking into account the economic importance of the sector, the potential impacts on tourism infrastructure will result in significant losses of revenue and employment for the Bahamas islands (Pathak et al., 2021).

In addition to the impacts of hurricanes, which are well documented in the literature, the accumulation of sargassum seaweed on beaches due to its massive stranding, the nauseating odours arising from its decomposition, and the deterioration in the quality of beaches and coastal waters, are other threats to tourist activities in the Caribbean islands. In fact, all these symptoms linked to sargassum seaweed stranding could cause a reduction in tourist numbers, resulting in significant economic losses (Bartlett and Helmer, 2021; Lopez-Contreras et al., 2021). More specifically, sargassum strandings reduce growth in tourist arrivals by an average of 1.1% up to eight months after they occur (Mohan and Strobl, 2023).

III. Some empirical investigations of the climate change hypothesis and macroeconomic impacts in Guadeloupe based on rainfall and temperature series

3.1. Data

The acceptance or rejection of the hypothesis of climate change naturally invites us to examine the evolution of the multitude of parameters that characterize meteorology. As awareness of the stakes and consequences of climate change has grown, a number of preventive organizations have sprung up. Throughout the world, many of them have specialized in observing and measuring the climate.

Today, the situation is one of thousands of climatological stations scattered in cities and rural areas all over the world, along with satellites specialized in collecting meteorological data.

Under the coordination of the World Meteorological Organization (WMO), a weather measurement network collects data on a daily basis, in accordance with international standards, most often covering temperature (maximum and minimum), wind speed and direction, humidity, pressure, radiation (solar and/or infrared) and precipitation. These variables, cited by Barrette (2005) and added to those mentioned by Taha et al. (1999) (river discharge, lake levels, ice cover break-up date and duration, and groundwater levels), are among the most relevant indicators for climate monitoring.

The data we use in this study comes from Météo-France's Regional Service for Guadeloupe. The data cover the period from January 1951 to September 2023, that is to say a period of 73 years, almost three quarters of a century, and which defines, above all, a time scale well adapted to grasp the ongoing changes. Our monthly series trace the measurements of two essential climatic components: average rainfall (or precipitation) expressed in millimetres (mm), this is the RRE variable; and the temperatures (average, minimum and maximum) expressed in degrees Celsius (°C), are denoted respectively as TNE, TXE and TM. Each of the four series recorded a total of 885 observations.

3.2. Description of the climate time series

Based on our four time series, the aim is to identify the main lessons to be learned from an examination of their evolution, and to provide answers to important questions that are central to the concerns of decision-makers and the general public. What are the characteristics of their individual trajectories? What can be deduced from a comparison of their trends? Can we accept the hypothesis of a change in monthly rainfall over recent decades? Can we validate the hypothesis of a global rise in temperature over recent decades?

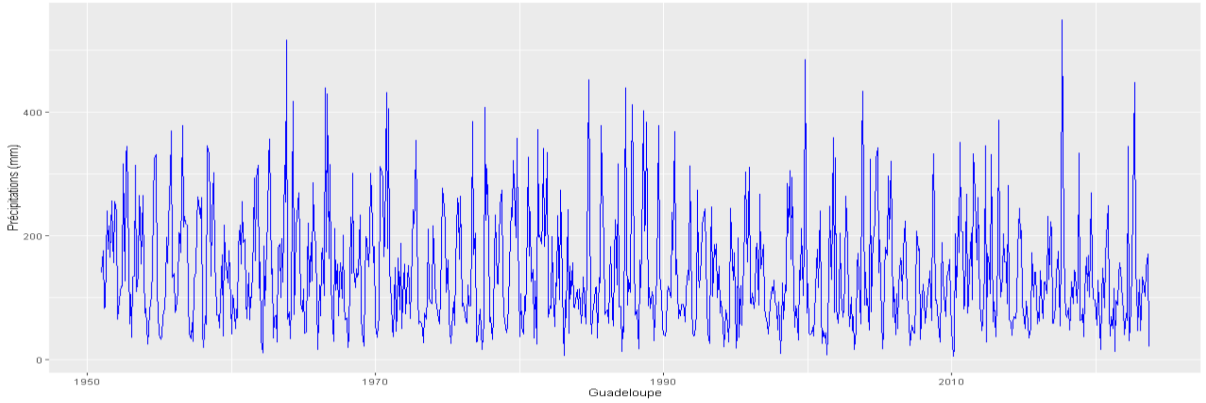
3.2.1. Chronological profiles of variables

As regards the visualisation of the changes to the Guadeloupe climate indicators and the analysis of their progressions, it must be noted that the climate in Guadeloupe is tropical oceanic and is mainly characterised by two seasons, the "dry" season and the "rainy" season, which is a time of frequent and intense rains. Between these two seasons there are also two more or less marked shoulder-seasons. Chronologically, the sub-annual division is as follows: the dry season is from February to April, the first shoulder-season from May to June, the rainy season is from July to October and the second shoulder-season from November to January.

Figures 1 and 2 illustrate the monthly changes in rainfall and the average, minimum and maximum temperatures over the entire period. Without any ambiguity, the trajectories obtained draw curves which show that they combine well-known movements associated with the components of a time series. There is clearly a trend in both the rainfall series and the temperature series, a seasonal component with a generating process that closely follows the above climate characteristics and an irregular component.

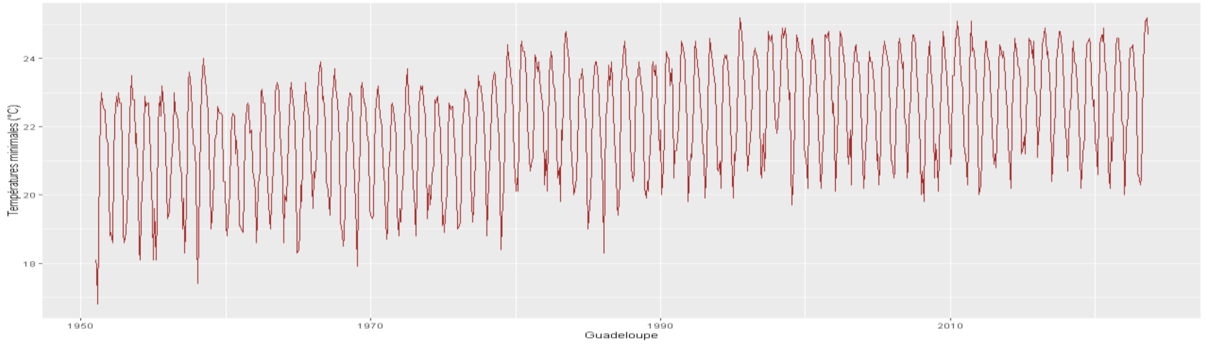
Figure 1. Evolution des variables « Précipitations » et « Température » sur la période 1951-2023

Average rainfall in millimetres in Guadeloupe | 1951-2023

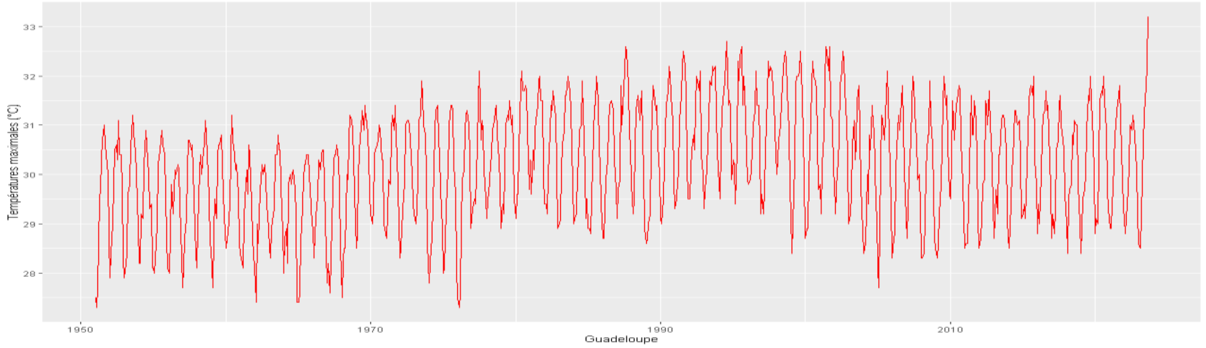


Average temperatures in °C in Guadeloupe | 1951-2023

Minimum temperatures in °C in Guadeloupe | 1951-2023



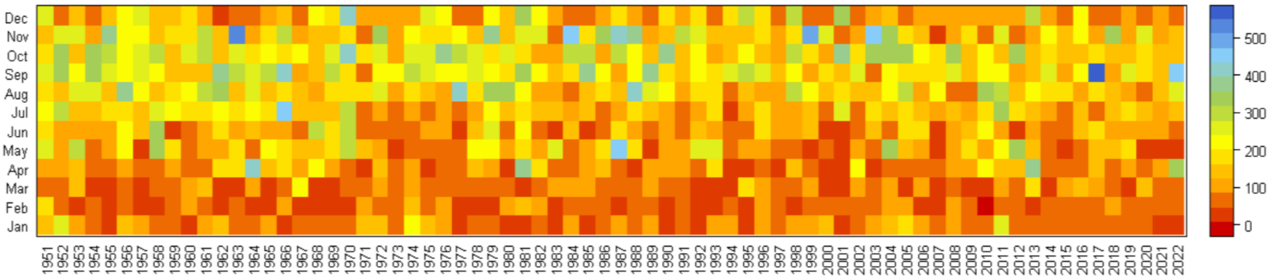
Maximum temperatures in °C in Guadeloupe | 1951-2023



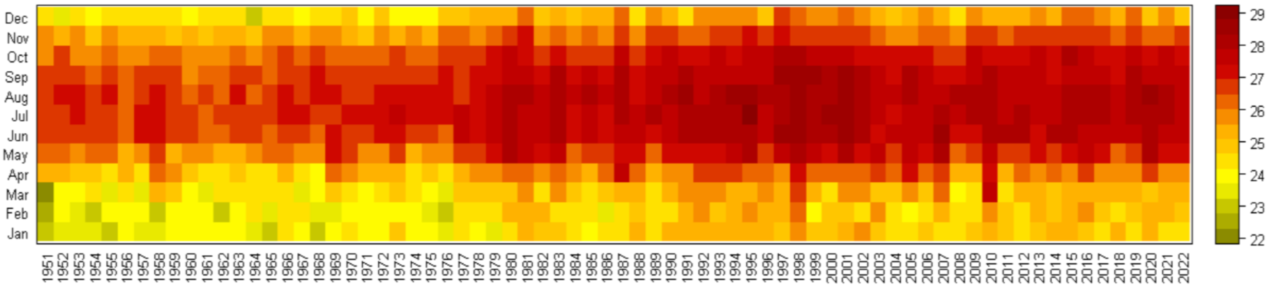
Sources : Auteurs à partir des données Météo-France

Figure 2. Evolution des variables « Précipitations » et « Température » sur la période 1951-2022

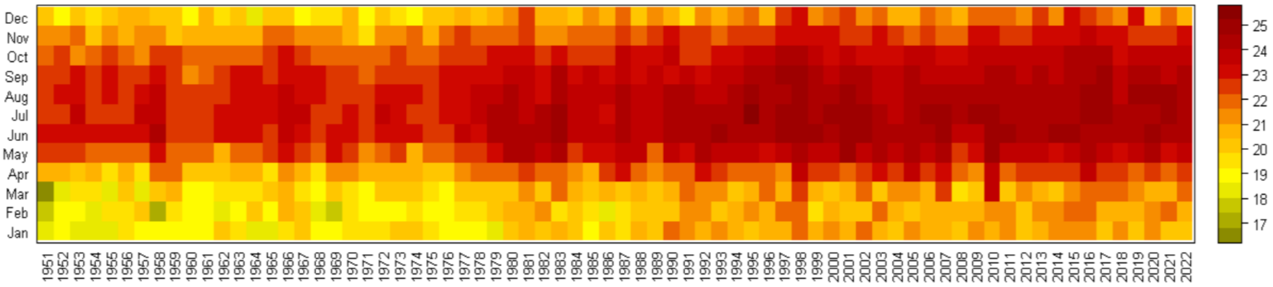
Monthly rainfall in Guadeloupe from 1951 to 2022 [mm/month]



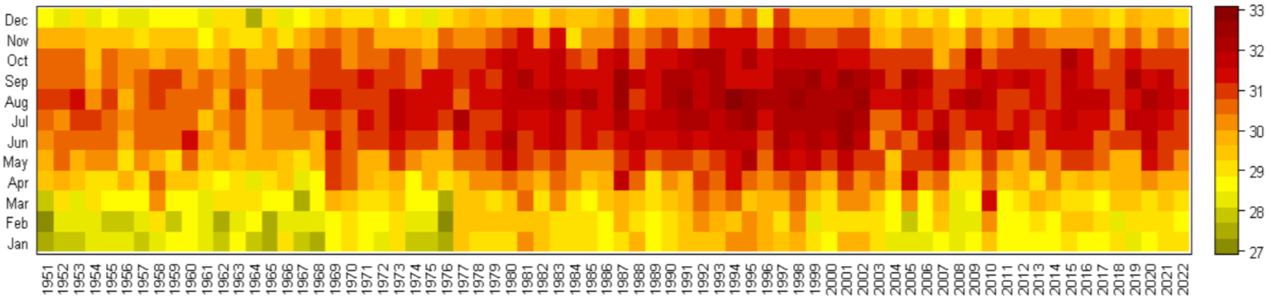
Average monthly temperature in Guadeloupe from 1951 to 2022 [°C/month]



Minimum monthly temperature in Guadeloupe from 1951 to 2022 [°C/month]

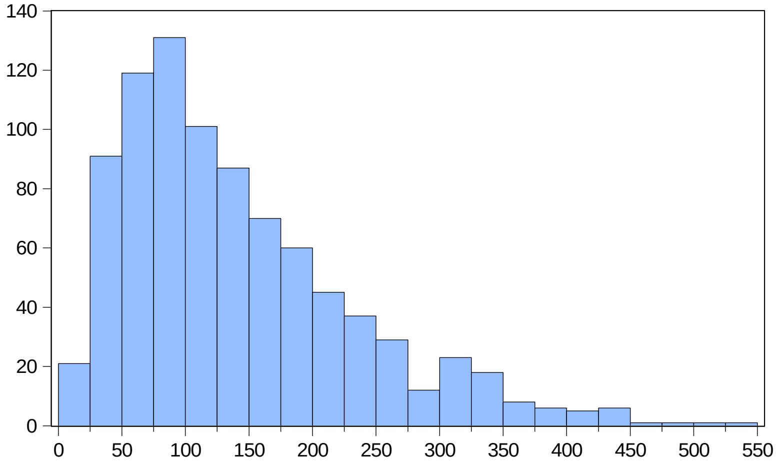


Maximum monthly temperature in Guadeloupe from 1951 to 2022 [°C/month]

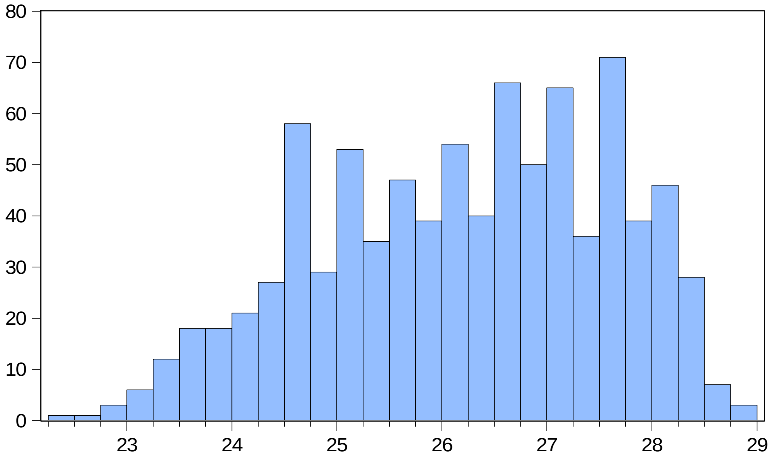


Sources : Auteurs à partir des données Météo-France

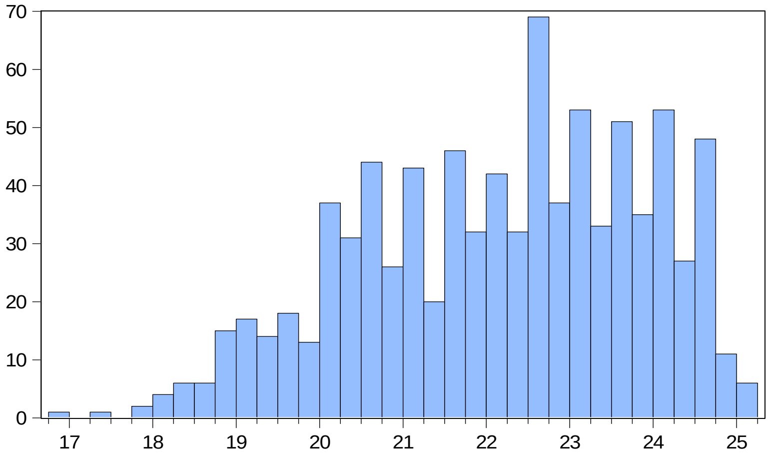
Table 1. **Descriptive statistics (Quantitative data)**:



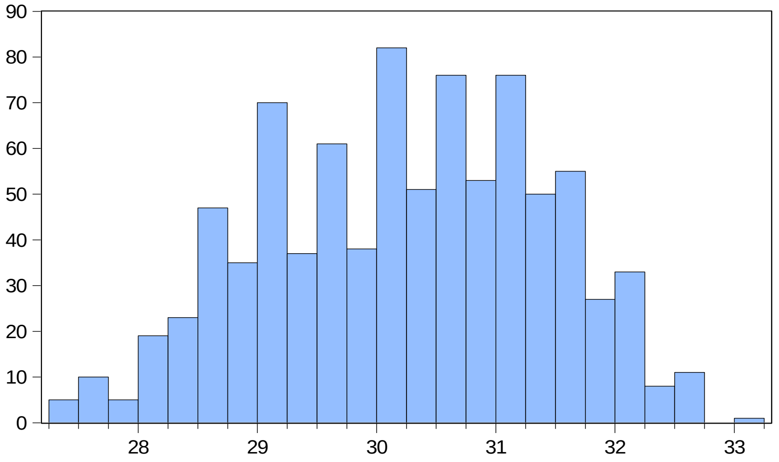
```
Series: RRE
Sample 1951M01 2023M09
Observations 873

Mean          140.8286
Median        118.2000
Maximum       549.3000
Minimum       6.000000
Std. Dev.     92.40349
Skewness      1.160854
Kurtosis      4.219226

Jarque-Bera   250.1451
Probability   0.000000
```



```
Series: TM
Sample 1951M01 2023M09
Observations 873

Mean          26.17274
Median        26.30000
Maximum       28.95000
Minimum       22.30000
Std. Dev.     1.382698
Skewness     -0.281152
Kurtosis      2.187108

Jarque-Bera   35.53766
Probability   0.000000
```



```
Series: TNE
Sample 1951M01 2023M09
Observations 873

Mean          22.13814
Median        22.40000
Maximum       25.20000
Minimum       16.80000
Std. Dev.     1.694608
Skewness     -0.366456
Kurtosis      2.311471

Jarque-Bera   36.78356
Probability   0.000000
```



```
Series: TXE
Sample 1951M01 2023M09
Observations 873

Mean          30.20619
Median        30.30000
Maximum       33.20000
Minimum       27.30000
Std. Dev.     1.165131
Skewness     -0.154248
Kurtosis      2.289888

Jarque-Bera   21.80421
Probability   0.000018
```

Sources : Auteurs à partir des données Météo-France

3.2.2. Variability of observations

It is these trajectories that need to be dissected in order to identify elements that reveal the changes taking place in Guadeloupe's climatic environment. On the basis of graphs 1 and 2 and simple descriptive statistics indicators, we can easily draw some conclusions about the behavior of the variables.

Short term movements

The average monthly rainfall has a very wide range, between 6 mm and 549.3 mm. This range reflects a very high variability in the amount of rainfall that combines the effects directly linked to the seasonality intrinsic to the rainfall patterns of the Guadeloupe archipelago and those arising from long-term climate trends.

As regards this rainfall seasonality, the various figures show this significant difference between the rainfall amounts recorded during the first half of the year (dry season) and those reached during the second half (rainy season). More specifically, Figures 1 and 2 show an intra-annual distribution that remains fairly rigid over time, with the presence of the lowest average rainfall in the first quarter in particular and, conversely, the significantly higher contributions of the months of September-October- November.

As regards the distribution of the values of the four series, it is observed that the variation between the temperature series are quite close whereas it is much more significant for the rainfall series. The calculated standard deviations reflect a similar finding: small variations in the temperature series values and, on the contrary, a relatively high variation in rainfall. For the latter, fifty percent of the values are below 118.2 mm, and the difference between the median and the minimum is 112.2 mm, while the difference between the median and the maximum is close to 431.1 mm. This difference between the average and the median as well as the distribution of the monthly rainfall amounts reveal a certain asymmetry of the distribution of the variable, characterised by heterogeneous values and the presence of extreme values. It is well known that the latter reflect the occurrence of hurricanes and periods of droughts.

Beyond the parameters of central tendency and dispersion, it is also important to examine the shape of the distribution of the variables by the average of moments of order 3 and 4. The first, the Skewness coefficient, provides a measure of their degree of asymmetry in the distribution. It is symmetrical when this coefficient is zero, it is spread to the left when it is negative and, it exhibits a long tail on the right when it is positive. The coefficients obtained suggest a slight asymmetry to the right for rainfall and a left asymmetry for the temperature variables. The central moments of order 4, the Kurtosis coefficients provide information on the degree of flattening of a distribution. The calculated values of the respective series RRE (4.22), TNE (2.31), TXE (2.29) and TM (2.18) suggest that they exhibit a leptokurtic effect with tails that are wider than those of the normal law.

Long-term trends

More than for rainfall, examining temperature trajectories is the key exercise for detecting climate changes. Figure 1 shows curves whose profile for each year accurately reflects the seasonal variations of the tropical ocean climate, marked in Guadeloupe by the highest temperatures between April and November and the lowest from December to March. This seasonality is the result of the climate phenomena that occur during the dry season, namely the presence of a constant trade wind and cool nocturnal temperatures and the rainy season which is rather marked by hot and humid weather.

Figure 3 shows two contrary trends for our two climate parameters: a decrease in average annual rainfall over the period 1951-2015 and an increase in annual temperatures over the same period. In other words, rainfall tends to decrease in a context where temperatures become progressively warmer. The report by Météo-France experts published in 2014 corroborates this observation, at least in part, since it shows an increase in average annual temperatures of about 1.2°C over the last 60 years but no significant statistical changes in rainfall over the same period.

If rainfall is examined in greater detail, the average decrease seems to be insignificant but two years are particularly noteworthy: 1997 and 2007. With rainfall below 90mm, more precisely 83mm in 1997 and 89mm in 2007, these two years have the lowest levels of rainfall during the 1951-2015 period.

Unlike the rainfall variable, changes in the three series of temperatures make it possible to clearly support the presumption of a global trend of average temperature warming in Guadeloupe. From these curves, two "climate peaks" are observed over the last two decades: one in 1998 and one in 2010. With an average temperature of 27.4°C, 1998 is the record year of the period 1951-2015. Only the year 2010 comes close with an average temperature of 27.1°C. Consequently, these two years, which were among the hottest of the last 60 decades, already seemed to confirm the warming trend of +0.28°C per decade recorded since 1951. Observed values over the past ten years support these findings of very high average temperatures, in excess of 27°.

In summary, the last two decades have two record years with the lowest rainfall (1997 and 2007) and two record years with the highest temperatures (1998 and 2010) over the 1951-2015 period. From the visualisation of the changes (in particular figures 1, 3 and 4), it can clearly be seen that the temperatures were in a generally upward trajectory. These graphs unequivocally provide an illustration of global warming, with a discernible rise in average, minimum and maximum temperatures since the 1980s. Figure 4 allows the two subsets of points to be identified, showing that the current period displays average temperatures one to two degrees Celsius higher than the start period.

Figure 3. Series of means and standard deviations, 1951-2015

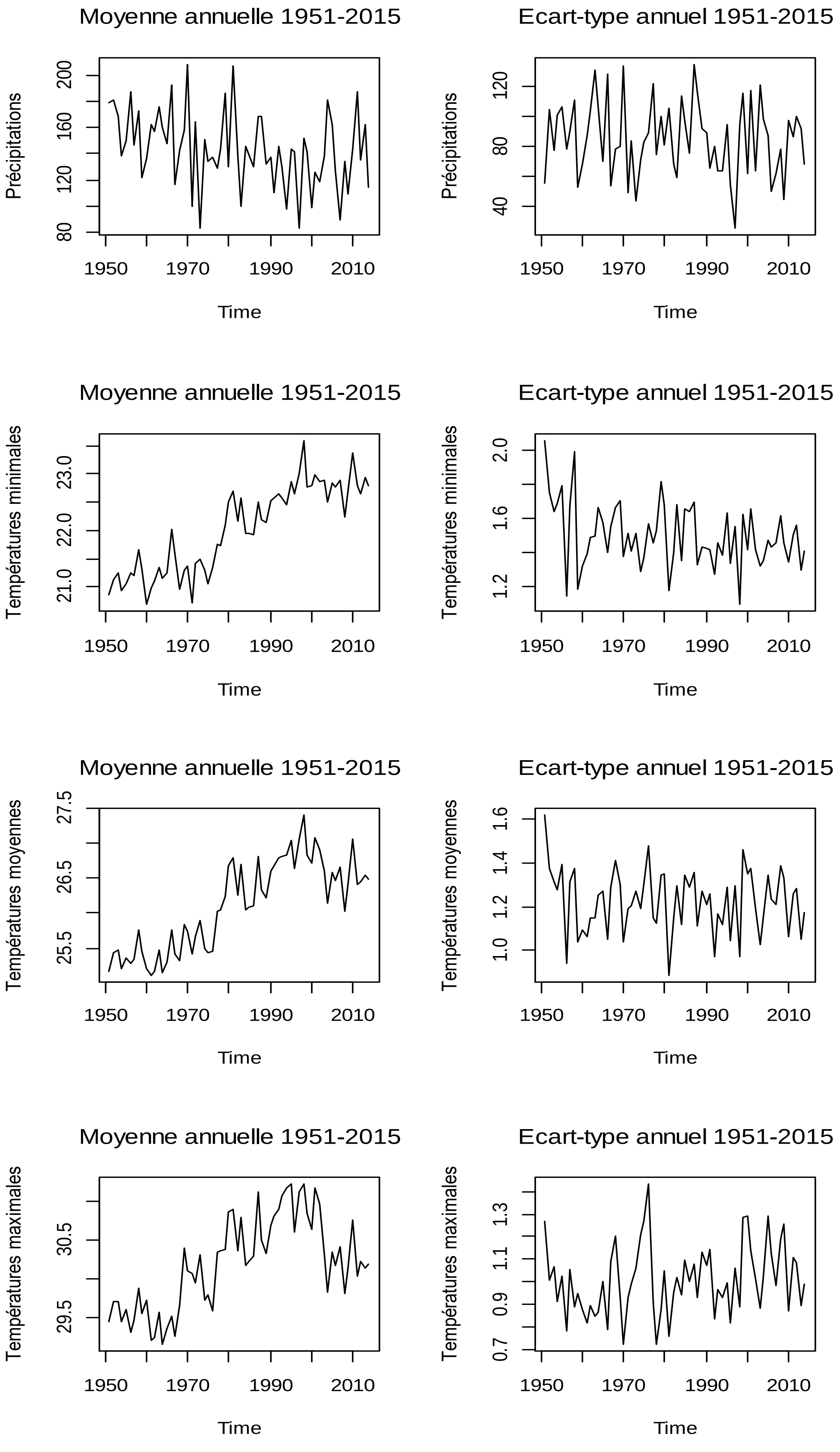
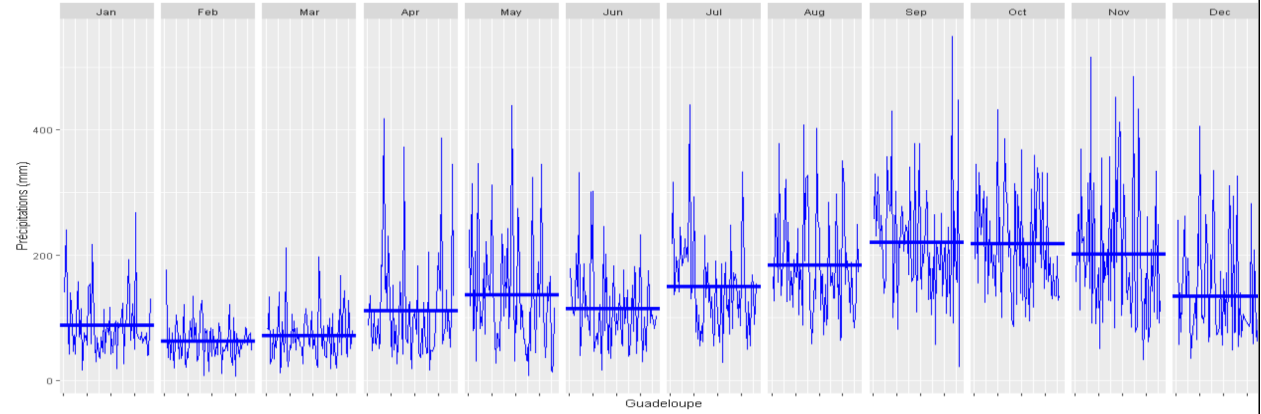
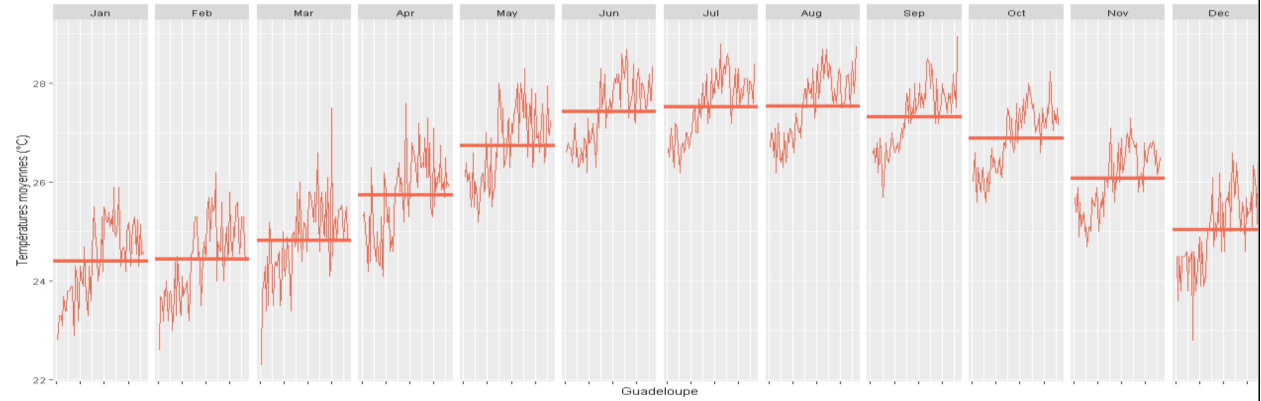


Figure 4. Monthly precipitation and temperature time series, 1951-20123

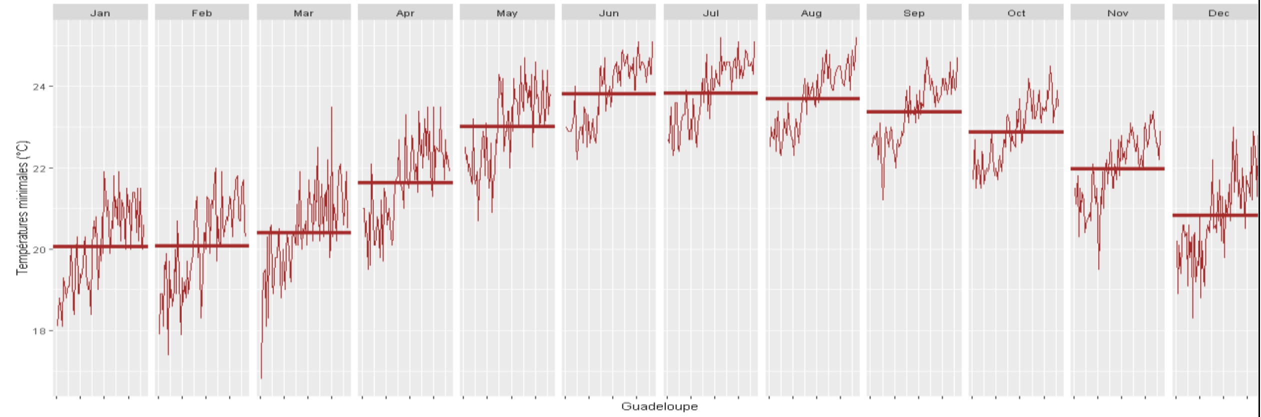
Average rainfall in millimetres in Guadeloupe | 1951-2023



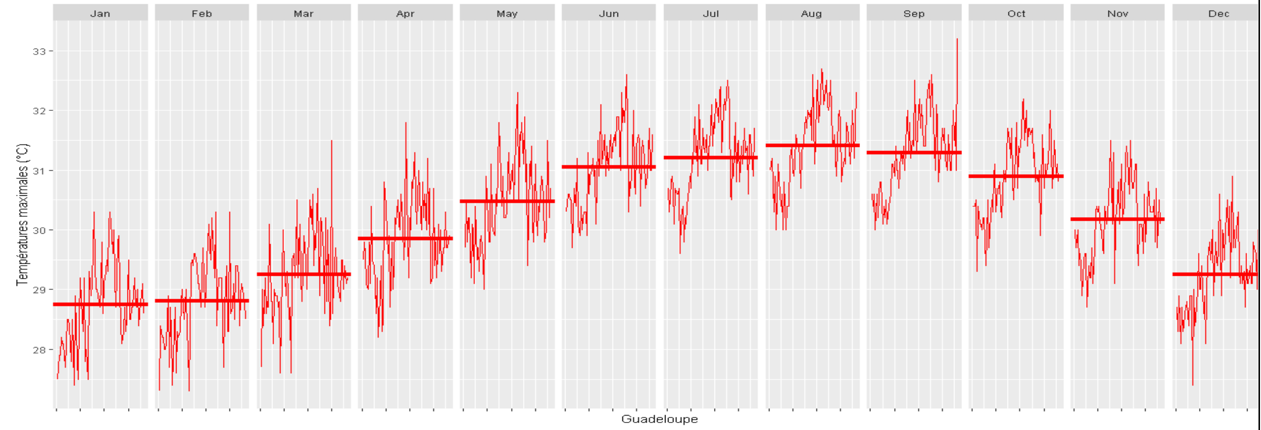
Average temperatures in °C recorded in Guadeloupe | 1951-2023"



Minimum temperatures in °C recorded in Guadeloupe | 1951-2023"



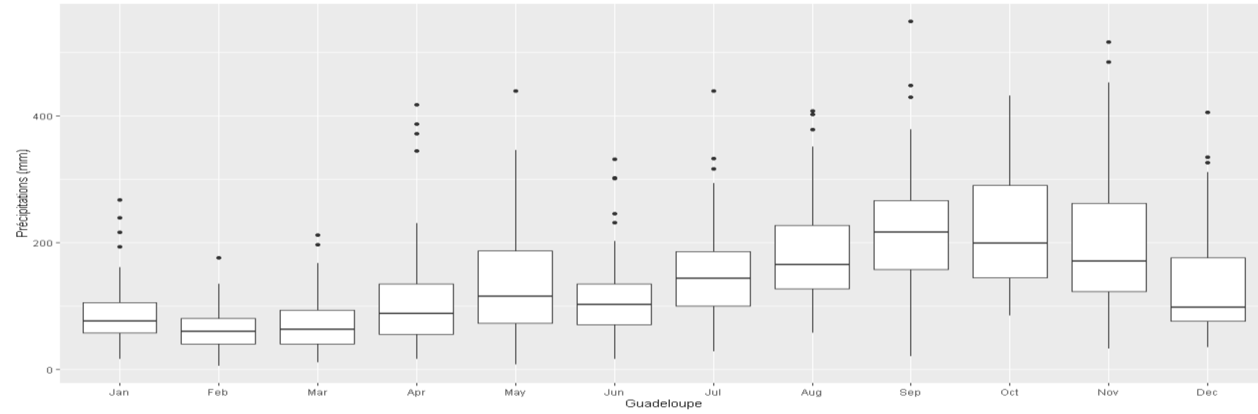
Maximum temperatures in °C recorded in Guadeloupe | 1951-2023"



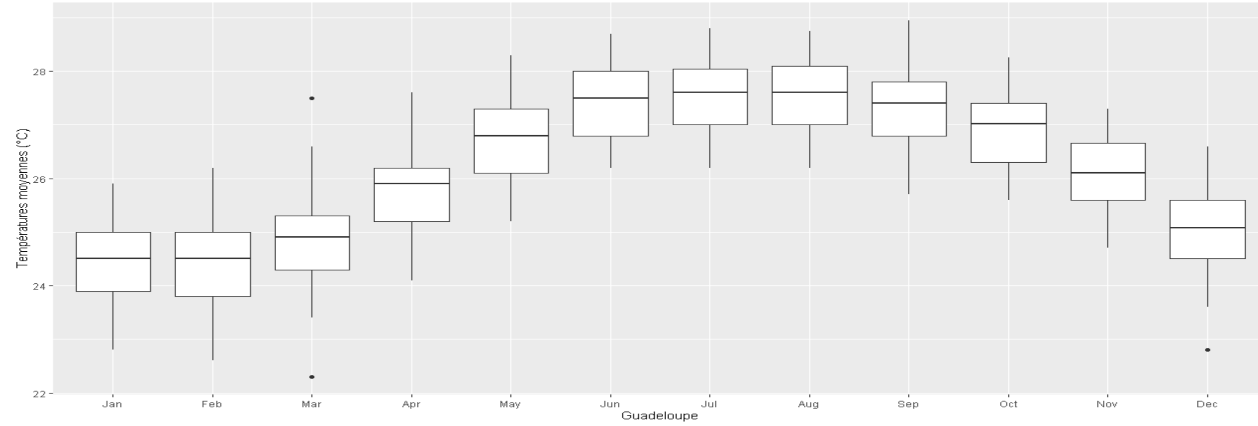
Sources : Authors based on Météo-France data

Figure 5. Monthly precipitation and temperature times series, 1951-2023

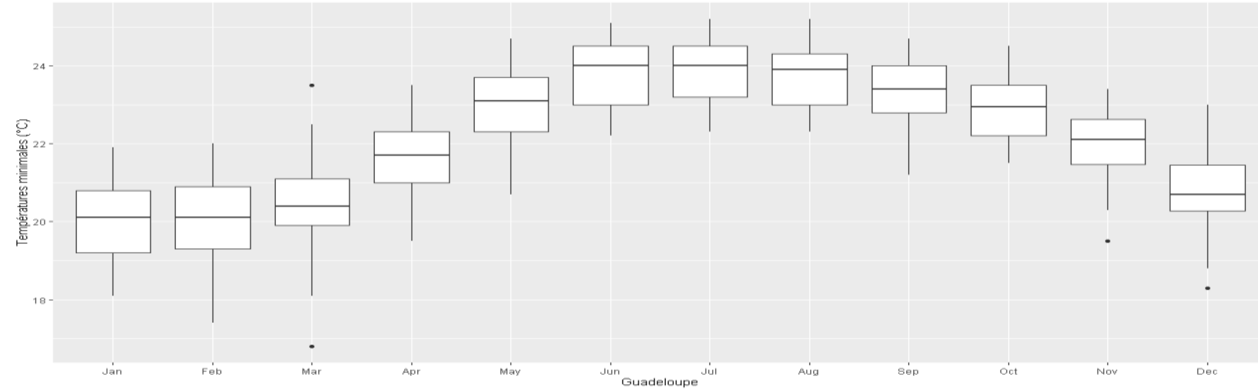
Boxplot of average rainfall in millimeters in Guadeloupe | 1951-2015



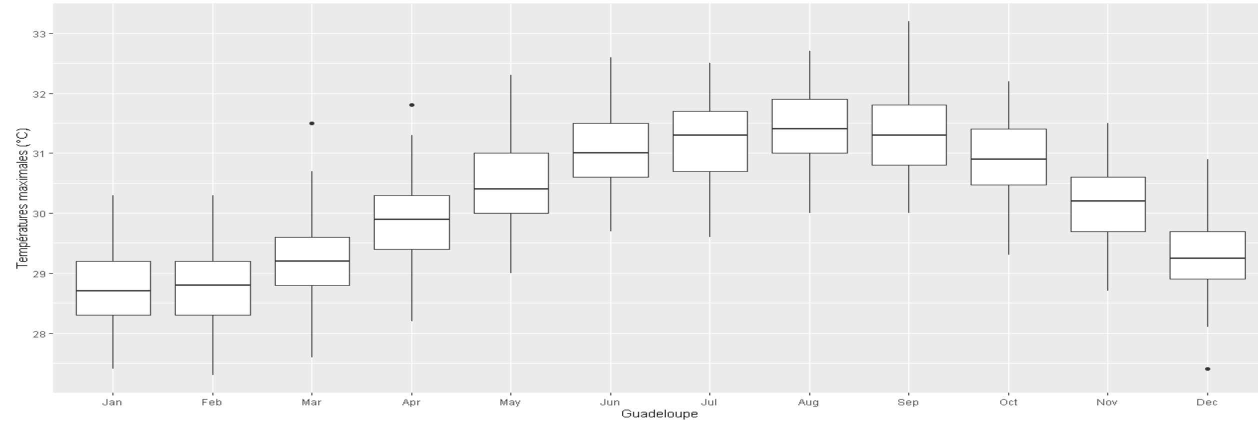
Boxplot of average temperatures in °C recorded in Guadeloupe | 1951-2023"



Boxplot of minimum temperatures in °C recorded in Guadeloupe | 1951-2023"



Boxplot of maximum temperatures in °C recorded in Guadeloupe | 1951-2023"



Sources : Authors based on Météo-France data

Figure 5. Number of temperature and rainfall shocks per year

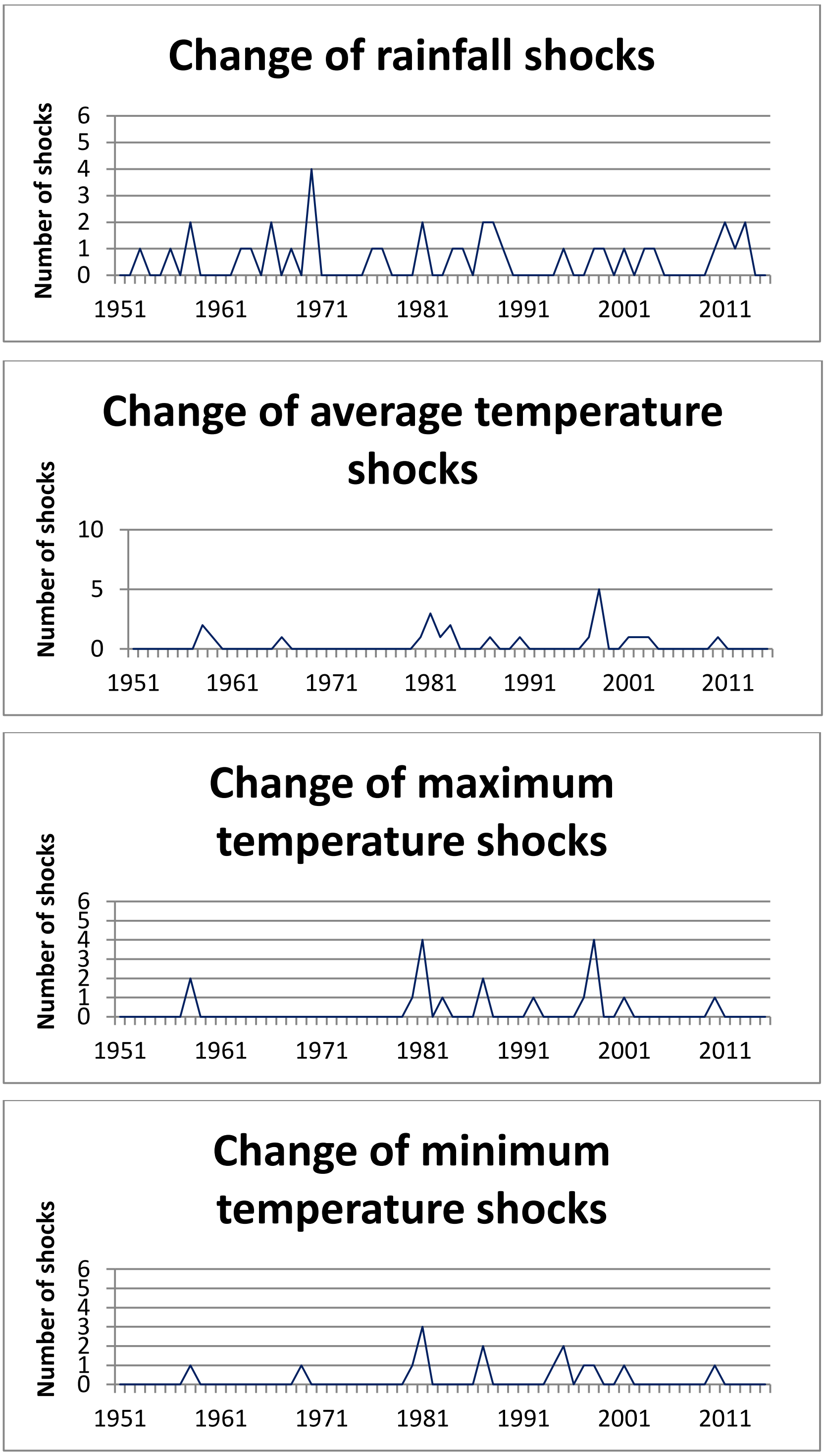


Table 2. Shocks and trends in temperature and rainfall from 1951 to 2015

	Shocks	Trend	
	Number	Gradient	T-statistic
Rainfall	36	-0.04431	-3.64354
Min temperature	15	0.003020	32.0093
Av temperature	23	0.00232	28.8221
Max temperature	18	0.001639	17.2059

Our results show significant trends for all the climate parameters studied. Indeed, the t-statistics are quite satisfactory and therefore the coefficients of the trend are very significant - positively significant for the temperature series and negatively significant for the rainfall series. Over the period studied, the minimum, average and maximum temperatures account for nearly the same number of shocks, respectively 15, 23 and 18. It is interesting to note that these shocks are much more numerous over the last four decades. Temperature shocks have therefore multiplied over the last few years, especially for average and maximum temperatures, which experienced the same shock peak in 1998. A year that, as we saw earlier, is distinguished by a record temperature during the 1951-2015 period. As regards rainfall, there are considerably more shocks than for the temperatures series (36). However, they are distributed homogeneously and do not appear to have significantly changed over the period except for a peak in 1970 with four shocks during the year.

The graphical analyses previously carried out show unequivocally that changes in climate variables are not stable over time. On the contrary, they sketch slightly increasing curves and different average values according to sub-periods. But beyond these graphic examinations, the econometric literature teaches that characterising the behaviour of a time series is based on formal tests of its non-stationarity.

Non-seasonal unit roots tests

We applied standard unit root tests. The results of the Dickey-Fuller (ADF) test, Phillips-Perron (PP) unit root tests and Kwiatkowski, Phillips, Schmidt and Shin (KPSS) test are reported in Table 3. For the first two, the test statistics were calculated using regression equations with or without a constant and a deterministic trend under the null hypothesis of the presence of a unit root.

Applied to the series level while evaluating the deterministic and stochastic nature of the trend, the various tests lead to generally unanimous results: the rainfall variable and the temperature variables are all characterised by the lack of a non-seasonal unit root and are generated by a *Trend Stationary* process. In particular, the ADF and Phillips-Perron test regressions produce high t-statistics for time constant and drift as well as very low critical probabilities, well below the 5% threshold.

Table 3. Classical unit root test for the unemployment rates

	ADF			Phillips-Perron		
	Without constant	With constant	With constant and trend	Without constant	With constant	With constant and trend
RRE	-0.98	-4.51	-5.42	-10.09	-18.08	-18.19
TNE	0.96	-1.47	-3.29	0.19	-11.06	-5.74
TXE	0.38	-1.93	-2.31	0.51	-12.58	-9.15
TM	0.78	-1.65	-2.55	0.28	-9.38	-5.76

Note: ADF, Phillips-Perron and KPSS are the ADF test statistics that include a constant and a time trend in the model, with optimal lag selected automatically with the Akaike criterion.

For the model without trend, the 5% and 1% asymptotic critical values for the ADF and Phillips-Perron statistics are −1.94 and −2.56, respectively. For the model without trend, the 5% and 1% asymptotic critical values for the ADF and Phillips-Perron statistics are -3.44 and -4.02, respectively.

Seasonal unit roots tests

We performed the HEGY test from the estimate of the equation's OLSs (2) within the EVIEWS platform. An advantage of the add-in module of this software is that it proposes the automatic selection of the number of delays to be introduced in the regressions, using the AIC criterion.

Referring to Wasserfallen (1986)'s recommendation, which suggests starting from a maximum delay of up to twice the period of the series, the test is generally carried out by performing the regressions of the four classical variants of the model (2): the presence of the constant, temporal drift and seasonal dummies; the constant and seasonal dummies; the constant and the time drift; only the constant term. But in reality, with our datasets whose deterministic seasonality has been clearly demonstrated, the relevant equations for correctly conducting the HEGY test must contain these seasonal deterministic terms. Using numerical simulation, Ghysels et al. (1994) have demonstrated that their exclusion in the HEGY test can lead to biases and seriously distort the results:

> *"it was found that when the data-generating processes have seasonal dummies, the regression without seasonal dummies seriously distorts the test result [i.e. it leads to a large bias in the size or too low power]. Hence, although inclusion of too many lags or irrelevant deterministic terms (i.e. a constant, seasonal dummy, and/or a trend) tends to reduce the power of the tests, the safe strategy in empirical applications is the inclusion of these (possibly irrelevant) terms in the model."*

The results reported in Table 4 are also to be complemented with those in Annex 1, which includes the details of the estimates made. The null hypothesis of the presence of the non-seasonal root is rejected for the two specifications considered with the critical values provided by the EVIEWS software and extracted from Franses and Hobijn (1997). We find the same conclusion with the comparison of t-statistics by considering the critical values given in table A.1 of Beaulieu and Miron (1993, p.325). For the root -1, the results are unambiguously convergent. Indeed, the root -1 is rejected in the two specifications that include them. The same is true for other seasonal modular unit roots. In the regression results, it can thus be seen that the calculated F-statistics are well above the critical values associated with the F-statistics of the Beaulieu and Miron table (1993).

In the light of the foregoing, we can accept the result that the four climatic series of Guadeloupe considered here have no unit roots, both for the null frequency and for the frequencies relative to the seasonal roots.

In addition to revealing the non-stationarity of the series and the influence of the seasonal component in this non-stationarity, the HEGY test also provides another important teaching: identifying the most appropriate filter for stationary data. When the series has a unit root at the zero frequency, it is obviously the$(1-L)X_t$ filter that must be applied. Conversely, if the unit roots are present at all frequencies, it is the$(1-L^{12})X_t$ filter that must be favoured. On the other hand, when there is a small number of unit roots, systematic application of the$(1-L^{12})X_t$ filter is contraindicated. It is this perspective that Pichery and Ouerfelli (1998) have highlighted in their report on this issue. They recall that practical cases of integrated series at all frequencies are rare and that this is due to a strong deterministic seasonal component that absorbs the variability of seasonal variations (see HEGY, 1990, p.219).

Here, then, the implications of the absence of modular unit roots for the Guadeloupe climate series suggest that most of the seasonality is deterministic in nature and that the latter should be captured by seasonal dummies.

Table 4. Results of the HEGY tests of seasonal unit roots (*)

		RRE Series				TNE Series			
		Ctd model		Cd model		Ct model		C model	
Null	Frequency	Crit. val. 5%*	Statistic.	Crit. val. 5%*	Statistic.	Crit. val. 5%*	Statistic.	Crit. val. 5%*	Statistic.
Non seasonal u. r	. (Zero frequency)	-3.35	-7.2667	-2.81	-6.6493	-3.35	-4.8618	-2.81	-4.8618
Seasonal u. r.	(2 months per cycle)	-2.81	-6.4967	-2.81	-6.8354	-2.81	-7.4724	-2.81	-7.4724
Seasonal u. r.	. (4 months per cycle)	6.35	43.1334	6.35	71.5341	6.35	69.8389	6.35	69.8389
Seasonal u. r.	(2.4 months per cycle)	6.48	32.8672	6.48	50.9152	6.48	65.1171	6.48	65.1171
Seasonal u. r.	. (12 months per cycle)	6.30	28.7028	6.33	56.7358	6.30	61.9211	6.33	61.9211
Seasonal u. r.	. (3 months per cycle)	6.40	34.909	6.41	51.8535	6.40	67.5176	6.41	67.5176
Seasonal u. r.	. (6 months per cycle)	6.46	51.2846	6.47	66.9181	6.46	67.4298	6.47	67.4298

(*) Specification with c (constant), t (time drift) and d (seasonal indicators).

Table 4. Results of the HEGY tests of seasonal unit roots (continued) (*)

		TM Series				TXE Series			
		Ctd model		Cd model		Ct model		C model	
Null	Frequency	Crit. val. 5%*	Statistic.	Crit. val. 5%*	Statistic.	Crit. val. 5%*	Statistic.	Crit. val. 5%*	Statistic.
Non seasonal u. r	. (Zero frequency)	-3.35	-7.2667	-2.81	-1.8947	-3.35	-3.7206	-2.81	-3.7200
Seasonal u. r.	(2 months per cycle)	-2.81	-6.4967	-2.81	-6.4614	-2.81	-7.5006	-2.81	-7.5006
Seasonal u. r.	. (4 months per cycle)	6.35	43.1339	6.35	25.3058	6.35	60.7072	6.35	60.7072
Seasonal u. r.	. (2.4 months per cycle)	6.48	32.8672	6.48	39.2332	6.48	71.7559	6.48	71.7559
Seasonal u. r.	. (12 months per cycle)	6.30	28.7028	6.33	33.5549	6.30	75.7785	6.33	75.7785
Seasonal u. r.	. (3 months per cycle)	6.40	34.9095	6.41	26.1494	6.40	58.0955	6.41	58.0955
Seasonal u. r.	. (6 months per cycle)	6.46	51.2846	6.47	33.1442	6.46	72.4652	6.47	72.4652

(*) Specification with c (constant), t (time drift) and d (seasonal indicators).

Conclusion

Although monitoring the evolution of climate indicators is central to the day-to-day activities of meteorological professionals and a major exercise in the work of geoscience and energy researchers, it is relatively recent in the context of economic analysis. Indeed, the issue of global warming has become a major concern for economists and policy-makers since the end of the 1990s, particularly since the adoption of the Kyoto Protocol in December 1997 to the United Nations Framework Convention on Climate Change (UNFCCC).

Within the Guadeloupe archipelago, as in the other Caribbean islands, the effects of climate change are not a myth, but now seem to be tangible facts affecting the entire population, local and regional authorities and even corporate performance. At the purely economic level, the stakes are considerable and concern sectoral impacts in agriculture, fisheries, tourism, health, biodiversity and among many others, the insurance industry.

The literature is full of empirical studies devoted to analysing climate change with a focus on the change of the rainfall and temperature series. To this end, we conducted extensive statistical investigations of the evolution of climate parameters in Guadeloupe. Various graphs and indicators allowed us to characterise the movements of the series and to conclude on the greater variability of rainfall compared to temperature measurements. The decomposition of the series and the estimation of their components revealed their non-stationarity and the deterministic nature of their source of variation. From the measurement of the shocks, there is evidence of an increase in the instability of rainfall over the last years on the one hand and a significant positive trend for temperature and a negative trend for rainfall on the other.

In order to deepen the modelling of the Guadeloupe climate time series, we used the seasonal integration tests and the univariate approach of Box-Jenkins, which is a relevant alternative to the large models frequently used in meteorological centres.

Our results show that the rainfall and temperature series of Guadeloupe are derived from non-stationary processes whose trend and seasonality are purely deterministic in nature. Impelled by deterministic processes, the Guadeloupe climate parameters taken into account here return to their long-term movement and behaviour. For these series, modern econometric theory makes it possible to detect that their structure has changed over time and makes it possible to accurately detect that only the trend suggests climate change by slowly increasing over time (temperatures) and conversely, seasonality remains overall stable. Moreover, the properties of these series also reveal that the impacts generated by one or more random shocks at a given instant are only transient.

Bibliographie

Albalate, Daniel, et Gabriel R. Padró-Rosario. « The economic cost of a hurricane: A case study of Puerto Rico and Hurricane Georges 1998 using synthetic control method ». *IREA–Working Papers, 2018, IR18/27*, 2018. https://diposit.ub.edu/dspace/handle/2445/126952.

Bartlett, Debbie, et Franziska Elmer. « The impact of Sargassum inundations on the Turks and Caicos islands ». *Phycology* 1, nº 2 (2021): 83-104.

Benjamin, Lisa, et Adelle Thomas. « Climate Change Impacts and Research in the Caribbean: Constraints, Opportunities and the Role of Tertiary Institutions ». In *University Initiatives in Climate Change Mitigation and Adaptation*, édité par Walter Leal Filho et Rafael Leal-Arcas, 131-42. Cham: Springer International Publishing, 2019. https://doi.org/10.1007/978-3-319-89590-1_8.

Berge, Manon, Camille Parrod, Audrey Pastel, et Pascal Saffache. « Perceptions et mécanismes de compréhension du changement climatique dans le centre de la Martinique (Antilles françaises) ». *Études caribéennes*, nº 53 (2022). https://journals.openedition.org/etudescaribeennes/25161.

Bertinelli, Luisito, Preeya Mohan, et Eric Strobl. « Hurricane damage risk assessment in the Caribbean: An analysis using synthetic hurricane events and nightlight imagery ». *Ecological Economics* 124 (2016): 135-44.

Bilionière, Maurice et Lanneau Katie. « Une approche prospective des coûts de la chaîne logistique amont par la méthode PREVA dans un contexte de valorisation des algues sargasses », 2023.

Billings, Stephen B., Emily A. Gallagher, et Lowell Ricketts. « Let the rich be flooded: the distribution of financial aid and distress after hurricane harvey ». *Journal of Financial Economics* 146, nº 2 (2022): 797-819.

Birchenough, Silvana NR. « Impacts of climate change on biodiversity in the coastal and marine environments of Caribbean Small Island Developing States (SIDS) ». *Caribbean Marine Climate Change Report Card: Science Review* 2017 (2017): 40-51.

Björnberg, Karin Edvardsson, Mikael Karlsson, Michael Gilek, et Sven Ove Hansson. « Climate and environmental science denial: A review of the scientific literature published in 1990–2015 ». *Journal of Cleaner Production* 167 (2017): 229-41.

Boustan, Leah Platt, Matthew E. Kahn, Paul W. Rhode, et Maria Lucia Yanguas. « The effect of natural disasters on economic activity in US counties: A century of data ». *Journal of Urban Economics* 118 (2020): 103257.

Brei, Michael, Preeya Mohan, et Eric Strobl. « The impact of natural disasters on the banking sector: Evidence from hurricane strikes in the Caribbean ». *The Quarterly Review of Economics and Finance* 72 (2019): 232-39.

Chávez, Valeria, Abigail Uribe-Martínez, Eduardo Cuevas, Rosa E. Rodríguez-Martínez, Brigitta I. Van Tussenbroek, Vanessa Francisco, Miriam Estévez, Lourdes B. Celis, L. Verónica Monroy-Velázquez, et Rosa Leal-Bautista. « Massive influx of pelagic Sargassum spp. on the coasts of the Mexican Caribbean 2014–2020: Challenges and opportunities ». *Water* 12, nº 10 (2020): 2908.

Davis, Doleasha, Rachael Simister, Sanjay Campbell, Melissa Marston, Suranjana Bose, Simon J. McQueen-Mason, Leonardo D. Gomez, Winklet A. Gallimore, et Thierry Tonon. « Biomass composition of the golden tide pelagic seaweeds Sargassum fluitans and S. natans (morphotypes I and VIII) to inform valorisation pathways ». *Science of the Total Environment* 762 (2021): 143134.

Delcroix, Thierry, et Sophie Cravatte. « Le changement climatique: une réalité pour l'outre-mer français ». *La Météorologie* 2009, nº 65 (2009): 33-38.

Deryugina, Tatyana. « The fiscal cost of hurricanes: Disaster aid versus social insurance ». *American Economic Journal: Economic Policy* 9, nº 3 (2017): 168-98.

Deryugina, Tatyana, Laura Kawano, et Steven Levitt. « The economic impact of Hurricane Katrina on its victims: Evidence from individual tax returns ». *American Economic Journal: Applied Economics* 10, nº 2 (2018): 202-33.

Desse, Michel. « Les îles de la Caraïbe: enjeux et perspectives ». *Les îles de la Caraïbe*, 2013, 1-292.

Douville, Hervé, et Pascal Terray. « Réponse du cycle hydrologique aux forçages anthropiques: Que nous disent les dernières simulations du GIEC? » *La météorologie*, nº 57 (2007): 31-36.

Dupont, Louis. « Le changement climatique et ses implications économiques sur le secteur touristique à la Guadeloupe et à la Martinique (Petites Antilles) ». *Études caribéennes*, nº 26 (2014). https://journals.openedition.org/etudescaribeennes/6750.

Duvat, Virginie. « Changement climatique et risques côtiers dans les îles tropicales ». In *Annales de géographie*, 541-66. Cairn/Publilog, 2015. https://www.cairn.info/revue-annales-de-geographie-2015-5-page-541.htm.

Emanuel, Kerry. « Global warming effects on US hurricane damage ». *Weather, Climate, and Society* 3, nº 4 (2011): 261-68.

Foden, Wendy, Georgina M. Mace, Jean-Christophe Vié, Ariadne Angulo, Stuart HM Butchart, Lyndon DeVantier, Holly T. Dublin, Alexander Gutsche, Simon Stuart, et Emre Turak. « Species susceptibility to climate change impacts ». *Wildlife in a changing world–an analysis of the 2008 IUCN Red List of threatened species* 77 (2009). https://books.google.com/books?hl=fr&lr=&id=hgErHErt6-gC&oi=fnd&pg=PA77&dq=Species+susceptibility+to+climate+change+impacts&ots=umvsMnh3Iu&sig=1BowZhUsTsv49RerFWfBzi_vmws.

Frame, David J., Michael F. Wehner, Ilan Noy, et Suzanne M. Rosier. « The Economic Costs of Hurricane Harvey Attributable to Climate Change ». *Climatic Change* 160, nº 2 (mai 2020): 271-81. https://doi.org/10.1007/s10584-020-02692-8.

Frazier, J., R. Webster, T. Linton, et B. N. Hill. « The use of satellite imagery in the monitoring and forecasting of Sargassum seaweed in the Caribbean Phase II of the Sargassum Early Advisory System ». In *AGU Fall Meeting Abstracts*, 2013:ED51B-0609, 2013. https://ui.adsabs.harvard.edu/abs/2013AGUFMED51B0609F/abstract.

Frazier, Tim G., Nathan Wood, Brent Yarnal, et Denise H. Bauer. « Influence of potential sea level rise on societal vulnerability to hurricane storm-surge hazards, Sarasota County, Florida ». *Applied Geography* 30, nº 4 (2010): 490-505.

Gargominy, Olivier. « Biodiversité et conservation dans les collectivités françaises d'outre-mer », 2003. https://policycommons.net/artifacts/1377169/biodiversite-et-conservation-dans-les-collectivites-francaises-doutre-mer/1991439/.

Goujon, Michaël, et Jean-François Hoarau. « Les îles touristiques à la merci du changement climatique: une évaluation par un indice synthétique de vulnérabilité physique ». *Revue d'economie du developpement* 28, nº 1 (2020): 69-106.

Gower, Jim, Erika Young, et Stephanie King. « Satellite Images Suggest a New *Sargassum* Source Region in 2011 ». *Remote Sensing Letters* 4, nº 8 (août 2013): 764-73. https://doi.org/10.1080/2150704X.2013.796433.

Jerch, Rhiannon, Matthew E. Kahn, et Gary C. Lin. « Local public finance dynamics and hurricane shocks ». *Journal of Urban Economics* 134 (2023): 103516.

Karmalkar, Ambarish V., Michael A. Taylor, Jayaka Campbell, Tannecia Stephenson, Mark New, Abel Centella, Arnoldo Benzanilla, et John Charlery. « A review of observed and projected changes in climate for the islands in the Caribbean ». *Atmósfera* 26, nº 2 (2013): 283-309.

Kemp-Benedict, Eric, Jonathan Lamontagne, Timothy Laing, et Crystal Drakes. « Climate impacts on capital accumulation in the small Island state of Barbados ». *Sustainability* 11, nº 11 (2019): 3192.

Knutson, Thomas, Suzana J. Camargo, Johnny CL Chan, Kerry Emanuel, Chang-Hoi Ho, James Kossin, Mrutyunjay Mohapatra, Masaki Satoh, Masato Sugi, et Kevin Walsh. « Tropical cyclones and climate change assessment: Part I: Detection and attribution ». *Bulletin of the American Meteorological Society* 100, nº 10 (2019): 1987-2007.

Kousky, Carolyn. « Informing climate adaptation: A review of the economic costs of natural disasters ». *Energy economics* 46 (2014): 576-92.

López-Contreras, Ana M., Matthijs van der Geest, Bea Deetman, Sander van den Burg, Hanneke Brust, et Truus de Vrije. *Opportunities for valorisation of pelagic Sargassum in the Dutch Caribbean*. 2137. Wageningen Food & Biobased Research, 2021. https://library.wur.nl/WebQuery/wurpubs/582759.

Louime, Clifford, Jodany Fortune, et Gary Gervais. « Sargassum invasion of coastal environments: a growing concern ». *American Journal of Environmental Sciences* 13, nº 1 (2017): 58-64.

Mejia, Mr Sebastian Acevedo. *Gone with the Wind: Estimating hurricane and climate change costs in the Caribbean*. International Monetary Fund, 2016. https://books.google.com/books?hl=fr&lr=&id=WVsZEAAAQBAJ&oi=fnd&pg=PA3&dq=Gone+with+the+Wind:+Estimating+Hurricane+and+Climate+Change+Costs+in+the+Caribbean&ots=S8Y9J-GRAv&sig=eMB4iOuRPnCurZF-6DS2IHVByTY.

Milledge, John J., et Patricia J. Harvey. « Golden tides: problem or golden opportunity? The valorisation of Sargassum from beach inundations ». *Journal of Marine Science and Engineering* 4, nº 3 (2016): 60.

Mohan, Preeya, et Eric Strobl. « Tourism and Marine Crises: The Impact of Sargassum Invasion on Caribbean Small Island Developing Sates ». *Available at SSRN 4537720*. Consulté le 2 octobre 2023. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4537720.

Montador, Laurent. « Le changement climatique et ses conséquences économiques ». In *Annales des Mines-Responsabilité et environnement*, 59-64. Cairn/Softwin, 2022. https://www.cairn.info/revue-responsabilite-et-environnement-2022-2-page-59.htm.

Moore, Winston, Wayne Elliott, et Troy Lorde. « Climate Change, Atlantic Storm Activity and the Regional Socio-Economic Impacts on the Caribbean ». *Environment, Development and Sustainability* 19, nº 2 (avril 2017): 707-26. https://doi.org/10.1007/s10668-016-9763-1.

Moore, Winston R., Leandra Harewood, et Tiffany Grosvenor. « The supply side effects of climate change on Tourism », 2010. https://mpra.ub.uni-muenchen.de/id/eprint/21469.

Mulcahy, Matthew. *Hurricanes and society in the British Greater Caribbean, 1624–1783*. JHU Press, 2008. https://books.google.com/books?hl=fr&lr=&id=UziWDGd1TU4C&oi=fnd&pg=PP2&dq=Hurricanes+and+society+in+the+British+Greater+Caribbean,+1624%E2%80%931783&ots=MKBJrNY3or&sig=PmbhyMKW0JC7bBuaYC6mYXYHoIM.

Pielke, Roger A. « Future Economic Damage from Tropical Cyclones: Sensitivities to Societal and Climate Changes ». *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 365, nº 1860 (15 novembre 2007): 2717-29. https://doi.org/10.1098/rsta.2007.2086.

Rodríguez-Martínez, Rosa E., Eduardo Gabriel Torres-Conde, et Eric Jordán-Dahlgren. « Pelagic Sargassum cleanup cost in Mexico ». *Ocean & Coastal Management* 237 (2023): 106542.

Saffache, Pascal, et Yoann Pelis. « L'élévation du niveau de la mer menacerait-elle le littoral de la Martinique? L'exemple de la commune du Prêcheur ». *Études caribéennes*, nº 55 (2023). https://journals.openedition.org/etudescaribeennes/27346.

Salter, Michael A., Rosa E. Rodríguez-Martínez, Lorenzo Álvarez-Filip, Eric Jordán-Dahlgren, et Chris T. Perry. « Pelagic Sargassum as an emerging vector of high rate carbonate sediment import to tropical Atlantic coastlines ». *Global and Planetary Change* 195 (2020): 103332.

Schleupner, Christine. « Evaluation of coastal squeeze and its consequences for the Caribbean island Martinique ». *Ocean & Coastal Management* 51, nº 5 (2008): 383-90.

SDAGE. « L'impact du changement climatique dans le domaine de l'eau sur le bassin Martinique », 2016.

———. « SDAGE du district hydrographique comprenant la Guadeloupe et Saint-Martin 2022-2027 », 2021.

Smetacek, Victor, et Adriana Zingone. « Green and golden seaweed tides on the rise ». *Nature* 504, nº 7478 (2013): 84-88.

Spencer, Andrew. « Climate Change and the Sustainable Development of Tourism Within the Caribbean ». In *Travel and Tourism in the Caribbean*, par Andrew Spencer, 27-46. Cham: Springer International Publishing, 2019. https://doi.org/10.1007/978-3-319-69581-5_2.

Spencer, Nekeisha, et Eric Strobl. « Hurricanes, Climate Change, and Social Welfare: Evidence from the Caribbean ». *Climatic Change* 163, n° 1 (novembre 2020): 337-57. https://doi.org/10.1007/s10584-020-02810-6.

Stephenson, Tannecia S., et Jhordanne J. Jones. « Impacts of climate change on extreme events in the coastal and marine environments of Caribbean Small Island Developing States (SIDS) ». *Caribbean Climate Change Report Card: Science Review* 2017 (2017): 10-22.

Stewart, S. R., et R. Berg. « National Hurricane Center tropical cyclone report ». *National Hurricane Center*, 2017.

Strauss, Benjamin H., Philip M. Orton, Klaus Bittermann, Maya K. Buchanan, Daniel M. Gilford, Robert E. Kopp, Scott Kulp, Chris Massey, Hans de Moel, et Sergey Vinogradov. « Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change ». *Nature communications* 12, n° 1 (2021): 2720.

Strobl, Eric. « The economic growth impact of hurricanes: Evidence from US coastal counties ». *Review of Economics and Statistics* 93, n° 2 (2011): 575-89.

———. « The economic growth impact of natural disasters in developing countries: Evidence from hurricane strikes in the Central American and Caribbean regions ». *Journal of Development economics* 97, n° 1 (2012): 130-41.

Thomas, Adelle, et Lisa Benjamin. « Perceptions of Climate Change Risk in The Bahamas ». *Journal of Environmental Studies and Sciences* 8, n° 1 (mars 2018): 63-72. https://doi.org/10.1007/s13412-017-0429-6.

Thompson, T. M., B. R. Young, et S. Baroutian. « Pelagic Sargassum for energy and fertiliser production in the Caribbean: A case study on Barbados ». *Renewable and Sustainable Energy Reviews* 118 (2020): 109564.

United Nations Environment Programme. « , Marine and Coastal Ecosystems and Human Well-Being: A Synthesis Report Based on the Findings of the Millennium Ecosystem Assessment ». Nairobi, 2006.

Webster, P. J., G. J. Holland, J. A. Curry, et H.-R. Chang. « Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment ». *Science* 309, n° 5742 (16 septembre 2005): 1844-46. https://doi.org/10.1126/science.1116448.

Ye, Mengqi, Jidong Wu, Cailin Wang, et Xin He. « Historical and future changes in asset value and GDP in areas exposed to tropical cyclones in China ». *Weather, Climate, and Society* 11, n° 2 (2019): 307-19.