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Does lower troposphere turbulent CO_2-exchange determine plant growth?

P. Hu (1,2), C. H. Reick (1), and A. Kleidon (3)

(1) MPI for Meteorology, D-20146 Hamburg, Germany (christian.reick@mpimet.mpg.de;pinhsin.hu@mpimet.mpg.de), (2) School of Integrated Climate System Sciences (SICSS), University Hamburg, D-20144 Hamburg, (3) MPI for Biogeochemistry, D-07701 Jena, Germany (axel.kleidon@bgc-jena.mpg.de)

By photosynthesis plants convert solar energy into chemical energy stored in sugars. As known from measurements, the 'photosynthetic efficiency' for energy conversion is at best about two percent. This is only one-third of the theoretically obtained maximum efficiency. Due to the rising demand for food following ongoing population increase, there is quite some research on improving this low photosynthetic efficiency particularly in crops – but without significant success so far. A new theory brought up by Kleidon [1] suggests that the plant production is not only constrained by the physics and biochemistry of photosynthesis, but even more by the intensity of turbulent CO_2-exchange in the planetary boundary layer. This theory may provide a new way to explain the low efficiency of plants. It is based on the assumption that the atmospheric heat engine converts net absorbed radiative energy into turbulent kinetic energy at the Carnot limit in a state of maximum power. In this theory, photosynthetic production turns out to be proportional to the turbulent flux of CO_2 feeding the plants with CO_2 from the free troposphere. This leads to the hypothesis that during evolution plants may have adapted to work at the measured low efficiency because of the limited turbulent CO_2-exchange so that further improvement of the photosynthetic apparatus would be no gain.

In our study we investigate the limitation of global plant productivity by turbulent CO_2 transport by performing simulations with the atmosphere model ECHAM and its land component JSBACH. In contrast to Kleidon's thermodynamic approach, this model setup contains a more detailed description of the land-atmosphere interaction, turbulent CO_2-transport across the planetary boundary layer, photosynthesis (Farquhar model), and soil respiration. We perform simulation experiments in an AMIP setup where sea surface temperature (SST) is prescribed and ocean processes are excluded. For SSTs and atmospheric CO_2 pre-industrial conditions are assumed. Vegetation distribution is kept fixed and consists of only natural types because anthropogenic types (crops, pastures) are already manipulated towards high efficiency. By invoking the tracer module of ECHAM, atmospheric CO_2 transport is computed explicitly so that diurnal and seasonal cycles arising from plant carbon assimilation and soil microbial activity are reflected in atmospheric CO_2 concentrations. To study the effect of turbulent transport on plant productivity, we artificially modify the intensity of turbulent CO_2 mixing while keeping turbulent mixing for heat and moisture unchanged to assure similar meteorological conditions for plant growth. This setup allows for analyzing the sensitivity of global plant productivity to changes in the intensity of turbulent CO_2 mixing. We present global maps for the dependence of plant productivity on turbulent transport and discuss differences arising for different vegetation types and climate zones.

[1] Axel Kleidon, Thermodynamic Foundations of the Earth System, Cambridge University Press, 2016.