Skill analysis of alarm system forecasts, for extreme gusts, and tree damage in Montevideo city.

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SUMMARY:
This study analyzes historical tree-damage records in Montevideo (2014–2022) to identify meteorological drivers of damage. An operational forecasting model was built using 30-member GFS-WRF ensemble simulations to predict damaging wind gusts 0–11 days in advance. Critical thresholds were identified: cumulative 7-day precipitation; maximum daily wind gusts at Carrasco and Prado; and a maximum daily hourly wind-direction change. An automated real-time alert system was implemented and evaluated for December 2024–March 2026, issuing email alerts to city authorities when thresholds are exceeded. The system successfully forecasted most events with more than 14 reported tree works; surprises occurred when forecast gusts were near but below alarm thresholds, underscoring gust-speed underprediction in some cases. The results support real-time warning capabilities to improve urban planning and resilience against wind-induced tree damage.

Keywords: extreme gust, trees damage, forecast.

1. INTRODUCTION

Tree damage related with wind, and wind gust poses significant municipal challenges due to cascading impacts on infrastructure. Montevideo (capital of Uruguay) is situated in the mid-latitudes of South America. The region is exposed to rapid meteorological changes driven by the interaction of cold air masses from the poles and warm air masses from the tropics. These frontal encounters frequently lead to precipitation and storms, which are formed within hours. Extreme convective storm events often cause significant damage to structures and infrastructure across the country (Durañona et al., 2019). Previous studies have contributed to exploring wind dynamics in the region. For instance, Gutiérrez and Fovell, 2018 developed a gust model for 100 meters above ground level using data from measurement towers in Uruguay. Later, Gutiérrez et al., 2020 evaluated the model's performance specifically for convective storms. Cook, 2023 attempted to develop and evaluate automated methods for classifying extreme gust events in the contiguous United States based on meteorological data, distinguishing between different types of gust mechanisms (e.g., synoptic-scale storms, thunderstorms, frontal downbursts).

Gutiérrez et al., 2025 investigated extreme wind gust events causing tree damage in Montevideo, Uruguay, and developed an operational forecasting alarm system using WRF ensemble simulations. Damage predominantly occurred during summer months, with Melia azedarach, Fraxinus pennsylvanica, and Platanus acerifolia species (shed leaves in winter) experiencing reduced vulnerability in colder seasons. Building on these foundations, this study analyzed meteorological events associated with tree damage in Montevideo City, utilizing historical data from 2014 to 2022. The data comprises records of emergency tree maintenance works documented by the Montevideo City Hall. Additionally, an operational alarm system, leveraging 30-member GFS-WRF ensembles, was implemented to issue automated email alerts to city authorities when forecasted conditions exceed thresholds. In this study, we present the operational performance evaluation of the alarm system for the period December 2024 - October 2025.

2. METHODOLOGY

This study developed an alarm model to identify the meteorological events responsible for damage to Montevideo's public tree inventory. To this end, meteorological observations and tree-damage records from 2014 to 2022 were analyzed. The damage database was obtained from emergency maintenance operations carried out by contractors of the Montevideo City Hall (IMM), including interventions from branch removal to complete tree extraction. These records provided information on affected species, spatial distribution, and incident frequency, allowing the relationship between severe weather conditions and urban tree damage to be assessed. In the following figures, we present photographs of trees damaged during MEs in Montevideo. Figures 1, 2, show a broken Fraxinus pennsylvanica tree, and a fallen Melia azedarach tree respectively.

Figure 1. A broken Fraxinus pennsylvanica tree in Montevideo city.

Figure 2. A fallen Melia azedarach tree in Montevideo city.

2.1. Characterization of extreme ME

During extreme meteorological events, trees experience intense wind loading, which, when combined with persistent rainfall, can lead to tree failure through increased soil saturation and reduced root anchorage strength. This study focused on identifying threshold values of wind speed, wind gust, and rainfall associated with 41 previously identified extreme events.

2.2. Gust Factor model

A gust-factor model was developed to improve wind-gust forecasting, building on the parameterization proposed by Gutiérrez and Fovell, 2018 . The approach relates gust intensity to mean wind speed and was calibrated using hourly wind velocity and gust observations from 2014 to 2022 at 10 m above ground level. Model development was based on a training period from 2014 to 2021, while independent validation was performed for 2022.

2.3. Operational alarm forecasting system

An operational alarm forecasting system was developed based on 30-member GFS-WRF ensemble simulations, executed once per day with an 11-day forecast range. The operational domain coincided with that used in the national forecasting tool for Uruguay's installed wind-power capacity Silveira et al., 2025, as shown in Figure 3.

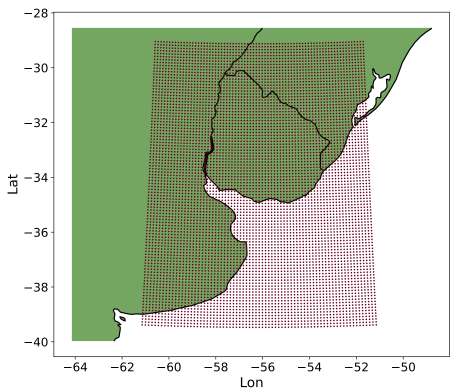

Figure 3. WRF simulation domain.

The operational alarm system automatically sends email alerts to Montevideo City Hall's Tree Management Team whenever alarm conditions are forecast at either the Carrasco or Prado station. Each alert provides a graphical summary of the ensemble minimum, maximum, and median forecasts of wind gust, cumulative precipitation, and wind direction shift from the 30-member GFS-WRF ensemble. Since an alarm at either station is considered representative of a large-scale event affecting the city, total reported tree-related incidents across Montevideo were used in model development.

The operational alarm system was evaluated for the period December 2024 to March 2026 using a three-day event window centered on the forecast day. An alarm was considered successful when at least one reported tree-related incident, including fallen trees or broken branches, occurred within this window. Results showed good overall performance. The system was particularly effective in identifying the most severe cases, although forecasted gust magnitudes were generally lower than observed values, indicating a systematic underestimation of wind gust speed.

3. CONCLUSIONS:

Extreme wind and gusts are primary drivers of urban tree damage; thresholds derived from local data provide practical predictors. Critical event associations: g_{max} thresholds (Carrasco 15 m/s, Prado 12 m/s), cumulative precipitation, and substantial wind-direction shifts are key indicators. The Gust Factor -based gust adjustment improved alignment between modeled winds and observed gusts, enabling more reliable gust forecasts within the ensemble framework. The 30-member GFS-WRF alarm system shows promise for operational use, delivering timely alerts up to 11 days in advance and supporting urban resilience planning. Some underestimation of gust speeds suggests potential improvements via higher-resolution modeling, balanced against computational constraints. Future work may include expanding data assimilation, refining thresholds, and integrating additional observational networks to enhance forecast performance.

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