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

Soil Moisture-Precipitation Interactions

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

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

\[ \sigma_{ac}^2 = f(\text{Total } w'^q_s - \Delta q, \Delta z, h, w) \]

Modification

- The Impact of the Surface on the Clouds

\[ ac_{surf} = m \times ac_{efc} + (1 - m) \times ac_h \]

\[ ac_{efc} = q_{sat,h} - N(q_{tfc}, \sigma_{ac_h}^2) \]

\[ ac_h = q_{sat,h} \sim N(q_a - \frac{(1 - m) \times q_{tfc}}{m}, \frac{\sigma_{ac_h}^2}{3}) \]

- \( m \) = mixing ratio be the BL and the Entrainmentzone.

Data

- The North American Regional 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

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

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

Acknowledgment

This study is funded by the NASA grant: 80NSSC20K1800: Explaining observed soil moisture-precipitation feedbacks using SMAP and cloud-topped mixed layer models.

We thank the Meteorology and Air Quality Section at Wageningen University and Research Centre for providing the Chemistry Land-surface-AirShemistry Soil Slab (CLASS) model freely available at https://classmodel.github.io/, and the Physical Research Centre for providing the Chemistry Land-surface-AirShemistry Soil Slab (CLASS) model freely available at https://psl.noaa.gov/data/gridded/data.narr.html

References


