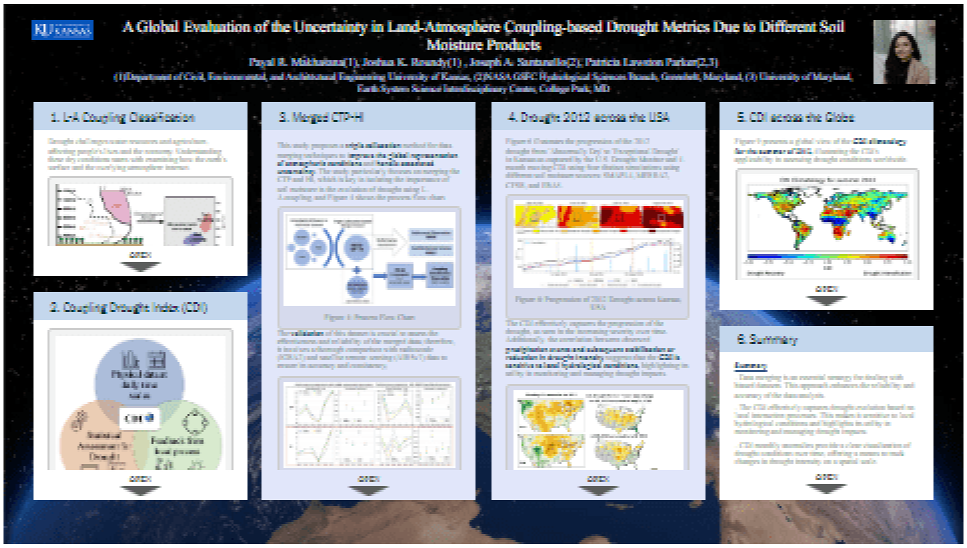
A Global Evaluation of the Uncertainty in Land-Atmosphere Coupling-based Drought Metrics Due to Different Soil Moisture Products



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PRESENTED AT:

1. L-A COUPLING CLASSIFICATION

Drought challenges water resources and agriculture, affecting people's lives and the economy. Understanding these dry conditions starts with examining how the earth's surface and the overlying atmosphere interact.

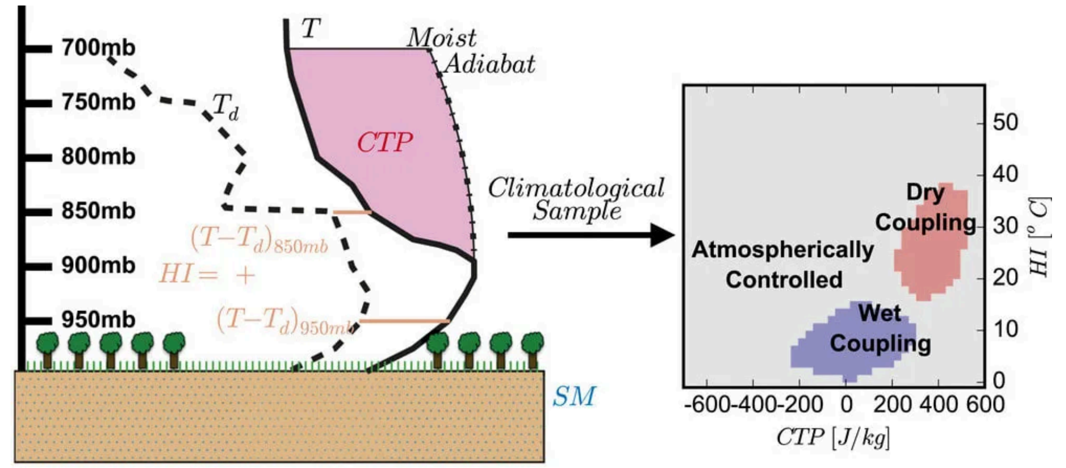

Figure 1: CTP-HI Framework for Coupling Classification (Roundy and Santanello, 2017)

Therefore, this study uses the **land-atmosphere (L-A) coupling classification** based on the work of Findell and Eltahir (2003) and was revised by Roundy et al. (2013) to utilize atmospheric stability (CTP - Convective Triggering Potential), a measure of atmospheric humidity (HI-Humidity Index) along with soil moisture to classify coupling regimes as shown in figure 1.

The CTP is the integrated area between the temperature profile and a moist adiabat between 100 and 300 hPa above the surface and is an indicator of the atmosphere's stability, with a negative value indicating stable conditions and vice versa. The HI measures moisture content in the lower atmosphere, which is calculated as the sum of the dew point depressions at 50 and 150 hPa above the surface. A large value of HI indicates a dry atmosphere as there is a significant difference between the temperature and the dew point temperature at those specific pressure levels, suggesting low moisture content in the atmosphere.

The Role of Soil Moisture in L-A Coupling

Soil moisture is a key variable that measures water and heat energy transfer between land and the atmosphere, and to quantify the influence of soil moisture on land-atmosphere coupling, we use the **Coupling Drought Index (CDI) as drought indices which is a summary metric of land-atmosphere coupling** and **analyze changes in the CDI due to different soil moisture datasets.**


Figure 2: Severely Dry Soil- A Visual Indicator of Drought's Harsh Impact

2. COUPLING DROUGHT INDEX (CDI)

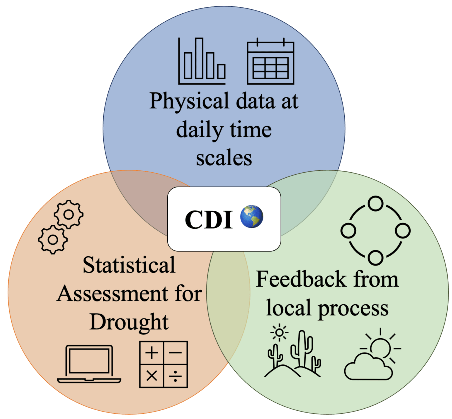

Figure 3: Conceptual Summary of CDI

Drought Indices

Despite the effectiveness of traditional drought indices, there remains a gap in addressing the complex dynamics of land-atmosphere interactions in developing drought index. Traditional indices do not fully account for the intricate feedback mechanisms of land surface and atmosphere. The CDI leverages soil moisture, humidity index (HI), and convective triggering potential (CTP) to fill this void.

The CDI is calculated based on coupling characteristics between the land and atmosphere that synergizes data at a daily time scale, statistical assessment, and feedback from local processes to provide a multifaced view of drought conditions. It represents an average measure of coupling over a selected time window, as mentioned in the equation below.

$$\mathrm{CDI} = \frac{(N_d^2 - N_W^2)}{N_t(N_d + N_W)}$$

$\mathrm{N_d}$ = Number of Dry Coupling
$\mathrm{N_w}$ = Number of Wet Coupling
$\mathrm{N_t}$ = Total Coupling Day

The CDI's range from -1 to 1. A value of 1 signifies that all days within the measurement period experience dry coupling, indicating drought intensification. On the other hand, a value of -1 indicates that all days are under wet coupling, signifying drought recovery.

3. MERGED CTP-HI

This study proposes a **triple collocation** method for data merging techniques to i**mprove the global representation of atmospheric conditions** and **handle associated uncertainty**. The study particularly focuses on merging the CTP and HI, which is key in isolating the importance of soil moisture in the evolution of drought using L-A coupling, and Figure 4 shows the process flow chart.

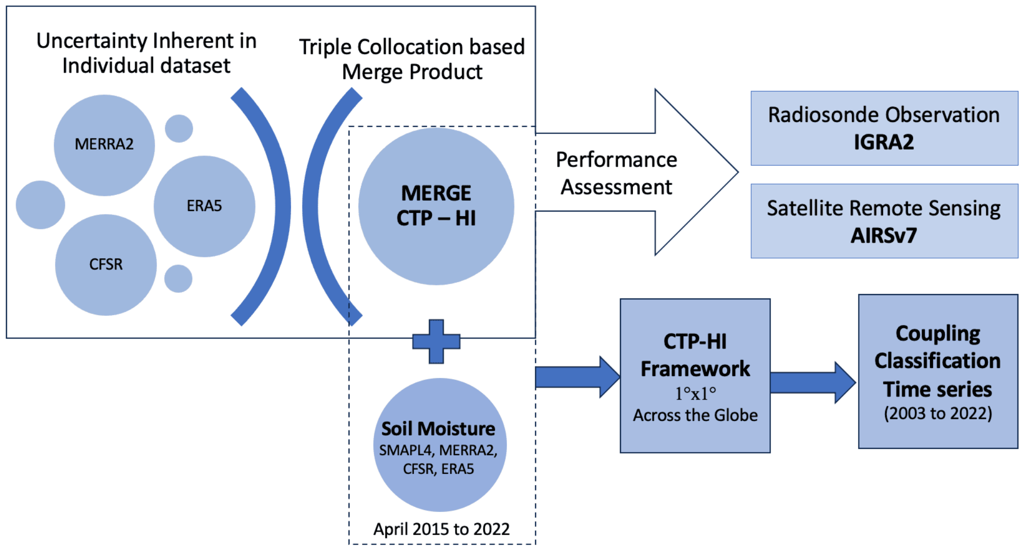

Figure 4: Process Flow Chart

The **validation** of this dataset is crucial to assess the effectiveness and reliability of the merged data; therefore, it involves a thorough comparison with radiosonde (IGRA2) and satellite remote-sensing (AIRSv7) data to ensure its accuracy and consistency,

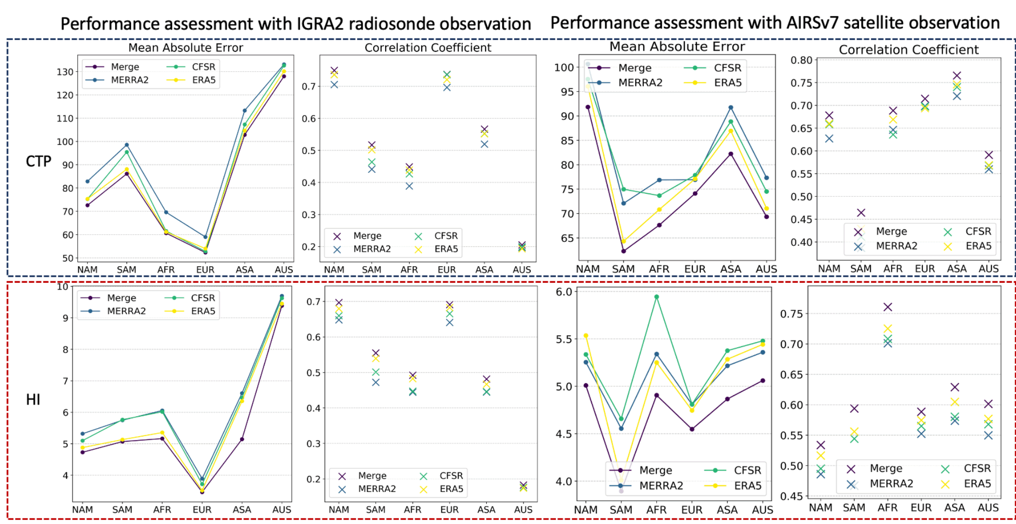

Figure 5: Performance Assessment of the Merged Dataset with Radiosonde and Satellite Remote Sensing (Makhasana et al. in preparation)

Although each reanalysis dataset contains significant correlated errors, when these datasets are combined into a merged product, there is a **noticeable performance improvement.** This combined dataset is more accurate in representing atmospheric conditions.

Once the **CTP-HI framework** is classified using a merged dataset and soil moisture from SMAPL4, Modern-Era Retrospective Analysis for Research and Application, version 2 (MERRA2); the Climate Forecast System Reanalysis (CFSR); and the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) for April 2015 to 2022. Using the CTP-HI framework, a time series of the coupling classification can be generated with only CTP-HI values starting from 2003 to 2022. The period used to classify the CTP-HI space becomes important, and ensuring that all datasets use the same classification period.

The primary focus of this research is to scrutinize the influence of soil moisture on the dynamics of land-atmosphere (L-A) coupling. The investigation first focuses on the **evolution of CDI** and emphasizes the **variance in CDI when utilizing soil moisture data** derived from reanalysis.

4. DROUGHT 2012 ACROSS THE USA

Figure 6 illustrates the progression of the 2012 drought from 'Abnormally Dry' to 'Exceptional Drought' in Kansas as captured by the U.S. Drought Monitor and 4-month moving CDI using four distinct simulations using different soil moisture sources: SMAPL4, MERRA2, CFSR, and ERA5.

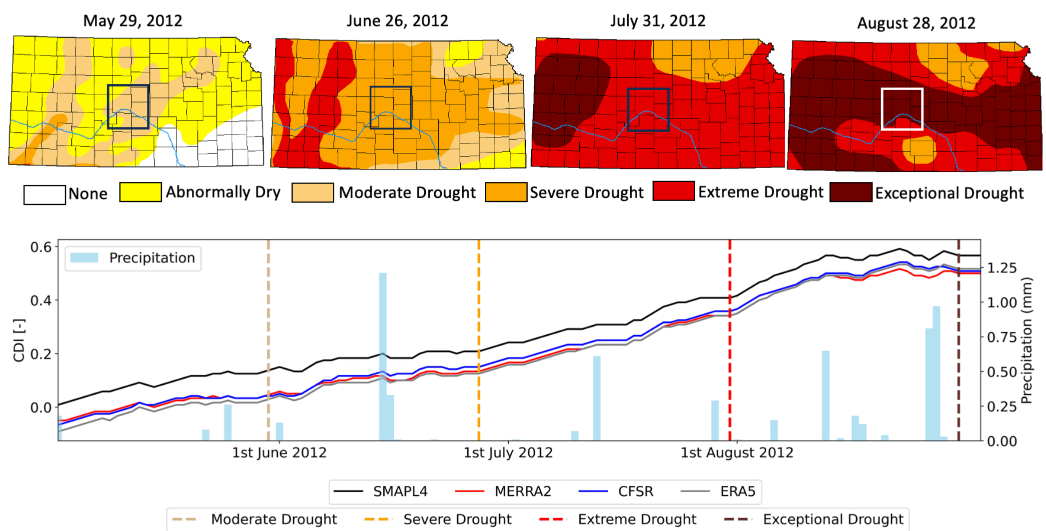

Figure 6: Progression of 2012 Drought across Kansas, USA

The CDI effectively captures the progression of the drought, as seen in the increasing severity over time. Additionally, the correlation between observed **precipitation events and subsequent stabilization or reduction in drought intensity** suggests that the **CDI is sensitive to local hydrological conditions,** highlighting its utility in monitoring and managing drought impacts.

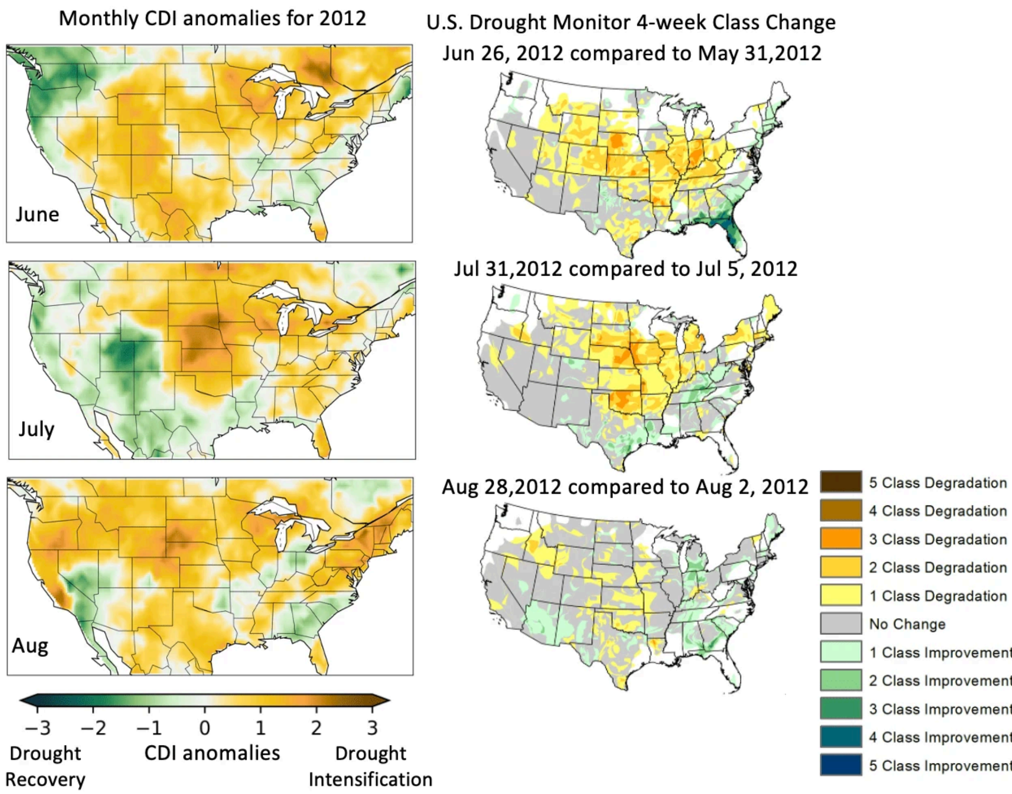

Figure 7: Comparative Analysis of Monthly CDI Anomalies and U.S. Drought Monitor 4-Week Class Change for the Year 2012

Figure 7 compares Monthly CDI anomalies for 2012 and the U.S. Drought Monitor's 4-week class change maps. The Monthly CDI anomalies clearly indicate **how drought conditions deviate from long-term average conditions for each month.** This is particularly useful for identifying the severity and spread of drought conditions over an extended period.

The similarities lie in their **capability to visualize drought conditions over time,** providing a mechanism to track changes in drought intensity over a spatial scale. However, the **differences are marked by their analytical approach.**

Drought Event:

2011-2012: One of the most severe droughts in recent history, it affected a major part of the country, especially Texas and the Great Plains.

2020-2022: Parts of the Western United States, including California, experienced severe to exceptional drought conditions.

2006: A severe to extreme drought affected about 27 percent of the contiguous United States as of the end of June 2006

2007-2009: A multi-year drought affected the southeastern United States, particularly Georgia and Florida.

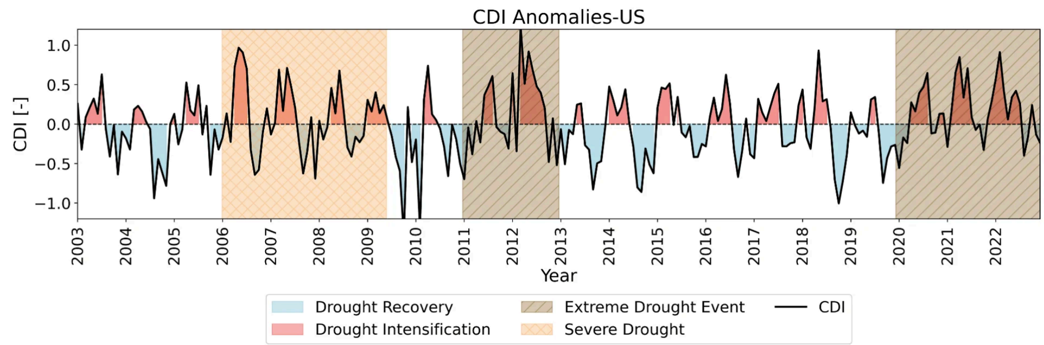

Figure 8: CDI's Ability to Capture Drought Intensification and Drought Recovery

Figure 8 represents CDI's ability to capture drought intensification and recovery based on the spikes with -ve and +ve CDI. However, due to averaging over the United States, the intensification of regional droughts may not be apparent. Nonetheless, this figure provides evidence that the **CDI can capture drought intensification and recovery and can be applicable globally.**

Discussion

The CDI simulation in Figure 6, using SMAPL4 soil moisture data, indicates a more pronounced intensification of drought conditions than other reanalysis soil moisture datasets. This discrepancy may be attributed to the differences in the measurement depth of the top layer of soil moisture. SMAPL4 measures soil moisture in the 0 to 5 cm range, whereas other reanalysis datasets provide soil moisture data for the 0 to 10 cm range. The shallower measurement by SMAPL4 could be more sensitive to short-term lack of rainfall and surface drying, thereby reflecting a quicker response to drought conditions.

5. CDI ACROSS THE GLOBE

Figure 9 presents a global view of the **CDI climatology for the summer of 2012,** illustrating the CDI's applicability in assessing drought conditions worldwide.

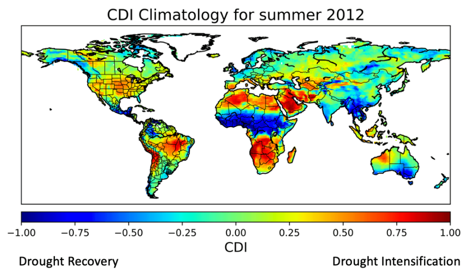

Figure 9: CDI Climatology Across Globe for Summer 2012 Using Soil Moisture from SMAPL4

The color gradient represents areas experiencing drought recovery (blues) and drought intensification (reds), indicating the dynamic nature of drought across various regions. The CDI is computed based on the prevalence of dry and wet coupling regimes over time, and as previously discussed, the results are sensitive to the choice of soil moisture data source.

The analysis also sets the stage for further investigation into how annual CDI values fluctuate in different geographic areas, providing insights into long-term climate trends and soil moisture sensitivity on drought assessment, as mentioned in Figure 10.

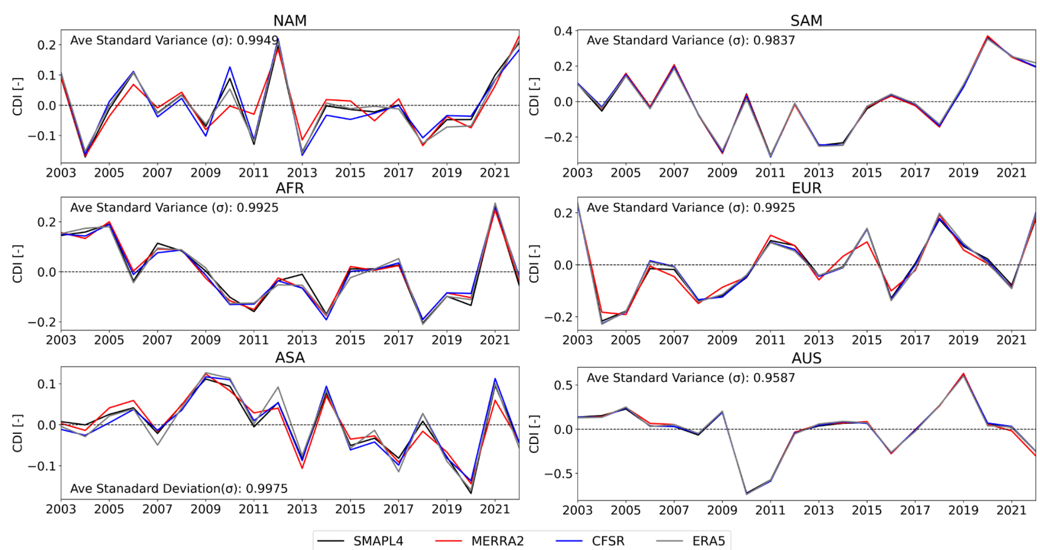

Figure 10: Annual CDI Anomalies in Different Regions across the Globe

In Figure 10, the graphs illustrate the variability in annual CDI anomalies over time, highlighting a **general agreement among various soil moisture data sources/models**, as evidenced by similar trends in the lines. However, there are notable discrepancies between the datasets. The graph includes an average standard deviation metric, which reveals that **Australia exhibits the least deviation among the datasets, followed by South America**. In other regions, the deviation is relatively consistent.

6. SUMMARY

Summary

- Data merging is an essential strategy for dealing with biased datasets. This approach enhances the reliability and accuracy of the data analysis.

- The CDI effectively captures drought evolution based on local interaction processes. This makes it sensitive to local hydrological conditions and highlights its utility in monitoring and managing drought impacts.

- CDI monthly anomalies provide a clear visualization of drought conditions over time, offering a means to track changes in drought intensity on a spatial scale.

- Notably, the CDI is adept at capturing both drought intensification and recovery, demonstrating its comprehensive applicability in drought studies.

- The CDI is an index based on local interaction processes, aiding in global daily, monthly, and annual monitoring and assessment of global drought conditions.

- The CDI's sensitivity to drought conditions is influenced when using varying soil moisture data. However, the overall pattern remains consistent.

Future Work

- Our research has opened the door to new studies to help us better understand droughts.

- Future research will focus on identifying drought intensification and recovery hotspots. We'll also look at how these patterns are connected to bigger climate changes that are happening all over the world.

- Additional studies will investigate the sensitivity of soil moisture in the representation of drought.

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- Advanced skills in statistical analysis, particularly related to hydrological studies and heat transfer.

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TRANSCRIPT

ABSTRACT

Accurately assessing drought conditions is essential for effective water resource management and mitigation. In this study, we use the triple collocation (TC) method to merge three reanalysis datasets of Convective Triggering Potential (CTP) and Humidity Index (HI) to evaluate the uncertainty in land-atmosphere coupling-based drought metrics due to soil moisture. Based on the validation results against the Integrated Global Radiosonde Archive version 2 (IGRA2) and the Atmospheric Infrared Sounder (AIRS), the merged product results in improved performance and enhanced accuracy in capturing the atmospheric state. By integrating the combined dataset, we strengthen the evaluation of land-atmosphere coupling-based drought metrics and investigate the sensitivity of these metrics to variations in soil moisture. The analysis focuses on identifying the impact of Soil Moisture Active Passive level 4 (SMAPL4) soil moisture variations on land surface conditions and drought dynamics compared to a reanalysis of soil moisture. The comprehensive evaluation sheds light on the role of SMAP soil moisture in shaping these outcomes. Results reveal consistent underestimation of drought severity by the Modern-Era Retrospective analysis for Research and Application, version 2 (MERRA2) compared to SMAPL4 soil moisture, particularly in the northern hemisphere. At the same time, a similarity is observed in South America with MERRA2 and other reanalysis soil moisture products from the Climate Forecast System Reanalysis (CFSR) and the European Center for Medium-Range Weather Forecast (ECMWF) Reanalysis v5 (ERA5). In the future, by incorporating merged soil moisture data, we can effectively address uncertainties associated with individual datasets, enabling a more comprehensive understanding of the land-atmosphere coupling framework and facilitating informed decision-making based on the quantification of soil moisture's significance.

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