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The First Systematic Meteorological Observations in the Americas (Recife, 1640–42)

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ABSTRACT: In 1639, the German naturalist Georg Marcgraf established the first astronomical observatory in the Americas, located in Recife (Brazil). There, he made the first daily systematic meteorological observations of wind direction, precipitation, fog, and thunder and lightning from 1640 to 1642. We outline the circumstances that led to this observatory being established and analyze the observations. The range of values obtained from all the variables recorded by Marcgraf corresponds well with Recife's current climate. However, wetter-than-normal conditions were recorded during 1640, while anomalous concentrations of foggy days occurred from May to December 1641. We hypothesize that these anomalous record foggy days could be associated with the highly explosive eruptions of the Komagatake and Parker volcanoes, both in 1640.

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The earliest instrumental meteorological observations recorded are those retrieved by the Medici Network. This started in 1654 with observations in present-day Italy, Austria, Poland, France, and Germany (Camuffo and Bertolin 2012). In the early eighteenth century, the number of observatories increased in Europe after James Jurin's invitation to keep meteorological observations (Jurin 1723). Jurin was the Secretary of the Royal Society, and during the 1720s he built a network of meteorological correspondents with standardized methods and instruments. In the Americas, there are fewer available instrumental observations from those early times (Brönnimann et al. 2019; Domínguez-Castro et al. 2017). The first observation retrieved was the short daily record of barometer readings made in Barbados by William Sharpe from 14 April to 24 August 1680 (Chenoweth et al. 2007). This was followed by the temperature measurements recorded by Henry Kelser in York Factory (Canada) during August and September of 1697 (Brönnimann et al. 2019). In the Southern Hemisphere the earliest known records are from Cape Town (South Africa) from 1751 to 1752 taken by Nicolas-Louis de Lacaille (Lacaille 1755); from Lima (Peru), going back to 1754 but only available at annual resolution (Domínguez-Castro et al. 2017); from Rio de Janeiro (Brazil) recorded by Bento Sanchez Dorta from 1781 to 1788 (Farrona et al. 2012); or in Sydney Cove (Australia), recorded by Lieutenant William Dawes from 1788 to 1791 (Gergis et al. 2009).

Although the thermometer and the barometer were developed in the first half of the seventeenth century, no instrumental readings had been preserved prior to the 1650s. However, a variety of documentary sources can provide collections from earlier weather observations. Logbooks are the main source of weather information over the oceans (García-Herrera et al. 2018). On land, these sources often take the form of weather diaries kept by individuals or institutions (Domínguez-Castro et al. 2015). The weather diaries usually include the presence or absence of hydrometeors such as rainfall, frost, hail, plant phenology, and perceived anomalies of temperature and precipitation. The authors of these diaries had different reasons for keeping these systematic records, e.g., applications for agriculture, astrometeorology, or health-related issues. In addition to climate information, weather diaries are also unique sources that enable us to understand how humans felt about and were connected with the climate (Adamson 2015).

Until now, the first weather diary record, credited in the "new world," was documented by Rev. Johan Campanius during 1644 and 1645 in the Swedes Fort colony (near present-day Wilmington, Delaware) (Collin 1818; Havens 1955; Landsberg 1980). However, his diary has not been preserved and we only know about the observations from the poorly detailed summaries, at monthly scales, that his grandson inserted in the book *Kort Beskrijtning om Provincien Nya Swerige uti America* (Campanius 1702), which were translated into English in 1833 (Campanius 1834). His grandson wrote, “My grandfather, John Campanius, who was a pastor in New Sweden, also made meteorological observations in the years 1644 and 1645. He recorded them every day and night each month. They are too long to be inserted here at large: I shall, therefore, only give extracts of those from the year 1644” (Campanius 1834, p. 56). Even after that date, there are few systematic non-instrumental observation studies in America. Some examples are (i) the weather diary of Herman Smith, a farmer in west-central New York State, which provides information from 1884 to 1886 for a region without instrumental measurements for these dates (Bernhardt 2015); (ii) the 21 weather diaries used, in combination with other documentary sources and natural proxies by Mock et al. (2007), to characterize the anomalous winter of 1827/28 in North America; and (iii) the weather diary documented by Felipe Zuñiga from 1775 to 1786, that allows for climate characterization during the “hunger year” 1785/86 in Mexico City with daily resolutions (Domínguez-Castro et al. 2019).

The systematic non-instrumental observations studied in the Southern Hemisphere are also scarce. Some examples are Grab and Williams (2022), who analyze the Dutch East India Company, recording “daily registers” in Cape Town (South Africa) from 1773 to 1791. Fortunately, further works are expected because this documentary source provides information from 1652. A more recent example, and the earliest on land in New Zealand, is the record taken by Rev. Richard Davis in Waimate North and Kaikohe from 1839 to 1851 (Lorrey and Chappell 2016).

In this research, we retrieve and analyze the first systematic land-based meteorological observations taken, to the best of our knowledge, in the Americas and the whole Southern Hemisphere. They were recorded by the German naturalist Georg Marcgraf (also referred to as Marggraf, Markgraf, Marcgrave, Marggraf; all the names in this paper are those that the people used at that time and with the spelling most commonly used in literature) in Recife, Brazil (Fig. 1), from 1640 to 1642. We also analyze the historical context and data reliability by comparing these observations with current meteorological observations. Although the observations retrieved only cover three years, they are very interesting due to the anomalous weather conditions recorded. These weather conditions may suggest anomalous climatic forcing at the time. The period of Marcgraf’s observations corresponds to one solar cycle (1635–45) before the Maunder minimum (1645–1715) (Eddy 1976; Usoskin et al. 2015). This cycle had low solar activity, producing a gradual onset of the Maunder minimum (Vaquero et al. 2011); with some authors even including this cycle in the Maunder minimum (Vaquero and Trigo 2015; Brehm et al. 2021). On the other hand, volcanic activity was particularly high during the Marcgraf observation period. During the years 1640 and 1641, there were four eruptions whose timing, location, and magnitude have been relatively well established (Global Volcanism Program 2013). In particular, there were two eruptions with a Volcanic Explosivity Index (VEI) of 5 (VEI is a scale that estimates the explosive magnitude of historical eruptions; for details, see Newhall and Self 1982), i.e., Parker (Philippines) and Hokkaido-Komagatake (Japan) in 1640, and two other less explosive volcanoes (VEI 4), i.e., Llaima (Chile) in 1640 and Kelud (Indonesia) in 1641 (Global Volcanism Program 2013).

The observer and the historical context

Georg Marcgraf was born on 30 September 1610, in Liebstadt (in the state of Saxony, present-day Germany). In September 1636, he started studying medicine at Leiden University in the Netherlands (Brienen 2001). During these years he was particularly interested in botany and astronomy, doing his first astronomical observation at the Leiden observatory

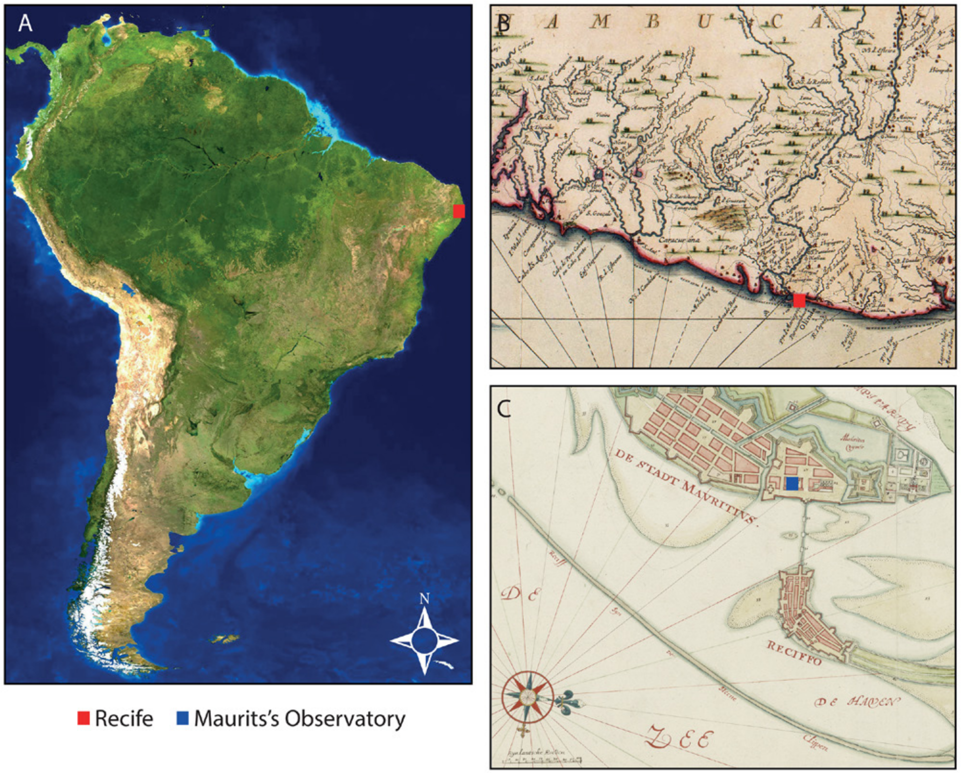


Fig. 1. Location of Recife and Maurits's observatory. (a) Location of Recife in South America. (b) Detail of *Brasilia qua parte paret Belgis* (part of Brazil that obeys the Dutch Colonies) 1647 by Georg Marcgraf. (c) Watercolor chart of the city of Recife (Brazil) in 1665 by Johannes Vingboons (National Archives of the Netherlands).

on 13 January 1637. On 1 January 1638, Marcgraf departed from Texel (Netherlands), having enrolled in an expedition to Recife that had been financed by Johan Maurits van Nassau-Siegen. Maurits had been the Governor of the Dutch possessions in Brazil since 1636.

Maurits had a wide range of interests in the sciences and arts. He financed the setup of the astronomical observatory and the botanical garden in Antonio Vaz Island (Recife). Both were the first institutions of their type in the Americas and, indeed, in the entire Southern Hemisphere.

Before departing, Marcgraf had obtained a recommendation letter for Maurits written by Johannes de Laet, a prestigious geographer and founder of the West Indian Company. Laet recommended that the Count employ Marcgraf as a mathematician. This letter had a very speedy impact, and shortly after arriving, Maurits allowed Marcgraf to construct an astronomical observatory. Subsequently, Marcgraf was appointed as the company's official mathematician (Matsuura and Zuidervaart 2014).

The first astronomical observation in the observatory took place on 15 September 1639. Marcgraf observed regularly until 22 June 1643 (North 1989). During the day he made solar and meteorological observations, while at night, observations of stars and planets took place, with special attention paid to Mercury. The precise observatory location was a cause of discussion and conjecture for decades (North 1979, 1980, 1989; Gonsalves de Mello 1978). Nevertheless, the meticulous study of Matsuura (2013) confirms that the observatory was on the roof of the Count's main residence. In fact, we can see the observatory in Frans Post's painting and in a watercolor by Zacharias Wagener (Fig. 2). We can see in the first-floor corner window a man using some kind of instrument. Moreover, if we take a closer look (Fig. 2d) we can also see someone in the right window of the observatory, possibly representing observers. The coordinates of the observatory were 8°3′51″S, 34°52′37″W, currently at the crossroads of 1 de Março and Imperador D. Pedro II streets. Marcgraf performed a multitude

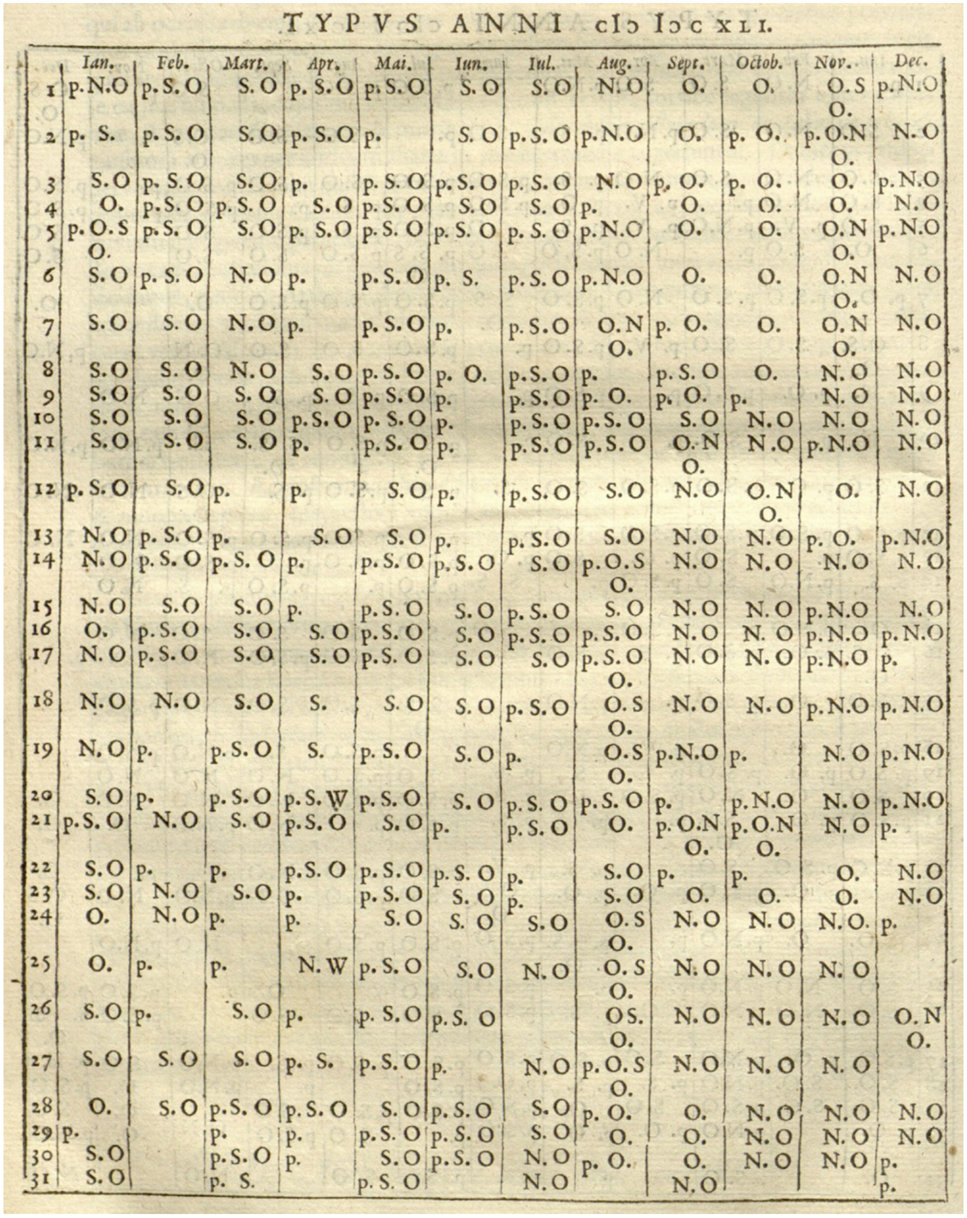
Fig. 2. Maurits's observatory. (a) *Mauritiopolis* graven Georg Marcgraf 1647. (b) Detail of *Mauritiopolis* showing the observatory marked with a "c." (c) *Der Hof Sein Excellenz* watercolor by Zacharias Wagener (~1640) (Kupferstich-Kabinett, Dresden State Art Collections). (d) Detail of the Zacharias Wegener watercolor.

of astronomical and meteorological observations there. Due to this work, he is considered the first trained astronomer in the Americas (Brienen 2001). In any case, the extent of Marcgraf's activities in Brazil was not limited to those observations, as he also explored the country, producing cartographic maps and studying the natural history of the region [see Brienen (2007) for zoological works; Da Silva and Menezes (2016) for geographical works; Ossenbach (2017); Alcantara-Rodriguez et al. (2019) for botanical works; and Matsuura (2013) for astronomical works]. Marcgraf's observations and collections were shipped to the Netherlands on Maurits's return trip. However, Marcgraf never returned to the Netherlands because he was sent from Recife to Angola in 1644 to carry out a topographical survey, and it was there where he eventually died.

Marcgraf's weather diary

The daily observations recorded by Marcgraf from 1640 to 1642 were published by Piso in *De Indiae utriusque re naturali et medica* (Piso 1658), specifically, in chapter 2, De Aeris temperie atque Anni tempestatibus," of the first book, which was titled *Tractatus topographicus et meteorologicus Brasiliae, cum observatione eclipsis Solaris*. At the beginning of the chapter, Piso made it clear that Marcgraf recorded meteorological observations over six years, collecting several observations per day. Nevertheless, Piso only published the daily observations for the years 1640, 1641, and 1642: "Our author [Marcgraf], throughout the time he lived in Brazil (almost six years) had observed and documented each day, and more precisely in certain parts of the day, the atmospheric weather, the wind, and also the other phenomena that concern meteorology in order to elaborate this chapter, which he could not finish because death befell him. On my part, with a view to providing some samples to those interested in these issues, I will offer the three-year tables" (Piso 1658, p. 8). It is difficult nowadays to understand why Piso did not provide information on the rest of the years. When considering the relevance of the work involved, space does not seem a problem. Perhaps he just considered the additional meteorological information irrelevant because he wrote "the remaining years show a similar record with little variability" (Piso 1658, p. 9).

The observations are recorded in three tables, one per year, which exhibit wind direction and the presence of rainfall (Fig. 3). Rainy days are identified with a "p." (for *pluvia*). Piso wrote, "In these tables, we have noted with the letter P all the days with even very fine and brief rainfall so that no one thinks that during those days it rained continuously" (Piso 1658, p. 9). Wind direction is registered in 24 directions using letters according to the Frankish names, e.g., N (Nordroni), E (Ostroni), S (Sundroni), W (Vuestroni) dating back to the eighth century. This is known thanks to Marcgraf's note: "We have annotated the winds with letters: S.O. designates the *Euro*, N.O. the *Boreas or Aquilon*" (Piso 1658, p. 9).



TYPVS ANNI cIↃ IↃc XLI.

	Ian.	*Feb.*	*Mart.*	*Apr.*	*Mai.*	*Iun.*	*Iul.*	*Aug.*	*Sept.*	*Octob.*	*Nov.*	*Dec.*
1	p. N.O	p. S.O	S.O	p. S.O	p. S.O	S.O	S.O	N.O	O.	O.	O.S O.	p. N.O
2	p. S.	p. S.O	S.O	p. S.O	p.	S.O	p. S.O	p. N.O	O.	p. O.	p. O.N O.	N.O
3	S.O	p. S.O	S.O	p.	p. S.O	p. S.O	p. S.O	N.O	p. O.	p. O.	O.	p. N.O
4	O.	p. S.O	p. S.O	S.O	p. S.O	S.O	S.O	p.	O.	O.	O.	N.O
5	p. O.S O.	p. S.O	S.O	p. S.O	p. S.O	p. S.O	p. S.O	p. N.O	O.	O.	O.N O.	p. N.O
6	S.O	p. S.O	N.O	p.	p. S.O	p. S.	p. S.O	p. N.O	O.	O.	O.N O.	N.O
7	S.O	S.O	N.O	p.	p. S.O	p.	p. S.O	O.N O.	p. O.	O.	O.N O.	N.O
8	S.O	S.O	N.O	S.O	p. S.O	p. O.	p. S.O	p.	p. S.O	O.	N.O	N.O
9	S.O	S.O	S.O	S.O	p. S.O	p.	p. S.O	p. O.	p. O.	p.	N.O	N.O
10	S.O	S.O	S.O	p. S.O	p. S.O	p.	p. S.O	p. S.O	S.O	N.O	N.O	N.O
11	S.O	S.O	S.O	p.	p. S.O	p.	p. S.O	p. S.O	O.N O.	N.O	p. N.O	N.O
12	p. S.O	S.O	p.	p.	S.O	p.	p. S.O	S.O	N.O	O.N O.	O.	N.O
13	N.O	p. S.O	p.	S.O	S.O	p.	p. S.O	S.O	N.O	N.O	p. O.	p. N.O
14	N.O	p. S.O	p. S.O	p.	p. S.O	p. S.O	S.O	p. O.S O.	N.O	N.O	N.O	N.O
15	N.O	S.O	S.O	p.	p. S.O	S.O	p. S.O	S.O	N.O	N.O	p. N.O	N.O
16	O.	p. S.O	S.O	S.O	p. S.O	S.O	p. S.O	p. S.O	N.O	N.O	p. N.O	p. N.O
17	N.O	p. S.O	S.O	S.O	p. S.O	S.O	S.O	p. S.O O.	N.O	N.O	p. N.O	p.
18	N.O	N.O	S.O	S.	S.O	S.O	p. S.O	O.S O.	N.O	N.O	p. N.O	p. N.O
19	N.O	p.	p. S.O	S.	p. S.O	S.O	p.	O.S O.	p. N.O	p.	N.O	p. N.O
20	S.O	p.	p. S.O	p. S.W	p. S.O	S.O	p. S.O	p. S.O	p.	p. N.O	N.O	p. N.O
21	p. S.O	N.O	S.O	p. S.O	S.O	p.	p. S.O	O.	p. O.N O.	p. O.N O.	N.O	p.
22	S.O	p.	p.	p. S.O	p. S.O	p. S.O	p.	S.O	p.	p.	O.	N.O
23	S.O	N.O	S.O	p.	p. S.O	S.O	p.	S.O	O.	O.	O.	N.O
24	O.	N.O	p.	p.	S.O	S.O	S.O	O.S O.	N.O	N.O	N.O.	p.
25	O.	p.	p.	N.W	p. S.O	S.O	N.O	O.S O.	N.O	N.O	N.O	
26	S.O	p.	S.O	p.	p. S.O	p. S.O		OS. O.	N.O	N.O	N.O	O.N O.
27	S.O	S.O	S.O	p. S.	p. S.O	p.	N.O	p. O.S O.	N.O	N.O	N.O	
28	O.	S.O	p. S.O	p. S.O	S.O	p. S.O	S.O	p. O.	O.	N.O	N.O	N.O
29	p.		p.	p.	p. S.O	p. S.O	S.O	O.	O.	N.O	N.O	N.O
30	S.O		p. S.O	p.	S.O	p. S.O	N.O	p. O.	O.	N.O	N.O	p.
31	S.O		p. S.		p. S.O		N.O		N.O			p.

Fig. 3. Example of Marcgraf's daily records during 1641; each column corresponds to a month, and days are represented in rows (extracted from Piso 1658, p. 10).

SO stands for Sundostroni and corresponds to the southeast direction from which the Euro wind blows. NO stands for Nordostroni, which corresponds to the northeast direction from which the Aquilon or Boreas blow. Marcgraf did not define the meaning of the days without wind direction but a comparison with current observations suggests that these days could be considered as calm days.

In addition to the tables similar to Fig. 3, the chapter provides information about the days with fog, thunder and lightning. All the meteorological information has been transcribed and is available by Domínguez-Castro et al. (2022).

It is important to note that it was impossible for Marcgraf to record the observations over the entire period because at times he was exploring the region outside Recife. Some examples of those expeditions are, for example, from 20 October to 10 November 1640, where he was carrying out geographical studies in an unknown region. In addition, from 9 February to November 1641, he explored the São Francisco River and the “western lands.” Likewise, between 10 December 1641 and 16 June 1642, he explored the north and he was at Forte Ceulen where he observed a lunar eclipse on 14 April 1642. The observations at Recife during these periods were probably recorded by his assistants, Ordman and Mols (Matsuura 2011), who were likely trained to record the meteorological observations, but not the astronomical ones, because when Marcgraf was convalescing from an injury to his left arm, the astronomical observations stopped for a time, whereas the meteorological ones continued as normal.

Marcgraf’s observations compared with modern instrumental data from Recife

There are no available systematic observations on a daily scale than can be considered contemporaneous with Marcgraf’s records, nor is there a natural proxy with enough temporal resolution to be useful for comparison with the daily observations recorded by him and his two assistants. Therefore, to evaluate the reliability of Marcgraf’s observations, we have compared them with an instrumental series from the Guararapes Gilberto Freyre station, available from the ICEA network (Brazilian Air Traffic Control Institute) (code 82899) 8°7′S, 34°55′W, 11 m MSL. This station is located approximately 68 km south of Maurits’s observatory.

Rainy days. The daily precipitation data from the Guararapes station covers the period 1951–2019, with only 0.18% of missing data. To compute the frequency of wet days from this series, we followed the recommendations of the World Meteorological Organization (WMO), choosing a threshold of 1 mm to consider a day wet (WMO 2009). This is the most common threshold used to differentiate appreciable precipitation from negligible precipitation. We have computed the monthly and annual frequency of rainy days only for complete months and years. The annual mean of rainy days during the instrumental period is 153 days. This value is very close to the number of rainy days reported during 1641 and 1642 (166 and 164 days, respectively) and clearly shows that the year 1640 was particularly wet, with 201 days of precipitation. This record is only exceeded in the Guararapes station in 1963 (considering the quasi 70-yr-long period of precipitation available), with 207 rainy days. Figure 4 shows the comparison between the Guararapes station and Marcgraf’s monthly frequency of rainy days. The Marcgraf record reflects the current seasonal variability of rainy days, characterized by a wet season from April to August. The maximum level occurs around July, with a dry season from September to March, with a minimum around November. The rainy season is associated with cold fronts, land and sea breezes (Kousky 1979), and easterly wave disturbances (EWDs), which propagate westward over the tropical South Atlantic Ocean during the austral autumn and winter seasons (Gomes et al. 2015). EWDs have an average period of 5.5 days, wavelengths of around 4,500 km (Gomes et al. 2015) and contribute at least 60% of the total precipitation during the rainy season (Gomes et al. 2019).

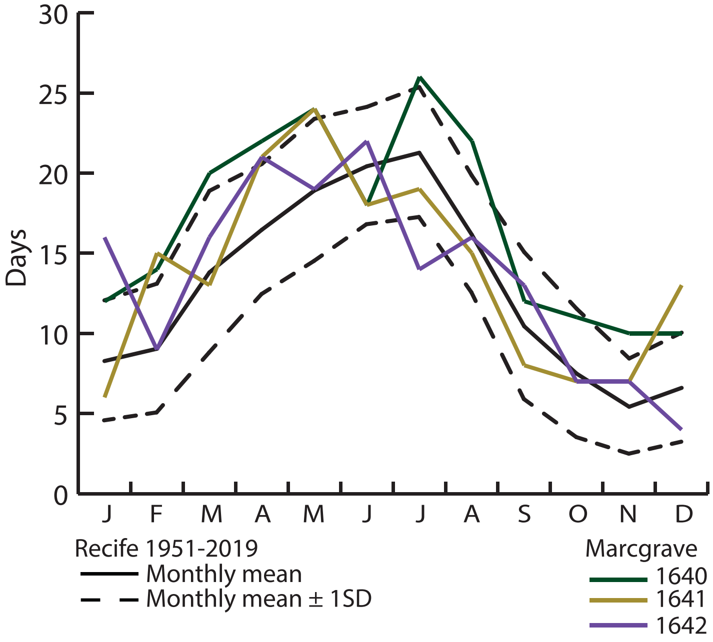


Fig. 4. Monthly rainy days. During 1951–2019: mean annual cycle (solid black line), mean monthly rainy days ±1 SD (dashed black lines). During Marcgraf's record: 1640 (green), 1641 (brown), 1642 (red).

EWDs are very rare during the dry season. Marcgraf's record fluctuates around the mean of the instrumental period and rarely stands out from the mean (plus or minus one standard deviation) of the Guararapes station record. Nevertheless, as we mentioned, 1640 was particularly wet, showing monthly values of rainy days superior to the Guararapes station's mean over the whole year, except in June and September. According to Marcgraf, that year the rainfall was mainly during the day: "no matter how it rained during the day, the nights were mostly clear and serene, some even chilly" (Piso 1658, p. 10). Marcgraf's affirmation is interesting because, currently around 50% of the precipitation in the region occurs at night. Kousky (1979) proposes that most of this precipitation is produced by the convergence of the mean onshore flow and the offshore land breeze. This could suggest changes in the intensity of the offshore land breeze during 1640.

Wind direction. To compare Marcgraf's wind direction observation with the instrumental measurements is difficult because we have very few details regarding observational methodology. In particular, the daily direction provided in the tables could result from the most common direction during the day being computed subjectively. However, it could also be an observation at a specific time or computed from subdaily observations. It is also a short period, thus highly susceptible to the peculiarities of those three specific years. Moreover, we must consider that although Marcgraf documented the wind direction observations with an accuracy of 21 courses, it is evident that this resolution is not constant during the whole period and that some intermediate courses are clearly underrepresented. This could be explained by the fact that different observers (Marcgraf and his two assistants) recorded the observations with different resolutions. To homogenize the series we have resampled the 21 courses to 8 principals (N, NE, E, SE, S, SW, W, NW). This resampling has also been done in the instrumental hourly record with a 10° resolution from the Guararapes station, which covers the recent 1991–2021 period. However, the past and present sites that are considered are not located as close, and therefore observations can be affected differently by local effects, hence making the comparison difficult with the current climate. Figure 5a shows the percentage of days with a specific wind direction at noon, midnight, and during the whole day (considering all the hourly observations) throughout the instrumental period, because we do not know Marcgraf's observational time. Figure 5b shows the percentage of days with a specific wind direction during the Marcgraf period. In both periods the predominant wind direction is SE, however, it is more frequent during the Marcgraf period (51.7%) than during the instrumental record (42% at noon and 33.6% at midnight). Nevertheless, the second most common direction in Marcgraf's record is NE (22.9%) followed by E (17.2%), however, in the instrumental record, it is E (noon 24.5%, midnight 22.3%) followed by

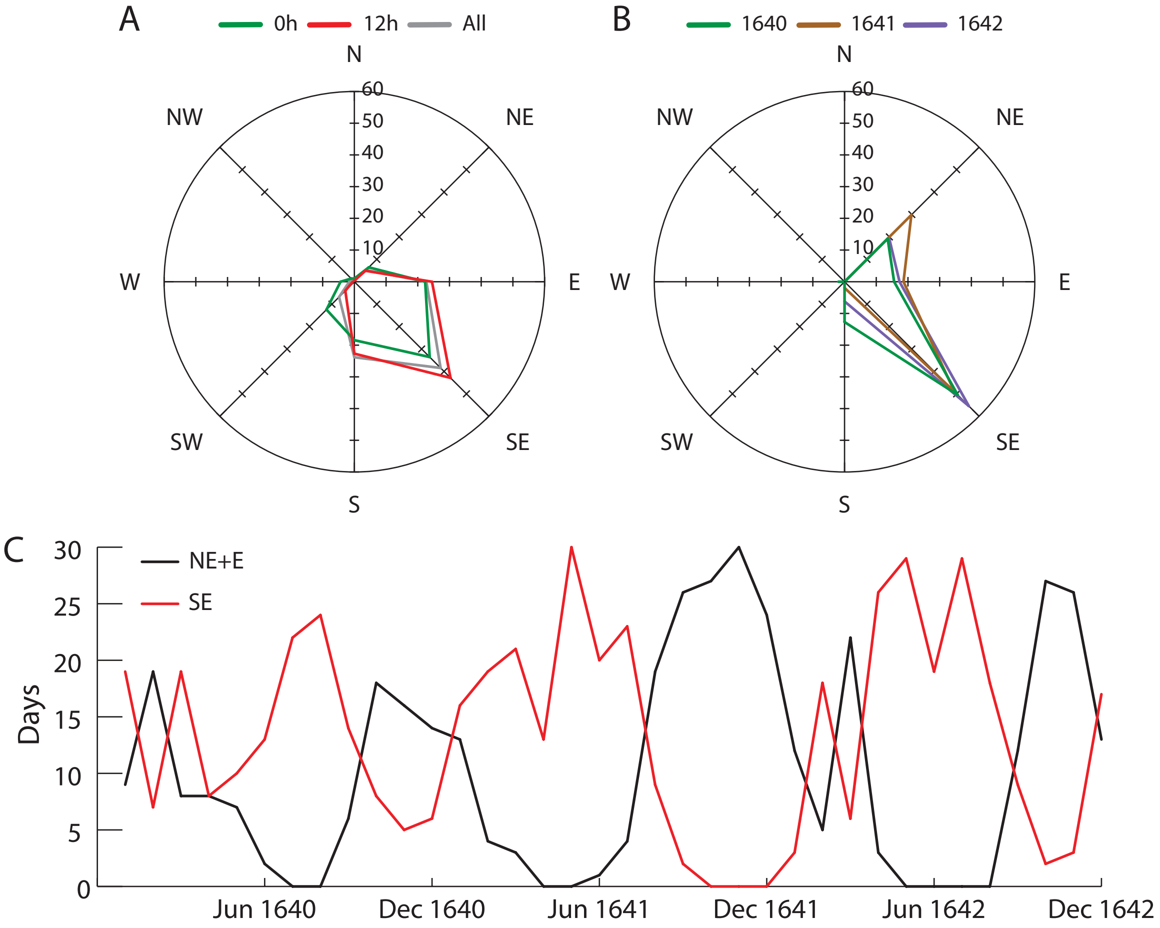


Fig. 5. (a) Guararapes station wind direction (1991–2021). (b) Marcgraf wind direction in 1640, 1641, and 1642. (c) Days with SE and NE+E wind direction during Marcgraf's period.

S (noon 22.7%, midnight 18.4%), while the NE records are relatively scarce (noon 4.9%, midnight 6.4%). On the other hand, S (7%) is rare in Marcgraf's record.

The variability of wind direction during Marcgraf's record is also interesting. The record shows an alternation between SE versus E+NE winds (Fig. 5c), with the maximum NE+E level occurring from September to January and the minimum from April to August. On the other hand, the SE winds exhibit the opposite pattern. This seasonality in predominant wind directions was also noted by Marcgraf as documented in his record: "These winds (in reference to NE and SE) are dominant with certain alternation throughout this region and stipulate the difference in the navigation rules" (Piso 1658, p. 9). Meanwhile, on an annual basis, he also annotated the dates when the NE started to blow, i.e., 1640: 19 September; 1641 and 1642: 11 September.

The seasonality of the winds in the region is mainly controlled by the position of the intertropical convergence zone (ITCZ) and the position and intensity of the South Atlantic anticyclone (SAA) (Sun et al. 2017; Gilliland and Kein 2018). The high frequency of NE wind in Marcgraf's record during the austral spring could suggest an extension and reinforcement of the SAA at that time. Moreover, there was also an anomalously high amount of NE+E winds between February 1640 and March 1642. Taking into account that these months are considered to be when the ITCZ reaches its southernmost location, this could suggest that the ITCZ reached an anomalously southern location during these years, even reaching Recife's latitude and with the E, and even NE winds, increasing. This southern displacement of the ITCZ during the Little Ice Age (LIA) has been recorded by different proxies (Haug et al. 2001; Baker et al. 2001; Sachs et al. 2009) with the most likely cause being a cooler North Atlantic during this period (Peterson and Haug 2006). However, as noted above, it is difficult to extract robust conclusions from the wind direction recorded by Marcgraf due to the lack of metadata and the possible presence of a variety of local effects in the record.

Thunder and lightning. We have used the “present weather” information covering 1991–2020 from the Guararapes station to compare the weather phenomena recorded by Marcgraf. This is a human observational record that the Brazilian Air Traffic Control Institute catalogs in 99 weather codes (DECEA 2017). The information is fragmentary, showing important gaps, but could be useful to gain an insight into the current climatology of thunder and lightning in the region. We have considered a thundery day to be any day when a code that includes thunder is recorded at any moment throughout said day. It is interesting to note that every single day that thunder was recorded in the instrumental period is restricted to January–April. This concurs with Marcgraf’s record in most of the cases; however, he also recorded thunder in May (1640, 1642) and December (1641) (Fig. 6a). This could suggest a slightly longer storm season during the years covered by Marcgraf records.

Fog. To compare Marcgraf’s foggy days with the current climate, we have analyzed the frequency of days with horizontal visibility below 1,000 m at the Guararapes station between 1951 and 2021. This is a currently accepted definition of fog, but Marcgraf did not define foggy days in his record. With this criterion, the annual mean of foggy days during this period is 2.4 days yr^{-1}. This mean value is similar to that recorded by Fedorova et al. (2008) i.e., 2 days yr^{-1}. The Marcgraf series for foggy days is particularly interesting. There were relatively few foggy days during 1640 and 1642 (7 and 1, respectively). Even Marcgraf annotated in 1640, “here fogs are especially rare” (Piso 1658, p. 10). Nevertheless, a dramatic increase in the frequency of foggy days was recorded during 1641, with 42 days registered (Fig. 6a), with 20 of them occurring between 17 July and 1 September. This also captured the attention of Marcgraf, who wrote, “the fogs, certainly thick this year, were very frequent” (Piso 1658, p. 11). This record of 1641 has no analog in the instrumental period, with 1985 at the top of the instrumental period with only 12 foggy days. The seasonal distribution of foggy days during the instrumental period shows a maximum in June with more than 20% of total foggy days, and a minimum spanning from September to December with less than 2% of foggy days per month (Fig. 6b). This monthly pattern is similar to what was observed for the years 1640 and 1642. However, July, August, and November show the highest fog frequency in 1641. This led to a highly anomalous seasonal cycle (Fig. 6b) representing 84% of the total foggy days observed during Marcgraf’s period.

It is difficult to explain the high anomalous fog frequency recorded in 1641 through the regional atmospheric dynamics since it practically quadruples the second highest on record.

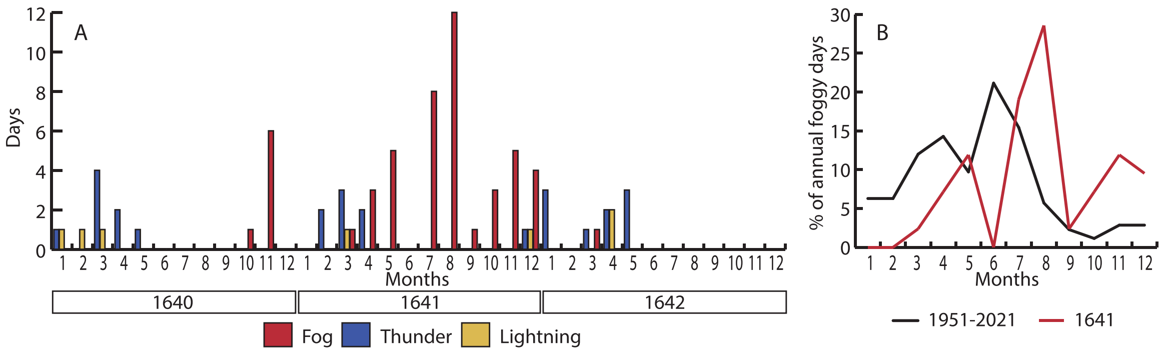


Fig. 6. (a) Monthly days with fog (red), thunder (blue), and lightning (yellow) from 1640 to 1642. (b) Seasonal distribution of foggy days from 1951 to 2021 (black line) and during 1641.

One possibility, difficult to confirm, is that they were dry fogs associated with a high concentration of volcanic aerosol in the troposphere. There are three facts that could support this theory: (i) volcanic activity during 1640 was elevated and this had an impact on the climate system (Stoffel et al. 2022); (ii) anomalous atmospheric phenomena, caused by a high amount of tropospheric aerosol were observed in Europe in 1641 (Stoffel et al. 2022); and (iii) there is evidence that anomalous fogs were recorded in Brazil during other historical eruptions, e.g., 1783/84 Icelandic Laki fissure eruption (Trigo et al. 2010).

First, two important eruptions (VEI 5) occurred during the second half of 1640: (i) Komaga-take (Japan) with elevated eruptive activity from 31 July to 2 August, and (ii) Parker (south of Mindanao) that started to erupt in the last few days of December and whose major explosive activity occurred on 4 January 1641 (Delfin et al. 1997). The emission signals from these events are clear in ice cores from both hemispheres and comparable with other great eruptions such as Tambora (Indonesia) (Stoffel et al. 2022). The climatic impact of Komaga-take/Parker is high throughout the years following the eruptions. In Europe, 1641 was one of the coldest summers for over 500 years, with an anomaly of –1.19°C, very close to that observed during 1816 which was provoked by the Tambora eruption –1.23°C (Stoffel et al. 2022). In China, Chen et al. (2020) showed that the megadrought that caused the collapse of the Ming Dynasty in 1644 was intensified and extended by these eruptions.

Second, Stoffel et al. (2022) reported anomalous atmospheric phenomena consistent with a high increase in volcanic aerosols in the atmosphere during 1642. Hermann IV, Landgrave of Hesse-Rotenberg, reported that several places in present-day Germany experienced atmospheric phenomena (e.g., thick fog, dull and smoky weather, hoarfrost) frequently from July to September 1641. In Paris, Canon Jean de Toulouse, from the Abbey of Saint-Victor stated that “from 25 August 1641, cold rains arrived, accompanied by unusual fogs and caused many diseases and fatalities in the city until March 1642” (Stoffel et al. 2022, p. 1091). Another effect of the high concentration of aerosols in the atmosphere was a full dark lunar eclipse recorded by Johannes Hevelius on 25 April 1642, when he could not ascertain the location of the moon, even with the aid of a telescope (Hevelius 1647).

Third, this was not the first time that an abnormally high frequency of fog, detected in the Southern Hemisphere, had been explained by high volcanic activity. Trigo et al. (2010) retrieved and analyzed the meteorological observations done by the Bento Sanchez Dorta from 1781 to 1788 in both Rio de Janeiro and São Paulo, Brazil. They found an anomalously high number of fogs during September and November 1784. These observations, coupled with modeling results on high latitude eruptions from Oman et al. (2005, 2006) and Sanchez Dorta’s own insights at the time (stating explicitly that an unknown eruption ought to be responsible), supported the hypothesis that these fogs could have been induced by the unusually prolonged Icelandic Laki fissure eruption of 1783/84 in the Northern Hemisphere. However, it is important to note that further research is necessary to confirm or reject the volcanic origin of the increased fog frequency. This would include the collection of new observational evidence in the Southern Hemisphere and ad hoc modeling of the plume from both eruptions.

Concluding remarks

In this work, we have retrieved and analyzed the first systematic meteorological observations from both the Americas and the Southern Hemisphere that were collected during the early 1640s. They are a prime example of the accuracy of these types of observations and the scientific context in which they were developed. In this case, the financial support and scientific interest shown by Count Johan Maurits van Nassau-Siegen allowed for the development and use of cutting-edge science, a particularly remarkable achievement, considering the location of Recife in the tropics, i.e., very far from the centers of knowledge, then located in Europe. The Marcgraf meteorological observations (i.e., wind direction, days with precipitation, fog, thunder and lightning) show a degree of quality that is comparable with both early instrumental meteorological observations from the Americas (Domínguez-Castro et al. 2017; Obregón et al. 2022), as well as with current meteorological observations.

The original observations have been lost, and as we only have daily summaries available, this makes precise comparisons difficult for some variables, e.g., wind direction. Although these observations do not provide measurements from thermometers, barometers, or rain gauges, they do provide other variables that could aid us in our understanding of the climate system. It is important to note that observations of fog and thunderstorms are not provided by any natural proxy, and the efforts made for their rescue are much less than for instrumental observations, which, in turn, increases the risk of losing this irreplaceable information.

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Data availability statement. Marcgraf's records are available at Domínguez-Castro et al. (2022). Meteorological data from the Guararapes station were made available by ICEA (Brazilian Air Traffic Control Institute).

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