Land-atmosphere interactions in a heterogeneous environment

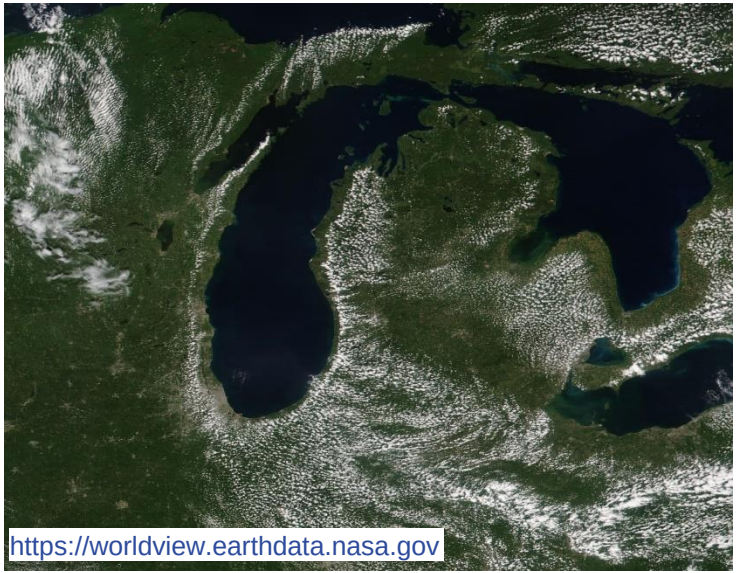
Linda Schlemmer

based on input of many persons

My link to FESSTVaL

- Background in convection, land-atmosphere interactions, modelling
- 2019: DWD HErZ Themenbereichsleiterin -> FESSTVaL, observations (turbulence measurements, FESST@MOL)
- Fall 2020: DWD physical processes section, process-based evaluation
- FESSTVaL – observations – evaluation - modelling

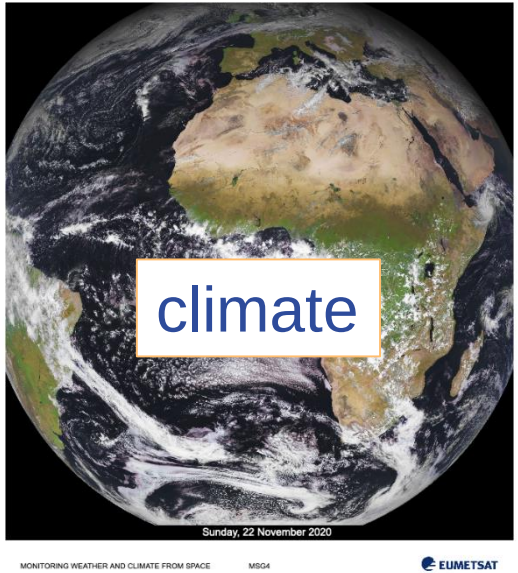
The state of the land surface (soil moisture contents and spatial distribution of soil moisture) influence the triggering of convection and influence the organisation of convection


https://worldview.earthdata.nasa.gov


https://worldview.earthdata.nasa.gov

Convection – why do we care?

Key process of the hydrological cycle



Involved in most severe precipitation events

Christoph Schmidt/AFP

Braunsbach Flooding 29 May 2016

Long-term memory of soil moisture

- Soil moisture introduces memory in the coupled land-atmosphere system
- Can influence the extent and severity of droughts and heat waves under certain conditions

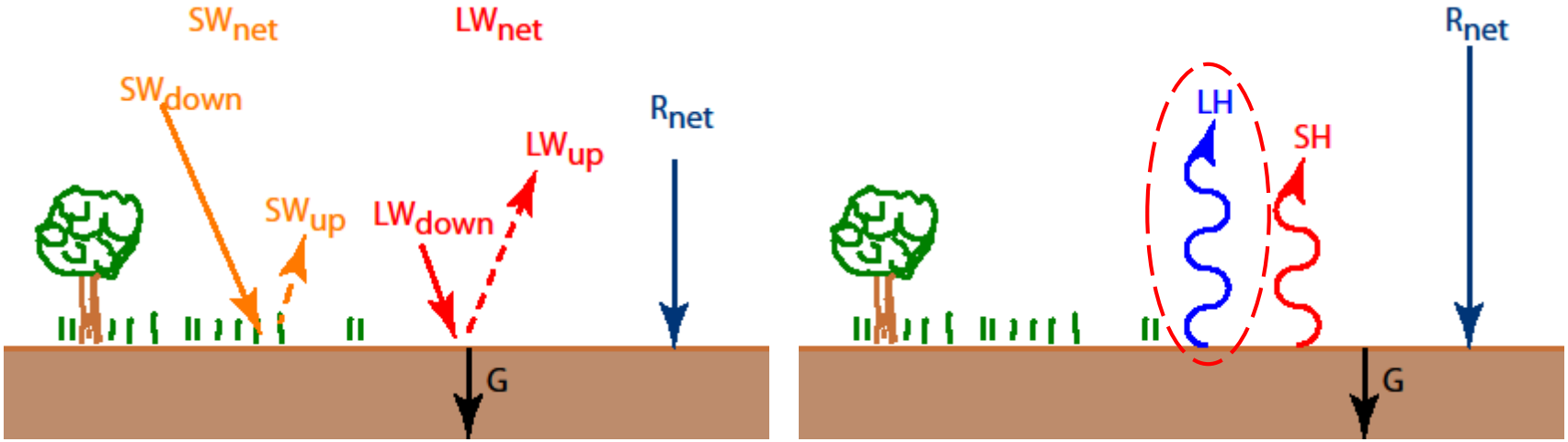
Contents of this lecture

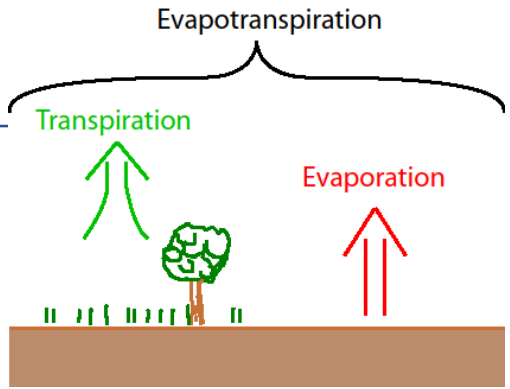
- Processes and Observations
  - Surface Energy Balance + Water Balance (constraints on the system)
  - Feedback on Atmosphere:
    - Homogeneous soil moisture distribution
    - Heterogeneous soil moisture distribution
    - Heterogeneous environment
- Modelling
  - Approaches
  - Challenges
- Discussion

Surface Energy Balance

$$0 = \underbrace{SW_{net} + LW_{net}}_{R_{net}} - G - SH - LH$$

Partitioning of the available energy R_{net} into ground heat flux, sensible and latent heat flux





Evapotranspiration (evaporation + transpiration)

$$ET = \frac{LH}{\lambda}$$

λ : latent heat of vaporization

Imagine a wet/damp cloth hanging in the wind.

What happens?

- The cloth will get dry, then heat up
- Faster drying for:
  - Stronger wind
  - Dryer surrounding air
  - Higher available energy

Potential Evapotranspiration ET_0

The amount of evaporation that would occur if a sufficient water source were available (atmospheric demand). Upper limit on actual evapotranspiration.

Penman Monteith Equation:

$$ET_0 = \frac{\Delta\left(R_n - G\right) + \rho_a c_p \left(\frac{e_s - e_a}{r_a}\right)}{\left(\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)\right)\lambda}$$

Δ : rate of change of saturation specific humidity with temperature

ρ_a : dry air density; c_p : specific heat capacity of air and constant pressure

γ : psychrometric constant

e_s : saturation vapour pressure; e_a : actual vapour pressure

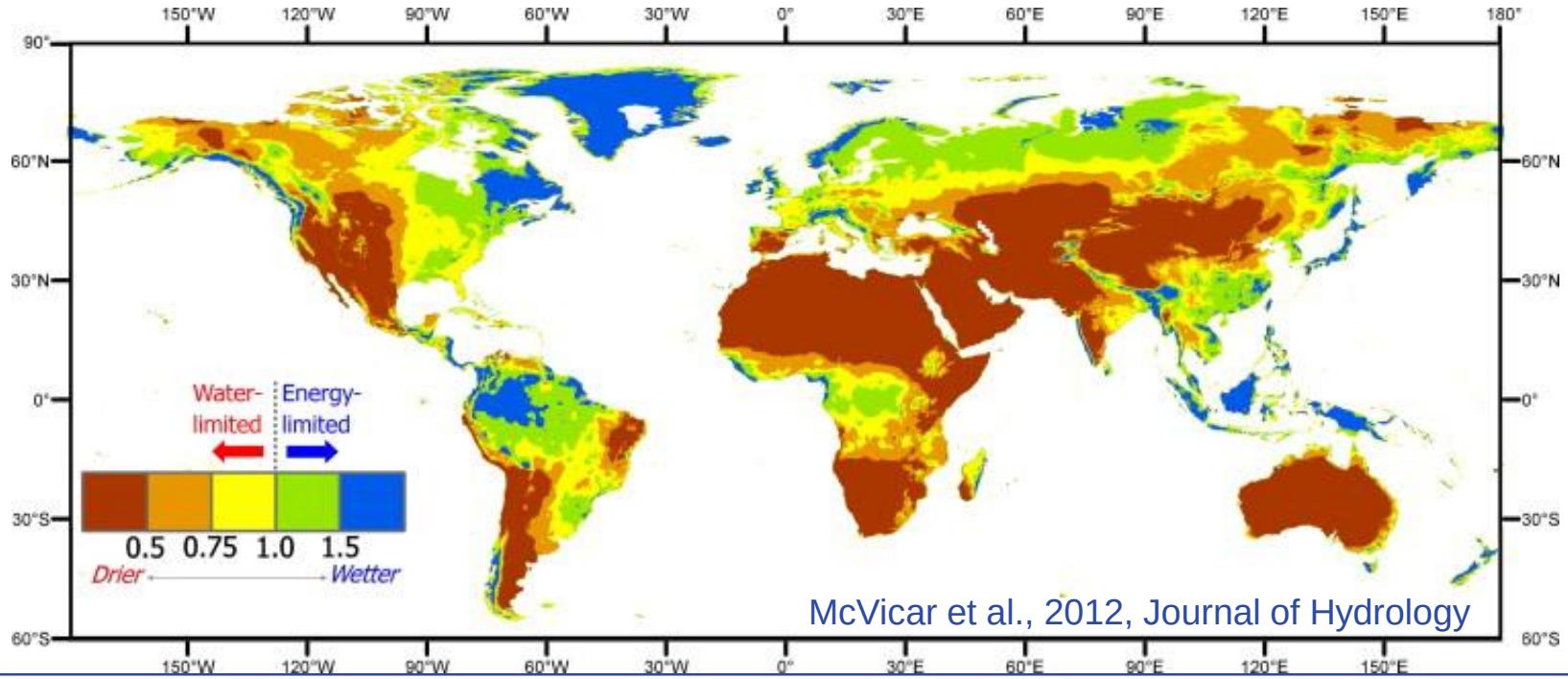
r_a : atmospheric resistance (wind speed); r_s : surface resistance

Energy limited vs. Water limited Evapotranspiration

Why does the actual ET not always match ET_0 ?

1. Not enough energy available (energy limited): mid-latitudes, wintertime
2. Not enough water available (water limited): arid or semi-arid regions

Energy limited vs. Water limited Evapotranspiration



McVicar et al., 2012, Journal of Hydrology

Bowen Ratio; Evaporative Fraction

$$BO = \frac{SH}{LH}$$

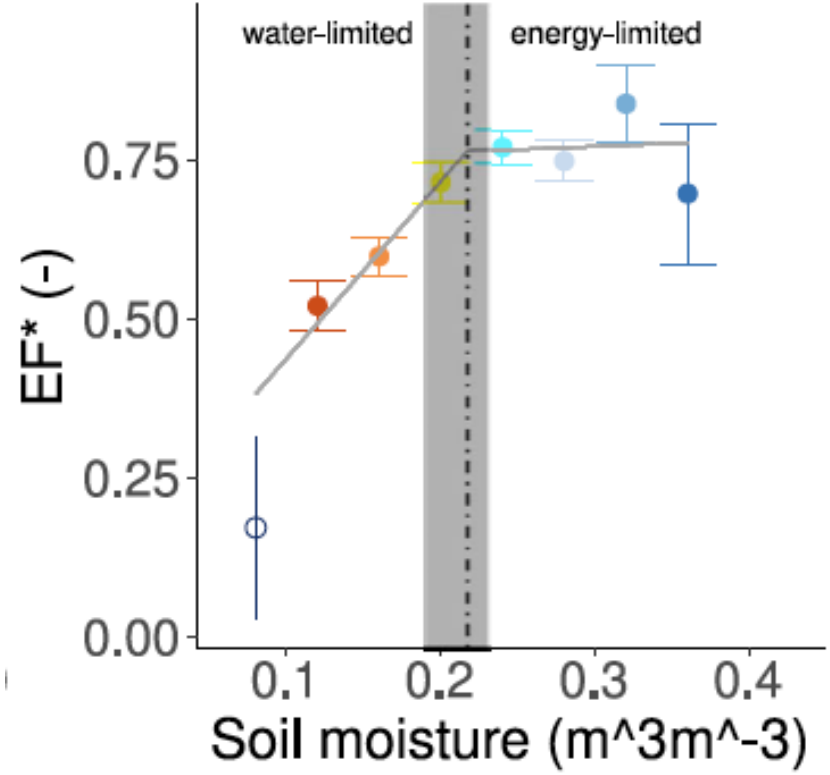
Deserts: BO>10
Tropical rainforests: BO=0.1-0.3

$$EF = \frac{LH}{LH + SH} = \frac{1}{1 + BO}$$

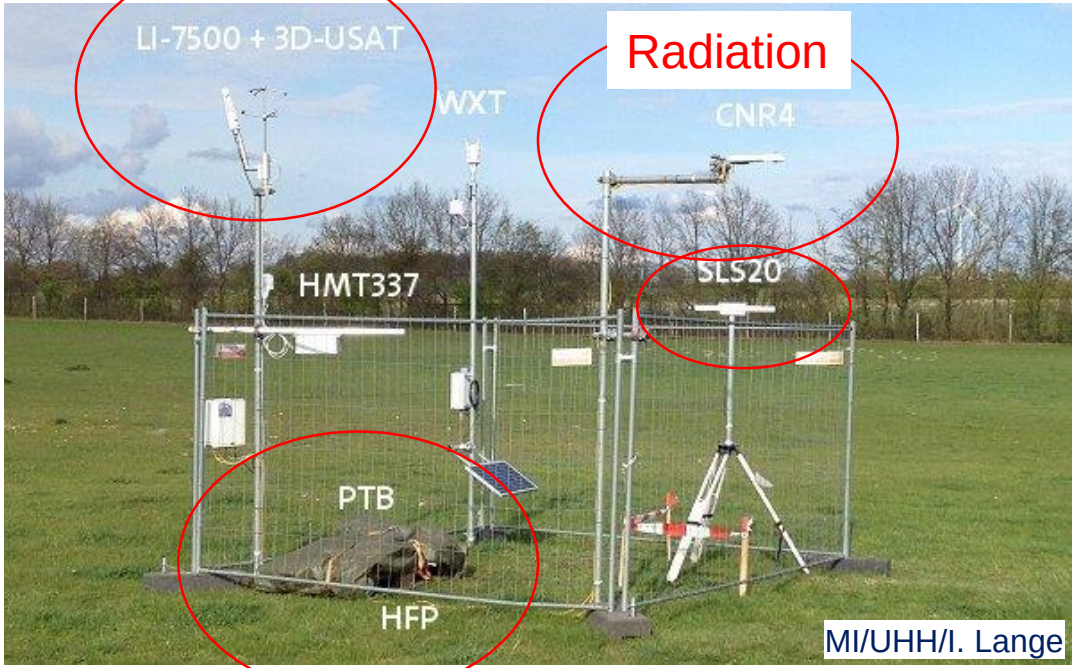
Evaporation Regimes

Denissen et al., 2021

combination of global radiosoundings, satellite-observed soil moisture, and a mixed-layer model for the atmosphere

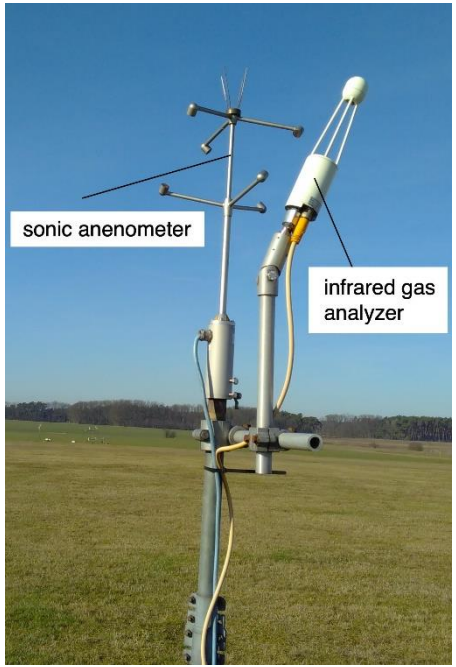


Surface Energy Balance Station; Birkholz



MI/UHH/I. Lange

Turbulent surface fluxes



$$SH = \rho c_p \overline{w'T'}$$

sonic + sonic temperature
or
sonic + fine-wire temperature

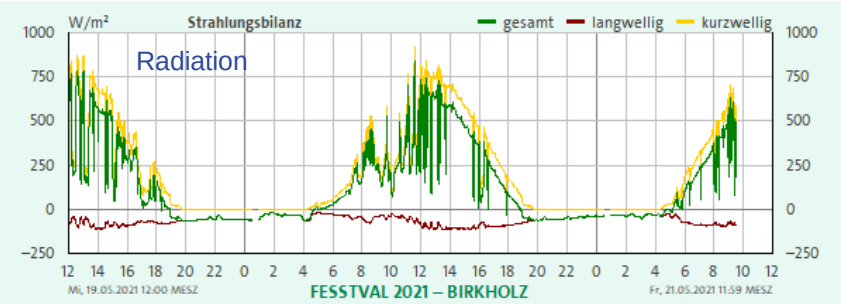
$$LH = \rho \lambda \overline{w'qv'}$$

sonic + infrared gas analyzer

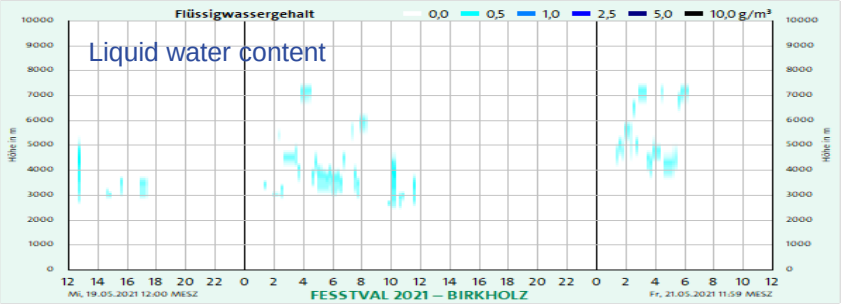
Local information

Scintillometer: turbulent fluctuations of the refractive index of air caused by variations in temperature or humidity
representative for a larger area

Example Diurnal Cycle, surface energy balance, Birkholz

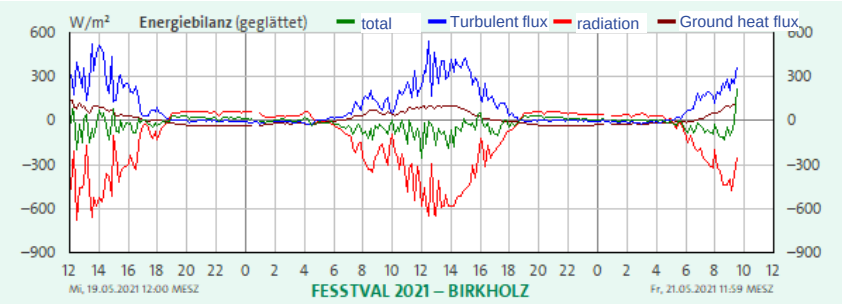


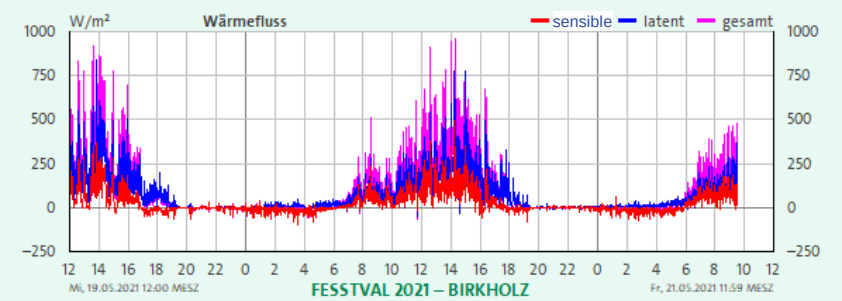
Source:DWD, MOL-RAO



Plots: MI/UHH

Example Diurnal Cycle, surface energy balance, Birkholz



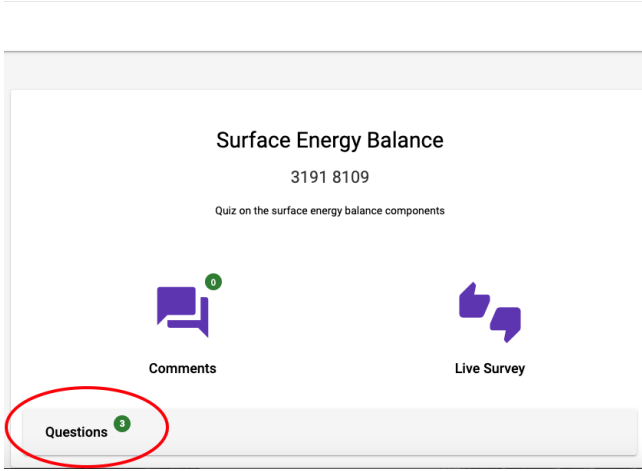


Plots: MI/UHH

Quiz: surface energy balance

https://partici.fi/31918109

partici.fi/31918109

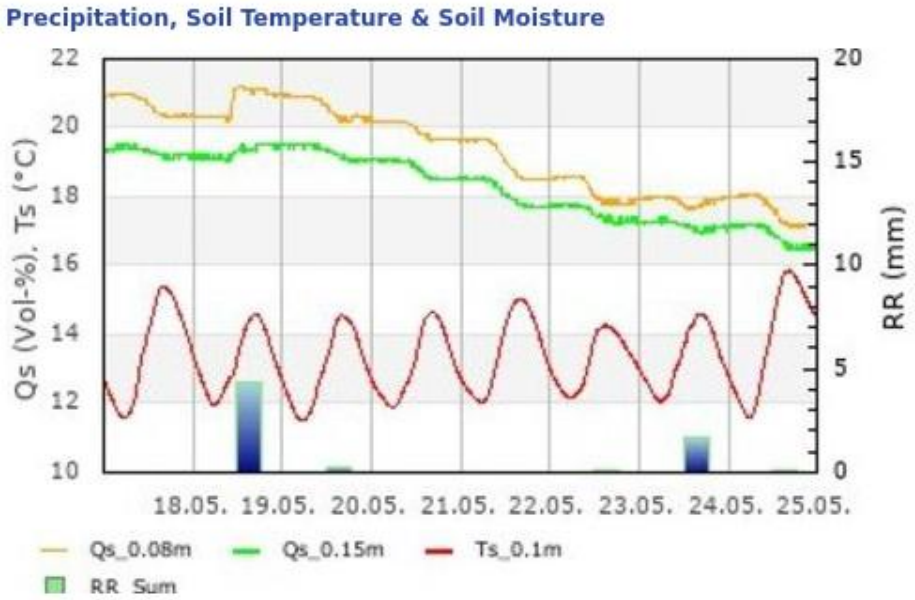


Surface Energy Balance Falkenberg; Soil moisture

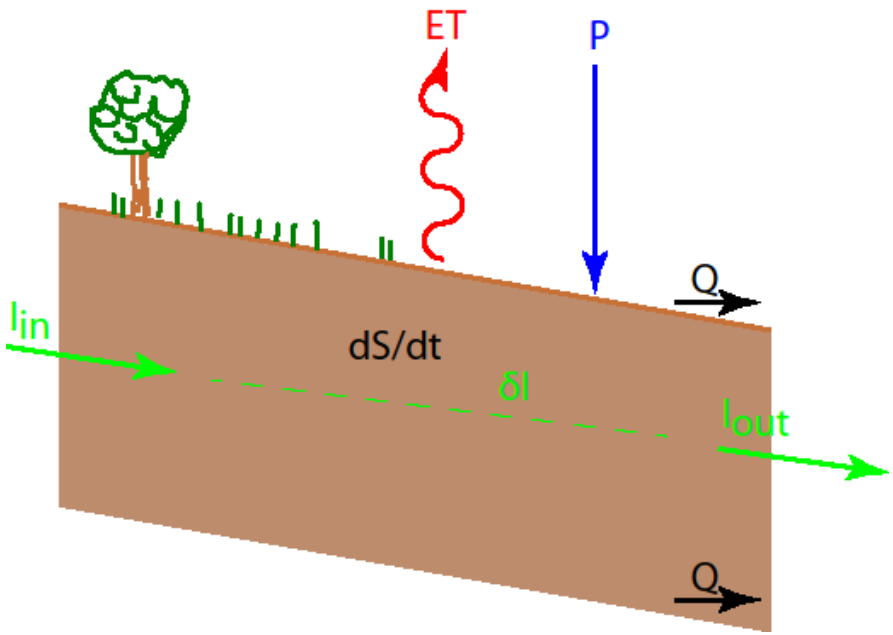
Lindenberg Meteorological Observatory - Richard Aßmann Observatory

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Falkenberg Boundary Layer Field Site 2021/05/24



Surface Water Balance



$$\frac{dS}{dt} = P - ET - Q + \delta I$$

S: terrestrial storage
P: precipitation
Q: runoff
δI: subsurface in- and outflow

Soil Moisture Measurements

DWD, MOL-RAO

TDR: time-domain reflectometry

measure propagation velocity *v* of a step voltage pulse that is reflected at the end of the transmission line.

v is a a function of the permettivity of the soil.

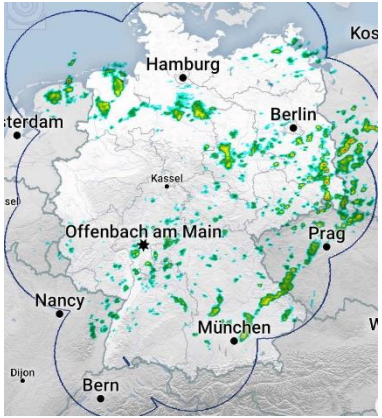
The permettivity of the soil is strongly related to its water content: in wet soils *v* is slower than in drier soils.

Indirect Measurements of Surface Water Balance: Catchment scale

Precipitation: Combined product

Rain gauge + Radar


ARM User Facility



Runoff:

River discharge measurements


www.bafu.admin.ch

cf. Regenass et al., 2021

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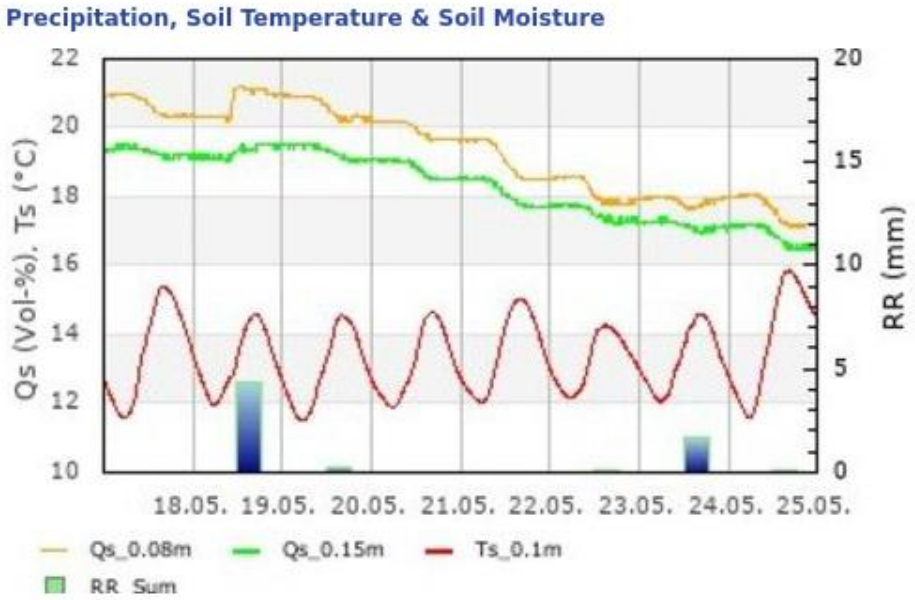


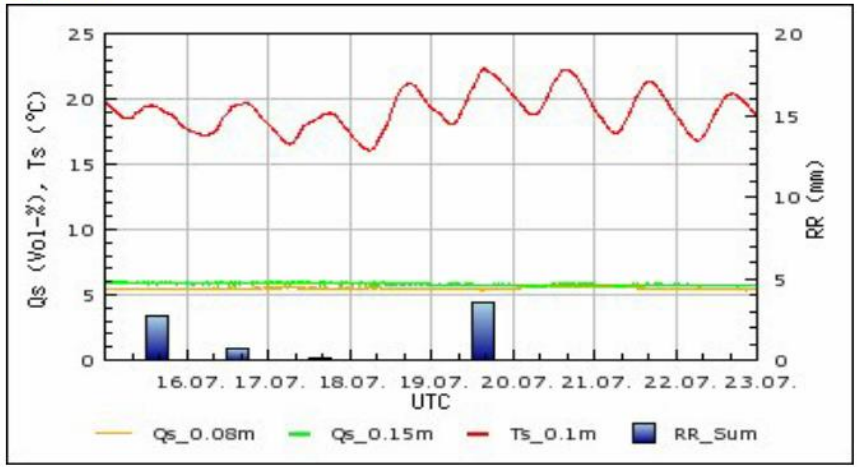
Surface Energy Balance Falkenberg; Soil moisture

Lindenberg Meteorological Observatory - Richard Aßmann Observatory

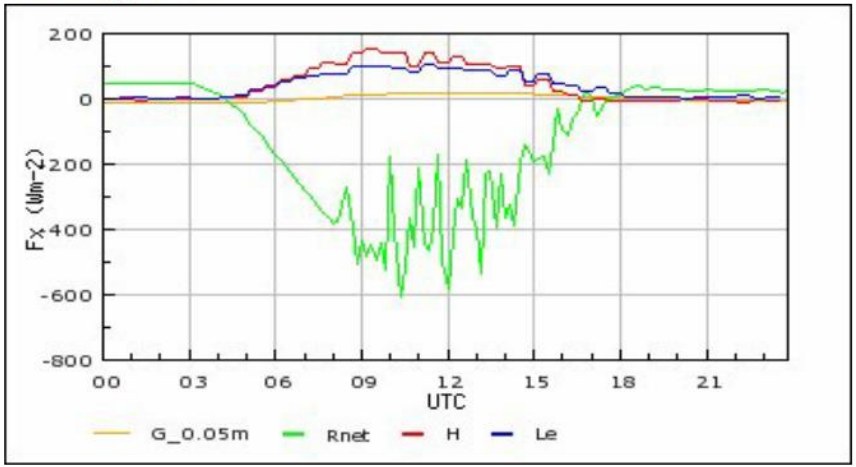
Messfeld Falkenberg 2020/07/22

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

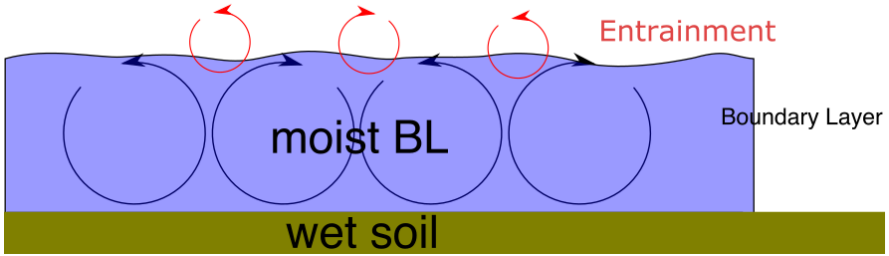
Precipitation

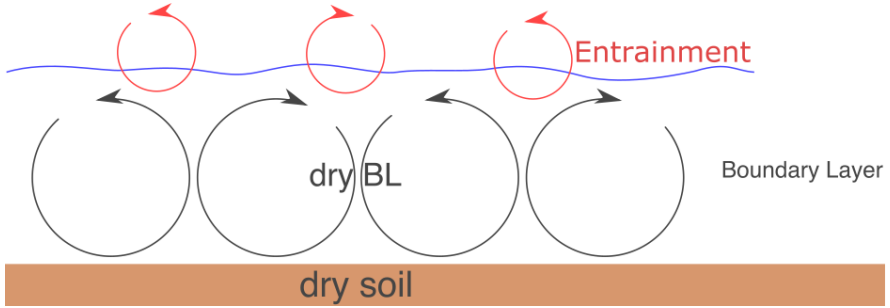


Surface Energy Fluxes



Influence on the boundary layer

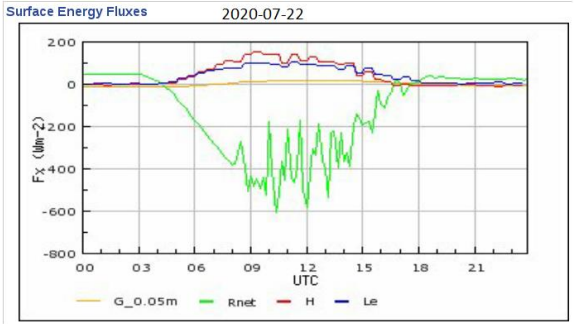


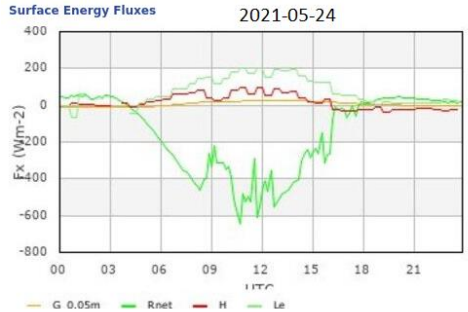


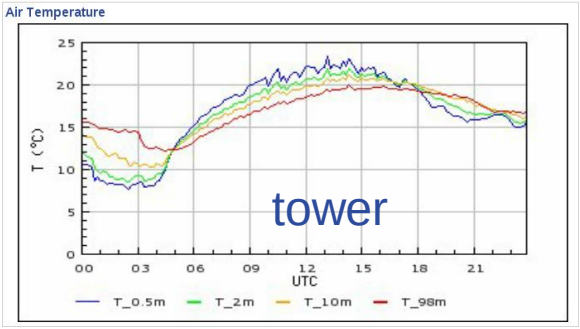
Driven by latent heat fluxes

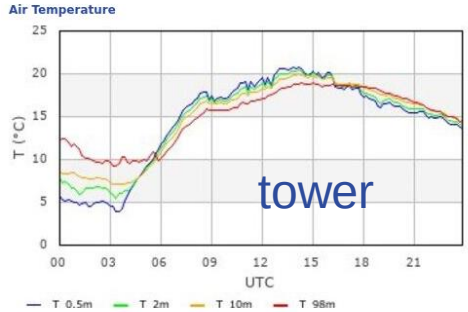
Driven by sensible heat fluxes

Influence on boundary layer

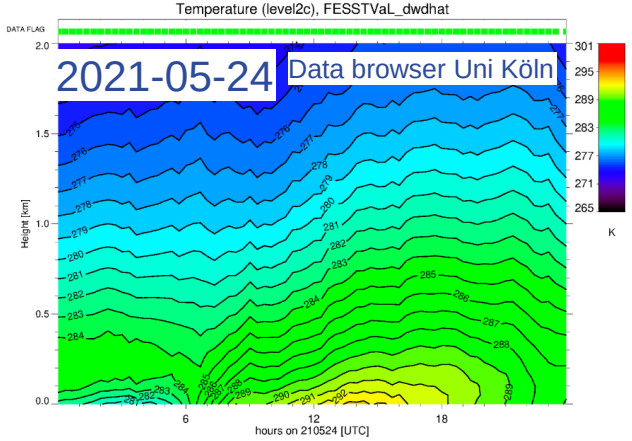


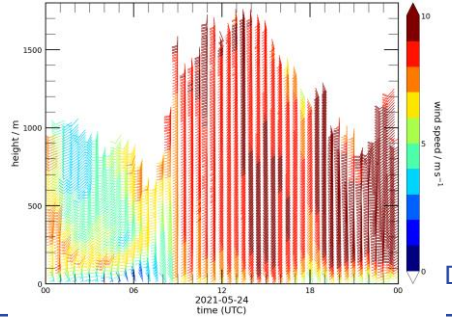






Microwave radiometer

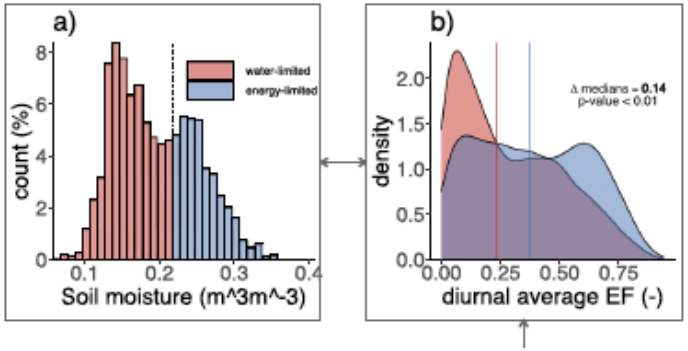




Doppler LiDAR

DWD-RAO

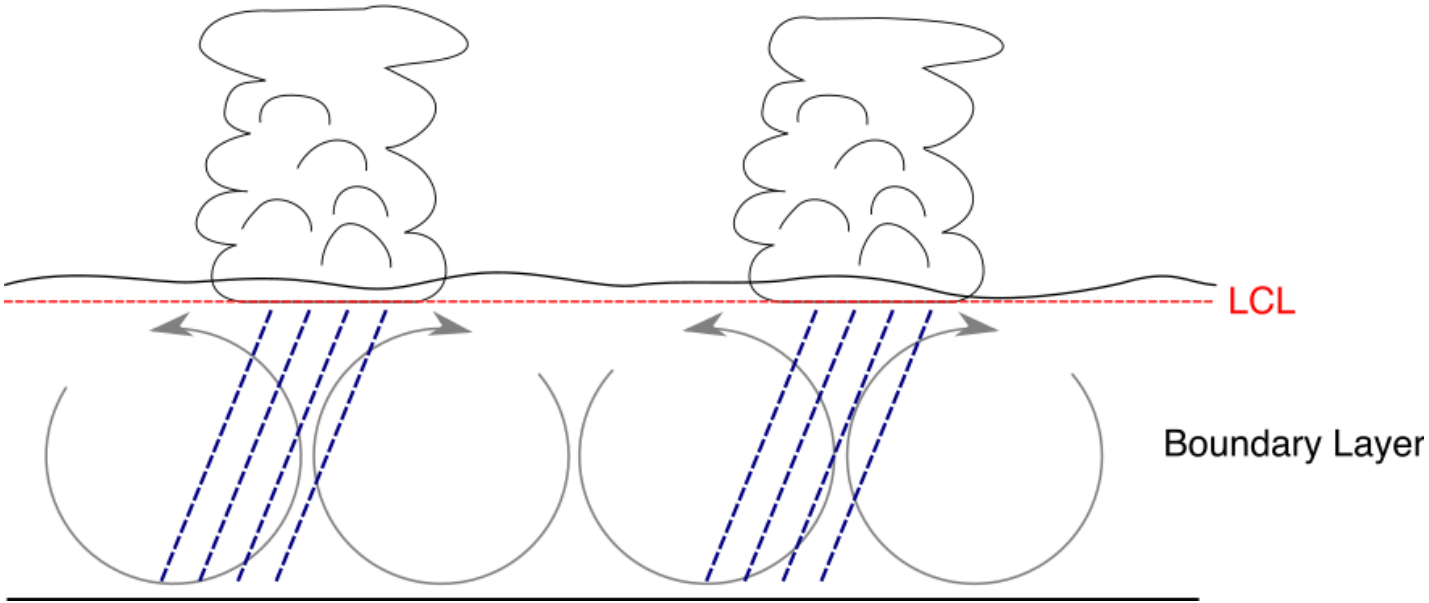
Influence on the boundary layer



Denissen et al., 2021

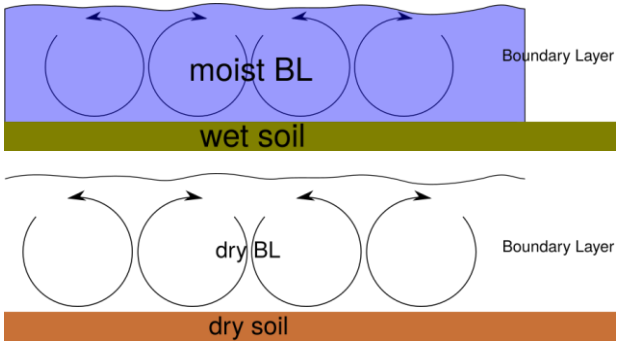
combination of global radiosoundings, satellite-observed soil moisture, and a mixed-layer model for the atmosphere

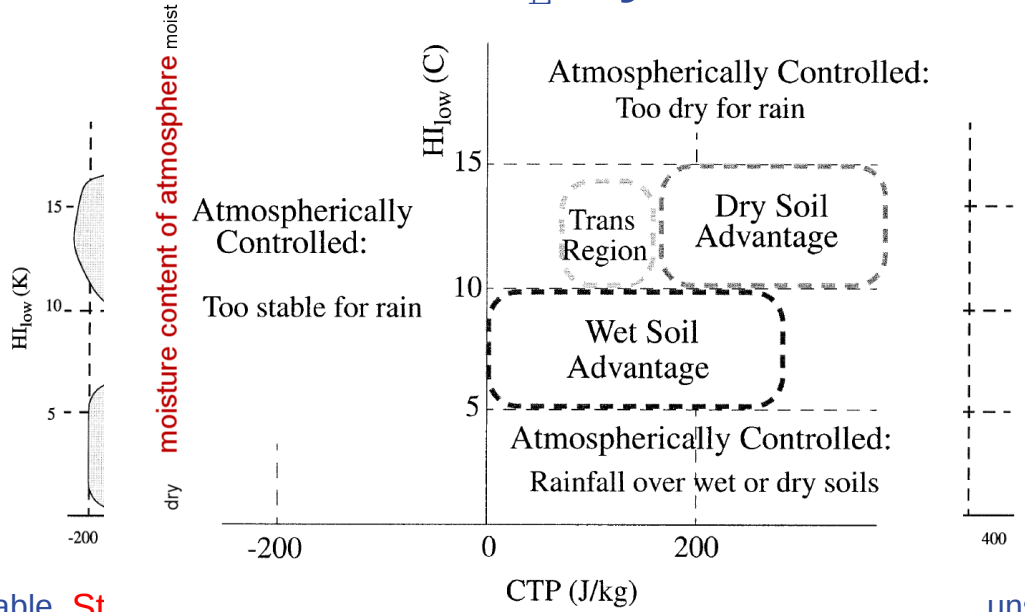
Influence on Clouds and Rain



Boundary-layer growth over wet or dry soil

Findell and Elthair (2003):
stability of the atmosphere and moisture content of boundary laye
Mixed-layer model fed by radiosoundings





stable St stable stability of the atmosphere unstable unstable

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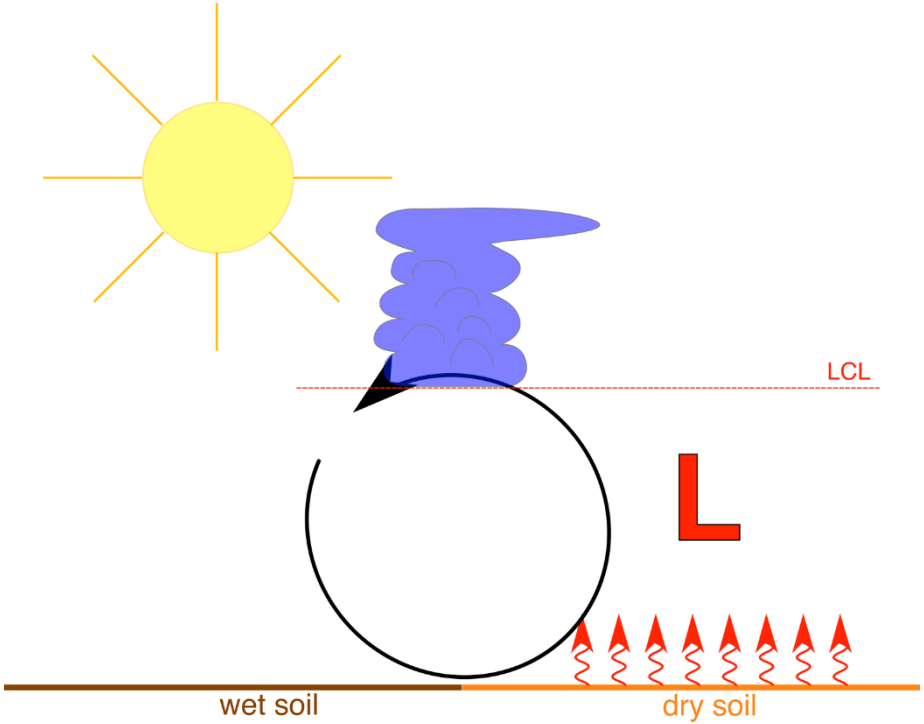
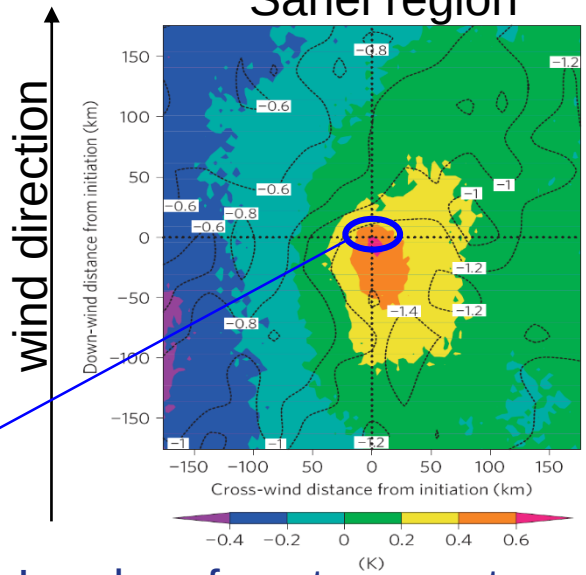
Heterogeneous soil moisture distribution



Soil-moisture gradients as triggers, satellite data (SEVIRI + Aqua AMSR-E)

Sahel region

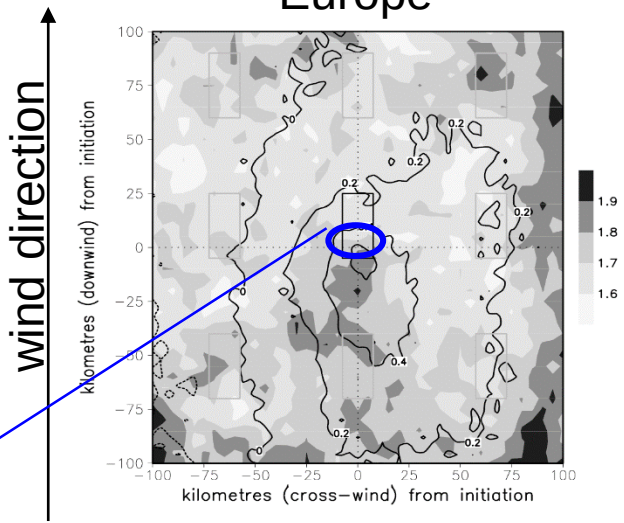


initiation

Land-surface temperature anomaly

Taylor et al., 2011

Europe

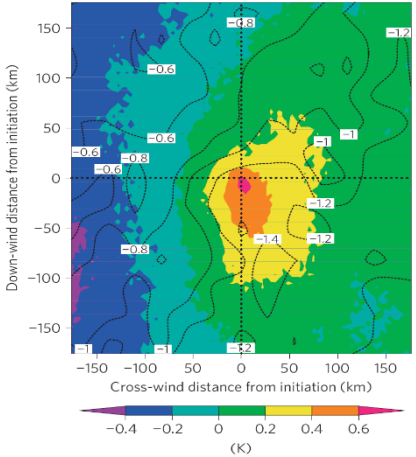


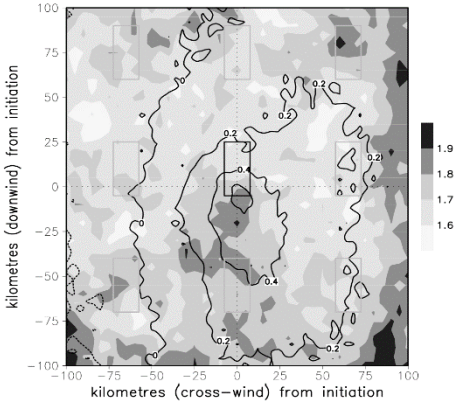
initiation

Taylor, 2015

Soil-moisture gradients as triggers

Sahel region





Europe

Taylor et al., 2011;
Taylor, 2015

- Convective initiation in the Sahel region and Europe occurs preferentially over negative LSTA gradients (positive soil-moisture gradients).
- Stronger sensitivity for overall drier soils (less rain in the previous month)
- The influence of surface heterogeneity on rainfall in Europe is stronger under lighter winds
- Typical horizontal scale of the anomaly: 40-50 km

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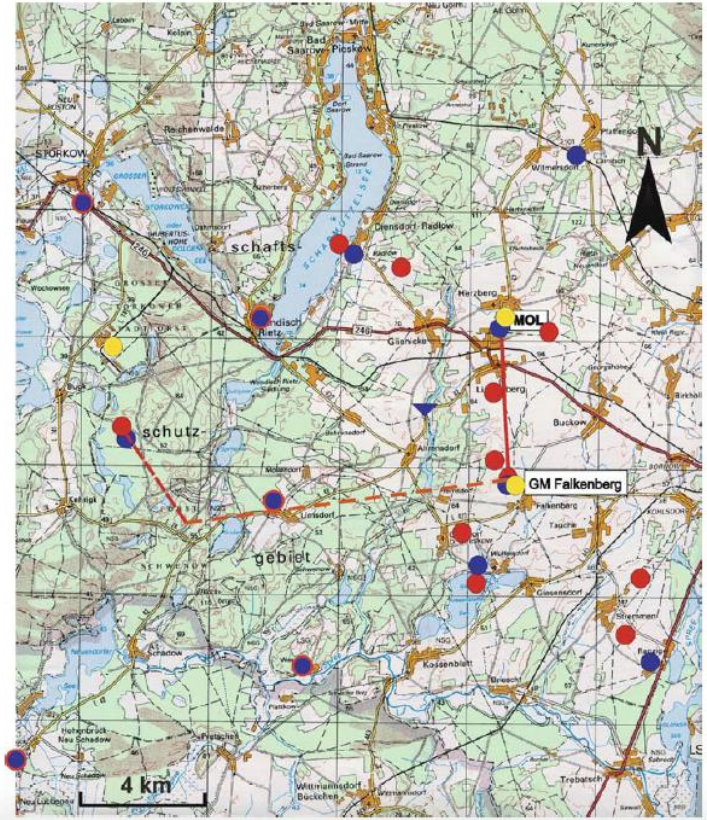
LITFASS
the older cousin of FESSTVaL

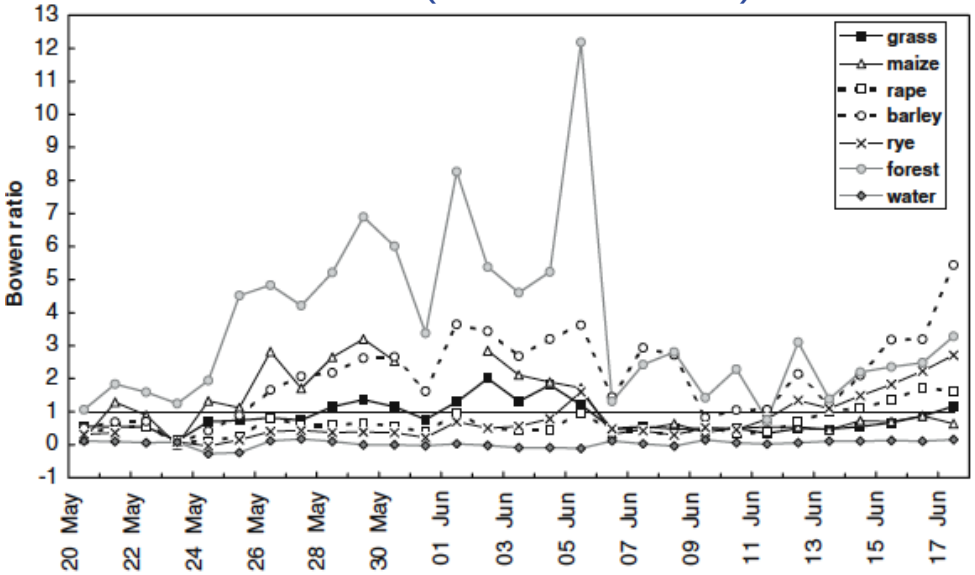
- Rain gauge with radiation meas.
- Micrometeorological station
- Rain gauge
- Remote sensing site
- Water table measurement
- Scintillometer path



Beyrich and Mengelkamp, 2006

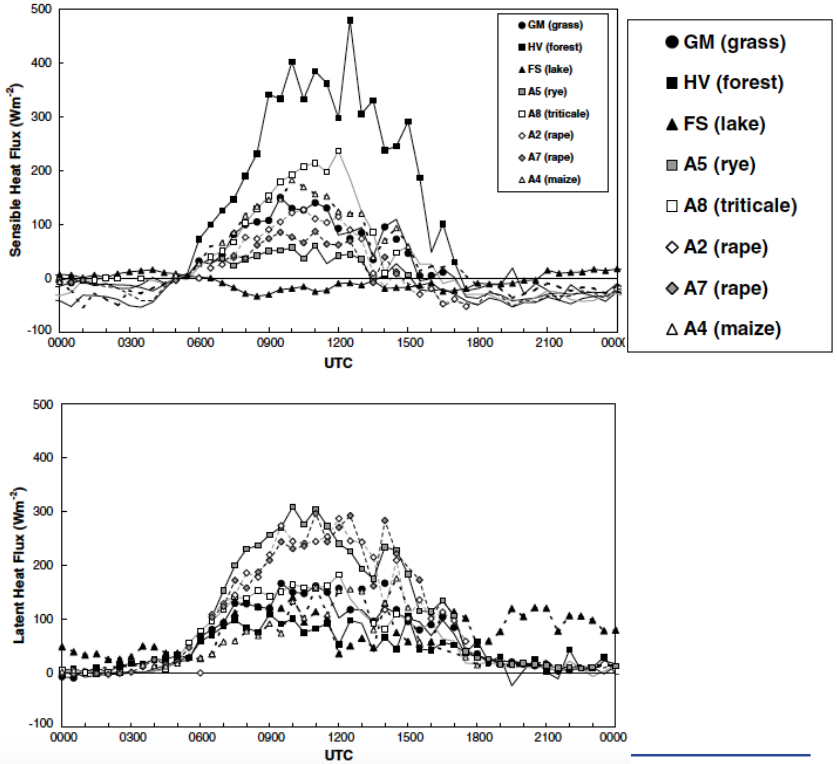
LITFASS

Mean Bowen ratio (0800-1400 UTC)



Beyrich and Mengelkamp, 2006; Beyrich et al, 2006

Diurnal cycle of SH and LH over different surfaces

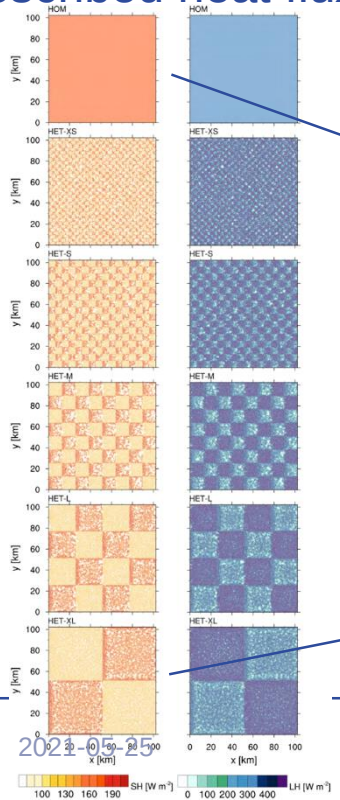


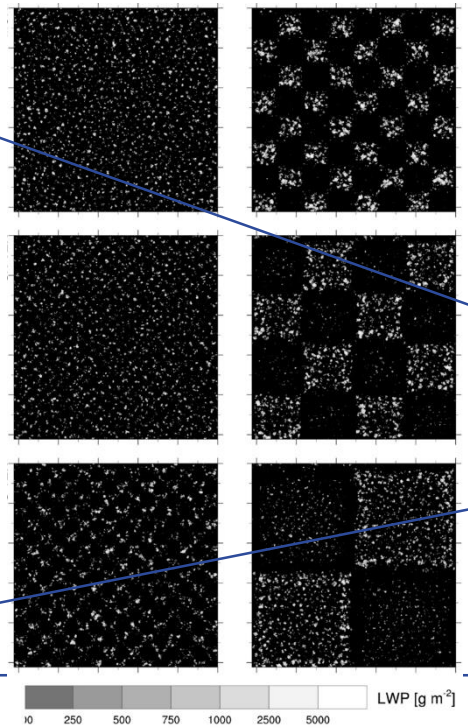
LES study: Land surface inhomogeneities

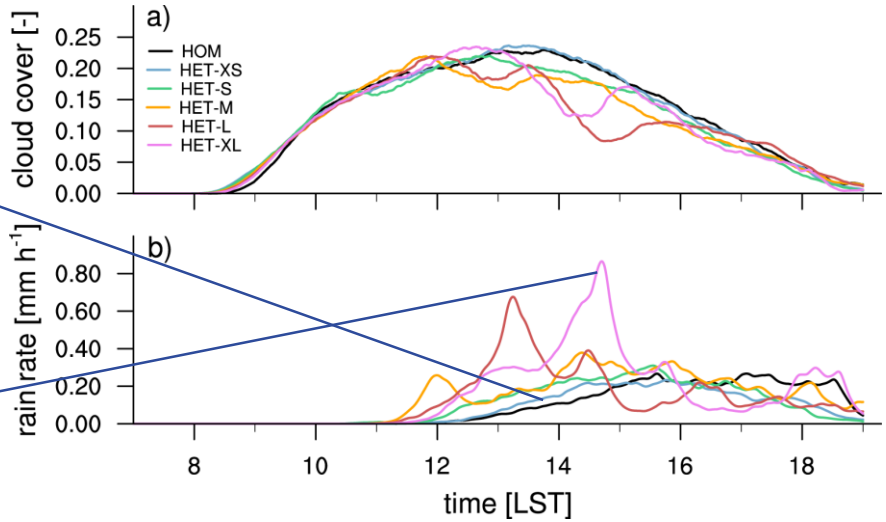
(Rieck et al., 2014)

Prescribed heat fluxes

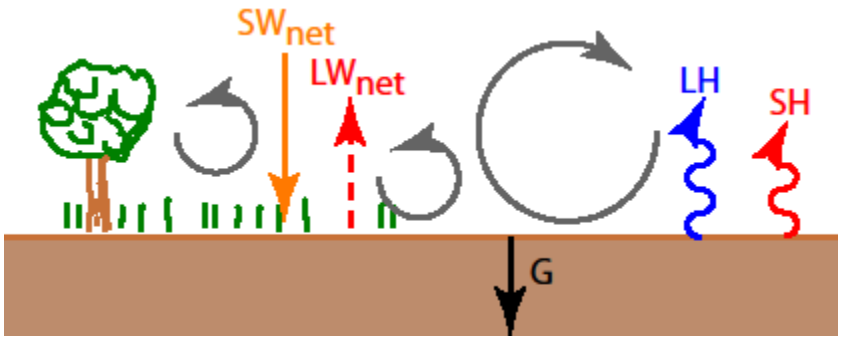
clouds



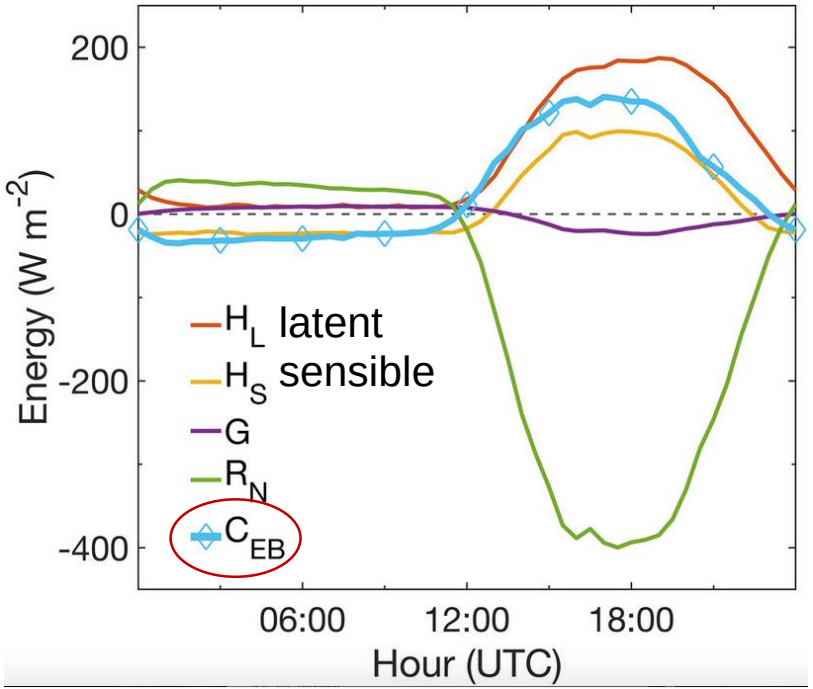




Closure of surface energy balance



Butterworth et al., 2021



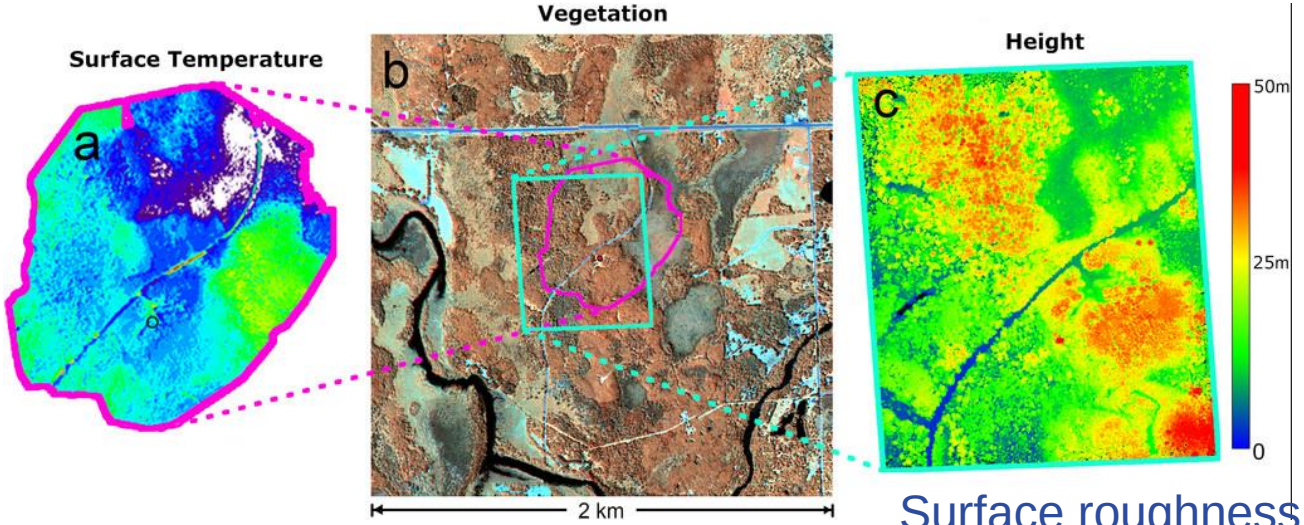
Local surface energy balance affected by advection of warmer/colder and drier/moister air

-> closure problem

-> also calculation of ET_0 (Penman-Monteith Eq.) affected (cf. de Bruin and Trigo, 2019)

Cheesehead19 campaign

Response of the atmospheric boundary layer to spatial heterogeneity in surface energy fluxes



Surface roughness

Vegetation state

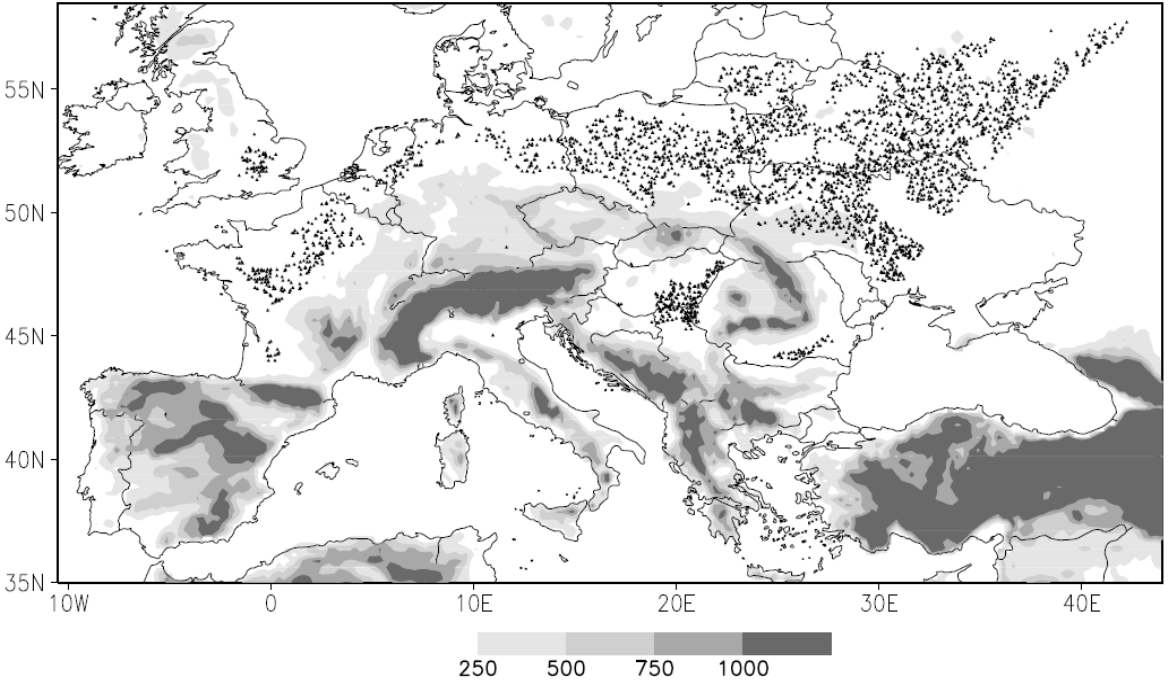
Butterworth et al., 2021

Quiz #2

https://partici.fi/71272198

partici.fi/71272198

Land-surface inhomogeneity + mountains



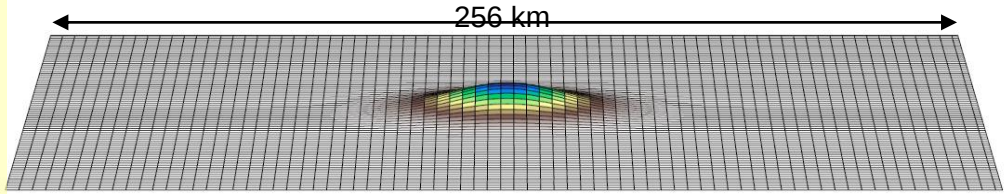
Taylor, 2015

Idealized COSMO simulations

- Cosmo v4.28
- 256 x 256 x 50 grid points
- Δx = 1 km
- 5 day run

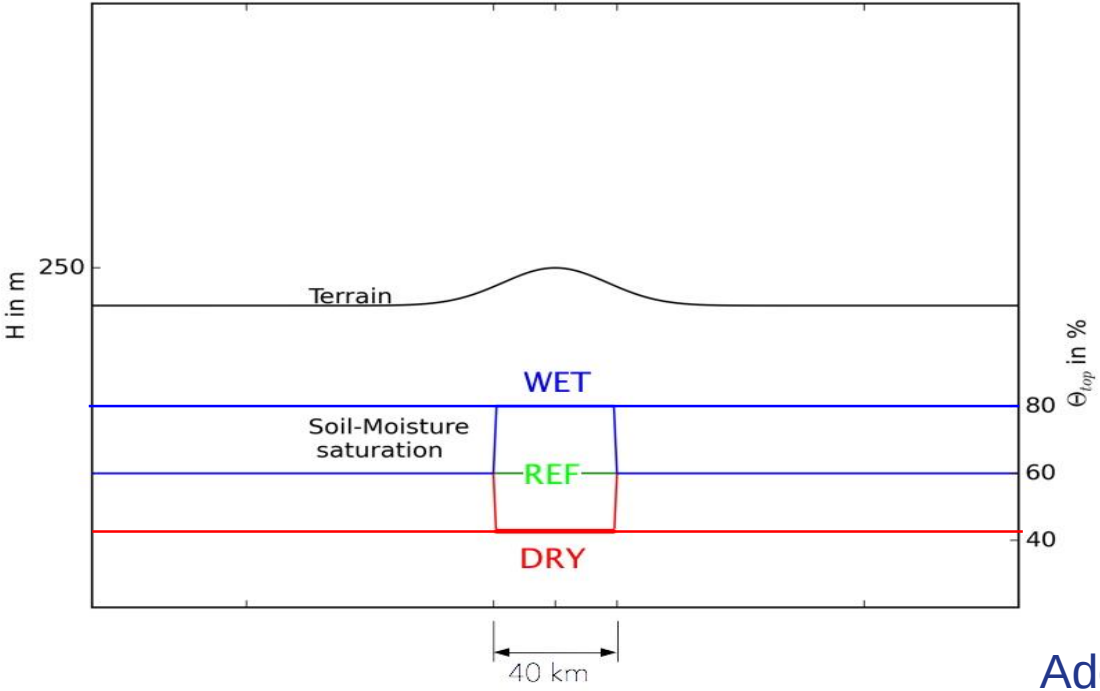
- Idealized domain
- Prescribed soil moisture
- No background wind

- European summertime conditions



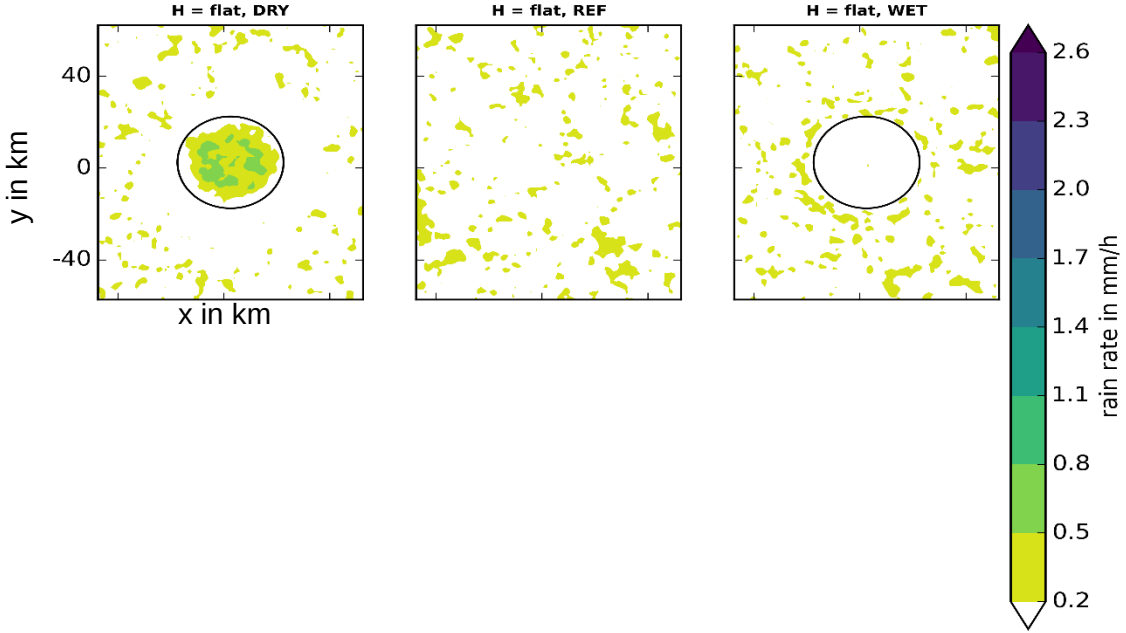
Imamovic et al., 2017

Soil-moisture anomaly / mountain



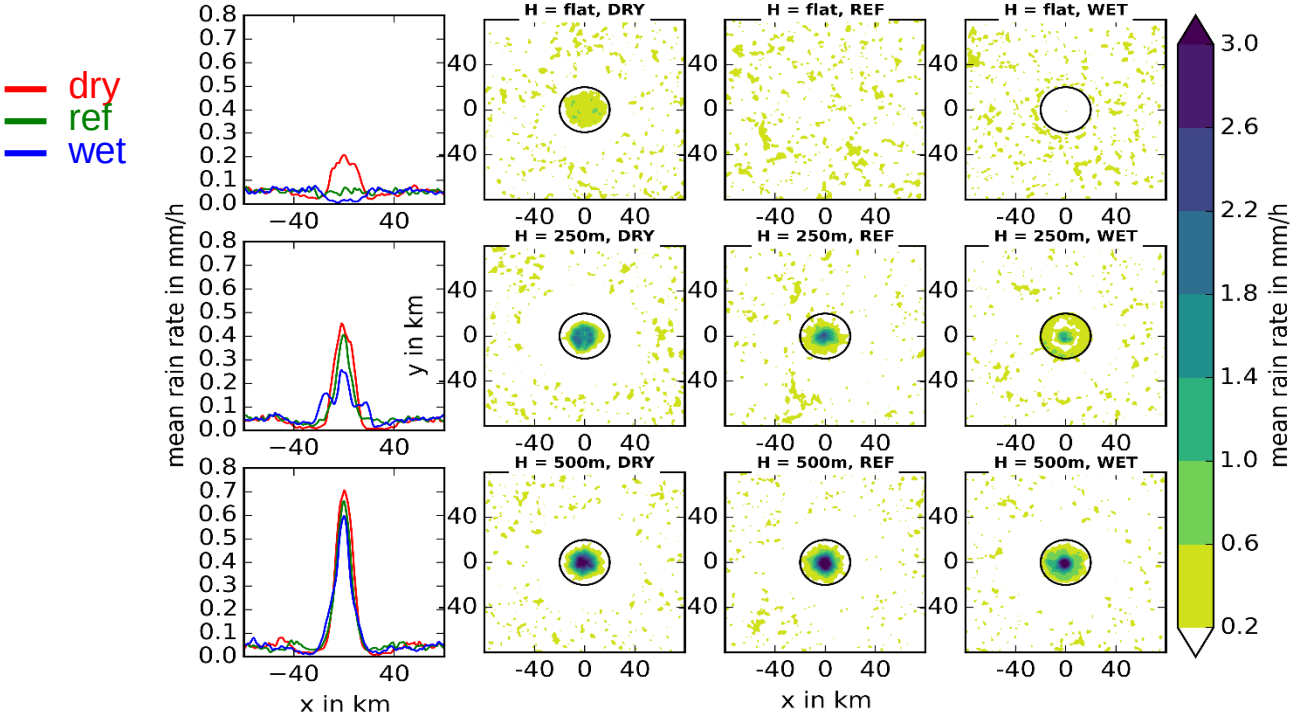
Adel Imamovic, ETHZ

Soil-moisture gradients as triggers



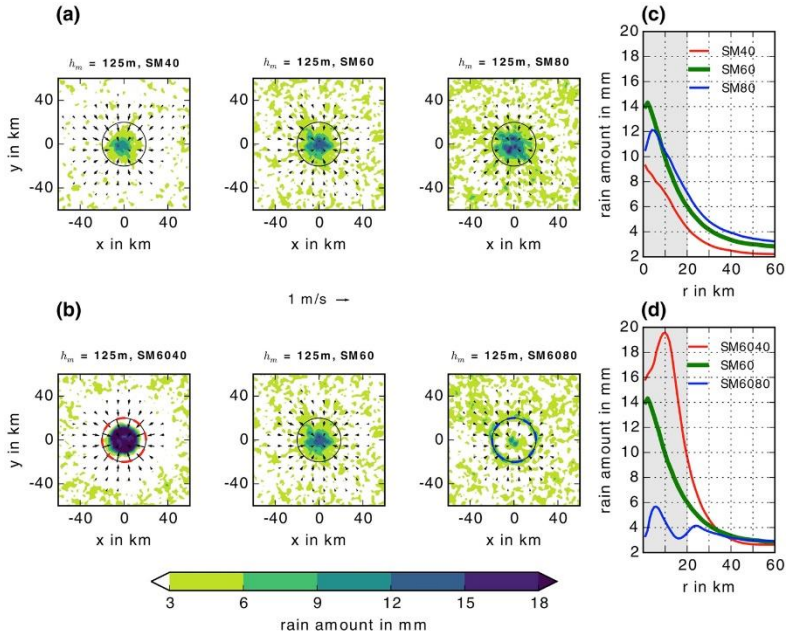
Imamovic et al., 2017

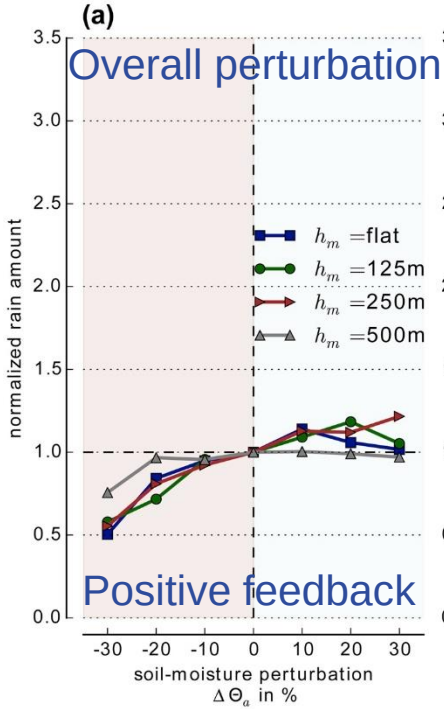
500 m high mountain dominates signal



Imamovic et al., 2017

Soil-moisture precipitation feedback

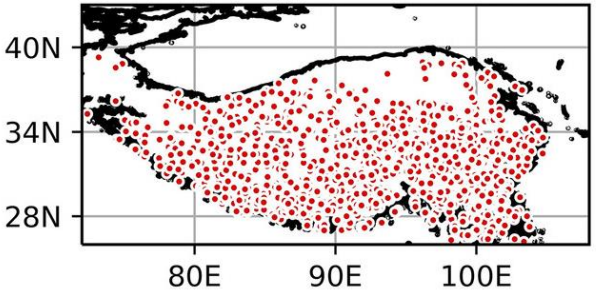


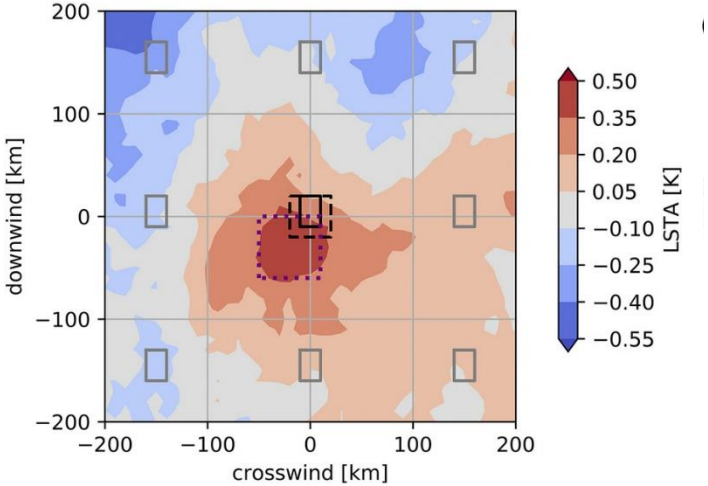


Imamovic et al., 2017

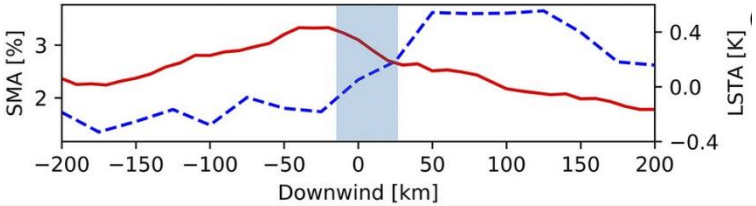
Triggering of Convection over the Tibetanian Plateau

Triggering locations





Barton et al., 2021

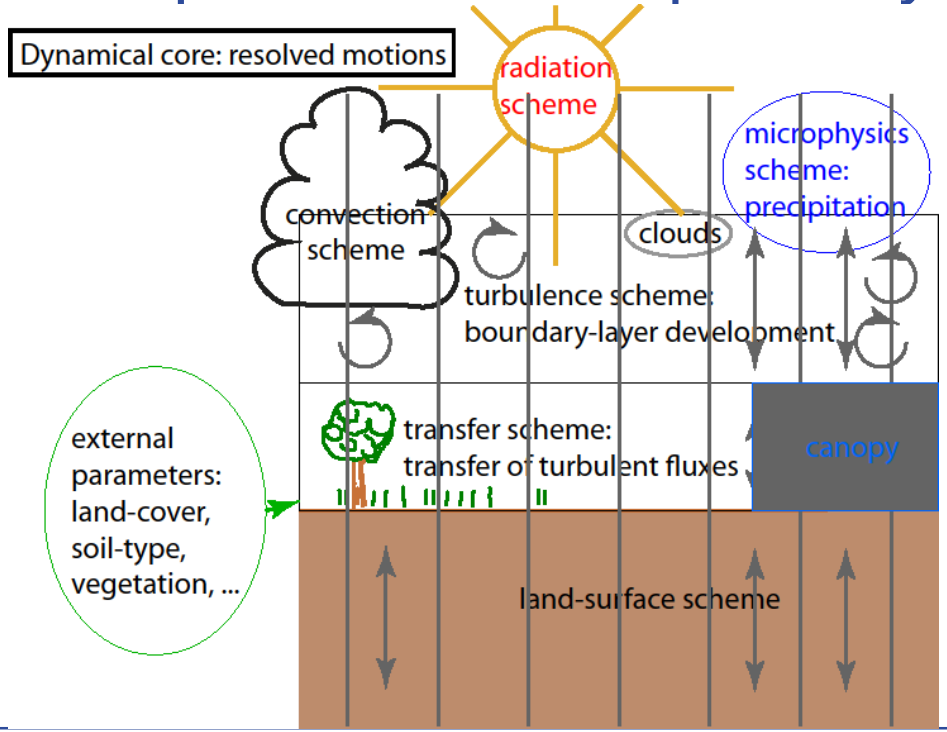


Weakening soil-moisture signal with increasing topographic complexity

Contents of this lecture

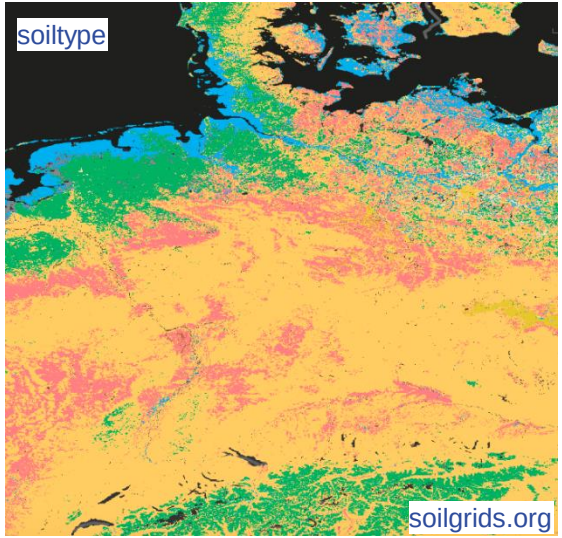
- Processes and Observations
  - Surface Energy Balance + Water Balance (constraints on the system)
  - Feedback on Atmosphere:
    - Homogeneous soil moisture distribution
    - Heterogeneous soil moisture distribution
    - Heterogeneous environment
- Modelling
  - Challenges
- Discussion

Modelling of the coupled land-atmosphere system

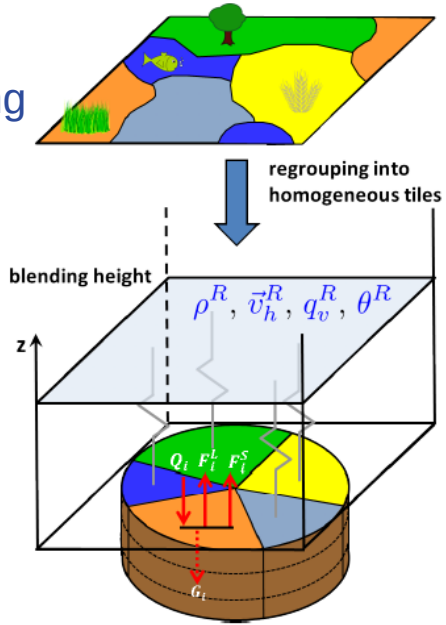


Focus on high spatial heterogeneity

ICON-D2: 2.2 km grid spacing;
Global climate model: O (50-100km) grid spacing

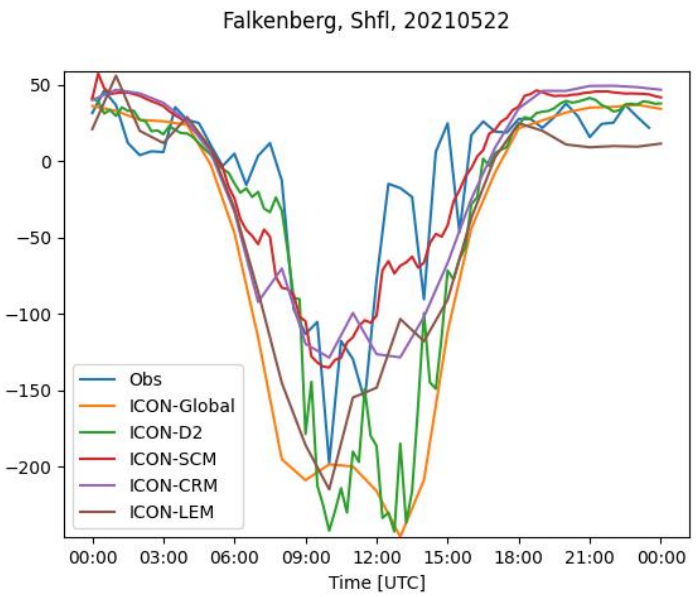


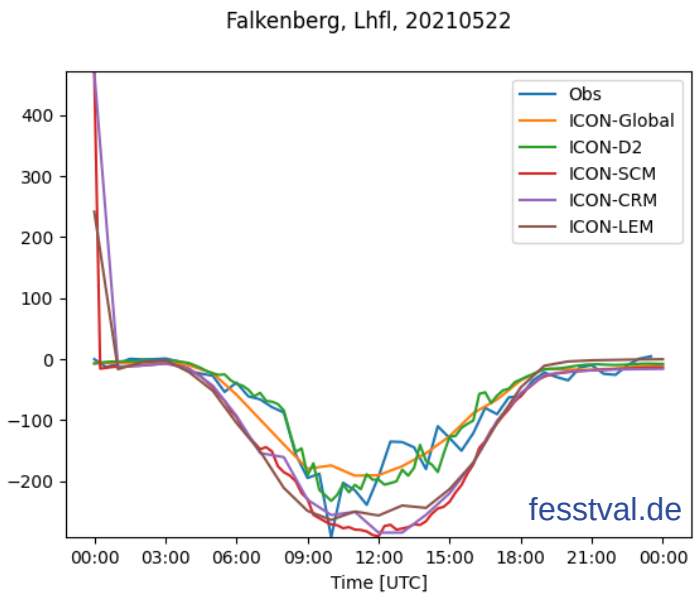
tiles



Prill et al., 2020

Modelling during FESSTVaL





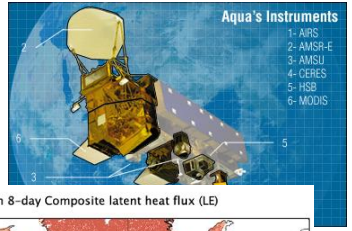
Turbulent surface fluxes are the result of many processes along the way
Incoming energy, soil-moisture content, partitioning, …

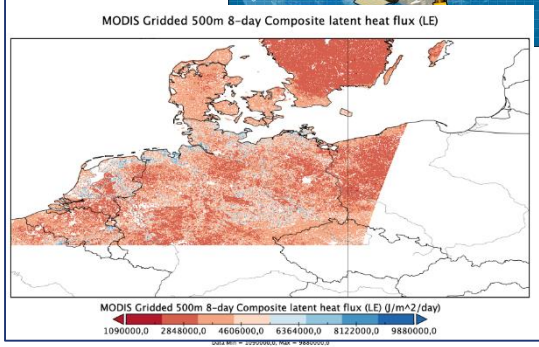
Information available on different scales

Satellite Imagery:

e.g. MODIS MOD16A. 500m spatial

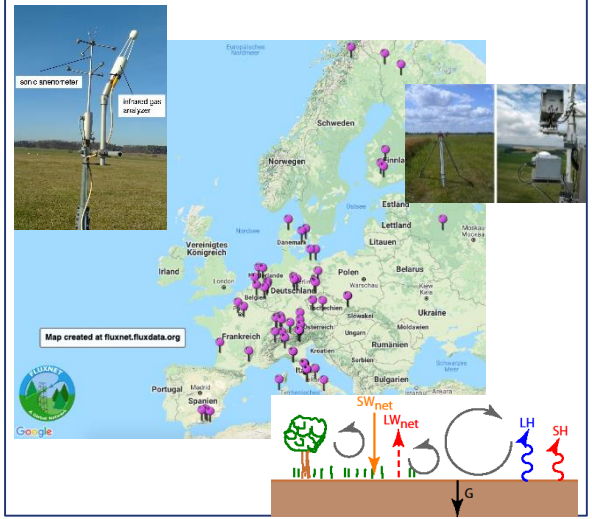
8 days



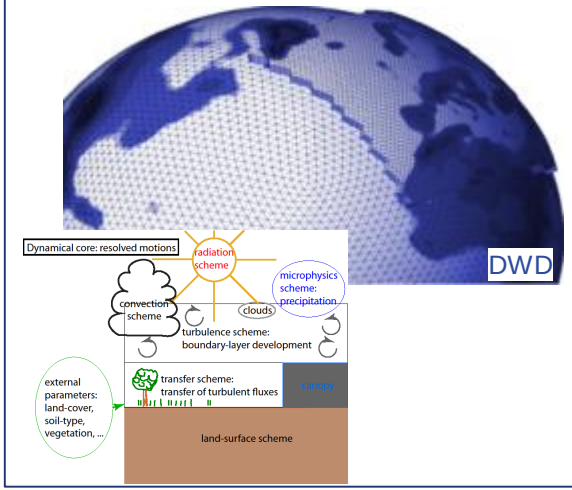


Eddy covariance data:

selected sites, footprint, high temporal resolution



Kilometer-scale numerical weather prediction, global climate modelling O(50 km)



Summary

- The state of the underlying surface crucially influences the development of the boundary layer, clouds and precipitation
  - partitioning of energy → boundary-layer
  - heterogeneities in soil-moisture, land-cover, vegetation & soil-temperature drive circulations
- Mountains dominate the triggering for mountains of ~500m height already
- Multiple challenges associated in modelling the coupled land-atmosphere system
- Comparisons between observations and models are challenging because of different scales, averaging times, indirect sensors, …