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Exploratory analysis of atmospheric modelling use over Pantanal wildfires

Análise exploratória do uso da modelagem atmosférica sobre os incêndios florestais no Pantanal

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Abstract

The study discusses in an exploratory way the atmospheric conditions leading to several fires in the Pantanal on November 12, 2023. These episodes were marked by two periods of maximum fire expansion, first in the early afternoon and another in the evening. The study is based on a set of observations from satellites and weather stations, which helped to identify these fires and some meteorological conditions at the surface. In addition, the Fire Weather Index (FWI) in the Pantanal was analyzed for a 44-year period. However, this dataset was not enough to completely explain the fire behavior on that day. In this context, atmospheric modeling was applied to find the possible causes of fire behavior in these two periods. The Meso-NH model was run with two nested domains of horizontal resolutions of 2500 m and 500 m. The results showed a positive trend of FWI in the last decades and a clear seasonality for the maximum values in 2023. Also, the simulation indicated favorable weather conditions for fire ignition, given the high temperatures and low relative humidity. However, the wind gust field showed moderate gusty winds in both periods but caused by different forces. In the early afternoon, the larger scale circulation favored fire propagation, whereas in the evening fire spread by a gust front. Furthermore, the findings highlight the role of weather conditions on a sub-daily scale, with sudden changes in surface winds throughout the day, which is strongly recommended to be considered when examining fire danger and firefighting action plans in the region.

Keywords:

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Active Fire, FWI, Meso-NH model, Gust fronts, Fire meteorology.

Resumo

O estudo discute de forma exploratória as condições atmosféricas favoráveis à evolução dos incêndios florestais no Pantanal em 12 de novembro de 2023. Esses episódios foram marcados por dois períodos de rápida expansão do fogo, primeiro no início da tarde e outro à noite. O estudo usa um conjunto de observações de satélite e estações meteorológicas, as quais ajudaram a identificar o fogo e algumas condições meteorológicas na superfície. Além disso, o *Fire Weather Index* (FWI) no Pantanal foi analisado para um período de 44 anos. No entanto, esse conjunto de dados não foi suficiente para explicar completamente o comportamento do fogo naquele dia. Nesse contexto, a modelagem atmosférica foi aplicada para encontrar as possíveis causas do comportamento do fogo em dois períodos. O modelo Meso-NH foi configurado com dois domínios aninhados e resoluções horizontais de 2500 m e 500 m. Os resultados mostraram uma tendência positiva do FWI nas últimas décadas, bem como uma clara sazonalidade para os valores máximos no ano de 2023. A simulação indicou condições favoráveis à ignição do fogo, e o campo de rajadas de vento mostrou ventos moderados em ambos os períodos, mas causados por diferentes forçantes. No início da tarde, a circulação em grande escala favoreceu a propagação do fogo, enquanto à noite uma frente de rajada foi observada. O estudo destaca o papel das condições meteorológicas na escala sub-diária, em particular para mudanças repentinas do vento à superfície ao longo do dia. Esse resultado deve ser considerado ao examinar o perigo de fogo e o planejamento das ações de combate aos incêndios na região.

Palavras-chave:
Focos de calor, FWI, Modelo Meso-NH, Frentes de rajadas, Meteorologia dos incêndios.

I. Introduction

In the context of current climate change, increased wildfire activity is foreseeable during the next decades in different parts of the world. Burton (2024) demonstrated that climate change is driving an increase in burned areas across most regions, particularly during peak fire seasons. Numerous studies have explored the connection between climate change and specific regions. For instance, Senande-Rivera et al. (2025) examined its impact on the rate of spread (ROS) in the Iberian Peninsula, finding that Northern Portugal and Southern Galicia exhibit the most significant variations in ROS. Abatzoglou & Williams (2016) estimated that anthropogenic factors doubled the expected burned area between 1984 and 2015 in the Western US. Similarly, Chang et al. (2024) provided evidence of increased fire activity in South Korea. Additionally, research has linked heatwaves and droughts to intensified fire seasons (e.g., Parente et al., 2018). Climate change is also expected to create favorable conditions for the development of severe fires in Australia, in particular due to a shift in the fire season associated with the pyro-convection phenomenon (Dowdy, 2018; Dowdy et al., 2019; Di Virgilio et al., 2019), but the trend may still be divergent between different ecoregions (Bradstock et al., 2014). The same

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scenario is expected for wildfire danger and activity in southern Europe (Dupuy et al., 2020), where climate change may also shift the burning season, as indicated by Couto et al. (2022). This study investigated the unusual winter fire event in January 2022 in Portugal, revealing how climate variability can lead to increased fire activity even in winter months.

In addition to climatic conditions conducive to fire, the wildfire system is composed of several components that can interact between them to create extreme events on a smaller temporal scale. The fire can grow induced by factors such as fuel and topographic aspects or meteorological conditions (e.g., Sharples, 2009). In this context, geoinformation is important to explore specific surface and fire aspects, but not enough to explain the dynamics of some events. Meteorology plays an important role in fire behavior, being able to suppress or intensify the combustion process. If fuel is available to burn, the fire can lead to a situation in which combat becomes dangerous or very difficult. In many cases, the large fire development can be directly linked to large-scale meteorological configurations (e.g., Raphael, 2003; Rolinski et al., 2019), that can influence fire behavior, or lead to favorable conditions through changes in the fuel's moisture condition.

Following the growing cause of concern about the impact of weather conditions on extreme fire frequency, there has been considerable effort in developing fire forecasting tools to help decision makers and firefighters. The atmosphere-fire models are an excellent approach examples that can help firefighters (e.g., Bakhshaii; Johnson, 2019), mainly because some fires can be related to strong convective processes and the formation of convective clouds (pyrocumulus or pyrocumulonimbus). These clouds can play a key role in the fire front's evolution, and it is already possible to represent this extreme environment from these coupled models when configured in very high temporal and spatial resolution. For instance, the development of a fire-generated thunderstorm during the Pedrógão Grande's fire, Portugal, was produced by the MesoNH/ForeFire code (Couto et al., 2024a), whereas the ACCESS-Fire model simulated pyrocumulonimbus clouds in two extreme wildfire events in Australia (Peace et al., 2022; Peace et al., 2023). Essentially, these studies highlight how wildfires influence local atmospheric conditions, revealing intense convective activity and associated cloud microphysics that enhance the understanding of such extreme events.

The Pantanal biome includes Brazil's border with Paraguay and Bolivia in the tropical latitudes, being the world's largest freshwater wetland with a seasonally flooded plain (Pott; Pott, 2004; Boin et al., 2019; CENTRE/UNESCO, 2025). The Pantanal's fires in the last years raised several questions about climate change and biome preservation, mainly in terms of sustainable development and biodiversity. The Pantanal is a vital habitat for countless species, and, in 2020, it was devastated by the occurrence of uncommon large fires (e.g., Libonati

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et al., 2022; Silva et al., 2024) with an unprecedented loss of biodiversity (Tomas et al., 2021; Mataveli et al., 2021; De Barros et al., 2022). From a tourism perspective, it is well recognized that these regions affected by wildfires, with the consequent loss of biodiversity, suffer impacts on the visitors' number and their image by losing their attractive activities (Kim; Jakus, 2019; Carrillo et al., 2022; Andrade et al., 2023), with also consequent risks to local communities (e.g., Silva et al., 2023). In addition to the immediate reduction in the number of visitors, frequent and devastating fires may lead to a structural change in the tourism profile of the Pantanal. According to Thapa et al. (2013), environmental degradation may alter visitor behavior and motivation, as well as compromise international certifications that drive sustainable tourism in the region.

Therefore, fires in Pantanal are an example of the wildfire system's complexity, and the use of different data sources is essential to understand the fire dynamics. The application of geoinformation systems is crucial for planning and/or management, being very useful in fire activity identification. On the other hand, atmospheric modelling can be a valuable methodology to represent the weather conditions on a sub-daily scale, capturing meteorological phenomena that occur at smaller spatial scales. Furthermore, the fact that climate change can have a high impact on fire weather conditions, exploring the current meteorological wildfire risk for the Pantanal region is also relevant to get a broad perspective of the fire dynamics.

The present study aims to discuss the main atmospheric conditions favorable to the evolution of some fires in the Pantanal wetland on November 12, 2023. Moreover, the Fire Weather Index in the Pantanal region for the last decades was analyzed to draw a picture of the current state of the fire danger. The manuscript is organized as follows: Section 2 describes the data and methodology, whereas the results are presented and discussed in Section 3. The concluding remarks are presented in Section 4.

II. Data and Methodology

This section describes the dataset used in this study, which consists of satellite observations, weather station data, and the description of a high-resolution numerical experiment.

Geoinformation data

Active fire information allows the identification of the fire location through satellite remote sensing. The Advanced Baseline Image (ABI) sensor aboard GOES-16, a meteorological geostationary satellite administered by the National Oceanic and Atmospheric Administration (NOAA), provides information at high temporal resolution (around 10 min). The Instituto Nacional de Pesquisas Espaciais (INPE) holds and disseminates an active fire database with information from various sensors called BDQueimadas available online

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(https://terrabrasilis.dpi.inpe.br/queimadas/bdqueimadas/). The data used in this work was retrieved from this database for 12 November 2023, over the Pantanal region.

Weather Observations

The hourly observational data from two weather stations located in Mato Grosso do Sul State, namely the Nhumirim (A717), and Aquidauana (A719) stations (Figure 1), are used to validate the model outputs. The data is available online (INMET, 2025) and obtained from the Instituto Nacional de Meteorologia (INMET). The study concentrates on meteorological variables related to fire danger, i.e., air temperature and relative humidity at 2 m, as well as wind gusts at 10 m.

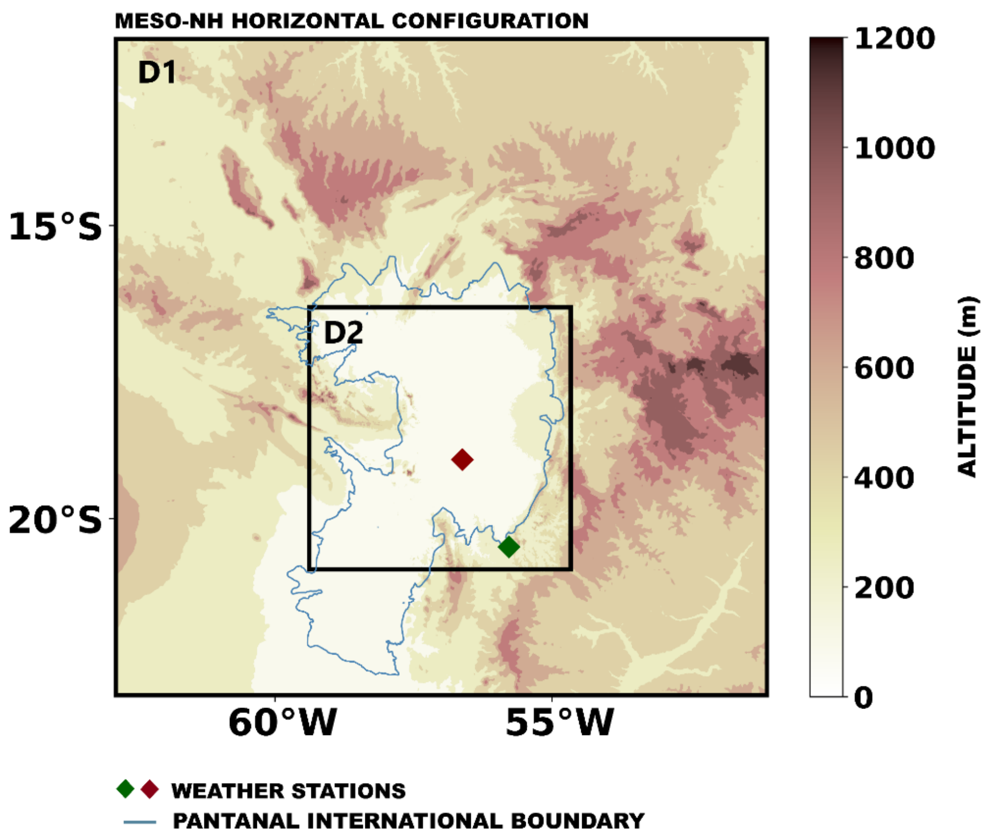

Figure 1 – Model configuration covering the Pantanal. The larger domain (D1) at 2.5 km horizontal resolution and the inner domain (D2) at 0.5 km grid spacing. Topography obtained from the Shuttle Radar Topography Mission (SRTM) database. Nhumirim (A717) and Aquidauana (A719) weather stations are represented by red and green icons, respectively.

Fire Weather Index data

The Canadian Forest Fire Weather Index System (CFFWIS), known as the Fire Weather Index (FWI), comprises six indices that quantify the effects of fuel moisture and wind on fire behavior (Van Wagner, 1987).

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The indices are calculated based on temperature and relative humidity values, both at 2 m and wind intensity at 10 m and accumulated precipitation over 24 h. To summarize, the FWI is a meteorological indicator of wildfire risk. The FWI data analysis was conducted in three parts that are explained below.

In the first part, historical data was used, and in this context, the dataset was produced by the European Center for Medium-Range Weather Forecasts (ECMWF) in its computational centre for the prediction of fire risk of the "Copernicus Emergency Management Service - CEMS" (FWI - ERA5 dataset: https://doi.org/10.24381/cds.0e89c522). The dataset provides a complete historical reconstruction of meteorological conditions favorable to the initiation spread, and maintenance of fires. The fire risk metrics provided are part of a dataset produced by the CEMS for the European Forest Fire Information System (EFFIS). EFFIS incorporates fire risk indices for three different models developed in Canada, the United States and Australia. In the dataset, fire risk indices are calculated using weather forecasts from historical simulations provided by the ECMWF ERA5 reanalysis. Here, gridded FWI data with a horizontal resolution of 0.25° x 0.25° are used, as well as temporal coverage from 1980 to 2023 (44 years) with daily temporal resolution. The interannual variability between 1980 and 2023, the intra-annual variability during 2023 and the daily variability of November 2023 from the FWI over the Pantanal region were considered.

Atmospheric modelling

This study uses the Meso-NH model (Lac et al., 2018), which is implemented with a rather complete parametrization package of sub-grid scale physical processes in the atmosphere, whereas the near-surface meteorological variables are obtained from the externalized platform of surface models coupled to the model, SURFEX (Masson et al., 2013).

In Portugal, Meso-NH has been successfully used in several research fields, related to precipitation over complex terrain (e.g., Couto et al., 2016), emission and transport of mineral dust (e.g., Couto et al., 2021), fire-generated thunderstorms (Couto et al., 2024a), fire meteorology (e.g., Couto et al., 2020), among others. On the other hand, Couto et al. (2024b) used the model to study unexpected fire behavior in the Pantanal. Concerning the previous study of Couto et al. (2024b), the simulation performed in the present study has an increased horizontal resolution. The convection-permitting simulation was configured into two domains as shown in Figure 1. The larger domain (D1) was designed with 500 × 500 grid points at 2.5 km resolution (1250 km × 1250 km). However, a large inner domain (D2) was configured with 500 m resolution (1000 × 1000 grid points; 500 km × 500 km). The vertical grid is not equally spaced and configured with 50 sigma levels, stretching gradually from 30 m, near the bottom, to 900 m, near the top. The simulation performed in a two-way

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interactive mode was initialized and forced using the ECMWF analysis updated every 6 h, with a spatial resolution of around 9 km (Lang et al., 2023).

The simulation was configured with the standard package of physical parameterization of the model, which considers a set of physical processes occurring in the atmosphere, such as convection, shallow convection, cloud microphysics, turbulence, among others. The deep convection was assumed to be explicitly resolved, and the shallow convection parameterized using the Eddy Diffusivity Kain-Fritsch (EDKF) scheme (Pergaud et al., 2009). The parametrization of cloud microphysics was made using the one-moment ICE3 scheme (Pinty; Jabouille, 1998), which can represent six categories of the water substance (water vapor, cloud water, rain, graupel, snow, and ice crystals). The turbulence scheme based on a 1.5-order closure was used (Cuxart et al., 2000), with only the vertical fluxes considered in the 2.5 km domain, while the full 3D turbulent fluxes scheme was activated in the inner 500 m resolution domain. Radiation parameterization is based on the Rapid Radiative Transfer Model (Mlawer et al., 1997). Finally, fire effects are not considered in these experiments.

Furthermore, the model incorporates different types of land cover, enabling it to represent the topography and landscape features of each location. Soil composition is assumed to be uniform in depth but varies horizontally, defined by its sand and clay fractions. The experiment used standard databases for land cover (ecoclimap_v1.9, Masson et al. (2003)) and soil type (Harmonized World Soil Database—HWSD v1, global, (Nachtergaele, 2025)), while the topography was obtained from the SRTM database (SRTM, 2025).

The model temporal integration started with the outer domain (D1) on 12 November at 0000 UTC, whereas the simulation with 500 m resolution (D2) began at 0600 UTC. The first 6 hours were considered the simulation spin-up period. The experiment ran until 13 November 2023, at 0000 UTC, totaling 18 hours simulated with 500 m resolution in a large domain and hourly outputs. The currently limited number of weather stations is insufficient for validation through statistical indices, such as the mean error or root-mean-squared error. Therefore, the model's performance was evaluated, comparing between observed data on air temperature, relative humidity, and wind gusts from two weather stations encompassed by the inner domain. The ability to represent near-surface meteorological variables is presented in Figure 2.

It is noteworthy that at weather station A717, the model overestimates temperatures mainly during the afternoon of November 12, 2023 (Figure 2a), whereas the air temperature was underestimated by the model in A719 until 1600 UTC of November 12, 2023 (Figure 2b). Regarding relative humidity, Figure 2c shows that the model underestimated the observed values in A717 throughout the verification period, except between 1200 and 1400 UTC. In contrast, there was an overestimation of the relative humidity by the model in station A719,

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except from 1800 UTC on November 12, 2023 (Figure 2d). For wind gusts, the model effectively captures the behavior of the variable throughout the day (Figure 2e), which is slightly underestimated in the early afternoon (Figure 2f). The wind gusts observation was overestimated by the model at the end of the simulation in both weather stations. It is noteworthy that these weather stations are distant from the fire events. However, despite some under- or overestimation, the behavior of the meteorological variables was well captured by the model throughout the day.

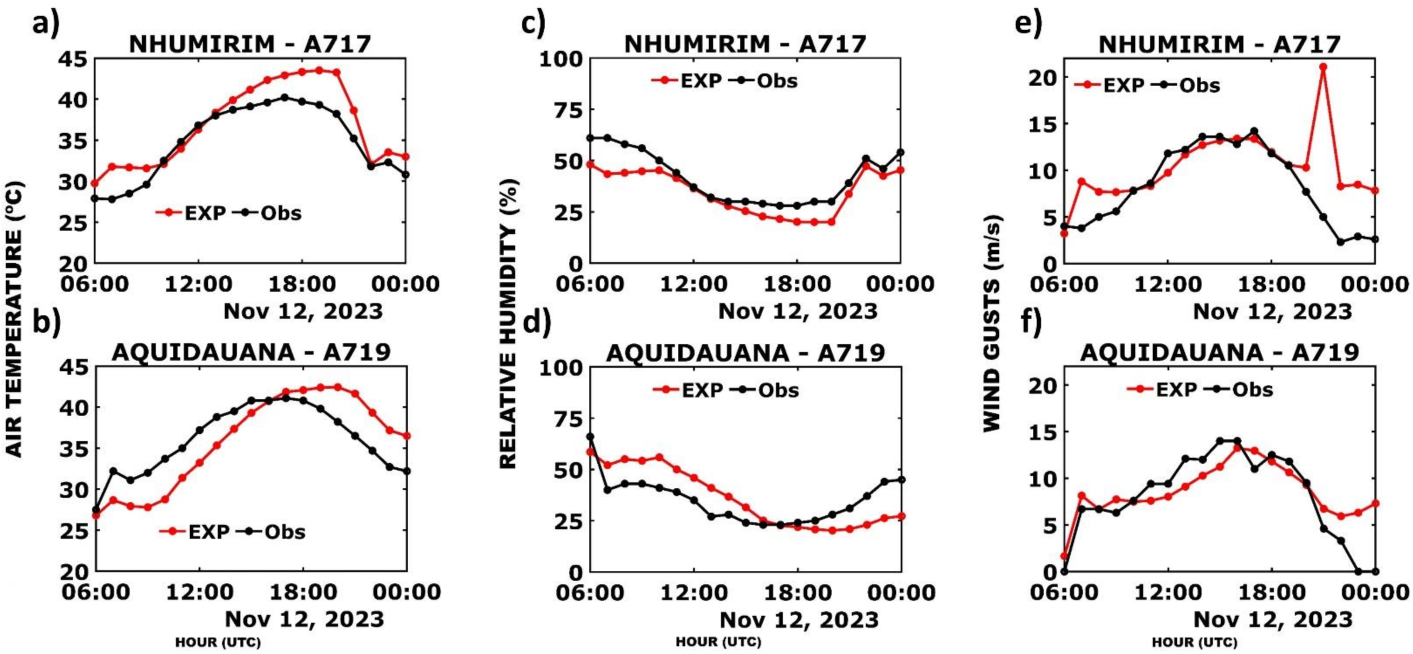

Figure 2 – Comparison between model at 500 m resolution and observation for the 18 h of simulation: a) – b) air temperature at 2 m, c) – d) relative humidity at 2 m, and e) – f) wind gusts at 10 m.

III. RESULTS AND DISCUSSION

FWI climatology analysis

This subsection introduces an analysis of the FWI index for the Pantanal region. Figure 3 shows the evolution of the FWI's annual average between 1980 and 2023. Figure 3a presents the trend analysis of FWI historical data for the Pantanal over a 44-year period (1980 – 2023). The region shows a positive trend, with annual average FWI showing an increasing fire risk in recent decades. Over the last 40 years, the trend of the average FWI increased from 6 to 16. Since 2000, there has been an increase in the frequency of years with higher FWI values (with values above 15, Figure 3a), and 2020 presenting the maximum value.

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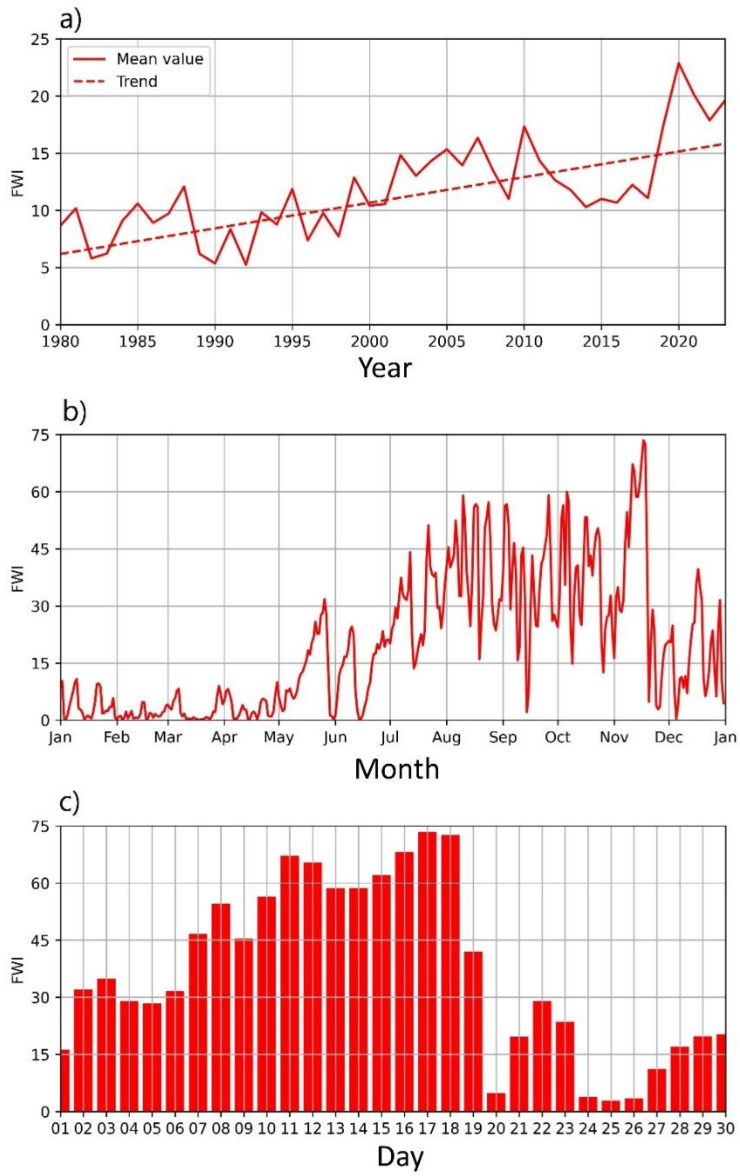

Figure 3 – Fire Weather Index in the Pantanal: a) annual average between 1980 and 2023, b) monthly average during 2023, and c) daily average during November 2023.

On the other hand, when analyzing only the 2023-year, Figure 3b shows the FWI monthly average distribution in the Pantanal region, revealing a seasonal pattern on the intensity of the meteorological fire risk in the region. The same figure shows a first peak in late May and a significant increase in the FWI from July onwards, with a maximum in November. Figure 3b also confirms that the winter and spring seasons are critical periods for fire activity in the region and that November 2023 can be highlighted by the highest fire risk.

When considering the daily average FWI, Figure 3c indicates extreme values in the middle of November, with a maximum above 70 on the 17^{th}. However, it is worth noting that November 12^{th} presents a FWI daily

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average above 60, being among the 6 days with the highest FWI in the month. This day was also preceded by a day with an extreme fire risk.

Fire outbreaks on November 12th 2023

Fire identification by satellite is shown in Figure 4, which illustrates the active fire spatial distribution throughout November 12th, 2023. It is possible to identify a region with a high active fire concentration in the Pantanal southern region, occurring essentially on the late afternoon of November 12th. This is the event previously studied by Couto et al. (2024b), which extended until November 15th 2023. Despite this, the present study highlights two extensive regions with active fire in the northern Pantanal on November 12th. The active fire spatial and temporal distribution indicates that there were two periods in when the fire spread rapidly: the first one between 1200 UTC and 1500 UTC (PERIOD I), and the second period after 2100 UTC (PERIOD II).

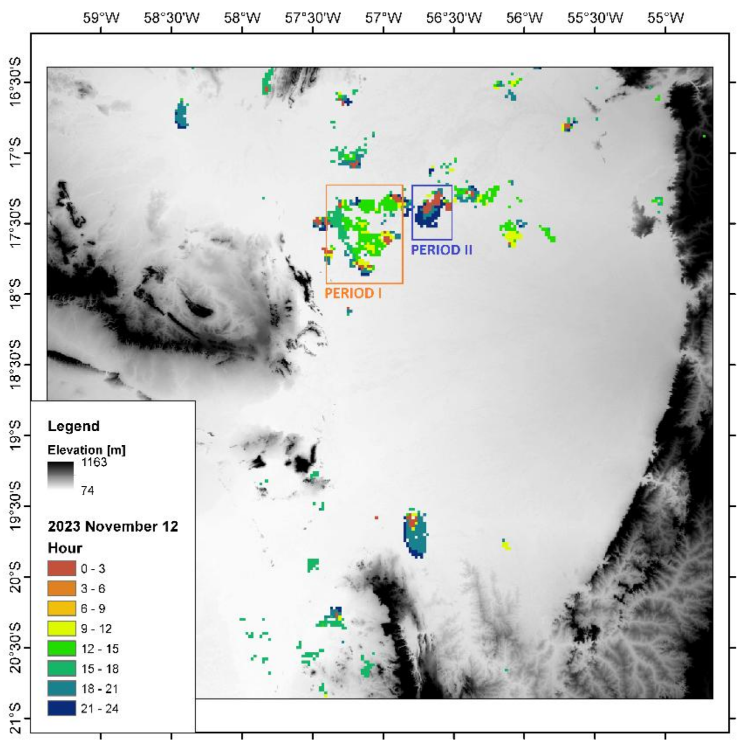

Figure 4 – Active fire spatial distribution from GOES-16 on November 12th 2023.

Fire meteorology

This sub-section explores the meteorological dynamics in the northern region of the Pantanal based on the simulation at 500 m resolution, seeking to find answers to the high active fire concentration and extensive burned area throughout November 12th. The meteorological analysis is divided in two periods based on Figure 4: PERIOD I (early afternoon) and PERIOD II (early evening).

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PERIOD I: Fire Weather

Figure 5 shows the spatial distribution of temperature, relative humidity near the surface at 1400 UTC, and wind gusts at 1300 and 1400 UTC. The temperature presents a greater spatial extension of values around 40 °C (Figure 5a). In addition, the largest portion of the Pantanal has relative humidity values below 40 % during this period (Figure 5b). Regarding near-surface winds, weaker wind gusts were simulated during the morning (not shown), but the wind gusts intensified from the end of the morning, reaching speeds above 10 m/s over the Pantanal throughout the afternoon. Figures 5c and 5d show a northerly flow affecting the fire region. This result for the first period indicates meteorological conditions conducive to fire in the early afternoon.

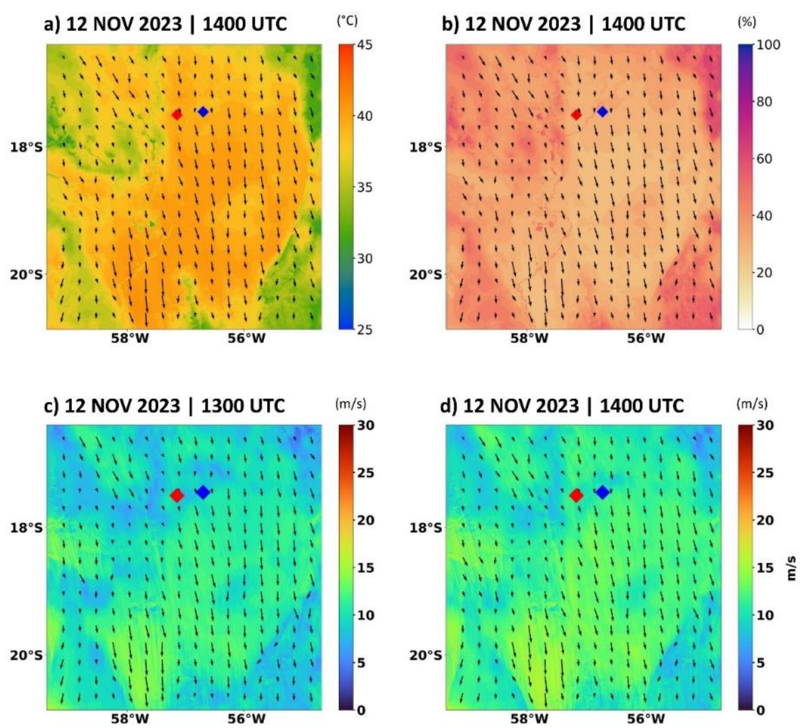

Figure 5 – Meteorological elements simulated at 500 m resolution during the Period I: a) temperature at 2 m, b) relative humidity at 2 m, c) and d) wind gusts at 10 m. Arrows represent the wind vectors near the surface. The icons represent the periods of largest fire propagation: red corresponds to Period I and blue to Period II, both identified in Figure 4.

PERIOD II: Fire Weather

Figures 6 and 7 represent the meteorological conditions for the second period. The figures show temperatures above 35 °C at 2200 UTC (Figure 6a), as well as low relative humidity (<40 %, Figure 6b). Regarding wind gusts, Figure 7a shows a gust front (dashed line) to the north of the fire region that moves southward (Figure 7b), reaching the fire around midnight (Figure 7c).

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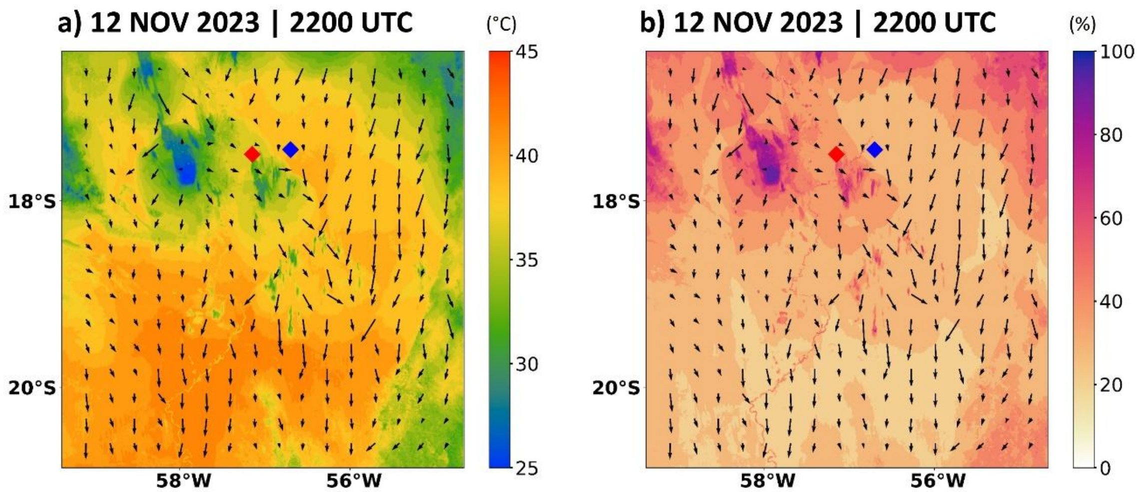

Figure 6 – Meteorological elements on November 12th, 2023: a) temperature at 2 m, b) relative humidity at 2 m. Arrows represent the wind vectors near the surface. The icons represent the periods of largest fire propagation: red corresponds to Period I and blue to Period II, both identified in Figure 4.

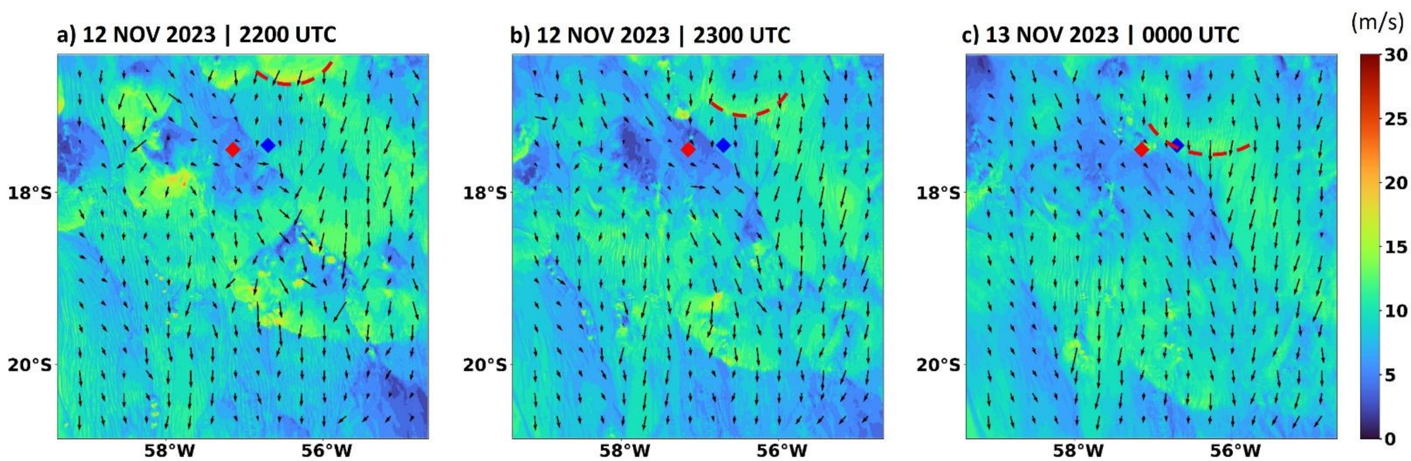

Figure 7 – Wind gusts at 10 m simulated at 500 m resolution during the Period II: a) 2200 UTC, b) 2300 UTC on November 12th, and c) 0000 UTC on November 13th 2023. Arrows represent the wind vectors near the surface. The icons represent the periods of largest fire propagation: red corresponds to Period I and blue to Period II, both identified in Figure 4. The dotted line represents the gust front.

Other fire-prone conditions

The two previous subsections suggest that the fires that occurred in the northern Pantanal plain on November 12th were influenced both by a larger-scale circulation (PERIOD 1) and by a mesoscale circulation (PERIOD 2). This section however, draws attention to the development of gust fronts. Figure 8a-8d is an example of a simulated situation in the late afternoon near the fires, which, according to the model, was not directly associated with the development of the fires. The wind gust field highlights the development of outflows marked by the existence of a pronounced front with higher wind intensity, expanding its size considerably from 1800 UTC to 2000 UTC.

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Figures 8e-8h display the total sum of hydrometeors, i.e., the vertical integration of the liquid water content (raindrops and cloud droplets) and frozen water (graupel, snow, and ice crystals). The figure shows the development of isolated convective nuclei, and for a more detailed analysis, we considered only the convective core with the highest concentration of hydrometeors (Figure 8f).

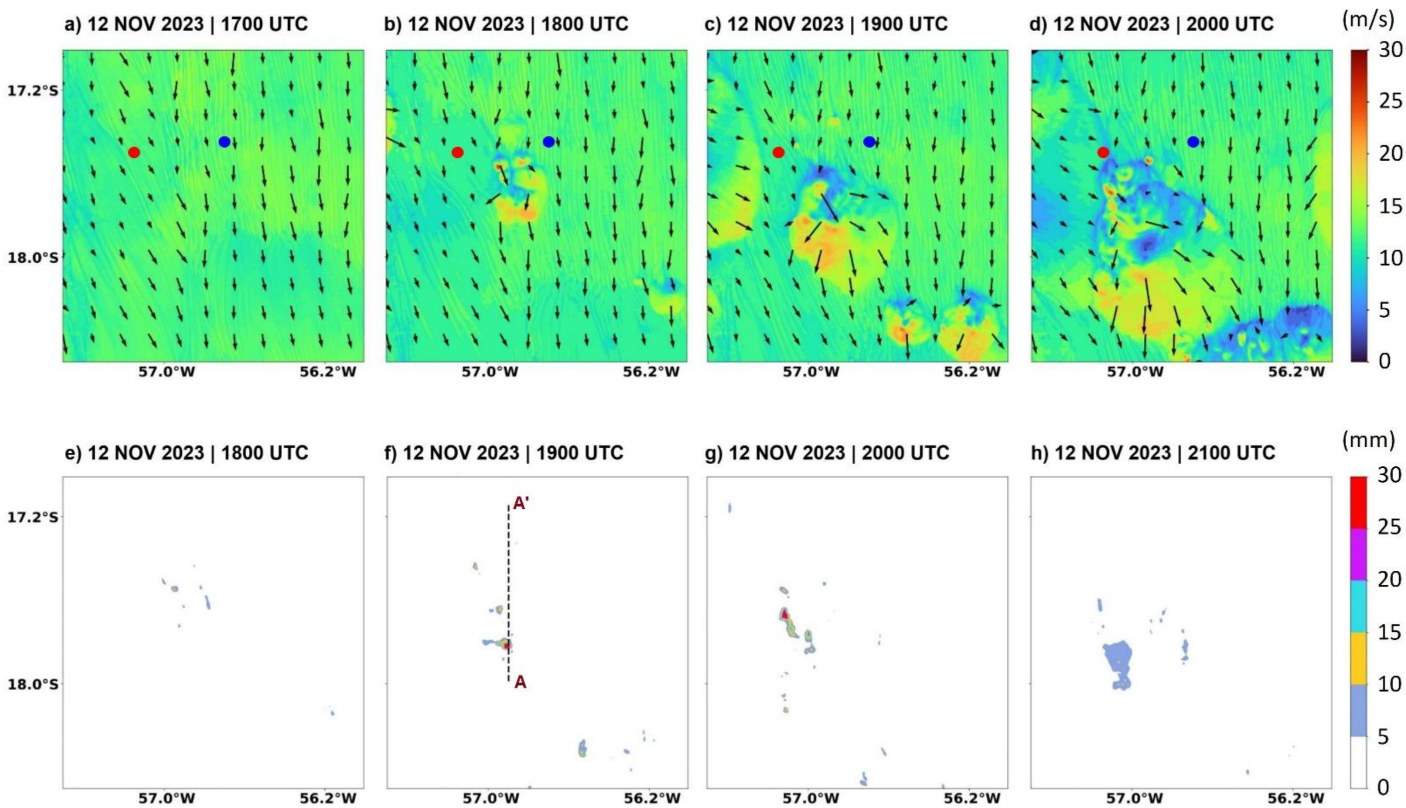

Figure 8 – Wind gusts at 10 m simulated at 500 m resolution during the late afternoon: a) 1700 UTC, b) 1800 UTC, c) 1900 UTC, and d) 2000 UTC on November 12th 2023. Arrows represent the wind vectors near the surface. Hydrometeors concentration e) at 1800 UTC, f) at 1900 UTC, A-A' dashed line indicates the location of the vertical cross-section, g) 2000 UTC, and h) at 2100 UTC. The icons represent the periods of largest fire propagation: red corresponds to Period I and blue to Period II, both identified in Figure 4.

From the vertical cross-section presented in Figure 9a, it is possible to highlight the presence of an isolated cumulonimbus (Cb) cloud. This cloud extends to approximately 14 km in altitude and is currently in a mature stage of development, with the presence of a downdraft region (blue shadows, Figure 9b), which is associated with intense downward motion and explains the formation of the outflow at the surface. Looking at the surface temperature and relative humidity fields, one sees that this downward motion is related to colder and more humid air (Figures 9c and 9d, respectively).

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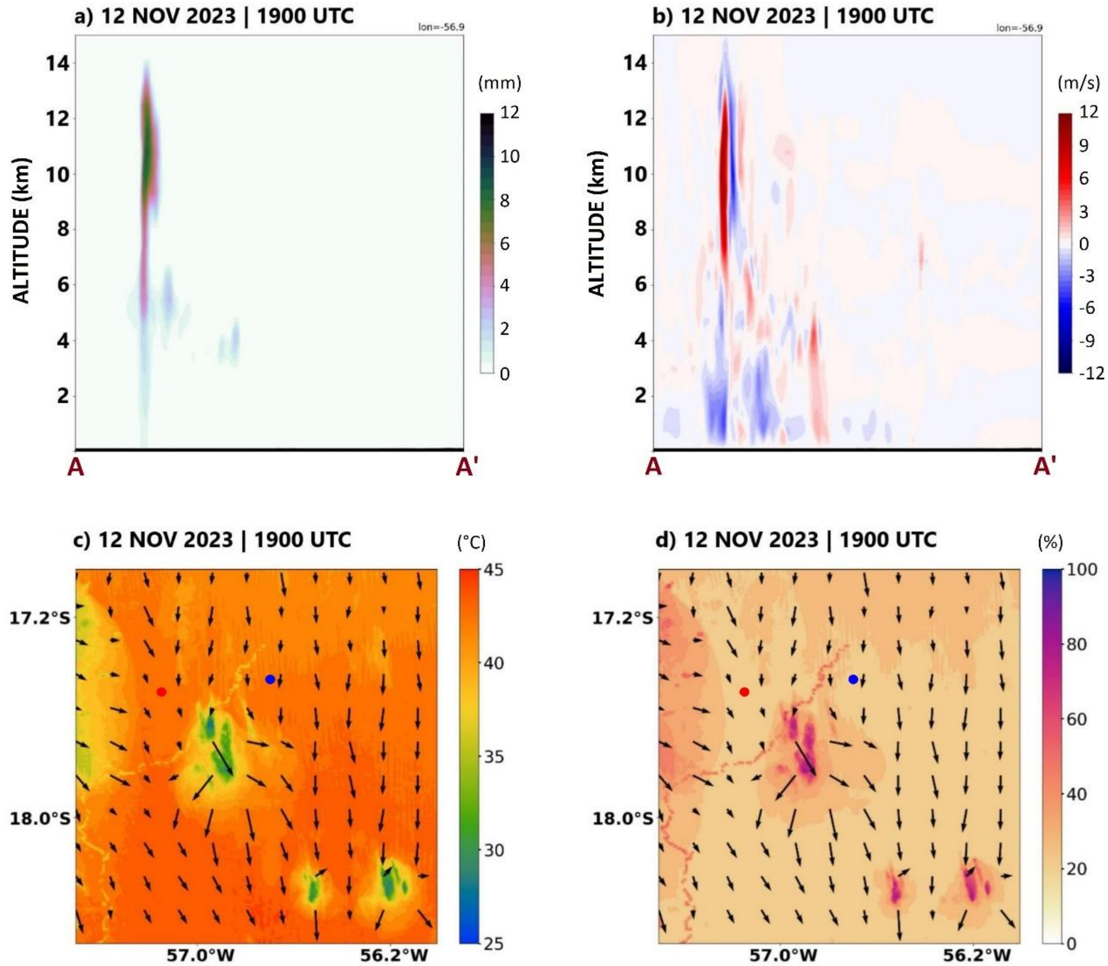

Figure 9 – A-A' vertical cross-section of a) total hydrometeors concentration at 1900 UTC, and b) vertical velocity at 1900 UTC. Fire weather variables c) air temperature at 2 m at 1900 UTC, and d) relative humidity at 2 m at 1900 UTC. Arrows represent the wind vectors near the surface. The icons in (c) and (d) represent the periods of largest fire propagation: red corresponds to Period I and blue to Period II, both identified in Figure 4.

Figure 10 illustrates the meteorological conditions at 1700 UTC, hours before the previously analyzed outflows in Figure 9. Figure 10a shows the Skew-T/Log-P thermo-dynamic diagram for 1700 UTC, presents a layer of warm and dry air in the lower troposphere, favoring the development of high-base clouds. A vertical cross-section through the point on the thermo-dynamic diagram, Figure 10b, indicates ascending currents hours before the start of the development from deep convective clouds and the respective outflows. Figure 10c indicates precipitable water content above 50 mm in Northern Pantanal. The dry and hot layer at the lower levels, Figure 10c, suggests the presence of moisture at higher levels.

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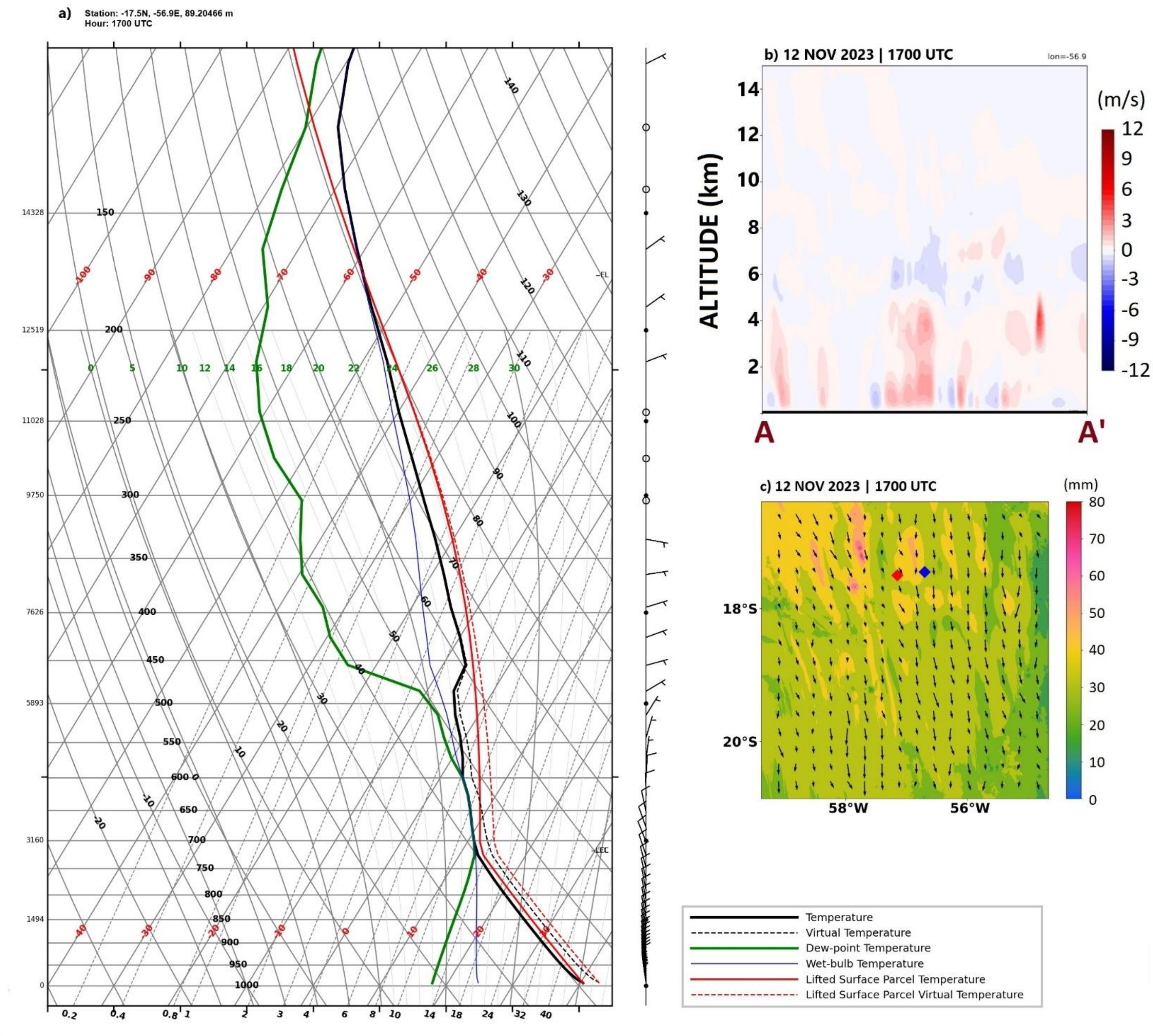

Figure 10 – a) Skew-T/Log-P diagram at 1700 UTC, b) A-A' vertical cross-section of vertical velocity, and c) precipitable water content at 1700 UTC. Arrows represent the wind vectors near the surface. The icons in (c) represent the periods of largest fire propagation: red corresponds to Period I and blue to Period II, both identified in Figure 4.

The study reveals the complexity of studying fire meteorology in the Pantanal when considering the sub-daily scale. Changes in meteorological conditions throughout the day, particularly from the development of the planetary boundary layer, can lead to the development of convective clouds, sometimes characterized as Cb, which give rise to intense outflows that make it difficult to predict the wind behavior at the surface.

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In general, several factors can cause an abrupt change in the wind field affecting fires, either in a mesoscale context or in a circulation created at the fire scale, particularly during fires that create its own meteorology (Fromm et al., 2010; Werth et al., 2011; Couto et al., 2024a). Nevertheless, this study does not consider fire in the simulation, and so these phenomena from fire-atmosphere interactions are neglected here. However, atmospheric simulation reveals an environment in which mesoscale meteorological conditions can be important for the development of gust fronts in the Pantanal. The development of convective outflows and gust fronts is recognized as a factor to increase fire danger (Haines et al., 1988; Potter et al., 2017). In some regions, such as the Iberian Peninsula, the occurrence of this phenomenon was identified as such a fire danger (Purificação et al., 2024) and, in a specific case, influencing the fire environment (Couto et al., 2020).

This phenomenon is widely recognized because it creates critical situations for firefighters worldwide. Although this environment was initially identified as associated with the dynamics of unexpected fire behavior in the southern Pantanal plain (Couto et al., 2024b), this study reinforces the significant role of gust fronts in fire spread, since PERIOD II was also favored by such a phenomenon. Furthermore, our findings confirm that the use of atmospheric modeling helps to understand fire environments, especially during complex situations, as identified on November 12th. In summary, synoptic-scale conditions can influence near-surface air temperature and humidity, which are determining variables for fuel flammability. On the other hand, understanding mesoscale weather patterns is important for predicting wind behavior, a crucial factor in fire propagation.

Although the fire risk in 2023 was not as severe as in 2020, it is still significant. Furthermore, the positive trend in FWI suggests that climate change has been influencing the FWI in recent decades. Like many regions worldwide experiencing increased fire activity due to climate influences, the Pantanal region may also become more susceptible to extreme events, and multiple studies have shown the critical role of climate conditions in the devastating fires in this region (Teodoro et al., 2022; Libonati et al., 2022; Pelissari et al., 2023).

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IV. Concluding remarks

This study shows the importance of different data sources to understand fire dynamics in the Pantanal wetland. Atmospheric modeling data proved to be useful to complement information obtained from geoinformation.

In summary, two different moments with a large concentration of active fire numbers were identified on November 12th, 2023: one in the early afternoon and the other at the end of the day. According to the model, two types of circulation affected the region. The first was related to larger-scale circulation, and the second one to the development of a gust front that reached the fire location. However, both fires occurred under the influence of fire weather conditions conducive to fire, namely temperatures above 35 °C and relative humidity below 40 %. Furthermore, the study highlights that this day presented an extreme fire risk, which was associated with a critical fire risk period in the first half of November. It is noteworthy that the study clearly identified a seasonality in fire danger for the year 2023, as well as a positive trend in the increase of fire risk over the last 40 years, with significant maxima from 2000 onwards and an extreme condition in 2020, also supporting the catastrophe experienced in the Pantanal in that year.

It is important to highlight that the study did not consider fire-atmosphere interaction in the simulation, which means that the results do not take into account the phenomena that may occur from this interaction, e.g., fire-generated thunderstorms and associated intense wind gusts. Therefore, the work presents, in an exploratory way through numerical simulations, the meteorological context that may have affected the development of the fires identified from the satellite information.

The study about fire meteorology in the Pantanal is ongoing, and future work is directed towards studying the atmospheric conditions during other fires, in particular those occurring at different seasons, that can be affected by different weather conditions. Such knowledge of the weather patterns that can increase the wildfire risk in the region is essential for the development of firefighting plans or preventive fire actions strategies.

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