A FIRST APPROACH TO CONSIDER THE INFORMATION OF THE MADDEN-JULIAN OSCILLATION IN THE OPERATION OF THE ELECTRICAL SYSTEM OF URUGUAY

PRIMEROS PASOS PARA CONSIDERAR LA INFORMACIÓN DE LA OSCILACIÓN MADDEN-JULIAN EN LA OPERACIÓN DEL SISTEMA ELÉCTRICO DE URUGUAY

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Resumen

La Oscilación Madden-Julian (MJO) es una perturbación intraestacional (30-90 días) en la atmósfera tropical que influye en configuraciones climáticas en distintas regiones. Por ejemplo, en el sudeste de América del Sur la MJO afecta las precipitaciones, especialmente durante verano austral, con fases que favorecen lluvias extremas en Uruguay y el sur de Brasil, influyendo en el caudal de embalses hidroeléctricos de Uruguay. La importancia de la MJO radica en que puede predecirse con hasta cinco semanas de antelación, permitiendo anticipar sus efectos en distintas regiones. En este estudio se compara la programación energética óptima del país considerando y sin considerar los efectos de la oscilación. Se simulan posibles realizaciones estocásticas de las condiciones futuras y se calcula la programación energética óptima. En la mitad de los casos se considera la información de MJO y en la otra mitad no. Los resultados indican que incluir la información histórica de MJO afecta el consumo de gasoil. En particular, cuando se considera la oscilación, la fase Niño muestra un comportamiento menos extremo y con menor variabilidad que cuando no se considera.

PALABRAS CLAVE: Oscillación de Madden-Julian, Uruguay, Energía hidráulica, ENSO, SIMSEE

Abstract

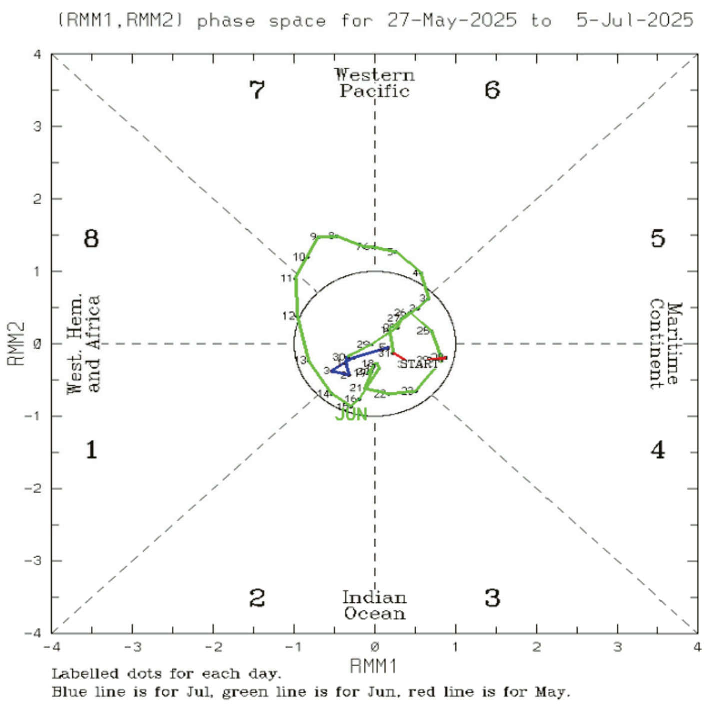
The Madden-Julian Oscillation (MJO) is an intraseasonal oscillation (30-90 days) in the tropical atmosphere that influences climate patterns in various regions. For example, in Southeastern South America, the MJO impacts rainfall, especially during the austral summer, with phases that favor extreme rainfall in Uruguay and southern Brazil, affecting the inflows to Uruguay's hydroelectric reservoirs. The importance of the MJO lies in its predictability, which extends up to five weeks in advance, allowing for the anticipation of its effects. This study compares the country's optimal energy programming, considering and not considering the effects of MJO. Possible stochastic realizations are simulated, and the optimal energy programming is calculated. In half of the cases, MJO information is considered, while in the other half, it is not. Results indicate that including historical MJO information affects diesel consumption. In particular, when the oscillation is taken into account, the El Niño phase exhibits less extreme behavior and lower variability than when it is not considered.

KEYWORDS: Madden-Julian Oscillation, Uruguay, hydropower, ENSO, SIMSEE

1. INTRODUCTION

The Madden-Julian Oscillation or MJO (Zhang, 2005) is an intraseasonal disturbance (30-90 days) in the tropical atmosphere that significantly impacts global climate conditions. It is an eastwardly propagating cell characterized by an enhanced and a suppressed convective region. The evolution of MJO is most typically represented by the Real-time Multivariate MJO index (RMM, Wheeler and Hendon, 2004). It is a numerical index that, considering 850 and 200 hPa zonal wind and outgoing longwave radiation, quantifies the intensity and phase of the oscillation. The RMM index is composed of two principal components, RMM1 and RMM2, which together define a two-dimensional phase space. The angle of the vector (RMM1, RMM2) indicates the location that has an associated phase (from 1 to 8), and its magnitude reflects the strength (amplitude) of the convective signal. Figure 1 shows an example for the period 27 May-5 July, with a weak MJO in May and July, and a higher intensity of phases 6, 7, and 8 between 4 and 12 June.

Figure 1. Example of Madden-Julian Oscillation vector (RMM1, RMM2) diagram from 27 May 2025 until 5 July 2025. Taken from http://www.bom.gov.au/



The importance of the MJO lies in the fact that it can be predicted with a lead time of five weeks (Kim et. al., 2018), allowing for the prediction of its worldwide effects. In particular, the effects of MJO in Southeastern South America have been analyzed in many publications. For example, (Alvarez, et. al., 2016) found that during austral summer phases 3, 4, and 5 favor simultaneous weekly rainfall in the upper tercile in Uruguay and southern Brazil (a region that influences the flow in the most important Uruguayan hydroelectric power plant) while in austral autumn phases, 4, 5 and 6 (8) are associated to enhanced (reduced) precipitation; in spring phases 4 and 5 are related to upper tercile. In winter, the relationship is less important. Additionally, in Ungerovich et. al. (2021), the authors conclude that the persistence of the MJO for more than five days in phases 4 and 5 during austral spring is a precursor to extreme rainfall events in southern Uruguay.

The Uruguayan precipitation regime imposes significant variability in the annual energy available from this source. The annual generation of the hydroelectric subsystem ranges from 3,300 to 9,300 GWh (BEN, 2023). The largest reservoir, located on the Río Negro river, can store enough energy to operate at full capacity (596 MW) for up to 135 days when full. It feeds a chain of three power plants (Chaer, 2008). Additionally, the binational Uruguayan-Argentinian Salto Grande hydroelectric plant on the Uruguay River has an installed capacity of 1800 MW, half of which corresponds to Uruguay, and a storage capacity of five days. National demand is about 1,300 MW (annual average), with peak values of about 2,200 MW and minimum values of around 700 MW. The sum of wind (1,550 MW) and solar (220 MW) installed capacity exceeds the daily peak demand on 70% of the days of the year. For instance, in 2023, the Uruguayan power system supplied a national demand of 11,472 GWh plus an export of 244 GWh. This energy was fulfilled by 39% wind, 3% solar, 9% biomass, 28% hydroelectric, 8% thermal, and 12% imports (ADME, 2025).

The main challenge for the system's optimal operation is the economic valuation of water resources from the three main reservoirs. The programming of the National Interconnected System (SIN) is carried out by the Electricity Market Administration (ADME). To achieve this, it utilizes two automatic power dispatch programs: Vates_MP and Vates_CP (ADME, 2023). They are constantly assimilating information on the state of the SIN, the forecasts of the surface temperature anomaly of the Pacific Ocean in the El Niño region, flow rates of contributions to the lakes, wind speed, solar radiation, and temperature.

Chaer et. al. (2010) provide the foundation for incorporating El Niño-Southern Oscillation (ENSO) forecasts into Uruguay's energy dispatch programming. Although the initial concept was developed in 2010, it was formally published in 2015 (Maciel et. al., 2015), providing a detailed approach to incorporating ENSO-related climate signals to optimize Uruguay's energy system operation. The paper focused on integrating ENSO forecasts into the stochastic modeling of streamflow, aiming to reduce operational costs by improving the management of hydroelectric resources, which are highly dependent on interannual climatic variations. This approach enables the system to anticipate periods of drought or excessive rainfall better, adjusting energy dispatch accordingly to ensure a more efficient and cost-effective operation.

This paper examines the incorporation of the MJO as an additional tool in the dispatch framework, serving as a complementary approach to enhance power systems operation under uncertainty. Specifically, the objective of this study is to evaluate the impact of incorporating MJO information into stochastic simulations used for medium-term energy planning, with a focus on its effect on diesel consumption under different ENSO phases.

2. METHODS

2.1 Simulation model: SimSEE

The Electric System Operation and Expansion Simulation (SimSEE, Chaer, 2008) is a modeling tool developed in Uruguay to analyze the behavior of electric power systems, particularly those combining hydroelectric and thermal generation. It enables simulation of system operation under varying hydrological and demand conditions and is widely used for both long-term planning and short-term operational studies. SimSEE operates with Correlations in Gaussian Space using Histograms (CEGH, Chaer et. al., 2011), a stochastic modeling framework that generates synthetic time series while preserving the key statistical features of historical data.

For this study, two cases were considered:

1. MI (More Informed): Using historical information from both the MJO and ENSO phases. This means that the CEGH will be based on historical information regarding the MJO, ENSO, and water flow rates in the hydroelectric dams.

2. LI (Less Informed): Only considering the historical information from ENSO phases and water flow data. This means that the CEGH will be based on historical information about ENSO and the water flow rates in the hydroelectric dams.

2.2 Variables and scenarios

The study focused on the impact of the MJO on fuel consumption in the electrical system, particularly during the austral summer (December-January-February). We considered a closed system without imports or exports of energy. Then, Uruguay's energy system is composed of both renewable and thermal energy sources. In that scenario, considering the amount of water available today and the amount that will be available during the following days, a decision is made on when and how much thermal energy will be used. To understand the MJO effect, we will analyze the amount of diesel that thermal machines will need over the next 90 days, considering both with and without the historical information of MJO (MI: more informed and LI: less informed, respectively). Specifically, we ran five sets of 3000 stochastic simulations using different initial random seeds (S1-S5) and analyzed thermal energy dispatch decisions. The idea behind the five sets is to make the results more robust than with an only set. Then, we analyzed how diesel consumption varies in the MI and LI simulations under the three phases of ENSO.

The CEGH models were trained to calculate incoming water flows to the lakes associated with hydroelectric plants and then determine the amount of diesel to be purchased to meet the thermal energy needs. To estimate the value of the information provided by the history of the MJO, statistical measures associated with the expected value of the operation's cost over the next 90 days were calculated.

3. RESULTS

3.1 MJO correlation with hydropower

For the purpose of assessing the effect of MJO in the availability of hydroelectric resources we shall define the Incoming Hydroelectric Energy (IHE) as the sum of the product of the inflow to each dam and the energetic coefficient given the height of the lake and the downstream river. IHE is presented in equation 1, where ρ, g, Q, and h correspond to water density, gravitational acceleration, flow rate and height, respectively.

$$\sum^{plants} \left(\int_{t-\Delta t}^{t} \rho g Q_i(t) \Delta h dt \right)$$

Equation 1- Incoming hydroelectric energy

Fig. 2 shows the iN34 index, RMM1, and RMM2 correlations with IHE. The first thing to observe is that the iN34 index presents correlations with the IHE that are three times higher than those observed with the components of the MJO.

In the operation, the forecast for the following 10 days is taken from meteorological forecasts and assimilated into the stochastic models to schedule the energy dispatch. The possible contribution of new information from the MJO is then in the time horizon after those first ten days. As shown in the figure, the RMM2 component exhibits a significant correlation with the IHE 15 days in advance.

3.2 Impact of MJO on diesel consumption

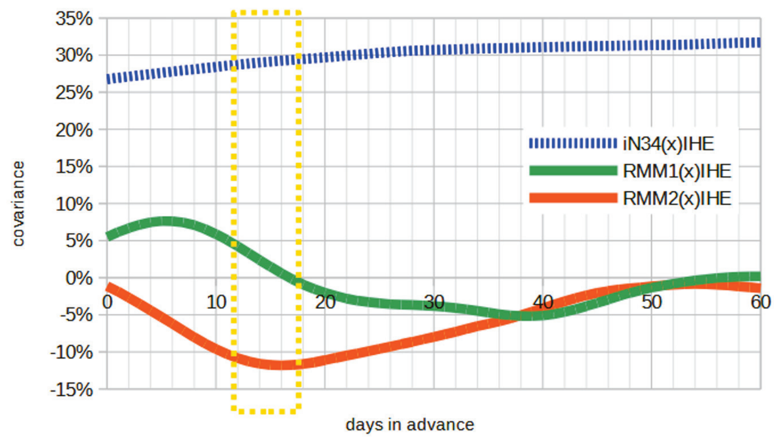
Figures 2 and 3 show the results of the average of the five sets of 3,000 simulations of cumulative 90-day diesel consumption under the three ENSO phases: La Niña, Neutral, and El Niño. The results correspond to the average of the five initial seeds, and the simulations have been sorted in ascending order of diesel usage to visualize the distribution across simulations.

The figures show that during the highest diesel demand periods (characterized by less rainfall) in both cases (MI and LI), La Niña corresponds to higher demand than El Niño. On the other hand, in the more rainy simulations (lower diesel demand), for LI cases, the demand is almost independent of ENSO, while for MI, El Niño seems to imply more diesel consumption than La Niña. However, the difference is less than 0.1 hm3, and as SimSEE also takes into account the economic aspect, it is not safe to make conclusions about the difference in rainfall.

Additionally, in MI, the variation in consumption between ENSO phases is more pronounced than in LI, with the most significant differences observed in the intermediate and driest periods (characterized by medium and high diesel consumption). These results are also shown in Table 1, which displays diesel consumption for the three ENSO phases. The data is presented for percentiles 10, 50, and 90 of the average of the five sets of 3000 simulations. Diesel consumption values are shown for both cases: LI and MI.

In addition, figures 4 and 5 present a more detailed analysis of 90-day diesel consumption using simulations initialized with the five different random seeds for LI and MI, respectively. Both figures show the 10th, 50th, and 90th percentiles, as well as the standard deviation of diesel consumption across ENSO phases. Comparing Figures 4 and 5 reveals that when MJO is considered, diesel consumption during El Niño increases in both the lower and upper extremes. This means that the 10th and especially the 90th percentiles are higher than in the case without MJO, suggesting that both dry and wet El Niño scenarios result in greater diesel use when MJO is taken into account. Specifically, the wettest El Niño years (10th percentile) require more diesel than when MJO is ignored. Likewise, but to a lesser extent, the driest El Niño years (90th percentile) become even drier, intensifying diesel needs. Moreover, the standard deviation is much lower in simulations that include MJO, indicating that diesel consumption during El Niño becomes more consistent and predictable. During La Niña or Neutral years, the differences between including and excluding the MJO are less significant, both in terms of percentiles and variability.

Figure 2. Correlations of iN34 and MJO with IHE



Source: Own elaboration

Figure 3. Cumulative 90-day diesel consumption from 3,000 simulations without taking into account MJO's historical information, under the three ENSO phases (La Niña, Neutral, and El Niño), using the average of the 5 seeds. Simulations are ordered from lowest to highest consumption to illustrate the distribution of outcomes. The left panel shows all the simulations, the middle one shows the 700 ones with the highest diesel consumption and the right one shows the lowest 700.

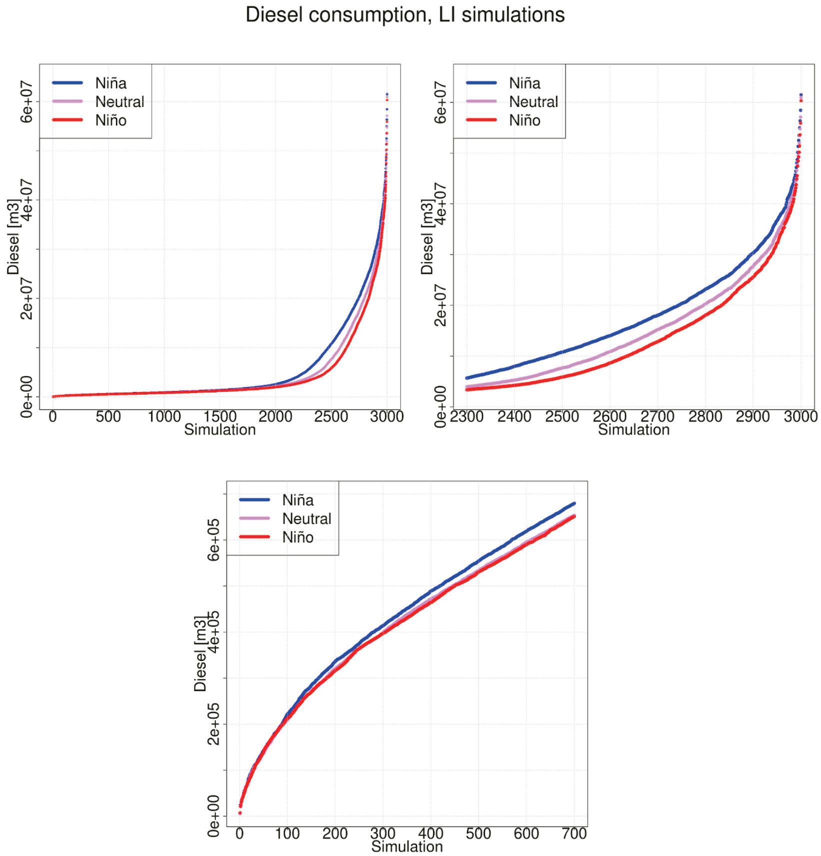


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Figure 4. Similar to figure 2 but MI

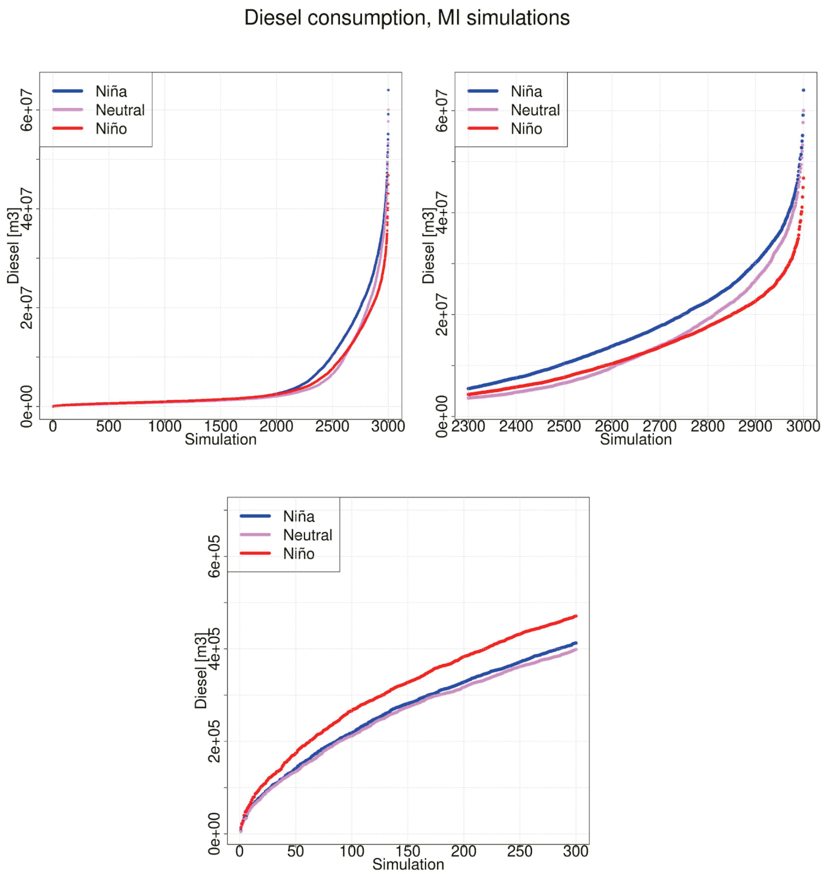

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Table 1. Diesel consumption values for percentiles 10, 50 and 90 of the average of the five sets of 3000 simulations under the scenarios of Niña, Neutral, and Niño. The values are shown for both conditions: LI and MI

	LI [hm³ of diesel fuel]			MI [hm³ of diesel fuel]		
Percentile	Niña	Neutral	Niño	Niña	Neutral	Niño
10	0.41	0.40	0.40	0.41	0.40	0.47
50	1.4	1.3	1.2	1.3	1.2	1.4
90	18	15	13	18	14	14

Source: Own elaboration

Figure 5. Diesel consumption over 90 days for simulations that do not take into account MJO phases (LI) and are initialized with 5 different seeds (S1-S5). The 10th, 50th, and 90th percentiles, along with the standard deviation, are shown

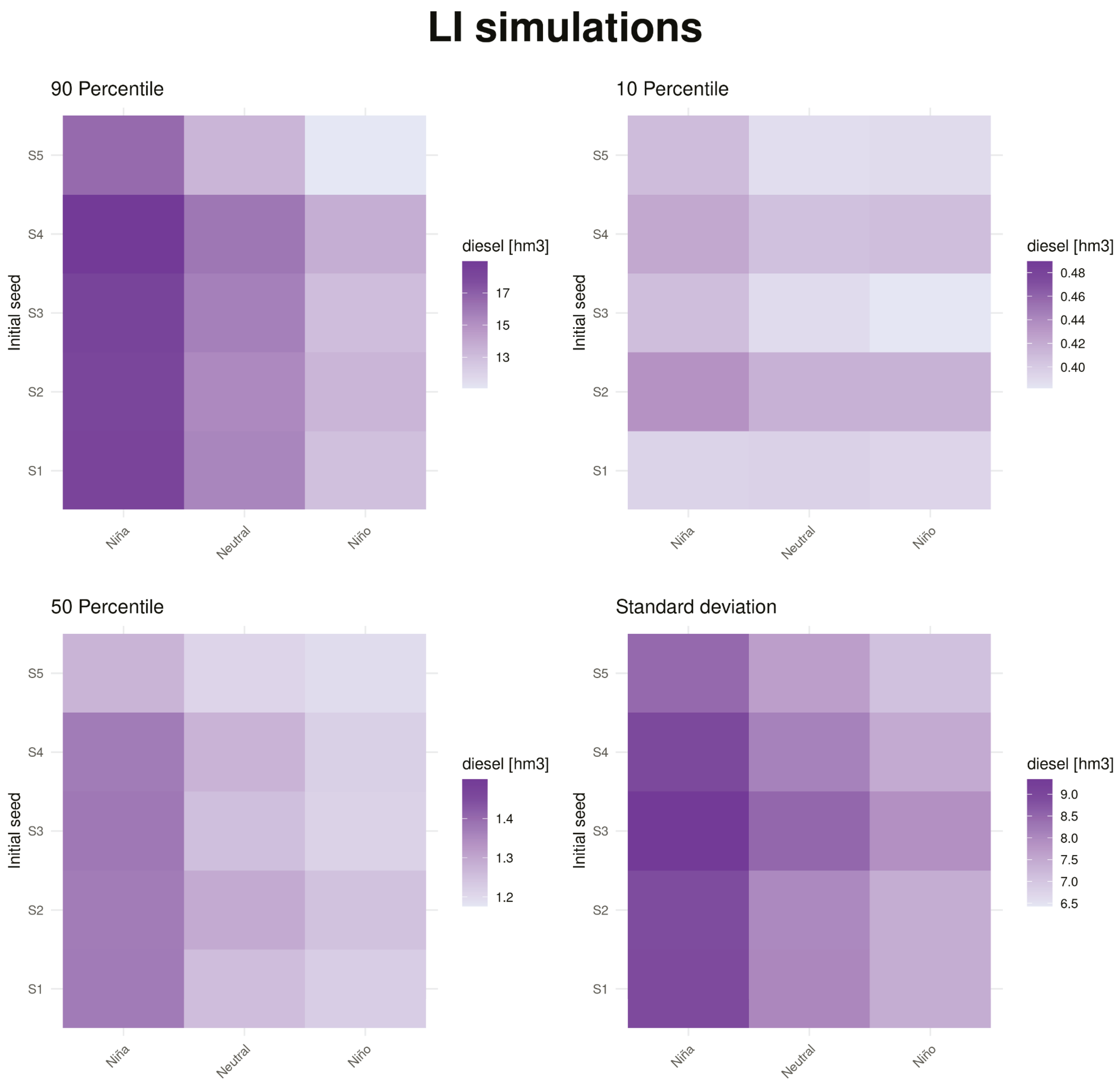

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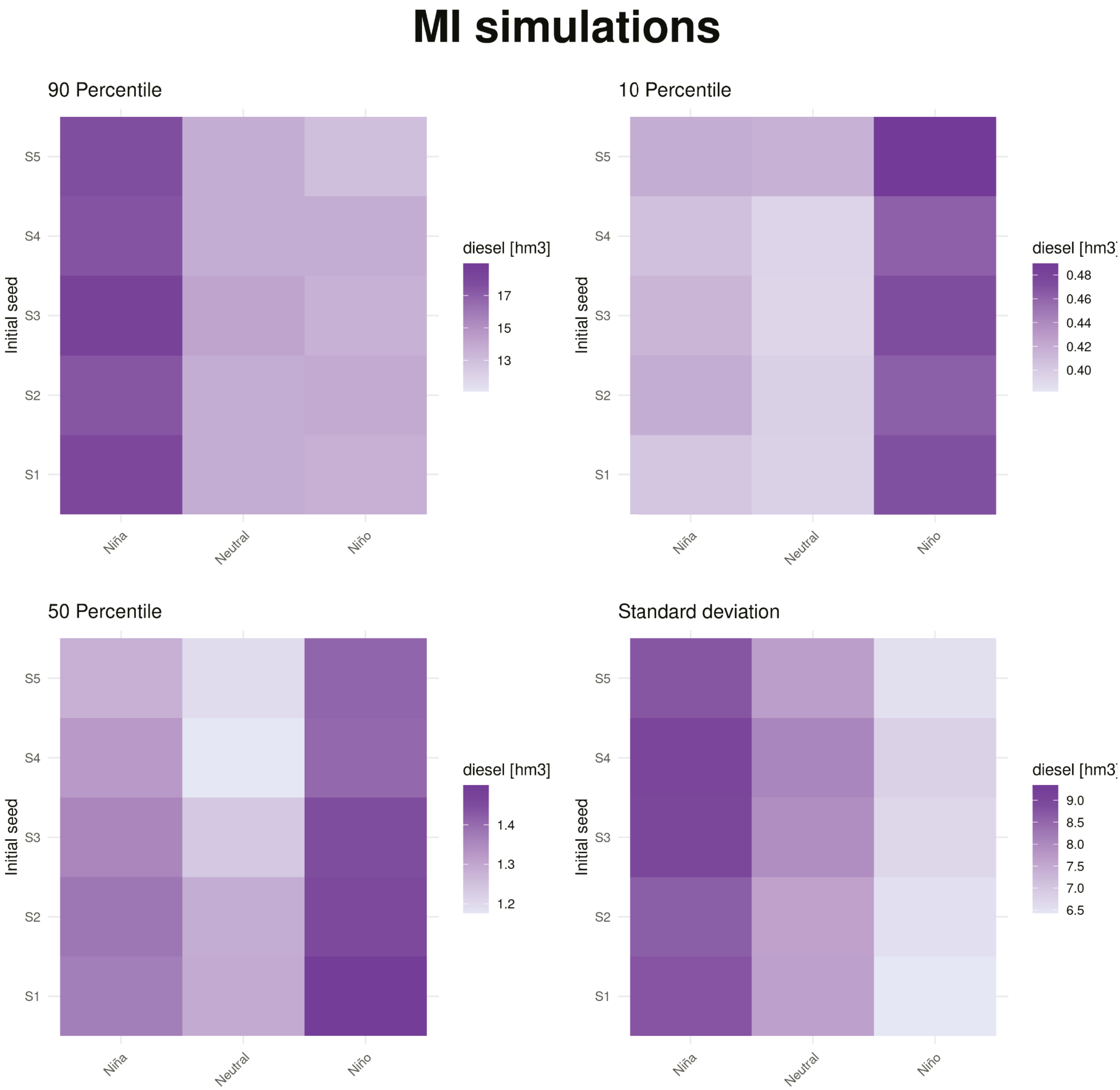
Figure 6. As figure 4 but considering MJO phases (MI)



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4. CONCLUSIONS

The research presented in this paper represents the first attempt to incorporate Madden-Julian Oscillation (MJO) information into Uruguay's energy dispatch programming. Based on the results obtained, some conclusions can be drawn. The study shows that the iN34 index (representing ENSO) has a stronger and more persistent correlation with incoming hydraulic energy than the MJO components. However, the RMM2 component of the MJO shows a relevant correlation 15 days in advance.

For dry and intermediate seasons, independent of MJO considerations, the analysis highlights seasonal differences in diesel consumption, with the drier La Niña phase requiring more diesel due to reduced rainfall and the El Niño phase requiring less. However, during rainy seasons, the relationship between consumption and ENSO phase differs for MI and LI. Also, including MJO information makes these differences more pronounced in the extreme values. Finally, it is shown that considering MJO during the El Niño phase results in higher percentiles for the highest diesel consumption, indicating greater need and suggesting lower rainfall. Additionally, the standard deviation is much lower. On the other hand, during La Niña or neutral years, the effects of MJO are less significant.

Previous analyses have demonstrated that the MJO influences rainfall in the region and that SimSEE can accurately reproduce the oscillation. Therefore, the fact that diesel consumption changes when MJO information is incorporated suggests that the results may be improved. Incorporating MJO could improve the decisions made by ADME, allowing for more accurate planning. Incorporating MJO into energy dispatch models not only improves predictive consistency but also enhances resilience in energy planning under climate variability.

5. DISCLAIMER

The content of this article is entirely the responsibility of its authors, and does not necessarily reflect the position of the institutions of which they are part of.

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