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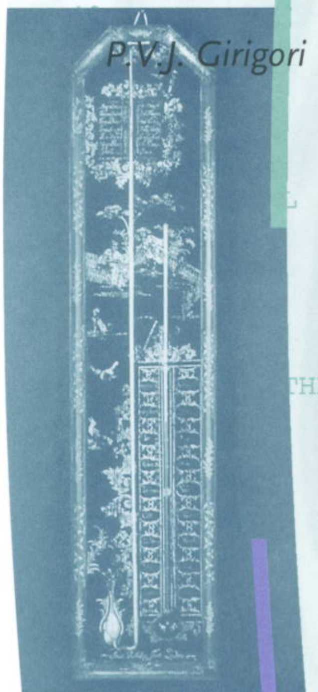
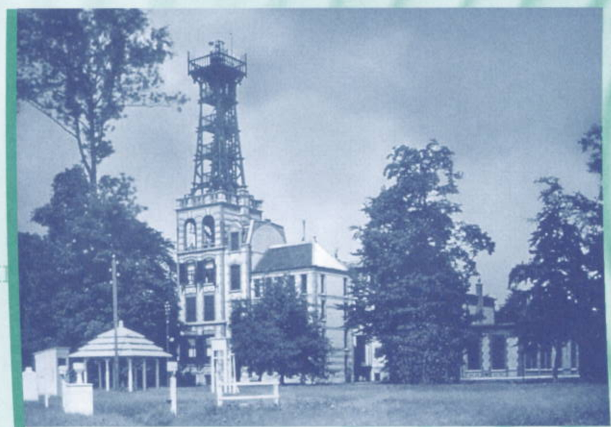
HISKLIM 10

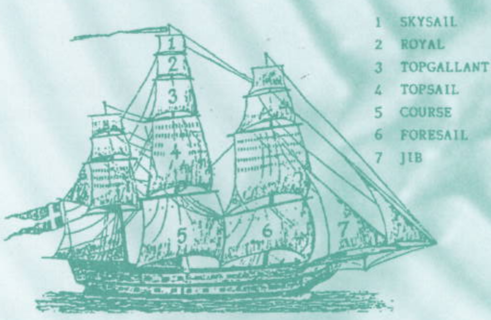
KNMI

Report on meteorological observations at Willemstad, Curaçao, during the period 1910 - 1946

P.V.J. Girigori







De Bilt, 2009

Koninklijk Nederlands Meteorologisch Instituut

KNMI-memorandum

HISKLIM-10

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The KNMI-program HISKLIM aims at making historical land and sea climate data from Dutch sources physically accessible, with the highest possible time resolution and quality. The program started in 2000 and will run 5 to 10 years.

HISKLIM-1	Het KNMI-programma HISKLIM (HIStorisch KLIMaat) / T. Brandsma, F.B. Koek, H. Wallbrink en G.P. Können. (also KNMI-publication 191)
HISKLIM-2	Gang van zaken 1940-48 rond de 20.000 zoekgeraakte scheepsjournalen / H. Wallbrink en F.B. Koek. (also KNMI-publication 192)
HISKLIM-3	Historische maritieme winsdschalen tot 1947 / H. Wallbrink en F.B. Koek. (Memorandum)
HISKLIM-4	Onbekende weersymbolen in oude Extract-Journalen (1826-1865). / H. Wallbrink en F.B. Koek. (Memorandum)
HISKLIM-5	CLIWOC, Multilingual Meteorological Dictionary; an English-Spanish-Dutch-French dictionary of wind force terms used by mariners from 1750-1850 (also KNMI-publication 205)
HISKLIM-6	DIGISTAD (DIGitaliseren STADswaterkantoor). H.W. Riepma. (Memorandum)
HISKLIM-7	Parallel air temperature measurements at the KNMI-terrain in De Bilt (the Netherlands) May 2003–April 2005, Interim report. / T. Brandsma. (also KNMI-publication 207)
HISKLIM-8	Hisklim COADS, Final report. / H. Wallbrink and F. Koek. (also KNMI-publication 210)
HISKLIM-9	DIGISTAD, Disclosure of the hourly meteorological observations of the Amsterdam City Water Office 1784-1963, Final report. / H. Wallbrink and T. Brandsma. (also KNMI-publication 220)

Report on meteorological observations at Willemstad, Curaçao, during the period 1910-1946

P.V.J. Girigori

July 3, 2009

Contents

Introduction

In an effort to gain some experience in doing climatological research a project has been set up to analyze the meteorological data from Willemstad, Curaçao, for the period 1910-1946. This set of data has recently been digitized by the Royal Netherlands Meteorological Institute, KNMI. It contains daily measurements with a frequency of twice, but more often 3 times a day, of different meteorological parameters.

Curaçao is the largest island among the islands that comprise the Netherlands Antilles. It is situated in the Caribbean sea, off the coast of Venezuela at 12° N.L. 68° W.L. Though the island is very close to the equator it has an semi-arid climate, which is not expected at these latitudes. The cause of this arid climate has been attributed to a ridge corresponding to the Bermuda high, which reaches far to the south-west. However also of influence was postulated an area of cold surface water, welling up from deeper oceanic layers. This area of cold sea surface temperature stretches from Santa Martha, Colombia in the west to the isle of Margarita in the east[1]. A north-easthern wind is being maintained throughout the year, making the tropical temperatures of averaged 27 °C more bearable.

The goal of this project was to

- Make a compilation of the metadata for the meteorological observatories at Curaçao.
- Analyze the available data for the temperature and daily precipitation amount.
- Calculation of some extreme temperature and precipitation indices.

[1] It was argued that the conditions to the welling up of this cold deeper layer water is favorable in this area, for the coastline turns to the west beyond Trinidad, and consequently guides the south equatorial current away from the continent.

This paper is structured as follows. An overview of the compiled metadata for the several locations of the meteorological observatory is given in section 1, followed by section 2, which gives a summary of the available data. Section 3 discuses the results for the different analyses. Conclusions and further discussions are given in section 4 and section 5 respectively.

1 Metadata

With the recent digitalization of the meteorological data from Willemstad, Curacao, by the Royal Netherlands Meteorological Institute KNMI it is now possible to conduct climatological research over the period 1910-1946. However to be able to interpret this data accurately it is necessary to have some knowledge of the instruments, measurement practice, and the measurement locations. This is necessary for interruption of the meteorological recordings, difference in the time at which the measurements are being conducted, moving of the observatory and uncertainties in the corrections applied on the readings, can make the series loose its homogeneity and therefore become less accurate to conduct meticulous calculations. In this chapter an overview is given of the different locations and the setup of the instruments.

1.1 Willemstad

The first records of organized meteorological observations on the island of Curacao were conducted in 1894 under the supervision of the Department of Public Works (*"Dienst Openbare Werken"*). The observations were made at the fortress Fort Amsterdam (12° 6" N.L. 68° 57" W.L.), located on the eastern far end of the harbor entrance of the St. Ann bay (see figure 1). This site is known as the Punda-side (formerly known as Punta, de Punt or Nederlandsche zijde) of Willemstad. Fort Amsterdam is irregularly shaped, and consists of four bastions which are separated by 250 m of battery wall, except for the southern battery which is somewhat longer. The battery walls are about 3.2 m high and gently slope upwards. They are made out of plastered limestone, with a rampart, consisting of narrow holes for firing purposes, built atop. The fortress is surrounded along the southwest by the Waterfort, which is basically a battery wall with underneath it a bomb shelter. Along the northeast it is surrounded by a settlement consisting of houses, office buildings, store- and warehouses up to 3 storeys high.

The observed and measured parameters were the dry - and wet bulb temperature, the maximum and minimum temperature, the pressure, wind velocity and direction, and the amount of precipitation. These observations were conducted 3 times a day at 8, 14, and 18 LT[2]. The instruments were situated on the battery wall and consisted of a barometer, 4 thermometers and a rain gauge. The wind velocity was estimated by an observer in Beaufort-scale. Concerning the wind direction no records of instruments used in this period were found. The thermometers were placed in 2 separate wooden slatted screens, with a double rooftop. The wooden screens were painted white and placed on 4 wooden pools. Table 1 shows some details of the instruments[3] .

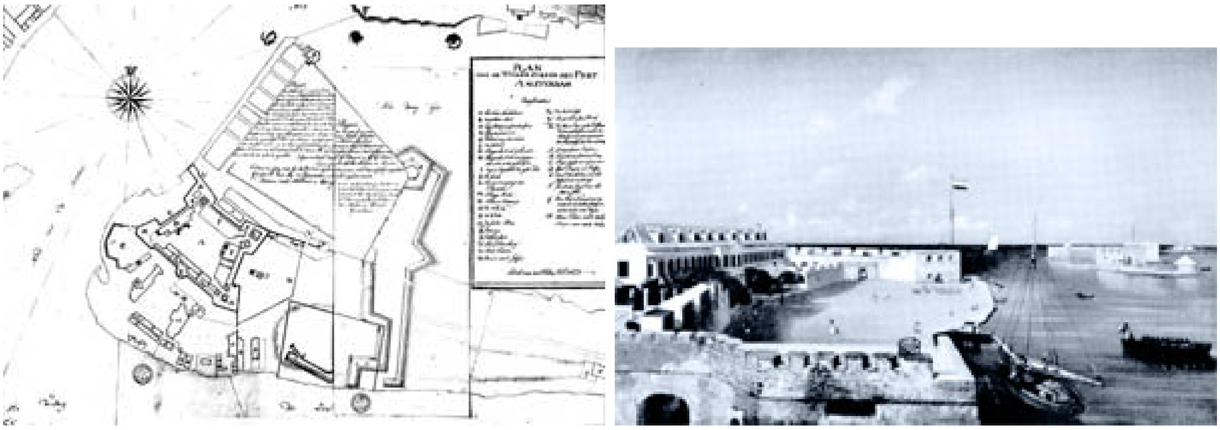
In June 1921 the meteorological station, was moved to a new location, namely plantation Cas Chikitu (also written as Caas Chikitoe and Cas Chiquito), situated northwest of Willemstad somewhat more inland along the Schottegat (see figure 2). This new station was situated on the Otrobanda-side (Overkant or Spaanse zijde). The observations were still being conducted 3

[2] Curacao is situated in the Atlantic Time zone. For measurements conducted before 1 January 1965 local time (LT) corresponds to GMT-LT= 4 h 30 min. After 1 January 1965 GMT-LT=4 h.

[3] The corrections for the thermometers are for certain valid from 1910 to march 1917.

Tab. 1: Instruments and their properties.

Instrument		Brand	Correction	First employed	Height
Barometer		W.C. Olland Utrecht	-0.5 mm Hg	-	9.90 m abv sealvl
Thermometer	Dry	W.C. Olland Utrecht	-0.4 °C	-	9.45 m abv grnd
	Wet	W.C. Olland Utrecht	0°C	-	9.45 m abv grnd
	Max	P.T.R.	0 °C	May 1908	9.45 m abv grnd
	Min	P.T.R.	-0.1($T > 30°$)C	May 1908	9.45 m abv grnd
Rain gauge		R. Feuss, system Hellman Feuss	-	Dec 1904	9.45 m abv grnd



(a) **(b)**

Fig. 1: Map of Fort Amsterdam (a), with a drawing of the fortress dated 1885 (b).

times a day at 8, 14 and 18 (19) LT. No records could be found about the layout and the types of instruments used at this new station. However there are strong indicatons that these instruments formerly belonged to the U.S. Weather Bureau[4] at Curacao, for an old station belonging to this bureau came into the possession of the Governments agriculture department. In this period the observatory was the responsibility of this department. This will especially be the case for the rain gauge, for the records show that measurements of the rainfall were still being conducted during this period at Fort Amsterdam. The corrections on the dry and wet bulb, maximum and minimum temperature thermometers were -0.1, 0, -0.1, +0.2 °C respectively, and valid for the period July 1922 to January 1928. Also worthy of mentioning in this period is the fact that after 1926 the wind velocity was being measured (in mph) rather than estimated by an observer. However no records of an instrument were found.

On the 22nd of February 1928 the observatory was moved to Fort Amsterdam for a period of 6 years, and the instruments again took their old spot on the battery wall surrounded by buildings. The barometer was placed in a screen 6.7 m above sea level, and the thermometers, of brand J. Green New York, were placed in their old screen, but this time at 1.15 m above the battery wall. Furthermore the rain gauge was placed with its upper rim 10.3 m above the ground.

[4] The U.S. Weather Bureau at Curacao conducted meteorological observations during 1903 up to July 1921. This survey was conducted in order to gain data for the early hurricane warning system.

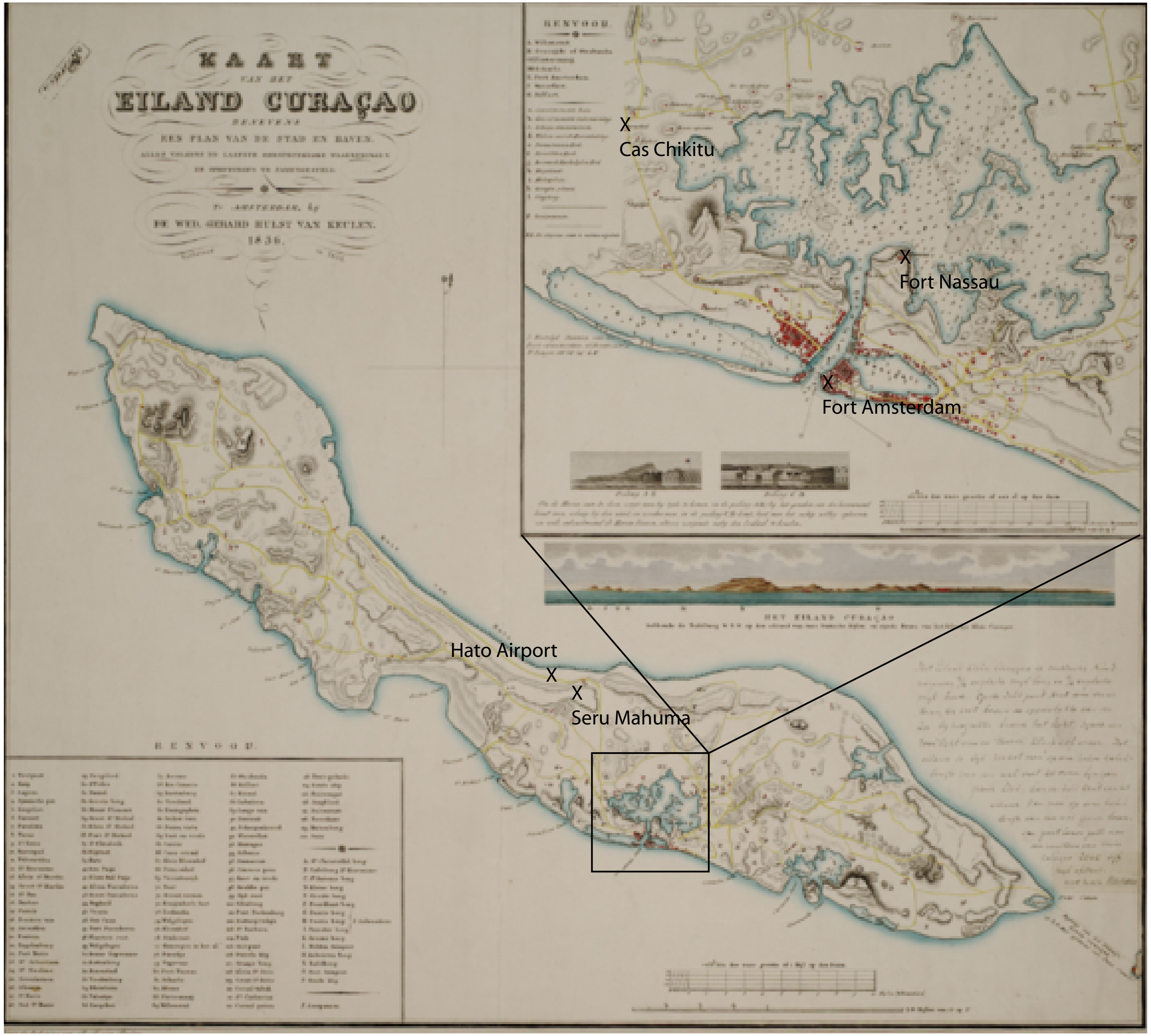
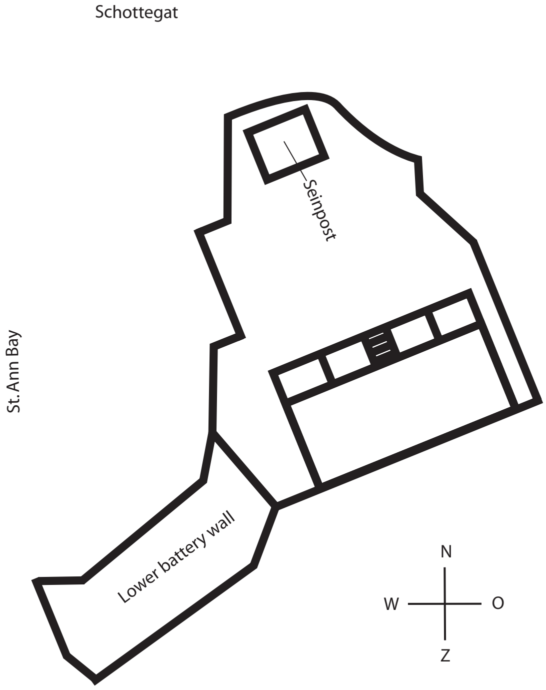


Fig. 2: A map of Curaçao with the different locations of the observatory (given by the X's and their names). The index shows the Willemstad area.

After this brief period at Fort Amsterdam the observatory came under the supervision of the head of the harbor office, and was therefore moved to a new location. Starting the 1st of March 1933 the observatory was now located 1.5 km to the north of Willemstad at Fort Nassau (12° 7" N.L. 68° 56" W.L.), also know as Fort Republiek). Fort Nassau (figure 3) is located 68.3 m above sea level on top of a ridge, the Siblica ridge, belonging to the Scharloo district. The fortress, made of plastered limestone, has an elevated rectangular platform for the artillery deployment which is connected in the southwestern to a lower laying battery. The observations were conducted at 8, 13 (14), and 18 LT. The instruments used at this new location were moved from Fort Amsterdam to this new location, where they were put in an environment free of surrounding buildings. The barometer however was moved to the harbor office and placed 7.2 m above sea level.

(a)



(b)

Fig. 3: South-western battery wall of Fort Nassau(a), and a schematic view of the fortress (b).

1.2 Hato

In 1946 the meteorological service was extended with a new observatory at the Dr. A. Plesman airport (12° 1" N.L. 68° 58" W.L also known as Hato airport), located 8 m above sea level (Fig. 4). The buildings were located on a 1 km wide lower terrace at the northern shore (110-290 oriented) of the island, surrounded in southerly direction by a 60 m high terrace. At first this new observatory was located in the former North-American military observatory, awaiting the finalization of the new observatory building at the airport. In June of 1946 the new building was inaugurated and the observations started there. The new observatory had the purpose of measuring hourly ground level meteorological data and 4 hourly upper air height winds, of interest for the aviation. The observations at Fort Nassau were still being maintained, but at slightly different hours, namely 7.30, 13.30 and 19.30 LT. It seems as if the observations at Fort Nassau were terminated at the end of 1946.

The instruments used at this new observatory were adopted from the North-American military observatory, where they were being employed since 1941 by the American air-force for aviation purposes. These were put due to the lack of open space, c.q. stretch of grass in the vicinity, on top of the observatory building. The ventilated thermometer screen, containing two mercury thermometers, together with the rain gauge were located at 12 m above the ground. The anemometer was located on top of the air traffic control tower at 21 m above the ground. These apparatus were all non-registering. The barometer was placed at 15.6 m above sea level inside the observatory. In 1961 a second thermometer screen containing 2 resistance thermometers together with a second rain gauge, were placed about 100m distance from the centre of the runway. This new location was about 300 m from the original thermometer screen and rain gauge. These new apparatus were self-registering. The observations with the old instruments were still being maintained for calibration purposes. Both the anemometer and the barometer remained at their location above the control tower, 15.6 m above sea level respectively. In 1961 a new meteorological parameter was also added to the observations, namely the total hours of sunshine. The measurements of this parameter were being conducted with a Campbell-Stokes recorder, which was located on top of the observatory building. In 1964 the thermometer screen and the rain gauge, located near the centre of the runway, were moved to a new location 400 m from the coast and 120 m from the centre line of the runway. The top rim of the rain gauge[5] was now located at 100 cm above the ground. A continuous registration of the dry- and wet-bulb temperature was now possible and was being conducted with a Honeywell-recorder. In February 1964 both the anemometer and the barometer were moved from their original location. The anemometer was mounted at a distance of 170 m from the centre line of the runway, near the thermometer screen, on a 10 m high pole. The barometer was placed in a new wing of the observatory at 17.4 m above sea level. From 1966 onwards the task of measuring the amount of artificial radioactivity was bestowed upon the meteorological service. The measurements were being conducted on top of the roof of the observatory.

1.3 Seru Mahuma

In 1976 the observatory was moved from the airport to a new site in the building of the Department for Aviation at Seru Mahuma. This new location had an elevation of about 60 m above sea level, and was located roughly 75 m away from the Hato airport on top of the southern terrace. It was surrounded by local vegetation, namely cacti and different types of thorn-bushes, with the sole and nearest building, the new meteorological observatory building. The instruments were placed in an instrument garden, situated at approximately 20 m away in westerly direction from the main building, where the local vegetation was cleared from their surroundings, and a wired fence was placed to keep animals away. The exact setup of the instruments could not be found, but are presumed to be available in hardcopy in the meteorological summaries *"Statstiek van de meteorologische waarnemingen in de Nederlandse Antillen, volume 21-29"*, and afterwards "*Overzicht weersgesteldheid 1981-1999*". In 2007, after the renovation of the building, the instruments were put on the rooftop of the observatory.

[5] This gauge was made self-registering in 1967.

Fig. 4: The Dr. Plesmann (Hato) airport, with in the background on the hilltops the building of the Department of aviation, c.q. the location of the meteorological observatory from 1976 and forth.

2 Data Availability

The measuring and recording of meteorological data at Curaçao dates, as mentioned before, back to the late 19th century. Since then meteorological data has been recorded up to present with little interruption, hence records of 116 years. To be able to conduct further research in the future it is of great importance to know which part of the meteorological data is available, whether it is in hardcopy or digitally available, and where it can be found. This section deals with all these questions first and foremost for the meteorological data belonging to Willemstad, but also any other type of meteorological data taken by different other institutes throughout the years. The meteorological data is available in surveys of monthly/yearly mean values, but also in unprocessed data, c.q. daily records of the observations. Subjected to the goal of future research, daily records or merely monthly surveys will be of interest.

2.1 Surveys

The early meteorological data from Willemstad has been assembled and documented by the Royal Netherlands Meteorological Institute in a series of surveys from 1905 up to 1952. However these surveys don't contain the daily measurements, but rather the monthly and yearly average values of the different meteorological parameters. These measured meteorological parameters consisted of the pressure, wet, dry bulb, maximum, and minimum temperature, relative humidity, wind velocity and -direction, cloudiness, amount of precipitation and special weather phenomena. These surveys, *"Meteorologische waarnemingen, gedaan op de meteorologische stations in de koloniën Suriname en Curaçao"*, contain also monthly averages of daily measurements of the different parameters for the different measuring times. From 1953 up to 1980 the statistics bureau of the Netherlands Antilles took over the task of publishing the meteorological data in monthly and yearly averages, together with a description of the metadata, for the Netherlands Antilles, thus Curaçao included. They were published in the *"Statistiek* *van de meteorologische waarnemingen in de Nederlandse Antillen, volume 1-29"*. The surveys from the period 1910-1972 are in hardcopy available at the KNMI, and also in digital copies (1919-1972) at *http://docs.lib.noaa.gov/rescue/data_rescue_netherlands_antilles.html*. The meteorological data from 1981 up to 1999 were published in *"Overzicht weergesteldheid"*. These are available at the Mongui Maduro Library at Curaçao. The annual surveys from 2000 to present are available online at *www.meteo.an/reports*.

2.2 Daily measurement records

The daily records of the meteorological observations can be subdivided in two groups, namely the Willemstad area and the Hato area. This subdivision is due to the geographical locations of the meteorological observatory throughout the years. The Willemstad area comprises the observatories at Fort Amsterdam, Cas Chikitu and Fort Nassau. These are all located near the Schottegat on the south side of the island. The Hato area, comprising airport Hato and Seru Mahuma, are located on the north side of the island.

2.2.1 Willemstad area

The daily records for the meteorological data have been recorded by several institutes throughout the period the meteorological observations were conducted. For the period 1884-1909 parts or complete series are missing. The most complete series are from 1886 (jan-oct), 1900 (feb-dec), 1901 (jan-dec), 1902 (jan-apr; jul-dec), and 1903 (jan-apr; aug-dec). These are all available in hardcopy at the KNMI. For the periods 1894-1895, 1897-1899, and 1904-1908 no hardcopies of daily meteorological data could be found. For 1909 a very short record from 5 dec to 12 dec is also available in hardcopy at the KNMI. A rather complete series for the period 1910 to 1946 is available at the KNMI in both hardcopy and in their database. Missing in this series is a short period from 3 to 7 november for 1918. During these days no measurements have been conducted. Furthermore for the year 1927 the period sept-dec is missing. In this period also no measurements have been conducted.

The U.S. Weather Bureau also conducted daily measurements of different meteorological parameters at Curaçao during the period 1908-1921. The records available in this period at the KNMI do not correspond to these observations. These observations were conducted at a different location and with different frequencies. The climate summary of the Netherlands West-Indies by C. Braak (1933) mentions the preservation of parts of these observations, but no records could be found of their existence today.

2.2.2 Hato area

The meteorological records from the Hato area are believed to be located at the meteorological services of the Netherlands Antilles (MDNA&A)in hardcopies, and should cover the years from 1946 to present. However till the date of this writing no confirmation of this fact was received from the met. service.

Daily measurements of different meteorological parameters have also been conducted during the period 1941-1946 by the U.S. air force. These data should also be present at the MDNA&A.

3 Results

The second part of this project consisted of the analysis of the climatological data set for the period 1910-1946. The parameters of interest to this project were the temperature and the precipitation, for these parameters give a global view on the climate of Willemstad, and its changes.

Different studies have been conducted concerning the warming of the earth's atmosphere. These studies were mainly focused on the computation of long-term monthly averages. In the early 90's this focus shifted to the long-term monthly maximum and minimum temperature. However this approach was crippled, for by averaging over a range one looses the information on the extremes. Hence an average may hardly show any long-term changes, whereas the day to day data show an increase in both maxima and minima occurrence, which somewhat cancel each other out. To take these problems into account and still get a good view on the climate change, extreme indices (EI) were introduced. These extreme indices indicate the changes in the weather extremes. A complete overview of the computation of the extreme indices can be found on $//http : www.cccma.seoss.uvic.ca/ETCCDMI/$ under the header indices.

During this part of the project the monthly mean and annual mean values were calculated, together with several EI. A small selection was made for the calculation of the EI, since not all the indices given on the above mentioned website are useful for the Willemstad area. In this section the method and the results obtained from these analysis are discussed.

3.1 Method

The daily mean temperatures are calculated by averaging over the daily maximum and the minimum temperatures. The monthly mean temperature can then be computed by averaging over the daily mean temperatures in a month. The annual mean temperature over the period 1910-1946 can be calculated by averaging over the monthly mean temperatures for the different years. Hence,

$$\begin{aligned} \overline{\mathrm{T_{jk}}} &= \frac{1}{N}\sum_{i=1}^{N}\frac{(\mathrm{Tmax})_{\mathrm{ijk}}+(\mathrm{Tmin})_{\mathrm{ijk}}}{2}, \\ \overline{\mathrm{T_{j}}} &= \frac{\sum_{k=1}^{M}\overline{\mathrm{T_{jk}}}}{M}, \end{aligned} \tag{1}$$

with $\overline{\mathrm{T_{jk}}}$ the mean temperature in month j and year k, $\mathrm{Tmax_{ijk}}(\mathrm{Tmin_{ijk}})$ the maximum(minimum) temperature on day i, month j, year k, N the number of days in month j. $\overline{\mathrm{T_j}}$ is the mean temperature over the period 1910-1946, and M the number of years with $\overline{\mathrm{T_{ij}}} \neq NA$. This type of averaging was chosen instead of the mean for the 24-hours' period, for the dry bulb temperature has been measured at different times during this period. Hence years where the temperatures have been measured at a period in time close to the time at which the highest temperature of the day is achieved, would render higher averages than those where this was not the case. This introduces a bias to the results, and thus the conclusions will not be unambiguous. On the other hand the measuring time for the maximum and minimum temperature are not known, but there are some indications that they were conducted during the early morning, concurrently with the first observation of the day.

The monthly mean precipitation sum, $\overline{\mathrm{p_j}}$, was calculated by summing over the daily precipitation value, and averaging over the period 1910-1946, namely

$$\begin{aligned} \overline{\mathrm{p_{jk}}} &= \sum_{i=1}^{N} \mathrm{p_{ijk}}, \\ \overline{\mathrm{p_j}} &= \frac{\sum_{k=1}^{M} \overline{\mathrm{p_{jk}}}}{M}, \end{aligned} \tag{2}$$

with $\overline{\mathrm{p_{ijk}}}$, the daily precipitation value on day i, month j, year k, N the number of days in month j, $\overline{\mathrm{p_{jk}}}$ the precipitation sum of month j in year k. Many data were missing from the precipitation data set, for the observers were often inclined to neglect the recording of days with zero precipitation. This introduced biases to the data set, since it is not always clear whether no measurements have been conducted or whether this day had a precipitation value equal to zero. This problem was partly solved by comparing the monthly sum values of the daily data with the surveys published in earlier years. Another problem with the precipitation data was the fact that at a certain point the observers started to record the daily precipitation amount in hundredths instead of tenths of mm. This was the case for the periods 1922/01/01-1924/01/31, 1924/04/01-1925/04/30, 1925/080/1-1926/02/28. This problem was easily solved with a simple algorithm.

The computed extreme indices of interest for the Willemstad data, together with their description are given in table 2. The data for the computation of the EI consisted of the maximum and minimum temperature (in [°C]), and the precipitation data (in [mm]) for the period 1910-1946. The extreme indices were calculated with a program available on *//http : www.cccma.seoss.uvic.ca/ETCCDMI/software.html*, supported by the free software for statistical analysis R. The data provided was subjected to a wide variety of quality control. These tests include evaluating the data for physically unreasonable values, unreasonably long consecutive occurrence of the same value, times when the daily maximum temperature (TX) was less than the daily minimum (TN) temperature, extreme outliers to the data series, and very long occurrence of zero precipitation data, indicating that missing data were erroneously set to zero. No significant problems with the data set were found. The results from the EI-calculations were plotted and fitted with the least square fit method. Table 2 shows the results for the regression slopes of the EI results.

3.2 Temperature

Figure 5 shows the yearly cycle of the monthly mean temperatures over the period 1910-1946 (blue line), with the monthly mean temperature variability. The mean temperature over this period was 27.4° C, with the highest mean temperature in September (28.8° C) and lowest in January (25.9° C). The increase of the temperature during March and April to a somewhat stable mean temperature in May, June and July can be attributed to the seasonal cycle on the northern hemisphere, hence high temperatures in the northern hemisphere's summer and lower temperatures in its winter. The second increase in the temperature during the fall, reaching the islands' maximum in September, suggests a strong correlation with the sea surface temperature (SST). The SST also reaches its maximum in September, due to the larger warmth capacity of the sea water. Hence the upper layers of the Caribbean sea work apparently as a warmth reservoir for the island.

The monthly mean temperature variability of the data has been computed over the period 1910-1946. The data set for each month contains 37 mean temperatures, except for the months

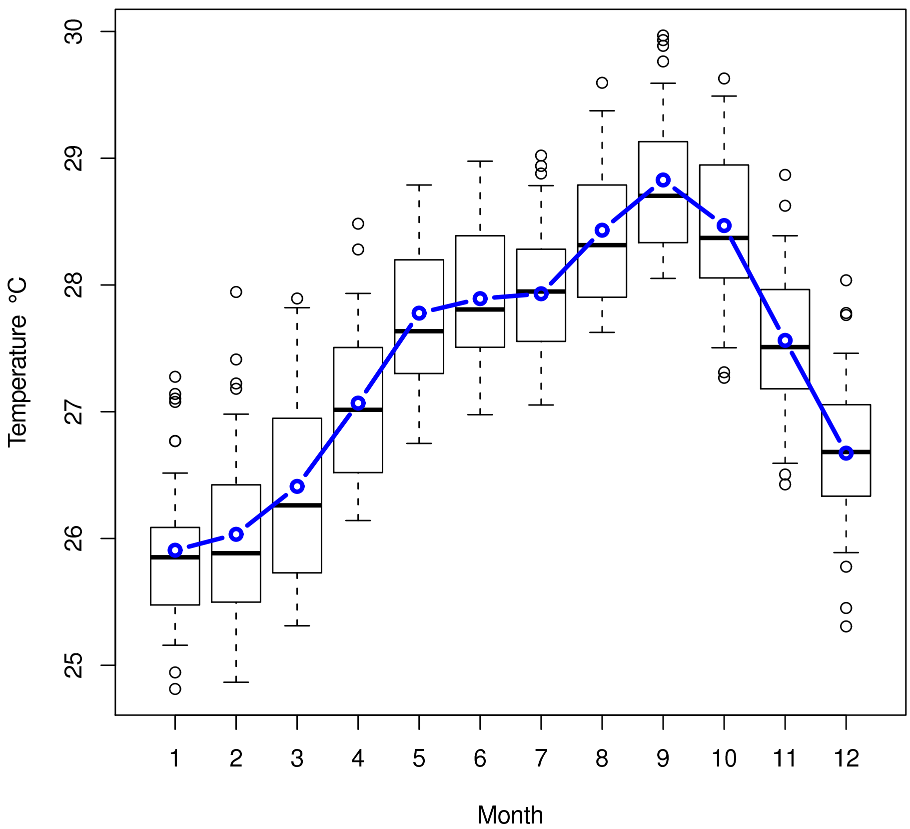


Fig. 5: Yearly cycle of the monthly mean temperatures. The blue line shows the mean temperature over the period 1910-1946. The box plots summarize the monthly mean temperatures for each year in the data set 1910-1946. The open circles show the outliers, whereas the whiskers extend to 0.75 times the interquartile range. For detailed discussion see text in this section.

Sept, Oct, Dec and Nov. The first 3 contain 36 mean temperatures due to the missing observations in 1927, and the second contains 35 data points due to the missing observations in 1918 and 1927 (see section 2.2.1). The box plot whiskers extend to 0.75 times the interquartile range on both ends of the box, and thus coincide approximately to the 90^{th} (upper whisker) and 10^{th} (lower whisker) percentile. The variability of the monthly mean temperature (box plots in fig. 5) show that the mean temperatures obtained from the data set fairly coincide with the medians, hence a small year to year variability of the monthly mean temperature.

3.2.1 Comparison with global climate

Different studies have shown that the global mean temperature has increased over time. A climatological study conducted in 2003 at the KNMI[6] states a total increase from 1860 to 2002 of 0.6 °C, wich corresponds to $4.2\text{x}10^{-3}$ °C/yr. The temperature increase with respect to the global mean temperature over the period 1900-1940, can be estimated at 0.017 °C/yr. Figure 6 shows the lapse of the annual mean temperature for Willemstad, during the period 1910-1946. The mean temperature in Willemstad also shows an increase over this. The regression slope found for this period is 0.02 °C/yr, and is significant at the 99% confidence level.

[6] *De toestand van het klimaat in Nederland 2003*

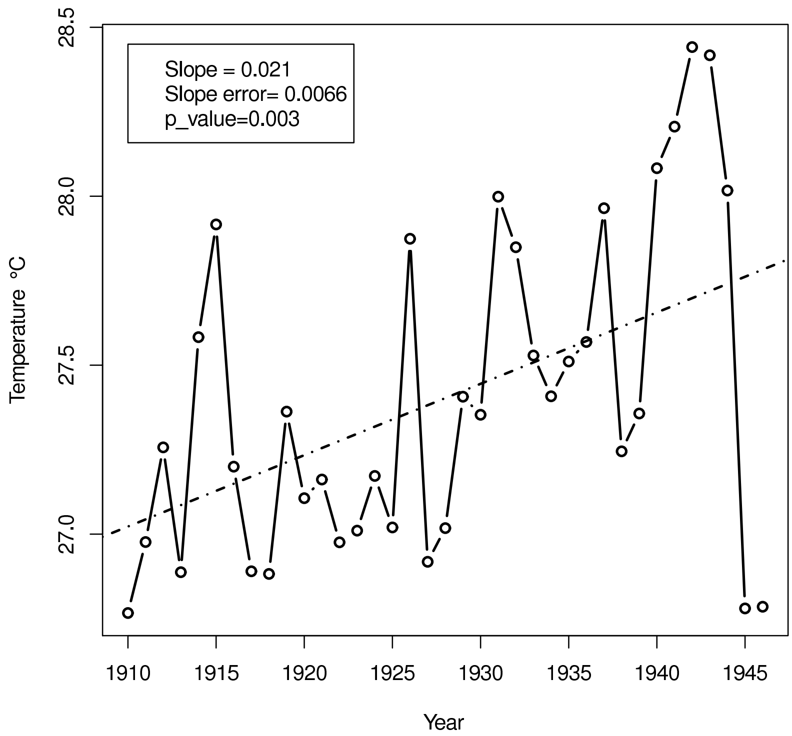


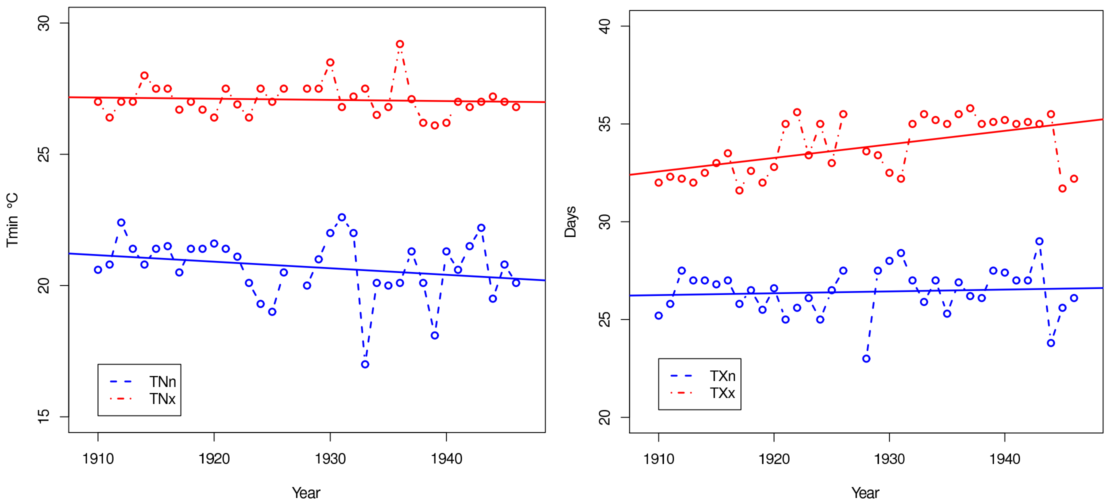
Fig. 6: The temperature lapse over the period 1910-1946. According to this plot the temperature has increased in this period with 0.02±0.0066 °C/yr.

3.2.2 Extreme temperature indices

The results for the annual maximum (red/dashed-dotted line) and minimum (blue/dashed line) value of the daily minimum (a) and maximum (b) temperature are shown in Figure 7. The Annual maximum (minimum) was calculated by taking the highest (lowest) temperature that occurred during a year. Both the annual maximum and minimum of the daily minimum temperature have a negative regression with the years, indicating that the minimum and the maximum of the daily minimum temperature have slightly decreased over this period. The annual maximum and minimum of the daily maximum temperature however show a positive correlation with the time, i.e. an increase over this period. Hence at first glance the daily maximum is increasing while the daily minimum is decreasing. The slope of the regression lines for TNx, TXn, and TNn indices are not significant (see p-values in table 2). The trend in TXx on the other hand the regression is significant at 99% level. Hence the above conclusion, namely an increase of the daily maximum and decrease of daily minimum, is rather disputable for the daily minimum but likely for the increase of the annual maximum of the maximum temperature.

Another method for quantifying the changes in the maximum and minimum temperatures is by calculating the percentage of days in a year with a maximum (minimum) temperature equal or above the 90^{th}, and less or equal to the 10^{th} percentile[7]. Values above the 90^{th} percentile show the extremely high temperatures or equivalent the number of warm days (nights), whereas the values below the 10^{th} percentile give the extreme low temperatures, c.q. the number of cool days (nights). Figure 8 (a) shows the results for the minimum temperature, i.e. night time, and (b) the maximum temperature, i.e. day time. The percentage of cool and warm nights show

[7] The 90^{th} and 10^{th} percentile are determined by assessing the full base period 1910-1946 for each day and calculating the 90^{th} and 10^{th} percentile for each calendar day.



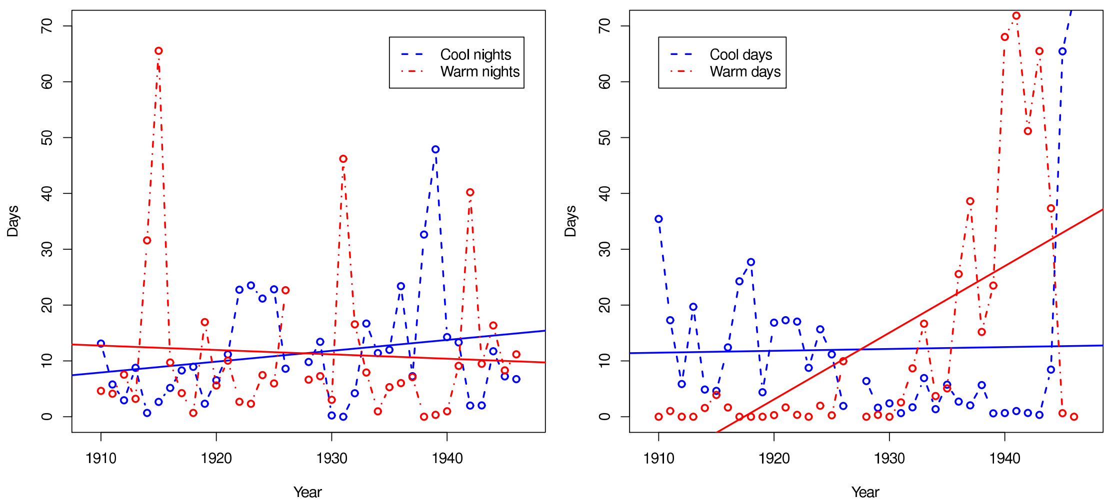
(a) Minimum temperature

(b) Maximum temperature

Fig. 7: Annual maximum (red/dashed-dotted line) and minimum (blue/dashed line) value of daily minimum (a) and maximum (b) temperature.

much variability over the chosen period. According to figure 8 (a) the number of cool nights has increased over the years, whereas the warm nights have slightly decreased. The trends are, however, not significant.

The number of warm days (figure 8 (b)) has increased in time. This is especially the case in the period 1940-1944. Yet the number of cool days has slightly decreased with time, and is not significant. The trend in the number of warm days is significant at the 99% level.



(a) Night

(b) Day

Fig. 8: Percentage of days with the temperature higher or equal to the 90th (red/dashed-dotted line) or lower to the 10th (blue/dashed line) percentile for the night (a) and day (b).

Figure 9 shows the consecutive warm (red/dashed/dotted line) and cold (blue/dashed line)

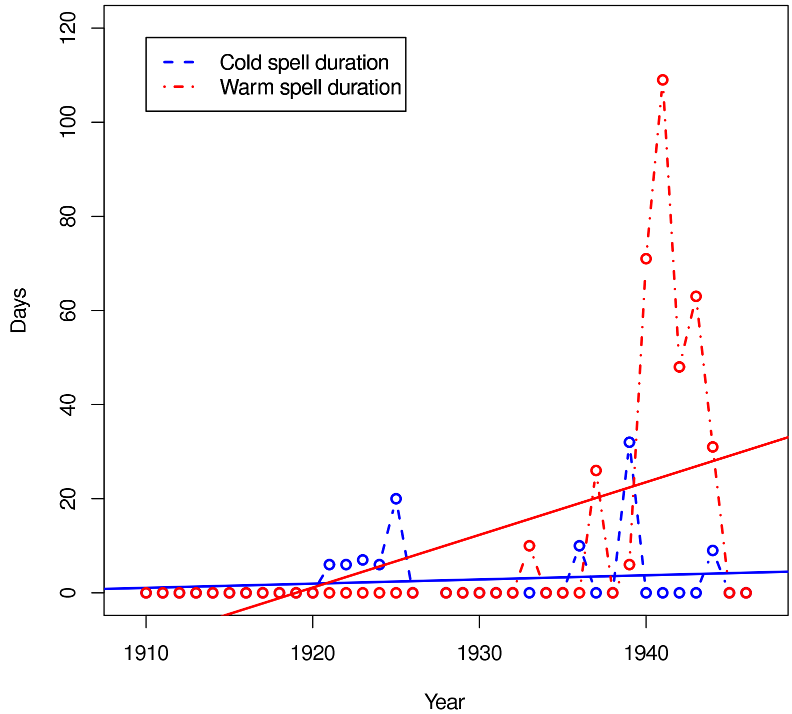


Fig. 9: The consecutive warm (red/dashed/dotted line) and cold (blue/dashed line) spell duration.

spell duration. The cold (warm) spell duration indicator is calculated by the annual count of days with at least 6 consecutive days when TN<10^{th} percentile (TX<90^{th} percentile)[8], hence the correlation with the percentage of cold nights (warm days). The warm spell duration indicator also shows an increase from 1940-1944. The trend is significant at the 99% level. The cold spell duration does not show any significant changes.

3.3 Precipitation

The monthly mean precipitation sum (blue line) is given in figure 10, together with the variability of the precipitation sum (box plots) over the period 1910-1946. The mean annual precipitation sum over the period 1910-1946 was 506.8 mm. The highest annual precipitation sum over this period was measured in 1933 with 1059.4 mm, and the lowest in 1930 with 136.5 mm. The precipitation cycle can be subdivided in three seasons, namely a dry season (Feb-May), a semi-arid season (Jun-Sep), and a wet season (Oct-Jan). The precipitation on the island is mainly produced by convective clouds. The formation pattern of these clouds and the seasonal variation of precipitation can be explained by the global circulation of the earth's atmosphere (fig. 11), and the SST of the southern Caribbean basin. A thermal low is formed during the winter of the northern hemisphere on the South-American continent due to the heating of the continent. This causes the Azores high to take a more northern position, and hence a more easterly oriented airflow towards the island. In the early morning and evening the sea surface temperature will be higher than the surface temperature and hence a continent breeze is present on the island. This continent breeze converges with the easterly airflow on the eastern side of the island. Due to this convergence the air is forced to lift up to its free condensation level, and at a certain point produce precipitation. The heating of the earth's surface during the day will cause the continent breeze to transform into a sea breeze and the cloud formation

[8] TN is the minimum and TX the maximum temperature.

will be shifted to the western side of the island. Figure 12 shows a schematic scheme of the above.

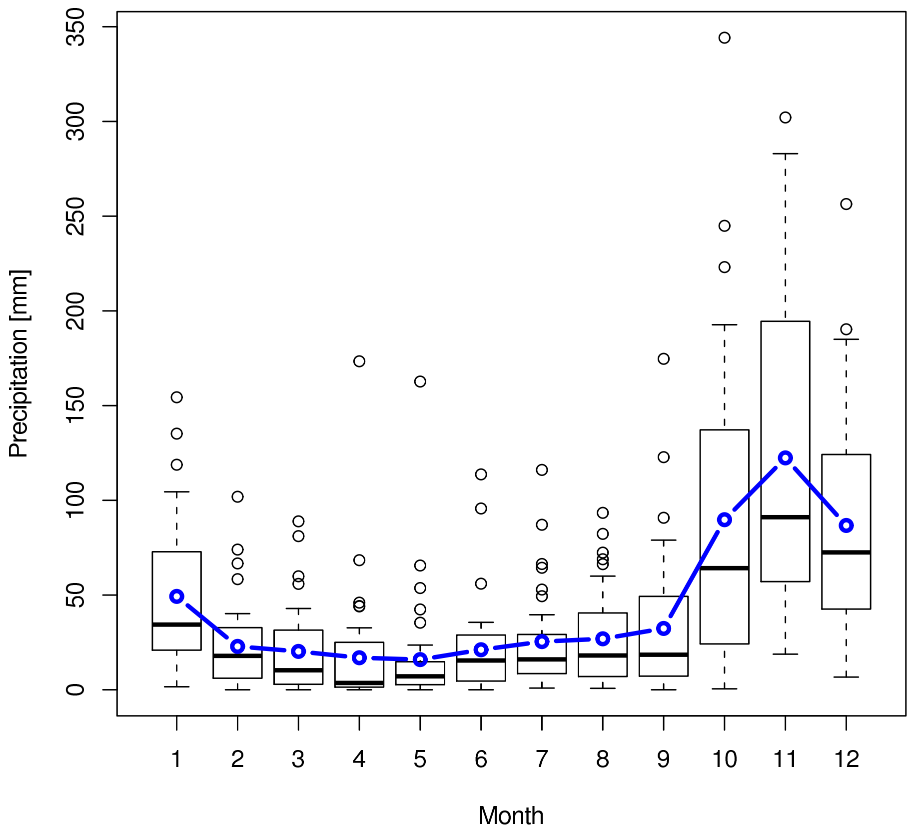
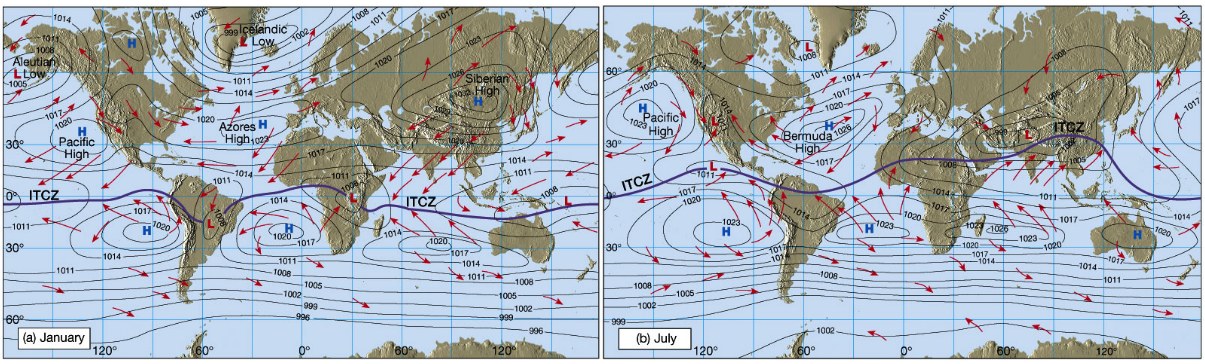


Fig. 10: Yearly cycle of the monthly mean precipitation sum. The blue line shows the mean precipitation sum over the period 1910-1946. The box plots contain the monthly mean precipitation for each year in the data set 1910-1946. The open circles show the outliers, and the whiskers extend to the 90th and 10th percentile. For detailed discussion see text in this section.



(a) **(b)**

Fig. 11: Global circulation of the earth's atmosphere in January and Juli.

During the dry season the equatorial through moves to its most northern position. The Azores high shifts to a more south-westerly position on the Atlantic Ocean, and flows at a certain point over into the Bermuda high. Along the west coast of Mexico a low will be formed.

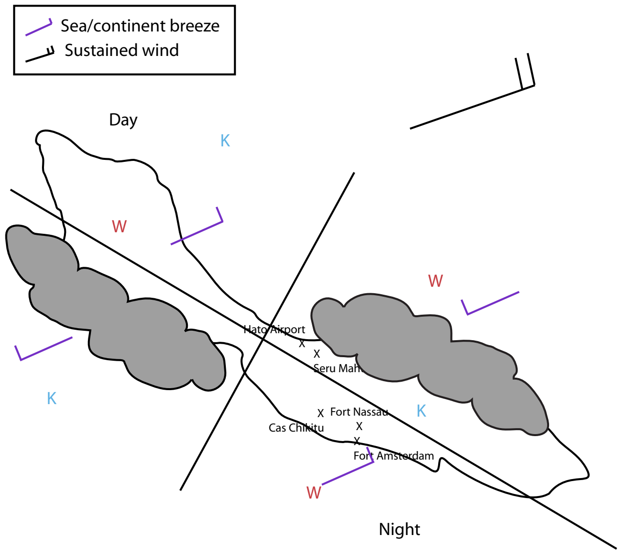


Fig. 12: Cartoon explaining the cloud formation pattern on Curaçao for day and night time. See text for further explanation.

This causes the airflow to back to a more north-easterly direction in the lower parts of the atmosphere and a descending motion of the air mass in the higher layers of the atmosphere, above the island. The convergence of the continent breeze and the sustained wind will still be present, but the upper air will be drier due to the descending motion of the air mass. The convective clouds will therefore have a limited vertical span and will not produce any precipitation. The semi-arid season is caused by the transition from one extreme to the other.

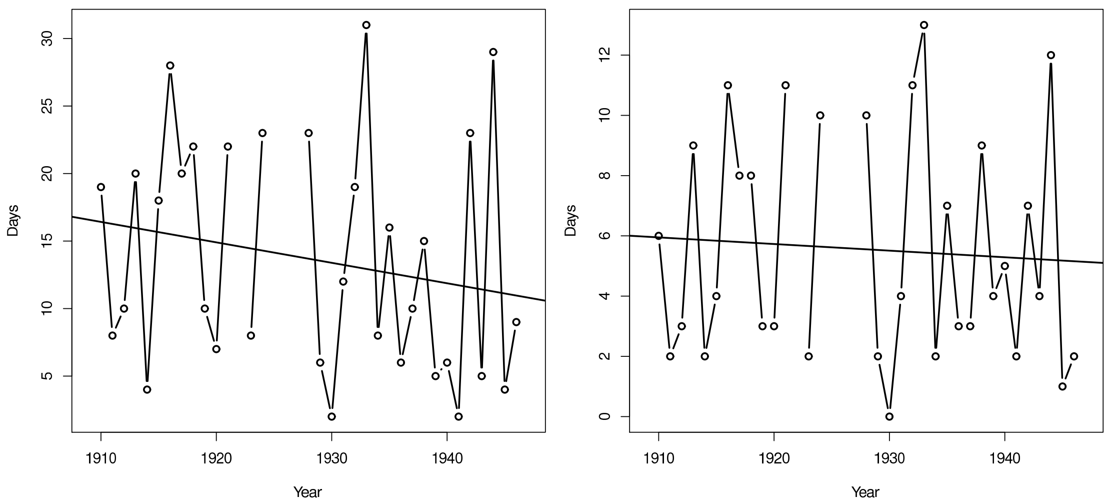
The monthly mean variability has been calculated over the period 1910-1946. However some parts of the precipitation data were missing. This was the case for 1922/04, 1918/11/05-1918/11/08[9], 1925/04, 1925/09-1925/12, 1926/01, 1926/06-1926/12, 1927/09-1927/12[10], and 1928/10. Like for the temperature variability, the box plot whiskers extend to the 90th and 10th percentile. The variability of the monthly precipitation sum shows that the island has a large year to year variation. The monthly precipitation sum is therefore better described by the median than the mean, for the extreme precipitation values have a relatively large effect on the mean. A study on the correlation between El Niño southern oscillation (ENSO) and the precipitation on the island showed a lagged correlation of 4 months. This year to year precipitation variability may be due to the ENSO.

3.3.1 Extreme Precipitation indices

The annual precipitation at Willemstad is dominated by large variability, as discussed in subsection 3.3. This variability is also seen in the results of the indices of precipitation extremes. Figure 13 shows the maximum number of days with daily precipitation amount (RR) $\geq$ 10 mm (a), and $\geq$ 20 mm (b). These indices are strongly related to the number of days with precipitation, for the precipitation at Willemstad is mainly of convective nature. Convective precipitation usually produces large precipitation amounts in a short time, whereas precipitation from

[9] no measurements have been conducted
[10] no measurements have been conducted

stratiform clouds last longer but produce small amounts of precipitation. Both indices show a decreasing trend with time. These trends are, however, not statistically significant, due to the large annual variability of the precipitation.



(a) **(b)**

Fig. 13: Annual count of days when RR≥10mm (a) and when RR≥20mm (b).

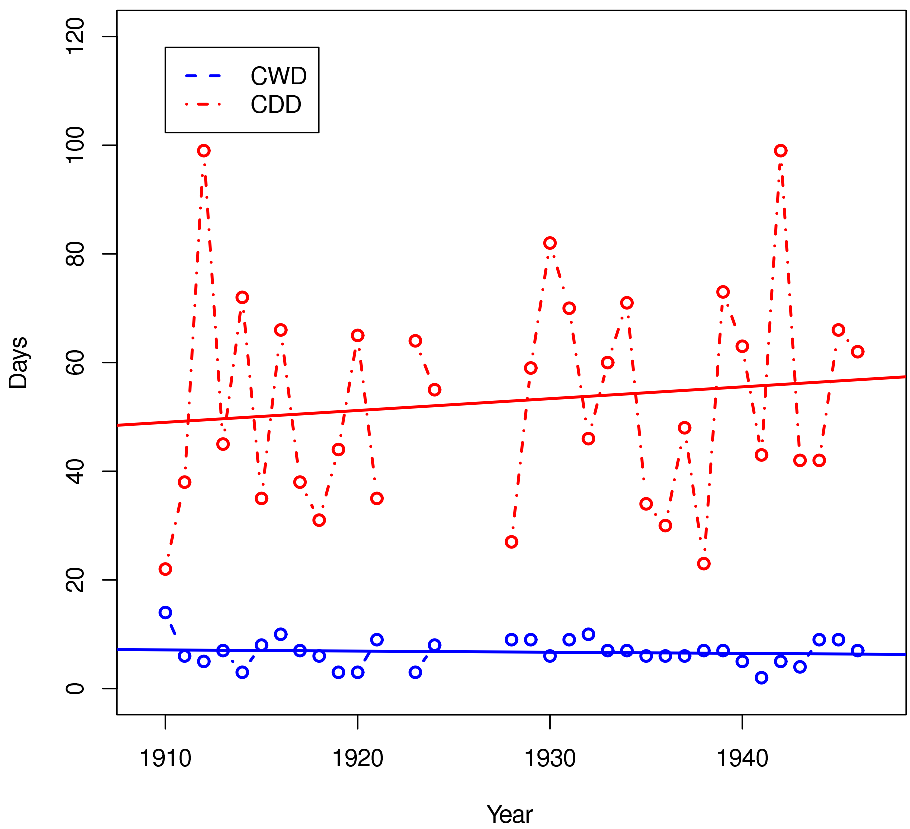
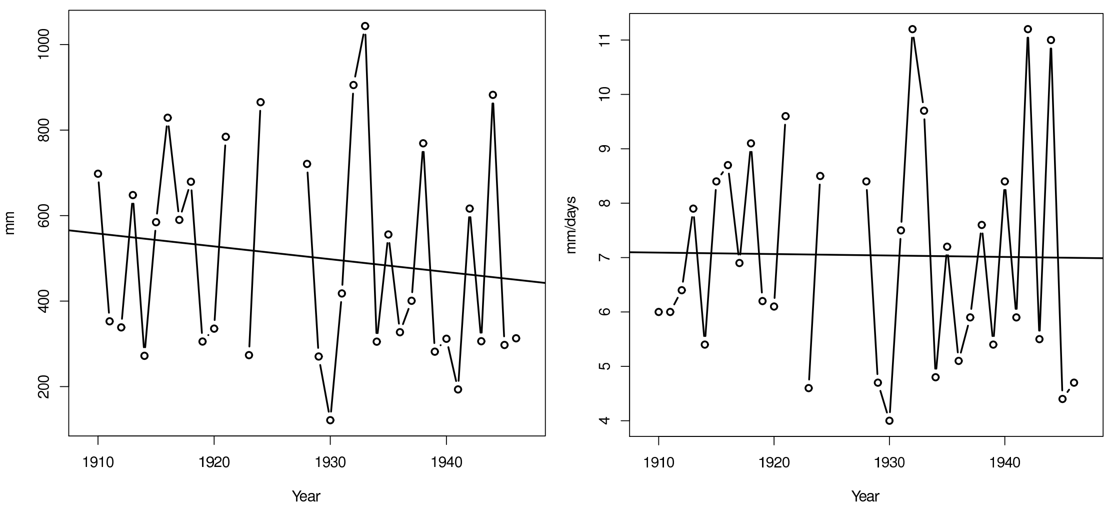


Fig. 14: Maximum number of consecutive days with RR<1 mm (red), and RR≥1 mm (blue)

The annual number of consecutive dry (CDD, red/dashed-dotted line) and wet days (CWD, blue/dashed line) are shown in figure 14. These are calculated by counting the consecutive number of days with RR<1 mm and RR≥1 mm respectively. The annual number of CWD, about 10 days per year, does not vary significantly, and shows a slight decrease over time. The annual count of CDD on the other hand increased over the period 1910-1946. The trend for CDD is, however not significant, due to the large annual precipitation variability.

The results for the annual total wet day precipitation, and the precipitation intensity are given in figure 15 (a) and (b) respectively. The annual precipitation amount was calculated by summing over all the wet days, i.e. days with RR≥1 mm. The precipitation intensity is defined as the annual total precipitation divided by the number of wet days in that year. The annual total wet day precipitation shows a decreasing slope over the period 1910-1946, whereas the precipitation intensity remains stable over this period. This suggests that the decrease in annual total wet day precipitation is rather due to a decrease in the number of wet days (as concluded from figure 13), than the change in precipitation intensity. However these indices are again plagued by the variability of the precipitation at Willemstad, and the results should, therefore, be taken carefully.



(a) Annual total wet-day precipitation

(b) Annual total precipitation divided by the number of days with PRCP≥ 1mm

Fig. 15: Total amount of precipitation (a) and the precipitation intensity (b).

Tab. 2: Extreme indices and linear fitting results.

Indices	Indicator	Unit	Slope	p-value [%]
Temperature related				
TXx	Monthly maximum value of daily maximum temperature	[° C]	0.069±0.019	0.1
TNx	Monthly maximum value of daily minimum temperature	[° C]	-0.004±0.01	64.9
TXn	Monthly minimum value of daily maximum temperature	[° C]	0.009±0.019	61.8
TNn	Monthly minimum value of daily minimum temperature	[° C]	-0.025±0.018	16.7
TN10p	Percentage of days when TN> 10^{th} percentile	[Days]	0.194±0.152	21
TN90p	Percentage of days when TN> 90^{th} percentile	[Days]	-0.078±0.218	72.2
TX10p	Percentage of days when TX> 10^{th} percentile	[Days]	0.033±0.261	89.9
TX90p	Percentage of days when TX> 90^{th} percentile	[Days]	1.194±0.26	0
WSDI	Warm spell duration indicator	[Days]	1.12±0.334	0.2
CSDI	Cold spell duration indicator	[Days]	0.089±0.101	38.5
Precipitation related				
R10	Number of heavy precipitation days	[Days]	-0.151±0.131	25.5
R20	Number of very heavy precipitation days	[Days]	-0.022±0.059	71.1
CDD	Consecutive dry days with $RR < 1mm$	[Days]	0.218±0.314	49.3
CWD	Consecutive wet days with $RR \geq 1mm$	[Days]	-0.021±0.04	59.6
PRCPTOT	Annual total PRCP in wet days ($RR \geq 1mm$)	[mm]	-3±3.861	44.3
SDII	Precipitation intensity	[mm/days]	-0.003±0.032	93.7

4 Discussion and Conclusion

The focus of this analysis was to gain some experience in doing climatological research by studying the climatology of Willemstad. The first part of this analysis consisted of describing the metadata and the data surveys for Willemstad over the complete period of meteorological observations, hence 1884 to present. After assembling the metadata and data survey information the mean monthly temperature and mean monthly precipitation sum were calculated from the available data set, which spanned the period 1910-1946. The extreme temperature and precipitation indices were also calculated using the R-software available at //http:www.cccma.seoss.uvic.ca/ETCCDMI/. The indices of interest for Willemstad with respect to the temperature were TXx, TXn, TNx, TNn, TN(TX)10p, TN(TX)90p, WSDI and CSDI. The extreme precipitation indices were R10, R20, CDD, CWD, PRCPTOT and SDII.

Temperature

The mean annual temperature over this period was 27.4 °C, with the highest mean temperature, namely 28.8 °C, in September, and the lowest mean temperature, i.e. 25.9 °C in January. The data showed a small year to year variability. Furthermore the trend of the annual mean temperature was studied. From this analysis it was evident that the temperature has increased over the period in question with 0.021 °C/yr. The global mean temperature for this period can be estimated at 0.017 °C/yr, which suggests an approximately one to one correlation with the increase for Willemstad.

The analysis of extreme temperature showed an increase of the monthly maximum of the daily maximum temperature, the percentage of warm days, and the warm spell duration on at least 95% confidence level. The monthly maximum of the daily minimum temperature, monthly minimum of the daily maximum/minimum temperature, and the number of warm nights have decreased over this period. These trends are however not significant.

Precipitation

The mean annual precipitation sum was 506.8 mm with the highest value, 1059.4 mm, in 1933, and the lowest value, 136.5 mm in 1930. The precipitation cycle of Willemstad can be subdivided in a dry (Feb-May), semi-arid (Jun-Sep), and wet season (Oct-Jan). The seasonal cycle of the precipitation can be explained by the global circulation, i.e. the horizontal shifting of the high sub-tropical pressure belt, the sea-continent breeze, and the sea surface temperature of the Caribbean basin. The monthly precipitation sum shows a large variability in the studied period.

The analysis of the extreme precipitation indices showed a decrease of the number of precipitation days (R10, R20), and the annual total precipitation in wet days (days with $RR \geq 1$ mm). The precipitation intensity however shows a very slight decrease over this period, and thus ascribing the decrease in annual total precipitation in wet days to the decrease in the number of precipitation days. The number of consecutive dry days, has increased in this period, whereas the number of consecutive wet days somewhat remained the same. However non of these trends are significant, due to the large variability of the precipitation data.

5 Recommendations

Some closing remarks for future studies concerning the topics treated in this report. The thermometers used throughout the years studied were not very accurate and needed to be corrected.

It is however not clear whether these corrections have already been done. This should normally be the case. A survey by C. Braak[11] suggests this was not the case. A simple homogeneity test was conducted with this data by comparing the dry bulb temperature with the maximum and minimum temperature. This test showed that in 8% of the data the dry bulb temperature exceeded the maximum temperature, or gave values below the minimum temperature. The correction values for the thermometers were then applied to the data. This did not decrease the number of dubious values. Applying only the corrections given in table 1 for the period 1910 to June 1921 proved effective, decreasing the systematic error to 4%. Hence this suggests that the mean annual temperature computed in this analysis has a systematic error of at least 1.1 °C. This uncertainty must be taken into account for all temperature analyses since it is not precisely clear which of the thermometers were lacking in accuracy.

The explosive increase of the percentage of warm days and the warm spell duration from 1933 and forth, especially the high values for the period 1940-1944, might not only be attributed to the global warming. These may be an artifact of a change in the instrument's setup, since the observatory was moved around this period to a new location. However the new location was at a higher altitude and should therefore show a decrease of these values, therefore suggesting there may be something wrong with the thermometers. Hence though the trend shows increase, it is not certain whether these can be attributed to the global warming. A comparison to the annual mean temperature for Grenada[12], showed that the temperature on Grenada for the period 1940-1943 ranged was within the temperature variance[13]. Other possible explanations for these extreme high temperatures may be an ENSO episode, or the extensive production of oil during this period[14]. Further exploration on this matter is recommended.

The work done on the calculation of the extreme indices served as an exploratory work on the behavior of the extremes. A rather short base-period was used to see whether these extremes have changed in the 1910-1946 period. A more detailed study spanning a longer period, preferably from 1894 to present, should render a better comprehension on this matter.

[11] Same as the one afore mentioned.

[12] Station Richmond Hill, 12° 3" N.L. 61° 45" W.L., altitude 509 feet

[13] The mean temperature and variance for the period 1911-1925 was 25.7±1.1 °C. The temperatures for 1940, 1941, 1942, 1943 were 26.6, 25.6, 24.7, and 24.2 °C. The data for Grenada is available at $//http:docs.lib.noaa.gov/rescue/cd318_pdf/LSN1579.PDF$. The annual means were computed by averaging over the annual values of the dry bulb temperature for the two measuring times.

[14] In this period the production capacity of the oil refinery was very high due to the large demand for refined oil during the second world war. The new observatory was situated across the Schottegat to the south of the refinery.