

# Connecting Land-Atmosphere Interactions to Surface Heterogeneity in CHEESEHEAD 2019

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## Abstract

The Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors 2019 (CHEESEHEAD19) is an ongoing National Science Foundation project based on an intensive field campaign that occurred from June-October 2019. The purpose of the study is to examine how the atmospheric boundary layer responds to spatial heterogeneity in surface energy fluxes. One of the main objectives is to test whether lack of energy balance closure measured by eddy covariance (EC) towers is related to mesoscale atmospheric processes. Finally, the project evaluates data-driven methods for scaling surface energy fluxes, with the aim to improve model-data comparison and integration. To address these questions, an extensive suite of ground, tower, profiling, and airborne instrumentation was deployed over a 10×10 km domain of a heterogeneous forest ecosystem in the Chequamegon-Nicolet National Forest in northern Wisconsin USA, centered on the existing Park Falls 447-m tower that anchors an Ameriflux/NOAA supersite (US-PFa / WLEF). The project deployed one of the world’s highest-density networks of above-canopy EC measurements of surface energy fluxes. This tower EC network was coupled with spatial measurements of EC fluxes from aircraft, maps of leaf and canopy properties derived from airborne spectroscopy, ground-based measurements of plant productivity, phenology, and physiology, and atmospheric profiles of wind, water vapor, and temperature using radar, sodar, lidar, microwave radiometers, infrared interferometers, and radiosondes. These observations are being used with large eddy simulation and scaling experiments to better understand sub-mesoscale processes and improve formulations of sub-grid scale processes in numerical weather and climate models.

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## ABSTRACT

The Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors 2019 (CHEESEHEAD19) is an ongoing National Science Foundation project based on an intensive field campaign that occurred from June-October 2019. The purpose of the study is to examine how the atmospheric boundary layer responds to spatial heterogeneity in surface energy fluxes. One of the main objectives is to test whether lack of energy balance closure measured by eddy covariance (EC) towers is related to mesoscale atmospheric processes. Finally, the project evaluates data-driven methods for scaling surface energy fluxes, with the aim to improve model-data comparison and integration.

To address these questions, an extensive suite of ground, tower, profiling, and airborne instrumentation was deployed over a 10×10 km domain of a heterogeneous forest ecosystem in the Chequamegon-Nicolet National Forest in northern Wisconsin USA, centered on the existing Park Falls 447-m tower that anchors an Ameriflux/NOAA supersite (US-PFa / WLEF). The project deployed one of the world's highest-density networks of above-canopy EC measurements of surface energy fluxes. This tower EC network was coupled with spatial measurements of EC fluxes from aircraft, maps of leaf and canopy properties derived from airborne spectroscopy, ground-based measurements of plant productivity, phenology, and physiology, and atmospheric profiles of wind, water vapor, and temperature using radar, sodar, lidar, microwave radiometers, infrared interferometers, and radiosondes. These observations are being used with large eddy simulation and scaling experiments to better understand sub-mesoscale processes and improve formulations of sub-grid scale processes in numerical weather and climate models.

## CAPSULE SUMMARY

A regional-scale observational experiment designed to address how the atmospheric boundary layer responds to spatial heterogeneity in surface energy fluxes.

## INTRODUCTION

Land-atmosphere exchanges of energy, water, and carbon influence weather and climate. The biological processes that mediate these exchanges with the atmosphere occur at multiple spatial and temporal scales, necessitating a variety of cross-scale observational platforms. Accurate accounting of land-atmosphere interactions is critical for improving the predictive performance of numerical weather and climate models. Unfortunately, there is a persistent mismatch between the scales of observations and models. This scale mismatch is problematic because natural environments exhibit substantial heterogeneity in their surface characteristics, which means that observations are not always accurate reflections of the entire model grid cell. Furthermore, the atmosphere is strongly influenced by nonlinear two-way interactions with radiation, land cover, and soil, so that the spatial and temporal scaling of surface fluxes is fundamental to assessing the parameterizations used in atmospheric models to represent land-atmospheric interactions.

The notion that land surface heterogeneity influences the surface energy balance, and the resulting atmospheric responses, emerged from early model simulations showing the importance of soil moisture, vegetation, albedo, roughness, and heating on the atmosphere (Garratt 1993; Mahrt 2000; Betts et al. 1996; Charney 1975; Avissar 1995; Pielke et al. 1998). Theories on how land surface variations drive atmospheric boundary layer (ABL) growth vary (e.g., Desai et al. 2006; Reen et al. 2014; Platis et al. 2017; Gantner et al. 2017), with no consensus on whether responses scale linearly or non-linearly and whether they differ for dry versus moist dynamics (Raupach and Finnigan 1995). Modeling studies on this topic have been developed from limited sets of observations of prior field experiments and from specialized modeling domains using simplified boundary conditions (e.g., Kang et al., 2007; Hill et al., 2008, 2011; Zhu et al., 2016). From these previous studies, scaling laws have been derived based on numerical simulations (van Heerwaarden et al. 2014; Rihani et al. 2015), but a systematic regional-scale observational experiment that quantifies the multi-scale nature of sub-grid scaling and patterning has never been fully realized (Steinfeld et al. 2007).

An issue related to how heterogeneity influences transport processes in the ABL is the energy balance closure problem. This refers to an observed tendency in eddy covariance (EC) flux measurements, where the sum of incoming available energy (net radiation [ $R_N$ ] minus ground heat flux [ $G$ ]) exceeds surface turbulent sensible and latent heat fluxes ( $H_s$  and  $H_L$ ) over sub-hourly time scales (Foken et al. 2011). Systematic studies have ruled out instrument errors as the primary cause (Twine et al. 2000; Frank et al. 2013; Liu et al. 2011). Incomplete observation of sub-measurement height storage flux accounts for only some of this lack of closure (Leuning et al. 2012; Xu et al. 2018). Advection terms are not expected to have a systematic direction that would always lead to lack of closure (e.g., Aubinet et al. 2010; Barr et al. 2013; Nakai et al. 2014; Zitouna-Chebbi et al. 2012), while topography contributes mostly in extreme cases (Mcglain et al. 2018).

EC sites with more variable land cover tend to have larger closure imbalances (Stoy et al. 2013; Xu et al. 2017b). One proposed hypothesis for lack of closure in the energy budget is that surface heterogeneity generates mesoscale features not adequately resolved by traditional EC methods (e.g., Charuchittipan et al. 2014; Gao et al. 2016; Foken et al. 2011; Mauder et al. 2007b). An intensive suite of energy flux measurements between surface and atmosphere at the mesoscale (on the order of tens of kilometers) can help address this key uncertainty in land-atmosphere exchange (Xu et al. 2020).

## EXPERIMENTAL GOALS

CHEESEHEAD19 was designed to provide a new level of observation density and instrumentation reliability to test hypotheses on spatial heterogeneity and atmospheric feedbacks. The two main research objectives for the CHEESEHEAD19 experiment were to 1) investigate causes of energy balance non-closure over heterogeneous ecosystems and 2) to address the problem of scaling surface energy fluxes.

There is currently no definitive answer as to what is responsible for energy balance non-closure. The project was designed specifically to test the hypothesis that heterogeneity is responsible for generating organized (sub-)mesoscale structures that are not resolved by traditional EC methods.

Various theories suggest that “spatial” EC, where multiple towers are combined to estimate the mesoscale contribution to the total flux, could be used to analyze this contribution and “close” the energy balance (Steinfeld et al. 2007; Mauder et al. 2008b). To calculate spatial fluxes, CHEESEHEAD19 deployed an EC tower network and airborne EC measurements. These measurements provide spatial patterns of surface energy fluxes across various vegetation and surface types in the heterogeneous landscape. Alongside this EC flux network, multiple platforms were deployed to characterize the atmospheric environment by profiling relevant atmospheric characteristics across a range of scales. This allows us to determine the existence and to characterize the nature of organized mesoscale structures. We can investigate the degree to which mesoscale eddies are responsible for energy balance non-closure in EC measurements, and whether land surface energy partitioning and atmospheric responses differ from the sum of their individual components.

To systematically address surface energy balance variability in the heterogeneous forested landscape, a pre-campaign large eddy simulation (LES) analysis of the study domain was conducted. It was found that, while 12 flux towers would be sufficient to adequately sample land cover variation, >15 flux towers are required to sample mesoscale eddy structures and close the energy budget (a similar result to Steinfeld et al., 2007). Therefore, the CHEESEHEAD19 field campaign deployed 20 flux towers, a marked increase over many previous experiments.

CHEESEHEAD19 asks how we can optimally observe and simulate the terms of the surface energy balance and the corresponding atmospheric responses to heterogeneous surface forcings. The objective is to evaluate methods for scaling surface energy fluxes, with the aim of improving model-data comparisons. To this end, we conduct LES and machine-learning scaling experiments to simulate sub-mesoscale responses. These will be compared to measured quantities to test existing theoretical concepts and to improve our understanding of how scale-dependent transport processes in the lower atmosphere respond to surface heterogeneity. The dataset collected during this study will help test multiple scaling methodologies across heterogeneous land cover. Specifically, it aims to test the *environmental response function - virtual control volume* (ERF-VCV) approach (Metzger 2018; Xu et al. 2018), which combines the strengths of both data-driven and mechanistic strategies.

Several additional research objectives are addressed by using the unique data resources of CHEESEHEAD19. These include a separately funded study to use CO<sub>2</sub> fluxes of Integrated Surface Flux System (ISFS) towers and hyperspectral imagery of canopy functional traits to determine the principal drivers of variation in NPP and carbon use efficiency across a broad array of forest ecosystems. Additionally, concurrent measurements of ozone (O<sub>3</sub>) mixing ratios at 30- and 122-m on the tall tower were made using a chemical ionization time-of-flight mass spectrometer (CI-ToFMS; TOFWERK AG and Aerodyne Research Inc.) and a photometric analyzer (Model 49i; Thermo Fisher) to obtain vertical O<sub>3</sub> profiles above the forest canopy

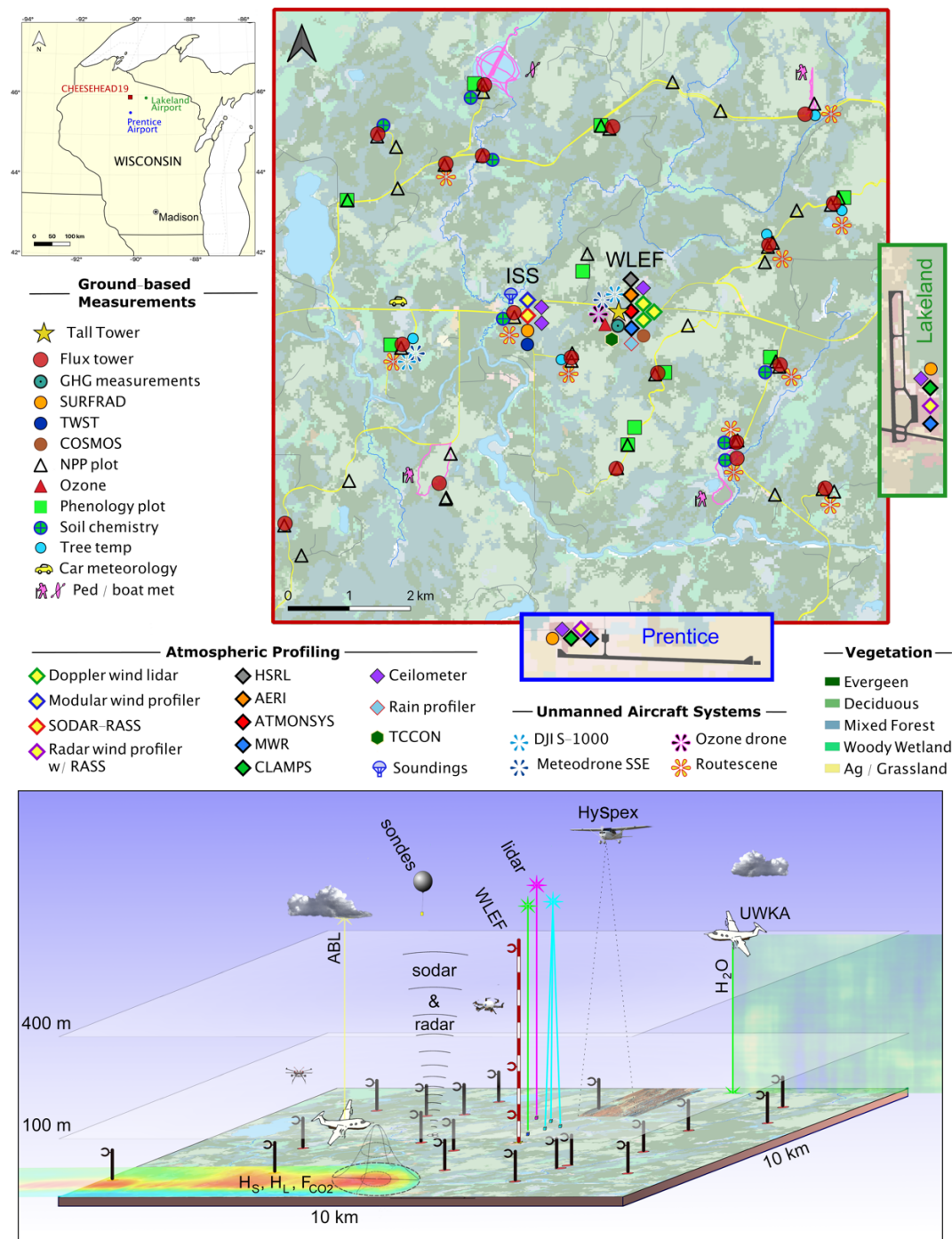
(Bertram et al. 2011; Novak et al. 2020). These measurements were accompanied by flights of a sUAS-mounted lightweight O<sub>3</sub> monitor (POM; 2B) that obtained vertical concentration gradients. These measurements are being used to determine the relative contributions of stomatal uptake and other nonstomatal loss pathways to O<sub>3</sub> deposition within a mixed forest canopy.

## THE EXPERIMENT

### Overview

CHEESEHEAD19 investigators deployed an extensive suite of ground, tower, profiling, and airborne instrumentation over a 10 × 10 km domain in a forested and aquatic landscape in northern Wisconsin USA (Fig. 1; Table 1), centered on the existing Park Falls 447-m tower Ameriflux/NOAA supersite (US-PFa / WLEF). The main components of the CHEESEHEAD19 field campaign were:

- a) ground-based fluxes and meteorology
- b) airborne fluxes and meteorology
- c) atmospheric profiling
- d) surface environment characterization



**Fig. 1. Map and schematic diagram of CHEESEHEAD19 domain. Map shows the location of all measurements made during the field campaign. Insets show Lakeland and Prentice airports where SURFRAD (in addition to the one in ISS field), radar wind profilers with RASS, and CLAMPS systems were installed. Schematic diagram shows instrument location and a conceptual model of airborne data collection. (Wisconsin Department of Natural Resources 2019)**

The EC tower network consisted of 17 towers from the NSF Lower Atmosphere Observing Facility (LAOF) ISFS, two additional towers, and the central tall Ameriflux tower. Ground-based measurement of vegetation occurred at 41 plots in the domain, plus an additional 10 plots for measuring phenology. Airborne spectroscopy imaging was used to map leaf chemistry and canopy properties.

The suite of atmospheric profiling instruments included the LAOF Integrated Sounding System (ISS; Fig. 2c) and the UW SPARC system (Fig. 2a). Additional instrument systems were brought by collaborators, including the combined ATMONSYS lidar for measuring aerosol, T, and H<sub>2</sub>O profiles and two Doppler wind lidars brought by Karlsruhe Institute of Technology (KIT), two Collaborative Lower Atmospheric Profiling Systems (CLAMPS – NOAA NSSL), two 915 MHz radar wind profilers with radio acoustic sounding systems (RASS) with MWRs (NOAA PSL), and the Surface Radiation Budget Network (SURFRAD – NOAA GML) systems for measuring incoming and outgoing radiation and cloud properties. While many of these instruments were located within the 10 × 10 km CHEESEHEAD19 domain, some instruments were located at the Prentice and Lakeland airports, located approximately 45 km south and east of the WLEF tower respectively, to provide information on the spatial variability of boundary layer structure and cloud and radiation fields.

Three seven-day intensive observation periods (IOP) occurred on July 7 – 13, August 18 – 24, and September 22 – 28. During these IOPs the University of Wyoming King Air (UWKA) flew transects over an extended 30 × 30 km domain to measure EC fluxes, ABL depth, and atmospheric profiles of water vapor and temperature. These observations will be used to test flux tower scaling, observe atmospheric mesoscale patterning, and evaluate large eddy simulations (LES). Also, during the IOPs, a team from NOAA ARL ATDD brought multiple sUASs for measuring profiles of meteorological variables (T, H<sub>2</sub>O, U, P – see appendix for a list of variables used in this paper) and land surface temperature. Additional information on the spatial variations of surface meteorology was obtained using mobile observing systems operated in pedestrian, boat, and car modes.

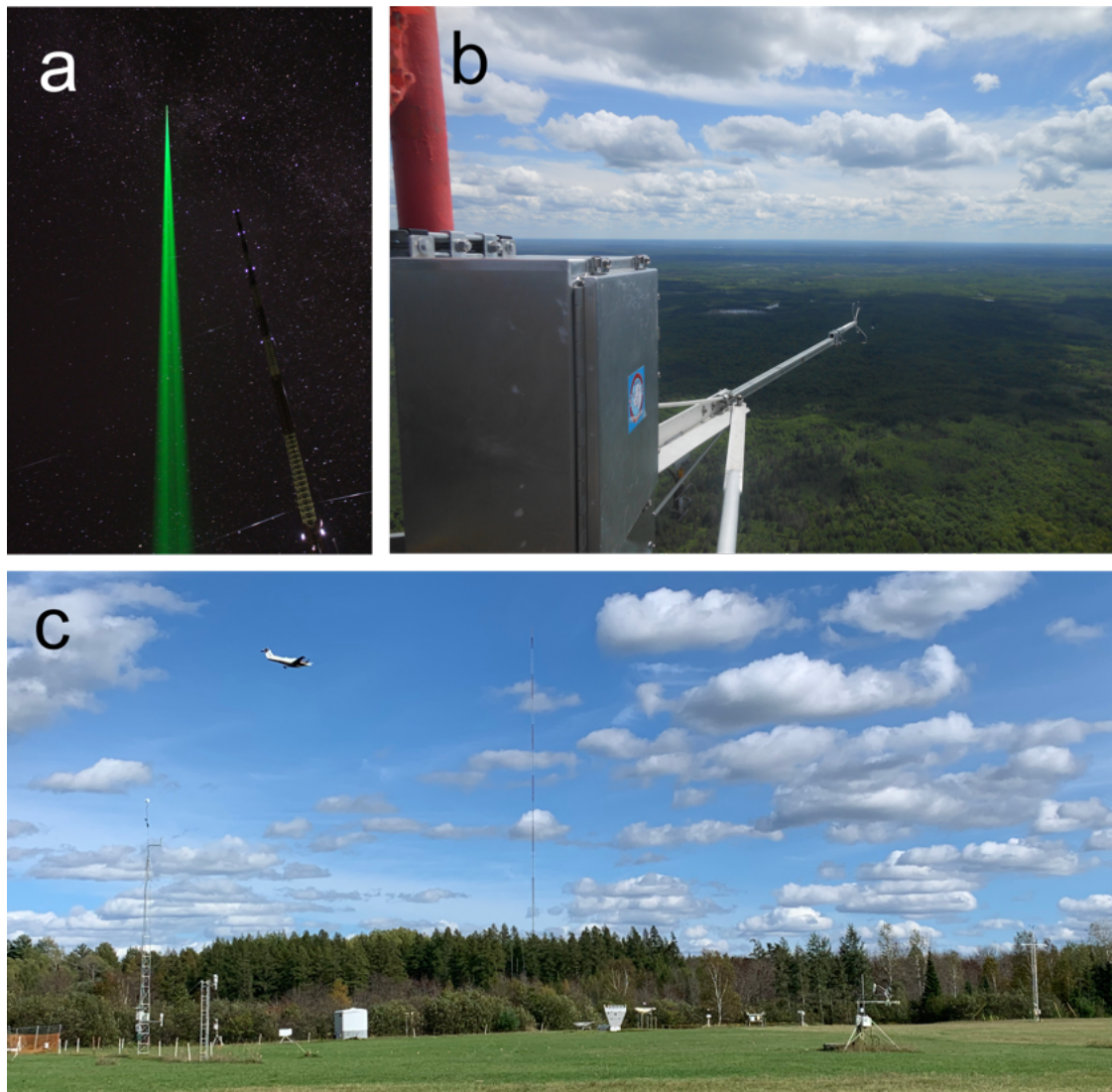
The four-month deployment spanned the summer to fall transition, capturing the shift in surface energy balance from a more uniform evapotranspiration (latent heat flux) dominated landscape to a patchy sensible heat flux dominated landscape. These energy balance shifts arise from seasonal changes in plant phenological phases, ecosystem water use for photosynthesis, and available net radiation. These shifts also provide a “natural experiment” with which to test hypotheses on how heterogeneity influences energy balance closure and spatial scaling.

The study domain was partly chosen due to the history of atmospheric science research in the region. Since 1995, University and NOAA investigators have sampled greenhouse gas profiles, meteorology, and EC flux measurements (energy, carbon, momentum) at 30 m, 122 m, and 396 m above ground level (AGL; Fig. 2b) on the WLEF tall tower (Bakwin et al. 1998; Davis et al. 2003). The site also includes an FTIR solar-pointing spectrometer (TCCON) for total greenhouse column observations operated by CalTech and NASA JPL. Two additional EC towers (US-WCr,



30 m in mature forest, and US-Los, 10 m in shrub fen wetland) have been operating for 20 years, approximately 20 km from the tall tower (Cook et al. 2004; Desai et al. 2005; Sulman et al. 2009).

CHEESEHEAD19 builds upon previous tower mesonet experiments, including BOREAS (Sellers et al. 1995), CASES99 (Poulos et al. 2002), SGP97 (Desai et al. 2006), IHOP (Kang et al. 2007), LITFASS-2003 (Beyrich et al. 2006), EBEX (Oncley et al. 2007), BEAREX (Anderson et al. 2012), HiWATER-MUSOEXE (Wang et al. 2015), SCALE-X (Wolf et al. 2017), that were aimed at understanding scaling of non-linear land-atmosphere interaction.



**Fig. 2. (a) HSRL beam next to WLEF tall tower, (b) EC instruments at 396 m AGL on the WLEF tall tower, and (c) the ISS field with modular wind profiler, sodar-RASS, ceilometer, SURFRAD, EC and meteorological towers with UWKA flying overhead and WLEF tall tower in the distance.**

**Table 1. List of instruments and data collected during CHEESEHEAD19. For explanation of the variable abbreviations please see the appendix.**

| Data source                                                     | Data provider            | Location(s)                                                                              | Measured Variables                                                                                                                                                                                                                                                                                                                  | Period                                                                 |
|-----------------------------------------------------------------|--------------------------|------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| <b>Ground-based Measurements</b>                                |                          |                                                                                          |                                                                                                                                                                                                                                                                                                                                     |                                                                        |
| Ameriflux/NOAA tall tower (US-PFa/WLEF)                         | UW AOS                   | WLEF                                                                                     | Hs, H <sub>L</sub> , F <sub>CO2</sub> , $\tau$ , R <sub>n</sub> , meteorology                                                                                                                                                                                                                                                       | Continuous                                                             |
| ChEAS Ameriflux towers: US-WCr / US-Los / US-Syv / US-Alq       | UW AOS                   | Ameriflux sites (4)                                                                      | Hs, H <sub>L</sub> , F <sub>CO2</sub> , $\tau$ , R <sub>n</sub> , meteorology                                                                                                                                                                                                                                                       | Continuous                                                             |
| ISFS Eddy covariance towers                                     | NCAR EOL ISFS            | 10x10 km (17 sites)                                                                      | Hs, H <sub>L</sub> , F <sub>CO2</sub> , $\tau$ , R <sub>n</sub> , meteorology, soil G, Q, Cv, T profile, precip (5 sites)                                                                                                                                                                                                           | June-Oct                                                               |
| MSU Eddy covariance towers                                      | Montana State U & UW BSE | NW5 (ISS) and SE1                                                                        | Hs, H <sub>L</sub> , F <sub>CO2</sub> , $\tau$ , R <sub>n</sub> , soil G, meteorology                                                                                                                                                                                                                                               | June-Oct                                                               |
| Surface meteorology                                             | NCAR EOL ISS             | ISS field                                                                                | T, RH, P, precip, wind, sky images                                                                                                                                                                                                                                                                                                  | July-Oct                                                               |
| SURFRAD & TWST                                                  | NOAA GML                 | ISS field <sup>1</sup><br>Prentice Airport <sup>2</sup><br>Lakeland Airport <sup>2</sup> | Downwelling SW/LW <sup>1,2</sup> , direct SW <sup>1,2</sup> , diffuse SW <sup>1,2</sup> , upwelling SW/LW <sup>1</sup> , PAR <sup>1</sup> , sky images <sup>1</sup> , cloud optical depth <sup>1</sup> , cloud fraction <sup>1,2</sup> , cloud base height <sup>2</sup> , mixed layer depth <sup>2</sup> , meteorology <sup>1</sup> | July-Oct (TWST: Sep-Oct)                                               |
| Vehicle/ Pedestrian/ Boat transects                             | Jackson State U          | 10x10 km – Roads/ Trails / Hay Lake                                                      | T, RH, P, total downwelling SW, IR brightness temperature, water T                                                                                                                                                                                                                                                                  | IOP 1, 2, 3                                                            |
| Chemical ionization mass spec & ozone photometric analyzer      | UW Chem                  | WLEF                                                                                     | Ozone concentration and flux                                                                                                                                                                                                                                                                                                        | IOP 1                                                                  |
| Tall tower greenhouse gases                                     | NOAA GML                 | WLEF                                                                                     | CO <sub>2</sub> , CH <sub>4</sub> concentration & CO <sub>2</sub> , CH <sub>4</sub> profiles                                                                                                                                                                                                                                        | Continuous & Biweekly                                                  |
| Tree temperature                                                | Chequamegon HS           | 5 sites, 10 trees                                                                        | T at breast height (1.37 m AGL)                                                                                                                                                                                                                                                                                                     | Oct                                                                    |
| <b>Atmospheric Profiling</b>                                    |                          |                                                                                          |                                                                                                                                                                                                                                                                                                                                     |                                                                        |
| 449 MHz modular wind profiler                                   | NCAR EOL ISS             | ISS field                                                                                | 3D wind profiles                                                                                                                                                                                                                                                                                                                    | July-Oct                                                               |
| Sodar / RASS                                                    | NCAR EOL ISS             | ISS field                                                                                | 3D wind, T <sub>v</sub> and $\theta_v$ profiles                                                                                                                                                                                                                                                                                     | July-Oct                                                               |
| Ceilmeter                                                       | NCAR EOL ISS             | ISS field                                                                                | Attenuated backscatter profiles, cloud base height, ABL height                                                                                                                                                                                                                                                                      | July-Oct                                                               |
| Daily radiosonde                                                | NCAR EOL ISS             | ISS field                                                                                | 18Z (1pm local)                                                                                                                                                                                                                                                                                                                     | July-Oct                                                               |
| 3-hourly daytime radiosondes                                    | NCAR EOL ISS             | ISS field                                                                                | 4-5 per day for 5 days per IOP                                                                                                                                                                                                                                                                                                      | IOP 1, 2, 3                                                            |
| AERI                                                            | UW SSEC<br>SPARC         | WLEF                                                                                     | Downwelling IR radiance, profiles of T, H <sub>2</sub> O, and cloud properties                                                                                                                                                                                                                                                      | July-Oct                                                               |
| HALO Lidar (1) – vertical stare                                 | UW SSEC<br>SPARC         | WLEF                                                                                     | Profiles of 3D wind (virtual tower)                                                                                                                                                                                                                                                                                                 | July-Oct                                                               |
| HSRL                                                            | UW SSEC<br>SPARC         | WLEF                                                                                     | Backscatter, depolarization                                                                                                                                                                                                                                                                                                         | July-Oct                                                               |
| Micro Rain Radar (MRR)                                          | UW SSEC                  | WLEF                                                                                     | Precipitation rate, reflectivity, particle size distribution (PSD)                                                                                                                                                                                                                                                                  | July-Oct                                                               |
| Precipitation Imaging Package                                   | UW SSEC                  | WLEF                                                                                     | PSD, fall speed, rain rate                                                                                                                                                                                                                                                                                                          | July-Oct                                                               |
| ATMONSYS: Backscatter, Raman, and Differential Absorption Lidar | KIT IMK-IFU              | WLEF                                                                                     | Vertical profiles of aerosol backscatter, T, H <sub>2</sub> O                                                                                                                                                                                                                                                                       | July-Sep                                                               |
| HALO Lidars (2,3) – RHI scans                                   | KIT IMK-IFU              | WLEF                                                                                     | Profiles of 3D wind (virtual tower)                                                                                                                                                                                                                                                                                                 | July-Sep                                                               |
| 915 MHz radar wind profiler w/ radio acoustic sounding system   | NOAA PSL                 | Prentice Airport, Lakeland Airport                                                       | Profiles of U, T <sub>v</sub> , Convective ABL height                                                                                                                                                                                                                                                                               | July-Oct                                                               |
| MWR                                                             | NOAA PSL                 | ISS field <sup>1</sup><br>Prentice Airport <sup>2</sup><br>Lakeland Airport <sup>3</sup> | Downwelling microwave radiance, profiles of T, H <sub>2</sub> O, and liquid water path                                                                                                                                                                                                                                              | July-Oct <sup>3</sup><br>July-Sep <sup>2</sup><br>Sep-Oct <sup>1</sup> |
| CLAMPS (MWR, AERI, Doppler wind lidar)                          | NOAA NSSL                | Prentice Airport, Lakeland Airport                                                       | Profiles of U, T, H <sub>2</sub> O                                                                                                                                                                                                                                                                                                  | Sep-Oct                                                                |
| <b>Airborne Measurements</b>                                    |                          |                                                                                          |                                                                                                                                                                                                                                                                                                                                     |                                                                        |
| Airborne eddy covariance                                        | UWKA                     | 30x30km, 24 flights                                                                      | 3D wind, T, H <sub>2</sub> O, CO <sub>2</sub> (25 Hz; ~3 m)                                                                                                                                                                                                                                                                         | IOP 1, 2, 3                                                            |
| Airborne met. and radiation                                     | UWKA                     | 30x30km, 24 flights                                                                      | Meteorology (1 Hz; ~80 m)                                                                                                                                                                                                                                                                                                           | IOP 1, 2, 3                                                            |

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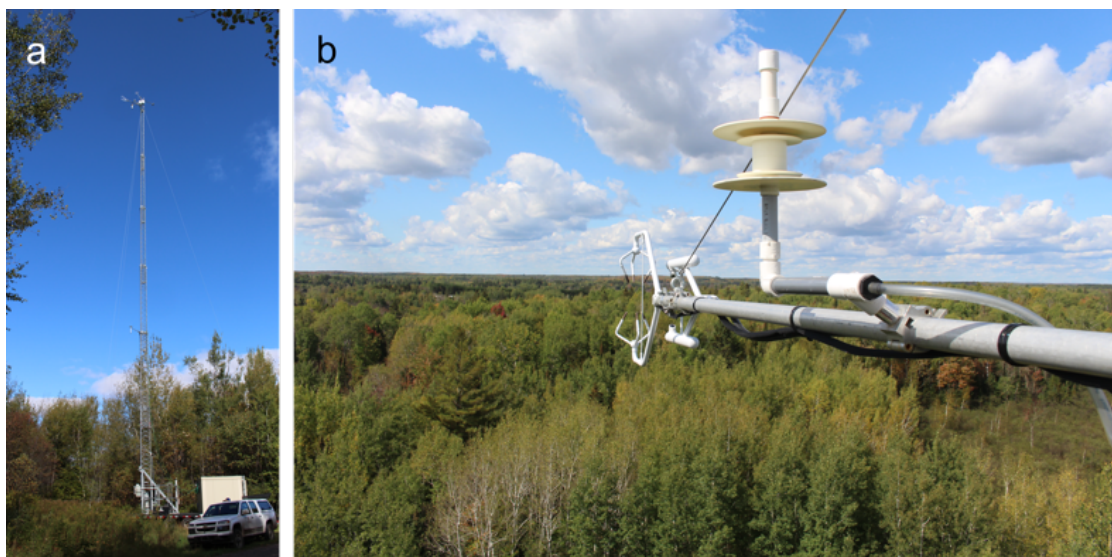
|                           |               |                     |                          |             |
|---------------------------|---------------|---------------------|--------------------------|-------------|
| Compact Raman Lidar (CRL) | UWKA          | 30x30km, 24 flights | H2O and T cross sections | IOP 1, 2, 3 |
| Wyoming Cloud Lidar (WCL) | UWKA          | 30x30km, 24 flights | ABL height               | IOP 1, 2, 3 |
| Meteorodrone SSE sUAS     | NOAA ARL ATDD | WLEF and SW2        | T, H2O, U                | IOP 1, 2, 3 |
| Ozone sUAS                | UWEC          | WLEF                | O <sub>3</sub> profiles  | IOP 1       |

#### Surface Environment

|                                     |                   |                     |                                                                                   |           |
|-------------------------------------|-------------------|---------------------|-----------------------------------------------------------------------------------|-----------|
| HySpex                              | UW FWE            | 10x10 km, 4 flights | hyperspectral imagery (474 bands), foliar functional traits                       | June-Aug  |
| DJI S-1000 (sUAS)                   | NOAA ARL ATDD     | WLEF and SW2        | LST, Hs                                                                           | IOP 1, 2  |
| sUAS leaf-on canopy LiDAR           | UW Geog           | 11 tower sites      | Ground and canopy height                                                          | June      |
| QL2 leaf-off LiDAR                  | USFS              | 30x30 km            | Ground and canopy height                                                          | Fall 2018 |
| Vegetation/phenology sampling       | UWM Geog          | 10x10 km (10 plots) | Leaf color / fall level                                                           | Sep-Oct   |
| Vegetation Sampling                 | UW FWE            | 10x10 km (41 plots) | inventory, root growth, NPP, biometry, leaf spectra, foliar tissue chemistry, LMA | June-Oct  |
| Soil bulk density and heat capacity | NCAR EOL          | 17 tower sites      | Q <sub>soil</sub> , ρ <sub>soil</sub>                                             | July-Oct  |
| Soil samples                        | UW AOS            | 16 tower sites      | Soil carbon, nitrogen                                                             | Oct       |
| Soil samples                        | Butternut Schools | 7 sites             | Soil and water chemistry                                                          | July      |
| ECOSTRESS, GEDI, OCO3               | NASA JPL          | 30x30 km            | LST, emissivity, evapotranspiration                                               | Oct 8     |

### Ground-based Measurements

Towers sampled three-dimensional wind velocity, temperature, moisture, and CO<sub>2</sub> at 20 Hz to measure land-atmosphere fluxes ( $\tau$ , H<sub>s</sub>, H<sub>L</sub>, F<sub>CO<sub>2</sub></sub>). Each tower also measured net radiation, soil heat flux at 5 cm depth (and soil temperature profile, heat capacity, and moisture to determine soil heat storage), and a 3-level air temperature and humidity profile to estimate canopy heat storage. A majority of the sites were forested and had flux instruments mounted 33 m AGL (Fig. 3; Table S1). Instruments for wetland, grass, and lake sites were mounted between 1 – 3 m AGL to maintain consistent vegetation within the flux footprint. Tower placement within the 10 × 10 km study domain followed a stratified random grid pattern, taking into account practical considerations including distance to road, suitable gap in trees for a tower, USFS-owned land, etc. Individual towers were an average of 1.4 km from their nearest neighboring tower and an average of 3.5 km from the tall tower. This meant that under certain conditions (e.g., high wind speeds, stable stratification) several of the towers shared overlapping flux footprints; a favorable condition for applying some of the data-driven scaling methods used in the project. Additionally, the semi-random placement meant that the towers were not chosen by distributing the towers in the centers of the most homogeneous areas of the various land cover types. Thus, within the individual footprint of each tower there was often spatial variability in vegetation height and type (deciduous vs. evergreen). While this can complicate analyses of flux measurements, it generates more representative data from these types of mixed forests. Furthermore, we expect it will enhance the ability of the data-driven methods for estimating domain-wide fluxes.



**Fig. 3. (a) EC tower SW1 – an example of the 33 m AGL telescoping towers deployed by NCAR ISFS and (b) EC instruments mounted at the top of tower SW2.**

A suite of high-quality radiation sensors was deployed in the ISS field as a complement to the net radiometers installed on each flux tower. The full suite included high-quality upwelling and downwelling broadband surface radiation measurements to determine the surface radiation budget, as well as ancillary measurements of meteorological parameters, photosynthetically active radiation (PAR), and clouds as described in Table S2. Radiation measurements are manually screened and then processed through an automated data quality procedure (Long and Shi 2008). Clear sky radiation fluxes are estimated using the Radiative Flux Analysis method (Long and Ackerman 2000; Long and Turner 2008), from which derivation of cloud radiative effects as well as other data products such as fractional sky cover (Long et al. 2006; Dürr and Philipona 2004) and cloud optical depth (Barnard and Long 2004; Niple et al. 2016) are calculated. Measurements of cloud properties will allow us to quantify their impacts on the radiative and turbulent heat fluxes to better understand the two-way coupling between cloud-radiative interactions and boundary layer evolution, and to investigate the effect on EC non-closure.

A smaller suite of radiation, cloud, and surface meteorological measurements were deployed at the Prentice and Lakeland Airports, approximately 45 km south and east from the ISS field, respectively (Fig. 1), to characterize the larger spatial scale inhomogeneities. These measurements include downwelling shortwave and longwave irradiance as well as diffuse and direct components of shortwave irradiance (Table S2); sufficient information to derive cloud radiative effects and fractional sky cover using the Radiative Flux Analysis method described above. Ceilometers deployed at the two airport sites provided additional cloud and boundary layer information.

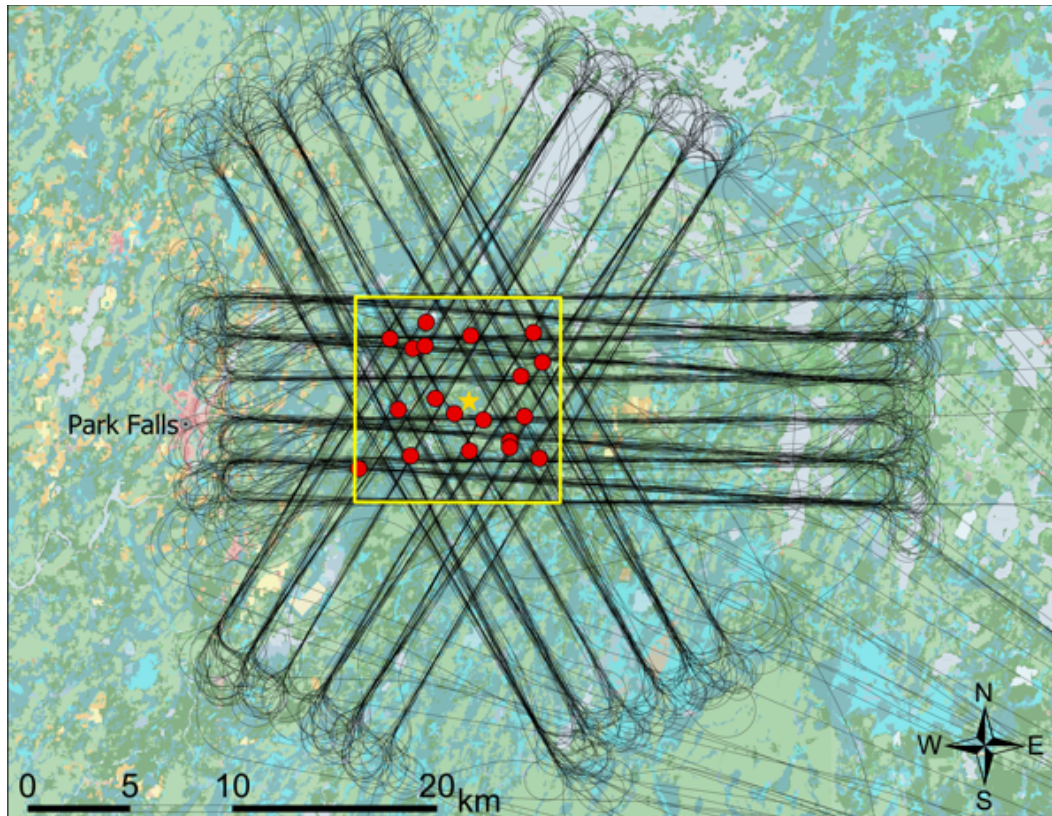
## Airborne Measurements

During each IOP the UWKA flew over the study area to measure spatial EC fluxes of heat, water vapor, and CO<sub>2</sub>. The purpose of the observations was to test flux tower scaling and observe atmospheric mesoscale patterning. The UWKA also measured cross-sectional profiles of water vapor and temperature below the flight level using a downward pointing Compact Raman Lidar (CRL, Wu et al. 2016) and ABL depth with the upward looking Wyoming Cloud Lidar (WCL, Wang et al. 2009).

Flights over the domain occurred on four days during each of the three IOPs (Table S3). On each day there were two three-hour flights, one in the morning (1400 – 1700 UTC) and one in the afternoon (1900 – 2200 UTC). Flights consisted of ten 30-km down-and-back transects across the domain. The first leg of each transect was flown at 400 m AGL, while the return leg was flown at 100 m AGL. Flight transects alternated between straight and diagonal passes.

Three different flight patterns were determined prior to the experiment (oriented SE→NW, SW→NE, and W→E). Flying them either in forward or reverse order resulted in six distinct flight sequences that maximize data coverage under different wind conditions (see sidebar *Continuity through Environmental Response Functions*). The main objectives were to maximize 1) the number of independent atmospheric eddies and 2) surface flux footprint observed by the aircraft EC measurements, while 3) ensuring crew safety. This was achieved by designing a parsimonious set of only three flight patterns that allowed the UWKA to fly perpendicular to the prevailing winds within a range of  $\pm 45^\circ$  on any given day (Metzger et al., in preparation). The 30-km flight legs extended an average of 10 km beyond the domain to compute a robust mesoscale eddy flux (Mauder et al. 2007a, 2008a) by capturing enough eddies and mesoscale variation to properly compute statistics for fluxes using the wavelet decomposition method.

The low-altitude legs were primarily used to measure EC fluxes. The altitude 100 m AGL was chosen to ensure flux measurements were made in the surface layer, as well as to minimize flux footprint errors over the  $10 \times 10$  km sampling domain. It was also the lowest altitude deemed safe to fly, as canopy height extended up to 35 m. The low-altitude legs were also used to identify ABL depth with the upward pointing 355 nm WCL. The primary purpose of the high-altitude legs (400 m AGL) was to map temperature and moisture profiles of the atmosphere with the CRL. These data were collected to estimate mesoscale development and calculate flux divergence and storage terms.



**Fig. 4. The location (superimposed) of all 480 flight legs completed during the CHEESEHEAD19 field campaign. The yellow square represents the study domain and the red dots indicate the flux tower locations.**

## Atmospheric Profiling

Characterizing the mesoscale environment over the study domain was accomplished with a range of platforms and instruments to measure profiles of wind, water vapor, temperature, aerosols, and gases at different temporal and spatial scales (Fig. 1; Table 1).

The NCAR ISS was located in a field 1.6 km west of the tall tower ( $45.946^{\circ}\text{N}$ ,  $90.294^{\circ}\text{W}$ ). It deployed a radar wind profiler, sodar-RASS, ceilometer, all-sky camera, and a surface meteorology station to measure ABL depth, winds, water vapor, and temperature. The 449 MHz modular wind profiler measured 30-minute wind profiles with 150 m vertical resolution up to several km AGL, while the sodar-RASS was capable of higher resolution (20 m; 10-minute), but only penetrated to  $\sim 400$  m AGL. Meteorological profiles were also measured with 172 radiosonde launches (daily 18Z soundings and 3 – 4 additional soundings on IOP days). These instruments characterized the ABL from nocturnal boundary layer (sunrise sounding), through ABL development (mid-morning and afternoon), to peak ABL (late afternoon sounding). In mid-September, one of the MWRs located at the Prentice Airport was relocated to this location, due to the failure of the AERI at the tall tower site in early September.



Several profiling systems were deployed at the base of the tall tower. SPARC (Wagner et al. 2019) was located 50 m north of the WLEF tower and was equipped with an Atmospheric Emitted Radiance Interferometer (AERI, a zenith-pointing infrared radiometer [Knuteson et al. 2004]), a High-Spectral Resolution Lidar (HSRL [Eloranta 2005]), and a ceilometer. Profiles of boundary layer temperature and humidity were retrieved from the AERI radiance observations (Turner and Löhnert 2014; Turner and Blumberg 2019). The HSRL sampled ABL aerosol backscatter and depolarization ratio at 532 nm and 1064 nm. The ceilometer provided an additional measure of ABL depth.

The ATMONSYS system was placed beside the SPARC system, measuring atmospheric water vapor, temperature, and aerosol. The primary light source of the ATMONSYS lidar is a 100 Hz diode pumped Nd:Yag laser with the harmonic generation of 532 nm and 355 nm. The 532 nm light ( $P \approx 27$  W) is used for optical pumping a Ti:Sapphire laser, generating 817 nm ( $P \approx 2$  W) for water vapor profiling with the high resolving DIAL (Differential Absorption Lidar) method as well as for profiling aerosol backscatter. The 355 nm light is used for temperature profiling from rotational Raman backscatter. The system setup as installed during CHEESEHEAD19 (Vogelmann et al. 2020) allows for spatial sampling of 7.5 m and integration times of 20 s for aerosols and water vapor measurements and 300 s for temperature profiling.

In the field to the east of the trailers were three Doppler wind lidars. One lidar (LVS) measured in vertical stare mode throughout the measurement campaign. The other two lidars (LA, LB) were placed 90 meters away from the LVS and made range–height indicator (RHI) scans ( $66^\circ$  –  $87^\circ$  elevation angle) pointing towards the LVS. This setup constitutes a virtual tower that provides vertical wind speed measurements and calculates average horizontal wind speed at multiple height levels above the LVS (Calhoun et al. 2006; Klein et al. 2015; Wulfmeyer et al. 2018). Additionally, the collocation of lidars for measuring 3D winds, temperature, and water vapor facilitates calculation of flux profiles of  $\tau$ ,  $H_s$ , and  $H_L$ , as well as flux divergence (Wulfmeyer et al. 2016).

Two precipitation instruments (a Precipitation Imaging Package [PIP] and a Micro Rain Radar Pro [MRRPro; Metek GmbH]) were installed at WLEF. The PIP is a video disdrometer system that records information about hydrometers and produces end user products such as particle size distributions, fall speeds, and rain rate at one-minute resolution (Newman et al., 2009; Pettersen et al., 2020a; Pettersen et al., 2020b). The MRRPro is a 24-GHz, frequency modulated continuous wave, vertically profiling Doppler radar (Klugmann et al. 1996) that is used for observations of both rain (i.e., Peters et al. 2002) and snow (Kneifel et al. 2011).

Additional thermodynamic profiling systems were operated at the Prentice and Lakeland airports throughout the experiment to characterize the boundary layer variability and evolution around the CHEESEHEAD19 domain. The primary motivation of these two profiling sites was to characterize the mesoscale transport and role of advection on the ABL mass balance of the CHEESEHEAD19 domain. At each location, a 915 MHz wind profiler with radio acoustic sounding system was deployed together with a multi-channel MWR. These instruments

provided profiles of horizontal wind and temperature, and low vertical resolution profiles of water vapor.

Prior to IOP3, two mobile CLAMPS facilities (Wagner et al. 2019) were deployed at Prentice and Lakeland. The systems contained a Doppler lidar wind profiler, an AERI, and a microwave radiometer (MWR). The information content in the AERI observations is higher than in the MWR, and thus the retrieved water vapor and temperature profiles have better vertical resolution and accuracy (Löhnert et al 2009; Blumberg et al. 2015). The Doppler lidars complemented the radar wind profilers by providing higher temporal and vertical resolution measurements than the radars, but the radars were able to profile winds several km higher than the lidars.

Two small unoccupied aircraft systems (sUAS) were flown to characterize surface and near-surface conditions (Fig. S1). During IOP1 (IOP2), a DJI S-1000 (e.g., Lee et al. 2019) was flown adjacent to the SW2 tower (WLEF tall tower) to quantify the variability in surface sensible heat flux (e.g., Lee et al. 2017). During all three IOPs, the Meteomatics Meteodrone SSE sUAS was used to sample the evolution of near-surface profiles of temperature, moisture, and wind up to 213 m AGL, which was the maximum altitude to which we could operate our sUAS per our cooperative agreement with the FAA. Additionally, the Meteodrone SSE was used to sample the horizontal variability in temperature, moisture, and wind fields over a  $\sim 100 \times 100$  m box surrounding the SW2 and WLEF towers. Over all IOPs, 26 (103) flights were conducted with the DJI S-1000 (Meteodrone SSE).

## Surface Environment

Data on the ecological environment were collected to provide the boundary conditions of canopy type, activity, and stress, needed for estimating scaling properties. This was done with a variety of methods, including airborne imaging spectroscopy, ground-based phenological characterization, and tree growth measurements.

Foliar functional traits such as leaf mass per area (LMA) and nitrogen concentration strongly influence photosynthetic capacity and plant growth (i.e., net primary production, NPP) (Niinemets 2001; Kattge et al. 2009), and can be mapped using imaging spectroscopy (aka hyperspectral remote sensing, Singh et al. 2015). To map foliar functional traits across the domain a full-range imaging spectroscopy system comprising two co-aligned imagers (VNIR-1800 and SWIR-384; HySpex, Skedsmokorset, Norway) was operated from a Cessna 210 at 1400 m AGL on four days (6/26, 7/11, 8/4, 8/30), producing images with 1 m spatial resolution. The HySpex collects 474 bands with a spectral resolution of 3.26 nm in the VNIR (400-1000 nm) and 5.45 nm in the SWIR (1000-2500 nm).

Extensive ground-based vegetation samples were collected to support the hyperspectral image analyses. These included 41 plots in the domain for measuring tree species (400+ trees), root growth, tree height, diameter at breast height (DBH), net primary production (NPP), biometry, leaf area index (LAI). This also included 122 top-of-canopy foliar samples to estimate leaf level function traits following the protocol from Serbin et al. (2014).

This work has been submitted to the Bulletin of the American Meteorological Society.

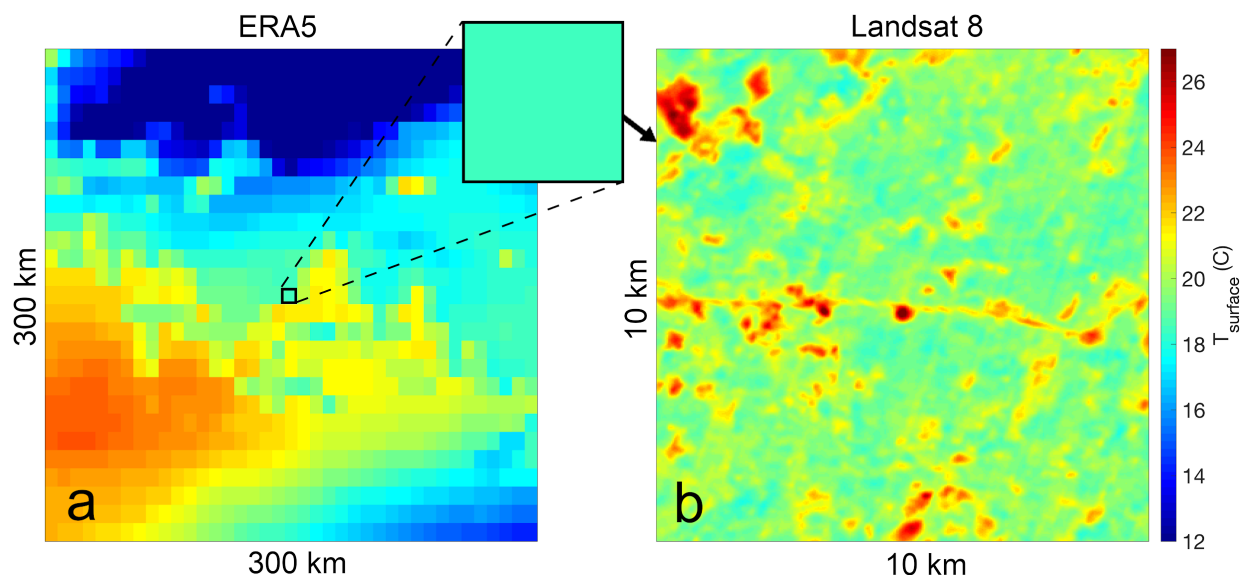
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In combination with an existing extensive database of foliar traits and image spectra (Wang et al. in press), we will use the 122 foliar samples to develop and validate 1 m resolution maps for all four dates of numerous foliar functional traits hypothesized to influence NPP, including LMA, nitrogen concentration, chlorophyll and other pigments, phosphorus, non-structural carbohydrates, fiber and lignin, and phenolics). From this, we will test the relationship between functional traits and GPP (as derived from towers) and peak-season integrated NPP (early-July to early-September, derived from the 41 plots). We will generate 1 m maps of NPP and GPP, and identify the foliar factors that most influence each.

Additional plots were used to measure vegetation phenology as it changed through the season, building upon several years of previous phenological observations collected in the domain. Autumn tree leaf color and fall phenology levels were visually observed and recorded at least twice weekly over six weeks during the senescence period (Sep 1 to Oct 25) for a group of 214 individual trees (at ten sites distributed over the 10 × 10 km area) that were representative of the major species.

Forest canopy structure was characterized using an sUAS-based lidar system (Routescene; Edinburgh, Scotland) acquiring high density point clouds (500 pts m<sup>-2</sup>) within footprints from 11 CHEESEHEAD19 flux tower sites including aspen, pine, poplar, larch, cedar, and hardwood forests. Areas surveyed ranged between 0.25 – 1 km<sup>2</sup> per site. Additional canopy information for the entire domain came from leaf-off LiDAR from USFS sampling (1 m<sup>2</sup> resolution) conducted for the three counties that comprise the study area between 2014 and 2017.

Land surface temperature (LST) is a key environmental driver of the surface energy balance (e.g., Metzger et al., 2013; Xu et al. 2017a). Spatially explicit LST can be acquired from satellite remote sensing (Fig. 5). However, there are tradeoffs in space and time resolutions such that no single sensor provides sufficient resolution for use as a land surface driver to map heat fluxes across space at sub-kilometer and hourly time steps required for the hypotheses here. Also, remote sensing methods may not be able to distinguish between true surface temperature and upper canopy temperature. Here, we are investigating multi-sensor fusion using a combination of in situ thermal drone and infrared camera imagery, ECOSTRESS, Landsat, VIIRS and/or GOES (Wu et al. 2013).



**Fig. 5. Land surface temperature on June 15, 2019 from (a) ERA5 reanalysis and (b) derived from Landsat 8, where sub-grid spatial resolution is present, but temporal resolution is low (Gerace et al. 2020; Landsat 8 data courtesy of the U.S. Geological Survey; ERA5 data generated using Copernicus Climate Change Service Information 2020).**

### *Data Analysis & Modeling*

Two analytical methods have been proposed to test the hypotheses of this study. The first is the application of ERF-VCV – a data driven approach that can be used to account for the dispersive fluxes missed by single-tower EC measurements, and to upscale fluxes across the CHEESEHEAD19 domain (Metzger, 2018, Xu et al., 2018, Xu et al., 2020). ERF-VCV uses a machine learning algorithm to find relationships between measured fluxes and their meteorological and surface drivers within the flux footprints (see sidebar).

We will perform LES for the IOP days using the Parallelized LES Model PALM (Raasch and Schröter 2001; Maronga et al. 2015; 2020). In the LES we will emulate airborne- and tower-mounted flux observations to compare them against the ‘real-world’ observations with the ability to also evaluate flux footprints using Lagrangian particle modelling, radiation footprints, storage fluxes at various locations and points in time. To accurately simulate the physical processes as observed during the IOPs of the field experiment as realistically as possible, we will assume realistic topography for the experiment site, and apply a Land Surface Model (LSM) with a coupled soil and radiation model, as well as a Plant Canopy Model (PCM). The use of the LSM and PCM runs instead of prescribed surface fluxes will allow us to study land-atmosphere feedbacks such as self-reinforcement of mesoscale circulations over the heterogeneous study domain. The LSM will be set up for each IOP test case, with land use classes, soil, and



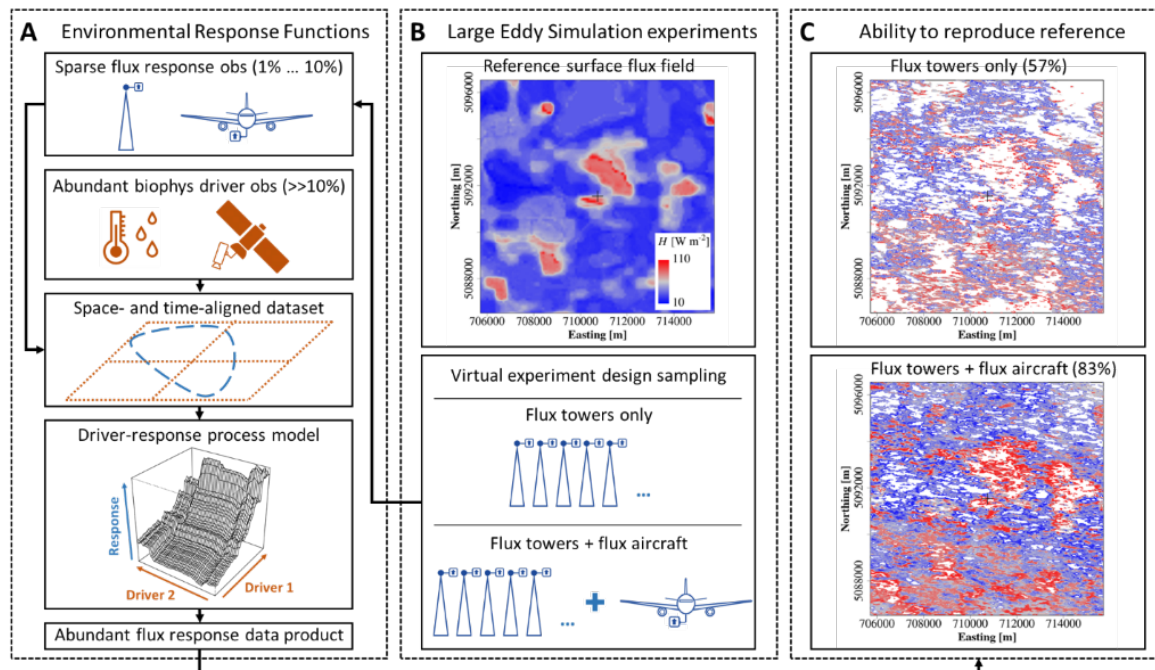
vegetation data as observed during the field experiment. Further, in order to account for synoptic-scale processes during the IOPs (e.g., advection of air masses with different characteristics) we will nest the LES domain into a larger-scale model.

One proposed goal is to derive a parametric heterogeneity correction of dispersive fluxes by setting up virtual towers within the LES, applying it to CHEESEHEAD19 tower flux field data, and evaluating it with ERF-VCV flux grids. Therefore, tower-level turbulence characteristics will be simulated as observed during the field campaign to investigate the energy balance non-closure problem. Additionally, by emulating 'real-world' measurements we intend to help interpret the observations – such as giving hints where secondary circulations occur or how far heterogeneity signals extend downwind.

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## **SIDEBAR: CONTINUITY THROUGH ENVIRONMENTAL RESPONSE FUNCTIONS**

CHEESEHEAD19 disentangles how land surface heterogeneity relates to atmospheric transport in mesoscale eddies, which contributes to the discrepancy between EC flux observations and model predictions. We strive to create a new class of observational flux data product that reconciles resulting biases on orders of 10% (Chen et al. 2011; Foken et al. 2011) and reveals actual surface emissions. For non-uniform exchange surfaces such as in CHEESEHEAD19, this requires us to evaluate the conservation of mass and energy continuously in time and space throughout the study domain (e.g., Finnigan 2008). However, even intensive field instrumentation campaigns such as CHEESEHEAD19 cannot produce observations everywhere, all the time. Here, Environmental Response Functions (ERF; Metzger et al. 2013; Metzger 2018) can help attain the necessary information continuum from individual observation plots to model grid scale. To achieve this, ERFs complement information across disciplines and observation types by using a machine learning algorithm to find relationships between measured fluxes and their meteorological and surface drivers within the flux footprints (Fig. 6A). This provides a powerful approach not only for post-field data synthesis, but already in the experiment planning stage e.g. in combination with Large Eddy Simulations (Fig. 6B). Maximizing scientific return on experimental investment (Fig. 6C; Metzger et al., in preparation) is one example of how ERFs can help close the circle among obtaining “knowledge from data” and “data from knowledge” (Reichstein et al. 2019).



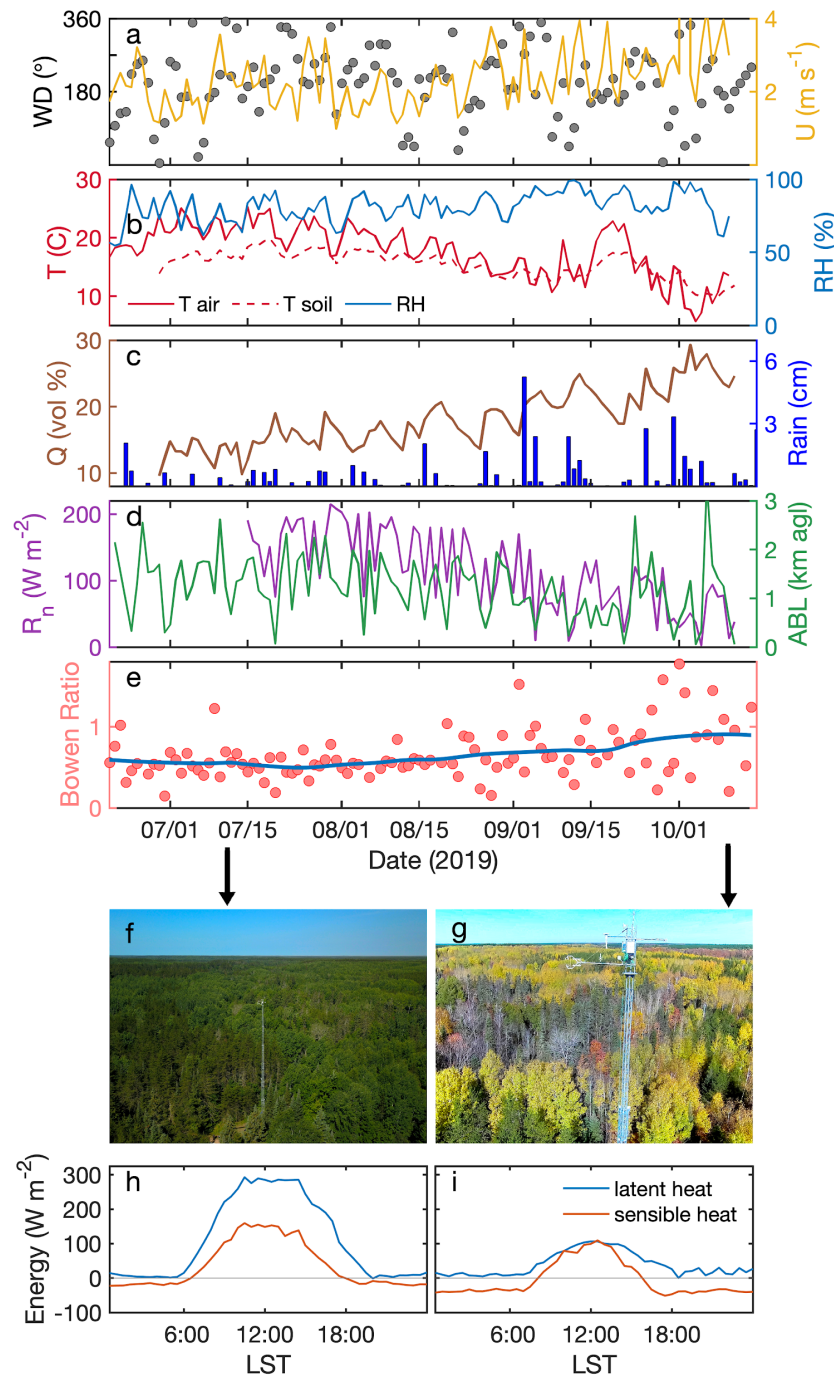
**Fig. 6. Panel A: Environmental Response Functions (ERFs) augment sparse response observations (e.g., tower and aircraft EC) with abundant driver observations (e.g., meteorological stations and satellites). High-rate time-frequency decomposition and source area modeling facilitate data joins among these response and driver observations at minute- and meter-scale. Machine learning then extracts a driver-response process model from the resulting space- and time-aligned dataset. Ultimately, this driver-response process model complements the properties of response and driver observations in the response data product. In the present example these are meter-scale sensible heat flux maps, which can be used to more reliably evaluate the conservation of energy across the non-uniform CHEESEHEAD19 experiment domain.**

**Panel B: During the experiment planning stage we used Large Eddy Simulations (LES) to create synthetic atmospheres over the CHEESEHEAD19 domain for different synoptic conditions. We simultaneously sampled the synthetic atmospheres as observed by different virtual experiment designs. Each experiment design resulted in a separate set of virtual observations which we independently processed through the ERFs in Panel A.**

**Panel C: We benchmarked the different experiment designs against their ability to reproduce the LES reference in the form of flux grids that ERF reconstructed from the virtual observations alone. Identifying the optimal experiment design not only allowed us to double the scientific return on experimental investment, but also to simplify flight plans and increase crew safety. For additional detail see the full study by Metzger et al. (in preparation).**

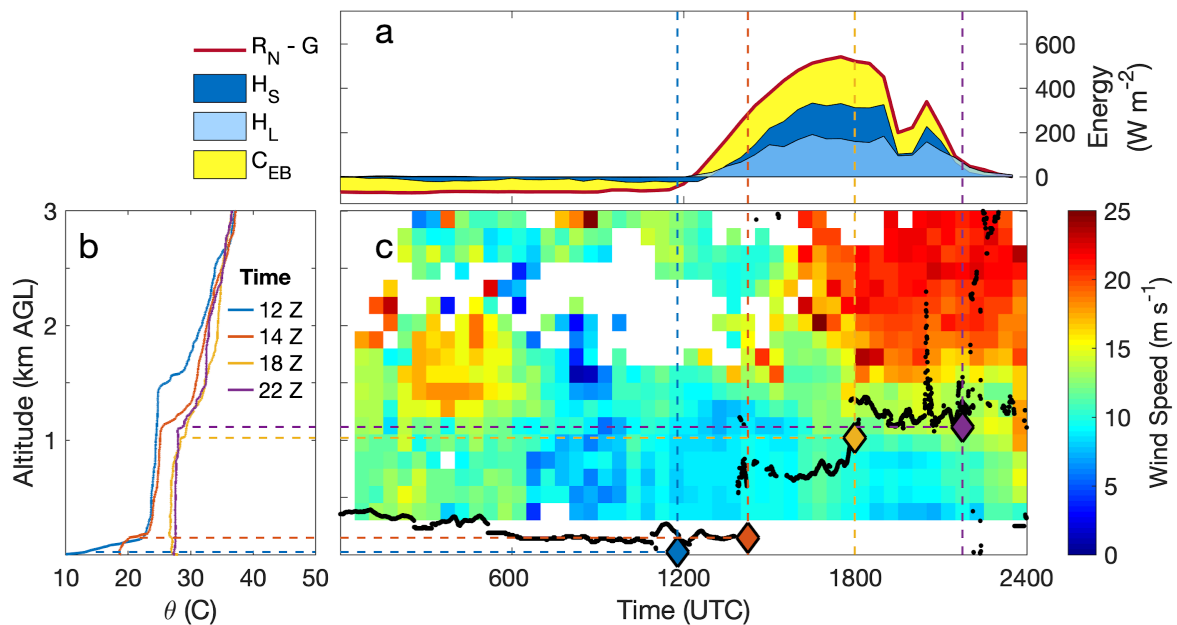
## PRELIMINARY RESULTS

Over the course of the four-month study period the region exhibited light winds (diurnal means from  $1 - 4 \text{ m s}^{-1}$ ) from all directions, with the most prevalent direction being southwesterly (Fig. 7). Air and soil temperatures decreased over the period, while soil moisture increased (Fig. 7b,c). Daily mean net radiation decreased over the course of the study, which showed a direct relationship with ABL height (measured as the height of the inversion on the diurnal radiosonde launches [Fig. 7d]). One of the most relevant seasonal changes with respect to energy balance was the change in the daytime Bowen Ratio ( $H_S / H_L$ ) which averaged 0.5 in the summer and 1.0 in the fall, with the latter period having more variability than the former. Diurnal cycles of sensible and latent heat flux show that latent heat flux is much larger in the summer when the canopy is fully evapotranspiring compared to the fall, when senescence of broadleaf trees reduces  $H_L$ , allowing  $H_S$  to comprise a larger share of the total heat flux over the region (Fig. 7f – i).



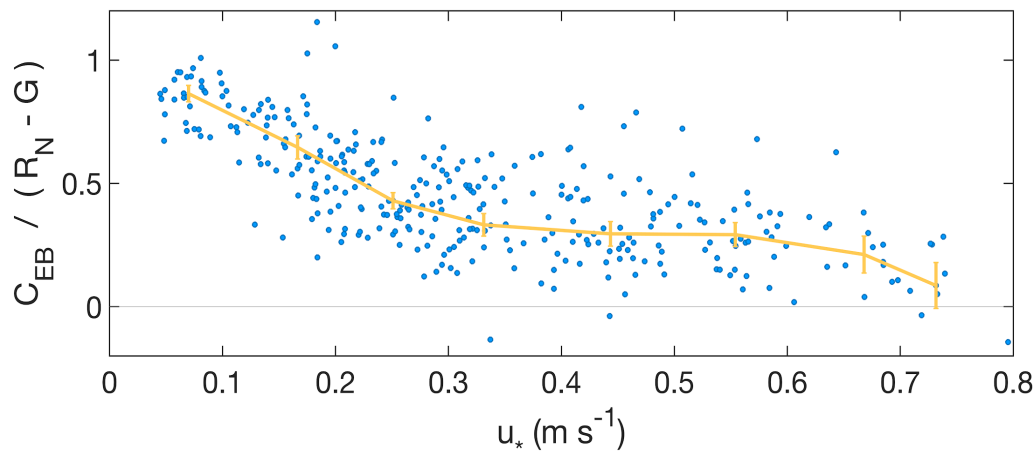
**Fig. 7.** Daily mean (a) wind speed and direction, (b) temperature and relative humidity, (c) soil moisture, (d) net radiation and ABL height, and (e) Bowen ratio averaged across all ISFS towers. Aerial view of site NE2 on (f) July 12, 2020 and (g) October 9, 2020. Diurnal cycles of sensible and latent heat averaged across all ISFS sites for the weeks of (h) Oct. 4 – 11 and (i) July 7 – 14.

Continuous data collection throughout the campaign linked the energy balance components to the remotely sensed atmospheric environment (Fig. 8). As is typical for EC measurements, we observed energy fluxes that were lower in magnitude than the net incoming energy ( $R_N - G$ ), when averaged across all sites. The magnitudes of the energy balance residual ( $C_{EB}$ ) was largest during the daytime, when incoming solar radiation was highest. The opposite sign of  $C_{EB}$  from day to night in part can be attributed to heat storage in the canopy. However, the magnitudes of the daytime values are larger than the nighttime values, which results in a daily mean imbalance.



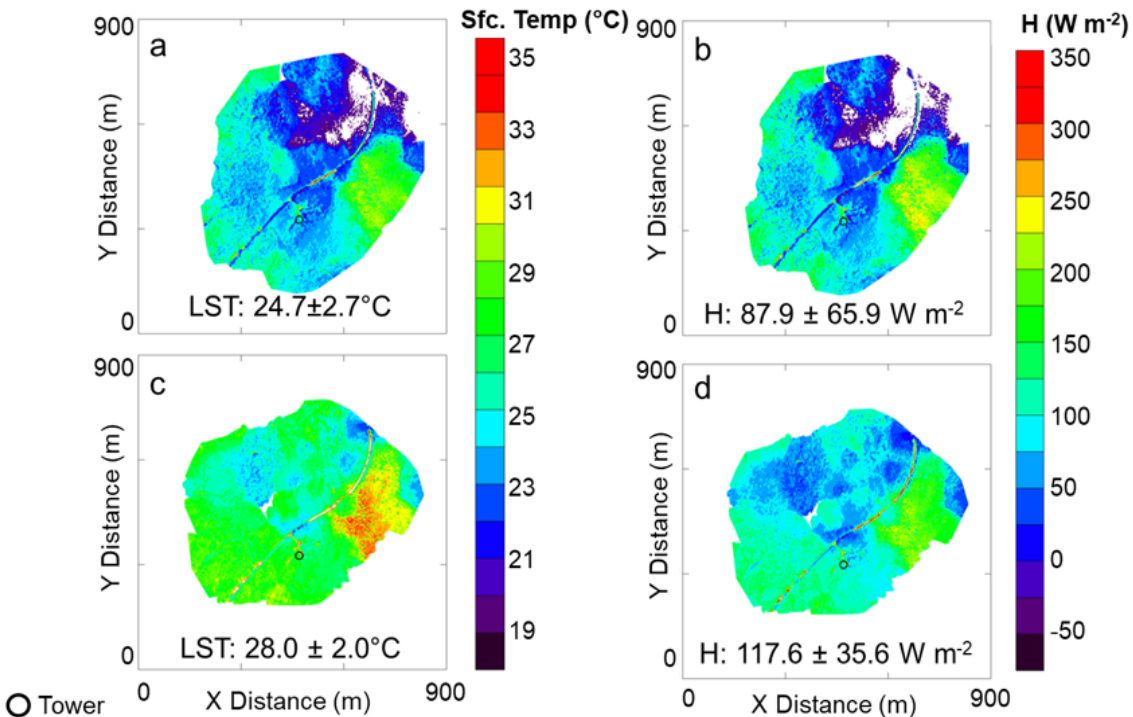
**Fig. 8. (a) Stacked energy balance components: net radiation minus ground heat flux ( $R_N - G$ ), sensible and latent heat flux ( $H_S$  and  $H_L$ ), and energy balance residual ( $C_{EB}$ ) on Sep 24, 2019; (b) radiosonde profiles of potential temperature ( $\theta$ ); and (c) time series of wind speed profile with overlaid ABL height from ceilometer (black dots) and radiosondes (colored diamonds and dashed lines correspond to radiosonde launches in (b)).**

The energy balance residual peaked under conditions of low turbulence (Fig. 9). It is during such periods of calm wind and strongly unstable stratification in which thermally-induced mesoscale eddies resulting from landscape-scale heterogeneity are expected (Steinfeld et al. 2007). This lends support to the hypothesis that mesoscale eddies are responsible for the energy balance non-closure.



**Fig. 9. Daily mean energy balance residuals ( $C_{EB}$ ) normalized by net radiation minus ground heat flux ( $R_N - G$ ) plotted against friction velocity ( $u_*$ ) for all ISFS EC towers for the entire CHEESEHEAD19 dataset (excludes individual towers on days without complete quality-controlled data).**

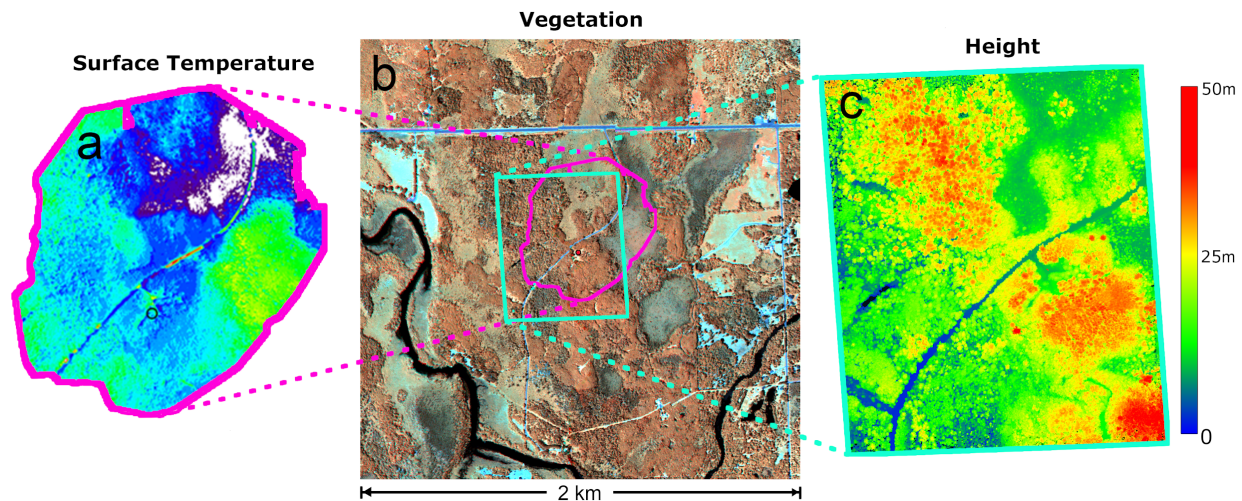
Tower measurements, combined with in-situ measurements of air temperature and land surface temperature from the DJI S-1000, were used to quantify variability in surface  $H_s$  following Lee et al. [2017], as shown in an example from 12 Jul 2019 (Fig. 10). On this day, as well as others, there was significant temperature and  $H_s$  variability; temperature ( $H_s$ ) differences were  $\sim 10^\circ\text{C}$  ( $100 \text{ W m}^{-2}$ ) over the  $\sim 500 \times 500 \text{ m}$  area surrounding the SW2 tower. Fig. 10 illustrates even finer scale resolution of surface temperature than the measures shown in Fig. 5. Such spatial variation is directly related to underlying surface characteristics.



**Fig. 10. Surface temperature (a) and  $H_s$  (b) from a downward-pointing infrared camera flown on the DJI S-1000 sUAS surrounding the SW2 tower between 1504 and 1518 UTC 12 Jul 2019. Same for panels (c) and (d), but between 1614 and 1628 UTC 12 Jul 2019.  $H_s$  computed following Lee et al. (2017). As the technique requires an initial  $H_s$  to derive the variability in  $H_s$ , and  $H_s$  was unavailable from SW2 on 12 Jul,  $H_s$  at SW2 was estimated using a linear regression with data from nearby towers. Mean  $\pm$  1 standard deviation shown at the bottom of each panel.**

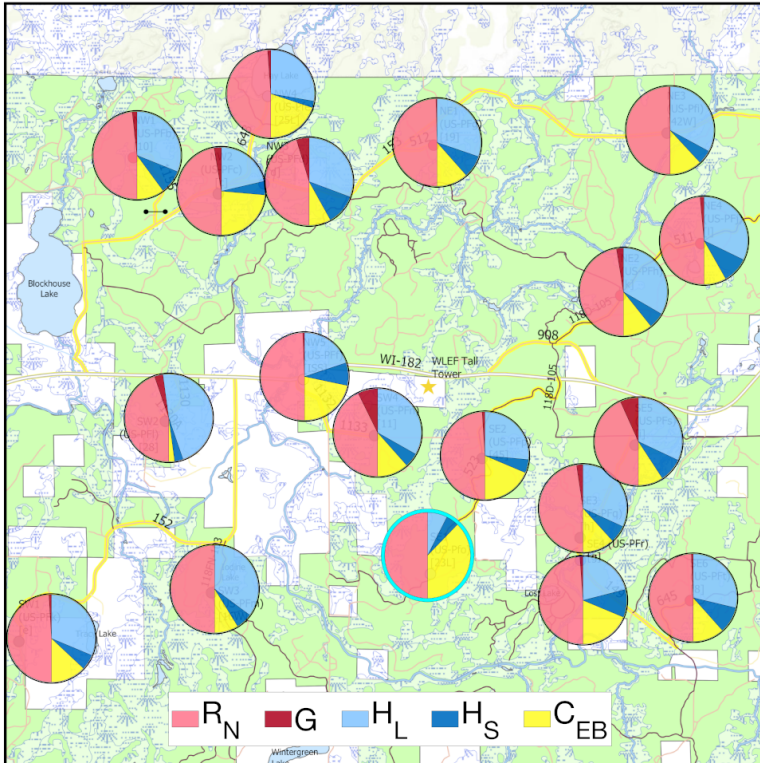
Landscape heterogeneity was observed for a range of environmental variables, including vegetation spectral characteristics and canopy height captured from downward-looking airborne remote sensing instruments (Fig. 11). False color HySpex imagery is being used to differentiate plant functional types at 1 m<sup>2</sup> resolution. Additional information on leaf-on canopy structure, obtained from the Routescene LiDAR at 11 flux sites and across the entire domain from the State of Wisconsin leaf-off LiDAR dataset, are being used to identify surface roughness in the flux footprints of the EC towers. In addition, these spatial data are being used as input drivers within the ERF-VCV machine learning approach.





**Fig. 11. Surface maps showing spatial variation around tower site SW2 in (a) surface temperature measured by the DJI S-1000 (same as Fig. 10a), (b) vegetation spectral characteristics measured by the HySpex shown as a false color image (849 nm – red, 1650 nm – green, 2217 nm – blue), and (c) surface/canopy height measured by the sUAS Routescene lidar.**

There is also spatial variation in the energy balance components across the domain on a typical day (Fig. 12a). This variability includes the relative weighting of latent and sensible heat fluxes, as well as the magnitude of the energy balance residual. The mean energy balance closure (calculated as  $[H_s + H_L]/[R_N - G]$ ) across all the sites over the entire study period was 0.8. This is typical for EC towers and supports the need for the advanced methods put forth by this study.



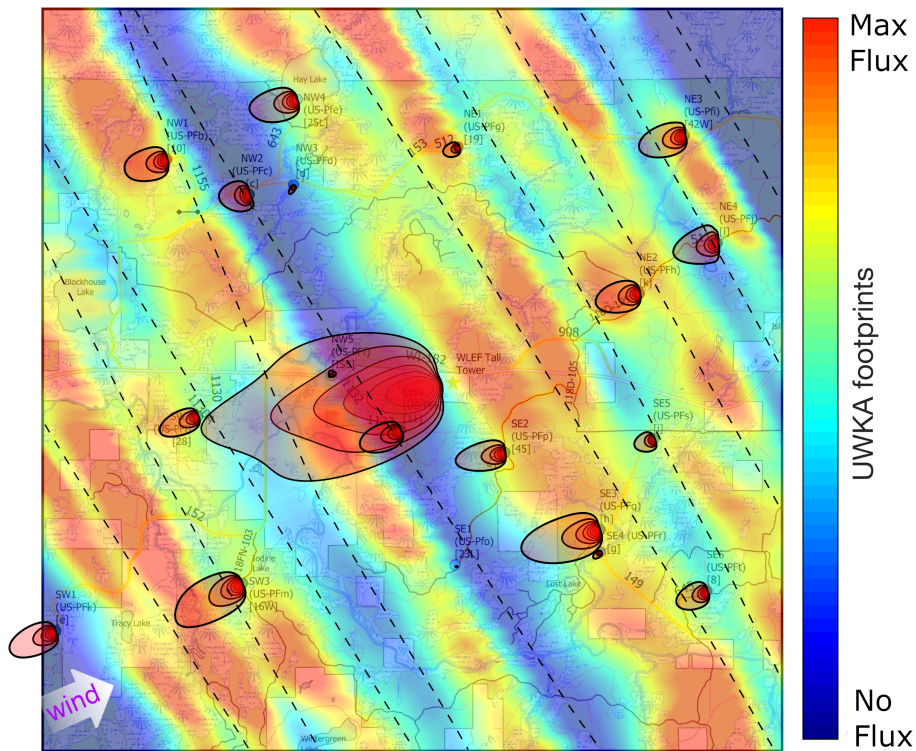
**Fig. 12. Average daily mean energy balance pie charts for the flux towers over the entire study period. The pie chart with the cyan outline (bottom center) was a buoy EC system deployed on a small lake.**

To address this spatial and temporal variability we are testing different types of spatial EC techniques, which have been suggested as a means of mitigating errors arising from single-site EC (Steinfeld et al. 2007; Mauder et al. 2008b). Using LES, Xu et al. (2020) found that standard spatial EC improved closure over standard temporal EC, while a combined spatio-temporal method performed better still. Further, by applying the ERF-VCV approach, the energy balance was found to be almost completely closed.

Here we had the ability to calculate spatial fluxes from two different sources. First, the spatial fluxes were calculated using a wavelet decomposition on the aircraft EC datasets. This dataset has good spatial coverage but limited temporal resolution, though, with 72 flight hours spread across 12 days, it is one of the largest airborne EC datasets ever collected.

The second data source for spatial EC was the set of 20 flux towers spread across the domain. Calculations for flux footprints on Sep 26, 2019 (Fig. 13) show that spatial coverage of the towers (including WLEF) covered roughly 8% of the domain (using Kljun et al. [2015]). This is a significant increase compared to a single tower set up (typically  $\ll 1\%$  of a  $10 \times 10$  km area). An additional benefit from the experiment design is that the towers cover a range of physical environments. These data are being used to confirm the LES model results for improvements to

energy balance closure. By combining the tower and aircraft EC datasets we have excellent coverage ( $\sim 80\%$ ) of the study domain on flight days (Fig. 13).



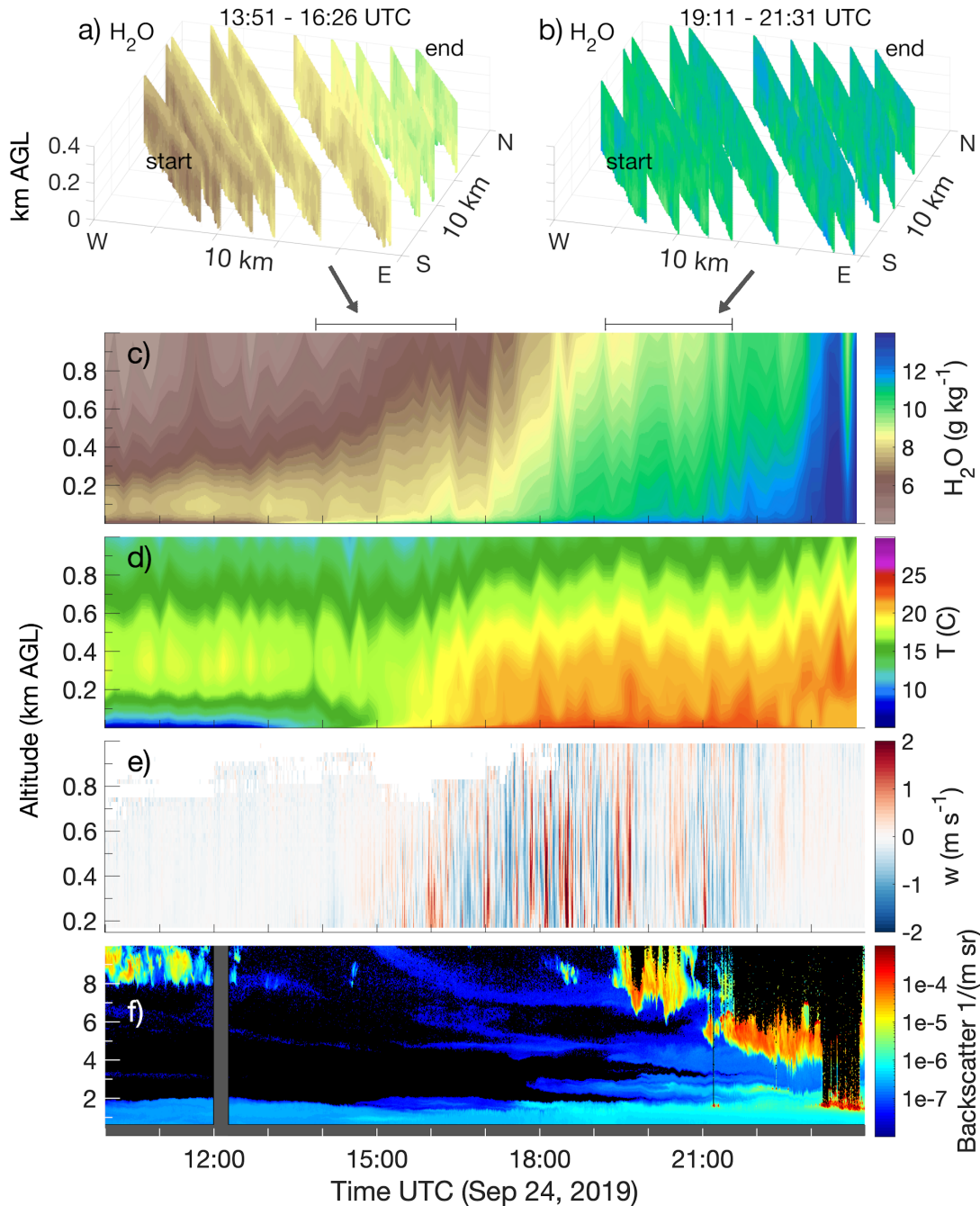
**Fig. 13. Flux footprint climatologies from the 20 flux towers and aircraft on the morning of September 26, 2019. Tower footprints extend to the 90% footprint with 10% contour lines shown down to 10% (calculated based on Kijun et al. [2015]). The heat map shows aircraft flux footprints with areas of strongest flux contribution in red, grading to blue where there was no contribution (calculated based on Metzger et al. [2013]). UWKA flight tracks shown as dashed black lines.**

The characterization of the ABL and identification of mesoscale eddies will be performed using lidar measurements of wind, water vapor, temperature, and backscatter. Figure 14 shows an example of this on September 24. Increasing water vapor through the day is representative of a large-scale warm, wet airmass entering the domain (Fig. 14c,d; Fig. S2a). This characterizes the variation in water vapor throughout the collection of the morning UWKA CRL dataset (Fig. 14a). The afternoon CRL dataset (Fig. 14b) shows a more evenly mixed ABL, with variation in water vapor due to local pockets of relatively moist and dry air. These two examples show the varying applications of the CRL data depending on the atmospheric environment, with the afternoon flight illustrating the potential of the dataset for determining the degree of ABL heterogeneity arising from surface heterogeneity. Further analysis will investigate relationships with underlying vegetation and LST.

728  
729 Around 1200 UTC (7am local time) net radiation becomes positive (Fig. 8a) and soon after we  
730 see the breakup of the surface inversion (Fig. 14d). Around 1400 – 1500 UTC we see the ABL  
731 grow (Fig. 8c) followed by development of large-scale structures revealed by strong oscillations  
732 in vertical wind speed ( $\pm 2 \text{ m s}^{-1}$ ; Fig. 14e). During peak hours the angle of attack of the wind  
733 vectors oscillate between roughly  $-30^\circ$  to  $50^\circ$  degrees on time scales of 10 minutes to an hour.  
734 These angles far exceed those of the underlying terrain, suggesting that these periodic updrafts  
735 and downdrafts are the result of mesoscale eddies.

736  
737 Around 1900 UTC the domain clouds over, seen in  $R_N$  and backscatter (Fig. 8a; Fig. 14f; Fig.  
738 S2b). This causes the strength of the oscillation in vertical wind to decrease (Fig. 14e), which  
739 coincides with a change in the relative weighting of the different energy balance components,  
740 with both  $R_N$  and  $H_S$  decreasing strongly, while  $H_L$  decreases only slightly (Fig. 8a). An increase  
741 in  $R_N$  around 2000 UTC corresponds to strengthening vertical wind speed oscillations. Further  
742 analyses will investigate the prevalence of this result across the entire dataset and examine  
743 specific drivers and possible implications for EC energy balance closure. These datasets show  
744 that changes in ABL development are closely tied to changes in the surface energy fluxes,  
745 highlighting the potential research applications of the CHEESEHEAD19 data.  
746





**Fig. 14.** (a) and (b) show CRL cross sections of  $\text{H}_2\text{O}$  mixing ratio (cut to domain size; panel c colorbar represents panels a - c) for each of 10 legs on Research Flights 17 and 18 (Sep 24 at 13:51 - 16:26 and 19:11 - 21:31 UTC); time series profiles of (c)  $\text{H}_2\text{O}$  mixing ratio and (d) T measured by the ground-based MWR, (e) vertical wind speed calculated using the ground-based RHI scanning wind lidars ( $L_A$ ,  $L_B$ ) for the column above  $L_{VS}$ , and (f) 532 nm backscatter from the ground-based HSRL at WLEF tall tower on Sep 24, 2019.

## EDUCATIONAL OUTREACH

Several public events were conducted to introduce and communicate the science goals and objectives of the project. These include a pre-experiment community-wide public presentation at the Park Falls Public Library and a summer open house at several sites, enabling members of the community to visit data collection locations, meet CHEESEHEAD19 team members, and participate in demonstrations of the instruments. CHEESEHEAD19 team members also participated in surveys and in training on fieldwork bullying and sexual harassment prevention (Fischer et al. in review).

The project also worked with two local school groups, one from Butternut, Wisconsin K-12 School and another from Chequamegon High School of Park Falls, WI, to include them as supporting data collectors. The GLOBE (Global Learning and Observations to Benefit the Environment) program trained Butternut K-12 students and a teacher to collect land cover classification data, soil properties, and atmospheric data at seven of the tower sites at multiple times throughout the summer. The high school group installed ten tree temperature sensors at five of the forest flux tower sites, which are being used to estimate biomass heat storage. We also hosted two undergraduate university field classes (UW-Madison and U-South Carolina), which conducted independent research projects on micrometeorology and carbon cycling.



**Fig. 15. Bill Brown (just right of the radiosonde balloon) describing the capabilities of the ISS facility during the community open house.**

## DATA AND CODE AVAILABILITY

The database of observations and models is currently online and freely available to the community and public for general use or for further scientific investigation. The datasets and supporting information have been gathered together in the NCAR Earth Observatory Laboratory (EOL) data repository which can be accessed through the project web page at [https://www.eol.ucar.edu/field\\_projects/cheesehead](https://www.eol.ucar.edu/field_projects/cheesehead). The project has open data and code policies, in which other researchers are encouraged to use CHEESEHEAD19 resources for their own research. The policies can be accessed through the above web page.

Additionally, data are stored and are being used for in-depth analysis and modeling purposes on the NSF-funded cloud computing platform CyVerse, with the goal of having a central location for users to bring their code to the data in a way that maintains data and code provenance for collaborative, multi-user projects. Additional information about the project, including descriptions of the sites, photographs, and data plots can be found on the CHEESEHEAD19 website, located at [www.cheesehead19.org](http://www.cheesehead19.org).

## CONCLUSIONS

The data collected during the CHEESEHEAD19 field campaign show a distinct seasonal shift in surface energy fluxes, as well as spatial patterning that appears to be directly related to the characteristics of the underlying surface environment. Consequently, the imbalance in the energy budget displays both temporal and spatial variability, with the imbalance becoming larger under periods of low turbulence. The broad coverage of the measured fluxes using the 20-tower network and airborne EC, combined with the collection of spatial data of surface characteristics like LST, vegetation type, and canopy structure, will enable thorough investigation of the causes of energy balance non-closure. Additionally, the suite of atmospheric profiling instrumentation characterizes the mesoscale structure of atmospheric flows over the study domain to an unprecedented degree, helping to determine how mesoscale eddies contribute to measured imbalances. The observational dataset provided by CHEESEHEAD19 will also enable the use of machine-learning approaches and LES for testing hypotheses on scaling and parameterization of sub-grid processes in mesoscale meteorological models. Findings emerging from this project are expected to have broad implications for heterogeneous terrestrial regions beyond the specific study domain.

## APPENDIX: LIST OF ACRONYMS

AGL – above ground level  
ARL - Air Resources Laboratory (NOAA)  
ATDD – Atmospheric Turbulence and Diffusion Division (NOAA)  
CHEESEHEAD19 – Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors 2019  
CLAMPS – Collaborative Lower Atmospheric Mobile Profiling System (NOAA NSSL)  
CRL – Compact Raman Lidar

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823 EC – Eddy Covariance  
824 GML – Global Monitoring Laboratory (NOAA)  
825 IOP – Intensive Observation Period  
826 LES – Large Eddy Simulation  
827 lidar – light detection and ranging  
828 LSM – Land Surface Model  
829 NCAR – National Center for Atmospheric Research  
830 NOAA – National Atmospheric and Oceanic Administration  
831 NSF – National Science Foundation  
832 NSSL – National Severe Storms Laboratory (NOAA)  
833 PALM – Parallelized LES Model  
834 PSL – Physical Sciences Laboratory (NOAA)  
835 radar – radio detection and ranging  
836 RASS – Radio Acoustic Sounding System  
837 sodar – sonic detection and ranging  
838 sUAS - small Unmanned Aircraft System  
839 SURFRAD – Surface Radiation Budget Network  
840 UWKA – University of Wyoming King Air

## 841 **APPENDIX: LIST OF VARIABLES**

842  $F_{CO_2}$  – CO<sub>2</sub> flux ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )  
843  $G$  – Ground heat flux ( $\text{W m}^{-2}$ )  
844  $H_2O$  – water vapor mixing ratio ( $\text{g kg}^{-1}$ )  
845  $H_s$  – sensible heat flux ( $\text{W m}^{-2}$ )  
846  $H_L$  – latent heat flux ( $\text{W m}^{-2}$ )  
847 LST – land surface temperature (C)  
848  $P$  – Pressure (mbar)  
849  $R_N$  – Net surface radiation ( $\text{W m}^{-2}$ )  
850  $T$  – temperature (C)  
851  $T_v$  – virtual temperature (C)  
852  $U$  – horizontal wind speed ( $\text{m s}^{-1}$ )  
853  $u^*$  – friction velocity ( $\text{m s}^{-1}$ )  
854  $w$  – vertical wind speed ( $\text{m s}^{-1}$ )  
855  $\theta$  – potential temperature (C)  
856  $\theta_v$  – virtual potential temperature (C)  
857  $\tau$  – momentum flux ( $\text{N m}^{-2}$ )  
858  
859

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## REFERENCES

- Anderson, M., J. Norman, W. Kustas, R. Houborg, P. Starks, and N. Agam, 2008: A thermal-based remote sensing technique for routine mapping of land-surface carbon, water and energy fluxes from field to regional scales. *Remote Sens. Environ.*, **112**, 4227–4241, <https://doi.org/10.1016/j.rse.2008.07.009>.
- Anderson, M. C., and Coauthors, 2012: Mapping daily evapotranspiration at Landsat spatial scales during the BEAREX'08 field campaign. *Adv. Water Resour.*, **50**, 162–177, <https://doi.org/10.1016/j.advwatres.2012.06.005>.
- Antonarakis, A. S., J. W. Munger, and P. R. Moorcroft, 2014: Imaging spectroscopy- and lidar-derived estimates of canopy composition and structure to improve predictions of forest carbon fluxes and ecosystem dynamics. *Geophys. Res. Lett.*, **41**, 2535–2542, <https://doi.org/10.1002/2013GL058373>.
- Aubinet, M., and Coauthors, 2010: Direct advection measurements do not help to solve the night-time CO<sub>2</sub> closure problem: Evidence from three different forests. *Agric. For. Meteorol.*, **150**, 655–664, <https://doi.org/10.1016/j.agrformet.2010.01.016>.
- Avissar, R., 1995: Scaling of land-atmosphere interactions: An atmospheric modelling perspective. *Hydrol. Process.*, **9**, 679–695, <https://doi.org/doi:10.1002/hyp.3360090514>.
- Bakwin, P. S., P. P. Tans, D. F. Hurst, and C. Zhao, 1998: Measurements of carbon dioxide on very tall towers: results of the NOAA/CMDL program. *Tellus B Chem. Phys. Meteorol.*, **50**, 401–415, <https://doi.org/10.3402/tellusb.v50i5.16216>.
- Barnard, J. C., and C. N. Long, 2004: A Simple Empirical Equation to Calculate Cloud Optical Thickness Using Shortwave Broadband Measurements. *J. Appl. Meteorol.*, **43**, 1057–1066, [https://doi.org/10.1175/1520-0450\(2004\)043<1057:ASEETC>2.0.CO;2](https://doi.org/10.1175/1520-0450(2004)043<1057:ASEETC>2.0.CO;2).
- Barr, J. G., J. D. Fuentes, M. S. DeLonge, T. L. O'Halloran, D. Barr, and J. C. Ziemann, 2013: Summertime influences of tidal energy advection on the surface energy balance in a mangrove forest. *Biogeosciences*, **10**, 501–511, <https://doi.org/10.5194/bg-10-501-2013>.
- Bertram, T. H., and Coauthors, 2011: A field-deployable, chemical ionization time-of-flight mass spectrometer. *Atmos. Meas. Tech.*, **4**, 1471–1479, <https://doi.org/10.5194/amt-4-1471-2011>.
- Betts, A. K., J. H. Ball, A. C. M. Beljaars, M. J. Miller, and P. A. Viterbo, 1996: The land surface-atmosphere interaction: A review based on observational and global modeling perspectives. *J. Geophys. Res. Atmos.*, **101**, 7209–7225, <https://doi.org/10.1029/95JD02135>.
- Beyrich, F., and Coauthors, 2006: Area-Averaged Surface Fluxes Over the Litfass Region Based on Eddy-Covariance Measurements. *Bound.-Layer Meteorol.*, **121**, 33–65, <https://doi.org/10.1007/s10546-006-9052-x>.
- Blumberg, W. G., D. D. Turner, U. Löhnert, and S. Castleberry, 2015: Ground-Based Temperature and Humidity Profiling Using Spectral Infrared and Microwave Observations.

This work has been submitted to the Bulletin of the American Meteorological Society.  
Copyright in this work may be transferred without further notice.

914 Part II: Actual Retrieval Performance in Clear-Sky and Cloudy Conditions. *J. Appl. Meteor.*  
915 *Climatol.*, **54**, 2305–2319, <https://doi.org/10.1175/JAMC-D-15-0005.1>.

916 Calhoun, R., R. Heap, M. Princevac, R. Newsom, H. Fernando, and D. Ligon, 2006: Virtual  
917 Towers Using Coherent Doppler Lidar during the Joint Urban 2003 Dispersion Experiment.  
918 *J. Appl. Meteor. Climatol.*, **45**, 1116–1126, <https://doi.org/10.1175/JAM2391.1>.

919 Cammalleri, C., M. C. Anderson, G. Ciraolo, G. D’Urso, W. P. Kustas, G. La Loggia, and M.  
920 Minacapilli, 2012: Applications of a remote sensing-based two-source energy balance  
921 algorithm for mapping surface fluxes without in situ air temperature observations. *Remote*  
922 *Sens. Environ.*, **124**, 502–515, <https://doi.org/10.1016/j.rse.2012.06.009>.

923 Charney, J. G., 1975: Dynamics of deserts and drought in the Sahel. *Q. J. R. Meteor. Soc.*, **101**,  
924 193–202, <https://doi.org/doi:10.1002/qj.49710142802>.

925 Charuchittipan, D., W. Babel, M. Mauder, J.-P. Leps, and T. Foken, 2014: Extension of the  
926 Averaging Time in Eddy-Covariance Measurements and Its Effect on the Energy Balance  
927 Closure. *Bound.-Layer Meteor.*, **152**, 303–327, <https://doi.org/10.1007/s10546-014-9922-6>.

928 Chen, B., and Coauthors, 2011: Assessing eddy-covariance flux tower location bias across the  
929 Fluxnet-Canada Research Network based on remote sensing and footprint modelling. *Agric.*  
930 *For. Meteor.*, **151**, 87–100, <https://doi.org/10.1016/j.agrformet.2010.09.005>.

931 Cook, B. D., and Coauthors, 2004: Carbon exchange and venting anomalies in an upland  
932 deciduous forest in northern Wisconsin, USA. *Agric. For. Meteor.*, **126**, 271–295,  
933 <https://doi.org/10.1016/j.agrformet.2004.06.008>.

934 Davis, K. J., P. S. Bakwin, C. Yi, B. W. Berger, C. Zhao, R. M. Teclaw, and J. G. Isebrands,  
935 2003: The annual cycles of CO<sub>2</sub> and H<sub>2</sub>O exchange over a northern mixed forest as  
936 observed from a very tall tower. *Glob. Chang. Biol.*, **9**, 1278–1293,  
937 <https://doi.org/10.1046/j.1365-2486.2003.00672.x>.

938 Desai, A. R., P. V. Bolstad, B. D. Cook, K. J. Davis, and E. V. Carey, 2005: Comparing net  
939 ecosystem exchange of carbon dioxide between an old-growth and mature forest in the  
940 upper Midwest, USA. *Agric. For. Meteor.*, **128**, 33–55,  
941 <https://doi.org/10.1016/j.agrformet.2004.09.005>.

942 ———, K. J. Davis, C. J. Senff, S. Ismail, E. V. Browell, D. R. Stauffer, and B. P. Reen, 2006: A  
943 Case Study on the Effects of Heterogeneous Soil Moisture on Mesoscale Boundary-Layer  
944 Structure in the Southern Great Plains, U.S.A. Part I: Simple Prognostic Model. *Bound.-*  
945 *Layer Meteor.*, **119**, 195–238, <https://doi.org/10.1007/s10546-005-9024-6>.

946 Desai, A. R., B. R. Helliker, P. R. Moorcroft, A. E. Andrews, and J. A. Berry, 2010: Climatic  
947 controls of interannual variability in regional carbon fluxes from top-down and bottom-up  
948 perspectives. *J. Geophys. Res. Biogeosciences*, **115**,  
949 <https://doi.org/doi:10.1029/2009JG001122>.

950 Dür, B., and R. Philipona, 2004: Automatic cloud amount detection by surface longwave  
951 downward radiation measurements. *J. Geophys. Res.*, **109**, D05201,  
952 <https://doi.org/10.1029/2003JD004182>.

- 953 Eder, F., M. Schmidt, T. Damian, K. Träumner, and M. Mauder, 2015: Mesoscale eddies affect  
 954 near-surface turbulent exchange: Evidence from lidar and tower measurements. *J. Appl.*  
 955 *Meteor. Climatol.*, **54**, 189–206, <https://doi.org/10.1175/JAMC-D-14-0140.1>.
- 956 Eloranta, E. W., 2005: High spectral resolution lidar. *Lidar: Range-Resolved Optical Remote*  
 957 *Sensing of the Atmosphere*, K. Weitkamp, Ed., Springer-Verlag, 143–163.
- 958 Engelmann, C., and C. Bernhofer, 2016: Exploring Eddy-Covariance Measurements Using a  
 959 Spatial Approach: The Eddy Matrix. *Bound.-Layer Meteor.*, **161**, 1–17,  
 960 <https://doi.org/10.1007/s10546-016-0161-x>.
- 961 Finnigan, J., 2008: An introduction to flux measurements in difficult conditions. *Ecol. Appl.*, **18**,  
 962 1340–1350, <https://doi.org/10.1890/07-2105.1>.
- 963 Emily V. Fischer, Brittany Bloodhart, Kristen Rasmussen, Ilana B. Pollack, Meredith G.  
 964 Hastings, Erika Marin-Spiotta, Ankur R. Desai, Joshua P. Schwarz, Stephen Nesbitt, and  
 965 Deanna Hence, 2020. Leveraging Field-Campaign Networks to Effect Collaborative  
 966 Change on Sexual Harassment, Bulletin of the AMS, submitted.
- 967 Foken, T., M. Aubinet, J. J. Finnigan, M. Y. Leclerc, M. Mauder, and K. T. Paw U, 2011:  
 968 Results Of A Panel Discussion About The Energy Balance Closure Correction For Trace  
 969 Gases. *Bull. Amer. Meteor. Soc.*, **92**, ES13–ES18,  
 970 <https://doi.org/10.1175/2011BAMS3130.1>.
- 971 Frank, J. M., W. J. Massman, and B. E. Ewers, 2013: Underestimates of sensible heat flux due to  
 972 vertical velocity measurement errors in non-orthogonal sonic anemometers. *Agric. For.*  
 973 *Meteor.*, **171–172**, 72–81, [https://doi.org/https://doi.org/10.1016/j.agrformet.2012.11.005](https://doi.org/10.1016/j.agrformet.2012.11.005).
- 974 Gantner, L., V. Maurer, N. Kalthoff, and O. Kiseleva, 2017: The Impact of Land-Surface  
 975 Parameter Properties and Resolution on the Simulated Cloud-Topped Atmospheric  
 976 Boundary Layer. *Bound.-Layer Meteor.*, **165**, 475–496, [https://doi.org/10.1007/s10546-017-](https://doi.org/10.1007/s10546-017-0286-6)  
 977 0286-6.
- 978 Gao, Z., H. Liu, E. S. Russell, J. Huang, T. Foken, and S. P. Oncley, 2016: Large eddies  
 979 modulating flux convergence and divergence in a disturbed unstable atmospheric surface  
 980 layer. *J. Geophys. Res. Atmos.*, **121**, 1475–1492, <https://doi.org/10.1002/2015JD024529>.
- 981 Garratt, J. R., 1993: Sensitivity of Climate Simulations to Land-Surface and Atmospheric  
 982 Boundary-Layer Treatments-A Review. *J. Clim.*, **6**, 419–448, [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0442(1993)006<0419:SOCSTL>2.0.CO;2)  
 983 0442(1993)006<0419:SOCSTL>2.0.CO;2.
- 984 Gerace, A., T. Kleynhans, R. Eon, and M. Montanaro, 2020: Towards an Operational, Split  
 985 Window-Derived Surface Temperature Product for the Thermal Infrared Sensors Onboard  
 986 Landsat 8 and 9. *Remote Sens.*, **12**, 224, <https://doi.org/10.3390/rs12020224>.
- 987 van Heerwaarden, C. C., J. P. Mellado, and A. De Lozar, 2014: Scaling Laws for the  
 988 Heterogeneously Heated Free Convective Boundary Layer. *J. Atmos. Sci.*, **71**, 3975–4000,  
 989 <https://doi.org/10.1175/jas-d-13-0383.1>.
- 990 Hilker, T., F. G. Hall, N. C. Coops, J. G. Collatz, T. A. Black, C. J. Tucker, P. J. Sellers, and N.

- 991 Grant, 2013: Remote sensing of transpiration and heat fluxes using multi-angle  
992 observations. *Remote Sens. Environ.*, **137**, 31–42, <https://doi.org/10.1016/j.rse.2013.05.023>.
- 993 Hill, T. C., M. Williams, and J. B. Moncrieff, 2008: Modeling feedbacks between a boreal forest  
994 and the planetary boundary layer. *J. Geophys. Res. Atmos.*, **113**,  
995 <https://doi.org/doi:10.1029/2007JD009412>.
- 996 —, —, F. I. Woodward, and J. B. Moncrieff, 2011: Constraining ecosystem processes from  
997 tower fluxes and atmospheric profiles. *Ecol. Appl.*, **21**, 1474–1489,  
998 <https://doi.org/doi:10.1890/09-0840.1>.
- 999 Kampe, T. U., J. McCorkel, L. Hamlin, R. O. Green, K. S. Krause, and B. R. Johnson, 2011:  
1000 Progress in the development of airborne remote sensing instrumentation for the National  
1001 Ecological Observatory Network. W. Gao, T.J. Jackson, J. Wang, and N.-B. Chang, Eds.,  
1002 81560A.
- 1003 Kang, S.-L., K. J. Davis, and M. LeMone, 2007: Observations of the ABL Structures over a  
1004 Heterogeneous Land Surface during IHOP\_2002. *J. Hydrometeor.*, **8**, 221–244,  
1005 <https://doi.org/10.1175/JHM567.1>.
- 1006 Kattge, J., W. Knorr, T. Raddatz, and C. Wirth, 2009: Quantifying photosynthetic capacity and  
1007 its relationship to leaf nitrogen content for global-scale terrestrial biosphere models. *Glob.*  
1008 *Chang. Biol.*, **15**, 976–991, <https://doi.org/10.1111/j.1365-2486.2008.01744.x>.
- 1009 Klein, P., and Coauthors, 2015: LABLE: A Multi-Institutional, Student-Led, Atmospheric  
1010 Boundary Layer Experiment. *Bull. Amer. Meteor. Soc.*, **96**, 1743–1764,  
1011 <https://doi.org/10.1175/BAMS-D-13-00267.1>.
- 1012 Kljun, N., P. Calanca, M. W. Rotach, and H. P. Schmid, 2015: A simple two-dimensional  
1013 parameterisation for Flux Footprint Prediction (FFP). *Geosci. Model Dev.*, **8**, 3695–3713,  
1014 <https://doi.org/10.5194/gmd-8-3695-2015>.
- 1015 Klugmann, D., K. Heinsohn, and H. J. Kirtzel, 1996: A low cost 24 GHz FM-CW Doppler radar  
1016 rain profiler. *Contrib. Atmos. Phys.*, **61**, 247–253.
- 1017 Kneifel, S., M. Maahn, G. Peters, and C. Simmer, 2011: Observation of snowfall with a low-  
1018 power FM-CW K-band radar (Micro Rain Radar). *Meteor. Atmos. Phys.*, **113**, 75–87,  
1019 <https://doi.org/10.1007/s00703-011-0142-z>.
- 1020 Knuteson, R. O., and Coauthors, 2004: Atmospheric Emitted Radiance Interferometer. Part II:  
1021 Instrument Performance. *J. Atmos. Ocean. Technol.*, **21**, 1777–1789,  
1022 <https://doi.org/10.1175/JTECH-1663.1>.
- 1023 Kobayashi, H., D. D. Baldocchi, Y. Ryu, Q. Chen, S. Ma, J. L. Osuna, and S. L. Ustin, 2012:  
1024 Modeling energy and carbon fluxes in a heterogeneous oak woodland: A three-dimensional  
1025 approach. *Agric. For. Meteorol.*, **152**, 83–100,  
1026 <https://doi.org/10.1016/j.agrformet.2011.09.008>.

This work has been submitted to the Bulletin of the American Meteorological Society.  
Copyright in this work may be transferred without further notice.



- 1027 Launiainen, S., and Coauthors, 2016: Do the energy fluxes and surface conductance of boreal  
1028 coniferous forests in Europe scale with leaf area? *Glob. Chang. Biol.*, **22**, 4096–4113,  
1029 <https://doi.org/10.1111/gcb.13497>.
- 1030 Lee, T. R., M. Buban, E. Dumas, and C. B. Baker, 2017: A New Technique to Estimate Sensible  
1031 Heat Fluxes around Micrometeorological Towers Using Small Unmanned Aircraft Systems.  
1032 *J. Atmos. Ocean. Technol.*, **34**, 2103–2112, <https://doi.org/10.1175/JTECH-D-17-0065.1>.
- 1033 ———, ———, ———, and ———, 2019: On the use of rotary-wing aircraft to sample near-surface  
1034 thermodynamic fields: results from recent field campaigns. *Sensors*, **19** (1), 10,  
1035 <https://doi.org/10.3390/s19010010>.
- 1036 Leuning, R., E. van Gorsel, W. J. Massman, and P. R. Isaac, 2012: Reflections on the surface  
1037 energy imbalance problem. *Agric. For. Meteorol.*, **156**, 65–74,  
1038 <https://doi.org/https://doi.org/10.1016/j.agrformet.2011.12.002>.
- 1039 Liu, S., and Coauthors, 2016: Upscaling evapotranspiration measurements from multi-site to the  
1040 satellite pixel scale over heterogeneous land surfaces. *Agric. For. Meteorol.*, **230–231**, 97–  
1041 113, <https://doi.org/https://doi.org/10.1016/j.agrformet.2016.04.008>.
- 1042 Liu, S. M., Z. W. Xu, W. Z. Wang, Z. Z. Jia, M. J. Zhu, J. Bai, and J. M. Wang, 2011: A  
1043 comparison of eddy-covariance and large aperture scintillometer measurements with respect  
1044 to the energy balance closure problem. *Hydrol. Earth Syst. Sci.*, **15**, 1291–1306,  
1045 <https://doi.org/10.5194/hess-15-1291-2011>.
- 1046 Löhnert, U., D. D. Turner, and S. Crewell, 2009: Ground-Based Temperature and Humidity  
1047 Profiling Using Spectral Infrared and Microwave Observations. Part I: Simulated Retrieval  
1048 Performance in Clear-Sky Conditions. *J. Appl. Meteor. Climatol.*, **48**, 1017–1032,  
1049 <https://doi.org/10.1175/2008JAMC2060.1>.
- 1050 Long, C. N., and T. P. Ackerman, 2000: Identification of clear skies from broadband  
1051 pyranometer measurements and calculation of downwelling shortwave cloud effects. *J.*  
1052 *Geophys. Res. Atmos.*, **105**, 15609–15626, <https://doi.org/10.1029/2000JD900077>.
- 1053 Long, C. N., and Y. Shi, 2008: An Automated Quality Assessment and Control Algorithm for  
1054 Surface Radiation Measurements. *Open Atmos. Sci. J.*, **2**, 23–37,  
1055 <https://doi.org/10.2174/1874282300802010023>.
- 1056 ———, and D. D. Turner, 2008: A method for continuous estimation of clear-sky downwelling  
1057 longwave radiative flux developed using ARM surface measurements. *J. Geophys. Res.*,  
1058 **113**, D18206, <https://doi.org/10.1029/2008JD009936>.
- 1059 ———, T. P. Ackerman, K. L. Gaustad, and J. N. S. Cole, 2006: Estimation of fractional sky cover  
1060 from broadband shortwave radiometer measurements. *J. Geophys. Res.*, **111**, D11204,  
1061 <https://doi.org/10.1029/2005JD006475>.
- 1062 Mahrt, L., 2000: Surface Heterogeneity and Vertical Structure of the Boundary Layer. *Bound.-*  
1063 *Layer Meteorol.*, **96**, 33–62.
- 1064 Maronga, B., and Coauthors, 2015: The Parallelized Large-Eddy Simulation Model (PALM)

This work has been submitted to the Bulletin of the American Meteorological Society.  
Copyright in this work may be transferred without further notice.

version 4.0 for atmospheric and oceanic flows: model formulation, recent developments, and future perspectives. *Geosci. Model Dev.*, **8**, 2515–2551, <https://doi.org/10.5194/gmd-8-2515-2015>.

Maronga, B., and Coauthors, 2020: Overview of the PALM model system 6.0. *Geosci. Model Dev.*, **13**, 1335–1372, <https://doi.org/10.5194/gmd-13-1335-2020>.

Mauder, M., R. L. Desjardins, and I. Macpherson, 2007a: Scale analysis of airborne flux measurements over heterogeneous terrain in a boreal ecosystem. *J. Geophys. Res.*, **112**, D13112, <https://doi.org/10.1029/2006JD008133>.

Mauder, M., O. O. Jegede, E. C. Okogbue, F. Wimmer, and T. Foken, 2007b: Surface energy balance measurements at a tropical site in West Africa during the transition from dry to wet season. *Theor. Appl. Climatol.*, **89**, 171–183, <https://doi.org/10.1007/s00704-006-0252-6>.

Mauder, M., R. L. Desjardins, and I. Macpherson, 2008a: Creating Surface Flux Maps from Airborne Measurements: Application to the Mackenzie Area GEWEX Study MAGS 1999. *Bound.-Layer Meteor.*, **129**, 431–450, <https://doi.org/10.1007/s10546-008-9326-6>.

Mauder, M., R. L. Desjardins, E. Pattey, Z. Gao, and R. van Haarlem, 2008b: Measurement of the Sensible Eddy Heat Flux Based on Spatial Averaging of Continuous Ground-Based Observations. *Bound.-Layer Meteor.*, **128**, 151–172, <https://doi.org/10.1007/s10546-008-9279-9>.

Mcgloin, R., L. Šigut, K. Havránková, J. Dušek, M. Pavelka, and P. Sedlák, 2018: Energy balance closure at a variety of ecosystems in Central Europe with contrasting topographies. *Agric. For. Meteorol.*, **248**, 418–431, <https://doi.org/10.1016/j.agrformet.2017.10.003>.

Metzger, S., Durden, D., Paleri, S., Sührling, M., Butterworth, B., Desai, A., Florian, C., Mauder, M., Wanner, L., and Xu, K.: Numerical experiment design doubles scientific return of surface-atmosphere synthesis, in preparation.

Metzger, S., 2018: Surface-atmosphere exchange in a box: Making the control volume a suitable representation for in-situ observations. *Agric. For. Meteorol.*, **255**, 68–80, <https://doi.org/10.1016/j.agrformet.2017.08.037>.

Metzger, S., and Coauthors, 2013: Spatially explicit regionalization of airborne flux measurements using environmental response functions. *Biogeosciences*, **10**, 2193–2217, <https://doi.org/10.5194/bg-10-2193-2013>.

Nakai, T., H. Iwata, Y. Harazono, and M. Ueyama, 2014: An inter-comparison between Gill and Campbell sonic anemometers. *Agric. For. Meteorol.*, **195–196**, 123–131, <https://doi.org/10.1016/j.agrformet.2014.05.005>.

Newman, A. J., P. A. Kucera, and L. F. Bliven, 2009: Presenting the Snowflake Video Imager (SVI). *J. Atmos. Ocean. Technol.*, **26**, 167–179, <https://doi.org/10.1175/2008JTECHA1148.1>.

Niinemets, Ü., 2001: Global-scale Climatic Controls of Leaf Dry Mass per Area, Density, and Thickness in Trees and Shrubs. *Ecology*, **82**, 453–469, <https://doi.org/10.1890/0012->

- 1103 9658(2001)082[0453:GSCCOL]2.0.CO;2.
- 1104 Niple, E. R., H. E. Scott, J. A. Conant, S. H. Jones, F. J. Iannarilli, and W. E. Pereira, 2016:  
 1105 Application of oxygen A-band equivalent width to disambiguate downwelling radiances for  
 1106 cloud optical depth measurement. *Atmos. Meas. Tech.*, **9**, 4167–4179,  
 1107 <https://doi.org/10.5194/amt-9-4167-2016>.
- 1108 Novak, G. A., M. P. Vermeuel, and T. H. Bertram, 2020: Simultaneous detection of ozone and  
 1109 nitrogen dioxide by oxygen anion chemical ionization mass spectrometry: a fast-time-  
 1110 response sensor suitable for eddy covariance measurements. *Atmos. Meas. Tech.*, **13**, 1887–  
 1111 1907, <https://doi.org/10.5194/amt-13-1887-2020>.
- 1112 Oncley, S. P., and Coauthors, 2007: The Energy Balance Experiment EBEX-2000. Part I:  
 1113 overview and energy balance. *Bound.-Layer Meteor.*, **123**, 1–28,  
 1114 <https://doi.org/10.1007/s10546-007-9161-1>.
- 1115 Peters, G., B. Fischer, and T. Andersson, 2002: Rain observations with a vertically looking Micro  
 1116 Rain Radar (MRR). *Boreal Environ. Res.*, **7**, 353–362, <http://www.borenv.net/BER/pdfs/ber7/ber7-353.pdf>.
- 1118 Pettersen, C., M. S. Kulie, L. F. Bliven, A. J. Merrelli, W. A. Petersen, T. J. Wagner, D. B.  
 1119 Wolff, and N. B. Wood, 2020a: A Composite Analysis of Snowfall Modes from Four  
 1120 Winter Seasons in Marquette, Michigan. *J. Appl. Meteor. Climatol.*, **59**, 103–124,  
 1121 <https://doi.org/10.1175/JAMC-D-19-0099.1>.
- 1122 Pettersen, C.; Bliven, L.F.; von Lerber, A.; Wood, N.B.; Kulie, M.S.; Mateling, M.E.; Moisseev,  
 1123 D.M.; Munchak, S.J.; Petersen, W.A.; Wolff, D.B., 2020b: Introducing the Precipitation  
 1124 Imaging Package: Assessment of microphysical and bulk characteristics of snow.  
 1125 *Atmosphere*, in review.
- 1126 Pielke, R. A., Sr, R. Avissar, M. Raupach, A. J. Dolman, X. Zeng, and A. S. Denning, 1998:  
 1127 Interactions between the atmosphere and terrestrial ecosystems: influence on weather and  
 1128 climate. *Glob. Chang. Biol.*, **4**, 461–475, <https://doi.org/doi:10.1046/j.1365-2486.1998.t01-1-00176.x>.
- 1130 Platis, A., A. F. Moene, D. M. Villagrasa, F. Beyrich, D. Tupman, and J. Bange, 2017:  
 1131 Observations of the Temperature and Humidity Structure Parameter Over Heterogeneous  
 1132 Terrain by Airborne Measurements During the LITFASS-2003 Campaign. *Bound.-Layer  
 1133 Meteor.*, **165**, 447–473, <https://doi.org/10.1007/s10546-017-0290-x>.
- 1134 Poulos, G. S., and Coauthors, 2002: CASES-99: A Comprehensive Investigation of the Stable  
 1135 Nocturnal Boundary Layer. *Bull. Amer. Meteor. Soc.*, **83**, 555–581,  
 1136 [https://doi.org/10.1175/1520-0477\(2002\)083<0555:CACIOT>2.3.CO;2](https://doi.org/10.1175/1520-0477(2002)083<0555:CACIOT>2.3.CO;2).
- 1137 Raasch, S., and M. Schröter, 2001: PALM - A large-eddy simulation model performing on  
 1138 massively parallel computers. *Meteor. Zeitschrift*, **10**, 363–372,  
 1139 <https://doi.org/10.1127/0941-2948/2001/0010-0363>.

- 1140 Ran, Y., X. Li, R. Sun, N. Kljun, L. Zhang, X. Wang, and G. Zhu, 2016: Spatial  
1141 representativeness and uncertainty of eddy covariance carbon flux measurements for  
1142 upscaling net ecosystem productivity to the grid scale. *Agric. For. Meteorol.*, **230–231**, 114–  
1143 127, <https://doi.org/https://doi.org/10.1016/j.agrformet.2016.05.008>.
- 1144 Raupach, M. R., and J. J. Finnigan, 1995: Scale issues in boundary-layer meteorology: Surface  
1145 energy balances in heterogeneous terrain. *Hydrol. Process.*, **9**, 589–612,  
1146 <https://doi.org/doi:10.1002/hyp.3360090509>.
- 1147 Reen, B. P., D. R. Stauffer, and K. J. Davis, 2014: Land-Surface Heterogeneity Effects in the  
1148 Planetary Boundary Layer. *Bound.-Layer Meteorol.*, **150**, 1–31,  
1149 <https://doi.org/10.1007/s10546-013-9860-8>.
- 1150 Reichstein, M., G. Camps-Valls, B. Stevens, M. Jung, J. Denzler, N. Carvalhais, and Prabhat,  
1151 2019: Deep learning and process understanding for data-driven Earth system science.  
1152 *Nature*, **566**, 195–204, <https://doi.org/10.1038/s41586-019-0912-1>.
- 1153 Rihani, J. F., F. K. Chow, and R. M. Maxwell, 2015: Isolating effects of terrain and soil moisture  
1154 heterogeneity on the atmospheric boundary layer: Idealized simulations to diagnose land-  
1155 atmosphere feedbacks. *J. Adv. Model. Earth Syst.*, **7**, 915–937,  
1156 <https://doi.org/10.1002/2014MS000371>.Received.
- 1157 Sellers, P., and Coauthors, 1995: The Boreal Ecosystem–Atmosphere Study (BOREAS): An  
1158 Overview and Early Results from the 1994 Field Year. *Bull. Amer. Meteor. Soc.*, **76**, 1549–  
1159 1577, [https://doi.org/10.1175/1520-0477\(1995\)076<1549:TBESAO>2.0.CO;2](https://doi.org/10.1175/1520-0477(1995)076<1549:TBESAO>2.0.CO;2).
- 1160 Serbin, S. P., A. Singh, B. E. McNeil, C. C. Kingdon, and P. A. Townsend, 2014: Spectroscopic  
1161 determination of leaf morphological and biochemical traits for northern temperate and  
1162 boreal tree species. *Ecol. Appl.*, **24**, 1651–1669, <https://doi.org/10.1890/13-2110.1>.
- 1163 Steinfeld, G., M. O. Letzel, S. Raasch, M. Kanda, and A. Inagaki, 2007: Spatial  
1164 representativeness of single tower measurements and the imbalance problem with eddy-  
1165 covariance fluxes: results of a large-eddy simulation study. *Bound.-Layer Meteorol.*, **123**, 77–  
1166 98, <https://doi.org/10.1007/s10546-006-9133-x>.
- 1167 ———, S. Raasch, and T. Markkanen, 2008: Footprints in Homogeneously and Heterogeneously  
1168 Driven Boundary Layers Derived from a Lagrangian Stochastic Particle Model Embedded  
1169 into Large-Eddy Simulation. *Bound.-Layer Meteorol.*, **129**, 225–248,  
1170 <https://doi.org/10.1007/s10546-008-9317-7>.
- 1171 Stoy, P. C., and Coauthors, 2013: A data-driven analysis of energy balance closure across  
1172 FLUXNET research sites: The role of landscape scale heterogeneity. *Agric. For. Meteorol.*,  
1173 **171–172**, 137–152, <https://doi.org/10.1016/j.agrformet.2012.11.004>.
- 1174 Sulman, B. N., A. R. Desai, B. D. Cook, N. Saliendra, and D. S. Mackay, 2009: Contrasting  
1175 carbon dioxide fluxes between a drying shrub wetland in Northern Wisconsin, USA, and  
1176 nearby forests. *Biogeosciences*, **6**, 1115–1126, <https://doi.org/10.5194/bg-6-1115-2009>.
- 1177 Turner, D. D., and W. G. Blumberg, 2019: Improvements to the AERIoe Thermodynamic Profile  
1178 Retrieval Algorithm. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, **12**, 1339–1354,

This work has been submitted to the Bulletin of the American Meteorological Society.  
Copyright in this work may be transferred without further notice.

- 1179 <https://doi.org/10.1109/JSTARS.2018.2874968>.
- 1180 Turner, D. D., and U. Löhnert, 2014: Information Content and Uncertainties in Thermodynamic  
1181 Profiles and Liquid Cloud Properties Retrieved from the Ground-Based Atmospheric  
1182 Emitted Radiance Interferometer (AERI). *J. Appl. Meteor. Climatol.*, **53**, 752–771,  
1183 <https://doi.org/10.1175/JAMC-D-13-0126.1>.
- 1184 Twine, T. E., and Coauthors, 2000: Correcting eddy-covariance flux underestimates over a  
1185 grassland. *Agric. For. Meteorol.*, **103**, 279–300, [https://doi.org/https://doi.org/10.1016/S0168-](https://doi.org/10.1016/S0168-1923(00)00123-4)  
1186 [1923\(00\)00123-4](https://doi.org/10.1016/S0168-1923(00)00123-4).
- 1187 Vogelmann, H., Speidel, J., and Perfahl, M.: Laser concept of the mobile ATMONSYS-lidar and  
1188 its application during CHEESEHEAD, EGU General Assembly 2020,  
1189 <https://doi.org/10.5194/egusphere-egu2020-16517>
- 1190 Wagner, T. J., P. M. Klein, and D. D. Turner, 2019: A New Generation of Ground-Based Mobile  
1191 Platforms for Active and Passive Profiling of the Boundary Layer. *Bull. Amer. Meteor. Soc.*,  
1192 **100**, 137–153, <https://doi.org/10.1175/BAMS-D-17-0165.1>.
- 1193 Wang, J., J. Zhuang, W. Wang, S. Liu, and Z. Xu, 2015: Assessment of Uncertainties in Eddy  
1194 Covariance Flux Measurement Based on Intensive Flux Matrix of HiWATER-MUSOEXE.  
1195 *IEEE Geosci. Remote Sens. Lett.*, **12**, 259–263,  
1196 <https://doi.org/10.1109/LGRS.2014.2334703>.
- 1197 Wang, Y. Q., Y. J. Xiong, G. Y. Qiu, and Q. T. Zhang, 2016: Is scale really a challenge in  
1198 evapotranspiration estimation? A multi-scale study in the Heihe oasis using thermal remote  
1199 sensing and the three-temperature model. *Agric. For. Meteorol.*, **230–231**, 128–141,  
1200 <https://doi.org/https://doi.org/10.1016/j.agrformet.2016.03.012>.
- 1201 Wang, Z., P. Wechsler, W. Kuestner, J. French, A. Rodi, B. Glover, M. Burkhardt, and D. Lukens,  
1202 2009: Wyoming Cloud Lidar: instrument description and applications, *Optics Express* Vol.  
1203 **17**, Iss. 16, pp. 13576–13587.
- 1204 Wang, Z., A. Chlus, R. Geygan, Z. Ye, T. Zheng, A. Singh, J.J. Couture, J. Cavender-Bares, E.L.  
1205 Kruger and P.A. Townsend, accepted: Foliar functional traits from imaging spectroscopy  
1206 across biomes in eastern North America. *New Phytol.*
- 1207 Wisconsin Department of Natural Resources. (2019). Wisconsin Wiscland 2 Land Cover  
1208 Database Level 4, 2019. Retrieved from <https://data-wi-dnr.opendata.arcgis.com>
- 1209 Wolf, B., and Coauthors, 2017: The SCALEX Campaign: Scale-Crossing Land Surface and  
1210 Boundary Layer Processes in the TERENO-preAlpine Observatory. *Bull. Amer. Meteor.*  
1211 *Soc.*, **98**, 1217–1234, <https://doi.org/10.1175/BAMS-D-15-00277.1>.
- 1212 Wu, D., Z. Wang, P. Wechsler, N. Mahon, M. Deng, B. Glover, M. Burkhardt, W. Kuestner, and  
1213 B. Heesen, 2016: Airborne compact rotational Raman lidar for temperature measurement,  
1214 *Opt. Express*, **24**, A1210-A1223.
- 1215 Wu, P., H. Shen, T. Ai, and Y. Liu, 2013: Land-surface temperature retrieval at high spatial and

1216 temporal resolutions based on multi-sensor fusion. *Int. J. Digit. Earth*, **6**, 113–133,  
1217 <https://doi.org/10.1080/17538947.2013.783131>.

1218 Wulfmeyer, V., S. K. Muppa, A. Behrendt, E. Hammann, F. Späth, Z. Sorbjan, D. D. Turner, and  
1219 R. M. Hardesty, 2016: Determination of Convective Boundary Layer Entrainment Fluxes,  
1220 Dissipation Rates, and the Molecular Destruction of Variances: Theoretical Description and  
1221 a Strategy for Its Confirmation with a Novel Lidar System Synergy. *J. Atmos. Sci.*, **73**, 667–  
1222 692, <https://doi.org/10.1175/JAS-D-14-0392.1>.

1223 Wulfmeyer, V., and Coauthors, 2018: A New Research Approach for Observing and  
1224 Characterizing Land–Atmosphere Feedback. *Bull. Amer. Meteor. Soc.*, **99**, 1639–1667,  
1225 <https://doi.org/10.1175/BAMS-D-17-0009.1>.

1226 Xu, K., S. Metzger, and A. R. Desai, 2017a: Upscaling tower-observed turbulent exchange at  
1227 fine spatio-temporal resolution using environmental response functions. *Agric. For.*  
1228 *Meteor.*, **232**, 10–22, <https://doi.org/10.1016/j.agrformet.2016.07.019>.

1229 ———, ———, and A. R. Desai, 2018: Surface-atmosphere exchange in a box: Space-time resolved  
1230 storage and net vertical fluxes from tower-based eddy covariance. *Agric. For. Meteor.*, **255**,  
1231 81–91, <https://doi.org/10.1016/j.agrformet.2017.10.011>.

1232 Xu, Z., Y. Ma, S. Liu, W. Shi, and J. Wang, 2017b: Assessment of the Energy Balance Closure  
1233 under Advective Conditions and Its Impact Using Remote Sensing Data. *J. Appl. Meteor.*  
1234 *Climatol.*, **56**, 127–140, <https://doi.org/10.1175/JAMC-D-16-0096.1>.

1235 Xu, K., M. Sührling, S. Metzger, D. Durden, and A. R. Desai, 2020: Can Data Mining Help Eddy  
1236 Covariance See the Landscape? A Large-Eddy Simulation Study. *Bound.-Layer Meteor.*,  
1237 **176**, 85–103, <https://doi.org/10.1007/s10546-020-00513-0>.

1238 Zhu, X., G. Ni, Z. Cong, T. Sun, and D. Li, 2016: Impacts of surface heterogeneity on dry  
1239 planetary boundary layers in an urban-rural setting. *J. Geophys. Res. Atmos.*, **121**, 164–179,  
1240 <https://doi.org/10.1002/2016JD024982>.

1241 Zitouna-Chebby, R., L. Prévot, F. Jacob, R. Mougou, and M. Voltz, 2012: Assessing the  
1242 consistency of eddy covariance measurements under conditions of sloping topography  
1243 within a hilly agricultural catchment. *Agric. For. Meteor.*, **164**, 123–135,  
1244 <https://doi.org/10.1016/j.agrformet.2012.05.010>.  
1245  
1246



SUPPLEMENTAL MATERIAL

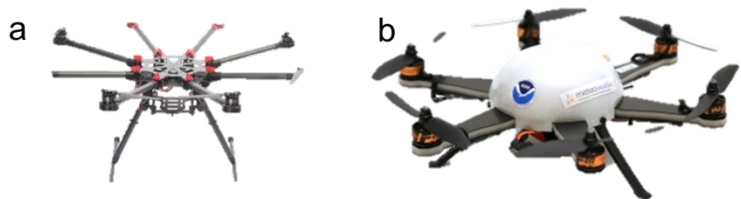


Fig. S1. The (a) DJI S-1000 and (b) Meteodrone SSE.

Table S1. List of the flux towers in operation during the CHEESEHEAD19 field campaign.

| Site # | Site Name | Ameriflu x ID | Latitude (° N) | Longitud e (° W) | Tower height (m) | Canopy height (m) | Vegetation | Contact |
|--------|-----------|---------------|----------------|------------------|------------------|-------------------|------------|---------|
| 1      | NW1       | US-PFb        | 45.97200       | 90.32317         | 32               | 25                | pine       | Oncley  |
| 2      | NW2       | US-PFc        | 45.96773       | 90.30878         | 12               | 3                 | aspen      | Oncley  |
| 3      | NW3       | US-PFd        | 45.96892       | 90.30103         | 3                | 0.3               | wetland    | Oncley  |
| 4      | NW4       | US-PFe        | 45.97925       | 90.30042         | 32               | 20.1              | lake       | Oncley  |
| 5      | NW5       | US-PFf        | 45.94583       | 90.29437         | 2                | 0                 | grass      | Stoy    |
| 6      | NE1       | US-PFg        | 45.97348       | 90.27230         | 32               | 33.2              | pine       | Oncley  |
| 7      | NE2       | US-PFh        | 45.95573       | 90.24060         | 32               | 19.2              | pine       | Oncley  |
| 8      | NE3       | US-PFi        | 45.97490       | 90.23273         | 32               | 18.3              | hardwood   | Oncley  |
| 9      | NE4       | US-PFj        | 45.96187       | 90.22703         | 32               | 18.3              | maple      | Oncley  |
| 10     | SW1       | US-PFk        | 45.91490       | 90.34250         | 32               | 24.4              | aspen      | Oncley  |
| 11     | SW2       | US-PFl        | 45.94090       | 90.31773         | 25               | 19.2              | aspen      | Oncley  |
| 12     | SW3       | US-PFm        | 45.92067       | 90.30990         | 32               | 15                | hardwood   | Oncley  |
| 13     | SW4       | US-PFn        | 45.93922       | 90.28232         | 32               | 25.9              | hardwood   | Oncley  |
| 14     | SE1       | US-PFo        | 45.92288       | 90.27283         | 1.5              | 0                 | lake       | Stoy    |
| 15     | SE2       | US-PFp        | 45.93652       | 90.26408         | 32               | 24.4              | hardwood   | Oncley  |
| 16     | SE3       | US-PFq        | 45.92715       | 90.24750         | 32               | 14.3              | aspen      | Oncley  |
| 17     | SE4       | US-PFr        | 45.92448       | 90.24745         | 3                | 0.3               | wetland    | Oncley  |
| 18     | SE5       | US-PFs        | 45.93808       | 90.23818         | 12               | 3.1               | aspen      | Oncley  |
| 19     | SE6       | US-PFt        | 45.91973       | 90.22883         | 32               | 21.6              | pine       | Oncley  |
| 20     | WLEF      | US-PFa        | 45.94590       | 90.27230         | 396              | n/a               | mixed      | Desai   |
| 21     | WCR       | US-WCr        | 45.80600       | 90.07980         | 30               | 24                | hardwood   | Desai   |
| 22     | LOS       | US-Los        | 46.08270       | 89.97920         | 10               | 2                 | wetland    | Desai   |

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**Table S2. Instrumentation deployed at the CHEESEHEAD19 campaign by the NOAA Global Monitoring Laboratory**

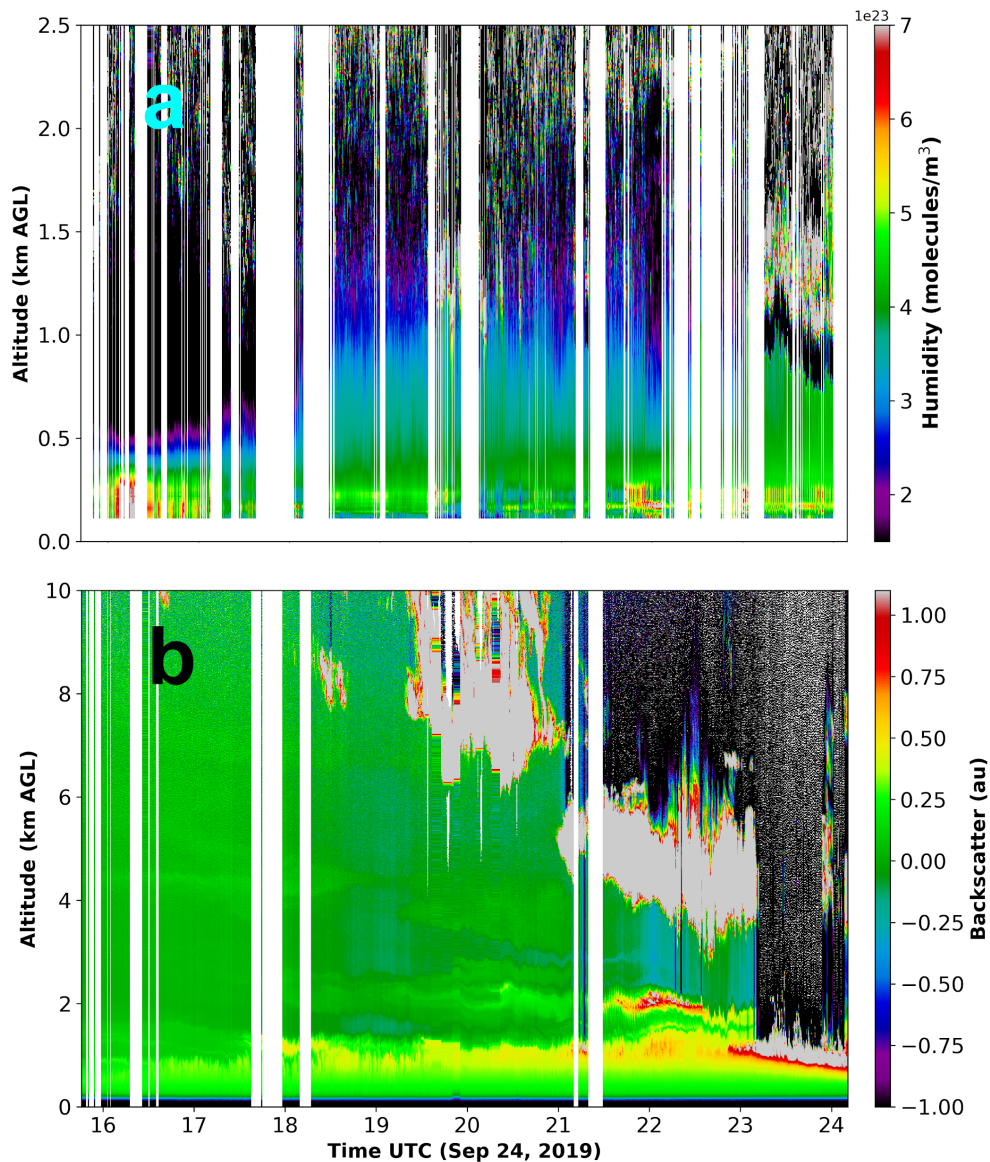
| Instrument                                                | Measurement                                                                                                                           | Dates (2019)  | Resolution |
|-----------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|---------------|------------|
| Central ISS Station                                       |                                                                                                                                       |               |            |
| Eppley Pyrgometer                                         | ↑↓ LW broadband hemispheric irradiance                                                                                                | 06/29 - 10/22 | 1 min avg. |
| Eppley Precision Spectral Pyranometer (PSP)               | ↑↓ SW broadband hemispheric irradiance                                                                                                | 06/29 - 10/22 | 1 min avg. |
| Shaded Eppley Black and White Pyranometer                 | Diffuse hemispheric broadband SW irradiance                                                                                           | 06/29 - 10/22 | 1 min avg. |
| Eppley Normal Incidence Pyrheliometer (NIP)               | Direct normal broadband SW irradiance                                                                                                 | 06/29 - 10/22 | 1 min avg. |
| Total Sky Imager (TSI)                                    | Images/movies of sky cover, fractional sky cover                                                                                      | 07/05 - 10/22 | 15 sec     |
| Vaisala CL51 Ceilometer                                   | Cloud base height, boundary layer height                                                                                              | 06/29 - 10/22 | 16 sec     |
| Multi Filter Rotating Shadowband Radiometer (MFRSR)       | ↓ hemispheric total and diffuse spectral irradiance at 6 bands: 415, 500, 670, 868, 940, 1625 nm; retrievals of aerosol optical depth | 06/29 - 10/22 | 20 sec     |
| Multi Filter Radiometer (MFR)                             | ↑ hemispheric total spectral irradiance at 6 bands: 415, 500, 670, 868, 940, 1625 nm. Spectral surface albedo and NDVI (with MFRSR).  | 06/29 - 10/22 | 20 sec     |
| LICOR Quantum 190R                                        | Photosynthetically Active Radiation                                                                                                   | 06/29 - 10/22 | 1 min avg. |
| Aerodyne Three-Waveband Spectrally-agile Technique (TWST) | Cloud optical depth, spectral SW zenith radiance (350-1000 nm, ~2.5 nm resolution)                                                    | 09/20 - 10/22 | 1 sec      |
| Vaisala HMP60                                             | Temperature and Relative Humidity                                                                                                     | 06/29 - 10/22 | 1 min avg. |
| RM Young, Model 05103                                     | Wind direction and speed at 10 m                                                                                                      | 06/29 - 10/22 | 1 min avg. |
| Prentice and Lakeland Airports                            |                                                                                                                                       |               |            |
| Eppley Pyrgometer                                         | ↓ LW broadband hemispheric irradiance                                                                                                 | 06/28 - 10/23 | 1 min avg. |
| Kipp & Zonen CMP11 Pyranometer                            | ↓ SW broadband hemispheric irradiance                                                                                                 | 06/28 - 10/23 | 1 min avg. |
| Delta-T SPN-1 Radiometer                                  | ↓ SW diffuse and total broadband hemispheric irradiance                                                                               | 06/28 - 10/23 | 1 min avg. |
| Vaisala HMP60                                             | Temperature and Relative Humidity                                                                                                     | 06/28 - 10/23 | 1 min avg. |
| Vaisala CL-51 Ceilometer                                  | Cloud Base Height (CBH)                                                                                                               | 06/28 - 10/23 | 16 sec     |

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| Table S3. The dates, times, and flight patterns of the UWKA flights. |               |               |               |                      |                     |                |
|----------------------------------------------------------------------|---------------|---------------|---------------|----------------------|---------------------|----------------|
| Date                                                                 | Flight Number | Takeoff (UTC) | Landing (UTC) | Entered Domain (UTC) | Exited Domain (UTC) | Flight Pattern |
| 7/9/19                                                               | RF01          | 13:57         | 16:47         | 14:06                | 16:16               | WE2            |
| 7/9/19                                                               | RF02          | 19:02         | 21:32         | 19:11                | 21:22               | WE2            |
| 7/11/19                                                              | RF03          | 14:10         | 17:00         | 14:22                | 16:36               | WE1            |
| 7/11/19                                                              | RF04          | 19:00         | 21:40         | 19:15                | 21:28               | WE1            |
| 7/12/19                                                              | RF05          | 13:40         | 16:45         | 13:49                | 16:06               | WE2            |
| 7/12/19                                                              | RF06          | 17:52         | 21:00         | 18:04                | 20:46               | WE2            |
| 7/13/19                                                              | RF07          | 14:05         | 16:52         | 14:22                | 16:32               | SE2            |
| 7/13/19                                                              | RF08          | 18:56         | 21:30         | 19:12                | 21:16               | SW1            |
| 8/20/19                                                              | RF09          | 13:40         | 16:23         | 13:51                | 16:12               | SE1            |
| 8/20/19                                                              | RF10          | 19:12         | 22:22         | 19:23                | 21:51               | SE1            |
| 8/21/19                                                              | RF11          | 13:54         | 16:50         | 14:08                | 16:36               | SW1            |
| 8/21/19                                                              | RF12          | 18:55         | 21:50         | 19:11                | 21:38               | SW1            |
| 8/22/19                                                              | RF13          | 13:57         | 17:15         | 14:11                | 16:55               | SW2            |
| 8/22/19                                                              | RF14          | 19:00         | 22:01         | 19:13                | 21:46               | SW2            |
| 8/23/19                                                              | RF15          | 13:57         | 16:48         | 14:07                | 16:38               | WE2            |
| 8/23/19                                                              | RF16          | 19:07         | 22:03         | 19:17                | 21:46               | WE2            |
| 9/24/19                                                              | RF17          | 13:37         | 17:00         | 13:53                | 16:24               | SE1            |
| 9/24/19                                                              | RF18          | 18:57         | 21:49         | 19:10                | 21:39               | SE1            |
| 9/25/19                                                              | RF19          | 14:20         | 17:22         | 14:41                | 17:09               | SW1            |
| 9/25/19                                                              | RF20          | 19:12         | 22:06         | 19:29                | 21:53               | SW1            |
| 9/26/19                                                              | RF21          | 13:52         | 16:46         | 14:05                | 16:35               | SE1            |
| 9/26/19                                                              | RF22          | 18:31         | 21:40         | 18:45                | 21:14               | SE1            |
| 9/28/19                                                              | RF23          | 14:14         | 17:30         | 14:37                | 17:17               | WE1            |
| 9/28/19                                                              | RF24          | 18:50         | 21:50         | 19:07                | 21:36               | WE1            |

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**Fig S2. Preliminary profiles of (a) H<sub>2</sub>O and (b) backscatter measured by the ATMONSYS lidar. These are complementary, collocated datasets with the HSRL, AERI, and MWR at WLEF. The high resolution data (vertical resolution of 110 m and 7.5 m for H<sub>2</sub>O and backscatter, respectively; 20 second temporal resolution for both) are capable of being combined with collocated Doppler wind lidar data to calculate flux profiles.**

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