Investigating The Probability of Compounding Heatwave and Extreme Rainfall Events in Brazil

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ABSTRACT

Heat waves and flooding events are deadly weather events that are expected to become more impactful as climate change continues to increase the frequency and intensity of these events, which makes it essential to better understand the relationship between heat waves and extreme rainfall events that lead to flooding. This study investigates the probability Brazil will experience an extreme rainfall event within 48 hours after a heatwave terminates. A ~10 km gridded, spatial daily temperature and precipitation dataset from 1961-2020 was used to identify heatwaves and extreme rainfall events. A heat wave is a period where the maximum daily temperature exceeds the 90th percentile for at least 3 consecutive days, while an extreme rainfall event is defined as an event where the daily precipitation accumulation exceeds the 95th percentile. São Paulo, Brazil showed the strongest compounding heatwave-extreme rainfall relationship, where the likelihood of extreme rainfall following a heatwave is increased nearly six times over the probability of extreme rainfall in general, with the extreme rainfall probability increasing from 4% to 23% following a heatwave. Brasilia displayed a slight increase in extreme rainfall probability following heatwave terminations, with the probability increasing by over twice as much compared to the climatological average probability. In contrast, for Manaus extreme rainfall very rarely occurs shortly after heatwave terminations, where only 5% of heatwave terminations are followed by extreme rainfall, which isn't higher than the general daily average of 5%. This suggests that heatwave terminations don't affect the probability of extreme rainfall events in Manaus. These heatwave-compounding extreme rainfall episodes are more prominent in the Southern cities of Brazil where the climate tends to be more seasonal with a stronger amount of temperature variability between seasons. This suggests that the southern portions of Brazil will likely experience severe impacts associated with climate change as the frequency of heatwaves continues to rise, further compounding potential extreme rainfall events in the future.

1. INTRODUCTION

Heat waves and flooding events are deadly weather events that are expected to become more impactful as climate change continues to increase the frequency and intensity of these events (Zhang et al. 2021; Mitchell et al. 2016). Heatwaves and flooding events are also responsible for affecting disease transmission rates (Barcellos et al. 2024), the mental health of a population (Stanke et al. 2012), and even food production (Week et al. 2020), this makes it essential to better understand the relationship between heatwaves and extreme rainfall events that lead to flooding, while identifying any potential compounding relationship between the two episodes.

Compound weather events are a combination of multiple weather drivers or hazards that contribute towards amplifying other weather events, which can pose a risk of multiple hazards occurring at the same time (Zscheischler et al. 2022). Compounding weather and climate events are quite common, with one notable example being the German floods in July 2021, a

flooding event that killed over 180 people that was primarily enhanced by a weak jet stream flanked by high pressure that forced the storms to move more slowly and dump heavy rain (Zscheischler et al. 2022). Climate change also played a role in compounding this flooding event, where climate change helped speed up the evaporation process while slowing the storms' forward speed down (Zscheischler et al. 2022).

Another example of this was the 2010 Russian heatwave, where the first seven months of the year brought below-normal precipitation which enhanced the likelihood and intensity of the heatwave since drier soil typically leads to higher temperatures (Zscheischler et al. 2018). The combination of the heat and dry conditions also strongly contributed to widespread wildfires in Russia during that time period (Zscheischler et al. 2018).

Climate driver interactions also contributed to Hurricane Sandy being as extreme as it was along the United States coast, causing over US$50 billion in damages and killing 233 people (Zscheischler et al. 2018). Hurricane Sandy steered toward the Northeast United States due to an unusually strong mid-latitude high pressure in combination with a trough that blocked Sandy from moving away from the United States (Zscheischler et al. 2018). Sandy would bring heavy rainfall throughout the Northeast leading to inland flooding, along with powerful winds that contributed to the historic storm surge flooding. The powerful storm surge Sandy brought also coincided with a spring high tide which only exacerbated the coastal flooding further (Zscheischler et al. 2018). The blocking mid-latitude high pressure, powerful winds, storm surge, inland flooding, and a spring high tide coinciding with each other all contributed to the coastal flooding being as extreme as it was for the Northeast (Zscheischler et al. 2018).

Due to the commonality of compound events in weather and climate, research on these events has been advancing, with numerous studies attempting to identify other potential compounding weather events in an attempt to improve the predictability and understanding of impacts associated with these episodes (Zscheischler et al. 2020).

A few studies have shown a strong correlation between heat wave terminations and extreme rainfall events (Chen et al., 2022; Li et al., 2022; Sauter et al, 2022). In one study, quality-controlled rainfall observations at an hourly scale from the Global Sub-Daily Rainfall Dataset along with daily maximum and minimum temperatures from weather stations with at least 12 years of record length were used in order to detect heat waves compounding extreme rainfall events. Based on this data, this phenomenon is most commonly found in mid-latitude regions such as Central Europe, the Northeast United States, and Japan (Sauter et al., 2023). In central Europe and along the northeast coast of Japan, it was discovered that approximately 30% of heatwave terminations are followed by at least one hour of extreme rainfall, which is a much higher probability relative to the climatological daily average probability of extreme rainfall for both regions. This phenomenon is primarily triggered by strong cold fronts that enhance atmospheric instability, convective available potential energy (CAPE), and total column water vapor (TCWV) levels, leading to heavy rain events attributed to thunderstorm development (Sauter et al., 2023).

However, this phenomenon hasn't been thoroughly investigated in Brazil since many studies primarily focus on the phenomenon on a global scale rather than on a localized scale. Extreme rainfall events tend to be very impactful for the country, with 74% of deaths related to natural disasters in Brazil attributed to extreme rainfall events inducing flooding and mudslides (Debortoli et al. 2017). Brazil's urban environment and infrastructure where the majority of the population lives is also highly vulnerable to extreme weather events such as flooding and heatwaves. With the frequency of heatwaves increasing gradually in Brazil especially in cities such as Sao Paulo, Manaus, and Brasilia due to climate change and increased urbanization (Geirinhas et al. 2018), investigating this phenomenon at a more localized, detailed level is crucial to better understand the potential impacts of rainfall events following heatwave terminations for the country.

2. Data & Methods

The primary data used in this project is a gridded, spatial dataset of daily maximum and minimum temperatures from the Brazilian Daily Weather Gridded Data (BR-DWGD), recorded from January 1961 through July 2020 from 1,252 weather stations across Brazil to identify heatwave events (Xavier et al. 2022). Precipitation data from 11,473 rain gauges over the same time period was also used to identify extreme rainfall events, more specifically immediately after heatwave terminations. The temperature and precipitation dataset had a spatial resolution of 10km (Xavier et al 2022).

In this study, an event is categorized as a heatwave if the maximum daily temperatures exceed the 90th percentile threshold for at least three consecutive days in the specified location. For a rainfall event to be categorized as an extreme rainfall event after heatwave termination, the daily total precipitation must exceed the 95th percentile threshold within a 48-hour period after a heatwave terminates. The extreme rainfall probability was separated between three different cities in Brazil, including Sao Paulo, Brasilia, and Manaus. This was done to give a more tailored probability of extreme rainfall events following heatwave terminations for each specific city, whose probability may vary significantly compared to other cities with different climates.

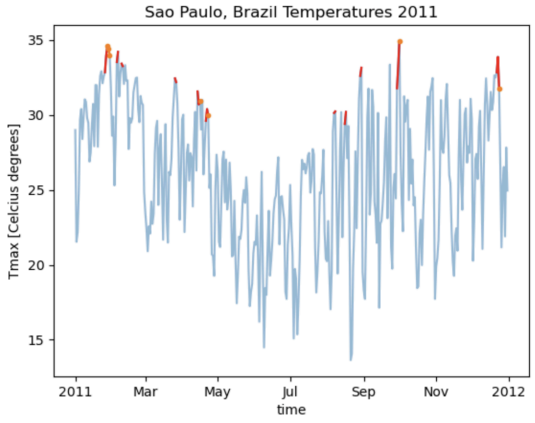

Figure 1: Line graph of daily maximum temperatures in Sao Paulo, Brazil for 2011. The red shaded lines represent heat waves detected in the temperature data.

To investigate the probability of compound heatwave and extreme rainfall episodes, the function 'xarray' in Python code was implemented to extract heatwave events and the precipitation data within 48 hours after the final day of the heatwave for each region of Brazil using the specified threshold. The graph shown in Figure 1 shows an example of this by using the daily maximum temperature data to detect heat waves, and shades the heat waves detected in red. The number of extreme rainfall events after heat waves was divided by the total number of heat waves that occurred during the specified timeframe to determine the probability of an extreme rainfall event following heat wave termination. That probability was then compared to the daily climatological average probability of extreme rainfall to determine the probability of extreme rainfall after heat waves relative to the climatological average for each region. A map of the annual mean amount of heatwave events for Brazil was created to investigate the frequency of heatwaves for different areas of Brazil and how it can potentially affect the frequency of extreme rainfall events for specific areas. Daily maximum temperature graphs ranging from 1961 through 2020 were compared to the long-term average temperature between 1961 and 2020, along with daily precipitation graphs created to analyze any extreme rainfall frequency trends correlated with the rising temperatures.

3. Results

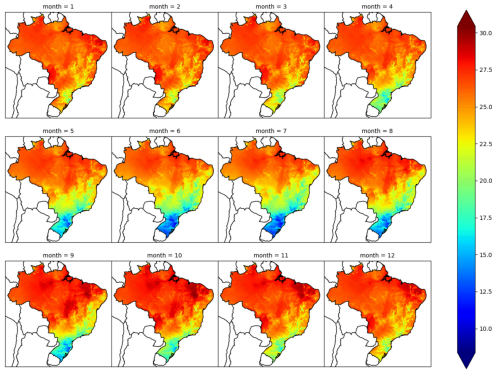

Figure 2: Maps of mean annual maximum daily temperatures for Brazil between 1961-2020 by month, with Month 1 representing January and Month 12 representing December.

The average temperature map from Figure 2 shows that the average temperatures in the northern half of Brazil primarily remain steady year-round, with the average annual maximum temperature hovering near 26C. The southern half of Brazil tends to have a more temperate climate, with temperatures ranging nearly 10C between the summer and winter months in the region.

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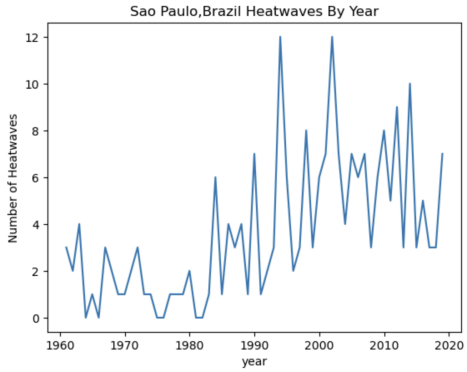

Figure 3: Line graph of the number of heat waves by year for Sao Paulo, Brazil between 1961-2020.

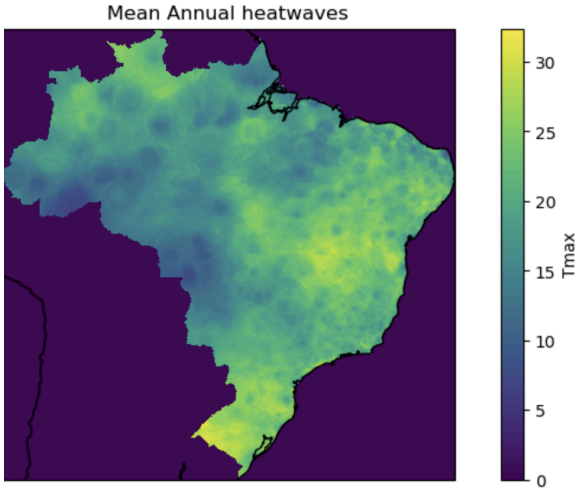

Figure 4: Map of mean annual heat waves for Brazil between 1961-2020.

The mean annual heat wave map from Figure 4 shows that from 1961 through 2020, the southern and eastern portions of Brazil experienced the highest mean annual amount of heat waves while the northwestern portion of the country on average experienced the least amount of annual heat waves. Since 1961, the frequency of heatwaves has been steadily increasing throughout the country including in cities such as Sao Paulo, Manaus, and Brasilia as shown on Figure 3 and Figure 4. Based on the heat waves by year graph from Figure 3, for Sao Paulo between the years 1961-1990, there were only two years where the number of heatwaves reached or exceeded six. However, between the years 1991-2019, Sao Paulo had 13 years where the number of heatwaves exceeded six for the year, indicating a strong trend towards the frequency of heat waves increasing.

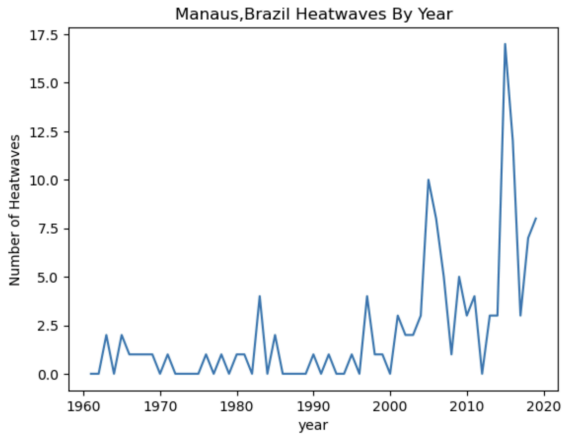

Figure 5: Line graph of the number of heat waves in Manaus, Brazil between 1961 and 2020.

In Manaus, Brazil, only 5% of heatwave terminations result in an extreme rainfall event, indicating no noticeable increase in probability compared to the climatological average. For Sao Paulo, Brazil, extreme rainfall is significantly more likely preceding a heatwave, where the probability of extreme rainfall after a heatwave termination is approximately 23% which is 5.75 times higher than the daily climatological average probability of extreme rainfall in Sao Paulo. In Brasilia, 8.6% of heatwaves are followed by extreme rainfall, which is a slight increase compared to the climatological average probability of 3.9%

4. Discussion

Based on the data, heatwaves in Brazil appear to occur more frequently in the more temperate regions in comparison to the warmer, more tropical areas further northward. Extreme rainfall events following heat waves were also

more commonly found in the southern cities in Brazil where the climate is more temperate. This indicates that the southern portions of Brazil, where the climate is more seasonal, will likely experience more noticeable and severe impacts associated with climate change as the frequency of heat waves continues to rise.

However, a more detailed analysis that investigates heatwave periods and precipitation data by day must be investigated before it can be determined whether or not this compounding effect occurs in Brazil.

In Manaus, Brazil between the years 1961 through 2020, extreme rainfall events following heatwave terminations very rarely occurred, with only 5% of heatwave terminations resulting in immediate extreme rainfall, which is the exact same percent as the climatological average probability. This gives a strong indication that the compounding heatwave and extreme rainfall episodes very rarely occur in Manaus. In São Paulo, Brazil, extreme rainfall is significantly more likely following a heatwave, The dramatic increase in extreme rainfall events preceding heat waves in Sao Paulo raises the concern that extreme rainfall events will significantly increase in frequency coinciding with the rise in heatwave frequency due to climate change, enhancing the risk of devastating flooding
events in an already highly vulnerable area. In Brasilia, 8.6% of heatwaves are followed by extreme rainfall, which is a slight increase compared to the climatological average probability of 3.9%. The dramatic increase in extreme rainfall events preceding heat waves in Sao Paulo and Brasilia raises the concern that extreme rainfall events will significantly increase in frequency coinciding with the rise in heatwave frequency due to climate change, enhancing the risk of devastating flooding events in already highly vulnerable areas.

However, the results likely depend on the exact definition of a heatwave and of an extreme rainfall event. This study exclusively used maximum daily temperature as opposed to using both daily minimum and maximum temperature, which may have affected the results by including heat wave periods that may not meet the criteria when it comes to their minimum temperatures. This study also defined heatwave periods and extreme rainfall days using the 95th percentile for the precipitation data and the 90th percentile threshold for the temperature data, which might not be interpreted as a heatwave or extreme rainfall in other studies. Additionally, the data used has limitations in terms of the area it covers, more specifically in the Amazon rainforest where the area density of weather stations is very limited and uses interpolation to fill in the missing gaps of weather stations in certain areas.

5. Conclusions

The purpose of this study was to analyze the probability different cities in Brazil experience an extreme rainfall event within 48 hours after a heatwave terminates to better understand the potential impacts of rainfall events following heatwave terminations for the country at a more localized, detailed level. Based on the data, the results indicate that extreme rainfall very rarely occurs shortly after heatwave terminations in Manaus, Brazil, suggesting that a compounding extreme rainfall after heat waves has a low probability of occurring in Manaus. In São Paulo, 23% of heatwaves are followed by extreme rainfall, which is a significantly higher probability compared to the daily climatology probability of 5%. These heatwave-compounding extreme rainfall episodes are more common in the Southern cities of Brazil where the climate tends to be more seasonal with a stronger amount of temperature variability between seasons. This indicates that the southern portions of Brazil will likely experience severe impacts associated with climate change as the frequency of heat waves continues to rise along with extreme rainfall events.

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