Influence of Soil Moisture on Cloud Properties and Rainfall in the Houston Area During TRACER

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Abstract

Interactions between land surfaces and cloud processes are among the most poorly understood topics in atmospheric science. As important contributors to Earth's atmospheric energy balance, clouds are crucial to understanding and forecasting weather and climate. This study analyzes soil moisture and cloud cover data collected at sites across the Houston region during the Tracking Aerosol Convection Interactions Experiment (TRACER) intensive operational period (June-September 2022). Cloud cover observations from the Atmospheric Radiation Measurement field campaign database are combined with soil moisture data from the Texas Soil Observation Network (TxSON) and Stage IV precipitation data from NCEP. Positive correlations between soil moisture and cloud cover (as well as rainfall) are observed. Relationships are most robust at 5cm and (especially) 10cm depths and during high pressure weather systems. Additionally, the CTP-HI_{low} framework, which anticipates the response of rainfall to soil moisture, seemingly predicts precipitation trends accurately across days forecast to have positive correlations.

Methods


Figure 2. View from the Total Sky Imager

Data Collection

- Data were collected during the TRACER Intensive Operational Period (IOP) of June 1 – September 30, 2022.
- Soil moisture measurements were taken at 5cm, 10cm, and 20cm depths from four TxSON[5] sites (see Fig. 3).
- All cloud data were obtained at the TRACER field campaign site at La Porte, Texas and accessed via the ARM field campaign database.
- **Instruments:**
  - Dielectric Permittivity Sensors – Soil moisture
  - Total Sky Imager (TSI)[6] – Cloudy fraction of the sky
  - Radar/Lidar[7] – Cloud base/top height
  - Rain Gauges/Radar[8] – Precipitation accumulation (standardized by Stage IV best-estimate analysis)
  - Weather Balloons[9] – Air temperature, relative humidity, and wind speed at different altitudes

Data Analysis

- Soil moisture data from the four sites were averaged into one dataset. Only the daily 6:00AM CDT data were used.
  - Intended to reduce biases resulting from soil type/location and solar radiation influences, as well as maximize independence between soil moisture and precipitation measurements for a given day.
- Averaged data were sorted by associated synoptic condition, as well as by CTP-HI_{low} classification.
- Sorted data were then compared to:
  - Daily averages of the fraction of sky covered by clouds during daylight hours.
  - Hourly averages of vertical cloud profiles.
  - Percentages of the area around the TxSON sites (see Fig. 3) for which daily rainfall accumulation exceeded three defined thresholds: 0.125in, 0.25in, 0.5in.

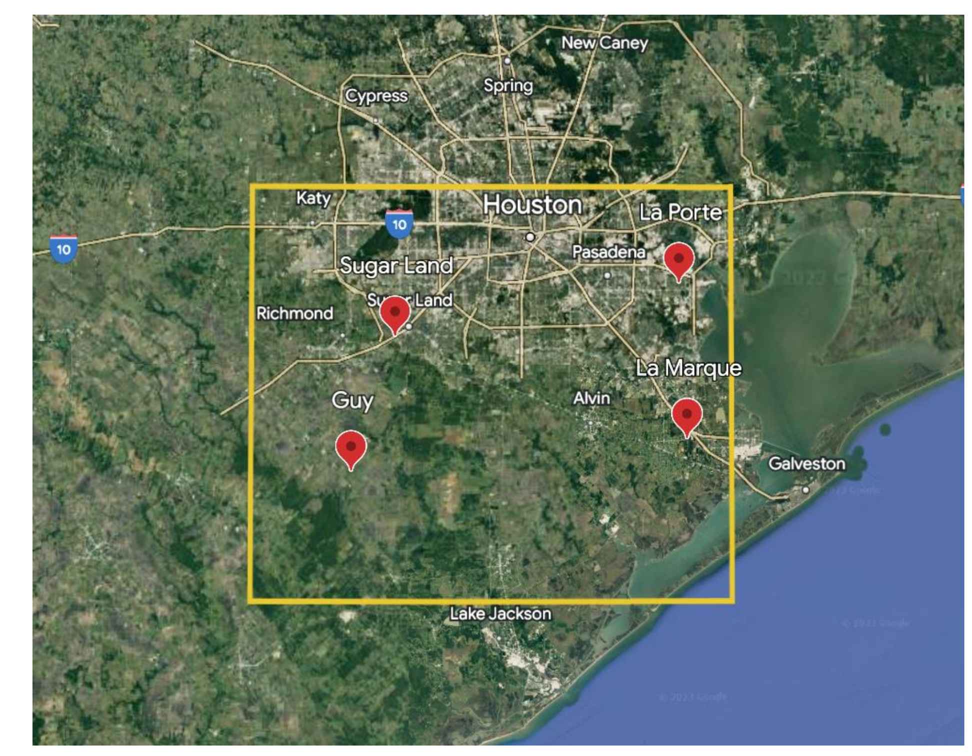


Figure 3. Google Earth map of the Houston, TX area. Red pin icons show the TxSON sites in La Marque, La Porte, Sugar Land, and Guy. All cloud data were obtained at La Porte. The yellow box shows the outer boundary of the analyzed precipitation area. (Area bounds: 29.1°N-29.85°N, 94.95°W-95.95°W)

Introduction

CLOUD FORMATION

- Air saturation occurs when air's humidity becomes great enough that the rate of liquid water evaporation equals the rate of water vapor condensation.
- *Supersaturation* occurs when the humidity in the air surpasses the saturation point, resulting in net condensation.
- Cloud droplets form due to supersaturation-induced condensation in the atmosphere.

EVAPOTRANSPIRATION[1]

- Evapotranspiration is the transfer of moisture from the land to the atmosphere through plant transpiration and soil evaporation, which both depend on soil moisture.
- It is a major component of the water cycle over land.

Putting it together: Cloud formation is dependent on the humidity of the air. Therefore, the conversion of soil moisture to air humidity via evapotranspiration influences cloud formation.

DOE ARM TRACER Field Campaign[2]

- TRACER was conducted in order to better understand cloud processes and their interactions with aerosols in the atmosphere.
- Various measurements were taken in the Houston, TX area to get a representation of the complex coastal environment.

SYNOPTIC CLASSIFICATION

- Each day was classified by Park et al.[4]
- Structures of the jet stream associated with different weather patterns (Fig. 1).
- **Ridge:**
  - High pressure system
  - Isolated precipitation/clouds
- **Pre-Trough:**
  - Decreasing surface pressure
  - Widespread light precipitation
- **Trough:**
  - Low pressure system
  - Widespread precipitation expected
- **Post-Trough:**
  - Increasing surface pressure
  - Decreasing precipitation
- **Weak Anomaly:**
  - No significant pattern

CTP-HI_{LOW} FRAMEWORK[3]

- Method for predicting the soil moisture-precipitation relationship.
- Combination of convective triggering potential (CTP) and the low-level humidity index (HI_{low}).
  - Based on early-morning profiles of temperature and humidity measured by weather balloons in the lowest ~3 km of the atmosphere.
  - CTP is a measure of the energy available to make air rise.
  - HI_{low} is a measure of humidity in the lower atmosphere.
- The framework defines days by their "soil advantage".
  - **Wet Soil Advantage:**
    Moist soil = more precipitation
  - **Dry Soil Advantage:**
    Dry soil = more precipitation
  - **Transition Zone:**
    No specific advantage
  - **Atmospherically Controlled:**
    Precipitation not sensitive to soil moisture

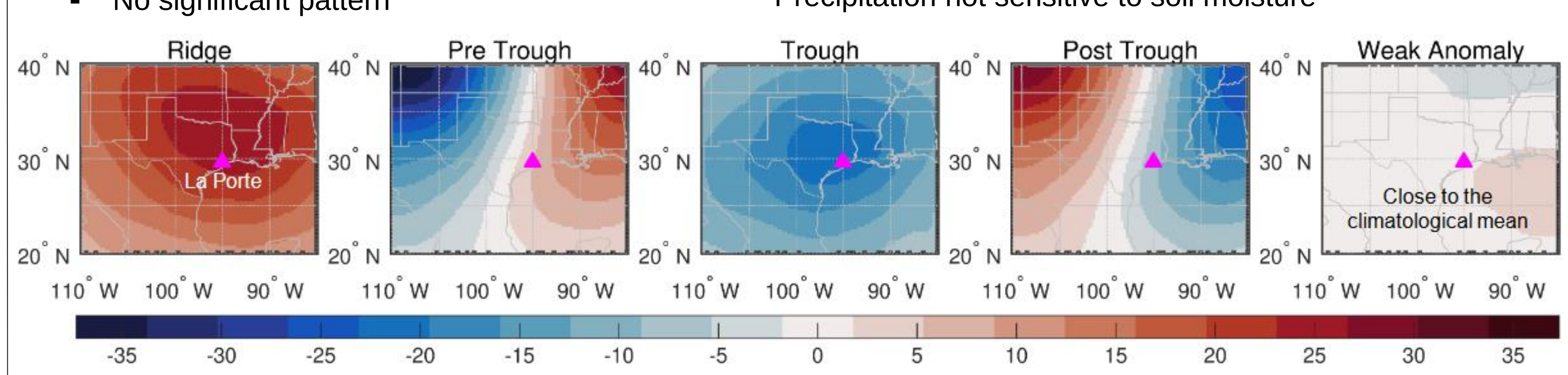


Figure 1[4]. Deseasonalized geopotential height anomaly (m) at 500 hPa (near 5.5 km height) for each synoptic classification.

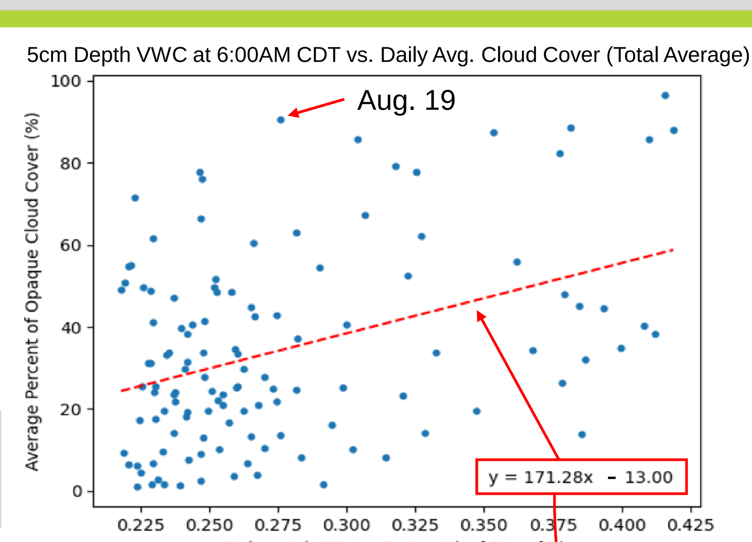
Research Goals

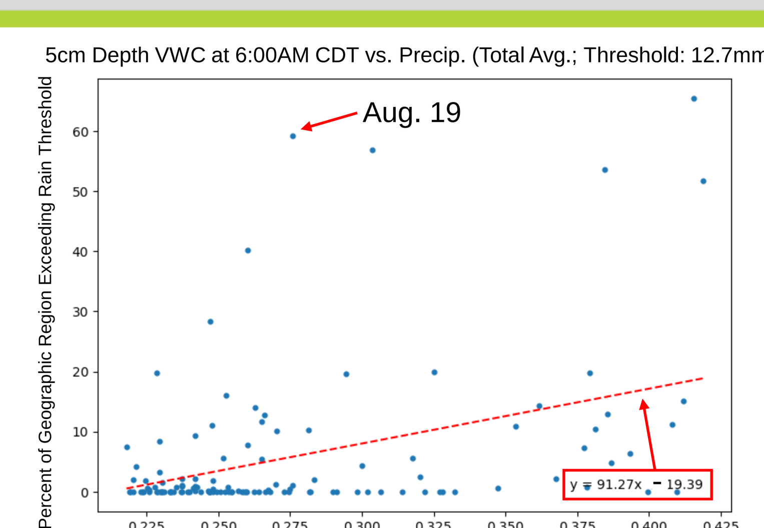
This project seeks to better understand the influence of soil moisture on precipitation and the formation of clouds.

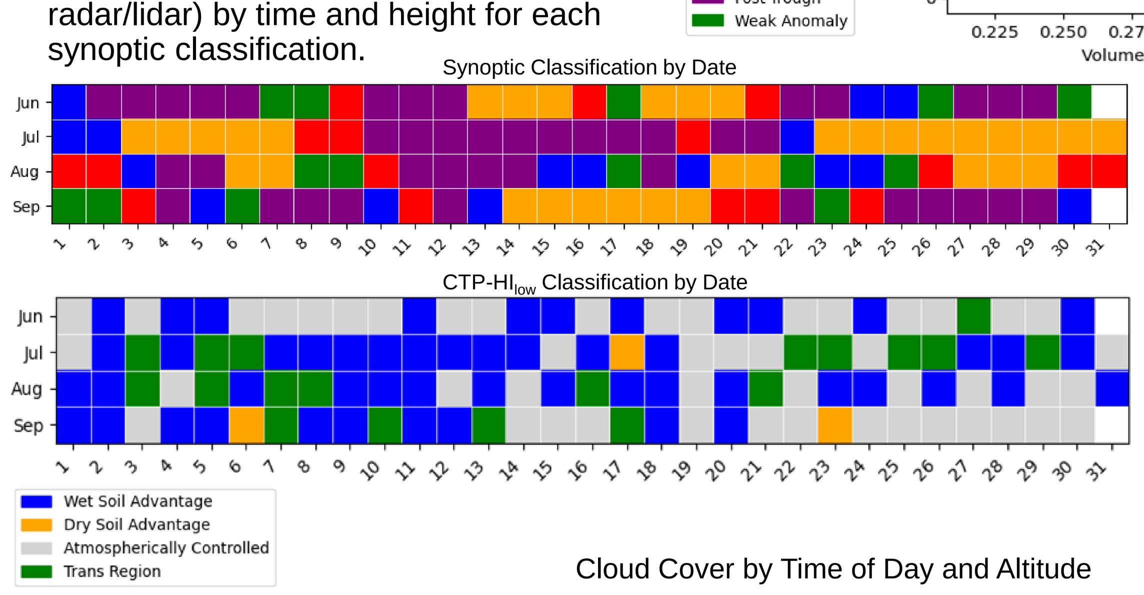
- **Hypothesis 1:** Soil moisture has a positive correlation with cloud cover and daily precipitation, with near-surface depths having the strongest correlation.
- **Hypothesis 2:** Synoptic patterns associated with fewer large-scale precipitation events will see the strongest correlation between soil moisture and cloud cover/precipitation.
- **Hypothesis 3:** The CTP-HI_{low} framework is an accurate predictor of precipitation trends across days of different soil advantage regimes.

Results

- Scatterplots show the relationship between daily average cloud cover/precipitation observations and 6:00AM CDT soil moisture. Each point corresponds to a single day. Linear regression is included.
- Statistical analyses were completed for all classifications. The ones shown here have been selected subjectively based on sample size and statistical significance.
- Grayscale panels (below) show average vertical cloud fraction (measured with radar/lidar) by time and height for each synoptic classification.







Cloud Cover

Depth	Statistic	Total Average	Ridge
5cm	p-value	0.000009	0.000971
	Slope	171.28	283.76
	R	0.3891	0.5269
10cm	p-value	0.0000005	0.001043
	Slope	278.47	426.11
	R	0.4373	0.7229
20cm	p-value	0.094422	0.059972
	Slope	68.64	185.17
	R	0.1521	0.4668

12.7mm - 0.5 inch

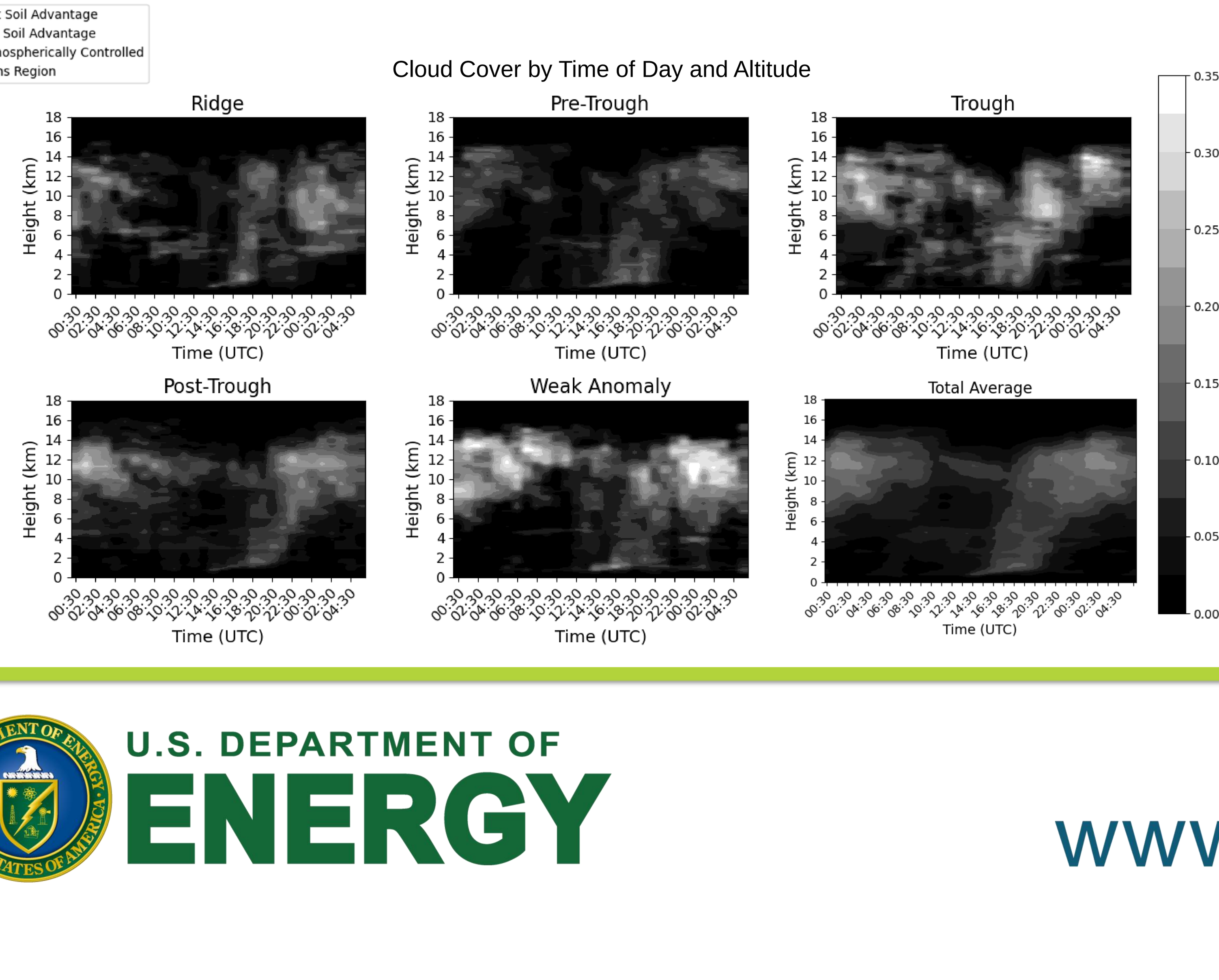
Depth	Statistic	Total Average	Ridge	Wet Soil Adv.
5cm	p-value	0.000007	0.000333	0.01019
	Slope	91.27	151.87	79.02
	R	0.3931	0.7664	0.3567
10cm	p-value	0.000001	0.001101	0.004734
	Slope	146.58	215.33	132.31
	R	0.4364	0.7206	0.1517
20cm	p-value	0.000778	0.011922	0.02638
	Slope	71.46	119.45	71.65
	R	0.3003	0.594	0.3109

6.35mm - 0.25 inch

Depth	Statistic	Total Average	Ridge	Wet Soil Adv.
5cm	p-value	0.000003	0.000022	0.006377
	Slope	132.1	234.41	110.14
	R	0.41	0.842	0.3771
10cm	p-value	0.00000013	0.000114	0.002421
	Slope	212.61	336.05	186.18
	R	0.4562	0.8005	0.4156
20cm	p-value	0.00095	0.003329	0.022141
	Slope	97.62	188.95	97.19
	R	0.2956	0.6688	0.3198

3.175mm - 0.125 inch

Depth	Statistic	Total Average	Ridge	Wet Soil Adv.
5cm	p-value	0.000007	0.000006	0.013237
	Slope	155.66	282.63	124.56
	R	0.3937	0.8678	0.3447
10cm	p-value	0.00000037	0.000034	0.00525
	Slope	252.28	408.8	213.46
	R	0.4411	0.8325	0.3852
20cm	p-value	0.002647	0.00173	0.041883
	Slope	109.39	231.55	107.51
	R	0.2699	0.7007	0.286



Discussion

- Across the total 122-day IOP, there appears to be a robust positive correlation between 6:00AM CDT soil moisture and daily average cloud cover. The same can be said for the percentage of the target area above the three daily accumulated precipitation thresholds.
- **Soil Depth:**
  - Among the full total and all filtered date ranges, soil moisture values at 5cm and 10cm depths appear to have positive correlations with both cloud cover and daily precipitation.
  - The 10cm level appears to have the strongest correlations.
  - The 20cm level appears to have a robust correlation with daily precipitation, but not cloud cover.
- **Synoptic Classification:**
  - Of all classifications, dates featuring ridge structures form the only group to contain robust correlations.
  - Ridge dates exhibit an overall positive correlation between soil moisture and both cloud cover and precipitation.
- **CTP-HI_{low} Classification:**
  - The results for "wet soil advantage" days are consistent with the CTP-HI_{low} framework.
  - On wet soil advantage days, early morning soil moisture is positively correlated with rainfall.

Next Steps

- Examining previous years' summers using the Stage IV precipitation dataset would increase the sample size, allowing more robust statistics.

Limitations

- The linear regression analysis makes assumptions that may not be valid for this dataset.
- Many classification subsets contained too few dates to assess statistical trends.

- Further investigation of soil type, local weather patterns, surface energy fluxes, and other environmental conditions would assist in understanding the physical processes underlying the results.
- Comparison with other regions would expose local biases and help assess the universality of results.

References

[1]S. I. Seneviratne, et. al, 'Investigating soil moisture–climate interactions in a changing climate: A review', Earth-Science Reviews **99**, 125-161 (2010).
[2]M. P. Jensen, et.al., 'A Succession of Cloud, Precipitation, Aerosol, and Air Quality Field Experiments in the Coastal Urban Environment', Bull. Amer. Meteor. Soc. **103**, 103–105 (2022).
[3]K.L. Findell and E. A. B. Eltahir, 'Atmospheric controls on soil moisture-boundary layer interactions. Part I: Framework development', J. Hydrometeor. **4**, 552-569 (2003)
[4]J. M. Park, et. al, 'Joint Variability of Aerosol, Clouds, and Synoptic Meteorology over Southeastern Texas' (2023).
[5]H. Dashtian and M. H. Young, 'Soil Water Content and Meteorological Data to Support Tracking Aerosol Convection Interactions ExpeRiment (TRACER) over Harris County, Texas', Texas Data Repository **1** (2023).
[6]Atmospheric Radiation Measurement (ARM) user facility. 2021. Total Sky Imager (TSISKYCOVER). 2021-08-02 to 2022-10-02, ARM Mobile Facility (HOU) Houston, TX; AMF1 (main site for TRACER) (M1). Compiled by D. Flynn and V. Morris. ARM Data Center. Data set accessed June-July 2023.
[7] Atmospheric Radiation Measurement (ARM) user facility. 2021. ARM Best Estimate Data Products (ARMBECLDRAD). 2022-07-01 to 2022-09-30, ARM Mobile Facility (HOU) Houston, TX; AMF1 (main site for TRACER) (M1). Compiled by C. Xiao and X. Shaocheng. ARM Data Center. Data set accessed June-July 2023.
[8]B. R. Nelson, et. al, 'Assessment and Implications of NCEP Stage IV Quantitative Precipitation Estimates for Product Intercomparisons', Wea. Forecasting **31**, 371–394 (2016).
[9]Atmospheric Radiation Measurement (ARM) user facility. 2021. Balloon-Borne Sounding System (SONDEWNPN). 2022-01-01 to 2022-10-01, ARM Mobile Facility (HOU) Houston, TX; AMF1 (main site for TRACER) (M1). Compiled by E. Keeler and K. Burk. ARM Data Center. Data set accessed June-July 2023.

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