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AFM Special Issue Summary - Integrating Surface Flux with Boundary Layer Measurements

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ABSTRACT

To help bridge science topics related to land-atmosphere interactions, we organized a virtual special issue in this journal (Agricultural and Forest Meteorology [AFM]) entitled, "Land-Atmosphere Interactions: Integrating Surface Flux with Boundary Layer Measurements." The motivation for the special issue was driven by existing disciplinary barriers between research areas that all address land-atmosphere interactions. In particular, it addressed research silos between those who study features of the land surface, surface fluxes (including water, energy, and trace gases), atmospheric boundary layer growth and thermodynamics, and atmospheric composition and aerosols. The special issue sought to bring these communities together to integrate multiple observations across the soil-vegetation-atmosphere continuum with the aim of 1) improving broader understanding of land-atmosphere interactions, feedbacks, and coupling, 2) fostering new collaborations between atmospheric and surface flux scientists, and 3) identifying new paths for integrative research. Here, we provide an overview and synthesis of the special issue.

1. Introduction and Synthesis

As with many areas of research in biogeosciences and Earth system science, progress in understanding land-atmosphere interactions is being facilitated by technological advances (Berg and Lamb, 2016; Helbig et al., 2021; Santanello et al., 2018; Späth et al., 2023). For example, new modeling approaches that leverage high-performance computing, compact new instrumentation that is commercially available and robust for field deployment, and airborne and satellite remote sensing that covers large areas of the Earth's surface with previously unparalleled resolution and return frequency, are all contributing new insights about the bi-directional nature of interactions and feedbacks that occur at the interface of the land surface and the atmospheric boundary layer (Beamesderfer et al., 2022). However, at the same time, disciplinary silos persist and, in many ways, are becoming even more entrenched with increasing technological and computational complexity creating more isolation between related fields than ever before.

To help bridge science topics related to land-atmosphere interactions, we organized a virtual special issue in this journal (Agricultural and Forest Meteorology [AFM]) entitled, "Land-Atmosphere Interactions: Integrating Surface Flux with Boundary Layer Measurements." Collectively, our expertise represents a variety of different fields of research on land-atmosphere interactions, including both "land-

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centric" and "atmosphere-centric" sides of the land-atmosphere paradigm. The motivation for the special issue was driven by recognition of the disciplinary barriers that exist between research areas that all address topics concerning land-atmosphere interactions. In particular, it addressed research silos between those who study features of the land surface, surface fluxes (including water, energy, and trace gases), atmospheric boundary layer growth and thermodynamics, and atmospheric composition and aerosols. The special issue sought to bring these communities together to integrate multiple observations across the soil-vegetation-atmosphere continuum with the aim of 1) improving broader understanding of land-atmosphere interactions, feedbacks, and coupling, 2) fostering new collaborations between atmospheric and surface flux scientists, and 3) identifying new paths for integrative research. Here, we provide an overview and synthesis of the papers published in that virtual special issue, which includes previously unpublished work that was submitted to the special issue along with other papers published recently in AFM that are directly related to the special issue topic. The papers included in this summary fall into the following topic areas that are illustrated in the overview figure (Fig. 1).

Topic Area I: Atmospheric properties (including composition, meteorology, and climate) have important effects on plants and soil on Earth's surface, thereby altering carbon transport and exchange between the land and atmosphere.

Topic Area II: Living and non-living surface features influence atmospheric composition, surface fluxes, and boundary layer dynamics

Topic Area III: Surface-atmosphere exchange of water is altered by surface properties and processes, and this influences the surface energy budget and boundary layer dynamics

Topic Area IV: Evaluation of methods used for modeling land-atmosphere interactions and estimating surface energy components

Topic Area I. Atmospheric composition influences plant physiology and terrestrial ecosystem function. These effects often vary depending on the type of plant. For example, Roberts et al. (2022) and Vo and Faiola (2023) illustrated that the air pollutant, tropospheric ozone, had very different effects on crops compared to conifers. This has implications for carbon cycling in systems with these different types of vegetation. Ozone exposure drastically reduced productivity of rapeseed cultivars, decreasing crop yields and the quality of the oil harvested (Roberts et al., 2022). In contrast, ozone exposure did not affect productivity of Canary Island Pines, and actually reduced the amount of carbon the plants released back to the atmosphere (in the form of biogenic volatile organic compound emissions) (Vo and Faiola, 2023). Studies on this topic advance our understanding of differences in land-atmosphere interactions across a range of land surface types, shedding light on the potential feedback between atmospheric pollution that could, in turn, influence surface emissions back to the atmosphere. Another constituent of the atmosphere that can significantly impact plant physiology is atmospheric aerosols, or small particles suspended in the atmosphere. Atmospheric aerosols scatter and absorb radiation, playing an important role in the quantity and properties of radiation at the surface – influencing local temperature and vapor pressure deficit, which in turn, alter ecosystem productivity, respiration, and evapotranspiration. Atmospheric aerosols also play an important role in cloud formation processes, thereby influencing radiation and precipitation. In current climate models, it is unclear how aerosols generated through human activities (anthropogenic aerosols) have perturbed terrestrial ecosystem processes. Zhang et al. (2023) used the Community Earth System Model to investigate this at regional and global scales. They found no significant effect of anthropogenic aerosols on the total carbon sink at the global scale, but there were significant effects in certain regions of the world. Furthermore, the magnitude and direction of the aerosol effect varied from region to region. The aerosol impact on temperature was the primary climate variable driving the effect on terrestrial carbon sink, followed by the aerosol impact on diffuse radiation and precipitation. All of these climate variables can alter gross primary productivity and total ecosystem respiration, which collectively determine the net productivity of the system and the magnitude of the terrestrial carbon sink. Importantly, this study provided new insight about the specific response mechanisms of aerosol-climate-ecosystem interactions that vary from region to region. Collectively, Roberts et al., Vo and Faiola, and Zhang et al. illustrated the important effects of atmospheric composition on terrestrial ecosystem processes, and how the mechanisms driving these effects vary across different ecosystem types and spatial scales.

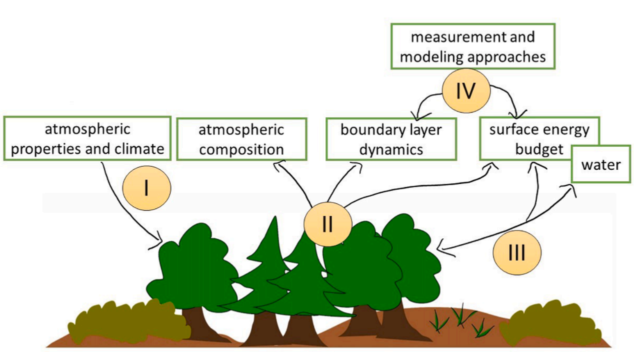

Fig. 1. Illustration of the topic areas covered by the papers in the virtual special issue.

Meteorological processes influence carbon exchange and storage through their effects on seasonal phenology and plant mortality. Shifts in spring phenology are known to affect plant and ecosystem interactions, surface energy budgets, and change temperature and precipitation patterns. However, the effects of preseason meteorological drought on spring phenology, and how this influences vegetation growth, are unclear. Zeng et al. (2021) explored the coupling effects of these unknowns by applying four remote sensing methods to estimate the start of the growing season in the Northern Hemisphere. These data were paired with monthly temperature, precipitation, cloud cover, and soil moisture data, as well as drought indices, to determine the cumulative effect of preseason drought on spring phenology. They found that preseason drought advanced the growing season in each biome, leading to increased spring growth, but it came at a cost, as the combined effects of preseason drought and an earlier start of the growing season greatly decreased summer vegetation growth. This study leveraged existing datasets to address important questions about the effect of shifting phenology on the overall productivity of an ecosystem throughout an entire growing season. In the same vein, the paper by Messori et al. (2022) showed that jet streams are another meteorological phenomena that can influence vegetation growth. They investigated the impact of mid-latitude jet streams on onset and duration of growing seasons in the Euro-Atlantic. They used jet and zonal flow indices calculated from ERA5 reanalysis and EVI2 data for vegetation activity. Results showed significant correlation between vegetation greenness anomalies and the jet stream index, which is largely defined by the correlation between jet streams with regional temperature, soil moisture and downward surface solar radiation anomalies with different seasonal patterns. This study creatively uses jet stream characteristics as a metric of climate variability to explore climate-vegetation feedbacks that affect plant productivity (and carbon cycling) in Europe. Zooming in on a smaller meteorological scale, turbulence regimes can also influence carbon cycling and storage through their effect on tree mortality. Mendonça et al. (2023) found that downdrafts propagate wind gusts, leading to increased tree mortality. These downdrafts occurred only in weakly stable turbulence regimes where wind flow within and above the canopy was coupled. The destructive potential of the wind gusts was four times higher than on nights without downdrafts. This study provided the first assessment of the interplay between boundary layer dynamics, winds, and tree damage and demonstrated that downdrafts can lead to substantial tree mortality. Together, the studies by Zeng et al., Messori et al., and Mendonça et al. provided insight about important meteorological processes that influence carbon cycling through their effect on growing season, total productivity, and tree mortality.

Topic Area II. Living and non-living components of the Earth's surface impact atmospheric composition by serving as a source of emissions. For example, plants and soil emit compounds to the atmosphere that participate in important atmospheric chemistry processes. An et al. (2023) investigated soils as a source of atmospheric nitric oxide (NO), which plays an important role in the production of the air pollutant, tropospheric ozone. They measured diurnal patterns of soil NO concentrations at two field sites representing very different background levels of atmospheric nitrogen oxides - a suburban field site in the United Kingdom and a remote site in Australia. Measurements were conducted at both sites during summer. At the UK site, measurements were collected again during winter to evaluate seasonality effects at a single location. They found that soil NO concentrations were higher at the UK site during both summer and winter compared to the remote Australian site in summer. They also found that the NO concentration was higher at the UK site in summer compared to winter. Soil NO emissions were significantly related to vapor pressure deficit at both sites and solar radiation at the Australian site. Soil emissions were estimated to contribute to ~1% and <0.5% of total NO emissions at the remote Australian site and the suburban UK site, respectively. Likewise, Nagalingam et al. (2023) explored how plant emissions of volatile organic compounds (VOCs, particularly terpenes) are altered under extreme heat to improve our understanding of how these emissions will change in a more heat-stressed world. VOCs are highly reactive compounds that play an important role in the production of atmospheric aerosols. Four different plant species were exposed to heat stress conditions and terpenoid emission rates were measured. They found that emissions remained low for three out of the four species when temperatures remained at or below 30 Celsius (°C). Above 35 - 37°C, emission rates increased drastically, much higher than predicted by current emission models. The studies by An et al. and Nagalingam et al. provided unique insights about the surface as a source of reactive atmospheric constituents that can generate secondary products (such as ozone and aerosol), which in turn, influence terrestrial ecosystem processes (see Topic Area I). The two papers by An et al. and Nagalingam et al. highlighted the diversity of compounds that can be exchanged between the land and atmosphere, and that the emission rates of these compounds vary across different surface types and environmental contexts.

Surface features such as canopy structure affect boundary layer processes and forest-atmosphere coupling. Corrêa et al. (2021) investigated the role of gravity waves and low level jets in facilitating transport inside and above the forest canopy. They used vertically-resolved wind velocity, temperature, sonic anemometer, and fast response carbon dioxide and water measurements to conduct the analysis. Wavelet analysis was used to identify the nature of flow structures, such as turbulent coherent structures and gravity waves. Topographic forcing of gravity waves was evaluated using the Froude number. They found that the first part of the night was characterized by strong turbulent activity and coupling between the flow within and above the canopy. The primary flow direction was from inside the canopy upwards. When gravity waves appeared, turbulence also decreased. This led to reduced vertical transport and a decoupling between the flow within the canopy and the flow above. During the third flow regime period, a low-level jet appeared with the nose located close to the canopy top indicating that the height of the nocturnal boundary layer was immediately above the forest canopy. Turbulence intensity increased with the presence of the jet, but there was still decoupling between air within and above the canopy. An increase in scalar concentration was associated with the low-level jet, likely caused by horizontal transport from the jet and the very shallow nocturnal boundary layer. The analysis by Corrêa et al. provides new insight about turbulent transport between the land and the atmosphere when gravity wave and low-level jet flow structures co-exist, and how the land structure itself plays a role in developing the different flow structures that influence forest-atmosphere exchange. Similarly, Schilperoort et al. (2022) provided another example of how the canopy structure can drive boundary layer processes by facilitating nighttime inversions. They used a distributed temperature sensor system to identify temperature inversions formed within a Douglas fir forest canopy. They found that the canopy morphology can promote stable stratification and strong net radiative cooling. The authors suggested it is likely that these nighttime inversions within a forest are more common than currently assumed. Schilperoort and colleagues' study was innovative in its use of temperature measurements at very high spatial (30 cm) and temporal (0.5 Hz) resolution with a distributed temperature sensor network, providing an example of how these types of measurement networks can be leveraged to answer challenging questions about land-atmosphere interactions. Together, the studies by Corrêa et al. and Schilperoort et al. highlighted how features at the land surface influence boundary layer processes that alter vertical transport and exchange between the land and the atmosphere.

One long-standing research question for the land-atmosphere interactions research community is how spatial heterogeneity in surface properties and surface energy fluxes interacts with boundary layer dynamics. Mangan et al. (2023) tackled this question using observations from the Land Surface Interactions with the Atmosphere in the Iberian Semi-Arid Environment (LIAISE) campaign combined with coupled atmospheric boundary layer modeling. The study area was characterized by a wide range of Bowen ratios from 0.01 in irrigated areas to 30 in non-irrigated areas. Despite these strong contrasts, the convective boundary layer height was similar across the study area. They argued that boundary layer dynamics at regional scale (~10 km) can only be explained when considering a composite of surface fluxes at local scales (~100 meters) and when accounting for effects of advective fluxes in these heterogeneous environments. The study builds an important bridge between observations from an intensive field campaign and how they relate to weather forecasting and climate models that operate on much larger spatial scales. Beamesderfer et al. (2023) similarly illustrated that landscape heterogeneity can influence boundary layer height and this effect likely varies from site to site. Using a novel combination of ceilometer and radiosonde data, they showed that diurnal patterns in retrieved boundary layer height vary seasonally, and across sites, with the highest mixing layer height in summer, and at warm and dry sites where sensible heat fluxes dominate the energy balance. Using regression tree analysis, they demonstrated that under clear sky conditions, site-level variables and surface fluxes can explain 53-76% of the variation in daily maximum boundary layer height, and the unexplained variation could partially be explained by landscape heterogeneity and synoptic flows. Babić et al. (2021) evaluated another important effect of landscape spatial heterogeneity, namely the potential for it to create surface energy balance underclosure - an ongoing challenge faced by the surface flux community using eddy covariance techniques. Babić et al. set out to test if, for a semiarid valley site, low-frequency circulation due to entrainment processes or horizontal advection due to spatial heterogeneity in surface properties caused the observed underclosure. They found that local horizontal advection was the main cause for the energy balance underclosure. Their findings highlighted the need for dense sensor networks when conducting surface flux measurements in heterogeneous and complex landscapes. These networks can help bridge the observational gap between local-scale and regional-scale atmospheric processes. Collectively, Mangan et al., Beamesderfer et al., and Babić et al. presented novel approaches to measurement and analysis that address a variety of complicated challenges associated with high spatial heterogeneity in the landscape.

Vegetation phenology is tightly coupled with surface energy fluxes through a number of different mechanisms, for example by affecting surface albedo, evapotranspiration, and surface roughness. Li et al. (2023) used the Community Earth System Model (version 2) to quantify the effect of phenology shifts on atmospheric boundary layer dynamics and surface climate in North America. They found that shifts in plant phenology directly affected energy partitioning and the absorption of solar radiation at the surface. Indirectly, phenology shifts affected cloud cover and thus reflection of solar radiation in the atmosphere. Additionally, they found differences in the temporal impacts of phenology shifts for the Great Plains and the Eastern US. This modeling study by Li et al highlighted where in North America land-atmosphere interactions might be most sensitive to phenology shifts, which is critical information for guiding future observational and model evaluation studies. Liu et al. (2022) used a different approach to address similar questions about feedbacks between shifting plant phenology and surface energy budgets. They used the intrinsic biophysical mechanism model (IBM) approach (Lee et al., 2011) to quantify the feedback effects of vegetation on land surface temperature (T_s) based on recent shifts in vegetation dynamics (greening and browning trends over the last 20 years) across high mountain Asia. Widespread greening was associated with decreases in albedo, Bowen ratio, sensible heat flux and aerodynamic drag. Changes in albedo were found to have an insignificant climate feedback effect. The decrease in Bowen ratio, driven by an increase in transpiration, was found to drive the largest decrease in T_s, while the decrease in aerodynamic drag was also associated with a small but significant cooling effect. Liu and colleagues nicely tease apart the ways land-atmosphere interactions and vegetation feedbacks to climate are driven by multiple covarying and interacting mechanisms, and the powerful new insights that can be gained by integrating remote sensing, gridded datasets from the Global Land Data Assimilation System (GLDAS), and tower flux measurements with synthesis in a model-based analytic framework. Both studies by Li et al. and Liu et al. highlighted the important effects of phenology shifts on surface energy fluxes, and identified the driving mechanisms for the effect across different areas.

Topic Area III. To better understand complex interactions between soil, vegetation, near-surface climate, and cloud and precipitation dynamics, accurate representation of surface-atmosphere water exchange is crucial. Evapotranspiration of water from soil and trees is one major contributor to water fluxes from the surface to the air. Flo et al. (2022) investigated the main controls of whole-tree canopy conductance using a large global database of sap flow observations. They found that vapour pressure deficit, and thus atmospheric humidity, exerted a more important control on canopy conductance than soil moisture or solar radiation. Furthermore, they assessed how the importance of the drivers varied between different biomes and soil types. This is important because the main drivers of evapotranspiration can differ depending on surface features, such as vegetation type and climate. This analysis uniquely leveraged a global data-set of sap flow measurements that allowed them to overcome many of the limitations of previous studies on this topic that used ecosystem-scale observations. In a separate study focused on drivers of surface-atmosphere water exchange, Ma and Zhang (2022) investigated the magnitude, trend, and drivers of evapotranspiration on the Tibetan Plateau using a combined measurement-modeling approach. They found that soil evaporation was the largest contributor to evapotranspiration followed by plant transpiration. Canopy evaporation was a minor contributor. They also found that total evapotranspiration across the Tibetan Plateau had increased from 1982-2016. The drivers of this increase varied across the study domain. In most locations, the change in evapotranspiration was due primarily to increased precipitation. Precipitation events played a large role in regulating changes in evapotranspiration because most of the Tibetan Plateau is dryland and therefore very sensitive to the addition of water from precipitation. In contrast, evapotranspiration changes in less arid regions such as the eastern plateau, were driven by vegetation change rather than any increase in precipitation. The study by Ma and Zhang was novel in its use of remote sensing that was calibrated with new monitoring network observations in the region, and their systematic evaluation of the main drivers of change through sensitivity analyses. Kannenberg et al. (2023) investigated how a different component of the water cycle, precipitation, influences vegetation health, particularly in dryland environments where moisture is limited. They explored this link between the carbon and water cycles in a dryland piñon-juniper ecosystem. They found that plant water potential and productivity were largely driven by shallow soil moisture, with a limited degree of coupling to daytime variability in atmospheric properties. Even small pulses of precipitation stimulated evapotranspiration for 1-2 weeks and influenced plant productivity (and therefore carbon fluxes) for up to 3 weeks. Kannenberg and colleagues' study is notable for its creative integration of co-located measurements of soil moisture, plant water potential, ecosystem fluxes and atmospheric conditions to address research questions about biome responses to future climate change. Together, Ma & Zhang and Kannenberg et al. provided new insight about the controls on evapotranspiration, a large component of the water budget, leveraging new observations and innovative analyses.

Some of the water released to the atmosphere from the surface is recycled locally in the form of precipitation. The local recycling ratio varies by land cover with interesting implications for the consequences of land management practices on the water cycle. Xiao et al. (2023) used a model-based approach to investigate water transport in the boundary layer, coupling a two-layer equilibrium boundary layer model to an idealized water isotope model with precipitation processes. They validated the model using flux and isotope data from a cropland site in Minnesota, as well as twice-daily sounding profiles from a nearby weather station. The paper by Xiao et al. is notable for its integration of surface, mixed layer, and convective boundary layer observations, all within a model-based framework. The local water recycling ratio was found to vary among years, with the lowest ratio observed in a drought year, with much higher ratios in non-drought years; on the other hand, heavy irrigation during drought years was expected to yield higher water recycling ratios. A particularly interesting finding was how land cover influences the local water recycling ratio; conversion of deciduous forest to cropland was predicted to decrease water recycling, while conversion of grassland to cropland was predicted to increase water recycling. An implication of Xiao et al.'s results is that over the last ~150 years, changing land use in the upper Midwest of the United States, with conversion of large amounts of land to agricultural crops, has almost certainly had an effect on local water recycling. Similarly, Li et al. (2023) explored another process that can recycle water from the surface but is not adequately represented in models - fog formation and evolution. The study is unique in its integration of a novel suite of measurements (including water vapor isotopes, meteorology, and eddy covariance) with high resolution numerical weather prediction modeling to characterize fog development and evolution. Variability in water vapor isotopes was tied to different stages of fog evolution, where strong fluctuations were linked to fog lifting and dissipation at the ground level, and highly correlated water vapor isotopes with specific humidity were linked to dew formation before the onset of fog. They also demonstrated that fog lifetime was linked to boundary layer processes, such as turbulent entrainment, and that these processes can be tied to trends in water vapor isotopes. Li et al proposed that more vertically-resolved measurements of water vapor isotopes are needed in the near-surface atmosphere combined with measurements in fog droplets and modeling to better constrain fog dynamics in numerical models. The papers by Xiao et al and Li et al nicely demonstrated how measurements and modeling can be combined to probe processes related to different components of the water cycle.

Accurately measuring water exchange comes with some very real challenges that have important implications for estimating surface energy budget terms. Wang et al. (2022) demonstrated there is a significant clear-sky bias in current approaches that are used to estimate evapotranspiration from satellites. They proposed a new method leveraging microwave-based satellite measurements to improve the estimate under cloudy-sky conditions, providing a roadmap for others to use to correct this bias in the future. In good news, Frank and Massman (2023) compared energy balance closure using seven different hygrometers and sensors that have been deployed for this purpose historically and found very little effect on the closure estimate based on measurements with different sensors and calibrations. This study highlighted the robustness of commonly used hydrometers for field observations of water exchange. Fischer et al. (2023) explored an interesting question related to the fate of water during precipitation events, and particularly, how rain interception can skew observations of the surface energy budget. They quantified rain interception by the canopy using a direct measurement-based throughfall approach and compared their observations with approaches that leveraged the eddy covariance technique to estimate rain interception from the surface energy budget terms. Fischer et al. demonstrated that Norway spruce intercepted approximately one-third of the total annual rainfall. The eddy covariance based approaches significantly underestimated this contribution to evapotranspiration. The authors highlighted the need to correct previous and future estimates of evapotranspiration during precipitation events to better account for rain interception, an often neglected component of the water budget. Wang et al., Frank et al., and Fischer et al. all provided information that can reduce uncertainties in water exchange measurements moving forward.

Topic Area IV. Models are often used to predict land-atmosphere exchange of water, carbon, and energy and different modeling approaches come with their own strengths and weaknesses for a given application. Zhang et al. (2023) quantified uncertainties in model simulations of land-atmosphere interactions stemming from uncertainties in soil data sources. They used a fully coupled atmosphere-hydrology model (WRF-Hydro), which was run on a 4-km convection permitting resolution. The authors found that differences in soil texture between different data sets substantially affected model results. Modeled soil hydrology (e.g., soil moisture), land-atmosphere exchange (e.g., sensible heat flux), and near-surface climate (e.g., air temperature) varied depending on the chosen soil input data highlighting the need to account for uncertainties originating from inherent uncertainties in currently available global soil datasets. Furthermore, Zhang et al highlighted the importance of soil texture and hydrology for planetary boundary layer growth, thus providing an integrated modeling perspective on complex interactions across the soil-vegetation-atmosphere continuum. Similarly, Alexander et al. (2022) found strong model sensitivity to soil moisture for estimating boundary layer height in the arid Central Valley, California. They conducted a comprehensive sensitivity analysis based on selection of different boundary layer schemes and land surface models in the Weather Research Forecasting model. They evaluated model performance using a series of multi-scale observations of PBL structure and height, near-surface meteorological conditions, and surface fluxes. They found that model performance was more sensitive to the land surface model than the PBL scheme. Interestingly, this result contradicts other similar analyses conducted in less arid regions (Cohen et al., 2015), highlighting that limitations in model performance can be region-specific. Alexander et al. identified 3 major deficiencies in the model. First, soil moisture initialization was too dry. Second, the land surface models did not accurately predict sensible heat flux and latent heat flux over croplands. Third, there was no significant improvement using the schemes that included data nudging of soil moisture and temperatures. Alexander et al. is notable in its identification of key parameters driving model uncertainty in arid landscapes, providing clear recommendations for prioritizing future measurements. In a modeling analysis focused on the role of plants, Muñoz and Sierra (2023) quantified uncertainties in plant-atmosphere gas exchange related to model treatment of atmospheric carbon dioxide (CO_2). Some models use quasi-deterministic or even fixed values for CO_2 where historical monthly averages or measurements high in the troposphere (where it is well-mixed) are used. In reality, gas exchange is subject to stochastic processes with a high level of variability. This discrepancy could create errors in estimates of CO_2 exchange. The authors addressed this challenge by evaluating the differences in gas-exchange estimates when using a deterministic versus stochastic treatment of CO_2. The study leveraged CO_2 measurements from 50 field sites in the Integrated Carbon Observatory System (ICOS) and the Amazon Tall Tower Observatory (ATTO) field site, focusing on vertically-resolved measurements within the canopy. This was a key attribute of their measurements because previous studies have often used CO_2 measurements collected above the canopy as model input to make these predictions. The Farquhar and Penman-Monteith models were used to quantify the effect of the stochastic treatment on CO_2 and water exchange, respectively. In general, accounting for stochasticity reduced carbon assimilation and increased transpiration, but the effect was small. The authors concluded that the stochastic component of atmospheric CO_2 concentrations can be ignored for predicting carbon and water exchange as long as CO_2 measurements within the canopy are used to drive the models, an important recommendation for future studies and analysis. Collectively, papers by Zhang et al., Alexander et al., and Munoz & Sierra identified key uncertainties in models used by the land-atmosphere interactions research communities and provided important recommendations for the measurements required to run the models effectively.

Different terms of the surface energy budget can be estimated using a variety of different measurement and calculation approaches. For decades, micrometeorologists have wrestled with the challenge of energy balance closure—the fact that the sum of sensible and latent heat (H + LE) is generally lower than the available energy, or the difference between the net radiation and the ground heat flux (Rn - G). The causes of this closure problem have been debated but are commonly thought to be at least partially the result of a finite averaging period driving inadequate sampling of large turbulent eddies and associated horizontal and vertical advection. Zhou et al. (2023) used large eddy simulation modeling with the PALM model to investigate the conditions under which a range of proposed corrections for energy imbalance can be reliably applied. The Bowen ratio (B = H/LE) method, which estimates "corrected" fluxes by assuming the measured B is correct, was generally found to be better than other closure adjustment methods. Specifically, when vertical advection drives energy imbalance, the Bowen ratio method correctly closed the energy balance. But, when horizontal advection drives energy balance, the Bowen ratio method—while better than other methods—remained an imperfect solution. Zhou et al. also confirmed that storage and horizontal flux divergence play a minor role in driving energy imbalance. Because of the critical role that sensible and latent heat fluxes play in driving many aspects of land-atmosphere interactions, Zhou and colleague's key contribution is the new insights it provides into the conditions under which vertical vs. horizontal advective fluxes drive the flux imbalance, and the ability of different methods to provide more accurate estimates of the "true" turbulent flux. In a related paper, Wei et al. (2022) addressed another challenge in accurately predicting turbulent flux. Pressure fluctuations are a particularly important variable for estimating turbulent flux because they act to redistribute fluctuations in velocity and turbulent kinetic energy. Several studies have demonstrated the importance of the pressure transport term using numerical simulations, but to date, very few observational studies have been conducted, largely due to the difficulty in making pressure flux measurements. Wei et al. addressed this knowledge gap by analyzing temporally- and vertically-resolved pressure fluxes using continuous, multi-height flux tower observations of turbulence at a field site with homogenous, flat terrain. They found that without accounting for the pressure transport in the turbulent energy redistribution process in the convective boundary layer, momentum and sensible heat fluxes were overestimated by > 60%. However, by incorporating the pressure flux contribution, the overestimation of those fluxes were effectively corrected. This study therefore described a novel approach to the estimation of pressure fluctuations, and provides a waypoint for the refinement of future boundary layer parameterization schemes in numerical weather models. The papers by Zhou et al and Wei et al provided clear recommendations moving forward for improving energy balance calculations.

2. Final Thoughts

One of the original goals of the special issue was to bring together scientists from a range of disciplinary silos who study surface fluxes (soil, vegetation, etc), atmospheric composition, and boundary layer dynamics. The breadth of the papers included in the issue represents research across this broad range of topics, and illustrates the immense diversity of research areas that are relevant for addressing knowledge gaps related to land-atmosphere interactions, feedbacks, and coupling. We hope that bringing all these topics together into a single special issue will help foster new cross-disciplinary collaborations between atmospheric and surface flux scientists by highlighting the types of questions, techniques, and frameworks employed by researchers in other fields, and the opportunities for synergy. A couple priorities that arose from the special issue were 1) establishing sensor networks to obtain measurements at higher spatial resolution and 2) collecting vertically-resolved measurements. The ultimate goal in bringing together these researchers was to explore the power of integrating approaches across these disciplines to probe questions related to land-atmosphere interactions that can only be answered by combining measurements and expertise across the different silos. A sub-set of papers in the SI directly addressed this goal. One notable example includes the paper by Beamesderfer et al., which integrated surface flux data, NWS radiosonde data, gridded atmospheric reanalysis products, and site-level lidar ceilometer data on cloud height and boundary layer height; coauthors came from a range of disciplinary specialties including atmospheric sciences, micrometeorology, climate science, geography, ecohydrology, and ecology. Recent papers from the GLAFO and LoCo communities likewise provide key examples of strong cross-disciplinary collaboration (Berg and Lamb, 2016; Santanello et al., 2018; Späth et al., 2023; Wulfmeyer et al., 2018). We anticipate that future advances in the field of land-atmosphere interactions will be facilitated by such collaborations. Importantly, this type of research can only be conducted with substantial financial support; feedback from participants at a virtual workshop on the same topic as this special issue highlighted that the instruments required to do this work (such as ceilometers) are expensive, and we need more funding opportunities that can support this science at the site-level and help build a coordinated network with similar observation platforms (Beamesderfer et al., 2022).

CRediT authorship contribution statement

C.L. Faiola: Conceptualization, Writing – original draft, Writing – review & editing. **M. Helbig:** Conceptualization, Writing – original draft, Writing – review & editing. **Y. Zhang:** Conceptualization, Writing – original draft, Writing – review & editing. **E.R. Beamesderfer:** Conceptualization, Writing – original draft, Writing – review & editing. **Z.M. Sanchez-Mejia:** Conceptualization, Writing – original draft, Writing – review & editing. **A.M. Yáñez-Serrano:** Conceptualization, Writing – original draft, Writing – review & editing. **A.D. Richardson:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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