Geophysical Research Abstracts
Vol. 17, EGU2015-9095, 2015
EGU General Assembly 2015

Decoupling in the land-atmosphere for carbon exchange during severe droughts

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When analyzing the terrestrial carbon cycle, a strong focus is generally placed on its surface drivers (e.g. leaf area index and soil moisture). However, free-tropospheric conditions and processes occurring at the top of the atmospheric boundary layer (ABL), like subsidence or cloud formation, can strongly impact entrainment fluxes and the surface energy balance, which in turn affect the atmospheric CO_2 mole fraction and surface CO_2 uptake. The free-tropospheric state and ABL-top processes are controlled by large-scale meteorological conditions, and can change drastically during for instance severe droughts. To quantify the importance of these upper-atmospheric processes for the carbon cycle, we perform a sensitivity analysis across a range of meteorological conditions inspired by field observations. We use a conceptual model that represents the daytime surface fluxes of carbon, water and energy for a maize field, coupled to the dynamics of a convective boundary layer. We find that the importance of upper-atmosphere conditions for the atmospheric CO_2 budget is strengthened under low soil moisture conditions, exceeding the influence of surface fluxes by a factor of four or more. Under these conditions the surface carbon, water, and energy exchange get decoupled from the atmosphere, and the surface energy is directed mainly towards sensible heat, which increases both the direct and entrainment heating of the ABL. This in turn contributes to further soil moisture depletion and thus forms a positive drought feedback. The occurrence of a decoupled state in our conceptual model strongly depends on how we parameterize soil moisture stress. Since the soil moisture stress parameterization impacts the rate of day-to-day soil moisture depletion under prolonged drought conditions, it is key to modeling drought situations and heat waves. We show how the decoupling, drought feedback and atmospheric CO_2 budget differ under various parameterizations for soil moisture stress.