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

Volker Wulfmeyer[1], Michael Ek[2], Craig R. Ferguson[3], Kirsten Findell[4], David D. Turner[5], Peter van Oevelen[6], Anne Verhoef[7], et al.

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

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

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

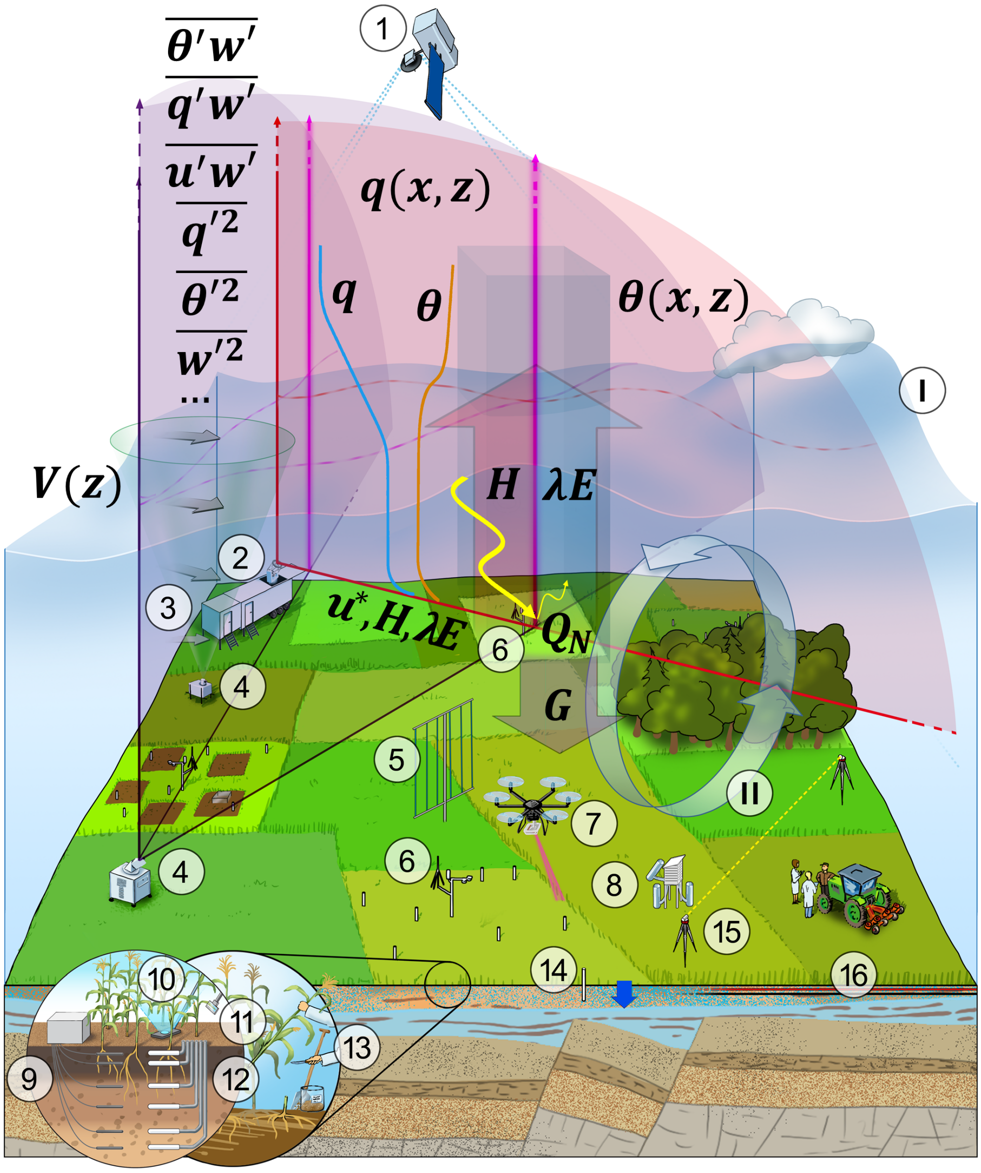
[4]Geophysical Fluids Dynamics Laboratory, NOAA, Princeton University, Princeton, USA

[5]GSD NOAA/ESRL, Boulder, USA

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

[7]University of Reading, Reading, UK

plus further coauthors



Abstract

Land-atmosphere (L-A) feedback is the result of the interaction between processes related to the exchange of momentum, heat, and mass in the land system. This system consists of the compartments soil, vegetation, and the lower troposphere including their modifications due to human activities. A profound understanding of L-A feedback 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 historic, current and projected land use and land cover changes (LUCC) as well as future bio-geoengineering 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 simulation of extreme events such as droughts and heavy precipitation events. The most important region affected by these events is also called the *critical zone*.

Currently, the understanding of L-A feedback is severly 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 the soil, the land cover, and the atmosphere simultaneously. Otherwise, we cannot expect a significant advance of our understanding of L-A feedback beyond the measurements that are already performed by various observatories and networks. With other words, we propose a new design or an enhancement of their current measurement capabilities by combining observations of the terrestrial and the atmospheric legs of L-A feedback together. 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**. What is to our knowledge, at the present time, not a single observatory of this kind exists yet combining the required measurements except the new Land-Atmosphere Feedback Observatory (LAFO) at the University of Hohenheim in Stuttgart, Germany (see https://lafo.uni-hohenheim.de/en). LAFO will serve as a prototype of this kind of observatory that we call the **GEWEX Land Atmosphere Feedback Observatory (GLAFO)**. The development and the operation of the GLAFOs is also very timely because the need of these

We proposed the development of a networks of GLAFOs in all climate zone and call for a corresponding collaboration of scientists, research centers, weather forecast centers and funding agencies that are interested to advance our understanding of L-A feedback and the performance of the next generation of weather forecast, climate, and earth system models.

GLAFOs will observe the relevant processes and variables with respect to mass, energy, water, and momentum transport with unprecedented spatial and temporal resolutions, from bedrock to the lower troposphere. The measurements will be realized through the synergistic combination of in-situ instruments as well as and passive and active remote sensing systems, partly with 3D scanning capability.

The observations are designed so that mean, the gradient, and the turbulent fluctuations (if applicable) of all relevant variables are resolved. Also, the sensor synergy and design of their operations permits 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, and vegetation processes) in heterogeneous terrain. As these measurements will be operational and available 24/7 at the sites, an unprecedented data sets will be provided for the study of L-A feedbacks from the diurnal cycle, via seasonal/annual to ideally climatological time scales.

Due to the high resolution and accuracy as well as the continuous operation of the instrumentation, the measurements will be used for 1) the characterization of L-A feedback by suitable metrics and the refinement of metrics in different climate zones, 2) Process studies with new data sets such as the derivation of sensible and latent flux profiles in the planetary boundary layer as well as observations of transpiration over heterogeneous landscapes, 3) the test and development of parameterizations of exchange processes between the different compartments, 3) the evaluation of remote sensing techniques, 4) the evaluation of weather, climate, and earth system models, and 5) the assimilation of the observations in research and operational data weather forecast models.

Consequently, the GLAFO concept complements the measurements of existing observatories, supports the development of the next generation of earth system models operating at the convection and the turbulence permitting scales as well as provides the basis for the understanding of the land system, climate change, and the evolution of extreme events in all climate zones.

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 include the soil, the land cover, and the lower troposphere including the influence of human activities. A profound understanding of L-A feedback is fundamental for

- the understanding of the earth system,
- optimizing the predictive skill of weather and seasonal forecast models,
- advancing regional and global climate models,
- studying and quantifying the effects of historic, current and projected land use and land cover changes (LUCC) on regional weather and climate (e.g., Dirmeyer et al. 2012, Seneviratne et al. 2018),
- evaluating future bio-geoengineering efforts as a mitigation pathway (e.g., Branch and Wulfmeyer 2019) with respect to climate change,
- advancing the prediction and the protection of humankind and the environment with respect to extreme events that are expected to become more likely as a result of climate change (IPCC 2019).

L-A feedback must be characterized through developing and applying suitable metrics (Santanello et al. 2018). 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 of 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.

By an extensive analysis of the present status of the science of L-A feedback, we identified the following research gaps in four areas:

1) Observations: Various L-A feedback studies have been performed based on observations, mainly using the global radiosounding network (Findell and Eltahir 2003) 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 the provide the required temporal resolution to resolve diurnal cyles and the coverage to observe spatial heterogeneities. Satellite data do not provide the required resolution in the atmospheric boundary layer (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.

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) as well as 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.

4) Feedback metrics: The derivation and investigation of metrics requires and encompasses 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 advanced metrics including these effects.

The GLAFO concept merges and combined research on all these areas in order to advanced 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. However, the current set of observations at most of the observatories is not yet of sufficient quality to provide reliable data sets for studying L-A feedback.
2) **Synergetic observations of weather-critical processes in the land system:** Due to the coupling of L-A processes and the feedback between them, it is necessary to extend

the observations to all compartments from bedrock to the lower troposphere, including the interfacial layer at the ABL top. Otherwise, the constraints provided by the observations will be inadequate with respect to the investigation of L-A feedback, 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 coarse profiles or integrated values of key variables in these compartments. It is critical that the measurements reach a 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 flux-gradient relationships possible as well as the study of higher-order moments such as skewness and kurtosis.

4) **A standard and hierarchic observatory configuration suitable for a global network deployment strategy in all climate zones:** The GLAFO equipment should be standardized in order to permit reproducible comparisons of the measurements. However, in order to evolve the equipment in different regions, a hierarchic design with different levels of complexity is necessary.

2.2 New measurement capabilities for observing L-A feedback

Meanwhile, several new instruments have become available, allowing the vision behind the GLAFO initiative to be realized. With respect to the soil, new spaceborne observations of soil moisture have become available, such as the Soil Moisture Active Passive (SMAP) products. In the future, these will be complemented by advanced products based on Sentinel 1 observations with the potential to reach a horizontal resolution of the order of 10 m (Gao et al., 2017; Lievens et al., 2017). These retrievals can be verified and extended with new ground-based sensors such as cosmic ray detectors (e.g., Montzka et al., 2017).

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-surface models (LSMs). 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 the profiles of variables in the surface layer and in the canopy and with model output.

Near-surface profiling capabilities are available via fiber-based distributed sensors (DTS, e.g., Thomas et al., 2012), 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 CO_2 assimilation, its dependence on air temperature, moisture and radiation profiles in the canopy must be known. This is essential for developing advanced photosynthesis models and implementing accurate vegetation dynamics in LSMs.

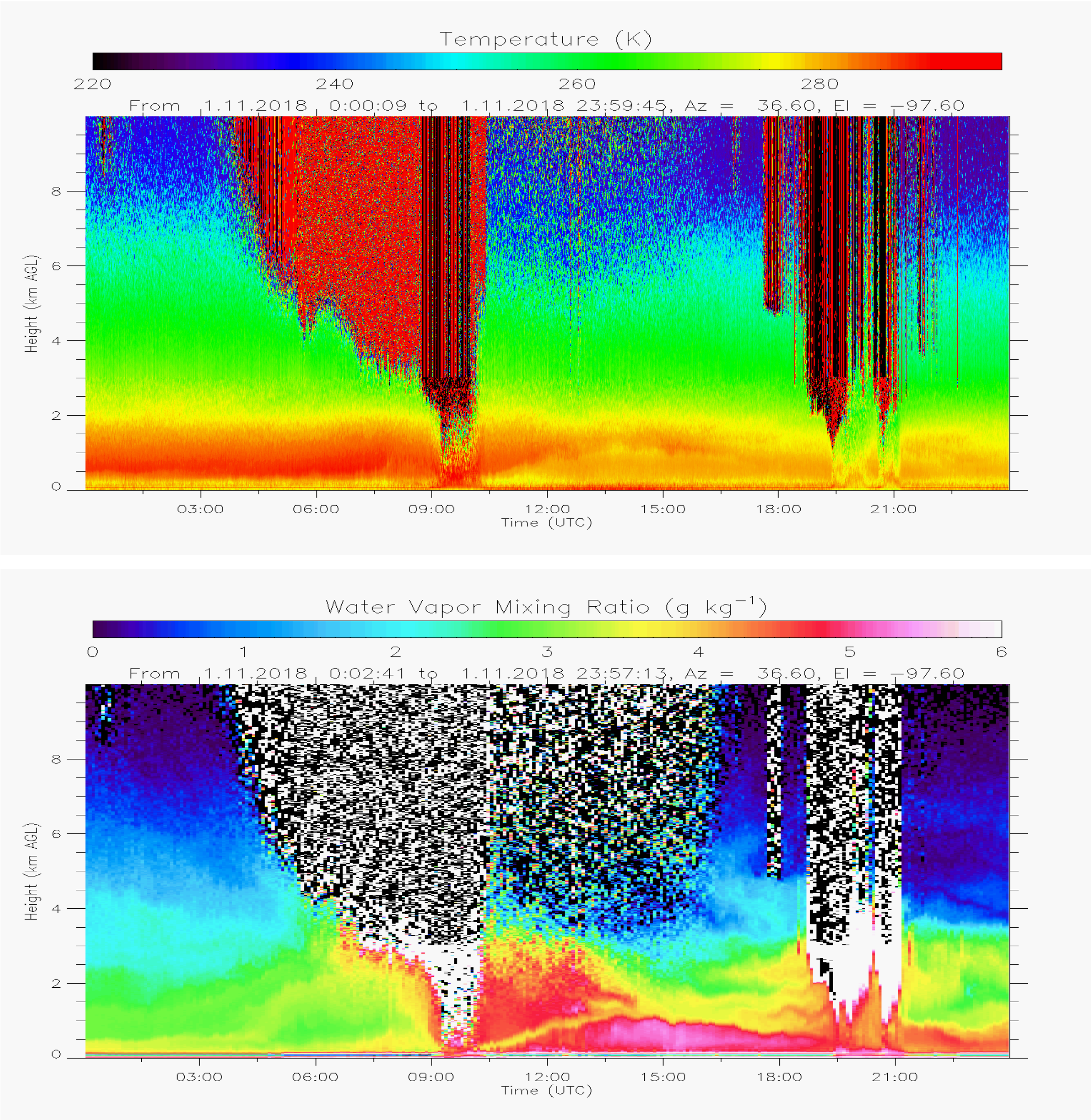


Fig. 1: Upper panel: Time-height cross-section of the temperature field measured with resolutions of 10 s and 100 m at the new Land-Atmosphere Feedback Observatory (LAFO; see https://lafo.uni-hohenheim.de/en) of the University of Hohenheim. Lower panel: Corresponding water-vapor mixing-ratio measurements. In many cases, measurements are also possible in clouds and rain.

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. 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. 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 PBL. 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). This new capability in combined temperature and water-vapor profiling is demonstrated in Fig. 1.

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, vertical profiling is performed in dependence of range and extended from the surface to the mixed layer. Surface in situ observations at 2 m and 10 m heights can be combined with lidar scans.

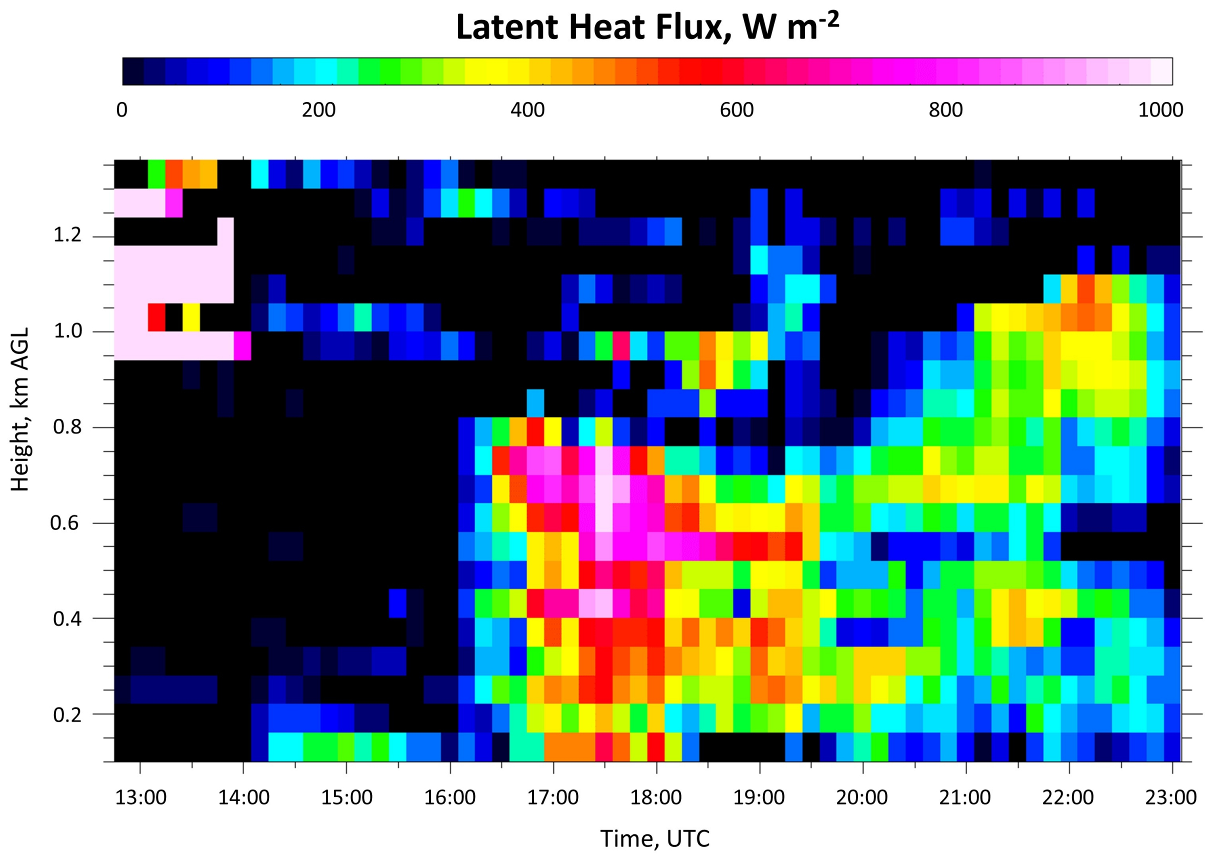


Fig. 2: First measurement of the daily cycle of the latent heat flux at the ARM SGP site on 23 August 2017 during LAFE. Note that sunrise occurred around 14 UTC.

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. 2.

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 (**reference). These results will permit the direct evaluation of flux-gradient similarity relationships (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 flux, mean and gradient profiles 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. Therefore, it is very timely to start the GLAFO initiative.

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 3 depicts the envisioned design.

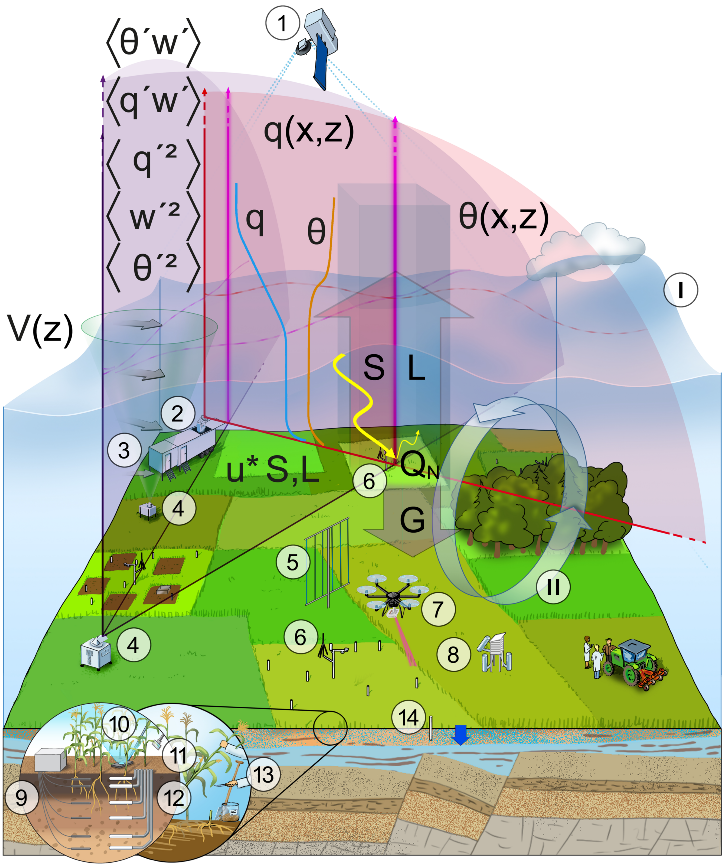


Fig. 3: Proposed sensor synergy for the GLAFOs. I: PBL top, II: mesoscale vortex. 1: Satellite remote sensing, 2: vertically staring Doppler, water vapor, temperature, and CO_2 lidar systems, atmospheric emitted radiance interferometer (AERI), microwave radiometer (MWR), cloud radar, 3: scanning Doppler, water vapor, temperature, and CO_2 lidar systems, 4: scanning Doppler lidar systems, 5: via 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 rate measurements, 12: tensiometers, 13: in-situ canopy measurements such as biomass and canopy height, 14: soil moisture and temperature network.

The GLAFO measurements should contain:

- **Soil texture, moisture and temperature:** Soil moisture, matric potential and temperature profiles complemented with hydrological components such as ground water level, surface and sub-surface runoff, soil evaporation from micro-lysimeters or equivalent and precipitation measurements. Ideally hydraulic and thermal conductivities are also determined (see, e.g., Tian et al., 2018). Possibly soil heat flux plates, although the profile measurements will allow for their determination using the calorimetric method.
- **Vegetation:** Vegetation type and state, rooting depth and distribution; leaf area index; biomass; canopy height; canopy properties (including "response curves" to determine key canopy exchange parameters such as Vc_{max}; vulnerability curves, etc.), radiation, moisture 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; 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 lidar; 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 in different levels of complexitiy, 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 1: Soil texture, moisture, and temperature; surface energy balance station; atmospheric wind profiles and PBL depth.

→ This configuration will allow for a first insight in the dependence of ABL properties, such as the ABL depth z_i, on surface fluxes. Consequently, a local characterization of L-A feedback at the sites will become possible.

Level 2: Ground-water level; soil texture, moisture and temperature; surface energy balance station; atmospheric wind profiles and ABL depth; vertical wind profiles, temperature and water vapor profiles with turbulence resolution

→ This level will permit the determination of key L-A metrics such as RHT and CTP_HI_{low} as well as flux gradient relationships and the study of turbulence parameterizations in the ABL convective mixed layer.

Level 3: Ground water level; soil texture, moisture, and temperature; vegetation state and variables, such as canopy temperature, moisture and radiation, surface energy balance station, atmospheric wind profiles and PBL depth; vertical wind profiles, temperature and water vapor profiles with turbulence resolution, atmospheric surface layer profiles.

→ The measurements of flux-gradient relationships and parameterizations can be enhanced into the ABL surface layer in heterogeneous terrain.

Level 4: A triangle of wind and thermodynamic profiles will be added around the central GLAFO site

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

Table 1: GLAFO hierarchical design matrix.

Level	Soil		Land cover		Atmosphere	
	State	Variables	State	Variables	Variables	Instrument
L1	Soil texture	T, q		Albedo, LST, surface energy balance	zi, V(z)	Doppler lidar (DL) scanning
L2	Soil texture	Ground-water level, T, q		Albedo, LST, surface energy balance	zi, V(z), w'(z), T(z), m(z)	L1 + DL, Raman lidar (RL) or DIAL vertical
L3	Soil texture	Ground-water level, T, q	Canopy height	Canopy T, m, rad, albedo, LST, surface energy balance	zi, V(z), T(z), m(z) also in the atmospheric SL	L2 + scanning DL, RL, and/or DIAL
L4	Same as L3 + a triangle of V(z), T(t) and m(z) profiles					L3 + scanning DL and vertical TD lidar or FTIR

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 current observatories is already very close to the requirements of GLAFOs with level 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
- German Meteorological Service (DWD), Meteorological Observatory Lindenberg - Richard-Aßmann-Observatory (MOL-RAO) in Germany
- Meteo Swiss Observatory in Payerne, Switzerland
- Cabauw CESAR site in the The Netherlands
- Chilbolton observatory in UK
- IPSL Sirta site close to Paris, France
- The Schneefernerhaus at the Zugspitze mountain in Germany
- A third-pole measurement site on the Tibetan plateau
- The Huancayo Observatory in Peru
- A potential site in New Zealand

without claim of completeness as this is work in progress. Further sites in Africa and Asia as well as in polar regions should 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 a reasonable statistical coverage.

Table 2: Current observatories with high potential to become a GLAFO site in comparison with their current level of equipment.

Level	ARM SGP site	ARM SE Site	UHOH LAFO	DWD MOL	IPSL Sirta	Meteo Swiss Payerne	Cabauw/ CESAR	Chilbolton	SFH
Loc.	N 36,61 W 97,49		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 47,42 E 10,98 2656m
L1				**X**	**X (?)**	**X**	**X**	**X**	**?**
L2	**X**	**X**					**?**		**X**
L3			**X**						
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://schneefernerhaus.de

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 to be relevant for the GLAFO initiative. These include the NOAA bedrock to boundary layer (B2B) 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 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 Observatoria (TERENO) in Germany with potential site 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 equipments towards 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	
L1	**adding a DL**	**TBD**	**adding a DL**	**adding a DL**	**X**	**TBD**
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 particularly high 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". It is envisioned that this collaboration will be expressed also in this GLAFO White Paper.

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 CHEESE-HEAD with respect to the set up and operation of sensor synergies that can be considered as GLAFOs demonstrators. **More. Another GLAFO demonstrator will be realized during LIAISE in a semi-arid region in Spain during this year. 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
L1		**X**			
L2		**or X ?**		**X**	
L3	**X (GLAFO demonstrator)**		**X**		
L4					**X?**
Web	https://www.hymex.org/LIAISE/campaign.html	https://www.eol.ucar.edu/field_projects/cheesehead	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

**CLASP?

3. Overarching Objectives and Scientific Goals of GLAFO

Based on the research potential and the overarching motivation following research objectives of the GLAFOs have been derived:

1. **Understand the L-A feedback chains over the regime of temperature, soil, and snow conditions, vegetation properties, PBL evolution and in dependence of large-scale forcing**
2. **Study and quantify the effects of land use and land cover changes (LUCC) on regional weather and climate**
3. **Contribute to an advanced simulation of extreme events**
4. **Protect humankind and the environment with respect to extreme events and climate change**
5. **Provide the basic knowledge and methodologies for evaluating future bio-geoengineering efforts**

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

- **Understand and characterize L-A feedback with advanced metrics**
- **Develop and operate GLAFOs from groundwater to soil to land cover to the lower troposphere**
- **Study transport and exchange processes at the interfaces between the compartments**
- **Identify the role of vegetation with respect to L-A feedback**
- **Assess the processes and scales at which L-A feedback is sensitive to terrestrial hydrology**
- **Investigate scale interactions and land heterogeneity from turbulent to micro- to mesoscale processes on the strength of L-A feedback**

The following scientific impacts of GLAFOs are envisaged:

- Verification of large eddy simulation model runs and improvement of turbulence representations in mesoscale models
- Improvements of we
- L-A data assimilation, regional-scale reanalyses leading to forecast improvement including extreme events, process understanding, impact analyses
- Testbed for providing synergetic data products leading to a refinement and extension of data sets, e.g., for L-A feedback
- 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)

4. Conclusion and Outlook

In summary, during the 2019 GLASS Panel Meeting, a new initiative was developed and designed for the establishment of the GEWEX Land-Atmosphere Feedback Observatories (GLAFOs). These sites will address the compelling needs of 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 possible to develop several GLAFOs in various climate zones within the foreseeable future.

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

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