Boundary Layer Interactions Explain Observed Patterns of Soil Moisture-Precipitation Interactions across the Conterminous United States

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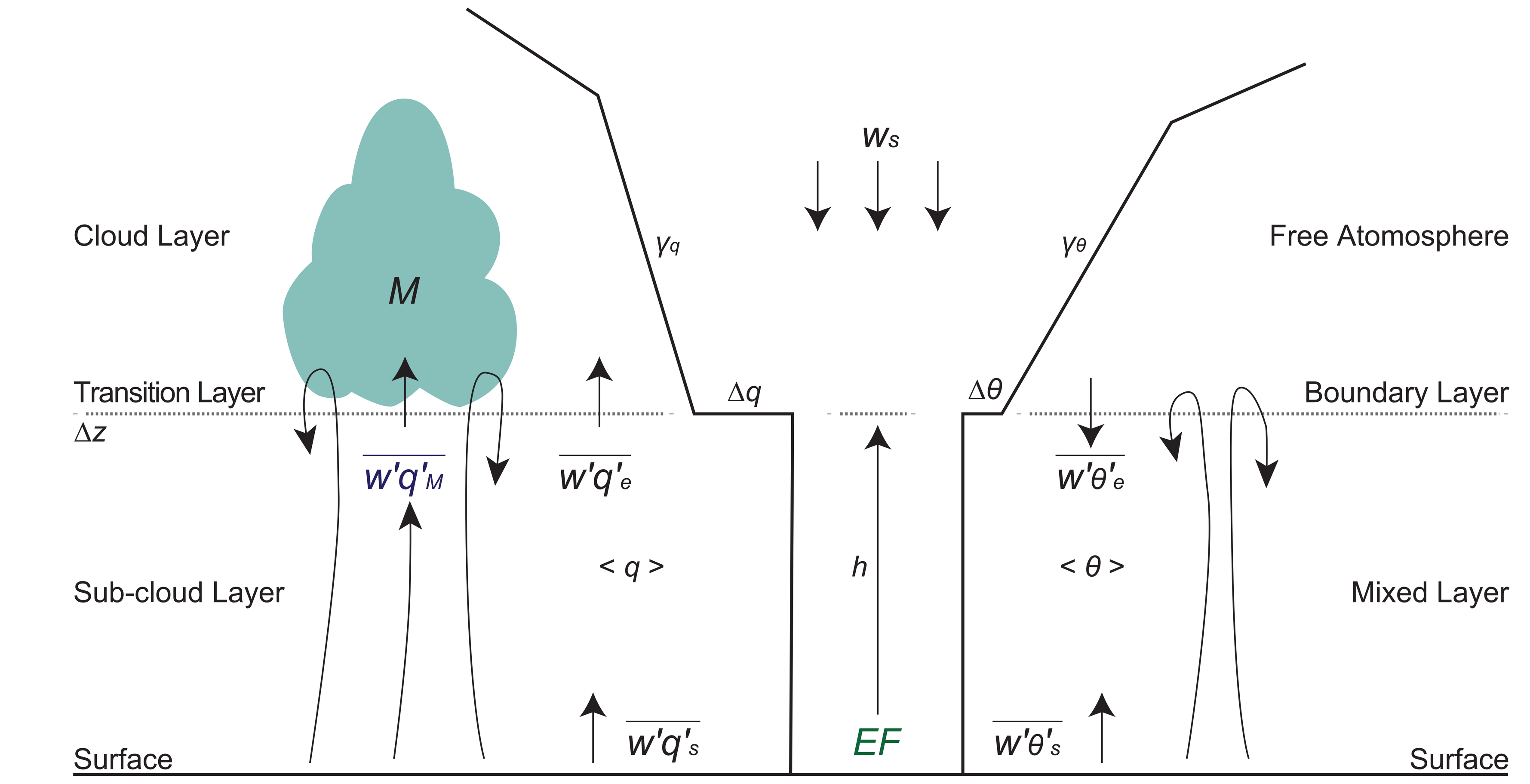
Abstract

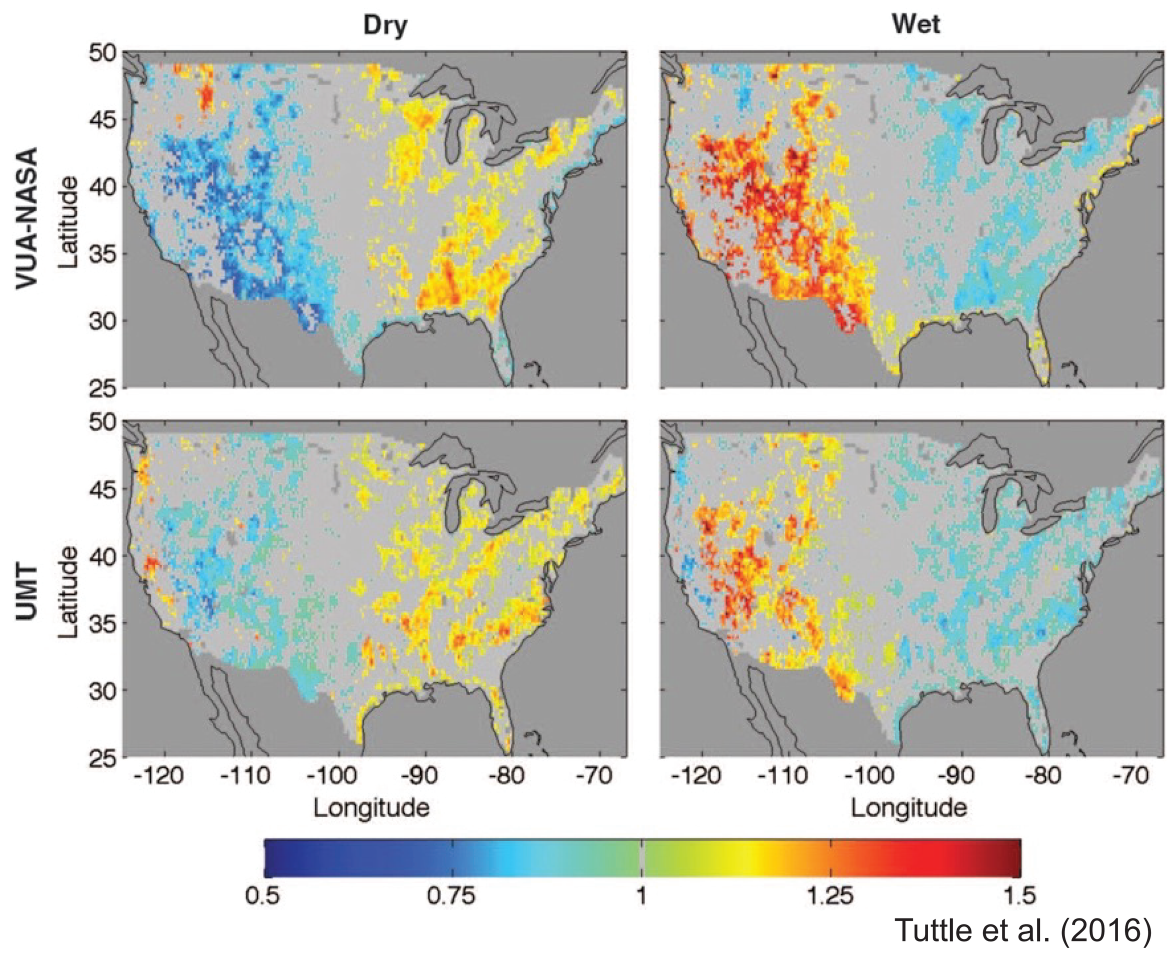
Changes in land surface moisture state alter the exchange of fluxes between land and the atmosphere and result in changes in the state of heat and moisture in the lower part of the atmosphere. Evaporative Fraction (EF), defined as the fraction of Latent Heat Flux to the available surface energy, represents such surface changes in the Surface Energy Balance framework. Given the framework and a boundary layer model, it is feasible to study how the atmosphere responds to land surface moisture state changes. Here we demonstrate that a simplified atmospheric boundary layer model can produce similar patterns of land-atmosphere interactions to that found empirically from remotely sensed soil moisture and ground-based precipitation data. The comparison of land-atmosphere interactions is indirect. It is made between two sensitivity analyses:
1) the sensitivity of vapor flux at cloud-base to surface evaporative fractions (EF) around their equilibrium value in the boundary layer model and 2) the sensitivity of precipitation probability to soil moisture perturbations in the empirical model. In the first sensitivity analysis, we applied equilibrium evaporative fraction between the land and the top of the boundary layer to estimate evapotranspiration across the United States. We find consistent results between the two approaches, with positive interactions in the western and negative interactions in the eastern of the United States. Results indicate surface moisture state changes result in the different tendencies of shallow cloud formation depending on location. The different evolutions of the boundary layer, and in particular the interaction of the boundary layer height and the lifting condensation level, explain the resulting patterns. Analyzing the sensitivity of fluxes to perturbations of evaporative fraction around the equilibrium evaporative fraction enhanced our understanding of hydrology-related issues in regions where in-situ measurements are not available.

Boundary Layer Interactions

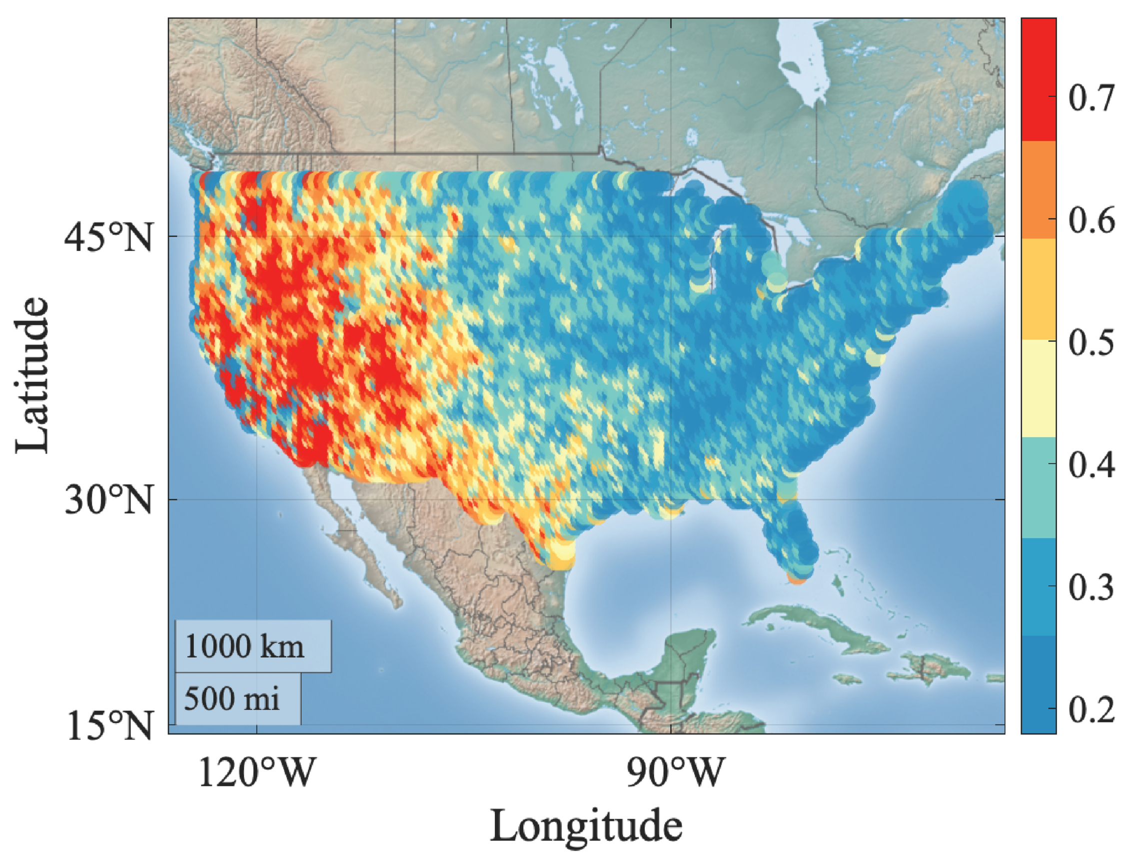


The CLASS model
Vilà-Guerau de Arellano et al. (2015)

Soil Moisture-Precipitation Interactions



Tuttle et al. (2016)



Taylor, J. and G. D. Salvucci, In preparation

Both figures used remote sensing soil moisture and precipitation data, but different soil moisture data sets, the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) (left), and the Soil Moisture Active Passive (SMAP) (right). Since 1 and 0.5 in each plot were the standard, color schemes represented dominant interactions: positive interactions (red) in the western and negative interactions (blue) in the eastern United States.

Methods

The CLASS Model

- The Scattered Shallow-Cumulus Clouds

$$ac = q_a - q_{sat,h} \sim N(0, \sigma_{q,h}^2)$$

$$\sigma_{q,h}^2 = f(\,Total\ \overline{w'q'}_e, \Delta q, \Delta z, h, w_*)$$

Modification

- The Impact of the Surface on the Clouds

$$ac_{new} = m * ac_{sfc} + (1-m) * ac_h$$

$$ac_{sfc} = q_{sat,h} \sim N(\,q_{sfc}, \sigma_{q,h}^2)$$

$$ac_h = q_{sat,h} \sim N\left(q_a - \frac{(\,(1-m) * q_{sfc}\,)}{m}, \frac{\sigma_{q,h}^2}{3}\right)$$

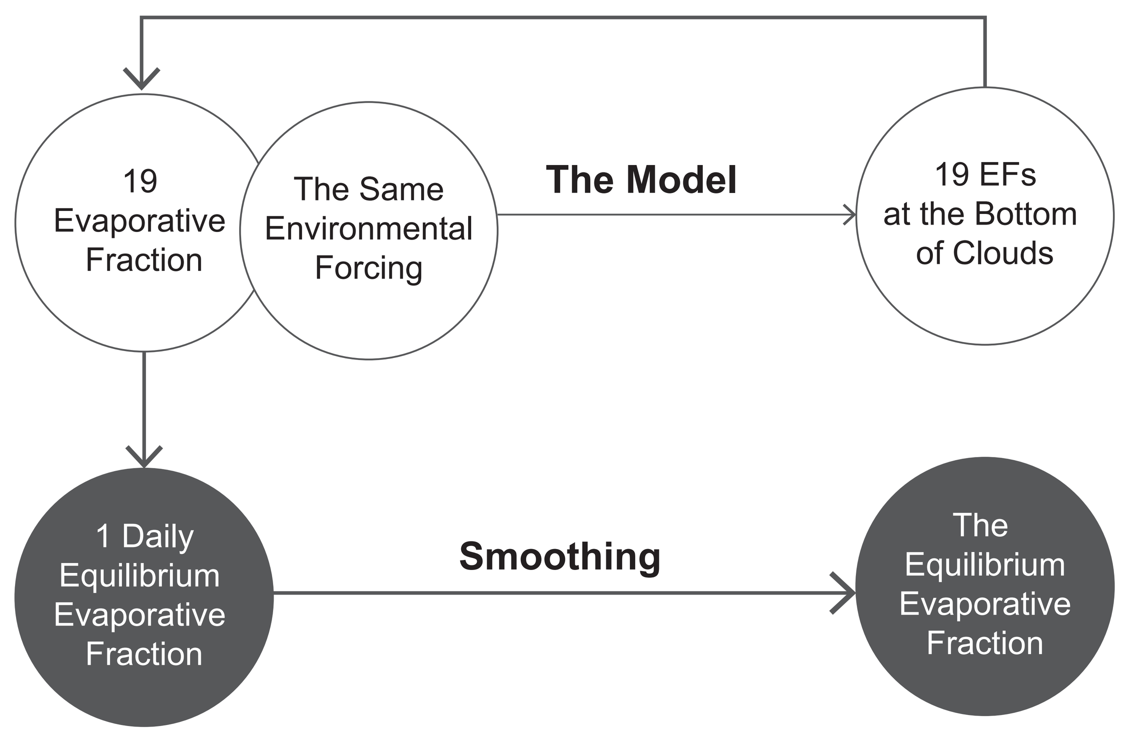
m = mixing ratio be the BL and the Entrainmentzone.

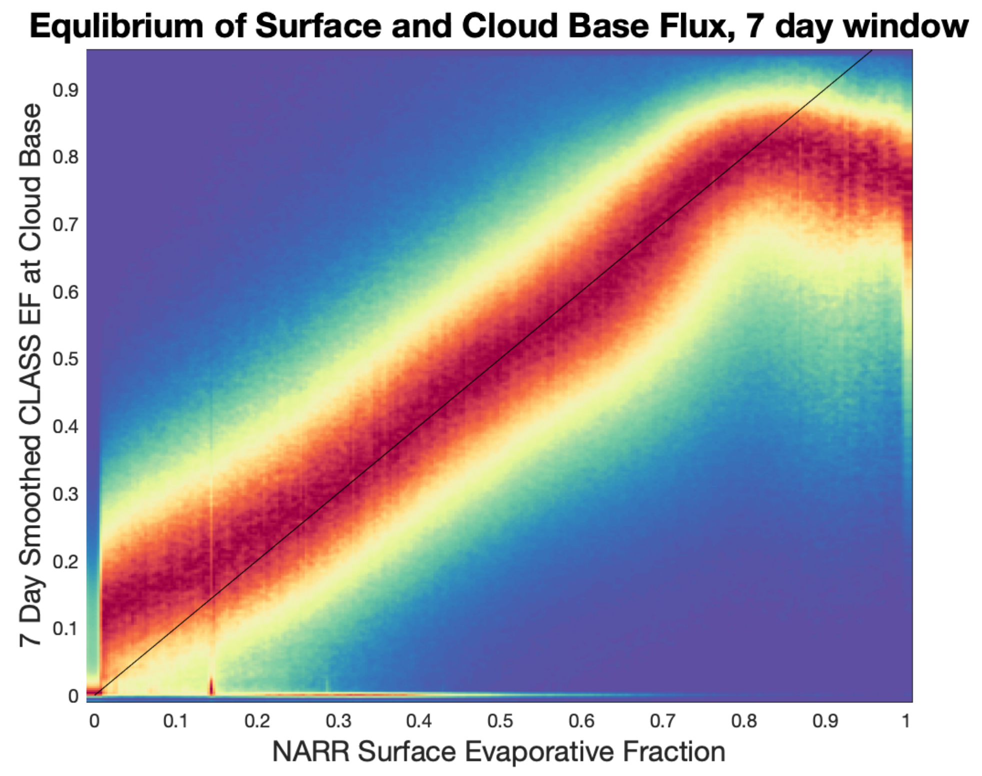
Data

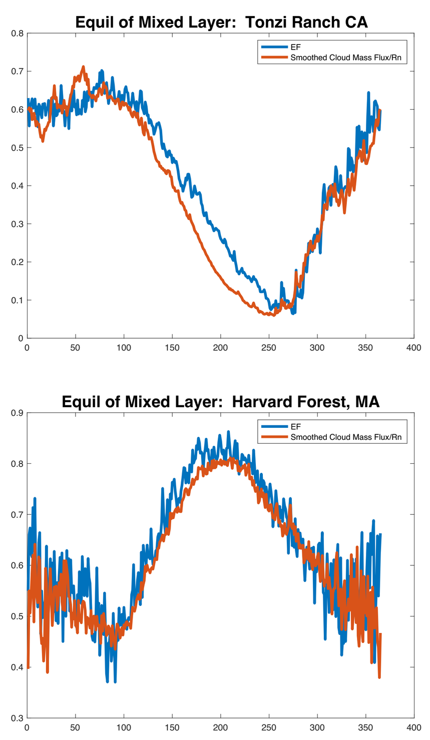
- The North American Regionalc Reanalysis (NARR)
- The Grid Resolution: About 32 km at the Lowest Latitude
- 29 Pressure Levels Measurements (Mesinger et al. 2006)
- Research Period: 06/02 – 06/11

Application of a Novel Method

- Eqilibrium Evaporative Fraction (Salvucci. 2019)
- An Analytical Way to Estimate Evapotranspiration
- Site-Specific Analyses







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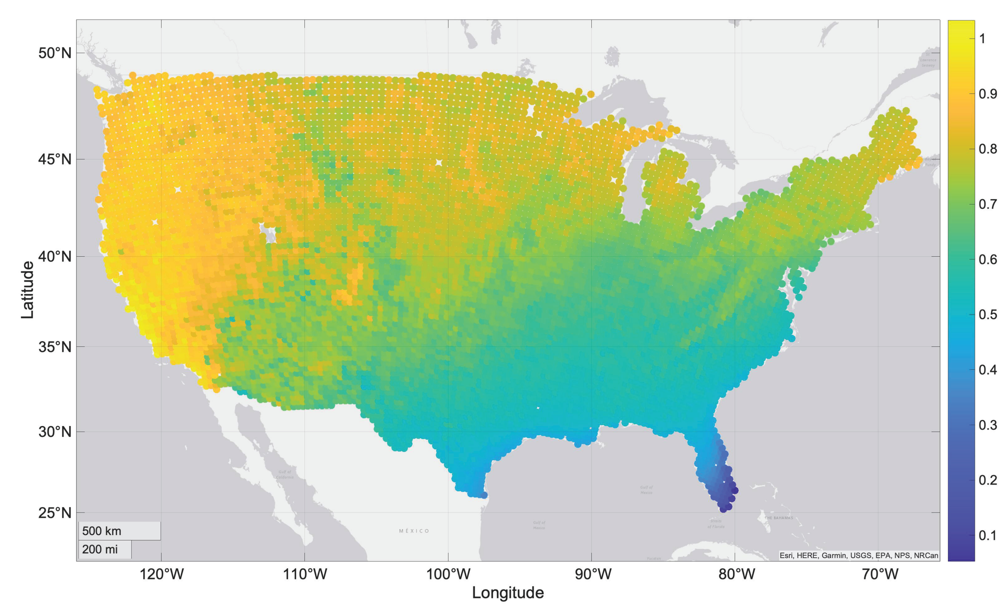
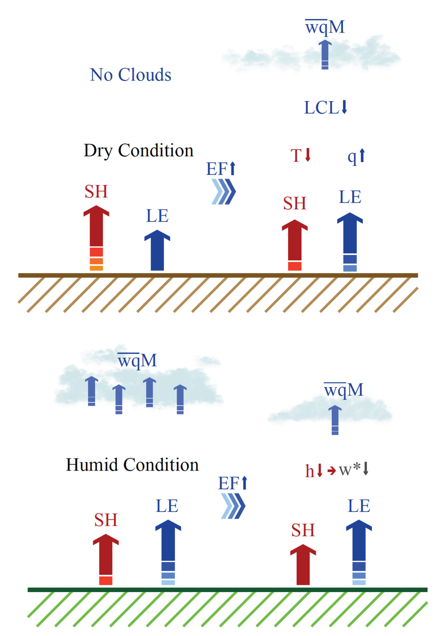
Result

The Sensitivity of EF at the Bottom of Clouds to EF at the Surface





The impact of the change in surface moisture on shallow-cumulus clouds formation is greater in the western but lesser in the eastern United States. It supports the observed pattern of soil moisture and precipitation. We think that the pattern mostly depends on a stronger impact of each of the mechanisms above.

Conclusions

- Boundary Layer Interactions between EF at the surface and vapor flux at the bottom of clouds could explain observed patterns of soil moisture and precipitation across the continental United States
- Characteristics of the surface play a significant role in the shallow-cumulus clouds formation
- Equilibrium Evaporative Fraction could be an alternative way to estimate Evaporative Fraction at the surface

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References

Mesinger, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P. C., Ebisuzaki, W., Jović, D., Woollen, J., Rogers, E., Berbery, E. H., Ek, M. B., Fan, Y., Grumbine, R., Higgins, W., Li, H., Lin, Y., Manikin, G., Parrish, D., & Shi, W. (2006). North American Regional Reanalysis. Bulletin of the American Meteorological Society, 87(3), 343–360. https://doi.org/10.1175/BAMS-87-3-34 3

Salvucci, G. D., Li, D., McColl, K. A., & Gentine, P. (2019). An explicit estimate of terrestrial evaporative fraction based on weather data for a boundary layer at diurnal equilibrium [A24D03] presented at 2019 Fall Meeting, AGU, San Francisco, CA, 9-13 Dec.

Tuttle, S., & Salvucci, G. (2016). Empirical evidence of contrasting soil moisture-precipitation feedbacks across the United States. Science, 352(6287), 825–828. https://doi.org/10.1126/science.aaa7185

Vilà-Guerau de Arellano, J., van Heerwaarden, C. C., Bart J.H. van Stratum, & van den Dries, K. (2015). Atmospheric Boundary Layer, Integrating Air Chemistry and Land Interactions. Cambridge University Press.