Exploring Terra Incognita in the Earth System:
The GEWEX Land-Atmosphere Feedback Observatory (GLAFO)

Volker Wulfmeyer[1], Arnoud Apituley[11], Franz Berger[10], Marcus Breil[1], Heye Bogena[9], Fred C. Bosfeld[11], Nathaniel Chaney[14], John Edwards[15], Michael Ek[2], Craig R. Ferguson[3], Kirsten L. Findell[4], Matthias Mauder[8], Mathias Rotach[13], David D. Turner[5], Peter van Oevelen[6], Nikki Vercauteren[12], Harry Vereecken[9], Anne Verhoef[7], Yunyang Zhang[16], et al.

[1]Institute of Physics and Meteorology, University of Hohenheim, Stuttgart, Germany

[2]Joint Numerical Testbed, NCAR/RAL, Boulder, CO, USA

[3]SUNY-University of Albany, Albany, NY, USA

[4]Geophysical Fluids Dynamics Laboratory, NOAA, Princeton University, Princeton, NJ, USA

[5]Global Systems Laboratory, NOAA, Boulder, CO, USA

[6]International GEWEX Project Office, George Mason University, Fairfax, VA, USA

[7]University of Reading, Reading, UK

[8]Technical University Dresden, Chair of Meteorology, Dresden, Germany

[9]Forschungszentrum Jülich GmbH, Jülich, Germany

[10]German Meteorological Service (DWD), Meteorologisches Observatorium Lindenberg, Germany

[11]Royal Netherlands Meteorological Institute (KNMI), The Netherlands

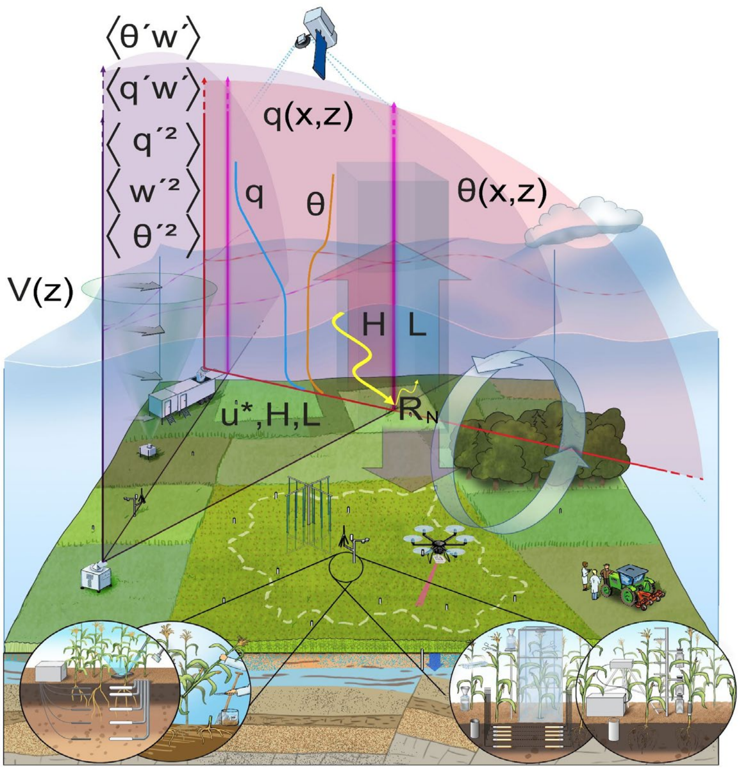
[12]University of Oslo, Section for Meteorology and Oceanography, Norway

[13]University of Innsbruck, Institute of Meteorology and Geophysics, Austria

[14]Duke University, Durham, USA

[15]UK Met Office, Exeter, UK

[16]Lawrence Livermore National Laboratory, Livermore, USA



Abstract

Land-atmosphere (L-A) feedbacks are the result of the interactions between processes related to the exchange of momentum, heat, and mass in the land system. This system consists of the compartments groundwater, the soil, the land cover such as vegetation, and the lower troposphere including their modifications due to human activities. These compartments encompass the critical zone (CZ) (see Richter et al. 2018) but go far beyond because the evolution of the entire atmospheric boundary layer (ABL) has to be included. A profound understanding of L-A feedbacks is fundamental not only for improving our understanding of the Earth system but also for the development and verification of the next generation of high-resolution earth system models.

Based on an advanced understanding of L-A feedback and its representation in models, effects of past, current, and projected land use and land cover changes (LULCC) as well as future biogeoengineering efforts as a mitigation pathway with respect to climate change can be studied with great detail and high confidence. Furthermore, over land, a significant improvement of the predictive skill of weather and seasonal forecast models and more accurate climate projections can be expected including the simulations of extreme events such as heatwaves, droughts, and heavy precipitation events (see, e.g., Dirmeyer et al. 2021).

Currently, the understanding of L-A feedback is severely limited by the lack of corresponding observations in all climate regions. These observations must cover all compartments of the land system, from bedrock to the lower atmosphere, and include simultaneous profiling of the soil, the land cover, and the atmosphere. Therefore, we propose a new type of observatory that will advance our current measurement capabilities by combining observations of the terrestrial and the atmospheric legs of L-A feedbacks (Dirmeyer et al. 2018). Particularly, the 3D dynamics and the thermodynamics of the atmosphere from the surface to the lower troposphere must be considered as **Terra Incognita in earth system science**. To the best of our knowledge, currently not a single observatory of this kind exists with the exception of the new Land-Atmosphere Feedback Observatory (LAFO) at the University of Hohenheim in Stuttgart, Germany (see https://lafo.uni-hohenheim.de/en, Späth et al. 2022a). LAFO will serve as a prototype of this kind of observatory that we call a **GEWEX Land Atmosphere Feedback Observatory (GLAFO)**. The overarching scientific goal of the **GLAFOs** is to **understand L-A feedbacks over the regimes of soil and snow conditions, vegetation properties, and ABL evolutions in the context of large-scale forcing.**

The development and the operation of the GLAFOs is very timely because a new synergy of in-situ as well as active and passive remote sensing systems covering all relevant compartments is now available and can be operated 24/7 at the envisioned GLAFOs (Wulfmeyer et al. 2018, 2020). Here, we propose the development of a global *network* of GLAFOs, and call for a fruitful collaboration of scientists, research centers, weather forecast centers and funding agencies that are interested in advancing our understanding of L-A feedback and the performance of the next generation of weather forecast, climate, and Earth system models.

1. Scientific Background

Land-atmosphere (L-A) feedback results from the process chain related to the exchange of momentum, heat, and mass between the different compartments of the land system. These compartments, which are separable subsystems with similar properties and processes, include the soil, the land cover, and the lower troposphere and account for the influence of human activities within each compartment. The complex interactions in the L-A system are depicted in Fig.1.

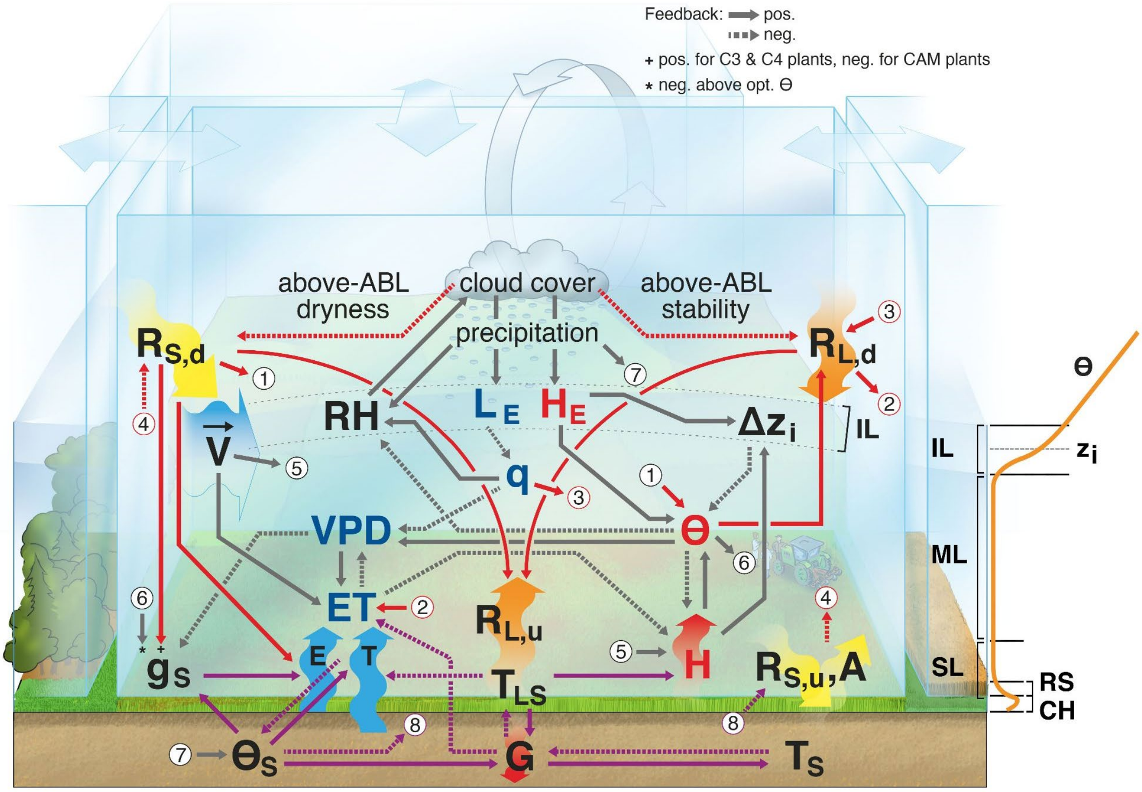


Fig.1 Feedback processes in the L-A system. Arrows indicate interactions between variables. For clarity, some arrows are disconnected, where the connections are indicated by numbers. $R_{i.j}$: Short- and longwave upwelling and downwelling radiations, RH: relative humidity, L_E and H_E: water-vapor and sensible heat entrainment fluxes, Δz_i: change of ABL depth, VPD: water-vapor pressure deficit, q: specific humidity, θ: potential temperature, g_S: canopy conductance, ET: evapotranspiration, T_{LS}: land surface temperature, H: surface heat flux, θ_S: soil moisture, G: ground heat flux, T_S: soil temperature. On the right-hand side, typical vertical sizes of the compartments and a θ profile during daytime are shown to indicate the measurement challenges. CH: Crop height, RS: roughness sublayer, SL: surface layer, ML: mixed layer, IL: interfacial layer (after Ek and Holtslag (2004), Helbig et al. (2021)).

A profound understanding of L-A feedback is fundamental for

- understanding of the Earth system,
- the predictive skill of weather and seasonal forecast models including extreme events,
- advancing regional and global climate model performance and projections,

- studying and quantifying the effects of historic, current, and projected land use and land cover changes (LUCC) on regional weather and climate (e.g., Seneviratne et al. 2018, Dirmeyer et al. 2012),
- evaluating future bio-geoengineering efforts as a mitigation pathway (e.g., Branch and Wulfmeyer 2019) with respect to climate change.

The study of L-A feedbacks necessitates highly interdisciplinary approaches given the process time and length scales involved across the bedrock to boundary-layer continuum covering but it not limited to soil physical processes as well as vegetation dynamics and atmospheric interactions. One way to better characterize observed and modeled L-A feedbacks is through the development of a common set of multivariate metrics that can be used across research disciplines (see, e.g., www.pauldirmeyer.com/coupling-metrics). These metrics can be derived from the measurements of profiles of the relevant variables across all compartments of the land system, extracted from model simulations or by the derivation of analyses and reanalyses from models and observations by means of data assimilation. However, to date, there are still fundamental knowledge gaps in the understanding and characterization of L-A feedback (Santanello et al. 2018).

Through an extensive analysis of the present status of the science of L-A feedback, we identified four opportunities for transforming and advancing L-A research:

1) Observations: Various L-A feedback studies have been performed based on observations, mainly using the global radiosounding network (Findell and Eltahir 2003a) or satellite data (Ferguson and Wood 2011). However, there is a severe lack of data sets suitable for advanced characterization and quantification of L-A feedback. These observations must include simultaneous profiles of critical variables in and across all compartments, and the measurements of transport processes and fluxes between all relevant interfaces. To the best of our knowledge, no observatory exists yet that meets these measurement needs. For instance, in view of mesoscale processes, radiosoundings do not provide the required temporal resolution to resolve diurnal cycles and the coverage to observe spatial heterogeneities. Satellite data do not provide the required vertical resolution in the ABL (Wulfmeyer et al. 2015). However, with recent advancements in soil, vegetation, and atmospheric measurements, the required state-of-the-art instrumentation is now available (**Helbig et al. 2021, Späth et al. 2022).

Therefore, the GLAFOs are designed so that the mean, the gradient, and the turbulent fluctuations (if applicable) of all relevant variables are resolved. The sensor synergy and design of their operations allows us to derive surface and entrainment fluxes, advection, as well as the evolution of key variables in all compartments of the critical zone (such as ground water levels, soil moisture content, and vegetation processes) in heterogeneous terrain. As these measurements will be operational and available 365 days of the year, unprecedented data sets will be provided for the study of L-A feedbacks from the diurnal cycle, to seasonal/annual to ideally climatological time scales.

2) Process understanding: The understanding of energy and matter cycles and the associated scales contributing to coupling strengths needs to be advanced. Process studies must consider the effects of land surface heterogeneity and the state of the atmospheric surface layer on surface fluxes. Also, strategies to close the surface energy balance based on a physically meaningful partitioning of fluxes at the land surface depending on land cover, vegetation properties and states as well as soil hydrology must be developed (Mauder et al. 2020). Furthermore, the interaction of processes at the land surface with the ABL including entrainment and encroachment processes must be investigated (e.g. Fritz et al., 2021). It is also important to study the effect of sub-mesoscale circulations and the organization of turbulence, e.g. the development of horizontal rolls, on surface fluxes and ABL states.

3) Models: In most feedback studies, model systems and reanalyses have been applied (e.g., Dirmeyer et al. 2021, Jach et al. 2020). However, across all forecast ranges, from short-range to seasonal weather forecasts to climate projections, predictions of the state of the Earth system suffer from limited representation of L-A feedback. It is necessary to incorporate the advanced representation of heterogeneous land surface properties and advanced understanding of key transport and exchange processes in model systems. These should be operated down to the turbulence-permitting scales so that their performance can be studied in relation to their grid increments (e.g., Bauer et al. 2020) and the chain of parameterizations can be tested and improved. These include parameterizations of vegetation properties affecting transpiration, land-surface exchange in heterogeneous terrain (e.g., by the improvement of Monin-Obukhov similarity theory (MOST) or alternative bulk Richardson number relationships), and of turbulence in the ABL. Furthermore, a better description of terrestrial hydrology needs to be implemented including lateral fluxes in sloped terrain depending on the properties of sites (Clark et al., 2015).

4) Feedback metrics: The derivation and investigation of metrics requires consideration of the three research areas above. These metrics have been developed and applied from regional to global scales covering diurnal to decadal temporal ranges (e.g. Findell and Eltair 2003a, b, Santanello et al. 2009, Tawfik et al. 2015). These metrics can be separated in process-, statistically, and correlation-based approaches. However, most of these metrics do not include critical processes such as entrainment fluxes (Ek and Holtslag 2004), atmospheric dynamics as well as vegetation dynamics and hydrological processes. Consequently, there is a need to develop new or expanded metrics including these effects with a new synergy of observations.

The GLAFO concept explores, merges, and combines research in all of these four areas in order to advance our observations and our understanding of L-A feedback.

2. Solution: The GEWEX Land-Atmosphere Feedback Observatory (GLAFO)

2.1 Principles of Design and Operations

Based on these considerations, we propose the development and operation of the GEWEX Land Atmosphere Feedback Observatories (GLAFOs). This must be an interdisciplinary effort bringing experts together from soil sciences, hydrology, biogeochemistry and plant physiology, as well as meteorology and remote sensing (see also Richter et al., 2018). An analysis of the status of current observatories and observational networks led mainly to four recommendations of the GLAFO design and operations:

1) **Dedicated long-term measurements (> 10 years) at observatories:** Statistically sound results with respect to the mean and the probability density function of critical variables must be achieved covering all compartments of the land system. The current data set of almost all observatories is not yet of sufficient quality to provide reliable data sets for studying L-A feedbacks, particularly considering the atmospheric leg.

2) **Synergetic observations of weather-critical processes in the land system:** Due to the coupling of L-A processes and the feedbacks between them, it is necessary to extend the observations to all compartments from bedrock to the lower troposphere, including the interfacial or inversion layer at the ABL top. Otherwise, the constraints provided by the observations will be inadequate with respect to the investigation of L-A feedbacks, current parameterizations and the development of advanced ones.

3) **Simultaneous profiling of atmospheric mean profiles, their gradients and turbulence:** In the atmosphere, it is not sufficient to measure only low-resolution profiles or integrated values of key variables. It is critical that the measurements reach a sufficient vertical resolution so that vertical (and possibly also horizontal) gradients of these variables are resolved. In addition, when going from the surface into the interfacial layer in the ABL, the observations must have turbulence-scale temporal and spatial resolutions in order to make the development of novel flux-gradient relationships possible as well as the study of higher-order moments such as skewness and kurtosis.

4) **Observing the subsurface and its role for land surface atmosphere interactions:** Earlier work of Kollet and Maxwell (2008) has shown that groundwater plays an important role not only in controlling land surface temperature but also hydrological and energy related fluxes such as evapotranspiration. Assessing this impact will require subsurface observations of groundwater levels and soil moisture profiles down to the groundwater. Embedding the observation sites within catchments will open the possibility to close the hydrological water balance.

5) **A standard and hierarchical observatory configuration suitable for a global network deployment strategy in all climate zones:** The GLAFO equipment should be standardized by dedicated comparisons and characterizations of instrumentation such as atmospheric temperature profiling. However, in order to evolve the equipment in different regions, a hierarchical design with different levels of complexity is necessary. This approach in elaborated in section 2.3.

2.2 New measurement capabilities for observing L-A feedbacks

Meanwhile, several new instruments have become available, allowing the vision behind the GLAFO initiative to be realized. With respect to the soil and the vegetation, new high-spatial resolution (< km scale) spaceborne observations are essential, which overcome the limitations of Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) products, such as the SAR instrument on Sentinel 1 (Gao et al. 2017, Lievens et al. 2017). These retrievals can be verified and extended to greater soil depth with new ground-based sensors such as Cosmic-ray neutron sensors (CRNS) that are capable of monitoring root zone soil moisture dynamics at the field scale (e.g., Montzka et al. 2017). The information from satellites can be combined with data from dense CRNS networks that allow wireless data transmission and automated data processing for near real-time provision of soil moisture information.

With respect to land cover, we expect that the new generation of high-spatial resolution, multispectral sensors, such as those installed on the Sentinel 2 satellite, will considerably advance our knowledge of soil properties, vegetation types and vegetation properties. This is fundamental information for the improvement of land models (LMs). However, these remote sensing observations do not provide direct information on land surface fluxes. Thus, the information obtained from these spaceborne imagers must be combined with profiles of variables in the surface layer and in the canopy and with model output.

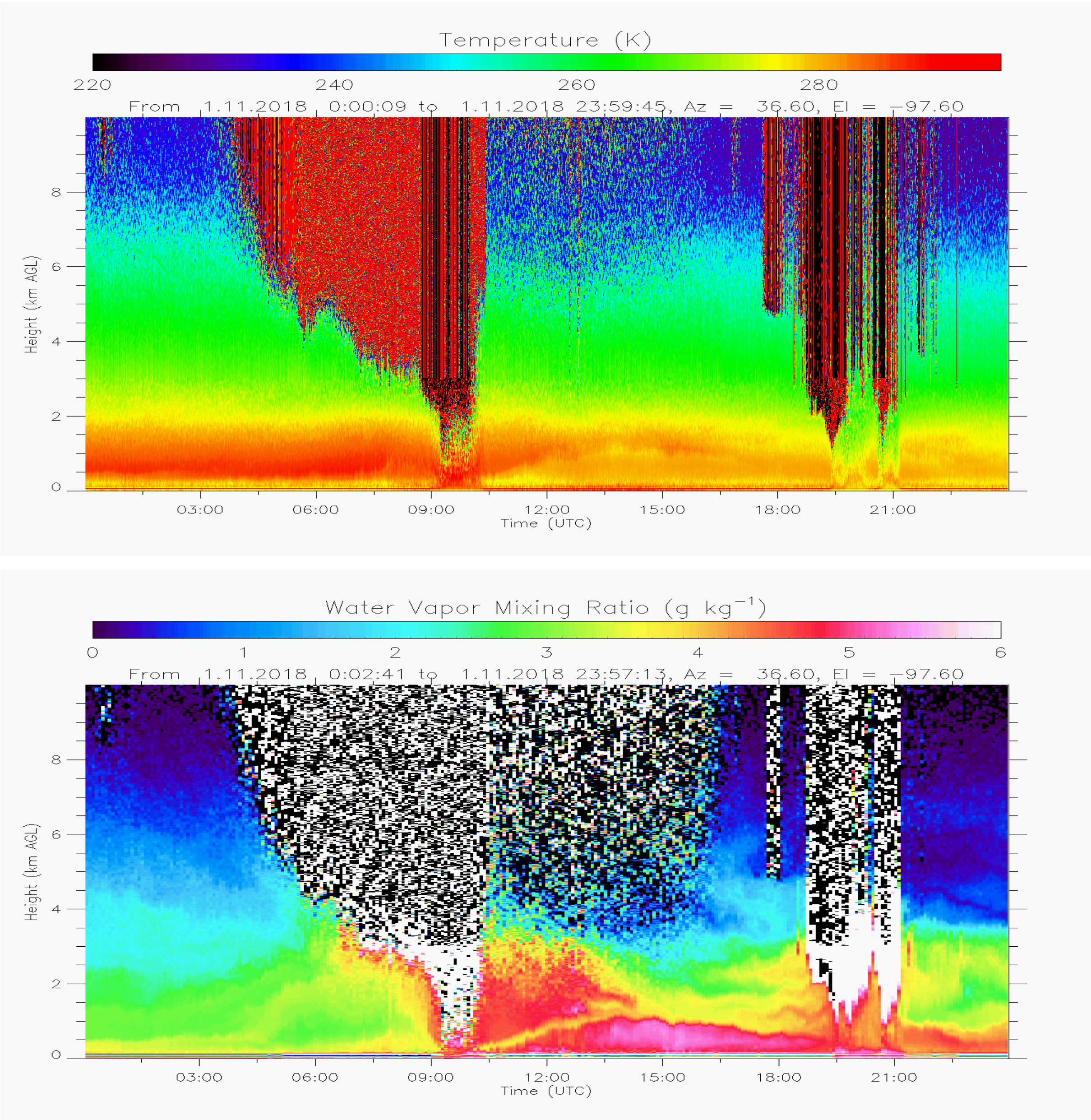


Fig. 2: Upper panel: Time-height cross-section of the temperature field measured with resolutions of 10 s and 100 m at the new LAFO at the University of Hohenheim. Bottom panel: Corresponding water-vapor mixing-ratio measurements. In many cases, measurements are also possible in clouds and rain.

Near-surface profiling capabilities are available via fiber-based distributed sensors (DTS), both above-ground and below-ground (Thomas et al. 2012, Bense et al. 2016), whereas isotope measurements can be used for separating evaporation from the soil and transpiration of the canopy (Dubbert and Werner 2019). Furthermore, for determining the assimilation of CO_2 and its dependence on air temperature, moisture and radiation profiles in the canopy in dependence of the CO_2 concentration must be known. This is essential for developing advanced photosynthesis models and implementing accurate vegetation dynamics in LMs.

For atmospheric measurements, it will be decades before spaceborne capabilities able to sense the lower troposphere will be advanced enough to obtain high-resolution measurements required for process-level L-A research (Teixeira et al. 2021). However, ground-based profiling instruments have been developed and applied for this purpose. For example, scanning Doppler lidar systems (DLs) have been available for more than a decade now and have been extensively used for wind and turbulence profiling in the ABL (e.g., Berg et al. 2017). For the understanding of exchange and transport processes, DL measurements must be complemented with high-resolution observations of temperature and water vapor, and ideally also CO_2. Only with this combination of measurements, it is possible to derive profiles of sensible and latent heat fluxes, which determine the evolution of moisture and temperature in the ABL. With respect to water vapor measurements, the water vapor differential absorption lidar (WVDIAL) (Muppa et al., 2016) and the Raman lidar (WVRL) (Wulfmeyer et al. 2010, Turner et al. 2014) techniques have demonstrated sufficient resolution for turbulence measurements.

With respect to temperature, a breakthrough has been achieved using the rotational Raman lidar technique so that it is now also possible to measure temperature profiles, inversions and turbulent quantities, even in the daytime convective boundary layer (CBL; Behrendt et al. 2015; Lange et al. 2019, Behrendt et al. 2020). This new capability in combined temperature and water-vapor profiling is demonstrated in Fig. 2.

During the Land-Atmosphere Feedback Experiment (LAFE, Wulfmeyer et al. 2018), which took place at the Southern Great Plains (SGP) site of the US ARM program in August 2017, for the first time, scanning WVDIAL, temperature Raman lidar and Doppler lidar systems were used to observe high vertical resolution (15-100 m) thermodynamic and wind profiles in the surface layer simultaneously. Due to their range resolution, 2D fields of moisture and temperature can be observed from the surface to the mixed layer. In-situ tower observations at 2 m and 10 m heights can be combined with these lidar scans (Späth et al. 2022b).

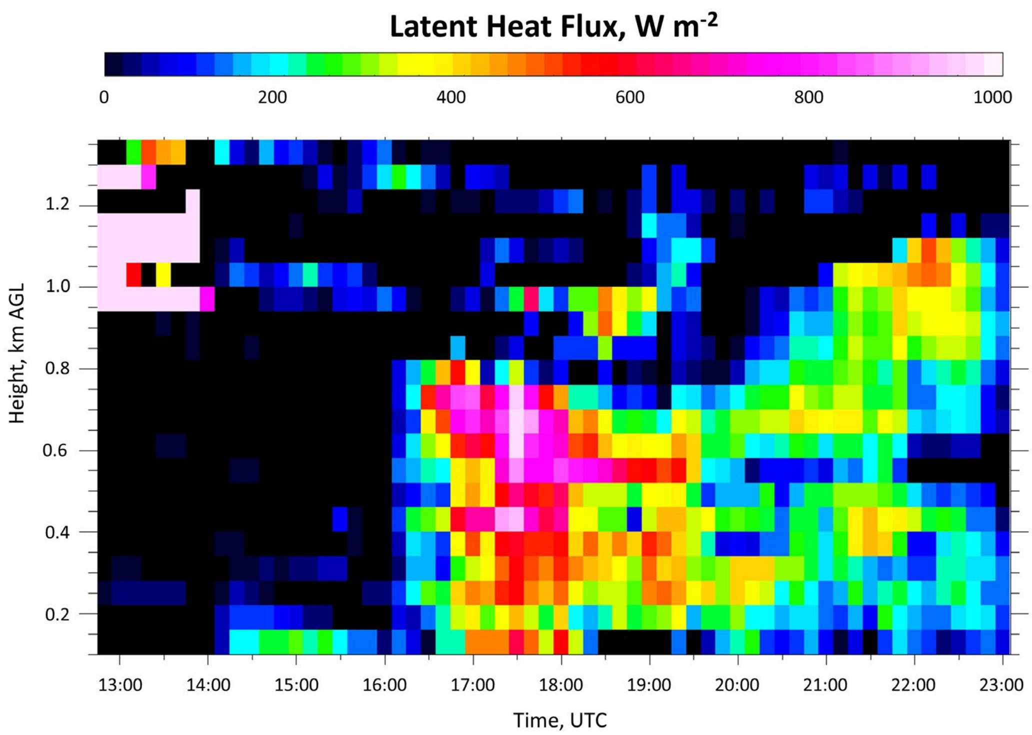


Fig. 3: First measurement of the daily cycle of the latent heat flux at the ARM SGP site on 23 August 2017 during LAFE. Note that sunrise occurred around 14 UTC.

In vertically staring mode, temperature and water vapor Raman lidar measurements have been combined with Doppler lidar for flux profiling so that the derivation of transport processes can be extended to the interfacial layer (Behrendt et al., 2019). Previously, this combination of instruments was merely used during case studies, but now these measurements are available routinely, e.g., at the ARM Southern Great Plains (SGP) site (Sisterson et al. 2016). An example of the daily cycle of the latent heat flux profile for the LAFE Intensive Operational Period 11 (IOP11) on 23 August 2017 is presented in Fig. 3.

The time-height cross section shows strong entrainment during the morning transition and a very reasonable evolution of the flux profiles during the evolution of the CBL with a latent heat flux of approximately 200-300 Wm^{-2} in the CBL. In the meantime, several years of fluxes have been processed in order to derive daily statistics of these flux profiles (Lareau 2020). These results will permit the direct evaluation of flux-gradient similarity relationships and the development of new theories (Wulfmeyer et al., 2016), which was recently demonstrated for variance-gradient similarity relationships (Turner et al. 2014, Osman et al. 2019).

Also, the availability of mean thermodynamic profiles with high vertical resolution will allow a comprehensive determination of L-A feedback metrics (Santanello et al. 2018). These examples illustrate the considerable progress made in recent years, and the potential of new instruments for the observation of L-A feedback.

An important term that must be measured is the advection of temperature and moisture over the GLAFO site. This is either possible by budget analyses where the advection term is the residual or by further distributed sites. The ARM SGP site has a set of 4 “boundary facilities” that are arranged in an approximate square around the SGP central facility, which is where the advanced lidars are located. At each boundary facility, there is a Doppler lidar and an infrared spectrometer; profiles of water vapor and temperature were retrieved from the latter (Turner and Blumberg 2019, Turner and Löhnert 2021). Wagner et al. (2022) used these wind and thermodynamic profile observations to derive the horizontal advection of water vapor and temperature over the domain. They also demonstrated that the spacing of the boundary facilities from the central facility, which is about 40 km to each, is close to ideal to minimize the uncertainties associated with sample error and random error. A minimum of three boundary facilities are needed, as the approach uses a line integral technique; however, additional boundary facilities would reduce the sampling error.

2.3 GLAFO Design

We now have the capability to build L-A observatories that reflect the scientific community’s requirements to advance our understanding utilizing recent developments in measurement techniques. For the first time, a suitable design was set up and operated successfully within the LAFE mentioned above (Wulfmeyer et al. 2018). Figure 4 depicts the envisioned design, which will be broken down with respect to different levels of complexity.

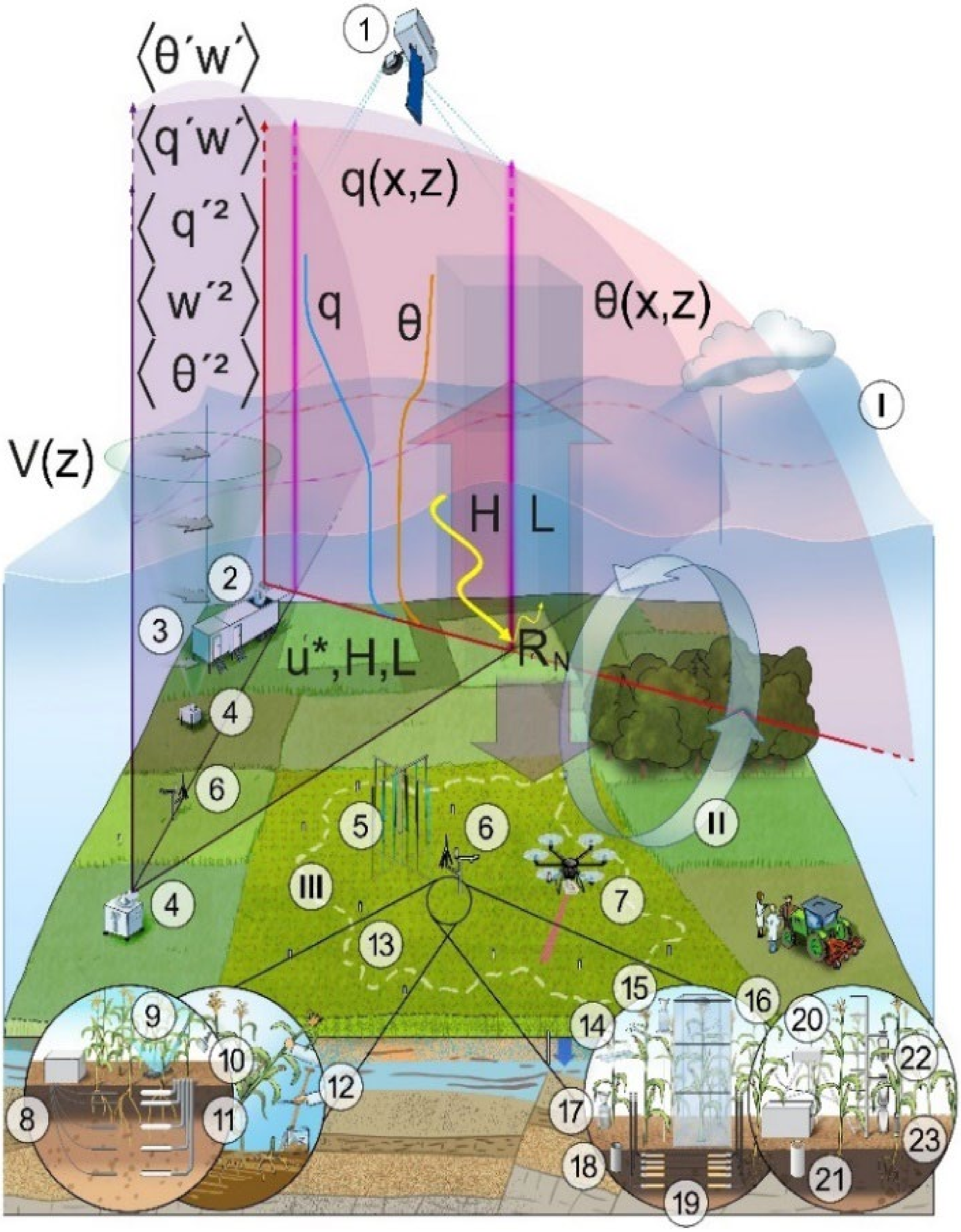


Fig. 4: LAFO yields unique continuous observations across the soil-plant-ABL continuum and offers unique sensor synergy through complementary systems: I: PBL top, II: mesoscale vortex, III: flux footprint. 1: Satellite remote sensing, 2, 3, 4: vertically staring and scanning Doppler, water vapor, and temperature lidar systems, 5: 3D FODS in combination with distributed wind and trace gas sensors, 6: energy balance and eddy covariance stations, 7: unmanned aerial vehicle (UAV), 8: time-domain reflectometers (TDRs), 9: leaf area index (LAI) measurement, 10: gas exchange system for photosynthesis and transpiration rate measurements, 11: tensiometers, 12: in-situ crop measurements such as root and shoot biomass as well as canopy height, 13: soil moisture, temperature, and matric potential network, 14: leaf cuvette, 15: open rainfall sampler, 16: gas exchange chamber, 17: throughfall sampler, 18: groundwater well, 19: in-situ soil water probes (14-19 all coupled to water isotope analyzer), 20: IR gas analyzer, 21: mini lysimeter, 22: canopy temperature, water vapor, and CO_2 profiles, 23: sap flow sensors.

The GLAFO measurements should contain:

- **Soil hydrological and thermal measurements:** Soil moisture, matric potential and temperature (ideally also below-canopy soil surface temperatures) profiles complemented with hydrological components such as ground water level; surface and sub-surface runoff by the definition of a catchment, if appropriate; soil evaporation from micro-lysimeters or equivalent and precipitation measurements. Hydraulic and thermal conductivities will also need to be determined (see, e.g., Tian et al. 2018), as well as underlying soil properties such as texture and dry bulk density. We will consider the employment of soil heat flux plates, although the profile measurements will allow for the determination of soil heat flux using the calorimetric method.
- **Vegetation:** Vegetation type, dynamics, and temperature (leaves, as well as trunk for forest); leaf area index; biomass; canopy height; canopy properties (including "response curves" to determine key canopy exchange parameters; vulnerability curves, etc.); rooting depth and distribution; within-canopy radiation, moisture, CO_2, and temperature profiles; sap flow and isotope measurements to separate respiration, interception, and transpiration from overall evapotranspiration measured with eddy covariance (EC); net ecosystem exchange; estimate of plant water stress.
- **Surface layer:** Energy balance using radiation and eddy covariance measurements; isotope measurement of water vapor; fiber optic-based temperature profiles; 10 m tower with measurements at 2 m and 10 m; scanning temperature, water vapor, Doppler and CO_2 lidar.
- **PBL mixed and interfacial layers:** Six-beam staring Doppler lidar for the profiling of turbulent kinetic energy (TKE), momentum flux, TKE dissipation rate and horizontal wind profiles; vertically staring Doppler lidar for vertical wind measurements; vertically staring water vapor, temperature and CO_2 lidars; Fourier-transform infrared spectrometers (such as the atmospheric emitted radiance interferometer, AERI; Knuteson et al., 2004) for measurements of temperature and water vapor profiles, cloud properties (e.g., liquid water path and effective radius) (Turner and Blumberg, 2019), and also for radiative heating profiles; microwave radiometer; scanning cloud and precipitation radar.

It is envisaged that the setup of this instrumentation is performed at different levels of complexity, e.g., setting up the vertically staring instruments first, followed by the scanning systems, etc. A corresponding matrix is presented in Table 1. Currently, the following steps for the establishment of a GLAFO are proposed:

Level 1a: Soil hydrological and thermal regime and profiles; overall land surface temperatures (LST, e.g., from IR radiometer); surface albedo; canopy profiling, if appropriate and a vertical structure can be expected; surface energy balance station with soil heat flux measurements; thermodynamic profiles up to the lower troposphere with resolutions of a few 100 m vertically and approx. 15 min temporally with accuracies of 0.5 K and 20% in mixing ratio including the determination of ABL depth z_i.

$\rightarrow$ This configuration will already allow for important insights in ABL properties, such as z_i, on land surface properties and fluxes. It would allow several L-A coupling metrics (e.g., CTP-HI_{low} or mixing diagram) to be derived directly.

Level 1b: Level 1a equipment plus scanning Doppler lidar wind measurements.

→ Studies of L-A feedbacks can be extended to analyze their dependence on wind direction and wind shears, turbulent kinetic energy (TKE), and momentum flux.

Level 2 (L2): L1 equipment plus: vertical wind profiles, temperature and water vapor profiles with turbulence resolution

→ This level will permit the determination of key turbulence profiles in the CBL such as vertical wind, moisture and temperature variances and skewnesses, TKE dissipation well as sensible and latent heat fluxes in the CBL. By means of these new measurement capabilities, flux-gradient relationships and, thus, the study of turbulence parameterizations in the CBL become possible. Also, more sophisticated L-A feedback metrics can be studied such as the relative humidity tendency (RHT) (Ek and Holtslag 2004).

Level 3 (L3): L2 equipment plus vegetation state and variables, such as canopy temperature, with-in canopy moisture and radiation, atmospheric surface layer profiles.

→ The measurements of flux-gradient relationships and parameterizations can be enhanced into the ABL surface layer in heterogeneous terrain. Effects of microscale circulations on surface fluxes can be studied.

Level 4 (L4): L3 equipment plus a triangle of wind and thermodynamic profilers will be added around the central GLAFO site

→ The direct and complete measurement of the advection of atmospheric variables for the closure of heat and water vapor budgets becomes possible.

Table 1: GLAFO hierarchical design matrix. This table also includes a symbolic cost estimate, one $ corresponds to approx. $300k.

Level, costs	Soil	Land cover	Atmosphere		Metrics and Process Studies
	State, variables	**State, variables**	**Variables**	**Instrument**	
L1a, $	Soil texture and profiles of T, Θ, Ψ	Type and state, albedo, LST, canopy profiles if appropriate, surface energy balance, snow	z_i, $q(z)$, $T(z)$, $\theta(z)$, $RH(z)$, aerosol particles (α_{par}, β_{par}), clouds	TD profiler (+ backscatter lidar, if the TD profiler is passive)	Mixing diagram, CTP-Hi_{low}, HCF, TCI, PBL process studies
L1b, $$			Plus $V(z)$, e, momentum flux	L1a plus scanning DL	Expansion of TCI, refined metrics including wind
L2, $$$	Plus ground-water level		Plus ε, $w'(z)$, $\langle a'^k \rangle$, $\langle w'q' \rangle$, $\langle w'T' \rangle$, $\langle a'^i b'^j \rangle$	L1 + vertical DL, WVTRL and/or WVDIAL	Plus RHT, WV and T budget closures
L3, $$$$	Plus run-off if appropriate		Plus atmospheric SL profiling	L2 + scanning DL, RL, and/or DIAL	Plus SL process studies
L4, $$$$$	Same as L3 + a triangle of $V(z)$, $T(z)$ and $q(z)$ profiles			L3 + scanning DL and vertical TD profiler	Plus advection, full budget analyses

2.4 Links to current observatories and their potential enhancement to GLAFOs

To date, observatories dedicated to the observation of L-A feedback are lacking. However, the equipment of several current observatories is already very close to the requirements of GLAFOs of levels 1 or 2. The following observatories are currently considered to become GLAFOs:

- University of Hohenheim LAFO site in Stuttgart, Germany
- SGP site of U.S. Department of Energy's ARM program

- The upcoming new ARM site in south-eastern US
- Four new “fire weather” sites being established in the western US by NOAA
- German Meteorological Service (DWD), Meteorological Observatory Lindenberg - Richard-Aßmann-Observatory (MOL-RAO) in Germany
- The Environmental Research Station Schneefernerhaus (UFS) at the Zugspitze mountain in Germany
- MeteoSwiss Observatory in Payerne, Switzerland
- Cabauw Ruisdael site in the The Netherlands
- Chilbolton observatory in UK
- IPSL Sirta site close to Paris, France
- A third-pole measurement site on the Tibetan plateau
- The Huancayo Observatory in Peru
- A potential site in New Zealand
- A site in Africa, e.g., in Nigeria
- A site in the Mediterranean

without claim of completeness as this is work in progress. Further sites in Asia as well as in polar regions should ideally also be established.

Exploitation and enhancement of these observations will allow for the classification of the observational data sets according to the atmospheric forcing and background conditions (radiation budget, geostrophic wind, stability, advection) with reasonable statistical coverage.

Table 2: Current observatories with high potential to become a GLAFO site in comparison with their current level of equipment. This table will be continuously extended. Green: Agreed to become a GLAFO, red: suitable sites, blue: more infos required.

Level	ARM SGP site	ARM SE Site	UHOH LAFO	DWD MOL-RAO	IPSL Sirta	Meteo Swiss Payerne	Cabauw/ CESAR	Chilbolton, UK	TERENO Fendt	UFS
Loc.	N 36.61 W 97.49	TBD	N 48.71 E 9.19	N 52.21 E 14.12	N 48.71 E 2.2	N 46.81 E 6.94	N 51.97 E 4.93	N 51.15 W 1.44	N 47.83 E 11.06	N 47.42 E 10.98 2656m
L1 a, b	**X**	**X**	**X**	**X**	**X (?)**	**X**	**X**	**X**	**X**	**X**
L2	**X**	**TBD**	**X**	**part.**	**TBD**	**X**	**TBD**	**TBD**	**in prep.**	**in prep.**
L3			**X**							**possible**
L4	**triangle available**									
Web	www.arm.gov/capabilities/observatories/sgp		https://lafo.uni-hohenheim.de/en/1670	https://www.dwd.de/EN/research/observing_atmosphere/lindenberg_column/lindenberg_column_node.html	https://sirta.ipsl.fr		https://ruisdael-observatory.nl/cesar	https://www.chilbolton.stfc.ac.uk	https://www.tereno.net/joomla/index.php/observatories/pre-alpine-observatory	https://schneefernerhaus.de

2.4.1. Cabauw Ruisdael Observatory

**Short overview of sensor synergy

**Duration of measurements

**Key applications and references

**Data archiving and access

2.4.2. DWD MOL-RAO

**Short overview of sensor synergy

**Duration of measurements

**Key applications and references

**Data archiving and access

2.5 Links to current networks and their potential enhancement to GLAFOs

One key motivation of the GLAFOs is the fact that many initiatives have emerged focusing on enhanced understanding and observations of the PBL and the L-A system, such as the U.S. Decadal Survey for Earth Observing Missions, the National Aeronautics and Space Administration (NASA) PBL Incubator Team and working groups of the Atmospheric Radiation Measurement (ARM) program. The following networks and upcoming efforts have been identified as relevant for the GLAFO initiative. These include the NOAA boundary layer initiative. This project has many overlapping goals, but it focuses more on hydrological aspects with respect to L-A feedback. Furthermore, there are several biogeoscience and environmental research networks with the potential and intention to enhance their measurement capabilities to a GLAFO such as:

- The AmeriFlux network where already a strong initiative towards observations of L-A feedback exists
- the US and the Azores ARM sites
- the international Long-Term Ecological Research Network programs (ILTERs)
- the Critical Zone Exploration Network and Critical Zone Observatory programs (CZEN and CZOs)
- the earth and ecological observatory networks (EONs)
- the National Ecological Observatory Network (NEON)
- FLUXNET
- the TERrestrial ENviromental Observatories Network (TERENO) in Germany with potential sites in Fendt close to Garmisch-Partenkirchen and Jülich
- the European ICOS network

again, without any claim of completeness. Table 3 summarizes the current state of evaluation of networks with respect to their equipment towards the establishment of GLAFOs.

Table 3: Current networks with high potential to become a GLAFO site in comparison with their current level of equipment.

Level	Ameriflux	NASA HTB	Critical zone, NEON	ICOS	TERENO	Tibetan plateau
Location	USA	USA	USA, Europe	Europe		China
Start	1996	2021	2007		~2010	
L1a	**plus thermodynamic profiler**	**TBD**	**plus thermodynamic profiler**	**plus thermodynamic profiler**	**X**	**TBD**
L1b	**adding a DL**		**adding a DL**	**adding a DL**	**X**	
L2					**Coming soon**	
L3						
L4						
Web	https://ameriflux.lbl.gov	TBD	https://czo-archive.criticalzone.org/national	https://www.icos-cp.eu	http://www.teamx-programme.org	

A high level of joint interest exists with the AmeriFlux community who summarized their research activities by the White Paper "Understanding land-atmosphere interactions through tower-based flux and continuous atmospheric boundary layer measurements". This collaboration is currently under discussion.

Cooperation is also foreseen with the TERENO network consisting of four terrestrial observatories that represent typical landscapes in Germany and Central Europe which are considered to be highly vulnerable to the effects of global and climate change. TERENO combines observations with comprehensive large-scale experiments, integrated modeling and remote sensing as well as novel measurement technologies to increase our understanding of the functioning of terrestrial systems and the complex interactions and feedback mechanisms between their different compartments.

2.6 Links to current and upcoming field campaigns as GLAFO demonstrators

We will also benefit from experiences and data analyses from previous field campaigns such as LAFE (Wulfmeyer et al. 2018) and CHEESEHEAD (Butterworth et al. 2021) with respect to the set up and operation of sensor synergies that can be considered as GLAFO demonstrators. Another GLAFO demonstration will be realized during LIAISE in a semi-arid region in Spain during the summer of 2021. Also, field campaigns will be considered where the new NCAR LOTOS equipment will be operated. In the future, the WWRP RDP TeamX field campaign will be another GLAFO demonstrator for measurements of L-A feedback in the challenging environment of high-mountain regions. This idea is now accepted in the TeamX community and establishes an exciting collaboration between WCRP and WWRP. These prospects are summarized in Table 4.

Table 4: Current and upcoming field efforts with high potential to become linked to GLAFO measurements and scientific applications.

Level	LIAISE	CHEESEHEAD	LAFO	DWD MOL	TeamX
Location	N 41,63 E 0,89	N 48,71 E 9,19	N 48,71 E 9,19	N 52,21 E 14,12	N 47,27 E 11,4
Time Period	Spring-summer 2021	Summer 2019	Fall 2021	Summer 2021	Spring 2024 – Spring 2025
L1a	**X**	**X**	**X**	**X**	**TBD**
L1b	**X**	**X**	**X**	**X**	
L2	**X**	**X**	**X**	**X**	
L3	**X (GLAFO demonstrator)**		**X**		
L4					
Web	https://www.hymex.org/LIAISE/campaign.html	https://flux.aos.wisc.edu/projects/2018/6/19/cheesehead19	https://lafo.uni-hohenheim.de/en/1670	https://www.dwd.de/EN/research/observing_atmosphere/lindenberg_column/lindenberg_column_node.html	http://www.teamx-programme.org

3. Overarching Scientific Goals and Objectives of GLAFO

3.1 Overarching Scientific Goals

Based on the design and operation modes of the GLAFO, the following overarching goals have been derived:

1. **Understand L-A feedbacks over the regimes of all compartments in the context of large-scale forcing and characterize L-A coupling strengths**
2. **Study transport and exchange processes between the compartments including surface and entrainment fluxes as well as the EBC in complex terrain**
3. **Advanced parameterizations of soil and vegetation properties, surface fluxes, and turbulence**
4. **Quantify the effects of land use and land cover change (LUCC) on regional weather and climate**
5. **Provide the basic knowledge and methodologies for evaluating bio-geoengineering efforts**
6. **Contribute to advanced simulations and predictions of extreme events**
7. **Operational assimilation of GLAFO data**
8. **Climate monitoring**

3.2 Research Objectives

These goals will be reached by addressing the following research objectives:

- **Understand and characterize L-A feedbacks with advanced observations and diagnostic metrics**
- **Identify the role of vegetation properties and dynamics with respect to L-A feedbacks**
- **Quantify ET and its separation in E and T**

- **Regional water and energy budget analyses**
- **Assess the processes and scales at which L-A feedbacks are sensitive to terrestrial hydrology as well as human land and water management**
- **Investigate scale interactions and land heterogeneity from turbulent to micro- to mesoscale processes on the strength of L-A feedbacks**
- **Verification of current operational and future advanced weather, climate, and Earth system models down to the turbulent scales**
- **Data assimilation impact studies towards operational assimilation of GLAFO data**

3.3 Expected Scientific Impacts

The following scientific impacts of GLAFOs are envisaged:

- **Provision of synergetic data products for the understanding of L-A feedbacks**
- **More detailed insight in and improvement of Earth system models down to the scales of LES**
- **L-A data assimilation, regional-scale reanalyses, and weather prediction leading to improved process understanding and forecasts including extreme events**
- **Calibration of passive remote sensors from ground and satellites, investigation of inter-sensor consistency with inter-site intercomparisons**
- **Incubator for interdisciplinary research, testbed for sensor development/collocation across a range of climates**
- **Training of future users of these data (e.g., in weather services, scientists and students)**

3.4 Envisioned Data Sets Provided by the GLAFOs

A GLAFO site needs to deliver data sets that quantify the local and regional L-A feedbacks. In fact, the GLAFO levels are chosen so that on each tier a variety of suitable metrics can be derived. Table 5 gives an overview of these metrics.

Table 5: Metrics that can be delivered at each GLAFO level.

Level	Metrics and Processes	Key Data	Postprocessing	Comments
1a	**TCI**	Soil moisture and surface fluxes	Quality control, soil moisture heterogeneity, footprint analyses	Requires at least seasonal data sets
1a	**Mixing diagram**	Surface fluxes, q and T profiles, z_i	z_i algorithm, close gaps of profiles to the surface	Profiles more accurate than surface data, advection remains as residual
	CTP-HI$_{low}$	q and T profiles	Derive CTP and HI$_{low}$	Choice of pressure range for CTP, choice of pressure levels for HI$_{low}$
1a	**HCF**	q and T profiles	Derive BCL and Θ_{BM}	High accuracy and vertical resolution required
1a	**Two-lagged metrics**	Soil, vegetation and atmospheric variables	Critical variables, such as z_i, their standard deviations, and slopes	Plus advection, full budget analyses
2	**RHT**	Surface and entrainment fluxes, WV and T profiles	Derive RH and d/dt RH, entrainment fluxes, and WV and T gradients	Requires high vertical and turbulence resolutions of the WV and T profiles
			Process studies	
	Entrainment	q‘, T‘, w‘	<w‘T‘>, <w‘q‘>, TKE	Near-operational with DL and WVTRL combi
	Turbulence param.	q‘, T‘, w‘, u‘, v‘	<w‘T‘>, <w‘q‘>, TKE, <u‘w‘>, <v‘w‘>, <q‘^{2}>, <T‘^{2}>, etc.	Requires special GLAFO lidar combi (L2), all tools are routinely available

The huge number of variables and derived products from a GLAFO site that can be provided on the process level are depicted in Table 6. Obviously, GLAFO provides data sets that are dedicated to new process studies in the L-A system and that are suitable to test a variety of parameterizations in heterogeneous terrain such as surface fluxes, ABL turbulence, and aerosol-cloud-precipitation microphysics. Furthermore, the GLAFO data set will be unique for model verification.

Instrument	Temperature†	Humidity†	Wind	Fluxes, dissipation	Aerosols†	Clouds
SRLID	$T(z)$, dT/dz	$m(z)$, dm/dz, $m'(z)$, $\langle m'^2\rangle$, $\langle m'^3\rangle$			$\beta_{Par}(z)$, $\alpha_{Par}(z)$	Base, partly τ_C
UDIAL, vertical		$\rho(z)$, $d\rho/dz$, $\rho'(z)$, $\langle\rho'^2\rangle$, $\langle\rho'^3\rangle$, $\langle\rho'^4\rangle$			$\beta_{Par}(z)$	Base, partly τ_C
UDIAL, RHI		2D ρ, $d\rho/dz$ above canopy			2D $\beta_{Par}(z)$ field	2D cloud field
NDIAL		$\rho(z)$, $d\rho/dz$			$\beta_{Par}(z)$	Base
URLID, vertical	$T(z)$, dT/dz, $T'(z)$, $\langle T'^2\rangle$, $\langle T'^3\rangle$	$m(z)$, dm/dz, $m'(z)$, $\langle m'^2\rangle$			$\beta_{Par}(z)$, $\alpha_{Par}(z)$	Base, partly τ_C
URLID, RHI	2D T, dT/dz above canopy	2D m, dm/dz above canopy			2D $\beta_{Par}(z)$, $\alpha_{Par}(z)$ field	2D cloud field
SDLID, vertical			$w(z)$, $w'(z)$, $\langle w'^2\rangle$, $\langle w'^3\rangle$, ε		$\beta_{Par}(z)$	Base, partly τ_C
UDLID, six-direction mode			$V(z)$, dV/dz	TKE, $\langle v'w'\rangle$, $\langle u'w'\rangle$		
NOAA DLID, RHI			2D LOS wind field		2D $\beta_{Par}(z)$ field	2D cloud field
SRLID-SDLID, vertical				$\langle w'm'\rangle$, $d\langle w'm'\rangle/dz$, $\langle w'm'^2\rangle$, $\varepsilon_m^\ddagger$, $\langle w'T'\rangle$, $d\langle w'T'\rangle/dz$, $\langle w'T'^2\rangle$, $\varepsilon_T^\ddagger$		
UDIAL-NOAA DLID, vertical				$\langle w'\rho'\rangle$, $d\langle w'\rho'\rangle/dz$, $\langle w'\rho'^2\rangle$, $\varepsilon_m^\ddagger$		
URLID-NOAA DLID, vertical				$\langle w'T'\rangle$, $d\langle w'T'\rangle/dz$, $\langle w'T'^2\rangle$, $\varepsilon_T^\ddagger$		
Two DLID RHIs			u, v, and u^* at crossing points			
UDIAL-URLID, RHI				λE, S, $L^\S$		
NOAA DLID-UDIAL-URLID, RHIs			w^*, q^*, $T^{*\S}$			
AERI	$T(z)$	$m(z)$				Liquid water path, effective radius
DJI S-1000 sUAS	$T(z)$, dT/dz, T'	$m(z)$, dm/dz		$\langle w'T'\rangle$		
Microdrone MD4–1000 sUAS	$T(z)$, dT/dz, T'	$m(z)$, dm/dz		$\langle w'T'\rangle$		
Piper Navajo	Surface skin temperature					

† Also used to measure the instantaneous CBL depth z_i using dT/dz, dm/dz, $d\rho/dz$, and $d\beta_{Par}/dz$.

‡ The measurement of molecular destruction rates of variances is possible by evaluation of the autocovariance functions.

§ In combination with u^* measurements and MOST.

Table 6: The huge number of products that can be derived from the GLAFO observations starting from Level 2 with respect to atmospheric measurements up to the lower troposphere. This set of variables can be derived due to the fact that all observations provide turbulence resolution and wind, temperature, and moisture are measured simultaneously (after Wulfmeyer et al. 2018).

4. Closing the Link to Model Physics and Simulations

- Strategies to study parameterizations
- Required data sets from GLAFO

- Model verification
- DA studies
- More

**Coordination with CLASP and GABLS

5. Conclusion and Outlook

In summary, during the 2019 GLASS Panel Meeting in Boulder, Colorado, USA, a new initiative was developed and designed for the establishment of the GEWEX Land-Atmosphere Feedback Observatories (GLAFOs). These sites will address the urgent need for advanced observations in the L-A system, for studying L-A processes in the era of climate change and for the development of advanced model systems to improve the prediction of extreme events in particular. We showed that this project is very timely due to the availability of a new set of novel instruments that can operate synergistically, which has the potential to improve and develop observationally-based parameterizations and to verify model output with unprecedented detail and accuracy. The new LAFO site in Germany may serve as the standard for this initiative but there are already many observatories, such as the ARM SGP site, that can be easily adapted, so it should be feasible to develop several GLAFOs in various climate zones within the foreseeable future.

There are several community efforts planned to foster the GLAFO vision at upcoming meetings and conferences. These include community meetings, contributions to conferences, and the development and realization of corresponding projects. We invite the GEWEX and Earth system science communities to join and strengthen this effort by their active participation.

References

Behrendt, A., V. Wulfmeyer, E. Hammann, S.K. Muppa and S. Pal, 2015: Profiles of second- to fourth-order moments of turbulent temperature fluctuations in the convective boundary layer: first measurements with rotational Raman lidar. Atmos. Chem. Phys. 15, 5485-5500, doi:10.5194/acp-15-5485-2015.

Behrendt, A., V. Wulfmeyer, C. Senff, C., S.K. Muppa, F. Späth, D. Lange, N. Kalthoff, and A. Wieser, 2020: Observation of sensible and latent heat flux profiles with lidar, Atmos. Meas. Tech. 13, 3221–3233, doi:10.5194/amt-13-3221-2020.

V.F. Bense, T. Read, A. Verhoef, 2016: Using distributed temperature sensing to monitor field scale dynamics of ground surface temperature and related substrate heat flux. Agri. Forest Meteorol. 220, 207-215, doi:10.1016/j.agrformet.2016.01.138.

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

Butterworth BJ, Desai AR, Metzger S, Townsend PA, Schwartz MD, Petty GW, Mauder M, Vogelmann H, Andresen CG, Augustine TJ, Bertram TH, Brown WOJ, Buban M, Cleary P, Durden DJ, Florian CR, Guzman ER, Iglinski TJ, Kruger EL, Lantz K, Lee TR, Meyers TP, Mineau JK, Olson ER, Oncley SP, Paleri S, Pertzborn RA, Pettersen C, Plummer DM, Riihimaki L, Sedlar J, Smith EN, Speidel J, Stoy PC, Sühring M, Thom JE, Turner DD, Vermeuel MP, Wagner TJ, Wang Z, Wanner L, White LD, Wilczak JM, Wright DB and Zheng T (2020) Connecting Land-Atmosphere Interactions to Surface Heterogeneity in CHEESEHEAD 2019. Bull Am Meteorol Soc E421–E445.

Clark, M. P., Y. Fan, D. M. Lawrence, J. C. Adam, D. Bolster, D. J. Gochis, R. P. Hooper, M. Kumar, L. R. Leung, D. S. Mackay, R. M. Maxwell, C. Shen, S. C. Swenson, and X. Zeng, 2015: Improving the representation of hydrologic processes in Earth System Models, Water Resour. Res., 51, 5929– 5956, doi:10.1002/2015WR017096.

Dirmeyer, P. A., Chen, L., Wu, J., Shin, C., Huang, B., Cash, B. A., Bosilovich, M. G., Mahanama, S., Koster, R. D., Santanello, J. A., Ek, M. B., Balsamo, G., Dutra, E., & Lawrence, D. M., 2018: Verification of Land–Atmosphere Coupling in Forecast Models, Reanalyses, and Land Surface Models Using Flux Site Observations. J. Hydrometeorol. 19(2), 375-392, doi: 10.1175/JHM-D-17-0152.1.

Dirmeyer, P. A., Balsamo, G., Blyth, E. M., Morrison, R., & Cooper, H. M., 2021. Land-atmosphere interactions exacerbated the drought and heatwave over northern Europe during summer 2018. AGU Advances, 2, e2020AV000283, doi:10.1029/2020AV000283.

Dubbert, M., and C. Werner, 2019: Water fluxes mediated by vegetation: emerging isotopic insights at the soil and atmosphere interfaces. New Phytol., 221: 1754-1763, doi:10.1111/nph.15547.

Ek, M., and A.A.M. Holtslag, 2004: Influence of Soil Moisture on Boundary Layer Cloud Development. J. Hydrometeorol., 5(1), doi:10.1175/1525-7541(2004)005<0086:IOSMOB>2.0.CO;2.

Findell, K. L., and E. A. B. Eltahir, 2003a: Atmospheric controls on soil moisture–boundary layer interactions: Part I: Framework development. J. Hydrometeor. 4, 552–569, doi.org/10.1175/1525-7541(2003)004<0552:ACOSML>2.0.CO;2.

Findell, K. L., and E. A. B. Eltahir, 2003b: Atmospheric controls on soil moisture–boundary layer interactions: Part II: Feedbacks within the continental United States. J. Hydrometeor. 4, 570–583, https://doi.org/10.1175/1525-7541(2003)004<0570:ACOSML>2.0.CO;2.

Fritz, A. M., Lapo, K., Freundorfer, A., Linhardt, T., & Thomas, C. K., 2021: Revealing the Morning Transition in the Mountain Boundary Layer Using Fiber-Optic Distributed Temperature Sensing. Geophysical Research Letters, 48(9), e2020GL092238, doi:10.1029/2020GL092238.

Gao, Q., M. Zribi, M.J. Escorihuela and N. Baghdadi, 2017: Synergetic Use of Sentinel-1 and Sentinel-2 Data for Soil Moisture Mapping at 100 m Resolution. Sensors 2017, 17, 1966.

Jach, L., K. Warrach-Sagi, K., J. Ingwersen, E. Kaas, and V. Wulfmeyer, 2020: Land cover impacts on land-atmosphere coupling strength in climate simulations with WRF over Europe. J. Geophys. Res. Atmospheres 125, e2019JD031989, DOI:10.1029/2019JD031989.

Knuteson, R.O., et al., 2004: Atmospheric Emitted Radiance Interferometer. Part II: Instrument performance. J. Atmos. Ocean. Technol. 21, 1777-1789.

Kollet, S. J., and R.M. Maxwell, 2008: Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model, Water Resour. Res. 44, W02402, DOI:10.1029/2007WR006004.

Lange, D., A. Behrendt, and V. Wulfmeyer, 2019: Compact Operational Tropospheric Water Vapor and Temperature Raman Lidar with Turbulence Resolution. Geophys. Res. Lett. 46, 14,844-14,853, doi:10.1029/2019GL085774.

Lareau, N. P., 2020: Subcloud and Cloud-Base Latent Heat Fluxes during Shallow Cumulus Convection, Journal of the Atmospheric Sciences, 77(3), 1081-1100, doi: 10.1175/JAS-D-19-0122.1.

Lievens, H., R.H. Reichle, Q. Liu, G.J.M. De Lannoy, R.S. Dunbar, S.B. Kim, N.N. Das, M. Cosh, J.P. Walker and W. Wagner, 2017: Joint Sentinel-1 and SMAP data assimilation to improve soil moisture estimates. Geophys. Res. Lett., 44, 6145– 6153, doi:10.1002/2017GL073904.

Mauder M, Genzel S, Fu J, Kiese R, Soltani M, Steinbrecher R, Kunstmann H, Zeeman M, Banerjee T, Roo F De, De Roo F, Kunstmann H and Zeeman M, 2018: Evaluation of energy balance closure adjustment methods by independent evapotranspiration estimates from lysimeters and hydrological simulations. Hydrol Process 32:39–50, doi: 10.1002/hyp.11397.

Montzka, C., H.R. Bogena, M. Zreda, A. Monerris, R. Morrison, S. Muddu and H. Vereecken, 2017: Validation of Spaceborne and Modelled Surface Soil Moisture Products with Cosmic-Ray Neutron Probes. Remote Sens. 2017, 9, 103.

Muñoz-Esparza, D., R.D. Sharman and J.K. Lundquist, 2018. Turbulence Dissipation Rate in the Atmospheric Boundary Layer: Observations and WRF Mesoscale Modeling during the XPIA Field Campaign. Mon. Weather Rev. 146, 351–371, DOI:10.1175/MWR-D-17-0186.1.

Muppa, S.K., A. Behrendt, F. Späth, V. Wulfmeyer, S. Metzendorf and A. Riede, 2016. Turbulent humidity fluctuations in the convective boundary layer: Case studies using water vapour differential absorption lidar measurements. Bound.-Layer Meteorol. 158, 43-66, DOI:10.1007/s10546-015-0078-9.

Osman, M.K., D.D. Turner, T. Heus and V. Wulfmeyer, 2019. Validating the Water Vapor Variance Similarity Relationship in the Interfacial Layer Using Observations and Large-eddy Simulations. J. Geophys. Res. Atmos. 124, 10662–10675, DOI:10.1029/2019JD030653.

Richter, D.D., et al., 2018. Ideas and perspectives: Strengthening the biogeosciences in environmental research networks. Biogeosciences 15, 4815–4832, DOI:10.5194/bg-15-4815-2018.

Santanello, J.A., P.A. Dirmeyer, C.R. Ferguson, K.L. Findell, A.B. Tawfik, A. Berg, M. Ek, P. Gentine, B.P. Guillod, C. van Heerwaarden, J. Roundy and V. Wulfmeyer, 2018. Land-Atmosphere Interactions: The LoCo Perspective. Bull. Am. Meteorol. Soc. 99, 1253-1272, DOI:10.1175/BAMS-D-17-0001.1.

Seneviratne, S., T. Corti, E. L. Davin, M. Hirschi, E. B. Jaeger, I. Lehner, B. Orlowsky, and A. J. Teuling, 2010: Investigating soil moisture–climate interactions in a changing climate: A review. Earth Sci. Rev. 99, 125–161, https://doi.org/10.1016/j.earscirev.2010.02.004.

Shin, H.H., and J. Dudhia, 2016. Evaluation of PBL Parameterizations in WRF at Subkilometer Grid Spacings: Turbulence Statistics in the Dry Convective Boundary Layer. Mon. Weather Rev. 144, 1161–1177, DOI:10.1175/MWR-D-15-0208.1.

Sisterson, D.L, R.A. Peppler, T.S. Cress, P.J. Lamb, and D.D. Turner, 2016: The ARM Southern Great Plains (SGP) site. The Atmospheric Radiation Measurement Program: The First 20 Years, Meteor. Mon., 57, Amer. Meteor. Soc. 6.1-6.14, doi:10.1175/AMSMONOGRAPHS-D-16-0004.1.

Teixeira, J., et al., 2021: Toward a global planetary boundary layer observing system. The NASA PBL Incubation Study Team Report.

Thomas, C.K., A.M. Kennedy, J.S. Selker et al., 2012. High-Resolution Fibre-Optic Temperature Sensing: A New Tool to Study the Two-Dimensional Structure of Atmospheric Surface-Layer Flow. Bound.-Lay. Meteorol. 142, 177–192 (2012) doi:10.1007/s10546-011-9672-7.

Tian, Z., D. Kool, T. Ren, R. Horton and J.L. Heitman, 2018. Determining in-situ unsaturated soil hydraulic conductivity at a fine depth scale with heat pulse and water potential sensors. J. Hydrol. 564, 802-810.

Turner, D.D., and W.G. Blumberg, 2019: Improvements to the AERIoe thermodynamic profile retrieval algorithm. IEEE J. Selected Topics Appl. Earth Obs. Remote Sens. 12, 1339-1354, doi:10.1109/JSTARS.2018.2874968.

Turner, D.D., V. Wulfmeyer, L.K. Berg and J.H. Schween, 2014. Water vapor turbulence profiles in stationary continental convective mixed layers. J. Geophys. Res. 119, 11,151-11,165, DOI:10.1002/2014JD022202.

Wulfmeyer, V., D.D. Turner, S. Pal and E. Wagner, 2010. Can water vapour Raman lidar resolve profiles of turbulent variables in the convective boundary layer? Bound.-Lay. Meteorol. 136, 253-284, DOI:10.1007/s10546-010-9494-z.

Wulfmeyer, V., S.K. Muppa, A. Behrendt, E. Hammann, F. Späth, Z. Sorbjan, D.D. Turner and R.M. Hardesty, 2016. Determination of convective boundary layer entrainment fluxes, dissipation rates, and the molecular destruction of variances: Theoretical description and a strategy for its confirmation with a novel lidar system synergy. J. Atmos. Sci. 73, 667-692, DOI:10.1175/JAS-D-14-0392.1.

Wulfmeyer, V., D.D. Turner, B. Baker, R. Banta, A. Behrendt, T. Bonin, W.A. Brewer, M. Buban, A. Choukulkar, E. Dumas, R.M. Hardesty, T. Heus, J. Ingwersen, D. Lange, T.R. Lee, S. Metzendorf, S.K. Muppa, T. Meyers, R. Newsom, M. Osman, S. Raasch, J. Santanello, C. Senff, F. Späth, T. Wagner and T. Weckwerth, 2018. A new research approach for observing and characterizing land-atmosphere feedback. Bull. Am. Meteorol. Soc. 99, 1639-1667, DOI:10.1175/BAMS-D-17-0009.1.