Analyzing the potential of ASCAT Surface Soil Moisture 6.25 km for drought monitoring over Mexico.

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Abstract:

This study assessed the potential of the ASCAT SSM 6.25 km product for agricultural drought monitoring across Mexico. The drought monitoring in Mexico currently relies on precipitation-based indices, without considering the use of in situ soil moisture observations and satellite-derived soil moisture products. To evaluate the performance, cross-validation was performed between ASCAT, ERA5-Land, and ESA CCI soil moisture products for assessing correlations under varying climatic and land cover conditions. Furthermore, drought indicators, including SMAPI and SPEI, were calculated and compared against the SPI from the Mexican Drought Monitor to evaluate the assessment during drought events. Results showed strong potential of ASCAT SSM in central and northeastern Mexico, while arid regions exhibited low correlation due to subsurface scattering effects. Otherwise, soil moisture anomalies derived from ASCAT aligned well with precipitation anomalies outside arid zones. In conclusion, ASCAT SSM 6.25 km demonstrates significant potential for integration into Mexico's drought monitoring systems as drought indicators based on ASCAT effectively captured precipitation deficits and drought conditions, mirroring SPI patterns reported by national monitoring agencies.

1.Introduction

In Mexico, the monitoring and analysis of drought are predominantly focused on precipitation deficits, often overlooking other critical factors such as soil moisture, streamflow in both surface and groundwater, and reservoir water levels. This narrow focus has led to an incomplete understanding of the drought phenomenon and its short and long-term impacts. The national reports typically conclude that drought is over when a significant portion of the territory experiences its first rainfall event, without accounting for low soil moisture levels and their implications for agriculture.

Mexico lacks a comprehensive network of in-situ soil moisture stations, relying primarily on limited streamflow and meteorological stations for drought monitoring. To address this gap, recent research projects have focused on evaluating satellite-derived soil moisture products such as the NASA Soil Moisture Active Passive (SMAP) in specific regions. Given the limitations of official in-situ observations, these projects often conduct their measurements over short periods to assess the accuracy of soil moisture estimates provided by satellite soil moisture products (Monsiváis-Huertero et al., 2022).

In 2015, the Mexican Institute of Water Technology (IMTA, by its initials in Spanish) conducted an analysis of SMOS (Soil Moisture and Ocean Salinity) for potential national coverage applications (Lobato-Sánchez, R., 2015). However, the study concluded that the satellite data required further calibration and post-processing to align with in-situ observations. Despite its promising potential, IMTA lacks the necessary resources and support to implement this calibration effectively. This limitation restricts the evaluation and calibration of soil moisture satellite products across Mexico, particularly in terms of precipitation data and cross-validation with other soil moisture products.

According to Van Loon, A.F., (2015), drought indices are essential tools for identifying and quantifying drought events. These indices are generally categorized into standardized indices and threshold-based indices, with the most commonly used being those based on meteorological and soil moisture data. The most common precipitation-based indices are the Standardized Precipitation Index (SPI), the Standardized Precipitation and Evapotranspiration Index (SPEI), the Standardized Snowmelt and Rain Index (SMRI), and the Palmer Drought Severity Index (PDSI). While soil moisture-based indices are the Z-index, the Standardized Soil Moisture Anomalies (SMA), and the Soil Moisture Anomaly Percentage Index (SMAPI).

As previously mentioned, drought monitoring in Mexico relies primarily on precipitation-based indices, specifically the Standardized Precipitation Index (SPI), which is used in the monthly reports of the Mexico Drought Monitor (MDM) and the Annual Climate Report (ACR) delivered by the National Water Commission (CONAGUA by its initial in Spanish).

The objective of this research is to evaluate the performance of the Soil Moisture (SM) product derived from the Advanced SCATterometer (ASCAT) in assessing soil moisture conditions by cross-validating with soil moisture data from ERA5-Land and the European Space Agency (ESA) in the Climate Change Initiative (CCI) Soil Moisture (SM) dataset. Additionally, evaluate the potential of ASCAT SSM-derived drought indicators, such as soil moisture anomaly percentage index (SMAPI) and soil moisture anomaly z-scores, to detect drought conditions by comparing against the Mexican Drought Monitor that uses the conventional precipitation-based drought indices such as the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI).

This research recognizes the following critical points related to drought monitoring by using satellite-delivered products:

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- The use of satellite-derived products without in-situ data presents significant challenges for accurate calibration and validation.
- Despite these limitations, satellite data offer valuable opportunities to enhance drought monitoring, particularly in data-scarce regions.
- Highlight the challenges associated with subsurface scattering effects on soil moisture measurements.
- Evaluate the temporal quality, consistency, and reliability over time of the ASCAT Soil Moisture dataset.
- Compare drought indicators in specific drought events by using various data sources.

1.1 Background Study Area

Mexico is located in North America, between the latitudes 14º N and 32º N, and longitudes 86º W and 117º W. Mexico is mainly composed of mountain ranges, valleys, and plateaus, which cover approximately 85% of the territory. The remaining 15% consists of coastal plains and the Yucatan Peninsula. The territory comprises 14 physiographic provinces, five are the largest mountain ranges, known as the "Sierra Madre" (Mother Mountain Range), which predominantly cross the country from north to south. According to the Koppen Climate Classification, Mexico has 16 distinct types of climates across the country, as illustrated in Figure 1. The Tropic of Cancer divides the country into temperate and arid zones, as well as tropical zones, in which the climate varies according to elevation.

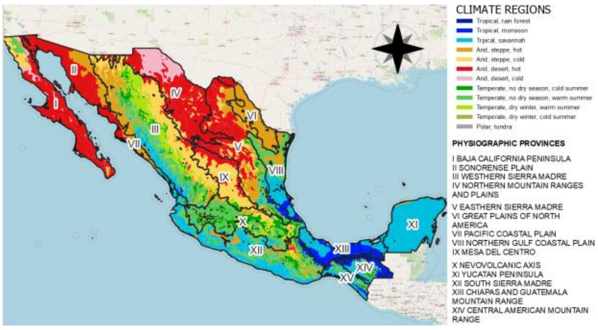

Fig. 1. Mexico's Koppen Climate classification and physiographic provinces.

The Mexico Drought Monitor (MDM) and the Annual Climate Report identified the years 2011, 2012, 2020, 2021, and 2023 as the driest years, marked by extensive drought conditions (CONAGUA & SMN, 2024). The drought event spanning 2011-2012 is noted as the most severe in recent Mexican history, affecting 85% of the country's territory, with 47% of the area experiencing exceptionally severe conditions.

The 2020 – 2021 drought lasted eleven consecutive months, affecting 65% of the national territory and resulting in a 2.7% deficit in annual cumulative precipitation. The most recent event began in June 2023 and persisted until May 2024. CONAGUA stabilised 2023 as the driest year in the last 80 years, and during September 2023, 30% of the national territory presented extreme and exceptional drought conditions, a month that normally tends to receive the most rain events (CONAGUA & SMN, 2024).

2. Methodology

2.1 Soil Moisture Data Acquisition

As it mentioned before, Mexico does not conduct systematic soil moisture monitoring, resulting in a lack of in situ observational data. Consequently, the assessments in this study were conducted through a cross-evaluation of three satellite-based products. The analysis aimed to assess the quality of the HSAF (Satellite Application Facility on Support to Operational Hydrology and Water Management) Surface Soil Moisture dataset by comparing it against other established Soil Moisture datasets, namely ERA5-Land and ESA CCI Soil Moisture (passive), Table 1 shows the characteristics of each product.

The selected time data series dates from 2007 to 2022. To ensure consistency for the correlation analysis, the SM datasets of ERA5 and ESA CCI passive are harmonized with the HSAF SSM data both spatially and temporally.

Product	Grid resolution	Spatial resolution	Reference and data source
HSAF Surface Soil Moisture	5° x 5° cells distributed at 6.25 km	10-15 km x 10-15 km	(Wagner et al., 2013)
ERA5-Land	9 km Gaussian grid scale		(Hersbach et al., 2020)
ESA CCI SM (passive)		0.25 °	(Dorigo et al., 2017)

Table 1. Soil moisture satellite products datasets.

2.2 Pearson Correlation

The Pearson Correlation Analysis is a parametric statistical test used to understand the temporal quality and underlying effects of subsurface scattering in arid and semi-arid climatic zones. To ensure consistency for the analysis, the datasets of ERA5 and ESA CCI passive were harmonized with the HSAF SSM data both spatially and temporally.

The correlation coefficient denotes a strong linear relationship when it closes to 1 or -1. Likewise, values close to 0 indicate a weak linear relationship. The correlation coefficient is equal to 1 (or -1) only when the points on the scatter plot lie exactly on a straight line with a positive (or negative) slope (Haan, 1979; Llamas, 1993). Pearson Correlation can be called by using the equation:

$$r = \frac{\sum(xi - \bar{x})(yi - \bar{y})}{\sqrt{\sum(xi - \bar{x})^2}\sqrt{\sum(yi - \bar{y})^2}} \qquad (1)$$

where r = Pearson correlation
x, y = the individual values of the x and y variables
$\bar{y}$, $\bar{x}$= the means of the x and y variables
$\sum$ = the summatory of all values

2.3 Soil Moisture Anomalies

The anomaly approach is ideal for utilizing HSAF SSM data to derive drought indicators. The extended 17-year data record of the ASCAT dataset enables the calculation of a reliable soil moisture climatology, including long-term means and standard deviations. This enables the identification of deviations in soil moisture from normal conditions, indicating anomalies in the soil moisture levels.

Anomalies function such that values close to zero indicate normal soil moisture conditions. Negative anomaly values represent drier-than-normal conditions, while positive values indicate a surplus of soil moisture, typically associated with significant precipitation events (Vreugdenhil, M., et. al., 2022).

For this analysis, the Soil Moisture Anomalies (SMA) delivered by ASCAT and the Monthly Precipitation Anomalies (MPA) delivered by CONAGUA and SMN were used. The comparison aims to evaluate the consistency between precipitation deficits and soil moisture patterns during the drought events in 2015, 2018, and 2021. Due to the available information on the MPA, the comparisons were only visual.

2.4 Drought Indicators Assessment

To evaluate ASCAT SM as a drought detection tool in Mexico, three drought indicators were selected: SPI and SPEI, which are precipitation-based, and SMAPI, which is a soil moisture-based indicator.

The Standardized Precipitation Index (SPI) and the Standardized Precipitation and Evapotranspiration Index (SPEI) are standardized indices based on meteorological drought monitoring. Both methods use precipitation as their leading statistical indicator, based on comparing the total amount of precipitation (mm) during a specific period (months), with a long-term precipitation distribution (Sepulcre-Canto, G. et al., 2012, and Peng et al., 2023).

On the other hand, standardized indices for soil moisture drought use soil moisture anomalies to standardize them, either by calculating the percentage using long-term means (SMAPI) to categorize the severity of droughts.

To evaluate the effectiveness of the product, the drought event that occurred during the latter part of 2020 and the early months of 2021 was selected for analysis. This comparison primarily aimed to assess the performance of SPEI and SMAPI, calculated using ASCAT data, against the SPI developed by the National Water Commission (CONAGUA) for the Mexico Drought Monitor (MDM).

3. Results

3.1 Correlation Analysis

The correlation test reveals that most of the Mexican territory exhibits coefficients above 0.6 with ERA5 and above 0.4 with ESA CCI, as shown in Figures 2 and 3, respectively. ERA5-Land exhibits high correlation coefficients of up to 0.8 in the West side of Mexico, while the East side presents correlation above 0.6 with some exceptions in the arid regions. This correlation performance between ERA5 and ASCAT has already been found in other regions such as Europe and Southeast Africa (Massart, S. et al., 2025) potentially induced as the base of ERA5 on the Sentinel-1 backscatter.

On the other hand, it can be noted that ESA CCI obtained lower correlations and areas without data that are mostly related to data gaps in the time series of the product. The product obtained better correlation in the North side of the country besides the arid areas.

Negative correlations are particularly situated in north-west and north-central Mexico in arid regions, and in the wetlands located on the Yucatan Peninsula in the southeast. This kind of performance has been seen before by Wagner et al. (2022 and Wagner et al. 2024). It explains that certain climate zones, such as arid, tropical, and wetlands, are susceptible to backscattering issues.

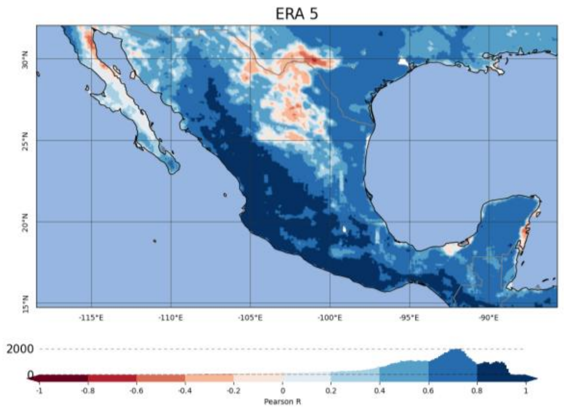

Figure 2. Pearson Correlations for the time series obtained with ERA5-Land data.

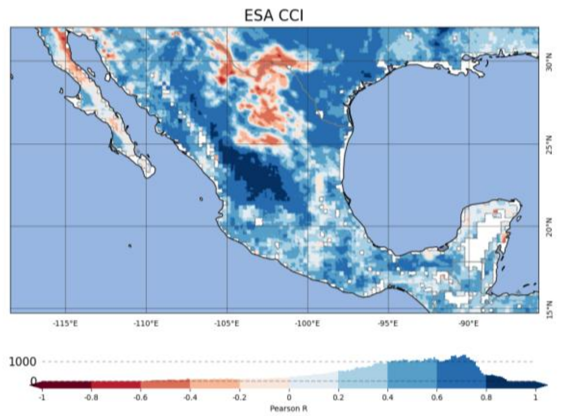

Figure 3. Pearson Correlations for the time series obtained with ESA CCI data.

Central and southern Mexico is primarily utilized for rainfed and seasonal agriculture, supported by the presence of tropical savannahs and temperate climates—both with dry winters and without a distinct dry season. These regions demonstrated strong correlation values, generally ranging between 0.7 and 0.9, with exceptions primarily attributed to data gaps in the satellite records. Additionally, forested and high-altitude areas also exhibited robust correlations, particularly evident within the physiographic region known as the Southern Sierra Madre (Figure 1). Moreover, the semi-arid and temperate dry zones of northeastern Mexico showed high correlation values exceeding 0.6, as illustrated in Figures 2 and 3.

As previously commented, arid and semiarid areas have lower correlations; for example, Figure 4 shows a point in the Chihuahuan Desert where correlations are -0.3 and -0.5 with ERA5 and ESA CCI, respectively. Furthermore, the time series reveals consistently high soil moisture values, with %Saturation frequently exceeding 40% as measured by ASCAT SSM, while ERA5 and ESA CCI show mostly values lower than 0.15 m^3m^{-3}.

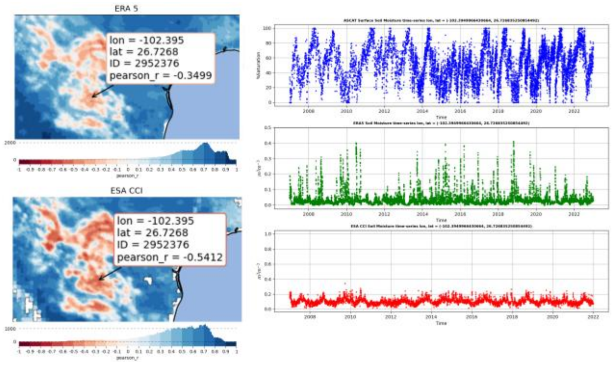

Figure 4. Point located in the Chihuahuan desert in north-central Mexico.

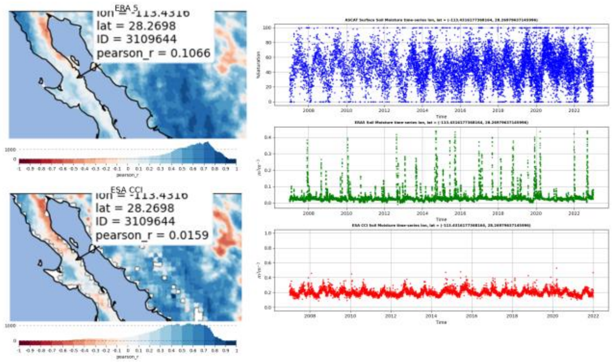

Figure 5. Point located on the Baja California coast, in a highly arid area, northwest Mexico.

Otherwise, semiarid areas commonly used for irrigated agriculture showed a better correlation than non-agricultural areas. Figure 6 shows the northwest of Sonora state, while Figure 7 shows the northeast of the state of Tamaulipas. In both cases, the correlations range between 0.5 and 0.7.

Moreover, ERA5 and ESA CCI exhibit soil moisture values ranging from 0.05 to 0.4 m3m-3. This behavior appears to be tentatively linked to irrigation, as all three products (ERA5, ESA CCI, and ASCAT SSM) demonstrate similar temporal patterns in the time series.

These findings suggest that irrigation activities may significantly influence the soil moisture values recorded by ASCAT SSM in arid and semi-arid regions. Moreover, similar behavior over croplands and irrigated agricultural areas has also been observed in other global regions. Studies by Massart (2015) and de Sousa (2019) both conclude that irrigated agriculture impact on rainfall variability in vegetation patterns, particularly across large-scale agricultural zones.

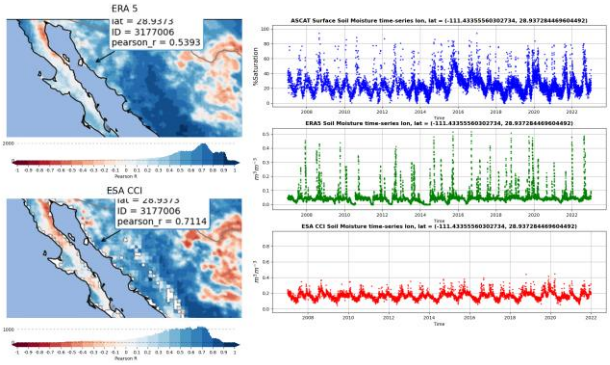

Figure 6. Time series correlations over irrigated agriculture areas for Sinaloa State in Northwest Mexico

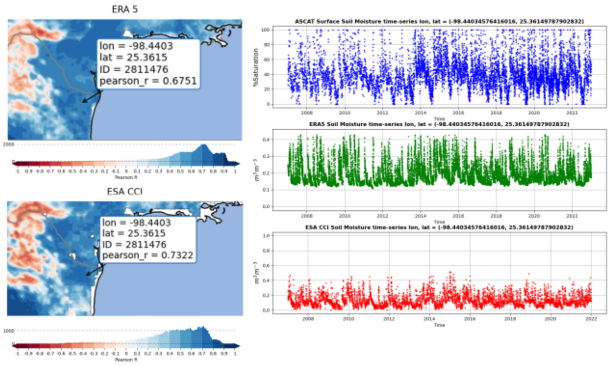

Figure 7. Time series correlations over irrigated agriculture areas for Tamaulipas State in Northeast Mexico

3.2 Precipitation and Soil Moisture Anomalies Comparison

In addition to interannual comparisons between years 2015, 2018 and 2021, specific months were also analyzed. According to CONAGUA and SMN (2024), the dry season in Mexico typically extends from November to April, while the wet season occurs from May to October. For this analysis, the driest months (February to April) and the wettest months (July to September) were specifically examined. In general, Soil Moisture Anomalies (SMA) delivered from ASCAT SSM and Monthly Precipitation Anomalies (MPA) from CONAGUA exhibited deviations in anomaly patterns over arid and dry areas, principally observed with the SMA, likely due to subsurface scattering issues of ASCAT.

Figures 8 to Figure 10, show the dry months of study years, where it can be appreciated that 2021 has more matched areas than 2015 and 2018, even in most of the arid and semiarid areas. Visual comparisons among years illustrate that February is the most matched month. Whereas April was the month with notable differences between precipitation anomalies, specifically in rainfall zones in both 2015 and 2018.

On the other hand, March 2015 is the month that presented the most mismatched areas as MPA indicated positive precipitation anomalies while SMA showed negative values, specifically in central Mexico. This means that while SMA reported low soil moisture values or drought conditions, MPA reported high precipitation during the month.

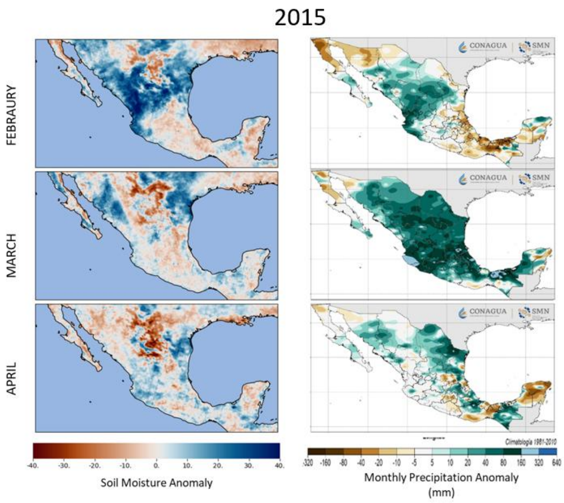

Figure 8. Monthly anomalies during dry months for 2015.

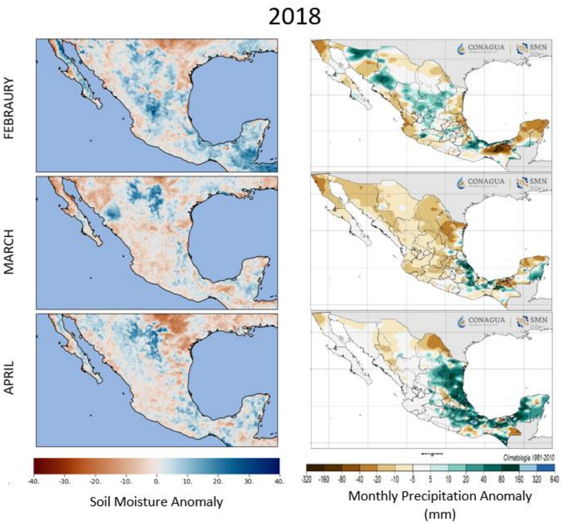

Figure 9. Monthly anomalies for dry months in 2018.

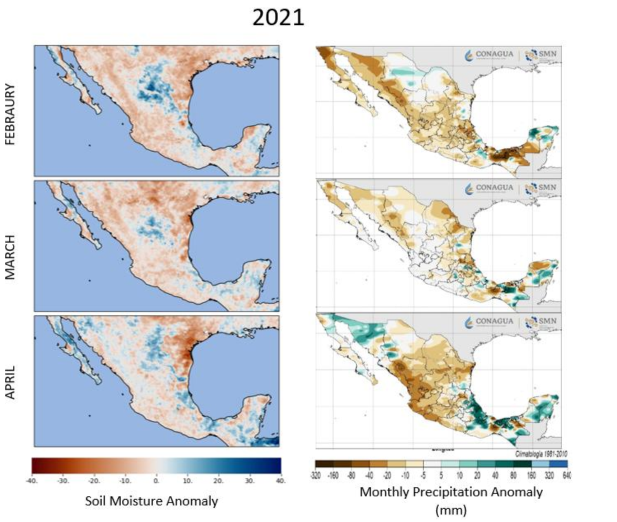

Figure 10. Monthly Soil Moisture and Precipitation Anomalies for 2021 during dry months.

On the other hand, all years exhibited some level of discrepancy during the wet months. Figures 11 to 13 illustrate these months for the same proposed years. July consistently showed the highest number of mismatches across the three analyzed years. In 2015 (Figure 11), these mismatches were predominantly concentrated along the eastern mountain range. However, in July 2018 (Figure 12) and 2021 (Figure 13), widespread mismatches were observed, regardless of climatic or physiographic regions, likely due to the onset of initial rains following preceding drought periods.

In contrast to the dry season of 2021, the wet season months exhibited a higher degree of spatial mismatches (Figure 13). In this year, August flowed by July, showing the most significant discrepancies. Principally, ASCAT delivered SMA exhibited high soil moisture values, while the MPA delivered by CONAGUA reported low precipitation values during July. Following August, the month continued to show the same situation. Contrary to expectation, this mismatch does not appear to be related to climate zones or irrigated agriculture.

As previously noted, satellite-based precipitation and soil moisture products often face limitations in detecting small-scale and short-duration precipitation events, low-intensity rainfall, brief dry spells, and rapid seasonal transitions. These limitations can reduce their effectiveness in certain hydrological and agricultural applications (Brocca et al., 2024; Peng et al., 2020). This may explain why the dry season exhibited a higher number of mismatched areas compared to the wet season, as the rapid shifts in weather conditions during drier months are more difficult for satellite sensors to accurately capture.

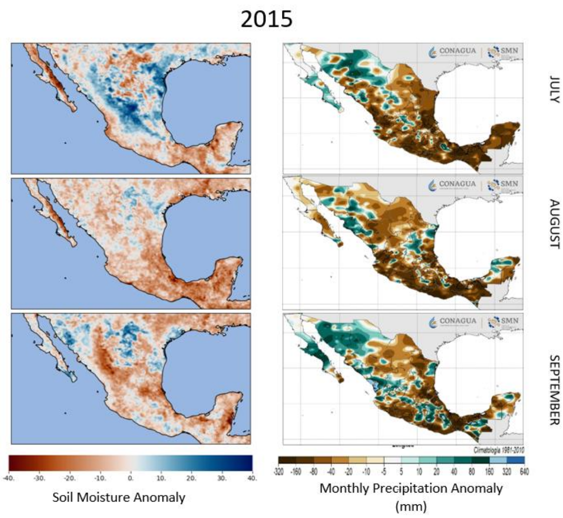

Figure 11. 2015 wet season months anomalies.

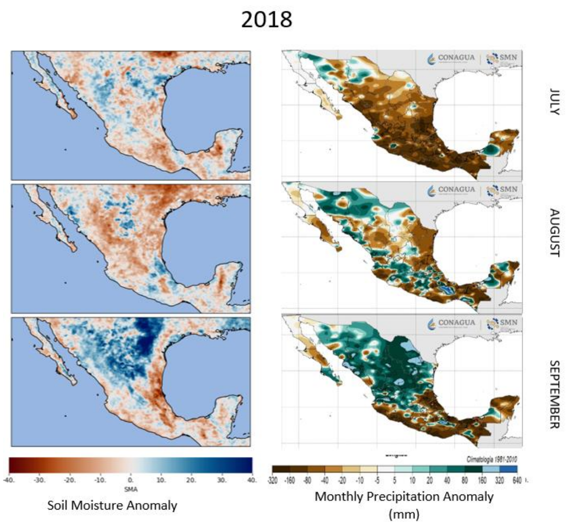

Figure 12. Monthly anomalies for wet months in 2018.

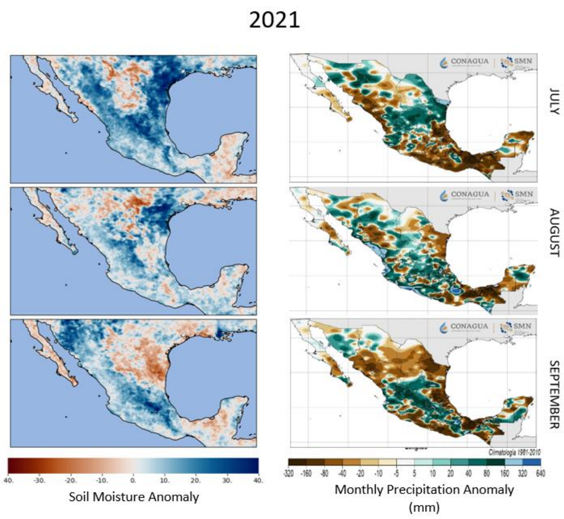

Figure 13. Monthly anomalies observed in wet months in 2021.

3.3 Drought Indicators Assessment

According to the Mexico Drought Monitor (MDM), at least 75% of Mexico's national territory experienced some degree of drought severity during the drought events of 2020 and 2021. Figure 14 to Figure 16 showed the drought indices delivered from August 2020 to May 2021.

As expected, the precipitation-based indices tend to match; this can be explicitly observed in September, March, and May. Furthermore, the rest of the months presented mismatches, more specifically over arid areas. For August, SPI and SPEI showed a similar area under drought conditions (Figure 14). Furthermore, the indices showed a different range of drought conditions, SPI indicates anomaly dry and moderate conditions, while SPEI denotes moderate to extreme conditions in the arid areas. On the other hand, tropical and temperate climate regions in central Mexico presented no drought conditions in SPI, but anomaly dry and moderate conditions according to the Mexico Drought Monitor (SPI).

The comparison between SPI and SMAPI showed more mismatches, especially over arid regions as expected due to the characteristics of the ASCAT SSM product. An example can be found in November and December (Figure 15). Both months revealed notable visual discrepancies over those arid regions. The national monitor (SPI) indicated severe to extreme drought conditions in northwest and northcentral Mexico, while SMAPI showed no drought and mild conditions over those regions.

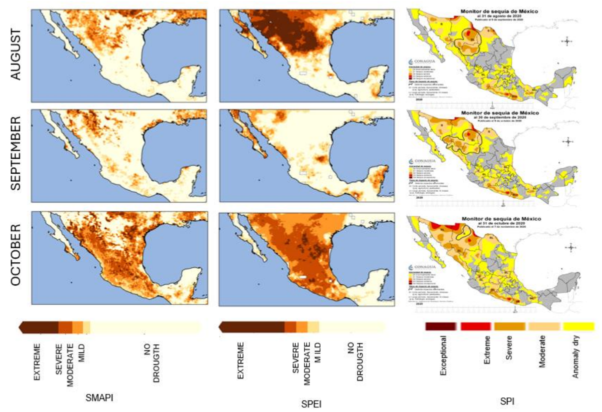

Figure 14. Drought indicators for the drought event of 2020, from August to October.

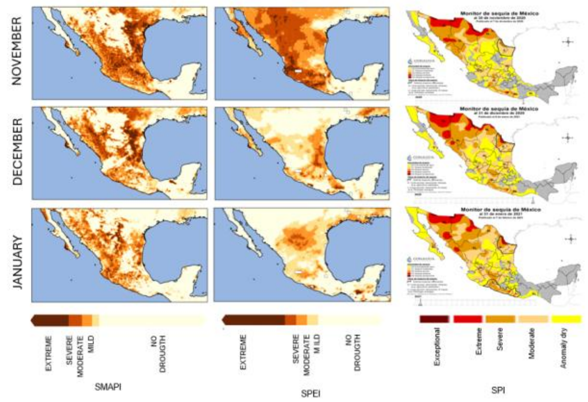

Figure 15. Drought indicators for the drought event from November 2020 to January 2021.

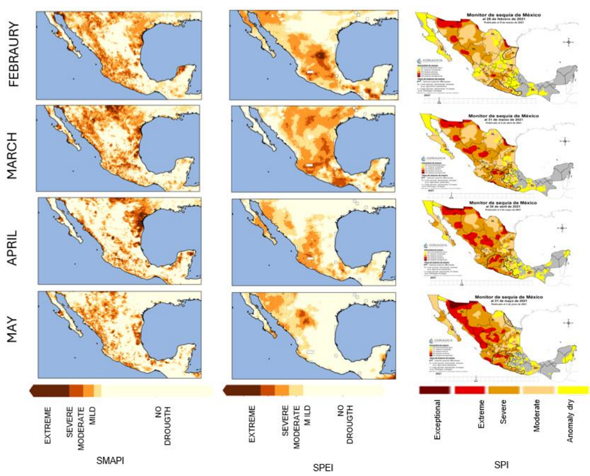

Figure 16. Drought indicators for 2021, months February to may.

Conversely, during the same months over central and eastern Mexico, the indices derived from ASCAT data indicated moderate to extreme drought conditions, meanwhile SPI denoted anomaly dry and moderate drought conditions.

Following the drought event, Figure 15 and 16 shows the period from January to March that exhibited notable discrepancies in capturing drought conditions. The discrepancies were not only over arid regions (northwest and northcentral), further temperate and tropical regions in central Mexico presented mismatches.

In general, SPI indicated moderate to extreme drought across most of the country, except for the southeastern region, particularly the Yucatán Peninsula. In contrast, SMAPI and SPEI predominantly indicated moderate drought conditions, with some instances of severe drought over central Mexico. However, discrepancies were consistently observed in the arid and semi-arid regions during these months, particularly within the Sonoran and Chihuahuan Desert areas.

As previously discussed, central Mexico exhibited notable mismatches between the three drought indicators, with April 2021 showing the greatest discrepancies. These variations were not confined to arid and semi-arid regions but extended across diverse climatic zones, including tropical rainforest, tropical savannah, and temperate climates. In this case, the inconsistencies were observed not only between SPI and the drought indicators derived from ASCAT SSM but also between SMAPI and SPEI, highlighting divergence among both soil moisture- and precipitation-based indices.

In the case of May 2021, SPEI indicated conditions ranging from no drought to moderate drought across most of the country (Figure 16). This contrasts with the SPI-based report from CONAGUA, which identified extreme drought conditions in western and northeastern Mexico. Notably, discrepancies between SMAPI and SPI were once again evident, as SMAPI reported several areas in the west and northeast experiencing extreme drought conditions differing from the spatial patterns reflected in the official SPI-based assessment.

4. Conclusions

The evaluation of the potential of the ASCAT SSM 6.25 km product for agricultural drought monitoring across Mexico revealed, as expected, correlation limitations over the country's dry regions, primarily due to subsurface scattering effects inherent to these areas. It is important to note that the current analysis relied on cross-comparisons with other satellite products, which may introduce biases or misinterpretations in the absence of in situ soil moisture data for robust validation.

Outside of arid regions, soil moisture anomalies derived from ASCAT generally showed good agreement with the monthly precipitation anomalies reported by the National Water Commission. To strengthen this finding, a detailed statistical evaluation at the pixel level is recommended to quantify the relationships better and support the operational use of these products.

The drought indicators' analysis demonstrated strong alignment with historically significant drought events. Like the monthly anomalies analysis, arid regions presented mismatches across all indicators, including those based on precipitation. Nonetheless, SPI and SPEI showed a generally strong correspondence in spatial drought patterns. At the same time, SMAPI effectively captured precipitation deficits and drought conditions, closely reflecting the patterns reported by the Mexican Drought Monitor SPI.

Overall, the ASCAT SSM 6.25 km product demonstrated strong potential for drought monitoring applications in central and northeastern Mexico. However, arid areas will require masking or calibration, ideally using in situ observations to improve accuracy. Future research should prioritize detailed statistical analyses at the pixel level to establish more robust interpretations and strengthen the operational integration of ASCAT soil moisture products for agricultural drought monitoring in Mexico.

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