WHAT HAPPENED IN 2021? ANALYZING THE BIGGEST NEGRO RIVER FLOOD IN MANAUS, BRAZIL

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ABSTRACT

Flood and ebb processes are common events in any hydrological system. In some cases, due to natural or anthropogenic conditions, such events can take place in an extreme manner, causing a lot of damage to the population. In 2021, in several municipalities in the Amazon basin, rivers reached levels higher than the maximum observed until then, making this year the biggest flood in the entire history of monitoring. Most Amazonian rivers have a high annual pulse of floods, as a result of the precipitation period in the upper part of their large basins. Most of the floodplains located in the central region of Amazonia become inundated from May to July, from which the water drains into the river systems slowly over the drought time. In the Amazon Basin, extreme events are mainly related to El Niño or La Niña events, resulting in some big floods and a long rainfall period. In 2021, the Negro river level exceeded the maximum level observed in the entire 119-year historical series of monitoring. On 30 May 2021, the previous record of 29.97 m observed in 2012 was equaled. The river continued to rise until reaching the level of 30.02 m on 16 June 2021. Other stations monitored by Geological Survey of Brazil, which were accomplished through bulletins, reached historical records in the same year, such as São Gabriel da Cachoeira, Barcelos and Manaus (Negro river), Manacapuru (Solimões river), Careiro da Várzea (Amazon river basin), Itacoatiara and Parintins (Amazon river), all located in the state of Amazonas. This study analyzes the conditions that favored the event of the greatest flood recorded in the Rio Negro in 2021. Some factors contribute to the flooding event, such as the rainfall regime distributed throughout the basin and how the main river and its various tributaries behave during the flooding period.

Keywords: flood record, Amazon basin, Negro river.

1 INTRODUCTION

The 2021 flood event represented the largest and most impactful flood event in its entire history of hydrological monitoring for the state of Amazonas, Brazil. 57 of 62 cities in Amazonas had recognized an emergency situation. In the state capital, Manaus, where data on river levels have been recorded since 1902, the level of the Rio Negro surpassed all previous records, confirming 2021 as the largest flood in the last 119 years in the region. Extreme flood events occurred mainly in the "central" region of the Amazon basin, including Manaus, Manacapuru (Solimões river), Careiro da Várzea, Itacoatiara and Parintins (Amazon river). Extreme flooding was also observed along the entire Rio Negro, such as São Gabriel da Cachoeira and Barcelos cities also reaching river levels never seen before.

The floods that occur on the edge of Manaus and its surroundings are due, for the most part, to the contributions of the Solimões and Negro rivers. They are floods that have a long journey time, due to the gigantic size of the hydrographic basin and the small slope observed in the beds of its main bodies of water [1]. The Amazon's many tributaries do respond in a similar fashion, but when all these inputs are integrated together down the main stem of the river, this results in a single monomodal flood wave that occurs with regularity on an annual

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basis. The flood wave elevation range at Manaus Station is around 9.5 m, with high water in June–July and the low water in October–November [2].

In the Amazon River Basin, backwater effects regulate the flow dynamics in the downstream reaches of main rivers. As examples of these effects in the basin, there is the influence of the main Amazon River on its tributaries' water levels [3], [4]. Hydrological regimes within the basin vary significantly. The peak water discharge of the Solimoes/Amazonas, Madeira and Negro Rivers are offset in time. For the upper Negro River, the high-water period arrives in the second half of the year [5].

Negro river level in Manaus is verified by monitoring some stations located before and in different waterbodies that contribute to Manaus station. These stations have scale meters installed on the banks and are accompanied by local people daily. The record of rivers rise and fall in these seasons are recorded in a weekly newsletter and published on the institutional homepage (www.cprm.gov.br/sace) of the monitoring responsible sector and it has a great importance to the resident population, the state and city halls, as well as for academic researchers [6].

The maximum rainfall in the Southern most parts of the Amazon River basin usually occurs in December, January and February. The maximum rainfall in the central basin along the Solimões–Amazon mainstem is in February, March and April and six months earlier than maximum rainfall in the northernmost parts of the basin (June–July–August) [4]. Daily water levels at the Manaus Port records since 1903 assists the Geological Survey of Brazil (CPRM) to identify severe droughts (15.80 m) and floods (29.00 m) in Manaus and characterize their frequency, duration, and severity. These river levels are critical for the functioning of the port and are used to declare emergency status in the city [8]. Meade et al. [4] present a comparison of the stage hydrograph for Manaus at the bottom with the hydrographs for station on the upper Negro River in the upper and with the hydrograph for the mainstream Solimões River at Manacapuru, shows that stages in the downstream reaches of the Negro reflect the stage of the mainstem.

In this paper we present the aspects that could be the responsible for the biggest flood in Negro river through more than a hundred years of observation and offer a kind of operational instrument to future studies and analysis.

2 CLIMATE

Hydrological drought and flood extreme events were quantitatively defined to occur when daily water levels in Manaus fall below 15.80 m or rise above 29.00 m. In the Solimões–Amazonas system, the flood intensity depends on the rainfall regime of the entire basin. Rainfall decreases in the Amazon are partially associated with the phenomenon popularly known as "El Niño" that produces severe drought or ebb and "La Niña" cause flooding intense [6].

Trigg et al. [2] mention that rainfall in the Amazon has a pronounced pattern across the Amazon basin, linked to global climate processes. The Intertropical Convergence Zone (ITCZ), where winds converge from the southern and northern hemispheres, induces wet and dry periods alternately in the northern and southern sides of the basin. South of the equator there is a wet period from December to February and north of the equator the dry period is from June to August. The South Atlantic Convergence Zone (SACZ), another axis of convergent winds oriented northwest southeast across southeast Brazil and into the southwest Atlantic Ocean also increases rainfall in these areas (see Fig. 1). Such combined rainfall patterns maintain a high base flow in the Amazon River, which added to the water storage in the floodplain, contributes to each year's flood event.

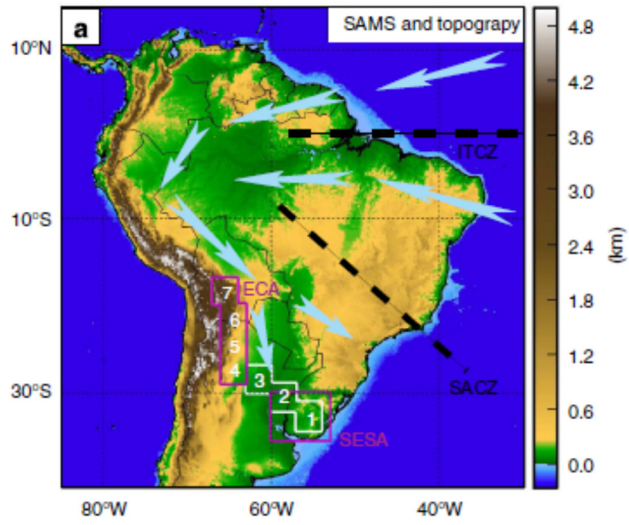

Figure 1: Geographic and climatic setting. Topography and simplified South American Monsoon System mechanisms. The boxes labelled 1 to 7 indicate the climatological propagation path of extreme events [10].

Large Amazonian rivers tend to have annual, predictable high-amplitude flood pulses, due to the seasonality of precipitation in their large catchments. Most Amazonian floodplains become inundated from January to March from which the water drains into the river systems slowly over the following months. Most of the rivers in the Amazon network reach flood levels during May to July and low levels during September to November, with variations in the average timing of peak/low discharge across the Amazon basin. The large drainage basins integrate precipitation variability; the river valley topography and wetlands attenuate and delay the flood wave. In the Central Amazon region, the maximum water level coincides with the beginning of the dry season, as the water needs 2–3 months to flow the several hundred kilometers from the headwaters to this region. Thus, interannual variability in the maximum water levels, in these free-flowing rivers, results from rainfall variability over the catchment regions in the months prior to the peak water level. Such regularity and temporal predictability enables statistical seasonal forecast models to predict the magnitude of hydrological peak water levels, which have high interannual variation [9].

Between December 2020 and January 2021, large areas of the western Amazon basin, a region that drains to Manaus and areas nearby, presented rainfall volumes above the climatology normally observed in the period (Fig. 2).

In February 2021, above-average rains were concentrated in the state of Acre, causing severe flooding in the state's municipalities, and also in cities in Amazonas close to the region, such as Ipixuna, Boca do Acre and Envira. In March, rainfall classified as "very rainy" to "extremely rainy" was observed throughout the entire western Amazon. In April, the entire Negro River basin maintained this pattern, as well as the entire region close to the Solimões main channel, and some points further south of the basin. In May, a large part of the basin presented rainfall below expectations for the period. In June, the signs were less intense, with regions scattered across the basin ranging from "trend to very dry" to "trend to very rainy".

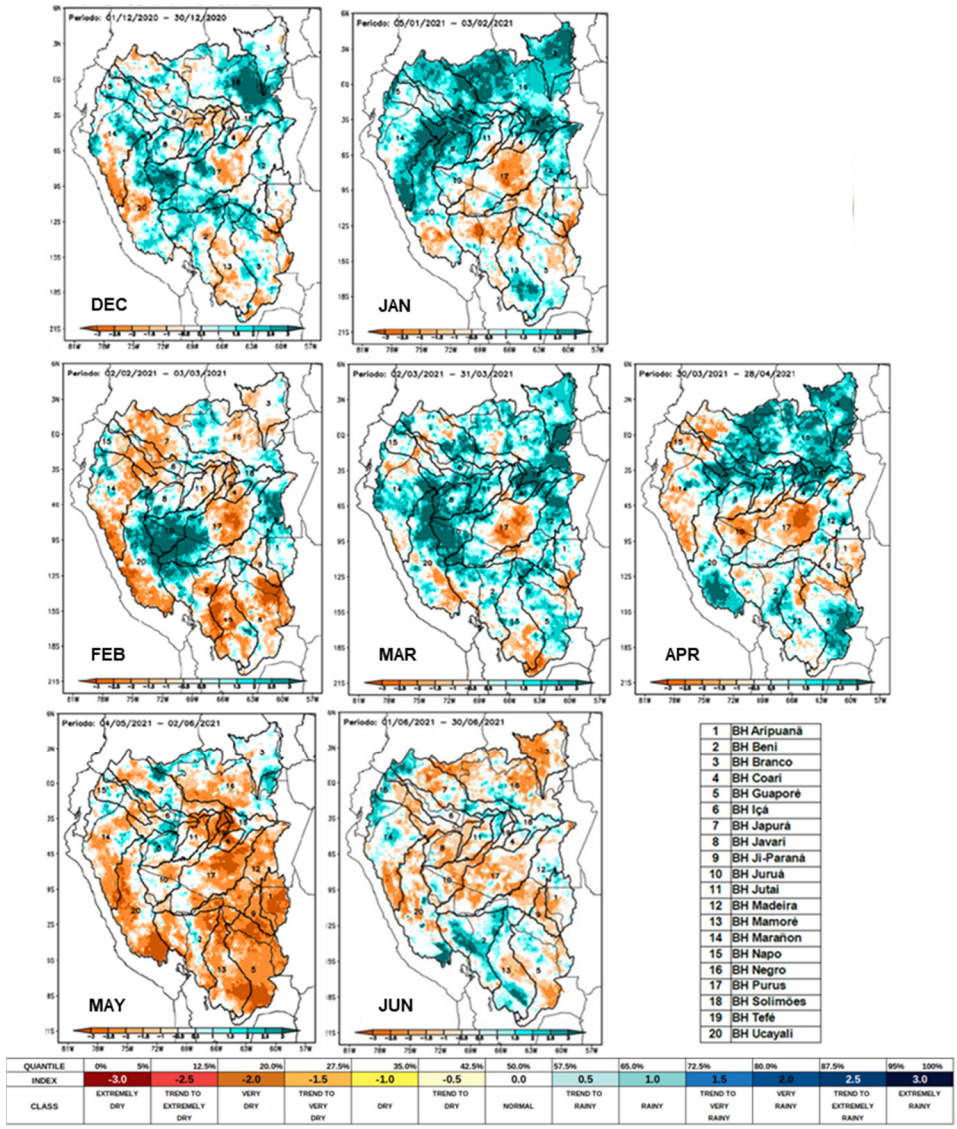

Figure 2: Monthly accumulated precipitation anomalies distribution between December 2020 and June 2021. *(Source: http://ftp.cptec.inpe.br/modelos/io/produtos/MERGE/.)*

Espinoza et al. [11] reveal that extreme flood years (1986, 1993, 1999 and 2012) are characterized by negative sea surface temperature (SST) anomalies on the central equatorial Pacific during austral summer and spring. This temperature alteration generates geopotential height anomalies over the subtropical South Atlantic and South America that contributes to a southern humidity flux anomaly over the Amazon. The climatological event "La Niña" shows a strong correlation with an increase in precipitation volumes in the region. As of the second half of 2020, the index that characterizes the event ("Oceanic Niño Index, ONI") on

the region called Nino 3.4 began to show signs of its establishment. Table 1 shows the monthly ONI values observed in 2020 and 2021, with the characteristic quarters of the phenomenon being marked in blue. From the third consecutive quarter of indices in blue, in the case at the end of the September–October–November 2020 quarter, the La Niña event was officially recognized.

Table 1: Oceanic Niño Index (ONI) in Niño 3.4 region. *(Source: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php.)*

	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2020	0.5	0.5	0.4	0.2	–0.1	–0.3	–0.4	–0.6	–0.9	–1.2	–1.3	–1.2
2021	–1.0	–0.9	–0.8	–0.7	–0.5							

The changes in the Amazonian rainfall patterns have been related to the intensification of the Hadley and Walker circulations. It was estimated a strengthened of the Hadley circulation by 1–5% in the period of 1979–2009. Substantial warming of the tropical Atlantic and simultaneously cooling of the tropical Pacific since the 1990s plays a central role in rainfall trends [12]. From the establishment of La Niña, an influence on atmospheric circulation through the Walker Cell is expected, whose main characteristic is the increase in convection and, consequently, greater cloud development and increased precipitation in different regions of the world. Over the Western Amazon, increases in precipitation are usually observed over the north of the region during the rainy season of the region (November to May), as occurred in the year 2021. These weather patterns, observed since the end of 2020, determined the great magnitude of the flood event observed in 2021, which was configured as the biggest flood in the entire history of hydrological monitoring in the state of Amazonas.

3 RIVER LEVEL

The city of Manaus, even located in the Negro River basin, is greatly influenced by the Solimões–Amazonas system, through the hydraulic backwater effect (Fig. 3). The Solimões River is the main source of the Amazon River, the behavior of the Solimões River in its more downstream stretch represents well what occurs along the westernmost stretch of the Amazon River.

In average, Negro river in Manaus takes 234 days of rising and 130 days of descent. The climb is smooth and striking, which facilitates predictability. Negro river levels have been measured since September 1902, with a historical series of 119 years. Analyzing this historical series, 6% of the floods occurred in May, 75% in June and 19% in July. The Manaus gage provides an accurate, long-term record of stage; it has been maintained at the same site by Manaus Harbor over the period of record [6].

For example, in 2009, the second highest flood at Manaus Station, not only Manaus registered a flood record in the first half of the year. At least five other locations also recorded maximum indices of their historical series and they could be presented as Manacapuru, Itapéua, Parintins, Careiro and the community called Forte de Nossa Senhora das Graças, situated in the gutter of Juruá [13]. In 2012, the flow in January was already with great measurements and this for both gutters (Negro and Solimões). In the comparison of flows, in Manacapuru, the discharges obtained in the months preceding the flood were higher than those recorded in before years. For instance, Manacapuru discharge in 2011 was 63,139 m^3/s, however in 2012 it was 105,641 m^3/s, both in January [6].

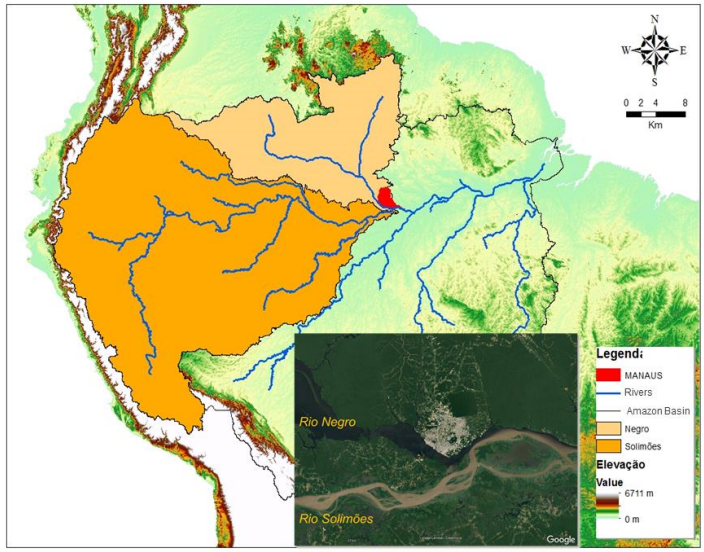

Figure 3: Manaus location in relation the main basins (Negro and Solimões).

In 2021, for the Rio Negro basin, the large volumes precipitated in December made the river level start the year with levels higher than expected. In February, normal rainfall in the drainage basin allowed for a drop in the river level. However, from March onwards, the river began to rise again, always at levels above expectations. In São Gabriel da Cachoeira, the maximum level previously observed was surpassed in May, continuing to rise to the level of 12.68 m (on 6 May 2021), 51 cm above the previous maximum. In Barcelos, the historic record was also surpassed, reaching the maximum that year (10.46 m) on 27 June 2021, also determining the largest flood of the historic series in the region. In Santa Isabel do Rio Negro (Tauruquara station), the same patterns were observed, but the historical record was not surpassed (see Fig. 4).

The pattern observed throughout 2021 at the monitored stations in the Amazon basin (Careiro da Várzea, Itacoatiara and Parintins) is similar to that observed in Manacapuru, in the Solimões river. In all seasons, river levels rose significantly between January and February 2021, and maintained an average rising pattern, which caused a river level behavior with levels significantly higher than expected over the following months.

Thus, the behavior of the river at Manaus station is similar to that observed in Manacapuru, Itacoatiara and Parintins, for example (Fig. 5). Between the months of January and February, all the excessive rain that had been precipitated in the previous months led to a significant increase in the level of the river. Since then, the combination of precipitation patterns observed in the basins that drain into the region caused, in general, a rate of rise in level considered normal over the following months. Therefore, a beginning of the year with levels higher, associated with an average subsequent ascent speed, culminated in a river level significantly higher than expected at the time when the river annually reaches its maximum level (June and July). Consequently, in 2021, Negro river level exceeded the maximum level previously observed in the entire 119-year historical series of station data. On 30 May 2021, the previous record of 29.97 m observed in 2012 was equaled. The river continued to rise until reaching the level of 30.02 m on 16 June 2021.

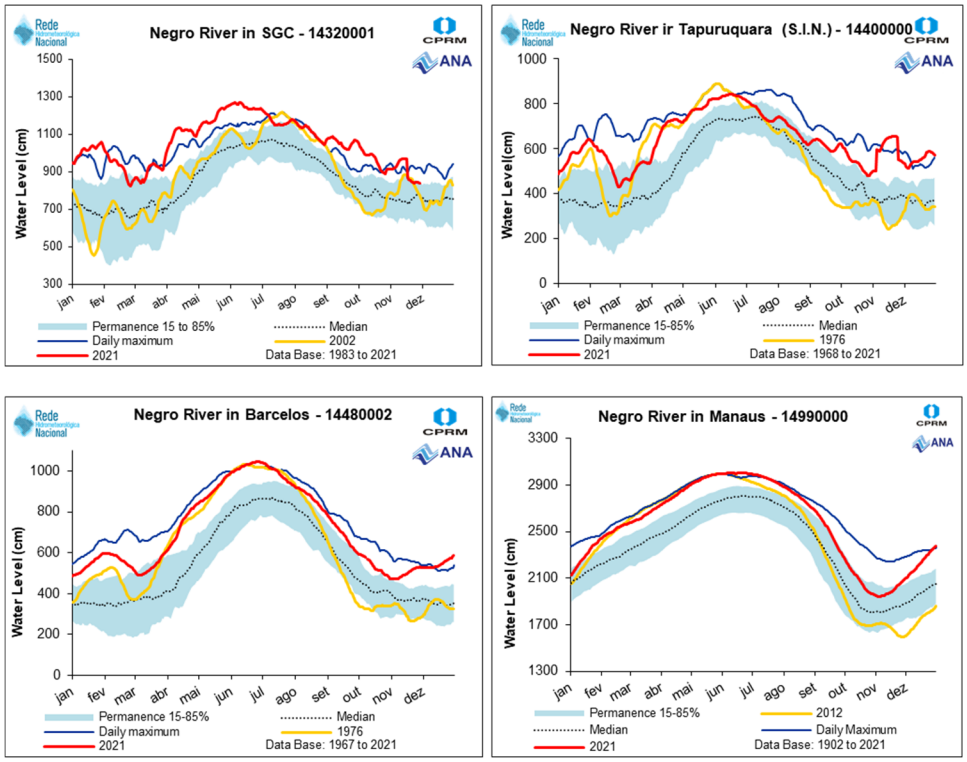

Figure 4: Negro river stations graphs during 2021. The yellow lines represents the year that the maximum level was observed before 2021.

In addition to the great magnitude in terms of impacts associated with the flooding observed that year, the event was also very expressive in terms of temporal duration, as several parts of the municipality were flooded for a long time. The flood stage, which for Manaus is considered to be 27.50 m, when the first point of its urban area begins to be flooded, was reached on 4 April 2021. The severe flood stage, however, was 29.00 m, when the central region of the municipality begins to be flooded, was reached on 30 April 2021. As the river rose much above these levels, even after the beginning of the ebb process, it took many days for the river to leave its present stage above the reference ones. The severe flood stage, for example, was yet observed until the end of July. In other words, the municipality of Manaus spent 90 days in severe flooding in 2021. In 2012, the year of the previous record flood, the river had remained approximately 75 days in this situation.

4 CPRM FORECAST

Since 1989, the Geological Survey of Brazil in Manaus has been developing the "Amazon Hydrological Alert System" where the annual flood and ebb monitoring process is performed in the Solimões–Negro–Amazonas system. Among the products generated by the project is the Manaus Flood Alert, which presents the forecast of the maximum stage to be reached by the Negro River in Manaus each year. The results are released to the relevant agencies and the press at the end of March, April and May, preceding the maximum Negro river stage, which usually occurs between June and July.

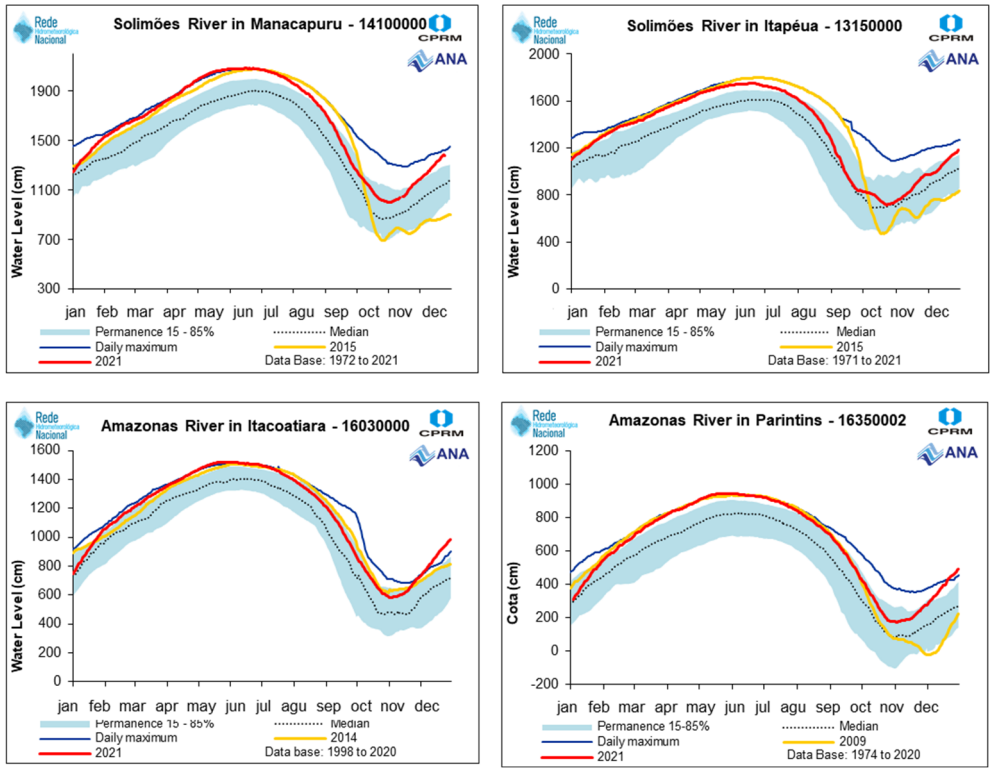

Figure 5: Manacapuru, Itapéua, Itacoatiara and Parintins graphs with a similar behavior in 2021. The yellow lines represents the year that the maximum level was observed before 2021. See Fig. 4 for Manaus graph.

The flood alert system in Manaus is a non-structural measure adopted in order to minimize the damage caused by floods and leaks in river watershed. The operation of the flood alert system in Manaus has been developing positively, with institutional cooperation from the Civil Defense, the State Government, the City Hall and the various press vehicles.

An average flood year, Negro river has increased flow in the months of May and June. Thus far Solimões has this increase in March and April. Already in an above-average flood year, the flow of Solimões grows in February.

Since 2007, the Amazonas Hydrological Alert System has been publishing the "Western Amazon Hydrometeorological Monitoring Bulletin". The bulletin provides updated information on fluviometric stations considered strategic that make up the National Hydrometeorological Network, under the responsibility of the National Water and Basic Sanitation Agency (ANA), operated by the Geological Survey of Brazil (SGB-CPRM).The rivers levels are presented, in comparison to the data of the respective historical series, in the form of maps, graphs, figures and text, in order to facilitate the understanding by the user public, composed mainly by the local press, government agencies, universities and the general population.

In addition to monitoring the level of the rivers, a climatological monitoring of the last 30 days is also presented, accompanied by a forecast of precipitation for the next 15 days, in

which the data are discretized according to the large basins of the Amazon. The rainfall monitoring data are obtained, organized and interpreted by meteorologist from the Amazon Protection System (Manaus Regional Center), through satellite data.

In 2021, many of the stations monitored in the bulletin reached historic records, which were communicated through bulletins. Table 2 presents the maximum levels observed in 2021, as well as the largest floods observed previously. Highlighted in red are the stations in which the previous records were surpassed in 2021. They are: São Gabriel da Cachoeira, Barcelos and Manaus (Negro river), Manacapuru (Solimões river), Careiro da Várzea (Amazon river basin), Itacoatiara and Parintins (Amazon river), all located in the state of Amazonas.

Table 2: Previous historical maximum quotas and those reached in 2021. Highlights indicate the stations in which the previous records were surpassed in 2021.

Station (river)	**Year related to the maximum quote**		**Year 2021**		
	Date	Quote (cm)	Date of the maximum level	Maximum level (cm)	Comparison to the maximum level before (cm)
Barcelos (Negro)	**13/06/76**	**1,032**	**27/06/21**	**1,046**	**14**
Beruri (Purus)	24/06/15	2,236	29/06/21	2,198	–38
Boa Vista (Branco)	08/06/11	1,028	10/06/21	856	–172
Caracaraí (Branco)	09/06/11	1,114	12/06/21	947	–167
Careiro (P. Careiro)	**30/05/12**	**1,743**	**06/06/21**	**1,746**	**3**
Fonte Boa (Solimões)	06/06/15	2,282	21/05/21	2,218	–64
Humaitá (Madeira)	11/04/14	2,563	10/04/21	2,248	–315
Itacoatiara (Amazonas)	**19/06/09**	**1,505**	**28/05/21**	**1,520**	**15**
Itapeuá (Solimões)	24/06/15	1,801	21/06/21	1,750	–51
Manacapuru (Solimões)	**25/06/15**	**2,078**	**17/06/21**	**2,086**	**8**
Manaus (Negro)	**29/05/12**	**2,997**	**16/06/21**	**3,002**	**5**
Parintins (Amazonas)	**31/05/09**	**936**	**21/05/21**	**946**	**10**
Rio Branco (Acre)	05/03/15	1,834	17/02/21	1,578	–256
São Gabriel da Cachoeira (Negro)	**20/07/02**	**1,217**	**11/06/21**	**1,268**	**51**
Tabatinga (Solimões)	28/05/99	1,382	07/05/21	1,282	–100
Santa Isabel do Rio Negro, Tapuruquara	02/06/76	890	17/06/21	843	–47

Geological Survey of Brazil forecasts are based on a simple linear regression, where the maximum annual stages are correlated with the forecast dates, which are 31 March, 30 April and 31 May [6]. In 2021, since the first flood alert, forecasts have indicated the possibility of a significant flood event in the studied stations. The second and third forecasts indicate an increasing probability of one of the biggest floods in the hydrological monitoring history in some cities of Amazonas. The observed results confirmed the forecasts presented, marking the year 2021 as the record flood (Fig. 6).

1st Forecast 2021	31 March	29.45 m (maximum 30.35 m)
2nd Forecast 2021	30 April	30.00 m (+/– 50 cm)
3rd Forecast 2021	31 May	30.00 m (+/– 2 cm)

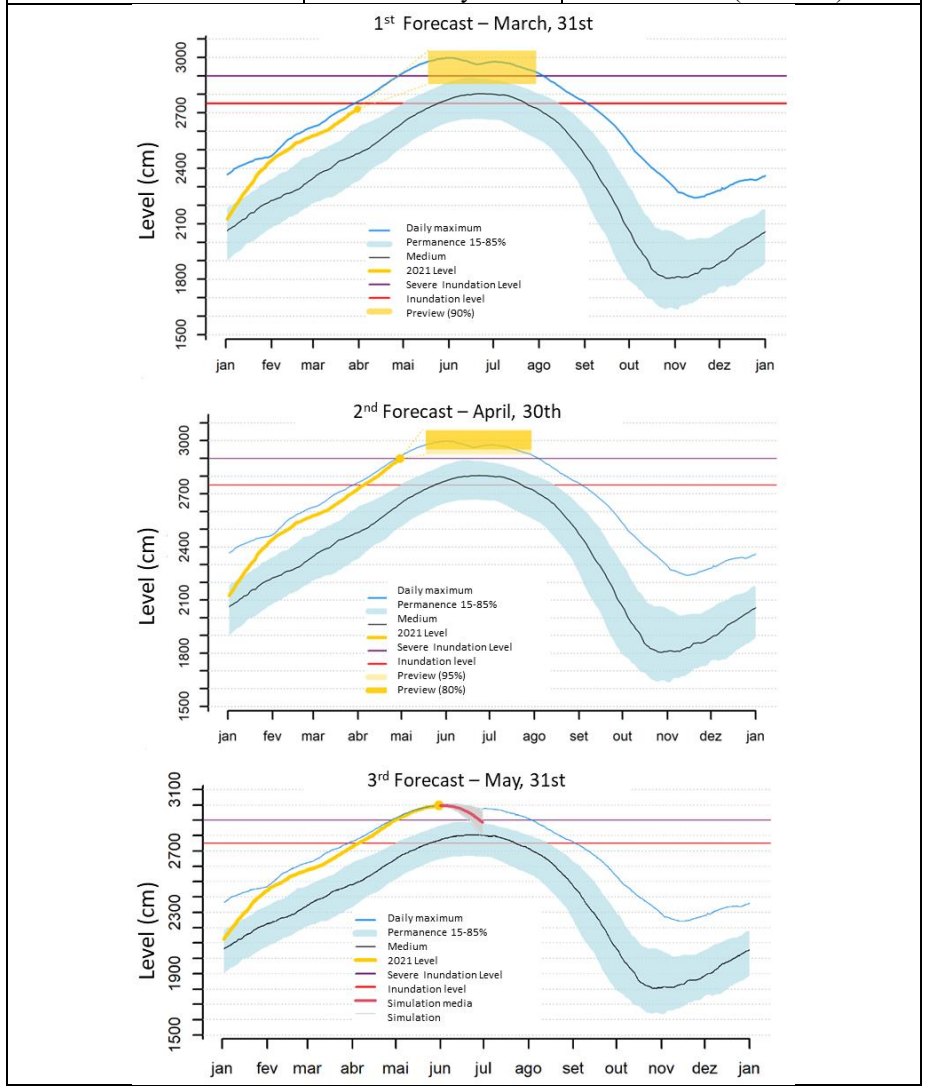

Figure 6: The flood forecast presented by Geological Survey of Brazil in 2021.

5 CONCLUSIONS

To analyze the flooding at the Manaus Station, it is necessary to monitor the evolution of the level of the rivers rising in the different stations, to know the difference between two important river flows (Negro and Solimões), in addition to understanding the dynamics of the entire basin and the other events flooding occurred on the Negro River at the Manaus Station. Considering the important historical series recorded at this station and the use of

static analysis methods with hydrological data, it was possible perform a flood forecasting model for the Manaus Station on the Negro river.

In 2021 some monitored stations in the Amazon reached river levels higher than the maximum observed until then, making this year the biggest flood in the entire history of monitoring in the state of Amazonas. This event had the contribution of a La Niña event, which increased precipitation in different regions of Amazon Basin.

Geological Survey of Brazil forecasts have indicated the possibility of a significant flood event in the studied stations. The observed results confirmed the forecasts presented (second and third), marking the year 2021 as the record flood.

In 2021, from the establishment of La Niña in the Western Amazon, increased the precipitation observed the north of the region during the rainy season from November 2020 to May 2021, as a result, we had the great flood event observed in 2021. Weather issues are considered in the forecasts, as they are reflected in the river level and in the time to the flood peak. By the way, in 2022 the Civil Defenses in Amazonas are following weather and hydrological forecasts in advance for the year flood alert.

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