Land-Atmosphere (L-A) Feedback

Amplification of extreme events ***(Miralles et al. Nature Geosci. 2014)***

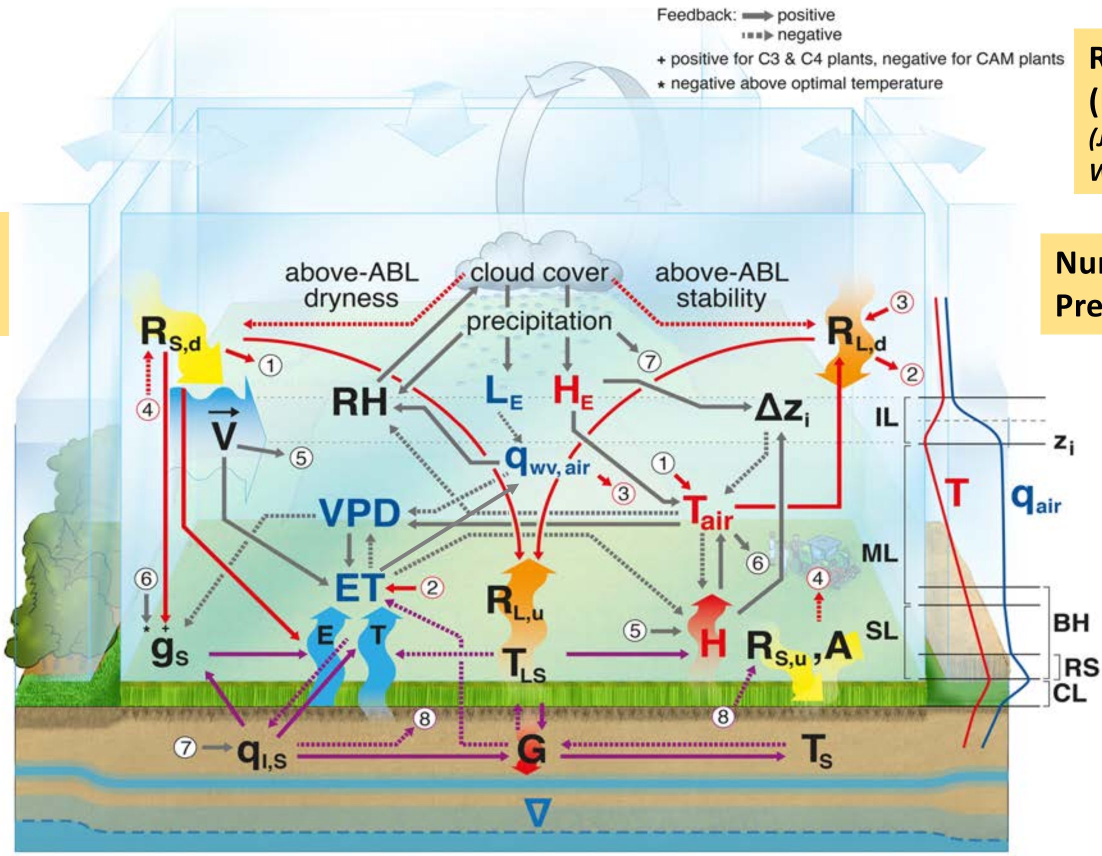
Ecosystem functioning ***(Humphrey et al. Nature 2021)***

Agriculture ***(Decker et al. ERL 2017)***

Urban effects ***(Haeffelin et al. AG 2005)***

Response to climate change ***(Novick et al. NCC 2016)***

Bio-geoengineering ***(Branch and Wulfmeyer PNAS 2019)***



After Helbig et al. AFM 2021, Ek and Holtslag JH 2004

Regional climate model (RCM) performance ***(Jacob et al. REC 2020, Warrach-Sagi et al. JGR 2022)***

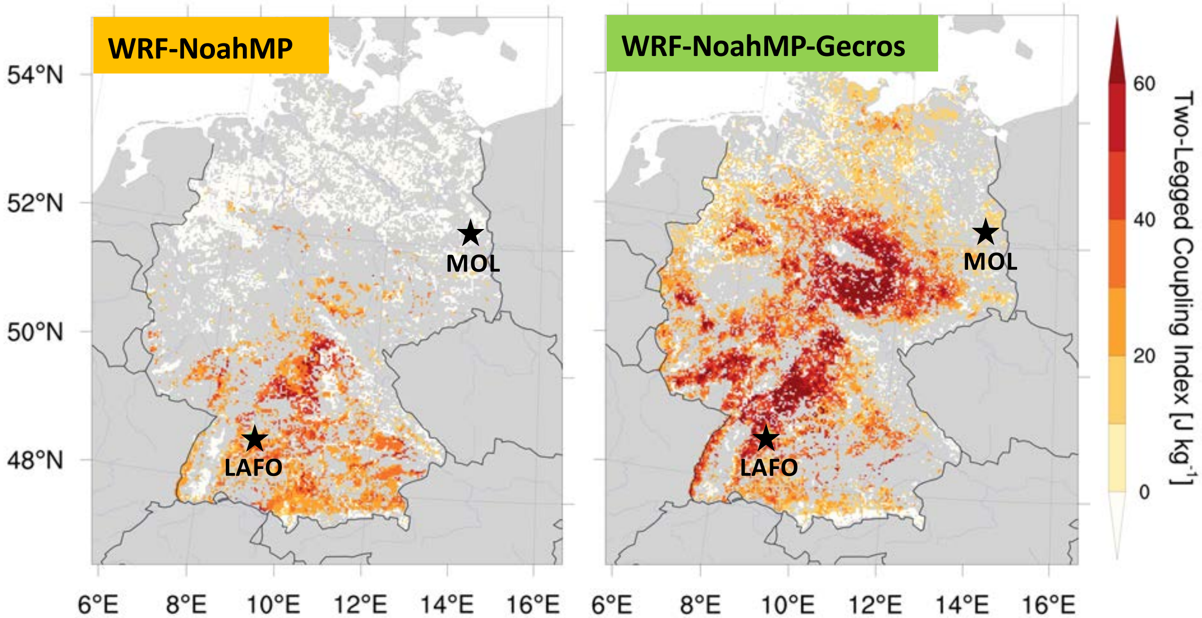
Numerical Weather Prediction (NWP) model skill

L-A feedback metrics ***(Santanello et al. BAMS 2018)***

Parameterizations

Crucial is the synergetic 3D observation and modeling of the L-A system covering all compartments.

How do State-of-the-Art Models Represent Land-Atmosphere (L-A) Feedback?



April-August 2005, grid increment 3 km (Warrach-Sagi et al. JGR 2022)

$$TLCI = \sigma(q_{l,s}) \frac{d\,ET}{dq_{l,s}} \frac{d\,CAPE}{dET}$$

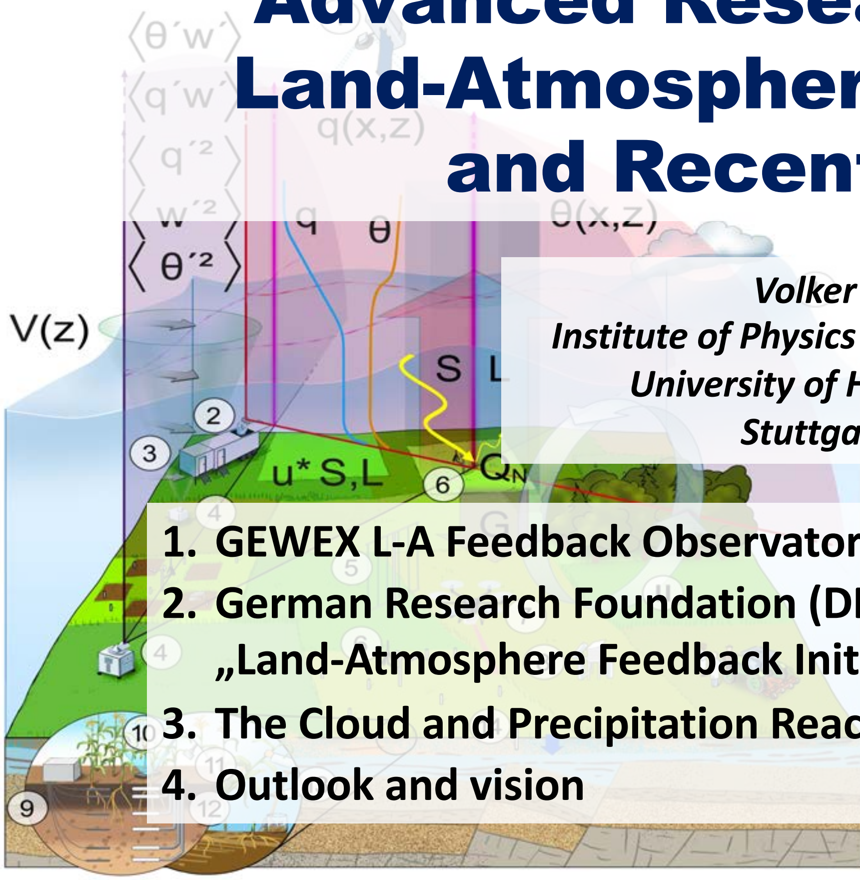
$TLCI$: Two legged-coupling index
σ: Standard deviation
$q_{l,s}$: Soil moisture content
ET: Evapotranspiration
$CAPE$: Convective available potential energy

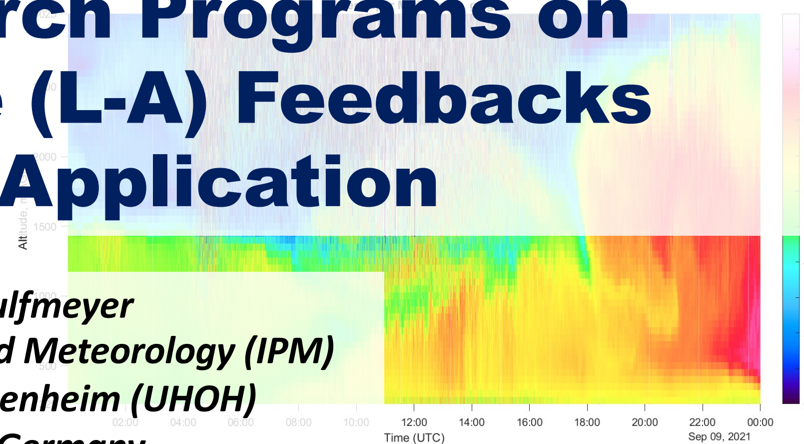
White: No two-legged coupling
Grey: Not analyzed due to lack of observations outside Germanys or no significance

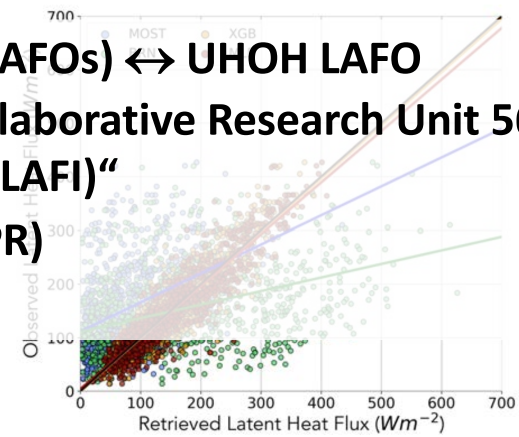
- **Current L-A system models seem to underestimate the sensitivity of cloud formation to land-surface properties.**
- **This requires an understanding of land-atmosphere (L-A) feedback on the km-scale.**

Advanced Research Programs on Land-Atmosphere (L-A) Feedbacks and Recent Application

Volker Wulfmeyer
Institute of Physics and Meteorology (IPM)
University of Hohenheim (UHOH)
Stuttgart, Germany

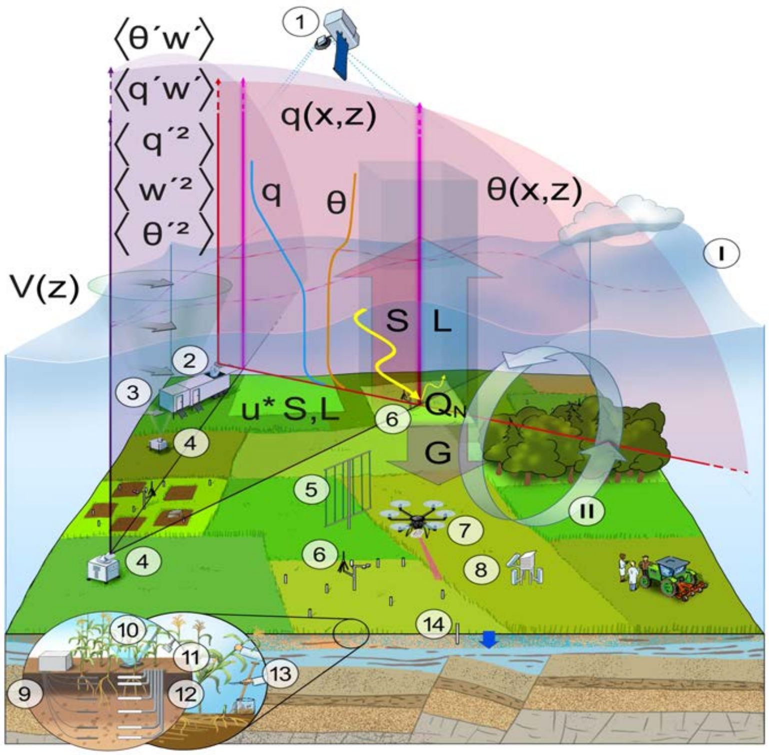






1. **GEWEX L-A Feedback Observatories (GLAFOs) ↔ UHOH LAFO**
2. **German Research Foundation (DFG) Collaborative Research Unit 5639 „Land-Atmosphere Feedback Initiative (LAFI)“**
3. **The Cloud and Precipitation Reactor (CPR)**
4. **Outlook and vision**

1. GEWEX LAFO (GLAFO) Design



Proposed sensor synergy:
I: PBL top, II: mesoscale vortex
1: Satellite remote sensing
2: Vertically staring Doppler, water vapor, temperature, and CO_2 lidar systems, infrared spectrometer (IRS), microwave radiometer (MWR), cloud radar
3: Scanning Doppler, water vapor, temperature, and CO_2 lidar systems
4: Scanning Doppler lidar systems
5: Fiber-based distributed sensors
6: Energy balance and eddy covariance stations
7: Unmanned aerial vehicle (UAV)
8: Water vapor and CO_2 isotope sensor
9: Time-domain reflectometers (TDRs)
10: Leaf area index (LAI) measurement
11: Gas exchange system for photosynthesis and transpiration rates
12: Tensiometers
13: In-situ canopy measurements such as biomass and canopy height
14: Soil moisture and temperature network

Wulfmeyer et al. GEWEX Newsletter 2020, GLAFO White Paper 2021 (see https://www.gewex.org/panels/global-landatmosphere-system-study-panel/glass-projects)

Overarching Scientific Goals

- Understand the L-A feedback chains over the regimes of all compartments in the context of large-scale forcings and characterize coupling strengths
- Quantify the effects of LULCC on regional weather and climate also in connection with future bio-geoengineering efforts
- Observation of surface and entrainment fluxes in complex terrain
- Quantify ET and its separation in E and T
- Study the energy balance closure (EBC) in heterogeneous terrain
- Advanced parameterizations of surface fluxes and ABL turbulence
- Regional water and energy budget analyses
- Verification of Earth system models down to the turbulent scales
- Impact studies towards operational assimilation of GLAFO data
- Climate monitoring

The Land-Atmosphere Feedback Observatory (LAFO)

Location:
Stuttgart, Germany
48° 42‘ 38.0“ N
9° 11‘ 26.6“ E

https://lafo.uni-hohenheim.de/en, Späth et al. *GI* 2023

Atmos. surface layer, two energy balance stations:

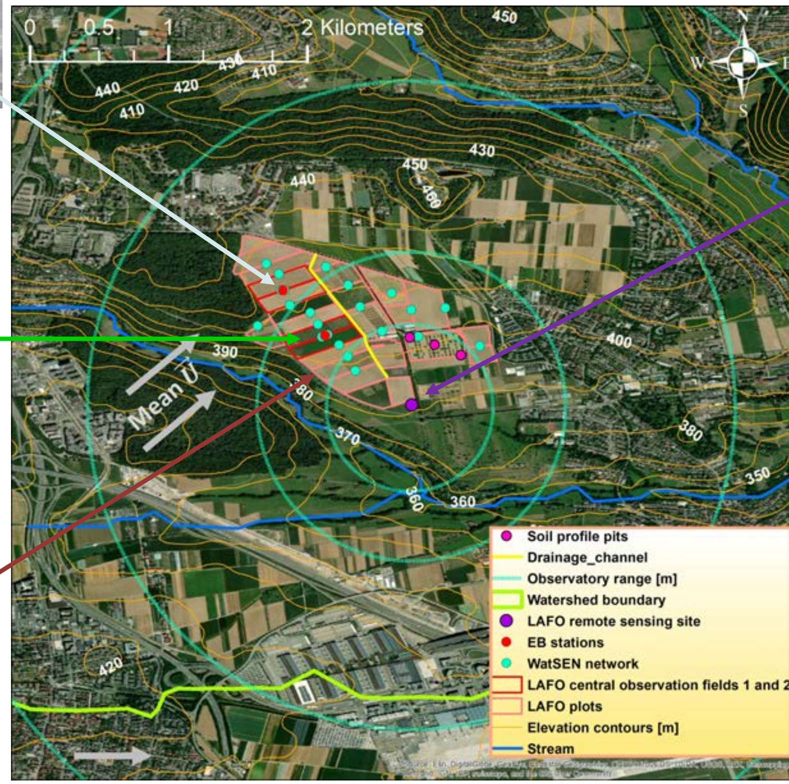
- T_{air}, q_{wv}, p, WS, WD, RR
- $R_{i,j}$, G, H, L, F_{CO2}

Canopy:

- LAI
- Phenological state
- Canopy profiling of $T_{air,can}$ and $q_{wv,can}$ in prep. (4 heights, 5 locations)
- UAV ($h_{can}(x,y)$)

Soil:

- Probes such as q_{soil}
- Profiles (T_{soil}, $q_{l,soil}$, Ψ_{soil}, $v_{l,soil}(\Psi_m)$)
- WaTSeN: T_{soil}, $q_{l,soil}$, 22 stations operational since July 2018 in 40-cm depth
- Drainage flow in prep.

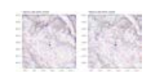


Atmos. boundary layer:

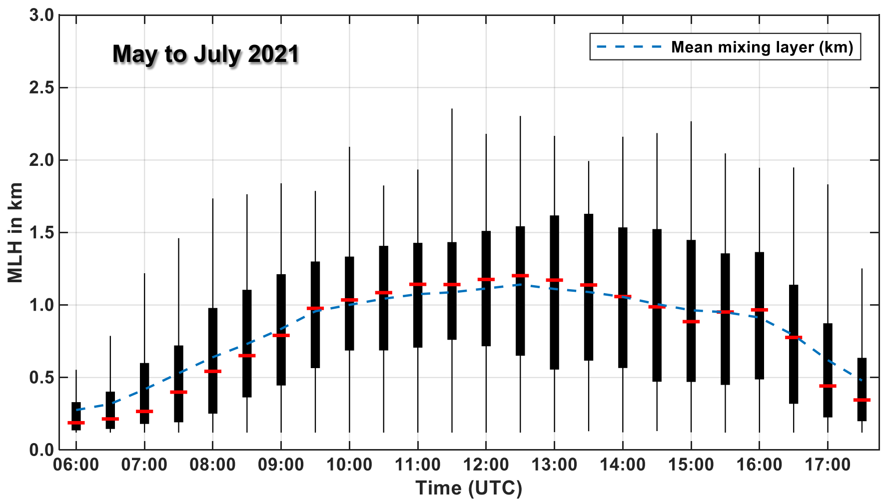
- Scanning WVDIAL, WVTRL ($T_{air}(r)$, $q_{wv}(r)$, $H(z)$, $L(z)$, $\langle q'^2_{wv} \rangle$,…)

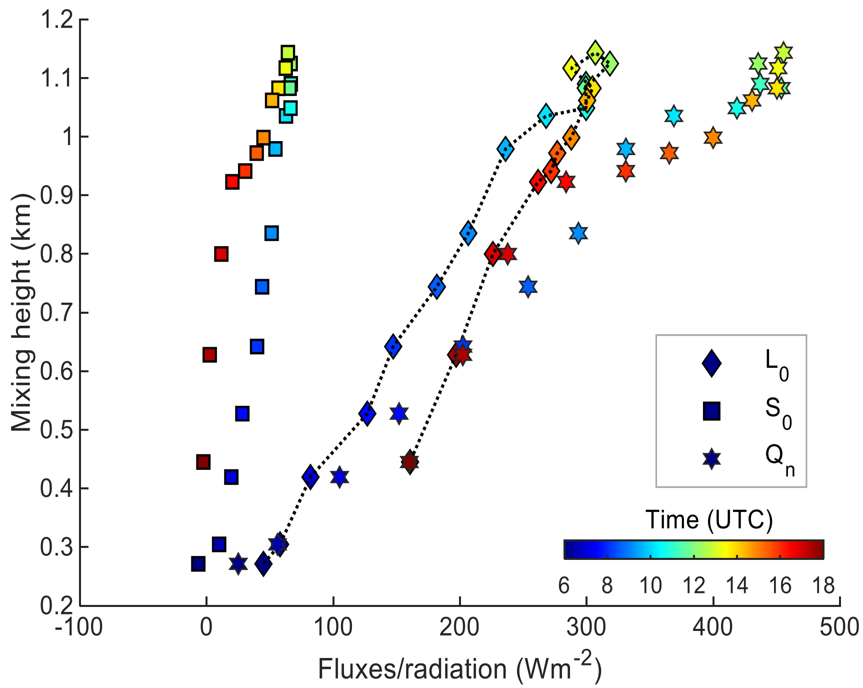
- Doppler lidar, vert. staring and scanning (WS, WD, $e(z)$, $\tau_{Rey}(z)$)

- Doppler cloud radar (w, $Z(z)$)
- Disdrometer ($RR(d)$)
- Micro rain radar ($RR(d,z)$)



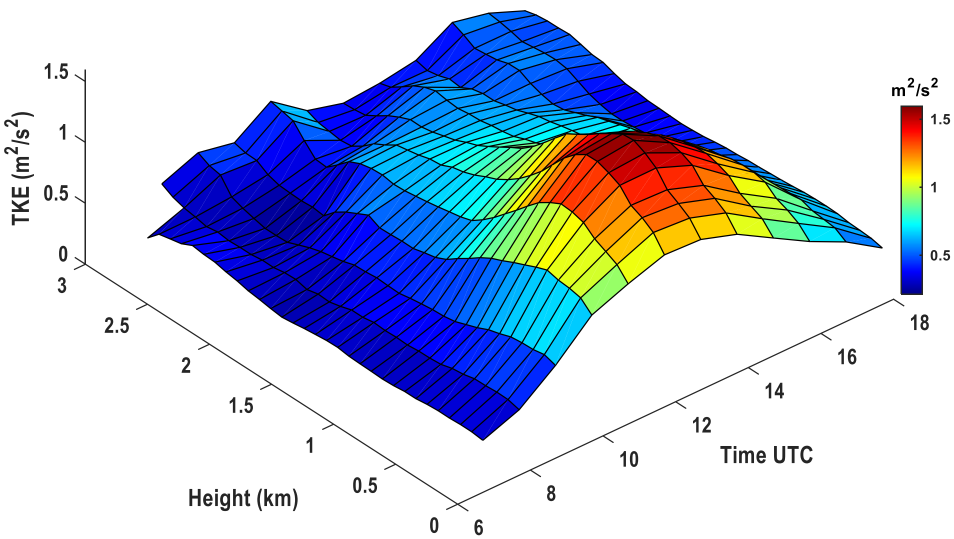
LAFO Diurnal Cycle Statistics and Feedback Metrics

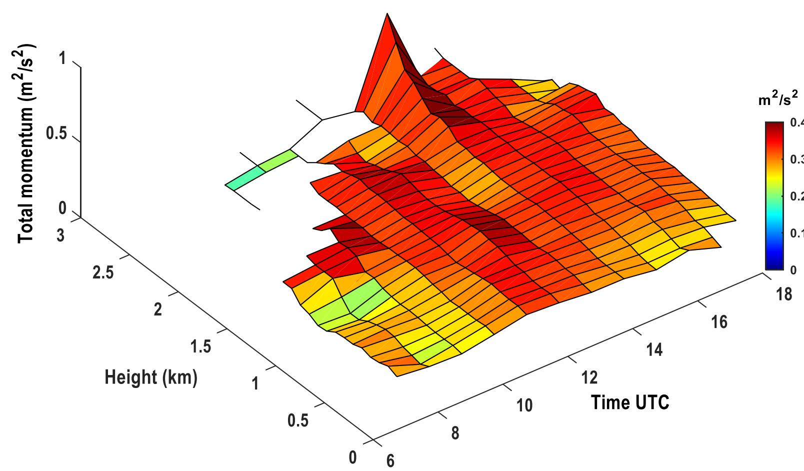




With (G)LAFO data, process-based feedback metrics can be derived routinely
(see also *Santanello et al. BAMS 2018, Wakefield et al. JH 2021, JAMC 2022*).

Turbulence Statistics from LAFO

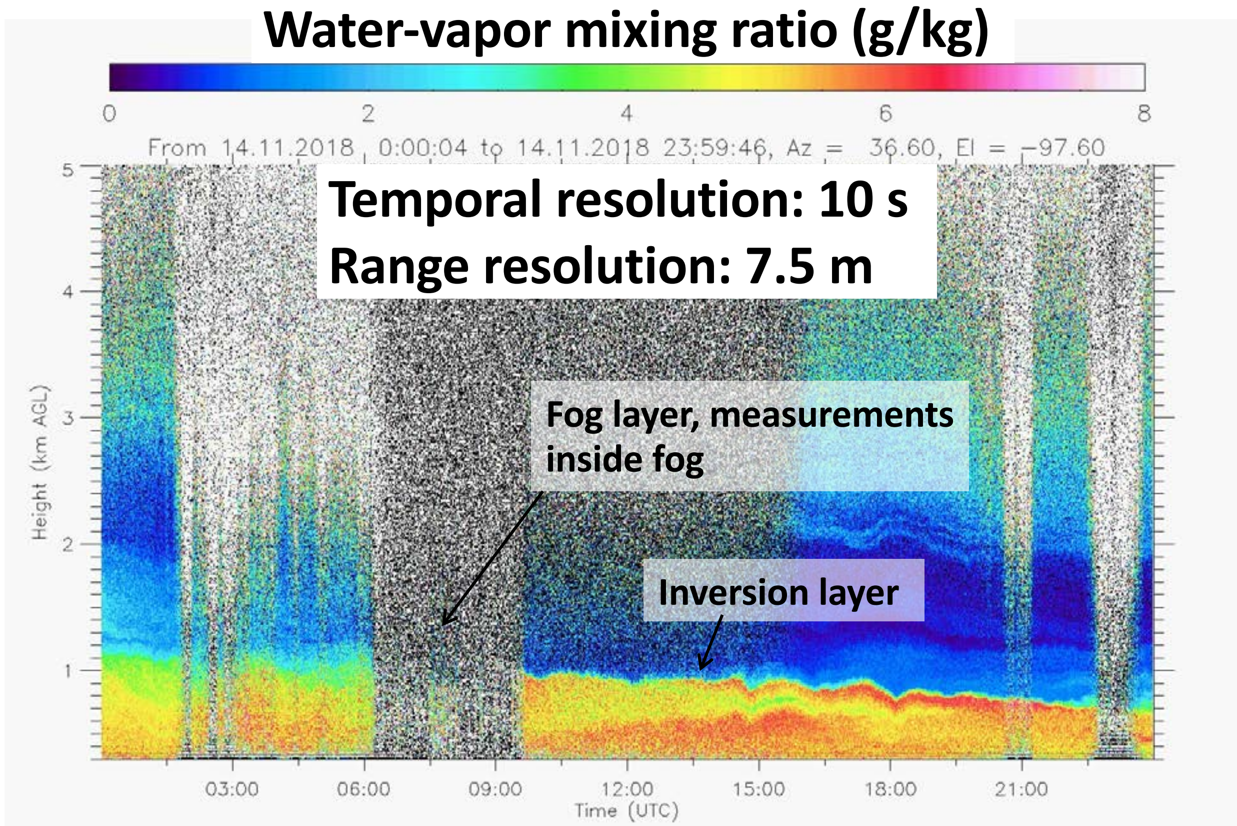




With GLAFO data it is feasible to provide statistics for turbulence parametrizations.

ARTHUS Performance, LAFO, November 14, 2018

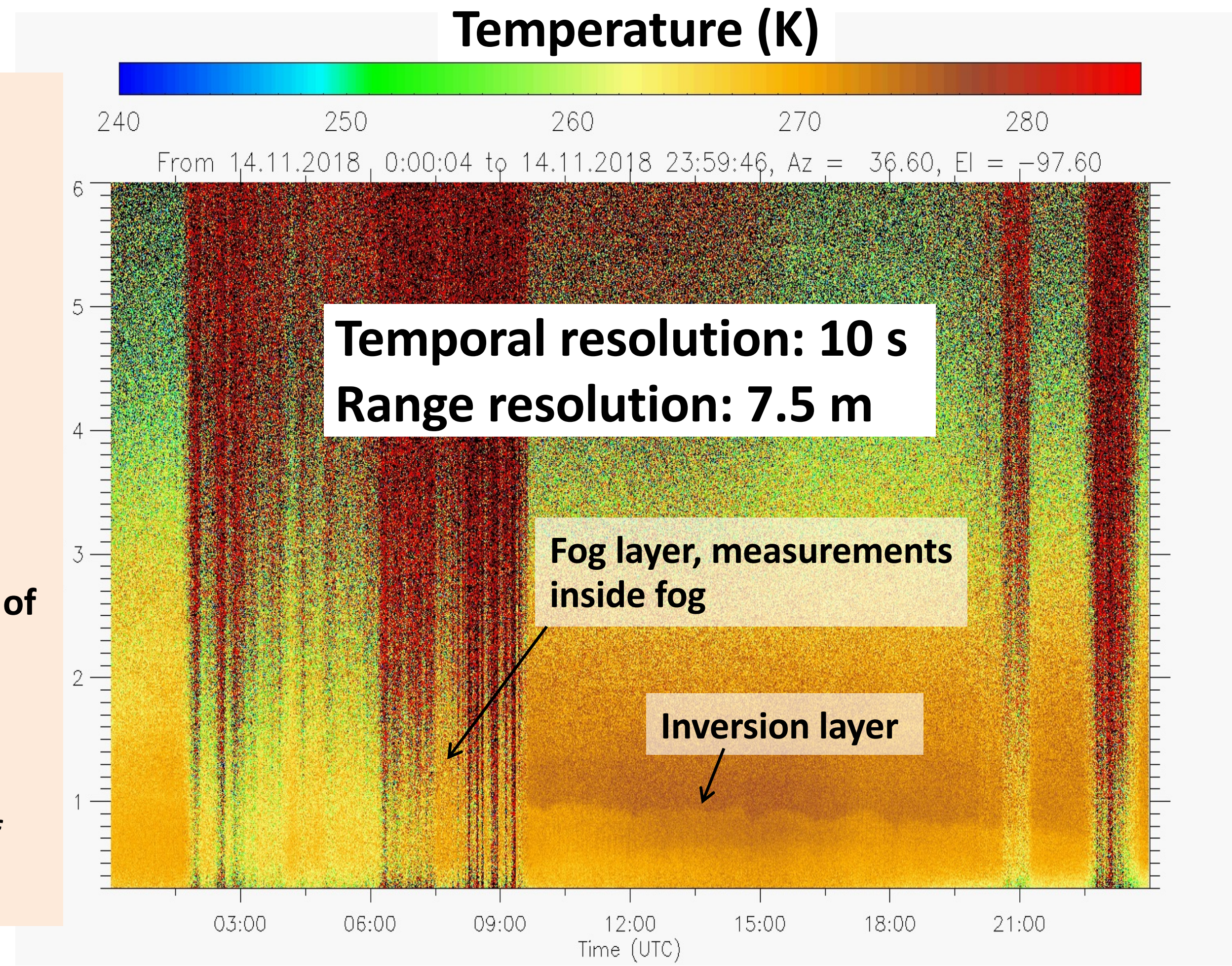
ARTHUS: Atmospheric Raman Temperature and Humidity Sounder



Key applications:

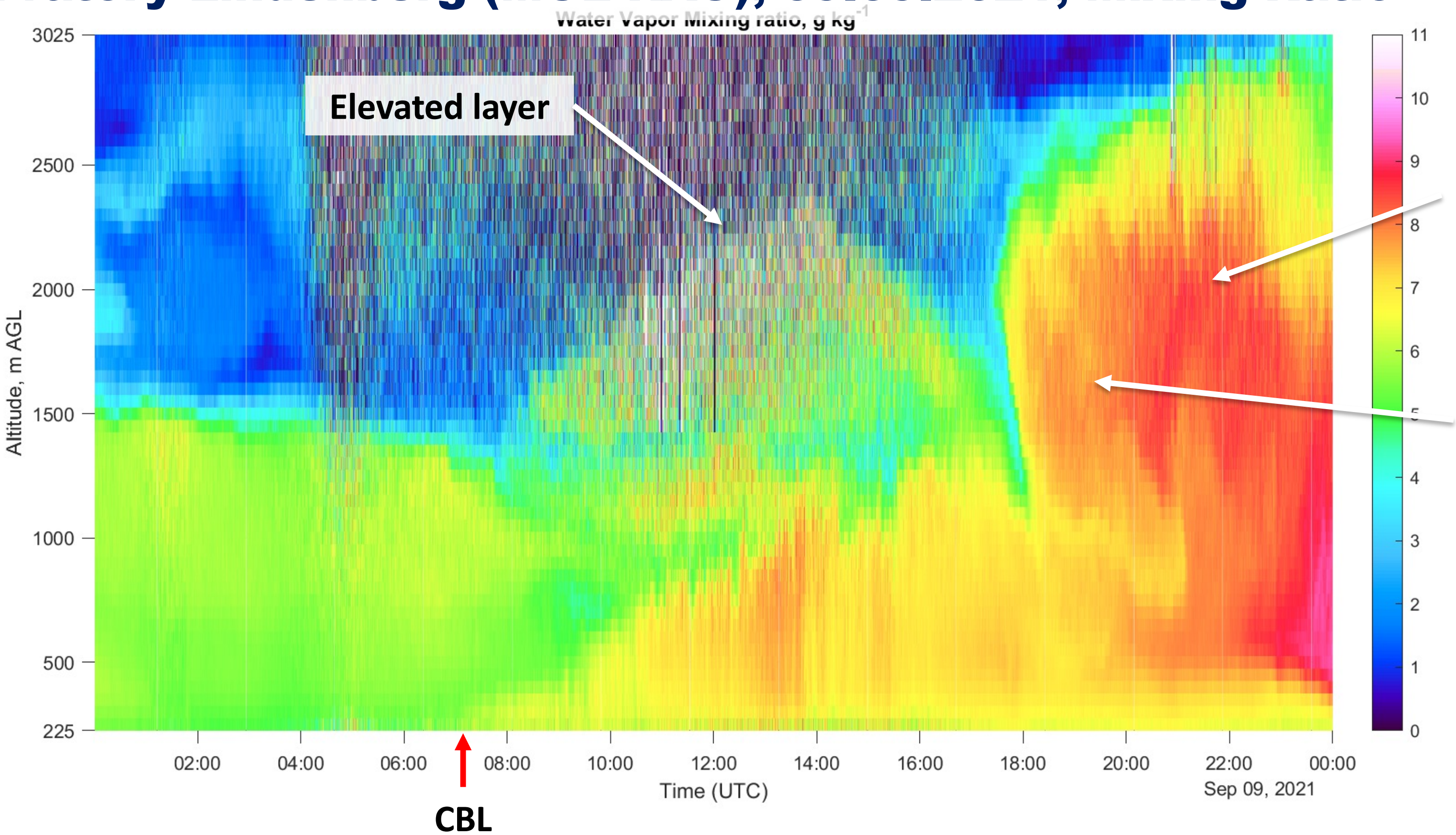
- Monitoring
- Verification of models and sensors, e.g., from space
- Data assimilation *(see, e.g., Thundathil et al. QJRMS 2021)*
- Radiative transfer
- Water and energy budgets
- L-A feedback
- ABL transport studies including the development of new parameterizations
- Convection initiation
- Mesoscale circulations
- ...

(see also Wulfmeyer et al. Review of Geophysics 2015)



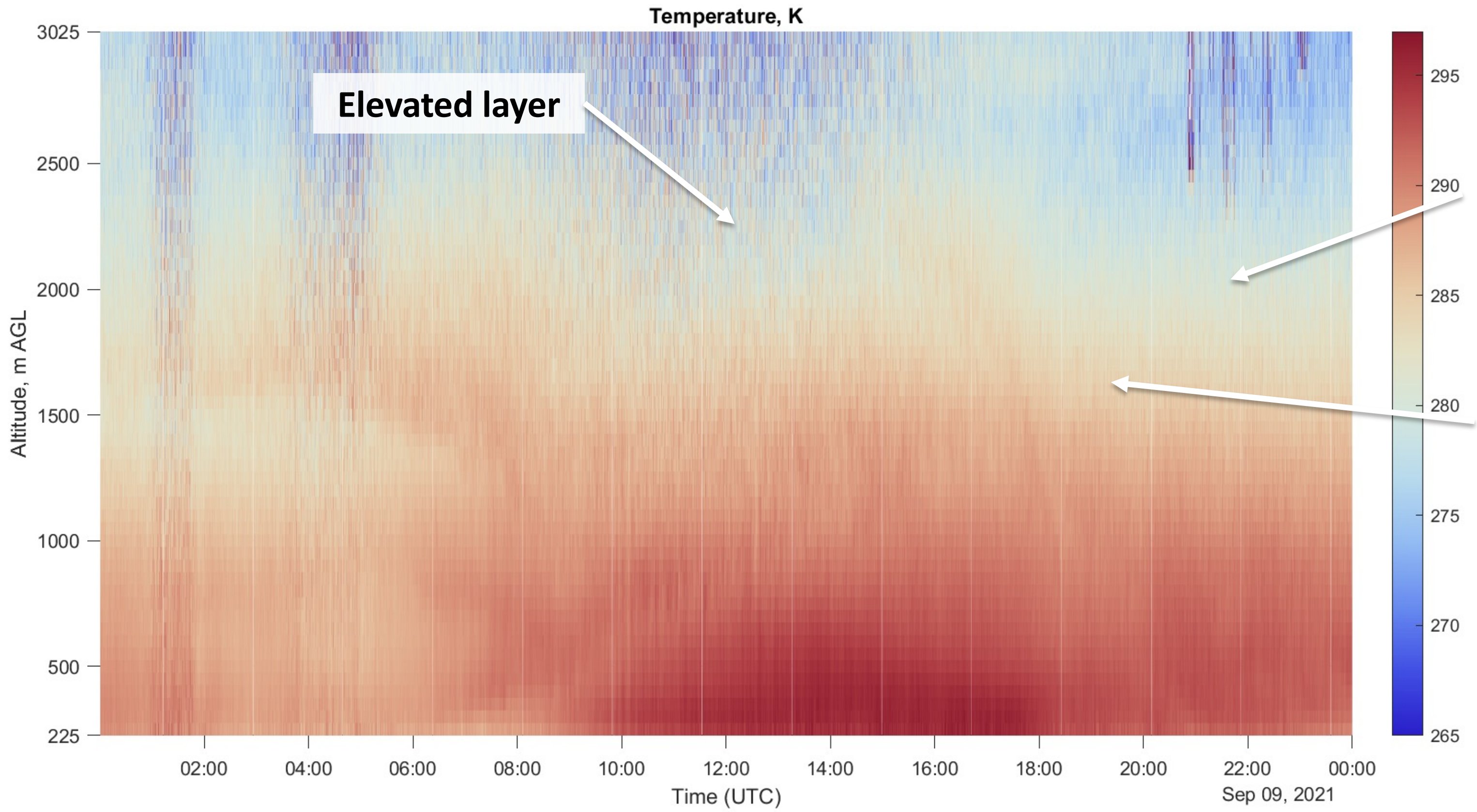
German Weather Service (DWD) Meteorological Observatory Lindenberg (MOL-RAO), 09.09.2021, Mixing Ratio

10 s, 50 m



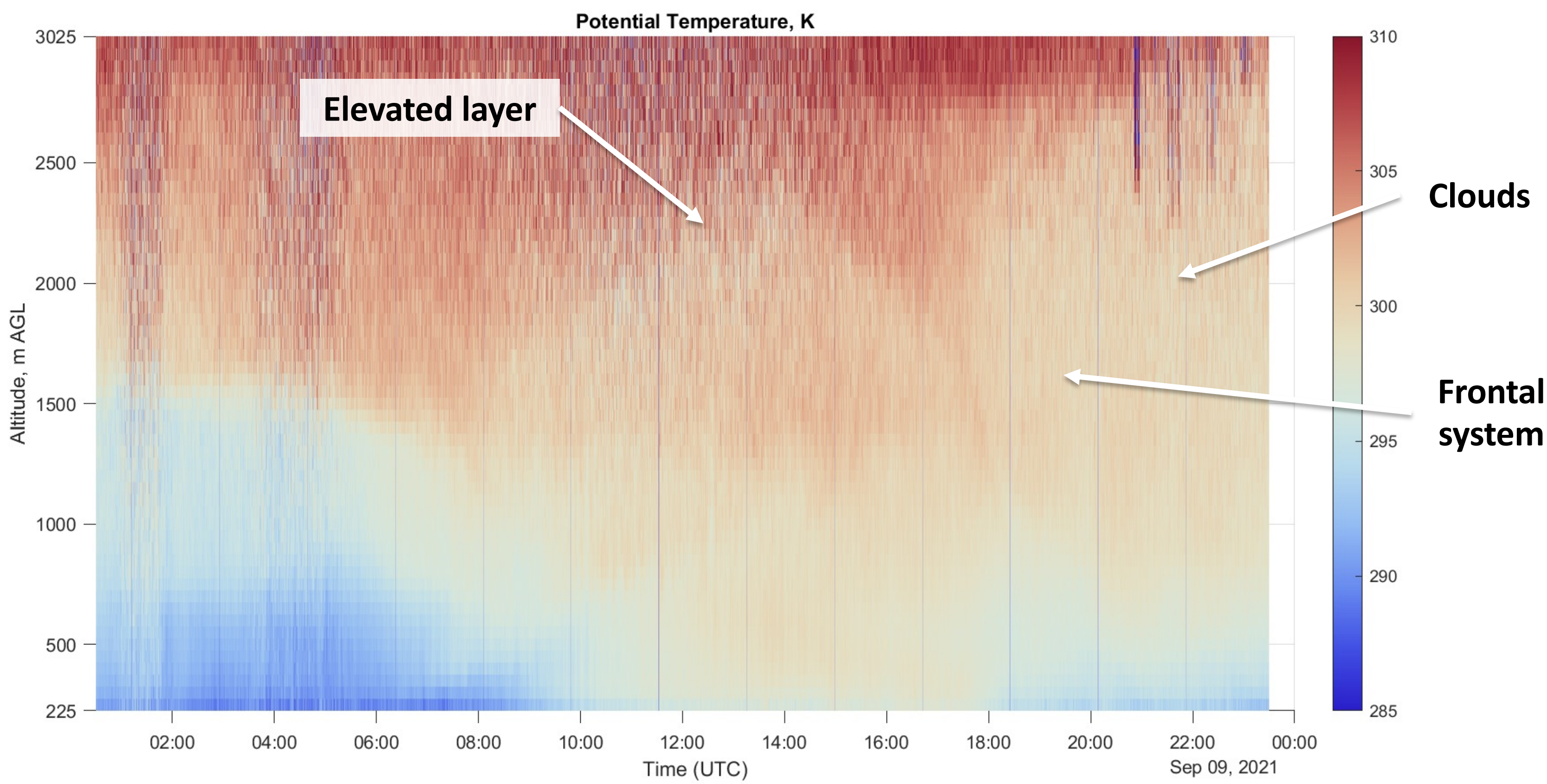
Temperature

10 s, 50 m



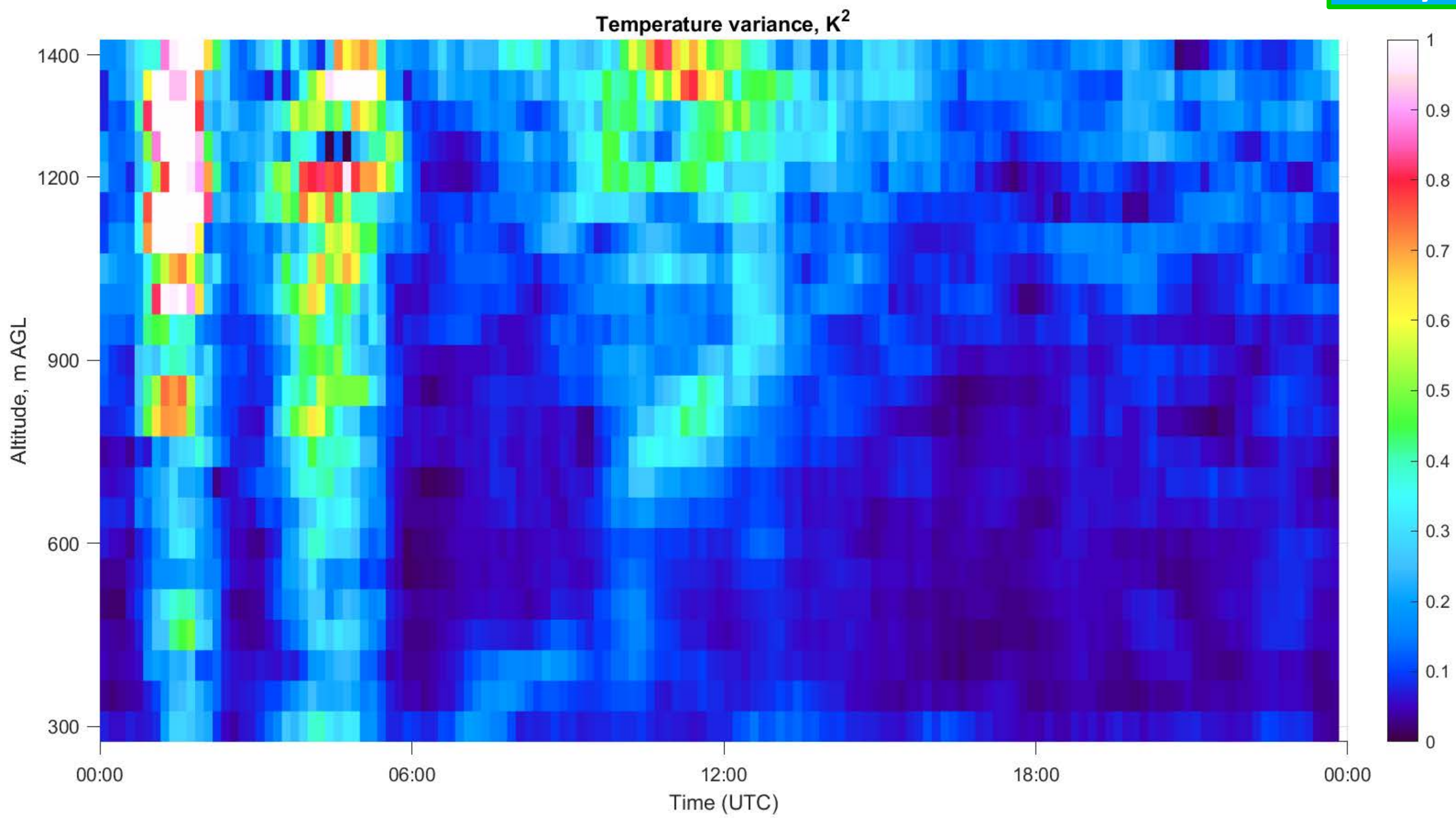
Potential Temperature

10 s, 50 m



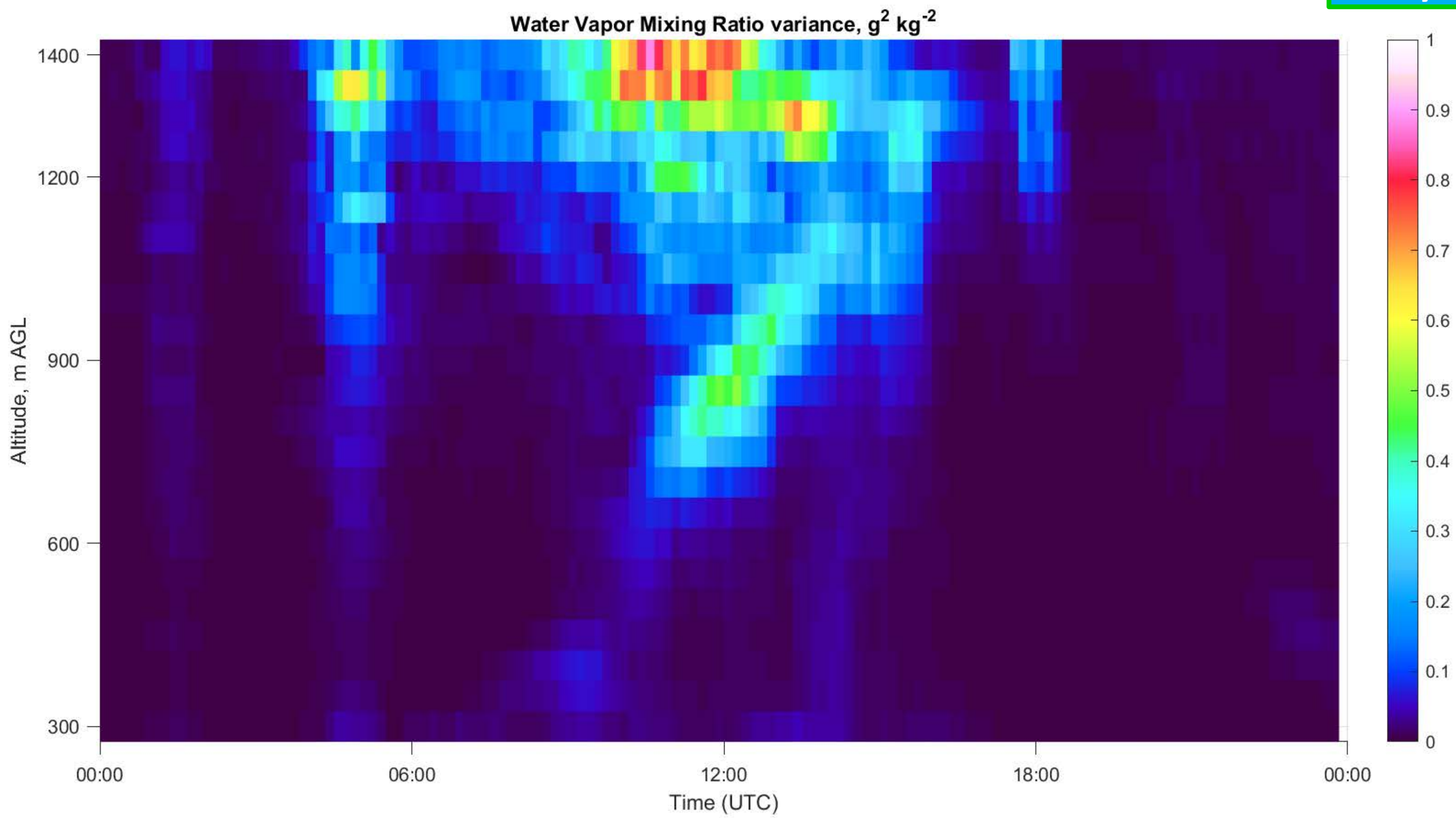
Temperature Variance

1 h (averaged every 600s), 50 m



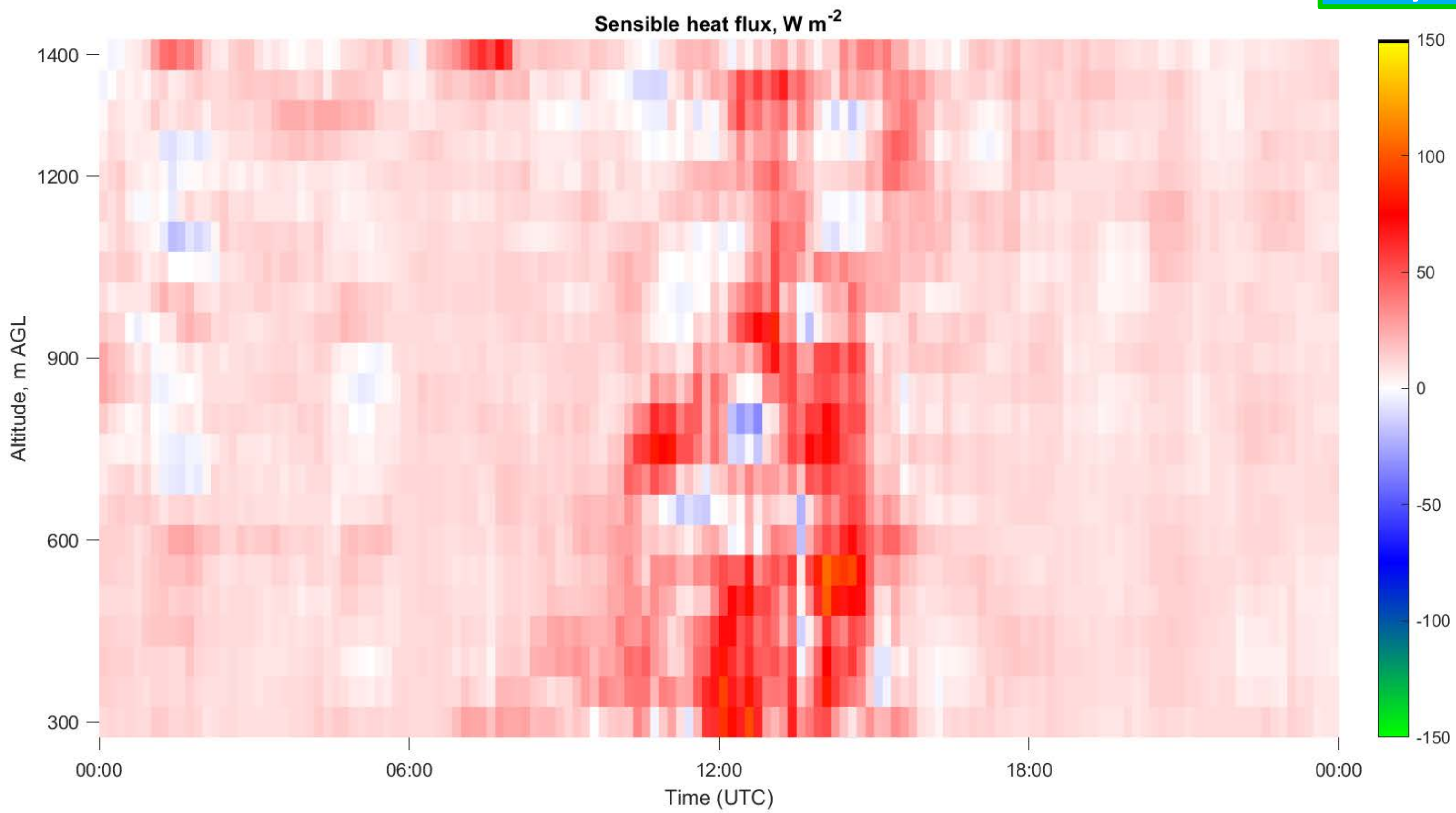
Mixing Ratio Variance

1 h (averaged every 600s), 50 m



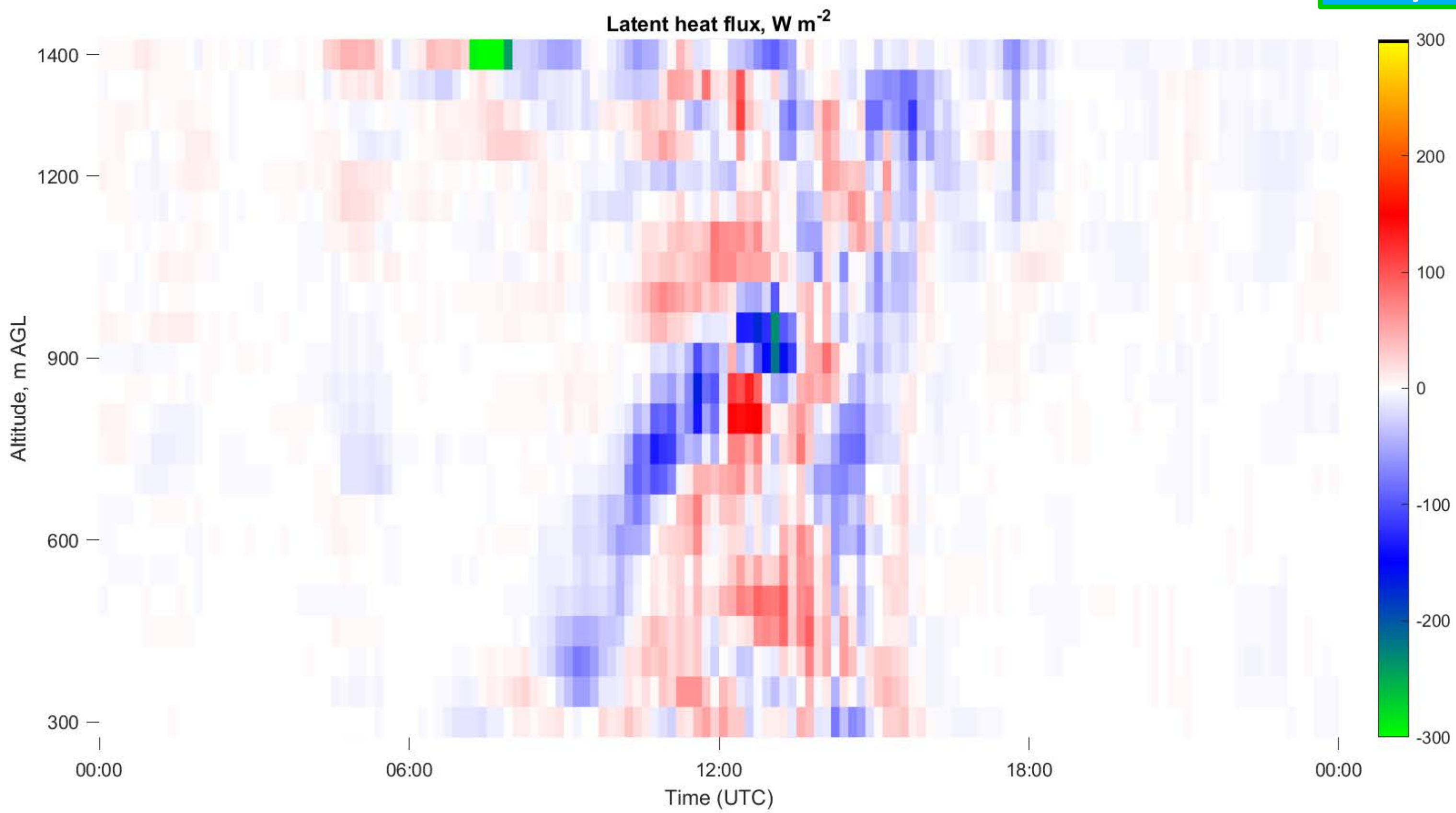
Sensible Heat Flux

1 h (averaged every 600s), 50 m



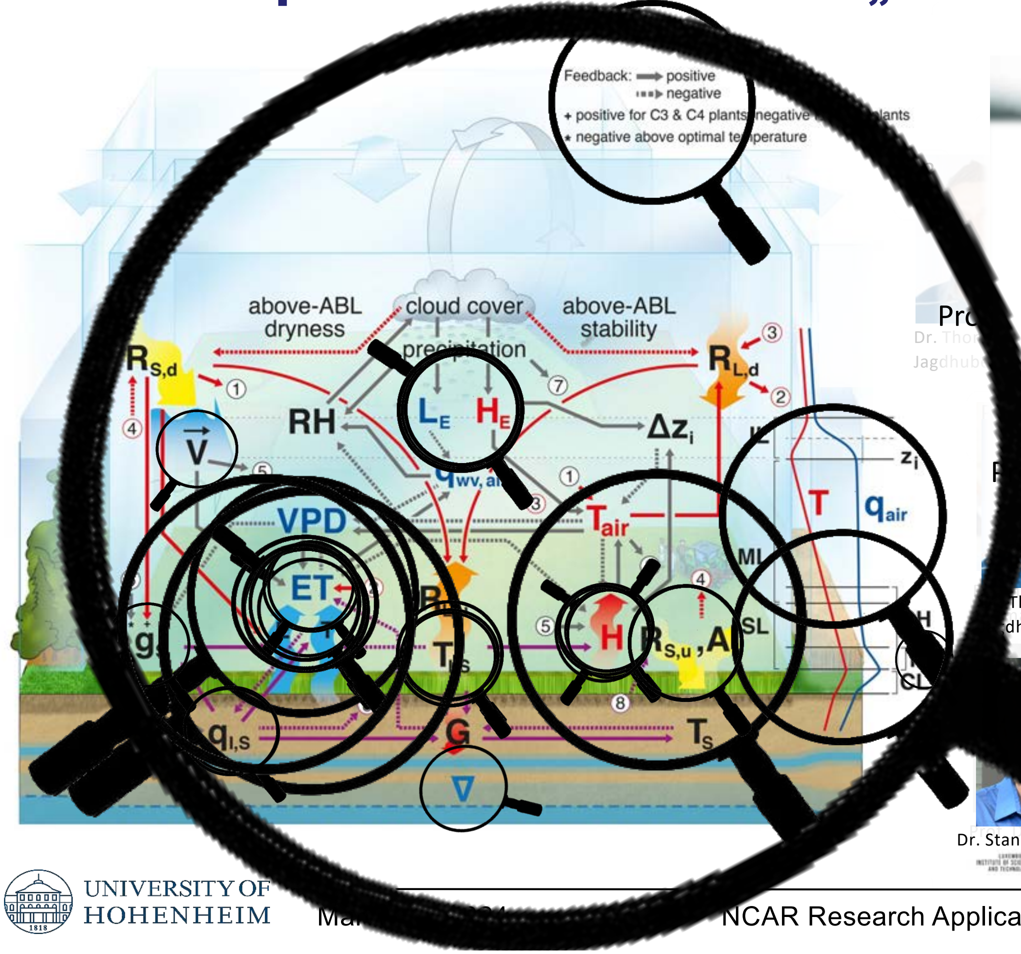
Latent Heat Flux

1 h (averaged every 600s), 50 m



2. DFG Research Unit 5639

Land-Atmosphere Feedback Initiative „LAFI“

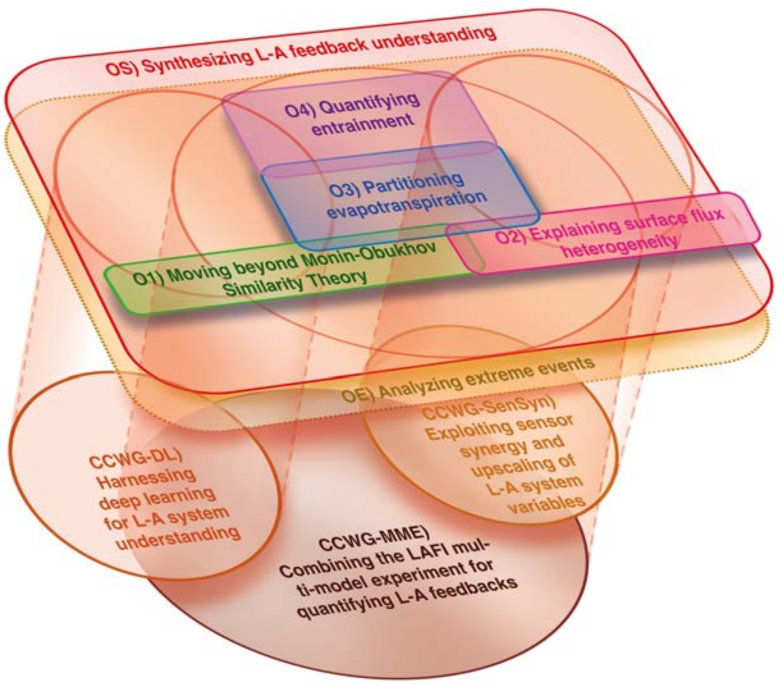


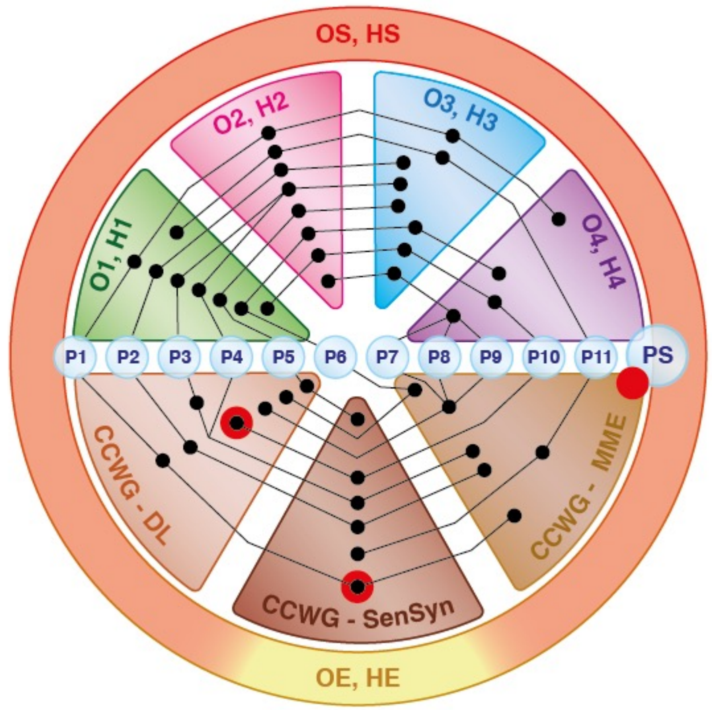
P1 – Observation and Investigation of L-A System, ABL Processes and Fluxes

PS – Understanding and Quantification of L-A Feedbacks

LAFI Objectives and Collaboration

Our goal is to understand and quantify L-A feedbacks via unique synergistic observations and model simulations from the micro-γ (≈ 2 m) to the meso-γ (≈ 2 km) scales across diurnal to seasonal time scales.

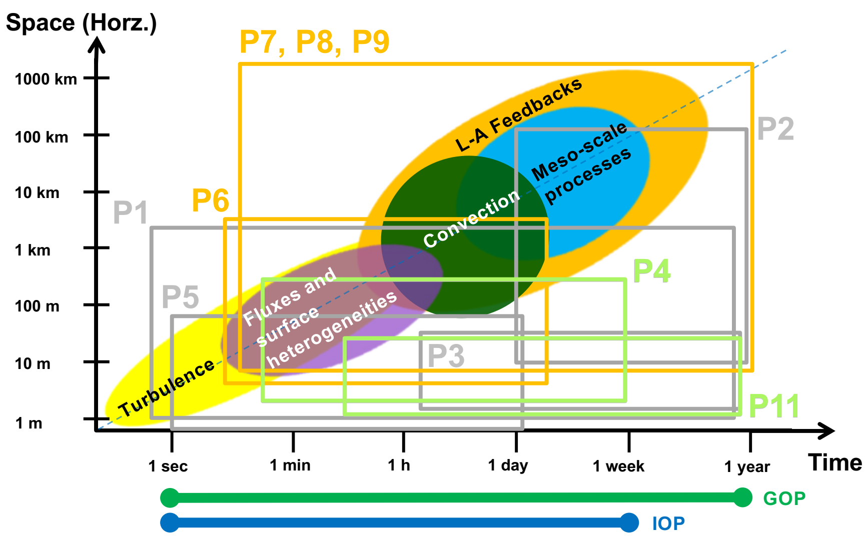




Research Component 1: New Synergistic Observations Enhancement of the Land-Atmosphere Feedback Observatory (LAFO)

Worldwide unique observatory: Profiling and horizontal measurements through all compartments, simultaneously, in the atmosphere with turbulence resolution. CCWG-SenSyn exploits its sensor synergy.

Research Component 2: The Multi-Model Experiment (MME)



- **Fundamental to understand the effects of heterogeneity on local to regional feedbacks**
- **Provide uncertainty estimates for metrics (PS)**

- **Fundamental to advance representation of water transport in the soil-plant system**

L-A SYSTEM MODELS

PALM (P6):
- Resolves turbulent transport in heterogeneous terrain with very high spatial resolution.

WRF-NoahMP-Gecros (P7):
- Operates with different resolutions simultaneously and uses a sophisticated representation of crop dynamics.

ICON-JSBACH (P8):
- Enables to study mesoscale effects of microscale surface heterogeneities and provides carbon fluxes.

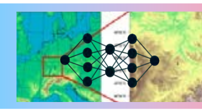
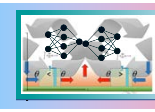
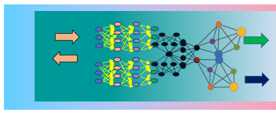
WRF-NoahMP-Hydro-Iso (P9):
- Provides a more sophisticated representation of hydrology and links to the isotope measurements of P3.

Offline LAND-SURFACE MODELS

NoahMP-Gecros (P4):
- Improves the representation of E and T of crops and of the soil water regime.

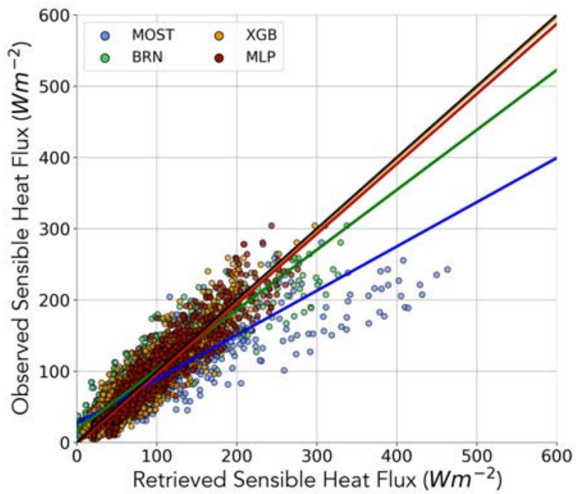
Vegetation Optimality Model (VOM) (P11):
- Realizes a detailed study of stomatal resistance models.

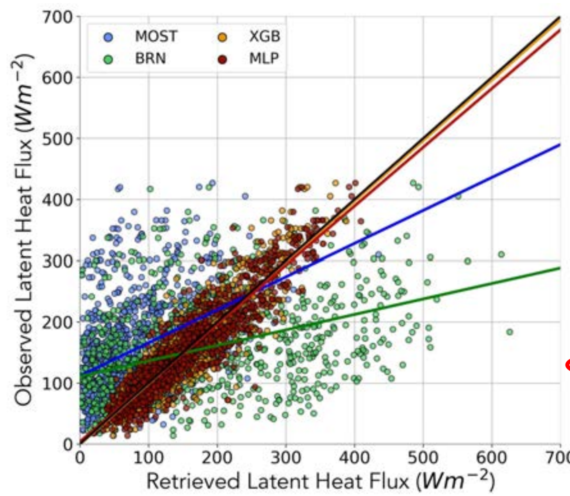
Research Component 3: Deep Learning

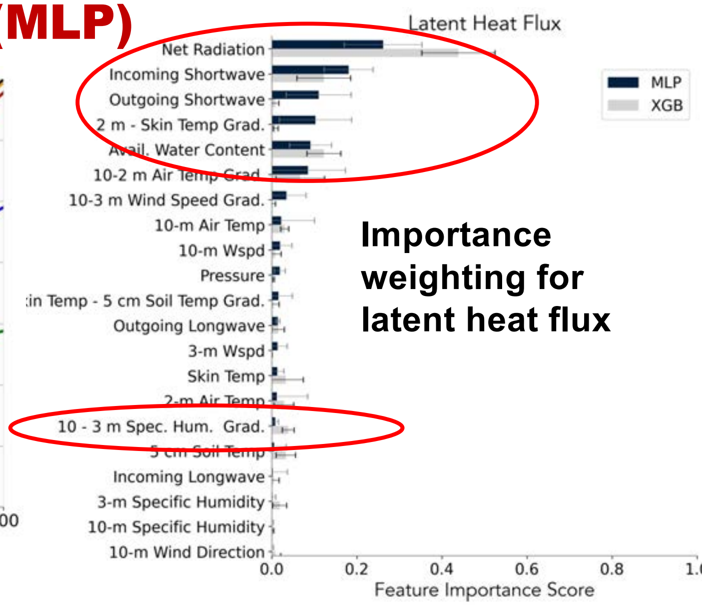
Aim	LAFI Research	Methodology		Process and system understanding
General similarities	Downscaling (satellite data of T_{LS}) (**P2**)	**Convolutional networks**		**Insight in the role of land-surface heterogeneity**
Process similarities	Fluxes and drivers (*ET, u*, H, H$_E$, L$_E$*), (*Wulfmeyer et al. 2023*) (**P5, P1, P3**)	**Machine learning with importance weighting**		**Alternative to MOST, turbulence similarities**
Process similarities + physics-informed	Fluxes and drivers (*ET, u*, H*) + energy conservation (**P5, P3, P1**), EBC (**P6**)	**Deep learning with regularization**		**Refined alternative to MOST with physical constraints, EBC**
Study of multi-dimensional phase space of L-A system	Structures and metrics in L-A system (**PS**)	**Foundation models**		**L-A system understanding and metrics**

LAFE Result: Surface Fluxes

Comparison of Monin-Obukhov Similarity (MOST), Bulk Richardson Number (BRN) and Machine Learning (ML) with Extreme Gradient Boosting (XGB) and Multilayer Perceptron (MLP)





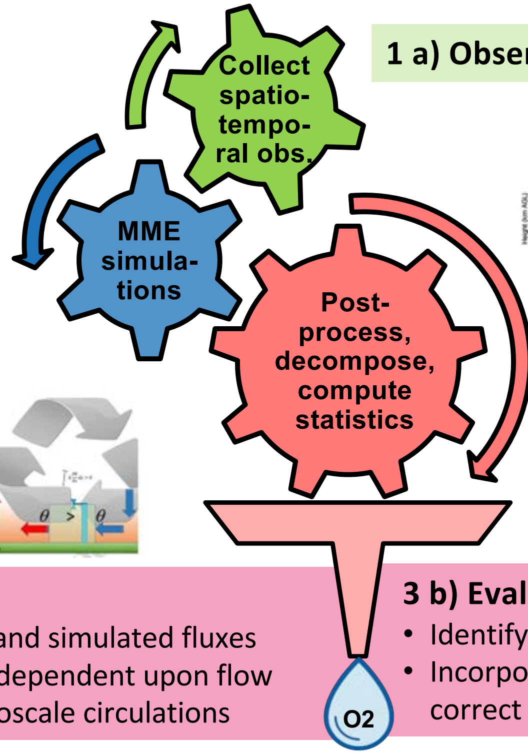


Importance weighting for latent heat flux

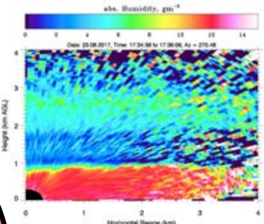
ML outperforms MOST and BRN. ML has great potential to improve surface layer flux relationships ***(Lee and Buban JAMC 2020, Lee et al. MWR 2021, Lee and Meyers 2023, Wulfmeyer et al. BLM 2023).***

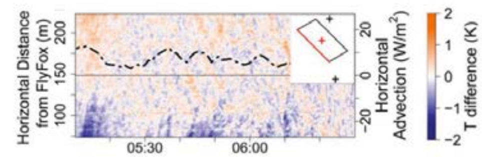
Research Component 4: Process Understanding Example: Objective 2 (O2) and Hypothesis 2 (H2)

Objective O2: Explaining surface flux heterogeneity. Key research on scaling and partitioning of surface fluxes as well as on the energy balance closure (EBC) across agricultural landscapes (P1-P11)

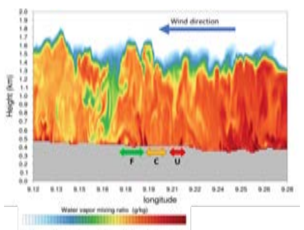


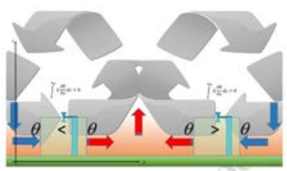
1 a) Observe L-A system states and variables



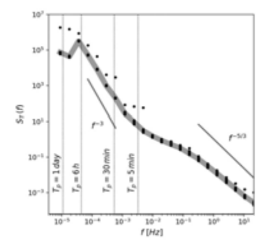


1 b) Simulate L-A system variables with MME:





2) Post-process, filter, scale-decompose



3 a) Synthesize:

- Analyze short-comings of measured and simulated fluxes
- Propose alternative scaling of fluxes dependent upon flow conditions as well as micro- and mesoscale circulations

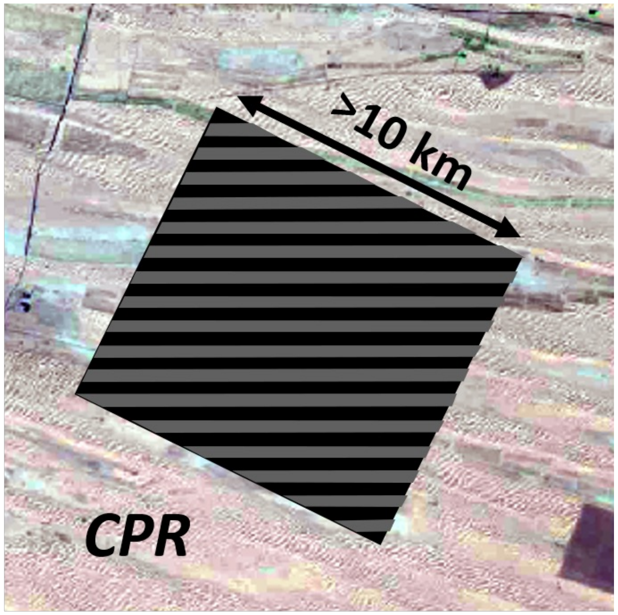
3 b) Evaluate hypothesis H2 (lead P6):

- Identify norm for comparing MME output and observations
- Incorporate co-spectral modifications and dispersive fluxes to correct surface fluxes and recompute EBC

The Cloud and Precipitation Reactor (CPR)

Regional climate engineering is gaining interest as a means of combatting climate change impacts like water scarcity and higher temperatures.

Large artificial dark surfaces are proposed as a means of enhancing precipitation via surface heating and amplification of vertical motion

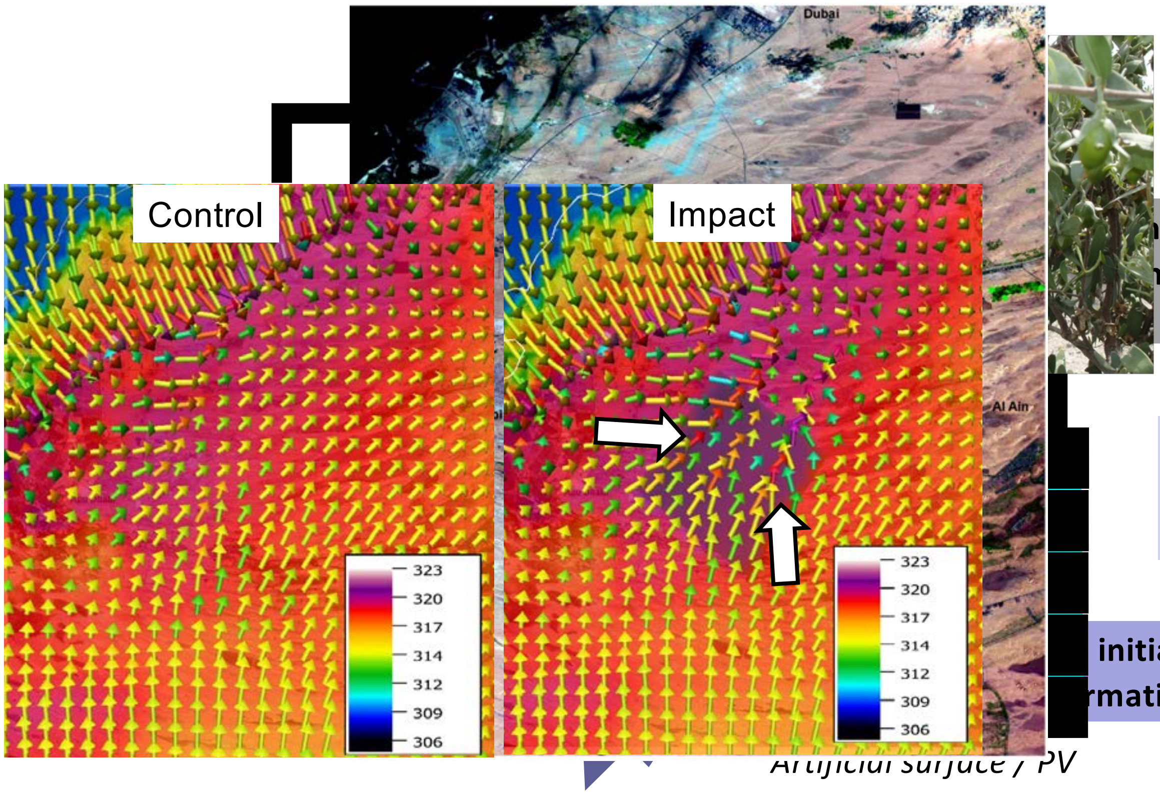


Branch, O., and V. Wulfmeyer, 2019: **Can desert plantations enhance rainfall?** P. Natl. Acad. Sci. 116 (38), 18841-18847, DOI:10.1073/pnas.1904754116.

Branch, O., L. Jach, T. Schwitalla, K. Warrach-Sagi, and V. Wulfmeyer, 2024: **Scaling artificial heat islands to enhance precipitation in the United Arab Emirates.** *Earth Syst. Dyn. 15*(1), 109–129, DOI:10.5194/esd-15-109-2024.

Voosen, P., 2024: **Massive solar farms could provoke rainclouds in the desert.** Science 383, DOI:10.1126/science.zqw0g2p.

Physical Principle of Land-Surface Bio-Geoengineering



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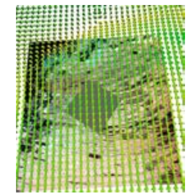
Large-scale upper level instability

initiation,
rmation

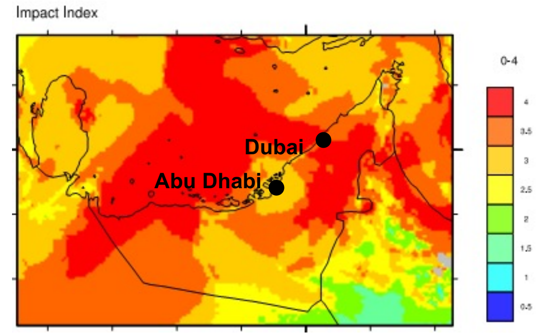
Artificial surface / PV



New Index for Prediction of Impacts

We understand and can predict:

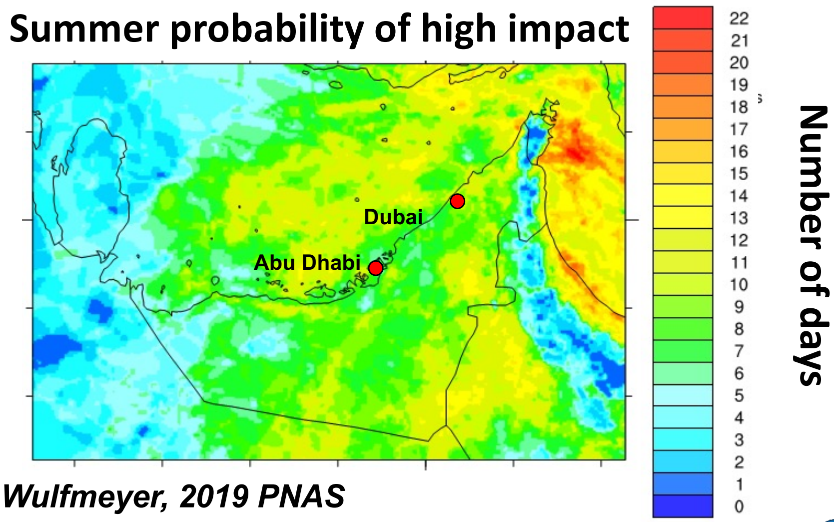
- Probability of rainfall impact
- Optimal locations
- Seasonal suitability



Impact Index based on:

- Stability
- Dynamics
- Moisture

Summer probability of high impact

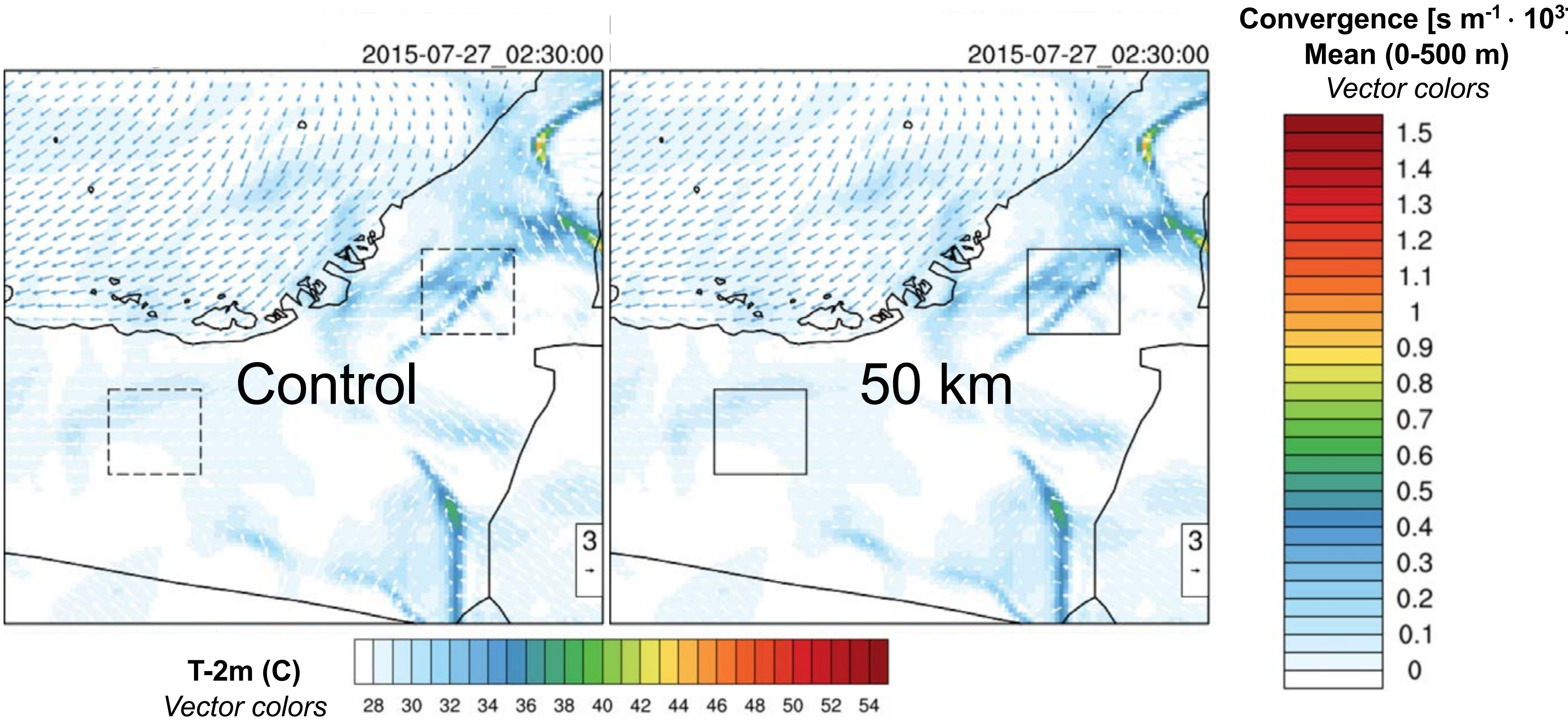


Key results:

- Clearest impact in summer under hot convective conditions
- Between 5-15 days (JJA) of high probability to induce rainfall

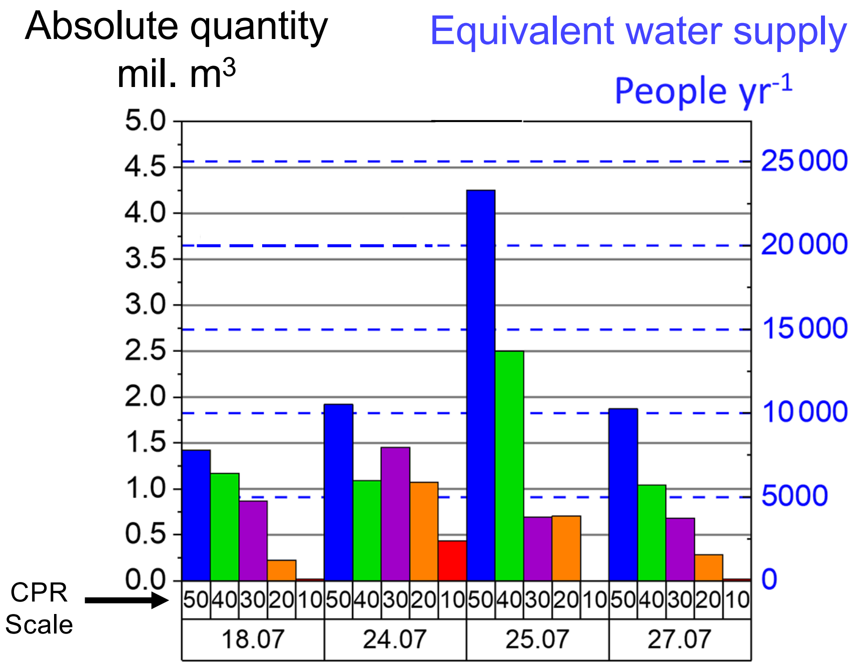
Branch & Wulfmeyer, 2019 PNAS

Impacts - low level convergence

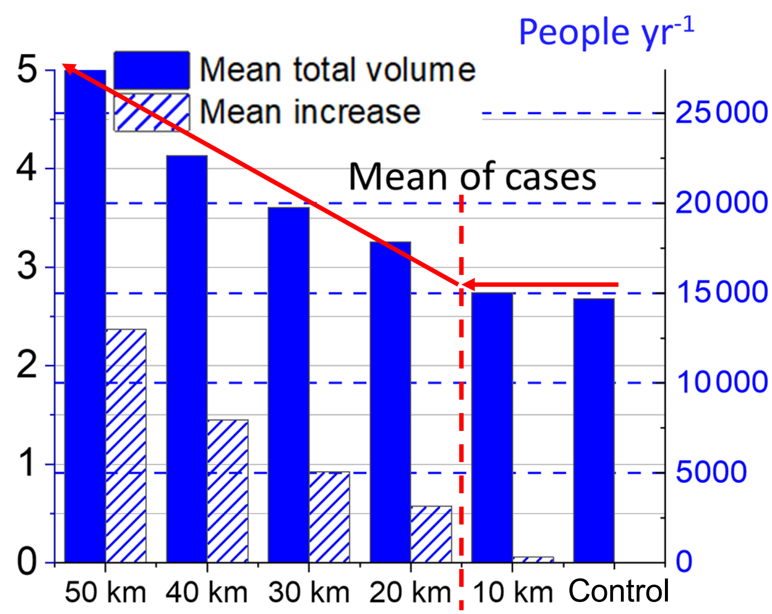


All scenarios – All case studies

Increase over Control



Mean of all cases



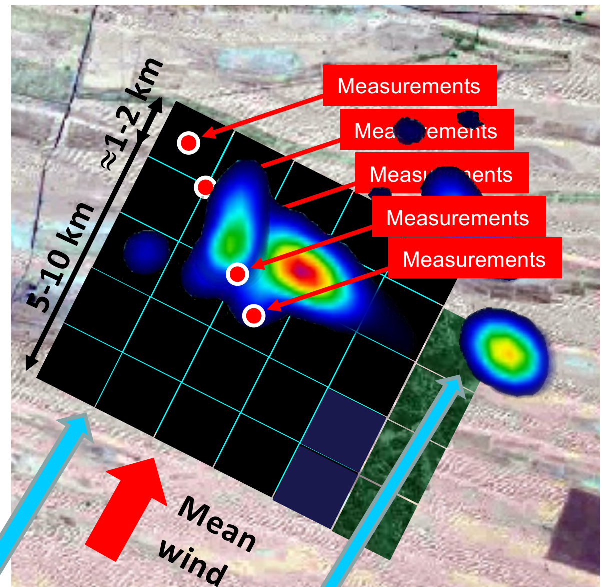
(Based on UAE water consumption 500 L day^{-1} capita^{-1})

Lower scale boundary for impacts?

CPR: design and construction

Branch et al., 2023 Earth System Dynamics

CPR system of dark thermal foil panels
- **Low albedo**
- **Robust**
- **Heat resistant**
- **Easy installation**
- **Easy removal**
- **Scalable size**



Timeframe for construction
1st year
2 years
3 years
4 years
5 Years

Measurements
- **Albedo**
- **Heating**
- **Turbulence**
- **Windflow**
- **Rainfall**

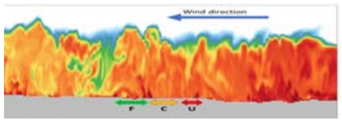
Rainwater flow:
- **Water collector system European Patent EP3909659**
- **+ Groundwater recharge**

Later additions / partial replacement
- **Low albedo PV solar**
- **Low albedo vegetation - Jojoba/Jatropha**

Conclusion and Vision

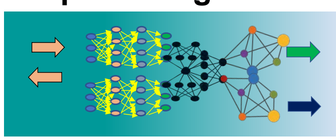
Highlights

Ultra-high resolution MME



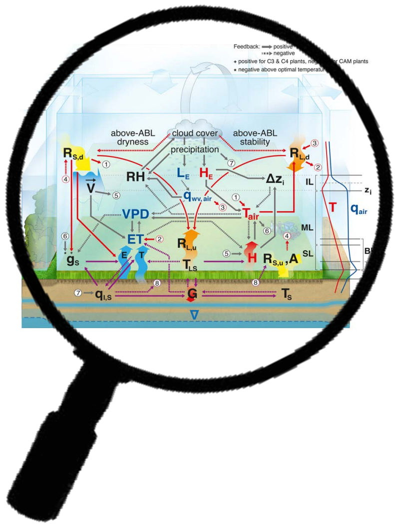
Unique sensor synergy

Deep learning

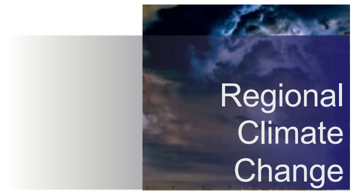


Interdisciplinary Teams

Advanced process understanding of land-atmosphere feedbacks



Implications



Outlook

Develop and implement parameterizations for heterogeneous terrain

Expand studies over forest (Tharandt, MOL-RAO)

Include coupling of carbon and water cycles