COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

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EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN) 396006492	SHOW PREVIOUS AWARD NO. IF THIS IS ☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE University of Wisconsin-Madison AWARDEE ORGANIZATION CODE (IF KNOWN) 0038950000	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE 21 North Park Street Suite 6401 MADISON, WI 53715-1218
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IS AWARDEE ORGANIZATION (Check All That Apply) ☐ SMALL BUSINESS ☐ MINORITY BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 1,659,876	36 months	07/01/18	

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES
- ☐ PROPRIETARY & PRIVILEGED INFORMATION
- ☐ HISTORIC PLACES
- ☐ VERTEBRATE ANIMALS IACUC App. Date ________
- PHS Animal Welfare Assurance Number ________
- ☒ TYPE OF PROPOSAL Research
- ☐ HUMAN SUBJECTS Human Subjects Assurance Number ________
- Exemption Subsection ______ or IRB App. Date ________
- ☒ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED GM
- ☒ COLLABORATIVE STATUS A collaborative proposal from one organization (PAPPG II.D.3.a)

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PROJECT SUMMARY

Overview:

The living biosphere interacts with atmospheric processes at a multitude of scales. Understanding these processes requires integration of multiple observations for comparison to theories embedded in atmospheric models. But, all observations mismatch the scale of all models. Therefore, spatial and temporal scaling of surface fluxes is fundamental to how we evaluate theories on what happens within the sub-grid of atmospheric models and how those feed back onto larger scale dynamics. The Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors (CHEESEHEAD) is an intensive field-campaign designed specifically to address long-standing puzzles regarding the role of atmospheric boundary-layer responses to scales of spatial heterogeneity in surface-atmosphere heat and water exchanges.

The field campaign will be held mid summer to early fall 2019 in a 10 km x10 km domain around the existing Park Falls, WI, WLEF 400?m very tall tower Ameriflux/NOAA supersite which has four existing long-running flux towers. Multi-scale observations will analyze how the planetary boundary layer develops with varying spatial patterns of energy flux, test the relationship between eddy-covariance (EC) flux tower surface energy balance closure and mesoscale atmospheric properties, and evaluate parametric and machine-learning-based methods for scaling surface energy fluxes for improving model-data comparison. The three-month period allows for observing the evolution of the land surface from latent-heat flux dominated to sensible-heat flux dominated as vegetation senesces across the landscape.

The project involves deployment of the National Science Foundation Lower Atmosphere Observing Facility (LAOF) Integrated Surface Flux System. This first-of-its-kind very high-density (17+ tower) EC flux tower network will intensively sample surface energy fluxes across a heterogeneous forest landscape representative of much of the mid-latitudes. Student observers will sample phenology and vegetation at the tower sites. Airborne spectroscopy imaging will map leaf chemistry and canopy properties for scaling purposes. Atmospheric profiles will be observed at the tall tower with the LAOF Integrated Sounding System, radiosondes, the University of Wisconsin SPARC AERI, HSRL, ceilometer and wind LiDAR, and the contributed instruments from collaborators. Two seven-day intensive observation periods will include University of Wyoming King Air to map EC fluxes and planetary boundary-layer depth and an ultralight aircraft for atmospheric profiles. These observations will be used to test flux tower scaling, observe atmospheric mesoscale patterning, and evaluate large eddy simulations (LES).

Intellectual Merit:

The high-density observing network is coupled to LES and machine-learning scaling-experiments to better understand sub-mesoscale responses and improve numerical weather and climate prediction formulations of sub-grid processes. This project will advance spatiotemporal scaling methods for heterogeneous land surface properties and fluxes and theories on the scales at which the lower atmosphere responds to surface heterogeneity. CHEESEHEAD aims to provide a level of observation density and instrumentation reliability never previously achieved to test and develop hypotheses on spatial heterogeneity and atmosphere feedbacks.

Broader Impacts:

The proposed experiment generates knowledge that advances the science of surface flux measurement and modeling, relevant to many scientific applications such as numerical weather prediction, climate change, energy resources, and computational fluid dynamics. We intend to train next generation land-atmosphere graduate and undergraduate students. Field support outreach and teacher training is included via middle, high school, and undergraduate student involvement at nearby schools and colleges in coordination with the GLOBE program, Northland College, and local school districts. The database of observations and models will be made immediately available to the community and public for general use for further scientific advancement.

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Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

CHEESEHEAD: Perspective

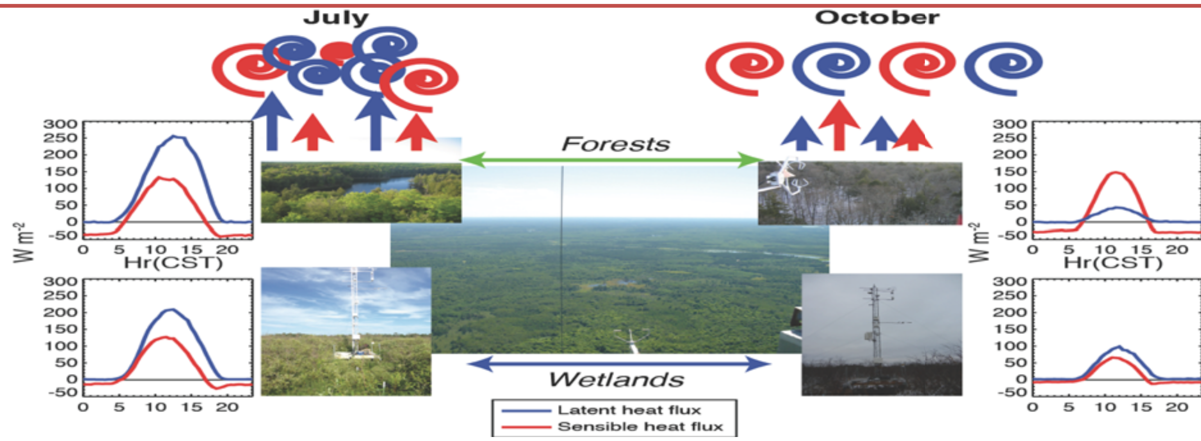

Figure 1. Spatial pattern of surface energy balance, shown here from nearby EC flux towers' mean diurnal cycle of latent (blue) and sensible (red) heat flux in a forest (top) and a wetland (bottom), drives patterning of atmospheric mixing that evolves in time (left vs right) as landscape energy partitioning heterogeneity (center photo from the very tall tower) increases from summer to fall.

Global cycling of energy, water and carbon drive important climate feedbacks and are mediated by biological organisms. However, the process by which the land surface biota exchange heat, water, momentum, and gases with the atmosphere are scale-dependent. Also, atmospheric responses to this heterogeneity exhibit patterns at multiple scales (Fig. 1), introducing substantial uncertainty in parameterizations for atmospheric modeling (Avissar, 1995), land surface remote sensing (Ershadi *et al*., 2013), landscape and urban ecology (Grimmond, *et al*., 2011), and hydrology (Gentine *et al., 2012;* Neale *et al*., 2012; Wang and Dickinson, 2012). While theoretical (van Heerwaarden *et al*., 2014) and simulated mechanisms (Rihani *et al*., 2015) exist, 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). Advances in flux observation, boundary layer profiling, and large-eddy simulation (LES) now allow us to pursue that goal with the *Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors* (**CHEESEHEAD**) intensive field-campaign.

CHEESEHEAD asks: do land surface energy partitioning and atmospheric responses differ from the sum of their individual components, and if so, a) how do these differences influence the atmosphere and b) how do we optimally observe and simulate these elements? These long-standing puzzles exist partly due to differing perspectives on the nature of scaling in ecology (upscale, from genes to ecosystems) and meteorology (downscale, from global energy transport to diffusive turbulence). We aim to provide the observational database and evaluation of simulations necessary to test hypotheses regarding spatial heterogeneity and lower atmosphere feedbacks. There are enormous possibilities with a state-of-the-art high-resolution dataset on land surface-atmosphere interactions. Findings here have broad implications for all heterogeneous terrestrial regions on Earth beyond the specific study location.

We propose to be deploy a high-density surface flux tower network (≥17 towers) across a heterogeneous 10x10 km Northern Wisconsin landscape within the sampling footprint of an existing 21-yr very tall (447m) eddy-covariance (EC) tower. Occasional aircraft flux sampling, continuous LiDAR and profiling atmospheric remote sensing, and frequent *in situ* sounding of atmospheric boundary layer properties will enable testing questions on scaling and parameterizing by employing LES of unprecedented realism. CHEESEHEAD incorporates a medium-term deployment (3 months) over the summer to fall growing season transition, which will allow for capturing ecologically and energetically important shifts in energy balance patterns responsible for heterogeneity in atmospheric boundary layer forcing. These energy balance shifts arise from seasonal changes in plant phenological phases, ecosystem water use for photosynthesis, and available net radiation, which will be monitored across the landscape.

CHEESEHEAD: Why Now?

The high density of flux towers will represent a first-of-its-kind intensive study of sub-mesoscale variation in energy partitioning, fundamental to understanding scaling of non-linear surface-atmosphere interaction. While some of these questions have been addressed from various angles in 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), there have not been any systematic studies of surface energy balance variability in the heterogeneous forested land cover characteristic of the temperate deciduous landscapes of the terrestrial mid-latitudes. Less-intensive flux tower mesonets have been deployed in former experiments such as BOREAS (Sellers *et al*., 1995) and LITFASS-2003 (Beyrich *et al*., 2006), but not for the duration and with the density proposed here. For all of these previous studies, the number of available towers was much smaller, on the order ten. HiWATER comes closest with 17, but data were focused on surface evaporation over a desert region with limited atmospheric profile observations. During BOREAS, the study area was larger and typical distance of towers was high so their data could not be combined to investigate spatial structures in the atmosphere. Integration was done by airborne turbulence measurements along the flight track (Sun *et al*., 1997; Mauder *et al*., 2007a), but not in two dimensions. LITFASS-2006 focused on a heterogeneous study area of 20×20 km^2 around a tall tower in Germany (Bange *et al*., 2006), but the meteorological tower there was much smaller, and only a smaller number of surface flux towers were available (13).

Existing experiments are thus insufficient to answer questions on ecological and atmospheric scaling, and to advance next generation LES and mesoscale models. Initial LES analysis of our study domain suggests that while 12 flux towers would be sufficient to adequately sample land cover variation, it takes potentially more (>15) to sample mesoscale eddy structures and close the energy budget CHEESEHEAD will provide a landmark dataset to improve use of EC flux measurements in model-data comparison, address parameterization of surface heterogeneity in gridded numerical models of the atmosphere, and test theories of boundary layer development arising from spatiotemporal variation in boundary conditions.

CHEESEHEAD: Response to Prior Reviews

This proposal is a resubmission of a 2015 submission to NSF and the 2016 OFAP review process. Both OFAP and science proposal reviews were positive, though the flux tower deployment was deemed not feasible due to close proximity in timing to another field experiment. As a result, we are resubmitting the proposal for a July-October 2019 deployment. We have also addressed comments made by the facilities panel and reviewers. As a result of the extra year, we were able to conduct initial LES studies with a graduate student and test virtual tower and sampling placement to estimate tower numbers and experiment plan. We also conducted a short-term deployment of the *in situ* remote sensing trailer (SPARC) at the tall tower site, to better motivate hypotheses and evaluate feasibility. We changed the flight track to better sample meteorological variability, reduced costs by removing several supplemental instruments (water vapor DIAL, CTEMPS distributed temperature sensing), and reapportioned tasks of the post-doc. The research plan is better organized around the central theme, and objectives and hypotheses have greater focus on science objectives and generalizability of the experiments. The ERF approach for tower based scaling proposed here has now been published (Metzger, 2017; Xu et al., 2017a,b). Flight tracks and LES now expand beyond core "model grid cell" (10x10 km) to better incorporate mesoscale contributions.

We are also aware of the trade-offs that come in sample size and costs, and that both the airborne costs and the tower infrastructure costs add up in this type of experiment. However, airborne sampling of the mesoscale environment and mapping fluxes among the towers is essential, and two seven-day campaigns each with now 4-5 days of samples is sufficient to capture the state of the environment in "snapshots". Flight legs have now been extended to 30+ km to compute a robust mesoscale eddy flux (Mauder *et al.*, 2007a, 2008). The long-term run of the flux towers provides the anchor points to test the core hypotheses that are then framed and evaluated against the aircraft.

CHEESEHEAD: Motivation

The idea that land surface heterogeneity influences patterns of surface energy balance and atmospheric response is not surprising or novel, going back to early model simulations showing the importance of soil moisture, albedo, roughness, and heating on the atmosphere (Betts *et al.,* 1996; Charney *et al.*, 1975; Garrat, 1993), foundational papers on the role of vegetation dynamics and scale (Avissar, 1995; Pielke et al., 1998), and theories of internal boundary layers arising from surface heterogeneity (Mahrt, 2000). Despite progress in sub-grid modeling of these (Zhang *et al.,* 2010; Baker *et al.,* 2017), scale issues remain that limit both observations of these process and theoretical consideration. Modern observations and modeling advances allow us to better test and improve these theories. *Two will be tested here.* First is the EC energy balance problem, which may be an indicator of mesoscale circulation in heterogeneous conditions. Second is the representation and measurement of scales of surface heterogeneity and their effect on lower atmospheric process. Together, they allow us to understand what conditions prompt mesoscale flows in response to surface energy balance patterning.

A number of theories exist on how hypothetical or land surface variations drive planetary boundary layer (PBL) growth (Desai *et al.*, 2006; Reen *et al.*, 2014), turbulence structure (Platis *et al.*, 2017), and cloud development (Gantner *et al.*, 2017), but real-world tests in complex environments are limited. Theories are mixed on whether responses scale linearly or non-linearly, or whether they differ for dry versus moist dynamics (Raupach and Finnigan, 1995). While we understand the direct response of surface forcing on PBL growth and convection (Yi et al., 2004), considerable disagreement exists on when organized mesoscale convection occurs. This convection has been show to occur under both homogenous surface forcing (Pielke *et al.*, 1991), for example, cellular convection over oceans (Marshall and Schott, 1999), and conversely under heterogeneous surface forcing, such as local convection spots that develop standing eddies (Mauder *et al.*, 2007b; Zhang *et al.*, 2010). Most modeling studies on this topic have been developed from limited sets of observations of prior field experiments or from specialized modeling domains using relatively simplified boundary conditions (e.g., Hill *et al.,* 2008, 2011; Kang *et al.*, 2007; Zhu *et al.*, 2016). Experiments on identifying how spatial scale of land surface variability imparts on the atmosphere have been limited by experimental design (Eder, 2015). The need for a stronger observational database is pressing given the strong dependence of numerical weather and climate models on PBL schemes (Milovac *et al.*, 2016) and surface variability (Yan Kam Wing *et al.*, 2016) and parameterization of convection (Sun and Pritchard, 2016) as spatial resolution and complexity of these models increase.

The energy balance closure problem

Resolution of surface energy balance contributions is a challenge, but may solvable by using the measurement limitation (lack of energy balance closure) as a diagnostic tool. Energy balance closure refers to a long-standing observed pattern in EC flux towers that the sum of incoming available energy (net shortwave and longwave radiation minus ground heating) almost always exceeds surface turbulent sensible and latent heat fluxes, when expected to match at half-hourly scales (Foken *et al.*, 2011). Systematic studies have ruled out radiation and ground heat measurements as the primary cause (Twine *et al.*, 2000; Frank *et al.*, 2013; Horst *et al.*, 2014; Liu *et al.*, 2011). Lack of full observation of sub-measurement height storage flux contributes to some of this closure (Leuning *et al.*, 2012, Xu *et al.*, 2017b), but storage flux is rarely sufficient. Advection terms do not 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, 2012), while topography contributes mostly in extreme cases (McGloin *et al.,* 2018).

One proposed hypothesis for lack of closure in the energy budget terms 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). Sites with more variable land cover have a larger closure imbalance (Stoy *et al*., 2013; Xu *et al.,* 2017c). Surface energy balance models provide additional considerations about the role of scale (Ingwersen *et al.,* 2011; Wohlfahrt and Widmoser, 2013). 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. When we tested this idea in a LES with heterogeneous surface forcing (Fig. 2), we were able to nearly close the energy balance with as few as 6 randomly placed flux towers in our 10x10 km domain.

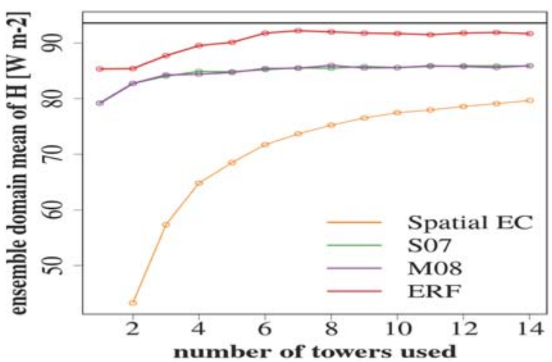

Figure 2. Estimates of 10x10 km LES domain mean sensible heat flux (black line: prescribed flux) as a function of number of "virtual" towers and EC method (orange: naive scaling, green: Steinfeld *et al* (2007), purple: Mauder *et al* (2008), red: ERF-VCV (see text)). Naïve upscaling of towers never reaches domain mean flux, while ERF approach needs as few as 6 towers.

The spatial scaling problem

The presence of heterogeneity also complicates upscaling of measurements for comparison to models. Rigorous testing of methods for scaling land-atmosphere exchanges to scales relevant for atmospheric processes is limited and efforts to date have been inconclusive (e.g., Desai *et al*., 2010; Ran *et al.,* 2017). Scaling has been shown to be non-linear with vegetation cover (Launianen et al., 2016) and sensitive to resolution, scaling method (Wang et al., 2016) and magnitude of heterogeneity (Liu et al., 2016). Individual towers can have systematic errors that exceed average of grid-mean fluxes (Ran et al., 2016).

Scaling methods broadly fall into two classes. *Data-driven approaches* infer relationships among observations directly from the available data. This approach minimizes the number of assumptions employed, but also limits their robustness and predictive performance (e.g., Beyrich *et al*., 2006, Desjardins *et al*., 1997; Chen *et al*., 1999; Hutjes *et al*., 2010; Ogunjemiyo *et al*., 2003). Such approaches are limited in particular by their neglect of intra-class variability (Bertoldi *et al*., 2013; Prueger *et al*., 2012). Advanced machine-learning techniques (e.g., Ueyama *et al*., 2013; Jung *et al*., 2011) suffer from insufficient sample sizes, such that the temporal resolution must be aggregated, thereby sacrificing information on the diurnal cycle that is critical to understanding atmospheric responses (Gentine *et al.*, 2011). *Process-based approaches* rely on prescribed mechanistic relationships, oftentimes inferred under and strictly valid for predictions representing a functional steady-state. One class of algorithms focuses on remotely-sensed properties of the land surface, allowing to determine biases introduced through spatial aggregation (e.g., Ershadi *et al*.; 2013, Stoy *et al*., 2009), while land surface models utilize a wider range of *in situ* observations (e.g., Chen *et al*., 2010, Fox *et al*., 2009; Kaminski *et al*., 2012; Koffi *et al*., 2013; Kuppel *et al*., 2012; Williams *et al*., 2009, Xiao *et al*., 2011). A key limitation is the assumption of energy and water balance closure (e.g., Anderson *et al*., 2008, Cammaleri *et al*., 2012).

Recently, environmental observations have become available at unprecedented spatial, temporal and spectral resolutions (e.g., Damian *et al*., 2014; Kampe *et al*., 2011; Musinsky *et al*. 2013). While enabling new insights into ecosystem functioning, such data also requires re-thinking scaling methodologies (e.g., Antonarakis *et al*., 2014; Hilker *et al*., 2013; Kobayashi *et al*., 2012). Here, we will provide a test-bed for scaling methodologies across heterogeneous land cover and propose to specifically test the *environmental response function - virtual control volume* (ERF-VCV) approach (Metzger, 2017; Xu et al., 2017b). ERF-VCV combines strengths of data-driven and mechanistic strategies as described in the analysis section.

CHEESEHEAD: Goals

The energy balance and spatial scaling problems point to an opportunity for a large-scale experiment to a) address the role of mesoscale energy flux contributions to observed lack of energy balance closure and b) understand how this is modulated by scale and pattern of surface heterogeneity (Fig. 3). The literature has

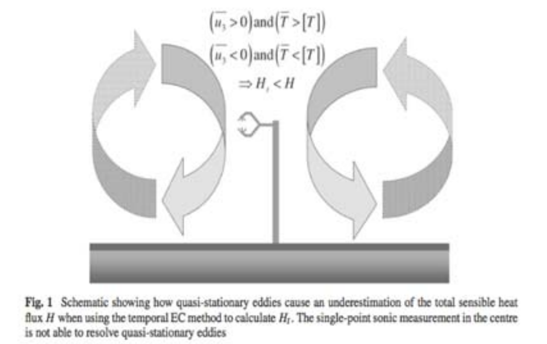

Figure 3. from Mauder *et al* (2008), a hypothesized source of “missing energy” arises from land surface heterogeneity developing stationary eddies in a convective boundary layer, advecting sensible heat flux to surface.

contradictory evidence that mesoscale eddies develop in both homogenous and heterogeneous landscapes, but in different patterns and with differing contributions to the net surface energy balance. Further, the lack of closure and the presence of heterogeneity complicate data-model comparison. The goal of CHEESEHEAD is to intensively sample and simulate the surface and boundary layer within the heterogeneous subgrid of a single “grid” cell of a weather or climate model (i.e., 10x10 km) to improve representation of surface energy balance and atmospheric response to surface heterogeneity in these models. Our analysis is based on mapping variation in surface energy balance, detecting atmospheric response to surface energy balance variability, and evaluating models for scaling and simulating these processes with statistical models and LES over a three months from mid-summer to early fall. During this time, we expect the surface energy balance to transition from more uniform transpiration (latent heat flux) dominated landscape to a patchy sensible heat flux dominated landscape (Fig. 1). Using this "natural experiment", we ask:

Q1: To what extent does local surface ecological homogeneity or heterogeneity drive variation in surface energy balance and what impact does that have on local lower atmospheric circulations?

H1) Higher heterogeneity of ecosystem state leads to higher variability of surface energy balance, which generates organized PBL convection, promoting greater energy transport in mesoscale eddies

H2) The lack of surface energy balance closure in EC indicates mesoscale energy transport in the PBL, which can be accounted and used to observe the “true” surface energy balance

Q2: How does the presence or absence of these circulations influence the representativeness of single or multi-site surface energy fluxes and ecological measurements when compared to the grid average?

H3) Advanced scaling methods, when applied to tall tower fluxes and high-resolution spectroscopic and ecological spatial measurements, more effectively downscales single tower eddy fluxes compared to linear scaling approaches of multiple short towers, regardless of mesoscale contributions.

Testing these questions across an intensive network of EC flux towers with continuous atmospheric profiles and maps of temperature, humidity, and winds could lead to new solutions to the energy balance closure problem of EC and guide approaches on number of observations required for upscaling or downscaling surface observations for comparison with weather, climate, and ecosystem models. These findings also have practical applications for advancing the parameterization of numerical boundary layer simulations and improving approaches for model evaluation against spatially distributed observations.

CHEESEHEAD: Research Plan

A high-density ground-based measurement network, well-characterized vertical profiles of temperature, humidity, and mixing as well as high-resolution grids of surface (albedo, land cover) and atmospheric variability can provide the necessary data basis for answering the questions above. Such data enable quantification of the extent by which spatial patterning of surface energy fluxes arise from patterning of the landscape and how this pattern imprints upon boundary layer eddies and development.

The project is centered on a field experiment and related analyses combined with model simulations in a 10x10 km region surrounding the WLEF very tall tower in Wisconsin. The area represents typical heterogeneity of mid-latitude forested regions (Fig. 4), unlike earlier studies that have mostly been in agricultural or grassland domains. In this domain, relying on the analysis in Fig. 2 on requirements for spatial EC, we propose deployment of 17 additional flux towers combining long-term existing Ameriflux facilities and 3-month deployments of NCAR NSF Lower Atmospheric Observing Facility (LAOF)

Integrated Surface Flux Facility (ISFS) and Ameriflux and National Ecological Observatory Network (NEON) mobile flux platforms. Additionally, we request an array of sounding and airborne measurements to sample the atmosphere in various configurations as the surface evolves from a homogenous energy balance to heterogeneous (Table 1).

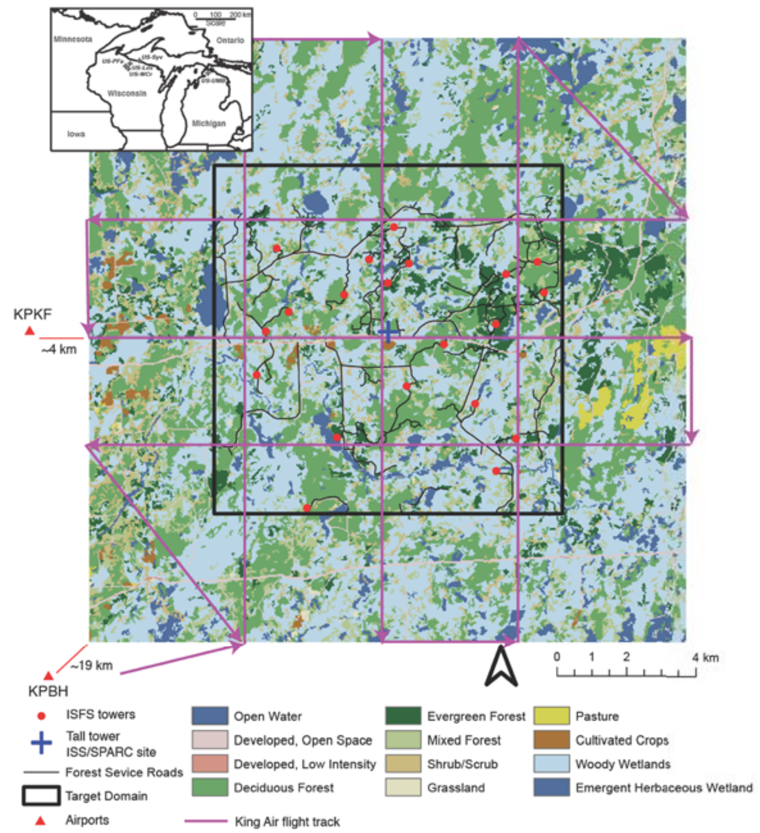

Figure 4 Landcover (NLCD2011) map of the 10x10 km study domain (black box), tall flux tower, ISS, SPARC, KIT instruments (blue cross), 20 candidate tower locations (red dots), airports (red triangle), and proposed flight pattern for the UWyo King Air (purple lines).

The 447-m tall tower is a long-running Ameriflux site (US-PFa), one of the original towers in the NOAA greenhouse gas tall tower network (LEF) (Andrews et al., 2014; Bakwin *et al*., 1998), and one of the oldest Total Carbon Column Observation Network (TCCON) site (Park Falls) (Keppel-Aleks *et al*, 2012). The region has been used for a number of short-term NASA field validation campaigns (e.g., Burrows *et al*., 2002). The surrounding landscape has a nearly fractal like land cover with approximately 30% wetland, 65% upland forest, and 5% clearings, grassy areas, and lakes. Typical homogenous patches of wetlands or forests are rarely more than 20 hectares, thus making it an ideal site for testing upscaling strategies. Flux measurements at the site have revealed the strong influence of spatial land cover heterogeneity on surface carbon and energy fluxes (Davis *et al*., 2003) and stronger influence of autumn over spring phenological control on interannual variability (Desai, 2010, Keenan *et al.*, 2015).

The focus of the campaign is to capture the mid-summer through fall senescent period, allowing for evaluation of surface energy balance from periods of transpiration and latent heat dominated exchange (mid-summer, Bowen ratio < 1) to sensible heat dominated exchange (fall, Bowen ratio > 1). Differences in timing of leaf-off of various species leads to differing configurations of leaf area and cover across the landscape, allowing for testing of the robustness of scaling approaches to shifts in total vegetated fraction.

Experimental Design

The experiment would be held June 24-Ocober 11 2019. Within this three-month time period, we propose two intensive observation periods (IOPs) where airborne sampling, student experiments, and increased balloon launches will allow us to "fill the gaps" in observational density. The IOPs are timed for peak greenness (Jul 1-7) and senescence (Sept 30-Oct 6) with intensive measurement during different surface energy balance spatial variability.

At least 17 NCAR Integrated Surface Flux System FluxPam EC flux towers, ranging in height from 5-23 m will be placed in a stratified random grid pattern in a 10x10 km box around the WLEF very tall tower and operate from July 1-Oct 6 in a mix forests, several wetlands, and open fields, mostly on US Forest Service land. We have found 12 to be the minimum number of sites needed to adequately represent expected land cover variability in the domain, but more than 15 to fully close the energy balance in our LES simulations of random flux towers and attempt spatial EC techniques (Fig. 2). The study design will

Table 1 List of facilities to be deployed for CHEESEHEAD

Surface (mostly distributed in 10x10 km area)	
University of Wisconsin-Madison, Atmospheric and Oceanic Sciences (DESAI)	
Ameriflux/NOAA very tall tower (US-PFa / WLEF)	Continuous, funded by DOE Ameriflux
ChEAS Ameriflux tower network (US-WCr/US-Los)	Continuous, funded by DOE Ameriflux
University of Wisconsin-Milwaukee, Geography (SCHWARTZ)	
Ground-based vegetation/phenology sampling	July-Oct, weekly, campaign/student-based
NCAR EOL Integrated Surface Flux System (ISFS)	
15-20 10-20 m EC flux towers	July-Oct, above canopy fluxes and met
In-Situ Profiling (mostly at US-PFa Very tall tower)	
NCAR EOL Integrated Sounding System (ISS)	
449 MHz modular wind profiler + RASS	July-Oct, Winds, T/RH profile
Radiosonde	Every morning (12 UTC) July-Oct
UW Space Science and Engineering Center Portable Atmospheric Research Center (SPARC)	
Atmospheric Emitted Radiance Interferometer (AERI)	July-Oct, T and RH profile
HALO Photonics Streamline scanning Doppler LiDAR	July-Oct, Winds and turbulence
High-Spectral Resolution Lidar (HSRL)	July-Oct, aerosol backscatter
Vaisala Ceilometer	July-Oct, PBL depth
University of Wisconsin-Madison, Atmospheric and Oceanic Sciences (DESAI)	
3-hourly high-resolution PBL sondes during IOPs	Daily during IOPs
Karlsruhe Institute for Technology (VOGELMANN)	
DIAL/Raman Lidar	July-Oct, T and H2O profile
2x HALO Photonics Streamline scanning Doppler LiDAR	July-Oct, Winds and turbulence
Airborne	
University of Wyoming King Air	
Eddy covariance, Raman LiDAR, cloud LiDAR (70 hours)	2 IOPs w/ 8 hour ferry + 26 hours sampling
University of Wisconsin Spectral Explorer (UWSpex) (TOWNSEND)	
Surface mapping of 400-2500 nm spectra	2 IOPs
University of Wisconsin Ultralight (PETTY)	
Boundary-layer heat and water budget of domain; low level characterization of BL inhomogeneities	2 IOPs

be further optimized with respect to scientific return on investment by applying the ERF-VCV method to existing LES datasets and specifying optimal combinations of hardware and sampling strategies.

A team of student observers will characterize vegetation phenology, canopy leaf area, and soil temperature and moisture weekly throughout the field season at each of the sites. In the 100 m grassy clearing around the tall tower or alternatively (if sky view is a factor) at the nearby Park Falls municipal airport, atmospheric profiling instrumentation from three groups (ISS, SPARC, and KIT, as noted in Table 1) will be installed and daily morning sondes launched to monitor high-resolution vertical profiles of temperature, moisture, winds, and PBL depth during the same time period. Together, these provide the base observations to evaluate atmospheric response to surface energy balance patterns and observations required to derive scaling functions and parameterize the LES experiments.

During the IOPs, UW-Madison will add additional high-resolution, low-altitude, inexpensive WindSond radiosonde profiles at three-hourly interval at multiple locations (including upwind for air trajectory analysis) as well as low-altitude transects and surface layer profiles utilizing the UW-Madison ultralight, while SPARC and ISS would launch daytime sondes. The UWyo King Air would fly on two 3.5-hour flights (mid-morning and mid-afternoon) on 4 or 5 of the 6 IOP days (depending on weather/logistics). Each 3.5 hour flight will include a series of stacked 30 km legs at 150 mAGL (100 m if permission is granted) and 300 m above ground level, spaced 8-10 km apart to sample EC fluxes, lower PBL meteorology both in situ and if available, by downward pointing Raman LiDAR, and PBL depth with the upward looking Wyoming Cloud LiDAR. IOPs would also support student field projects, including low-cost meteorological flow tracking with digital cameras and party balloons. Finally, high spatial resolution (2 m) full-range imaging spectroscopy (470 bands between 400-2500 nm) of visible (400-700 nm), near IR (700-1000 nm), and shortwave IR (1000-2500 nm) reflectance will be conducted during each IOP using UWSpex spectrometer flown on a Cessna-180 leased from the State of Wisconsin.

Experimental Design: Surface measurements

Long-term towers: The WLEF US-PFa 447-m very tall tower is a television tower owned by the State of Wisconsin Educational Communications Board (ECB). Since 1995, University (Davis *et al*., 2003) and NOAA investigators (Bakwin *et al.*, 1998) have made greenhouse gas profile, meteorology, and EC flux measurements (energy, carbon, momentum) at 30 m, 122 m and 396 m above ground level, in addition to surface meteorology (pressure, temperature, humidity, soil moisture). Two additional towers (US-WCr, 30m in mature forest, and US-Los, 10m in shrub fen wetland) are approximately 20 km to from the tall tower (Cook *et al*., 2004; Desai *et al*., 2005; Sulman *et al*., 2009). Desai operates these sites as sole PI and is funded on a facility contract from the DOE Lawrence Berkeley Laboratory American Network Management Project as part of the Chequamegon Ecosystem-Atmosphere Study (ChEAS). A full-time lab manager maintains the facilities for UW-Madison, in addition to technical support based at NOAA ESRL in Boulder, CO, and a contract is in place with USGS in Rhinelander, WI for weekly site visits. CalTech/NASA JPL also operate a FTIR solar-pointing spectrometer (TCCON) for total greenhouse column observations.

Short-term towers: We propose to deploy at 17+ towers (based on our analysis in Figs. 2 and 3) to supplement our existing three towers. Canopy heights range from 0 m to 23 m and tower heights would need to be at least 2 m above vegetation height, preferably 4 m, in the roughness sublayer. Towers can reach 25 m to allow for above canopy measurements (2-5 m above canopy). Our proposed tower locations are based on road access, public land permitting, and stratified random sampling across land cover and canopy height in a 10x10 km domain (Christianson *et al.*, 2016). We scouted potential locations, mostly on U.S. Forest Service land, with Steve Oncley from NCAR in December 2015.

Core measurements include 2-D and 3-D sonic anemometers, temperature, humidity, pressure, precipitation, open-path gas analyzers for H_2O and CO_2, four-component incoming and outgoing radiation, soil heat flux, and image capture. A 4-componet net radiometer will measuring incoming and outgoing shortwave and longwave broadband radiation. Soil sensors will include soil temperature, soil moisture, soil heat capacity, and soil heat flux, at 5 cm underneath the soil. Three levels of temperature and humidity will be profiled on the tower to measure sub-measurement height airspace storage fluxes and canopy micrometeorology. Soil sensors will include soil temperature, soil moisture, soil heat capacity, and soil heat flux, at 5 cm underneath the soil. Permitting for wetlands or lakes (at least 4 or 5) may require constructing tower on upland downwind of the wetland site, though alternative approaches (boats, floating docks) may be considered.

We are aware that significant infrastructure costs are likely with the short-term construction of 17+ flux towers and that further land cover sampling analyses suggest reduction in slope of representativeness after 8 towers (Fig. 2). However, the spatial EC analysis, whereby multiple towers are used in unison to detect mesoscale eddy contribution to fluxes, requires up to 17 towers, according to the preliminary LES analysis and previous literature. We are also planning to make requests for up to four towers combined from mobile deployment platforms offered by the *Ameriflux Mobile Rapid Deployment* and *NEON Assignable Assets* programs to leverage additional support and towers.

Vegetation sampling: To provide ecological indicators of change and validate airborne land cover, leaf chemistry, height, and roughness maps, the Schwartz lab at U. Wisconsin-Milwaukee will train undergraduate observers to characterize vegetation for each of the tower sites on a bi-weekly basis`. Undergraduate students from the primarily undergraduate institution Northland College in Ashland, WI and trained high school observers from nearby public schools (see letters) will also assist on these and related tasks. The primary observations to be collected will be species composition, optical leaf area (with Desai lab Li-Cor LAI-2200), and phenological state of the overstory in a 30 m radius of each tower. Select leaves will also be collected and analyzed for leaf chemistry (carbon, nitrogen) and photosynthesis using UW campus facilities (C/N analyzer and LI-6400).

Experimental Design: Boundary-layer vertical profiling

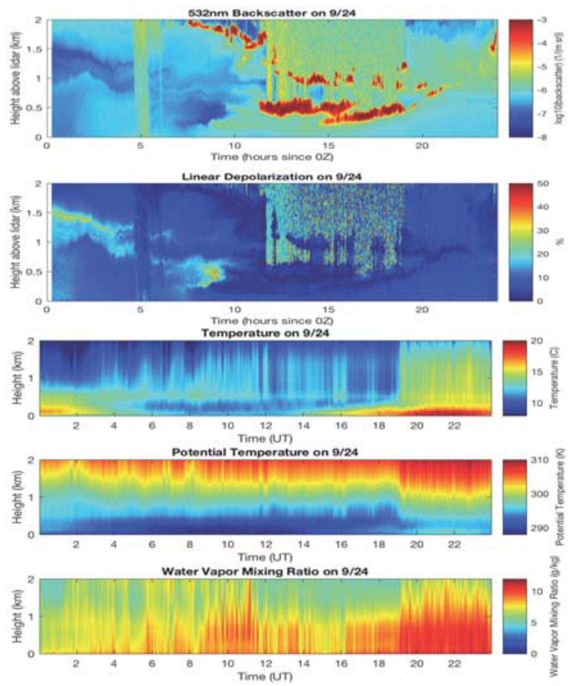

Figure 5. SPARC HSRL 532 nm backscatter and linear depolarization on Sept 24, 2016 and coincident AERI temperature and water vapor retrievals at the tall tower site during the test deployment. Turbulent mixing enhances surface fluxes and water vapor transport around 20Z, as clouds clear off earlier in day, as seen on HSRL

To connect the surface flux measurements to boundary layer responses, we propose to incorporate *in situ* profiling instruments that have been shown to be critical to diagnosing boundary layer structure (Wulfmeyer *et al.,* 2015). All instruments will be located in the 100 m clearing at the tall tower.

ISS: From the NCAR Integrated Sounding System, we will deploy the 449 MHz wind profiler and radio acoustic sounding system (RASS) to measure boundary layer winds and virtual temperature, operating in low-altitude mode to maximize sample (60 or 100 m resolution) in the first 2 km of the atmosphere at 5-minute intervals. Standard surface meteorology (pressure, temperature, humidity) is requested for inter-calibration with existing tall tower meteorology.

During normal operations, a single radiosonde balloon sounding at 12Z will be launched, During IOPs, additional radiosondes from SPARC (42 per IOP, 6 days) and UW (30 per IOP, flight days) would be launched at approximately three-hourly from sunrise to sunset. The UW Atmospheric and Oceanic Sciences (AOS) sounding system will also be used to capture upwind soundings for trajectory analysis (additional 5 per IOP).

SPARC: The Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison has recently renovated their mobile platform, now called the SSEC Portable Atmospheric Research Center (SPARC). The UW SSEC SPARC trailer would be co-located with the ISS instrumentation. The Atmospheric Emitted Radiance Interferometer (AERI) would pointed upward to retrieve boundary layer profiles of temperature and humidity, complementing the more qualitative profiles retrieved from the RASS. A HALO Photonics Streamline XR conical scanning wind LiDAR would provide high-resolution, 5-minute horizontal wind profiles (with 1-minute vertical winds every 15 minutes) to complement the ISS 449 MHz profiler, since the LiDAR has better retrieval quality near the ground. The High-Spectral Resolution Lidar (HSRL) would be pointed upward to sample boundary layer aerosol backscatter and depolarization ratio at 532 nm and 1064 nm. Finally, the Vaisala ceilometer provides a secondary evaluation of PBL depth. A recent (Sep 2016) 10-day installation of SPARC at the tall tower site (Fig. 5) showed high fidelity in capturing PBL mesoscale processes.

KIT: In a co-submitted proposal to the German DFG, collaborators Hannes Vogelmann and Matthias Mauder at the Karlsruhe Institute of Technology (KIT) (see letter) will develop and deploy their combination Raman (temperature)/DIAL (H_2O) LiDAR. If funded, this instrument would provide a unique opportunity to capture the water vapor and heat flux budget and compare directly to tower EC measurements, at least for the top height (396 m), which would overlap the first range of the DIAL (300 m, 150 m vertical resolution).

Experimental Design: Spatial sampling of atmospheric and land surface variability

Airborne measurements of atmospheric profiles and land surface state are critical inputs to evaluating land-atmosphere scaling strategies and spatial variability. We propose using the University of Wyoming King Air in "flux mode", an airborne hyperspectral spectral imager, and the new UW ultralight aircraft.

U Wyoming King Air: The King Air would be flown on each of the 2 IOPS and aim for a total of ~9 flight cases across them. The King Air will ferry from Laramie, WY to a nearby airport (KPBH). With student forecasting assistance, flights will focus on fair-weather days, with either clear sky or shallow cumulus. Two 3.5-hour flights will be conducted, one from 15Z-1830Z and another from 20Z-2330Z. Each flight will consist of 3 30 km legs roughly perpendicular to mean wind direction (prevailing westerly or south-westerly, and thus typically north-south legs) and a similar 3 in parallel, each located 4 km apart, flown at level altitudes of 150 m above ground (or at minimum safe/vectoring altitude) and repeated in the upper boundary layer (~600 m). If permission is granted, we request the 150 m leg to be flown at 100 m to minimize vertical flux divergence, especially in the 10x10 km sampling domain. While 30 km extends beyond the 10 km study domain, it allows for capturing enough eddies and mesoscale variation to properly compute statistics for fluxes and waves using the wavelet decomposition method.

Each altitude will require 5 minutes for sample and 2 minutes per turn, so a single leg will require 20 minutes and the total sample will take 100 minutes (1.6 hours), which will be repeated, for a total 3.2 hours + additional 0.3 hours for taxi, takeoff, and positioning. During the flight, CO_2 and H_2O will be sampled by an open-path Li-Cor 7500 and closed-path Licor 6262 or 7000. Reverse-flow temperature and gust-probe provide 10 Hz turbulent temperature and wind measurements for flux calculation. A chilled mirror will provide baseline dewpoint measurement. Upward and downward IR and visible radiation will also be analyzed for energy budget calculation. Fluxes will be processed using the ERF wavelet decomposition and flux footprint method to increase sampling resolution and identify individual surface contributions to the measured eddy flux (Metzger *et al*., 2013).

During the low-level leg, the Wyoming upward pointing 355 nm Wyoming Cloud LiDAR will be used to identify boundary layer depth during the low-level flight leg. During the upper-level leg, the Wyoming Compact Raman LiDAR will be flown downward pointing to map temperature and moisture profiles of the atmosphere, which would allow us to effectively estimate mesoscale development and calculate flux divergence and storage terms. Result from prior experiments suggest the LiDAR has excellent resolution in both daytime and nighttime conditions.

UW Ultralight: The University of Wisconsin Ultralight (N13UW) is a human-piloted airborne instrument platform built in the summer of 2017 from a commercial kit (the Aeromarine Zigolo) by personnel in the Atmospheric and Oceanic Sciences Department. It is an experimental platform intended for low-altitude, low-speed, low-cost airborne measurements. Operating characteristics are in many ways similar to those of small fixed-wing drones, but with greater payload and without the logistical and regulatory constraints of unmanned autonomous flight. It recently demonstrated the ability to observe evolving temperature and humidity profiles between the surface and 600 m altitude at 8 min intervals. The aircraft would be maintained and operated by co-PI Grant Petty. CHEESEHEAD will likely be the first major deployment of the aircraft in an experiment outside of testing or educational deployments. The aircraft is notable for its ability to safely fly at very low altitudes and ultra-slow cruise speed (~13–18 m s^{-1}), with up to 3 hours of on-site air time on one 19 L tank of fuel. The existing suite of instruments will log temperature, pressure, humidity, position, and altitude, but funding is being sought in a separate proposal (PI: Petty) for additional instrumentation supporting wind, flux, and thermal infrared measurements. During IOPs, the plane will be based at the Park Falls municipal airport, 12 km west of the WLEF US-PFa tall tower. Students will help design the final flight plan, but the preliminary plan is to sample the 10x10 km box in a square pattern at two heights (30 and 100 m) during King Air deployments to assist in the construction of a simple boundary layer budget. Additionally, low-level boundary layer transitions at the margins of contrasting surface types will be explored.

UW Spectral Explorer: UWSpex consists of the HySpex (Norsk Elektro Optikk, Skedsmokorset, Norway) VNIR-1800 and SWIR-384 boresighted imaging spectrometers measuring 470 bands between 400-2500, with high spectral resolution (3.26 nm in VNIR and 5.45 nm in SWIR). UWSpex was recently acquired by the University of Wisconsin, and is operated by co-PI Phil Townsend. Townsend has an agreement to fly this spectrometer on a Cessna 180J owned by the State of Wisconsin and operated by the Wisconsin Department of Natural Resources. Radiance spectra obtained by UWSpex are orthorectified using PARGE and atmospherically corrected using ATCOR (both ReSe, Wil, Switzerland), from which the reflectance spectra can be used to map spatial variation in foliar biochemical and physiological traits (e.g., Singh et al., 2015; Serbin et al., 2015). The 10x10 km study area will be flown with fully overlapping flightlines at an altitude (~2000 m) that allow for approximately 1 m spatial resolution during both IOPs, to capture both fully leaf on and partial leaf off. These maps will be connected to the ground based spectra and phenology to provides the boundary conditions of canopy type, activity, and stress, needed for estimating scaling properties. There may be opportunity for no-cost acquisition from a thermal band and canopy height LiDAR by coordinating with the NEON Airborne Observing Platform (AOP).

Analysis

Analysis: Atmospheric development

We will combine diagnostic and high-resolution model analyses to evaluate atmospheric development and test how changing heterogeneity in surface properties drives variance in surface energy balance and how that drives mesoscale atmospheric properties. Maps of land cover, chemistry, and vegetation state derived from spectrometer and calibrated from the ground-based observer network will be used to evaluate in a multi-level hierarchical regression framework, the drivers of regional surface energy balance. Indices of convection will be derived from temperature, moisture, and turbulence profiles from the King Air, Ultralight, ISS, SPARC, and tall tower instruments. PBL depth will be derived from HSRL or DIAL using the methods of Hicks et al (2015). Case studies across a range of surface energy balance patterns will be used to evaluate Hypothesis 1 on the role of energy balance variance on organized convection and mesoscale eddies. IOPs will also allow us to test how representative single-point measurements are of the entire atmospheric state across the domain.

Further, we will develop modeling case studies to evaluate mechanisms and sensitivity. We propose to run LES case studies for 48 hour simulations for each IOP period during aircraft flights, with lower boundary conditions from applying ERF-VCV to the observational dataset. PALM is a LES model for atmospheric flows, which is especially designed for performing on massively parallel computer architectures. The representation of tall canopies follows the work of Shaw and Schumann (1992) and Watanabe (2004). A model domain is proposed encompassing the entire tower array (15x15 km), with nested boundary conditions up to the regional domain (300x300 km) derived from 3 km NOAA HRRR numerical weather model, in an approach similar to Heinze *et al*. (2014). The LES will run with a 5-10 m spatial resolution and 0.3-1 s time step.

LES studies in heterogeneous terrain also require accurate estimate of surface conditions including surface fluxes. Both the spatial tower network results described above and the scaled-based mapping of tall tower and airborne fluxes provide boundary constraints for the LES model and will be compared. The LES can then directly show how spatial variation in energy fluxes and land cover impart on the atmosphere, which can be evaluated against LiDaR and airborne profiles, to further explore the hypothesis on the development of convection in response to increasing spatial variation in surface forcing.

Initial LES results of the domain during a case study analysis where the ERF technique was used to map energy fluxes showed that heterogeneous fluxes presents slightly stronger and larger patterns in turbulent structures than uniform forcing (de Roo *et al*., 2014). We know from idealized numerical experiments using LES that this outcome depends on the degree of heterogeneity and how the intensity of turbulent organized structures are modified. Kanda *et al*. (2004) show that weak inhomogeneity can reduce local advections and low frequency trends at local points, while stronger inhomogeneity can enhance secondary circulations and lead to resulting large heat transports due to local advection at a given geostrophic wind speed. Based on our findings, additional sensitivity runs or targeted case studies will be considered depending on science questions and needs. A second proposal will be submitted by collaborator Mauder to the German Research Foundation (DFG) for additional LES model experiments.

Analysis: Spatial scaling

The mismatch of spatial and temporal scales when comparing models, whether they be ecosystem, weather, climate, or hydrological, to observations, whether they be vegetation plots, EC fluxes, or atmospheric profiles, limits our ability to evaluate and improve those models. CHEESEHEAD provides an extensive database of multi-scale observations that allow us to ask: how many observations are needed to upscale to the grid average, can we quantify how representative any one observation is of a model grid cell, and can we use information theory to increase the representativeness of that observation?

For the first question, we will test a number of upscaling methods with the EC flux tower data, field ecology plots, and remote sensing land cover and vegetation properties. Simple and more complex weightings can be evaluated against the grid mean. We can also test how sensitive grid means are to presence or absence of certain atmospheric flows, mesoscale turbulent structures, and local flux hotspots. We will demonstrate how model-data comparison changes with assumptions on scaling and evaluate best practices for model-data evaluation. While upscaling has been studied extensively in the past, the observations here would be more wide-ranging than past, over a more representative and complex set of land cover types, and with attendant atmospheric profiles measured during IOPs.

While the scaling exercise naturally leads to a test of observational representativeness, we will also investigate a specific approach of downscaling individual EC tower measurements for improved representation of space and time grid-cell variability. We will apply the previously mentioned ERF-VCV procedure (Metzger, 2017; Xu *et al*., 2017b) and other footprint based approaches (Bertoldi *et al*, 2013) and benchmark these against the intensive flux tower observation network and LES data. ERF-VCV, whose open-source code is being developed by a number of partners led by co-PI Metzger, performs a variance and covariance-preserving extraction of landscape-scale processes by expanding data-fusion approaches to the sub-hourly timescale.

The essential steps of ERF-VCV are: observing key environmental drivers and responses (from towers and airborne maps of meteorology, roughness, height, cover coupled to flux footprint models), inferring processes among these environmental drivers and responses, projecting environmental responses in space and time, and applying environmental mapping and forecasting with the resulting functions and fields. In ERF-VCV (Metzger, 2017; Xu *et al*., 2017b), high-resolution (1-minute) flux footprints (Kljun *et al.*, 2015) and wavelet decomposition (Schaller *et al.*, 2016) are applied to the 20 Hz observations. These high-frequency fluxes are regressed in a machine-learning algorithm to airborne and tower temporal and spatial observations of vegetation, surface meteorology, boundary layer depth, and thermal/moisture profiles. A benefit of this approach is that assumptions remain minimal and weak, as no linearity or closure of energy or water balances are required. The machine learning algorithm outputs a multi-dimensional surface that connects flux to process, which is then used to explicitly address all transport terms in the mass balance equation underlying all EC measurements. ERF-VCV then projects the surface-atmosphere exchange field underlying EC measurements, which can be spatially integrated to probability density functions at hourly timesteps and sub-1 km resolution. We intend to demonstrate whether downscaling methods like ERF-VCV can improve the efficacy of environmental observations for building, parameterizing and constraining mechanistic models.

Metzger (2017) and Xu *et al*. (2017b) successfully applied the ERF-VCV procedure to the WLEF tall tower using downscaled MODIS remote sensing data. The method was able to capture known spatial variability at over ≥90 % at 25 km^2, over ≥80 % at 100 km^2 to ≥70 % at 400 km^2. The ERF outputs enable bridging from the spatio-temporally varying tower flux footprint to airborne to predefined model gridcells. Provided statistical significance, ERF-VCV promises to enable identifying environmental hot spots and hot moments, assessing and correcting ground-based measurements for observational biases, and building, parameterizing, initializing, constraining and validating models and inventories.

Analysis: Energy balance

Our 2nd hypothesis suggests that differences in the intensity of turbulent organized structure also contribute to lack of energy balance closure of *in situ* tower measurements. Thus, the flux towers and airborne flux observations will be analyzed for variability in surface energy partitioning of sensible and latent heat across space and time, to evaluate whether energy balance closure varies with heterogeneity and turbulence structures. We will examine variation of energy balance closure with respect to mesoscale variation in net radiation, canopy development, amount of standing water for wetlands, and presence or absence of mesoscale turbulent structures in the atmosphere. We will compare these to energy balance metrics including the Bowen ratio, evaporative fraction, and energy balance closure residual or ratios, which can be computed across time and space using statistical analyses of variance, including wavelet decomposition. When we sampled our preliminary LES study with “virtual” flux towers, and compared time-domain decomposed eddy flux to the “true” surface flux, we found consistent low bias at all sites only when we applied spatially varying surface fluxes instead of uniform fluxes.

The proposed timing of the experiment allows monitoring energy balance change over the phenological cycle, leading to shift in dominance of latent to sensible heat flux as the primary turbulent energy flux as photosynthetic demand for water increases. Our experiment also allows us to test a range of cases of heterogeneity during this shift, and thus we will assess the evolution of this energy balance residual in time. With the tower network, we will then apply proposed spatial EC techniques (Fig. 2) of Steinfeld *et al.* (2007), Engelman and Bernhofer (2016), Mauder *et al* (2008), and Metzger (2017) to test if they solve the energy balance problem. CHEESEHEAD would be the first attempt to do this in the real world, and develop an open-source transfer function library to rectify location and energy balance biases plaguing EC flux measurements of national and global networks such as AmeriFlux, ICOS, NEON and FLUXNET.

A number of additional questions can be analyzed by looking at energy balance residuals. Eder *et al*. (2015) show that the energy balance residual is inversely correlated with friction velocity and positively correlated with vertical gradients of potential temperature and specific humidity in the lower part of the atmospheric boundary layer for an intensively managed agricultural area in western Germany. The proposed instrumentation will allow us to assess whether similar correlations can also be found a more complex landscape and under different climatic conditions. We can also ask: Do energy balance closure residuals change across all sites as canopy demand for water decreases? How does this relate to atmospheric passage of internal boundary layers, mesoscale waves that transport warm/dry air aloft downward, atmospheric boundary conditions, and sensor uncertainty?

CHEESEHEAD: Broader Impacts

The database of observations and models that would be produced provide a significant advance in our ability to analyze the role of terrestrial ecosystems on atmospheric energy cycling, water vapor, and numerical weather prediction. Harmonized products can also be used to provide a broader conceptual understanding of spatial and temporal variation in terrestrial systems. High-resolution gridded maps of hourly, daily, seasonal energy flux, net radiation, temperature, water vapor, canopy type and height, and wind velocity all provide an unprecedented snapshot of the atmospheric surface layer. Scale analysis (wavelet based or similar) can be used to analyze the modes of variability of these field, identify critical spatial scales, and find how scaling relates to surface properties such as roughness and resulting shear stress, surface resistance, all of which are critical weakly constrained parameters for numerical models. While the variation itself may not be an important component for synoptic and large scale weather dynamics, accurate assessment of how to assimilate field observations of surface processes for these models is necessary for super-parameterization of land surface feedbacks.

Observations and modeling results provided in the context of this study also have broad application to other disciplines, including ecology, hydrology, and biogeochemistry. We hope this open-access, freely available database will be mined for many future papers and theses beyond our group. The launch of the GOES-R platform may be a game-changing tool for land surface energy balance mapping, and this experiment would provide critical evaluation. As the goal of all field experiments should be to generate broadly applicable observations for the community for science hypothesis testing and evaluation, we will request a DOI and broadly advertise the dataset in an overview paper, at conferences, on our website, and via social media. Desai will write public interest newsletter and tweets during and after the experiment.

The project will support two graduate students, five undergraduate students, and two post-doctoral scholars in lower atmosphere science and modeling at **UW-Madison**. Students from the primarily undergraduate **Northland College** in Ashland, WI will be invited to participate in experiment assistance, including balloon launches, flight forecasting, King Air flight assistance, and supporting student projects.

Three undergraduates at **UW-Milwaukee** will conduct most of the ground based ecology sampling. Desai and Petty teach a special topics course on meteorological measurements with typical enrollment of 10-15 undergraduates. In the 2019 class, students will use existing portable instrumentation at UW-Madison to develop 1 or 2 side projects to occur during the experiment IOPs, including mapping of sub-canopy flow with helium party balloons and digital cameras, deployment of a tripod based EC system and other meteorological sensors, or running of local mesoscale numerical simulations. We place high priority on recruiting under-represented and diverse scholars among all student positions.

Public outreach to local media and school groups is also expected and budgeted. Desai mentors middle school science students as part of an annual mentoring program run by the **Madison Metropolitan School District** and will recruit 2-3 6^{th}-8^{th} grade science students to participate in the field component of the project. Desai will coordinate to the Wisconsin office of the GLOBE program (based in SSEC with Rose Pertzborn) to organize teacher training and student data collection with the local **Buttnernut School District** and Park Falls, WI project-based **Class Act Charter High School**. Finally, for public outreach, Desai frequently (4-6 times per year) gives public talks in the region arranged by the UW Speaker's Bureau and also through the Kemp Natural Resources Station and the nearby NSF LTER field station (Trout Lake). Desai will work with SPARC to provide tours of the facility during operation.

CHEESEHEAD: Putting It All Together

Our Team

PI **Desai**, Professor of Atmospheric and Oceanic Sciences at University of Wisconsin-Madison is responsible for project coordination. He will work closely with all observational PIs (**Oncley** and **Brown**, NCAR; **Rodi** and **Wang**, U Wyoming; **Feltz**, **Wagner**, **Olson**, SPARC, **Petty** and **Townsend**, UW) and be responsible for all final field project day decisions, student coordination, and teleconferences. Desai will supervise data analysis and integration and continue his role as PI of the Ameriflux towers. One **post-doctoral scholar** at UW would lead field support operations and airborne data processing in the first year, living near the field site for the entire field experiment and lead the experiment paper and mesoscale eddy analyses. The **second post-doctoral scholar** will join the team after the experiment and focus on LES analysis. This post-doc would help mentor a **graduate student** who will also spend time in in Germany (KIT IMK-IFU) to gain LES modeling expertise with collaborator **Mauder**. Co-PI **Metzger** would apply ERF-VCV to evaluate CHEESEHEAD study design, produce lower boundary conditions for the LES runs, develop an open-source transfer function library to rectify EC energy balance and location biases, and co-mentor the **second graduate student** at UW on energy balance analysis and scaling methods. The **third graduate student** would focus on mesoscale atmospheric structures. **Schwartz** will mentor **three undergraduates** at UW-Milwaukee to collect ecological data. Desai will coordinate local school outreach with GLOBE project coordinator **Pertzborn**, and arrange research experiences for **three undergraduates** at UW and **students** at Northland College with **Martin** during the experiment, and support **two more undergraduates** in ensuing years on thesis projects.

Results from Prior NSF Support

DESAI: ***Collaborative Proposal: ABI Innovation: Model-data synthesis and forecasting across the upper Midwest: Partitioning uncertainty and environmental heterogeneity in ecosystem carbon*** *07/2011-06/2014 A Desai NSF-ABI-1062204, $103,922 & M Dietze, K McHenry NSF-ABI-1062547, $770,653* **Intellectual Merit**: The Predictive Ecosystem Analyzer (PEcAn) is a framework for ecosystem model analysis and data assimilation. It's open-source, modular workflow manages flow of information into and out of ecosystem models. **Broader Impacts**: Supported four postdoctoral fellows and one graduate student, and produced ten publications and ten training workshops. At UW, this included five publications (Becknell *et al.*, 2015; Desai, 2014; Dietze *et al.*, 2014; Kooper *et al.*, 2013; Viskari *et al.*, 2015). PEcAn is now used in many other research projects to assimilate data into ecosystem models.

SCHWARTZ: **Bridging Spatial Scales Using Phenological Measurements to Improve Understanding of Autumn Atmosphere-Biosphere Interactions**, *(NSF #1157215, 1 July 2012 to 12 December 2014),*

PI: Mark D. Schwartz, Univ. of Wisconsin-Milwaukee **Intellectual Merit:** Satellite-derived measurements of phenology were able to estimate ground-based autumn observations of tree full leaf coloration and fall timing. We found considerable variation in progression of leaf coloring among tree species, and the confounding issues regarding their environmental drivers (Liang *et al.*, 2016; Schwartz *et al.*, 2014). Progress was made on methods for concurrent acquisitions of under-canopy light measurements, autumn tree phenology, and EC flux phenology (Yu *et al.*, 2016). **Broader Impacts**: Findings support usefulness of MODIS for autumn phenology in forests (Liu *et al.*, 2015) and suggests effective approach for phenological monitoring during crucial, but less studied autumn season (Schwartz, 2013).
TOWNSEND: ***Dimensions NASA: Linking remotely sensed optical diversity to genetic, phylogenetic and functional diversity to predict ecosystem processes*** *05/2014-04/2019 P Townsend DEB-1342778 $311,702; J Cavender-Bares, S Hobbie, R Montgomery DEB-1342872 $886,274; J Gamon DEB-1342823 $716,893; and M Madritch DEB-1342827 $112,938* **Intellectual Merit:** Biodiversity manipulations at Cedar Creek LTER tested whether plant diversity (including differences in genotypes, species' function, and evolutionary lineages) can be detected remotely at multiple spatial scales. Foliar traits varied considerably within and among species based on plot diversity, and spectroscopic data were sensitive to phylogeny (Cavender-Bares et al. 2016). **Broader Impacts:** Funding supported four postdoctoral scholars, three graduate students, and seven publications to date (six with UW-Madison authors).
PETTY: None *METZGER*: None

Logistics and Timeline

Daytime operations in relative flat, unpopulated areas, with mostly uncontrolled airspace, and with good local options for aviation and lodging suggests limited safety issues. Desai has worked in this region for over 15 years, has sustained contact with local landowners and permitting authorities (**Bauder**), and has a full-time DOE-supported lab manager **(Thom)** to support flux tower operations. The 450-m tall tower is owned by the State of Wisconsin Educational Communication Board (ECB), who has had a good working relationship with Desai for the past decade. The clearing around the tower can provide support for trailers and other deployments, and line power and high-speed Internet can be accessed from the existing Ameriflux/NOAA trailer. The area around the tower is primarily land in the U.S. Forest Service and the local forest service research coordinator (**Parker**) will assist with site access and permitting. Adequate runway and hangar facilities are available locally at several airports. UW operates a field research station less than 45 minutes away from the tall tower site with low-cost dormitory-style lodging and lab facilities. Weekly project teleconferences will begin 12 months prior to operations, during and after.

We will make all data (raw high-rate and processed) freely available both through UCAR data archive and also locally at University of Wisconsin as soon as it is available as noted in the data management plan. At least ten publications are expected, including an overview paper in BAMS (Table 2).

Table 2. Timeline of activities and outcomes

Jul 2018- Feb 2019	- Project preparation, hiring/training of personnel, initial project meeting - Application of ERF-VCV to existing field and LES datasets to optimize study design - Site permitting, acquisition of instruments, outreach and field course development - AGU/AMS conference townhall meeting
Mar-May 2019	- Pre-field experiment site preparation, instrument course, IOP dry-run, shipping
Jun-Nov 2019	- Field component, IOPs (early July 2019 and early Oct 2019), ERF-VCV setup, teardown
Oct-Dec 2019	- ERF-VCV lower boundary conditions for KIT IMK-IFU LES - Most data public, BAMS manuscript written, AGU/AMS presentations
Jan-Jun 2020	- Performance evaluating of a-priori study design, scaling/energy balance analysis - Official public data release, theses development
Jul-Dec 2020	- Graduate student or Post-doc + Desai in Germany for LES analysis coordination - Scaling/spatial EC/mesoscale eddy manuscripts
Jan-Jun 2021	- First several manuscripts published (overview, scaling, ERF, phenology), LES manuscript - Public code repository release incl. transfer function library to rectify EC energy balance and location biases

CHEESEHEAD is not without risk and logistical complication, but we believe the project is feasible and likely to provide a landmark database for model evaluation and parameterization for some time to come.

References

Anderson, M. C., Norman, J. M., Kustas, W. P., Houborg, R., Starks, P. J., and Agam, N.: 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, doi:10.1016/j.rse.2008.07.009, 2008.

Anderson, M. C., Kustas, W. P., Alfieri, J. G., Gao, F., Hain, C., Prueger, J. H., Evett, S., Colaizzi, P., Howell, T., and Chávez, J. L.: Mapping daily evapotranspiration at Landsat spatial scales during the BEAREX'08 field campaign, *Adv. Water Res.*, 50, 162-177, doi:10.1016/j.advwatres.2012.06.005, 2012.

Andrews, A. E., J. D. Kofler, M. E. Trudeau, J. C. Williams, D. H. Neff, K. A. Masarie, D. Y. Chao, D. R. Kitzis, P. C. Novelli, C. L. Zhao, E. J. Dlugokencky, P. M. Lang, M. J. Crotwell, M. L. Fischer, M. J. Parker, J. T. Lee, D. D. Baumann, A. R. Desai, C. O. Stanier, S. F. J. De Wekker, D. E. Wolfe, J. W. Munger, and P. P. Tans: CO_2, CO, and CH_4 measurements from tall towers in the NOAA Earth System Research Laboratory's Global Greenhouse Gas Reference Network: instrumentation, uncertainty analysis, and recommendations for future high-accuracy greenhouse gas monitoring efforts. *Atmospheric Measurement Techniques*, *7*, 647-687, 10.5194/amt-7-647-2014, 2014.

Antonarakis, A. S., Munger, J. W., and Moorcroft, P. R.: 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, 2013GL058373, doi:10.1002/2013gl058373, 2014.

Aubinet, M., Feigenwinter, C., Heinesch, B., Bernhofer, C., Canepa, E., Lindroth, A., Montagnani, L., Rebmann, C., Sedlak, P., and Van Gorsel, E.: Direct advection measurements do not help to solve the night-time CO2 closure problem: Evidence from three different forests, *Agric. For. Meteorol.*, 150, 655-664, doi:10.1016/j.agrformet.2010.01.016, 2010.

Avissar, R.: Scaling of land-atmosphere interactions: An atmospheric modelling perspective. *Hydrol. Process*, 9, 679–695, doi:10.1002/hyp.3360090514, 1995.

Baker, I., Sellers, P.J., Denning, A.S., Medina I., Kraus, P., Haynes, K.D., Biraud, S.C.: Closing the scale gap between land surface parameterizations and GCMs with a new scheme, SiB3-Bins, *J. Adv. Model. Earth Syst.*, 9, 691–711, doi:10.1002/2016MS000764, 2017.

Bakwin, P. S., P. P. Tans, D. F. Hurst, and C. Zhao: Measurements of carbon dioxide on very tall towers: Results of the NOAA/CMDL program. *Tellus*, 50B, 401–415, 1998.

Bange, J., Spieß, T., Herold, M., Beyrich, F., and Hennemuth, B. Turbulent fluxes from Helipod flights above quasi-homogeneous patches within the LITFASS area. *Boundary-Layer Meteorology* 121(1), 127-151. 2006.

Barr, J. G., Fuentes, J. D., DeLonge, M. S., O'Halloran, T. L., Barr, D., and Zieman, J. C.: Summertime influences of tidal energy advection on the surface energy balance in a mangrove forest, *Biogeosciences*, 10, 501-511, doi:10.5194/bg-10-501-2013, 2013.

Becknell, J.M., Desai, A.R., Dietze, M.C., Schultz, C.A., Starr, G., Duffy, P.A., Franklin, J.F., Pourmokhtarian, A., Hall, J., Stoy, P.C., Binford, M.W., Boring, L.E., and Stuadhammer, C.L. Assessing interactions among changing climate, management, and disturbance in forests: A macrosystems approach. *Bioscience*, 65, 263-274, doi:10.1093/biosci/biu234, 2015.

Betts, A.K., Ball, J.H., Beljaars, A.C.M., Miller, M.J., and Viterbo, P.A.: The land surface-atmosphere interaction: A review based on observational and global modeling perspectives, *J. Geophys. Res.*, 101(D3), 7209–7225, doi:10.1029/95JD02135, 1996.

Bertoldi, G., Kustas, W., and Albertson, J.: Evaluating source area contributions from aircraft flux measurements over heterogeneous land using large-eddy simulation, *Boundary Layer Meteorol.*, 147, 261-279, doi:10.1007/s10546-012-9781-y, 2013.

Beyrich, F., Leps, J. P., Mauder, M., Bange, J., Foken, T., Huneke, S., Lohse, H., Ludi, A., Meijninger, W. M. L., Mironov, D., Weisensee, U., and Zittel, P.: Area-averaged surface fluxes over the LITFASS region based on eddy-covariance measurements, *Boundary Layer Meteorol.*, 121, 33-65, doi:10.1007/s10546-006-9052-x, 2006.

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

Cavender-Bares J, Meireles, J.E., Couture ,J.J., Kaproth, M., Kingdon, C.C., Singh, A., Serbin, S., Pilz, G., Center, A., Townsend, P: Associations of leaf spectra with genetic and phylogenetic variation in oaks: prospects for remote detection of biodiversity, *Remote Sensing*, 8, 221, doi:10.3390/rs8030221, 2016.

Charney, J. G.: Dynamics of deserts and drought in the Sahel. *Q.J.R. Meteorol. Soc.*, 101, 193–202, doi:10.1002/qj.49710142802, 1975.

Charuchittipan, D., Babel, W., Mauder, M., Leps, J.-P., Foken T.: Extension of the Averaging Time in Eddy-Covariance Measurements and Its Effect on the Energy Balance Closure, *Boundary-Layer Meteorology*, 152, 303-327, 2014.

Chen, B., Ge, Q., Fu, D., Yu, G., Sun, X., Wang, S., and Wang, H.: A data-model fusion approach for upscaling gross ecosystem productivity to the landscape scale based on remote sensing and flux footprint modelling, *Biogeosciences*, 7, 2943-2958, doi:10.5194/bg-7-2943-2010, 2010.

Chen, J. M., Leblanc, S. G., Cihlar, J., Desjardins, R. L., and MacPherson, J. I.: Extending aircraft- and tower-based CO_2 flux measurements to a boreal region using a Landsat thematic mapper land cover map, *J. Geophys. Res. Atmos.*, 104, 16859-16877, doi:10.1029/1999JD900129, 1999.

Christianson, D.S., and Kaufman, C.G., 2016. Effects of sample design and landscape features on a measure of environmental heterogeneity, *Methods in Ecology and Evolution*, 7, 770-782,doi: 10.1111/2041-210X.12539.

Cook, B.D., Davis, K.J., Wang, W., Desai, A.R., Berger, B.W., Teclaw, R.M., Martin, J.G., Bolstad, P.V., Bakwin, P.S., Yi, C., and Heilman, W.: Carbon exchange and venting anomalies in an upland deciduous forest in northern Wisconsin, USA. Agricultural and Forest Meteorology, 126(3-4): 271-295, doi:10.1016/j.agrformet.2004.06.008, 2004.

Damian, T., Träumner, K., Stawiarski, O., and Wieser, A.: Turbulent structures and coherence in the surface layer as observed by dual Doppler LIDAR measurements, *17th Symposium on Meteorological Observation and Instrumentation*, Westminster, U.S.A., 9 - 13 June, 2014.

Davis, K.J., P.S. Bakwin, C. Yi, B.W. Berger, C. Zhao, R.M. Teclaw, and J.G. Isebrands: The annual cycles of CO_2 and H_2O exchange over a northern mixed forest as observed from a very tall tower. *Global Change Biology*, 9(9):1278-1293, 2003.

De Roo, F., Huq, S., Metzger, M., Xu, K., Desai, A. R., and Mauder, M. On the benefit of driving Large-Eddy Simulation with spatially resolved surface fluxes derived from environmental response functions. *TERENO International Conference 2014*. P3-11. 2014. Bonn, Germany, 28-9-2014.

Desai, A.R., Bolstad, P.V., Cook, B.D., Davis, K.J., and Carey, E.V.: Comparing net ecosystem exchange of carbon dioxide between an old-growth and mature forest in the upper Midwest, USA. *Agricultural and Forest Meteorology* 128(1-2): 33-55, doi:10.1016/j.agrformet.2004.09.005, 2005.

Desai, A.R., Davis, K.J., Senff, C., Ismail, S., Browell, E.V., Stauffer, D.R., and Reen, B.P.: A case study on the effects of heterogeneous soil moisture on mesoscale boundary layer structure in the southern Great Plains, USA. Part I: Simple prognostic model. *Boundary-Layer Meteorology*, 119(2): 195-238, doi:10.1007/s10546-005-9024-6, 2006.

Desai, A.R.: Climatic and phenological controls on coherent regional interannual variability of carbon dioxide flux in a heterogeneous landscape. *Journal of Geophysical Research-Biogeosciences*, 115: G00J02 ,doi:10.1029/2010JG001423, 2010.

Desai, A.R., Helliker, B.R., Moorcroft, P.R., Andrews, A.E., and Berry, J.A.: Interannual variability in regional carbon fluxes from top-down and bottom-up perspectives. *Journal of Geophysical Research-Biogeosciences*, 115, G02011, doi:10.1029/2009JG001122, 2010.

Desai, A.R.: Influence and predictive capacity of climate anomalies on daily to decadal extremes in canopy photosynthesis. *Photosynthesis Research*, 119, 31-47, doi:10.1007/s11120-013-9925-z, 2014.

Desai, A.R., Xu, K., Tian H., Weishampel, P., Thom, J., Baumann, D., Andrews, A.E., Cook, B.D., King, J.Y., and Kolka, R.: Landscape-level terrestrial methane flux observed from a very tall tower. *Agricultural and Forest Meteorology*, 201, 61-75, doi:10.1016/j.agrformet.2014.10.017, 2015.

Desjardins, R. L., MacPherson, J. I., Mahrt, L., Schuepp, P. H., Pattey, E., Neumann, H., Baldocchi, D., Wofsy, S., Fitzjarrald, D. R., McCaughey, H., and Joiner, D. W. Scaling up flux measurements for the boreal forest using aircraft-tower combinations. *Journal of Geophysical Research* 102(D24), 29125-29133. 1997.

Dietze, M.C., Serbin, S.P., Davidson, C., Desai, A.R., Feng, X., Kelly, R., Kooper, R., LeBauer , D., Mantooth, J., McHenry , K., and Wang, D.: A quantitative assessment of a terrestrial biosphere model's data needs across North American biomes., *J. Geophys. Res-G*, 119, 286–300, doi:10.1002/2013JG002392, 2014.

Eder, F., Schmidt, M., Damian, Thomas, Träumner, K., and Mauder, M. Meso-scale eddies contribute to near-surface turbulent exchange: evidence from field measurements. *Journal Applied Meteorology and Climatology*, 54(1), 189-206. 2015.

Engelman, C., and Bernhofer, C.: Exploring Eddy-Covariance Measurements Using a Spatial Approach: The Eddy Matrix. Boundary-Layer Meteorol, 161, 1–17, doi:10.1007/s10546-016-0161-x, 2016.

Ershadi, A., McCabe, M. F., Evans, J. P., and Walker, J. P.: Effects of spatial aggregation on the multi-scale estimation of evapotranspiration, *Remote Sens. Environ.*, 131, 51-62, doi:10.1016/j.rse.2012.12.007, 2013.

Foken, T., Aubinet, M., Finnigan, J. J., Leclerc, M. Y., Mauder, M., and Paw U, K. T.: Results of a panel discussion about the energy balance closure correction for trace gases, *Bull. Am. Meteorol. Soc.*, 92, ES13-ES18, doi:10.1175/2011bams3130.1, 2011.

Fox, A., Williams, M., Richardson, A. D., Cameron, D., Gove, J. H., Quaife, T., Ricciuto, D., Reichstein, M., Tomelleri, E., Trudinger, C. M., and Van Wijk, M. T.: The REFLEX project: Comparing different algorithms and implementations for the inversion of a terrestrial ecosystem model against eddy covariance data, *Agric. For. Meteorol.*, 149, 1597-1615, doi:10.1016/j.agrformet.2009.05.002, 2009.

Frank, J. M., Massman, W. J., and Ewers, B. E.: Underestimates of sensible heat flux due to vertical velocity measurement errors in non-orthogonal sonic anemometers, *Agric. For. Meteorol*, 171–172, 72-81, doi:10.1016/j.agrformet.2012.11.005, 2013.

Gantner,L .,Maurer, V., Kalthoff, N., and Kiseleva, O.: The Impact of Land-Surface Parameter Properties and Resolution on the Simulated Cloud-Topped Atmospheric Boundary Layer, *Boundary-Layer Meteorol*, 165, 475–496, doi:10.1007/s10546-017-0286-6, 2017.

Gao, Z., Liu, H., Russell, E. S. , Huang, J., Foken, T., and Oncley, S.P.: Large eddies modulating flux convergence and divergence in a disturbed unstable atmospheric surface layer, *J. Geophys. Res. Atmos*., 121, 1475–1492, doi:10.1002/2015JD024529, 2016.

Garrat, J.R.: Sensitivity of Climate Simulations to Land-Surface and Atmospheric Boundary-Layer Treatments-A Review. *J Climate*, 6, 419-448, 1993.

Gentine, P., Entekhabi, D., and Polcher, J.,: The diurnal behavior of evaporative fraction in the soil–vegetation–atmospheric boundary layer continuum. *J. Hydrometeor.*, 12, 1530–1546, 2011.

Gentine, P., Troy, T. J., Lintner, B. R. and Findell, K. L.: Scaling in Surface Hydrology: Progress and Challenges. *Journal of Contemporary Water Research & Education*, 147, 28–40, doi:10.1111/j.1936-704X.2012.03105.x, 2012.

Grimmond, C. S. B., Blackett, M., Best, M. J., Baik, J. J., Belcher, S. E., Beringer, J., Bohnenstengel, S. I., Calmet, I., Chen, F., Coutts, A., Dandou, A., Fortuniak, K., Gouvea, M. L., Hamdi, R., Hendry, M., Kanda, M., Kawai, T., Kawamoto, Y., Kondo, H., Krayenhoff, E. S., Lee, S. H., Loridan, T., Martilli, A., Masson, V., Miao, S., Oleson, K., Ooka, R., Pigeon, G., Porson, A., Ryu, Y. H., Salamanca, F., Steeneveld, G. J., Tombrou, M., Voogt, J. A., Young, D. T., and Zhang, N.: Initial results from Phase 2 of the international urban energy balance model comparison, *Int. J. Climatol.*, 31, 244-272, doi:10.1002/joc.2227, 2011.

Heinze, Rieke, Böske, L., Moseley, C., Stevens, B., and Raasch, S. Can we produce realistic boundary layer turbulence by coupling large-eddy simulations with mesoscale model data? *21th Symposium of the American Meteorological Society (AMS) on Boundary Layers and Turbulence*. 9B.3. 2014. 11-6-2014.

Hicks, M., Sakai, R., and Joseph, E: The Evaluation of a New Method to Detect Mixing Layer Heights Using Lidar Observations. *J. Atmos Tech*. 32, 2014-2051, 10.1175/JTECH-D-14-00103.1, 2015.

Hilker, T., Hall, F. G., Coops, N. C., Collatz, J. G., Black, T. A., Tucker, C. J., Sellers, P. J., and Grant, N.: Remote sensing of transpiration and heat fluxes using multi-angle observations, *Remote Sens. Environ.*, 137, 31-42, doi:10.1016/j.rse.2013.05.023, 2013.

Hill, T. C., M. Williams, and J. B. Moncrieff: Modeling feedbacks between a boreal forest and the planetary boundary layer, J. Geophys. Res., 113, D15122, doi:10.1029/2007JD009412, 2008.

Hill, T.C., M. Williams, F. I. Woodward, and J. B. Moncrieff: Constraining ecosystem processes from tower fluxes and atmospheric profiles. *Ecological Applications* 21:1474–1489. doi:10.1890/09-0840.1, 2011.

Horst, T. W., Oncley, S. P., and Semmer, S.: Flow distortion in a non-orthogonal three-component sonic anemometer, *17th Symposium on Meteorological Observation and Instrumentation*, Westminster, U.S.A., 9 - 13 June, 2014.

Hutjes, R. W. A., Vellinga, O. S., Gioli, B., and Miglietta, F.: Dis-aggregation of airborne flux measurements using footprint analysis, *Agric. For. Meteorol.*, 150, 966-983, doi:10.1016/j.agrformet.2010.03.004, 2010.

Ingwersen, J., Steffens, K., Högy, P., Warrach-Sagi, K., Zhunusbayeva, D., Poltoradnev, M., Gäbler, R., Wizemann, H. D., Fangmeier, A., Wulfmeyer, V., and Streck, T.: Comparison of Noah simulations with eddy covariance and soil water measurements at a winter wheat stand. *Agricultural and Forest Meteorology* 151(3), 345-355. 2011

Jung, M., Reichstein, M., Margolis, H. A., Cescatti, A., Richardson, A. D., Arain, M. A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J. Q., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B. E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E. J., Papale, D., Sottocornola, M., Vaccari, F., and Williams, C.: Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations, *J. Geophys. Res. Biogeosci.*, 116, G00J07, doi:10.1029/2010jg001566, 2011.

Kaminski, T., Rayner, P. J., Voßbeck, M., Scholze, M., and Koffi, E.: Observing the continental-scale carbon balance: Assessment of sampling complementarity and redundancy in a terrestrial assimilation system by means of quantitative network design, *Atmos. Chem. Phys.*, 12, 7867-7879, doi:10.5194/acp-12-7867-2012, 2012.

Kampe, T. U., McCorkel, J., Hamlin, L., Green, R. O., Krause, K. S., and Johnson, B. R.: Progress in the development of airborne remote sensing instrumentation for the National Ecological Observatory Network, Proc. *SPIE Int. Soc. Opt. Eng.*, 8156, A1-A12, doi: 10.1117/12.892572, 2011.

Kanda, M., Inagaki, A., Letzel, M. O., Raasch, S., and Watanabe, T. LES study of the energy imbalance problem with eddy covariance fluxes. *Boundary-Layer Meteorology* 110(3), 381-404. 2004.

Kang, Song-Lak , Kenneth J. Davis, and Margaret LeMone: Observations of the ABL Structures over a Heterogeneous Land Surface during IHOP_2002. *J. Hydrometeor*, 8, 221–244., doi: http://dx.doi.org/10.1175/JHM567.1, 2007.

Keenan, T. F., and A. D. Richardson: The timing of autumn senescence is affected by the timing of spring phenology: implications for predictive models. *Global Change Biology*, 21, 2634-2641, 2015.

Keppel-Aleks, G., Wennberg, P.O., Washenfelder, R.A., Wunch, D., Schneider, T., Toon, G.C., Andres, R., Blavier, J.-F., Connor, B., Davis, K.J., Desai, A.R., Messerschmidt, J., Notholt, J., Roehl, C.M., Sherlock, V., Stephens, B.B., Vay, S.A., and Wofsy, S.C., 2012. The imprint of surface fluxes and transport on variations in total column carbon dioxide. *Biogeosciences* 9, 875-891, doi:10.5194/bg-9-875-2012.

Kljun, N., Calanca, P., Rotach, M. W., and Schmid, H. P.: A simple two-dimensional parameterisation for Flux Footprint Prediction (FFP), *Geosci. Model Dev.*, 8, 3695-3713, 2015.

Kobayashi, H., Baldocchi, D. D., Ryu, Y., Chen, Q., Ma, S., Osuna, J. L., and Ustin, S. L.: Modeling energy and carbon fluxes in a heterogeneous oak woodland: A three-dimensional approach, *Agric. For. Meteorol.*, 152, 83-100, doi:10.1016/j.agrformet.2011.09.008, 2012.

Koffi, E. N., Rayner, P. J., Scholze, M., Chevallier, F., and Kaminski, T.: Quantifying the constraint of biospheric process parameters by CO_2 concentration and flux measurement networks through a carbon cycle data assimilation system, *Atmos. Chem. Phys.*, 13, 10555-10572, doi:10.5194/acp-13-10555-2013, 2013.

Kooper R., McHenry, K., Dietze, M., LeBauer, D., Serbin, S., Desai, A.R:. Ecological Cyberinfrastructure and HPC Towards More Accurately Predicting Future Levels of Greenhouse Gases. *Proceedings of XSEDE13: Extreme Science and Engineering Discovery Environment*, 2013.

Kuppel, S., Peylin, P., Chevallier, F., Bacour, C., Maignan, F., and Richardson, A. D.: Constraining a global ecosystem model with multi-site eddy-covariance data, *Biogeosciences*, 9, 3757-3776, doi:10.5194/bg-9-3757-2012, 2012.

Launiainen, S., et al.: Do the energy fluxes and surface conductance of boreal coniferous forests in Europe scale with leaf area? *Global Change Biology*, doi:10.1111/gcb.13497, 2016.

Leuning, R., van Gorsel, E., Massman, W. J., and Isaac, P. R.: Reflections on the surface energy imbalance problem, *Agric. For. Meteorol.*, 156, 65-74, doi:10.1016/j.agrformet.2011.12.002, 2012.

Liang, L., Schwartz, M. D., and Zhang, X.: Mapping Temperate Vegetation Climate Adaptation Variability Using Normalized Land Surface Phenology, *Climate*, 4, 24, doi:10.3390/cli4020024, 2016.

Liu, L., Liang, L., Schwartz, M. D., Donnelly, A., Wang, Z., Schaaf, C. B., & L. Liu: Evaluating the Potential of MODIS Satellite Data to Track Temporal Dynamics of Autumn Phenology in a Temperate Mixed Forest. *Remote Sensing of Environment*, 160, 156-165, 2015.

Liu, S. M., Xu, Z. W., Wang, W. Z., Jia, Z. Z., Zhu, M. J., Bai, J., and Wang, J. M.: A comparison of eddy-covariance and large aperture scintillometer measurements with respect to the energy balance closure problem, *Hydrol. Earth Syst. Sci.*, 15, 1291-1306, doi:10.5194/hess-15-1291-2011, 2011.

Liu, S., Xu, Z., Song, L., Zhao, Q., Ge, Y., Xu, T., Ma, Y., Zhu, Z., Jia, Z., Zhang, F.: Upscaling evapotranspiration measurements from multi-site to the satellite pixel scale over heterogeneous land surfaces, *Agricultural and Forest Meteorology*, 230-231, 97-113, doi:10.1016/j.agrformet.2016.04.008, 2016.

Mahrt, L.: Surface Heterogeneity and Vertical Structure of the Boundary Layer. *Boundary-Layer Meteorol.*, 96, 33, doi:10.1023/A:1002482332477, 2000.

Marshall, J., and Schott, F.: Open-ocean convection: Observations, theory, and models. *Rev. Geophys,* 37, 1–64, doi:10.1029/98RG02739, 1999.

Mauder, M., Desjardins, R. L., and MacPherson, J. I. Scale analysis of airborne flux measurements over heterogeneous terrain in a boreal ecosystem. *Journal of Geophysical Research* 112, D13112, doi:10.1029/2006JD008133. 2007a.

Mauder, M., Jegede, O. O., Okogbue, E. C., Wimmer, F., and Foken, T.: 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, doi:10.1007/s00704-006-0252-6, 2007b.

Mauder M, Desjardins RL, MacPherson I: Creating surface flux maps from airborne measurements: Application to the Mackenzie Area GEWEX Study MAGS 1999. *Bound -Layer Meteor* 129:431-450, 2008.

McGloin, R., Šigut, L., Havránková , K., Dušek, J., Pavelka, M., Sedlák, P.: Energy balance closure at a variety of ecosystems in Central Europe with contrasting topographies, *Agirc. For. Meteorol.*, 248, 418-431, doi: 10.1016/j.agrformet.2017.10.003, 2018.

Metzger, S.: Surface-atmosphere exchange in a box: Making the control volume a suitable representation for in-situ observations, *Agric. For. Meteorol.*, in press, doi:10.1016/j.agrformet.2017.08.037, 2017.

Metzger, S., Junkermann, W., Mauder, M., Butterbach-Bahl, K., Trancón y Widemann, B., Neidl, F., Schäfer, K., Wieneke, S., Zheng, X. H., Schmid, H. P., and Foken, T.: Spatially explicit regionalization of airborne flux measurements using environmental response functions, *Biogeosciences*, 10, 2193-2217, doi:10.5194/bg-10-2193-2013, 2013.

Metzger, S., Xu, K., Desai, A. R., Taylor, J. R., Kljun, N., Fox, A., and Kampe, T.: Mapping the flux field around eddy-covariance measurements, *31st AMS Conference on Agricultural and Forest Meteorology*, Portland, U.S.A., 12 - 15 May, 2014.

Milovac, J., Warrach-Sagi, K.,Behrendt, A., Späth, F., Ingwersen, J., and Wulfmeyer, V., Investigation of PBL schemes combining the WRF model simulations with scanning water vapor differential absorption lidar measurements. *J. Geophys. Res. Atmos.*, 121, 624–649, doi:10.1002/2015JD023927, 2016.

Musinsky, J., Wasser, L., Kampe, T., Krause, K., Leisso, N., Petroy, S., Metzger, S., Cawse-Nicholson, K., van Aardt, J., and Serbin, S.: Developing a scalable remote sampling design for the NEON airborne observation platform, *46th AGU annual Fall Meeting*, San Francisco, U.S.A., 9 - 13 December, 2013.

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

Neale, C. M. U., Geli, H. M. E., Kustas, W. P., Alfieri, J. G., Gowda, P. H., Evett, S. R., Prueger, J. H., Hipps, L. E., Dulaney, W. P., Chávez, J. L., French, A. N., and Howell, T. A.: Soil Water Content

Estimation using a Remote Sensing Based Hybrid Evapotranspiration Modeling Approach, *Adv. Water Res.*, 50, 152-161, doi:10.1016/j.advwatres.2012.10.008, 2012.

Oncley, S.P., Foken, T., Vogt, R., Kohsiek, W., de Bruin, H., Bernhofer, C., Christen, A., Grantz, D., Lehner, E., Liebethal, C., Liu, H.P., Mauder, M., Pitacco, A., Ribeiro, L., and Weidinger, T.: The Energy Balance Experiment EBEX-2000. Part I: Overview and Energy Balance, Boundary-Layer Meteorology, DOI 10.1007/s10546-007-9161-1, 2007.

Ogunjemiyo, S. O., Kaharabata, S. K., Schuepp, P. H., MacPherson, I. J., Desjardins, R. L., and Roberts, D. A.: Methods of estimating CO_2, latent heat and sensible heat fluxes from estimates of land cover fractions in the flux footprint, *Agric. For. Meteorol.*, 117, 125-144, doi:10.1016/S0168-1923(03)00061-3, 2003.

Pielke, R.A., Dalu, G.A., Snook, J.S., Lee, T.J., Kittle, T.G.F: Nonlinear Influence of Mesoscale Land Use on Weather and Climate. *J Climate*, 4, 1053-1069, 1991.

Pielke, R.A., Sr,, Avissar, R., Raupach, M., Dolman, A.J., Zeng, X. and Denning, A.S.: Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. *Global Change Biology*, 4, 461–475, doi:10.1046/j.1365-2486.1998.t01-1-00176.x, 1998.

Platis, A., Moene, A.,F., Villagrassa, D.M., Beyrich, F., Tupman, D., and Bange, J.: Observations of the Temperature and Humidity Structure Parameter Over Heterogeneous Terrain by Airborne Measurements During the LITFASS-2003 Campaign, *Boundary-Layer Meteorol*, 165, 447–473 doi:10.1007/s10546-017-0290-x, 2017.

Poulos, S. G., Blumen, W., Fritts, D. C., Lundquist, J. K., Sun, J., Burns, S. P., Nappo, C., Banta, R., Newsom, R., Cuxart, J., Terradellas, E., Balsley, B., and Jensen, M.: CASES-99: A comprehensive investigation of the stable nocturnal boundary layer, *B. Am. Meteorol. Soc.*, 83, 555–581, 2002.

Prueger, J. H., Alfieri, J. G., Hipps, L. E., Kustas, W. P., Chavez, J. L., Evett, S. R., Anderson, M. C., French, A. N., Neale, C. M. U., McKee, L. G., Hatfield, J. L., Howell, T. A., and Agam, N.: Patch scale turbulence over dryland and irrigated surfaces in a semi-arid landscape under advective conditions during BEAREX08, *Adv. Water Res.*, 50, 106-119, doi:10.1016/j.advwatres.2012.07.014, 2012.

Ran, Y., Li, X., Sun, R., Kljun, N., Zhang, L., Wang, X., Zhu, G.: Spatial representativeness and uncertainty of eddy covariance carbon flux measurements for upscaling net ecosystem productivity to the grid scale. *Agricultural and Forest Meteorology*, 230-231, 114-127, doi:dx.doi.org/10.1016/j.agrformet.2016.05.008, 2016.

Raupach, M. R. and Finnigan, J. J.: Scale issues in boundary-layer meteorology: Surface energy balances in heterogeneous terrain. *Hydrol. Process.*, 9, 589–612, doi:10.1002/hyp.3360090509, 1995.

Reen, B.P., Stauffer, D.R., and Davis, K.J.: Land-Surface Heterogeneity Effects in the Planetary Boundary Layer, *Boundary-Layer Meteorol*, 150, 1–31, doi:10.1007/s10546-013-9860-8, 2014.

Rihani, J. F., F. K. Chow, and R. M. Maxwell: Isolating effects of terrain and soil moisture heterogeneity on the atmospheric boundary layer: Idealized simulations to diagnose land-atmosphere feedbacks. *J. Adv. Model. Earth Syst.*, 7, 915-937, 2015.

Sawyer, V., and Z. Q. Li: Detection, variations and intercomparison of the planetary boundary layer depth from radiosonde, lidar and infrared spectrometer. *Atmos. Environ.* 79, 518-528, 2013.

Schaller, C., Göckede, M., and Foken, T.: Flux calculation of short turbulent events – comparison of three methods. *Atmos. Meas. Tech. Discuss.*, doi:10.5194/amt-2016-259, in review, 2016

Schwartz, M. D. (editor): *Phenology: An Integrative Environmental Science, 2nd edition.* Springer, Netherlands, 610 pp., 2013.

Schwartz, M. D., Hanes, J. M., & L. Liang: Separating Temperature from Other Factors in Phenological Measurements. *International Journal of Biometeorology*, 58, 1699- 1704, 2014.

Sellers, P., Hall, F., Ranson, K. J., Margolis, H., Kelly, B., Baldocchi, D., den Hartog, G., Cihlar, J., Ryan, M. G., Goodison, B., Crill, P., Lettenmaier, D., and Wickland, D. E. The Boreal Ecosystem-Atmosphere Study (BOREAS): An Overview and Early Results from the 1994 Field Year. *Bulletin of the American Meteorological Society* 76(9), 1549-1577. 1995.

Shaw, Roger H and Schumann, Ulrich. Large-eddy simulation of turbulent flow above and within a forest. *Boundary-Layer Meteorology* 61(1-2), 47-64. 1992.

Steinfeld G, Letzel MO, Raasch S, Kanda M, Inagaki A: Spatial representativeness of single tower measurements on the imbalance problem with eddy-covariance fluxes: results of a large-eddy simulation study. *Bound -Layer Meteor* 123:77-98, 2007.

Stoy, P. C., Williams, M., Spadavecchia, L., Bell, R. A., Prieto-Blanco, A., Evans, J. G., and Wijk, M. T.: Using information theory to determine optimum pixel size and shape for ecological studies: Aggregating land surface characteristics in arctic ecosystems, *Ecosystems*, 12, 574-589, doi:10.1007/s10021-009-9243-7, 2009.

Stoy, P. C., Mauder, M., Foken, T., Marcolla, B., Boegh, E., Ibrom, A., Arain, M. A., Arneth, A., Aurela, M., Bernhofer, C., Cescatti, A., Dellwik, E., Duce, P., Gianelle, D., van Gorsel, E., Kiely, G., Knohl, A., Margolis, H., McCaughey, H., Merbold, L., Montagnani, L., Papale, D., Reichstein, M., Saunders, M., Serrano-Ortiz, P., Sottocornola, M., Spano, D., Vaccari, F., and Varlagin, A.: A data-driven analysis of energy balance closure across FLUXNET research sites: The role of landscape scale heterogeneity, *Agric. For. Meteorol.*, 171–172, 137-152, doi:10.1016/j.agrformet.2012.11.004, 2013.

Sulman, B.N., Desai, A.R., Cook, B.D., Saliendra, N., and Mackay, D.S., 2009. Contrasting carbon dioxide fluxes between a drying shrub wetland in Northern Wisconsin, USA, and nearby forests. *Biogeosciences*, 6: 1115-1126, doi:10.5194/bg-6-1115-2009.

Sun, J., Lenschow, D. H., Mahrt, L., Crawford, T. L., Davis, K. J., Oncley, S. P., MacPherson, J. I., Wang, Q., Dobosy, R. J., and Desjardins, R. L. Lake-induced atmospheric circulations during BOREAS. *Journal of Geophysical Research* 102(D24), 29,155-29,166. 1997.

Sun, J. and Pritchard, M.S.: Effects of explicit convection on global land-atmosphere coupling in the superparameterized CAM. *J. Adv. Model. Earth Syst.*, 8, 1248–1269, doi:10.1002/2016MS000689, 2016.

Thomas, C., Kennedy, A., Selker, J., Moretti, A., Schroth, M., Smoot, A., Tufillaro, N., and Zeeman, M.: High-resolution fibre-optic temperature sensing: A new tool to study the two-dimensional structure of atmospheric surface-layer flow, *Boundary Layer Meteorol.*, 142, 177-192, doi:10.1007/s10546-011-9672-7, 2012.

Twine, T.E., W.P. Kustas, J.M. Norman, D.R. Cook, P.R. Houser, T.P. Meyers, J.H. Prueger, P.J. Starks, M.L. Wesely. Correcting eddy-covariance flux underestimates over a grassland, *Agr. Forest Meteorol*, 103, 279-300, doi:10.1016/S0168-1923(00)00123-4, 2000.

Ueyama, M., Ichii, K., Iwata, H., Euskirchen, E. S., Zona, D., Rocha, A. V., Harazono, Y., Iwama, C., Nakai, T., and Oechel, W. C.: Upscaling terrestrial carbon dioxide fluxes in Alaska with satellite remote sensing and support vector regression, *Journal of Geophysical Research: Biogeosciences*, 118, 1266-1281, doi:10.1002/jgrg.20095, 2013.

van Heerwaarden, C. C., J. P. Mellado, and A. De Lozar: Scaling Laws for the Heterogeneously Heated Free Convective Boundary Layer. *Journal of the Atmospheric Sciences*, 71, 3975-4000, 2014.

Viskari T., Hardiman, B., Desai, A.R., Dietze, M.C.: Model-data assimilation of multiple phenological observations to constrain and forecast leaf area index. *Ecological Applications*, 25, 546-558, 2015.

Wang, K., and Dickinson, R. E.: A review of global terrestrial evapotranspiration: Observation, modeling, climatology, and climatic variability, *Rev. Geophys.,* 50, RG2005, doi:10.1029/2011rg000373, 2012.

Wang, J. M., J. X. Zhuang, W. Z. Wang, S. M. Liu, and Z. W. Xu: Assessment of Uncertainties in Eddy Covariance Flux Measurement Based on Intensive Flux Matrix of HiWATER-MUSOEXE. *IEEE Geosci. Remote Sens. Lett.*, 12, 259-263, 2015.

Wang, Y.Q., Xiong, Y.J., Qiu, G.Y., and Zhang, Q.T.: Is scale really a challenge in evapotranspiration estimation? A multi-scale study in the Heihe oasis using thermal remote sensing and the three-temperature model. *Agricultural and Forest Meteorology*, 230-231, 128-141, doi: 10.1016/j.agrformet.2016.03.012, 2016.

Watanabe, Tsutomu. Large-Eddy Simulation of Coherent Turbulence Structures Associated with Scalar Ramps Over Plant Canopies. Boundary-Layer Meteorology. *Boundary-Layer Meteorology* 112(2), 307-341. 2004.

Williams, M., Richardson, A. D., Reichstein, M., Stoy, P. C., Peylin, P., Verbeeck, H., Carvalhais, N., Jung, M., Hollinger, D. Y., Kattge, J., Leuning, R., Luo, Y., Tomelleri, E., Trudinger, C. M., and Wang, Y. P.: Improving land surface models with FLUXNET data, *Biogeosciences*, 6, 1341-1359, doi:10.5194/bg-6-1341-2009, 2009.

Wohlfahrt, G., and Widmoser, P.: Can an energy balance model provide additional constraints on how to close the energy imbalance?, *Agric. For. Meteorol.*, 169, 85-91, doi:10.1016/j.agrformet.2012.10.006, 2013.

Wolf, B., *et al.*: The ScaleX campaign: scale-crossing land-surface and boundary layer processes in the TERENO-preAlpine observatory. *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-D-15-00277.1, 2017.

Wulfmeyer, V., and Coauthors: A review of the remote sensing of lower tropospheric thermodynamic profiles and its indispensable role for the understanding and the simulation of water and energy cycles. *Rev. Geophys.*, 53, 819-895, 2015.

Xiao, J., Zhuang, Q., Law, B. E., Baldocchi, D. D., Chen, J., Richardson, A. D., Melillo, J. M., Davis, K. J., Hollinger, D. Y., Wharton, S., Oren, R., Noormets, A., Fischer, M. L., Verma, S. B., Cook, D. R., Sun, G., McNulty, S., Wofsy, S. C., Bolstad, P. V., Burns, S. P., Curtis, P. S., Drake, B. G., Falk, M., Foster, D. R., Gu, L., Hadley, J. L., Katul, G. G., Litvak, M., Ma, S., Martin, T. A., Matamala, R., Meyers, T. P., Monson, R. K., Munger, J. W., Oechel, W. C., Paw, U. K. T., Schmid, H. P., Scott, R. L., Starr, G., Suyker, A. E., and Torn, M. S.: Assessing net ecosystem carbon exchange of U.S. terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations, *Agric. For. Meteorol.*, 151, 60-69, doi:10.1016/j.agrformet.2010.09.002, 2011.

Xu, K., Metzger, S., Kljun, N., Taylor, J. R., and Desai, A. R.: How to consistently inform NEON's land surface model with tower-based eddy covariance flux observations? A novel approach to spatio-temporal rectification, *99th ESA Annual Meeting*, Sacramento, U.S.A., 10 - 15 August, 2014.

Xu, K., Metzger, S., Desai, A.R.: Upscaling tower-observed turbulent exchange at fine spatio- temporal resolution using environmental response functions, *Agricultural and Forest Meteorology*, 232:10-22, doi:10.1016/j.agrformet.2016.07.019, 2017a.

Xu, K., Metzger, S., Desai, A.R.: Surface-atmosphere exchange in a box: Space-time resolved storage and net vertical fluxes from tower-based eddy covariance, *Agric. For. Meteorol.*, in press, doi: 10.1016/j.agrformet.2017.10.011, 2017b.

Xu, Z., Ma, Y., Liu, S., Shi, W., and Wang, J.: Assessment of the Energy Balance Closure under Advective Conditions and Its Impact Using Remote Sensing Data, *J. Applied. Meteorol. Clim.*, 56, 127–140, doi:10.1175/JAMC-D-16-0096.1, 2017c.

Yan Kam Wing, G.., Sushama, L., and Diro, G.T.: The intraannual variability of land-atmosphere coupling over North Americain the Canadian Regional Climate Model (CRCM5), *J. Geophys. Res. Atmos.*, 121, 13859-13885, doi:10.1002/2016JD025423, 2016.

Yi, C., Davis, K.J., Bakwin, P.S., Denning, A.S., Zhang, N., Desai, A.R., Lin, J.C., Gerbig, C., and Wofsy, S.C.. Observed covariance between ecosystem carbon exchange and atmospheric boundary layer dynamics at a site in northern Wisconsin. *Journal of Geophysical Research*, 109(D08302), doi:10.1029/2003JD004164, 2004.

Yu, R., Schwartz, M. D., Donnelly, A., & L. Liang: An Observation-based Progression Modeling Approach to Spring and Autumn Deciduous Tree Phenology. *International Journal of Biometeorology,* 60, 335-349, 2016.

Zeeman, Matthias J., Selker, John S., and Thomas, Christoph K. Near-surface motion in the nocturnal, stable boundary layer observed with fibre-optic distributed temperature sensing. *Boundary-Layer Meteorology* , DOI 10.1007/s10546-014-9972-9. 2014.

Zhang, N., Williams, Q.L., and Liu, H.P.: Effects of land-surface heterogeneity on numerical simulations of mesoscale atmospheric boundary layer processes, *Theoretical and Applied Climatology*, 102, 307, doi: 10.1007/s00704-010-0268-9, 2010.

Zhu, X., Ni, G., Cong, Z., Sun, T., and Li, D.: Impacts of surface heterogeneity on dry planetary boundary layers in an urban-rural setting. *J. Geophys. Res. Atmos.*, 121, 12,164–12,179, doi:10.1002/ 2016JD024982, 2016.

Zitouna-Chebbi, R., Laurent Prévot, Frédéric Jacob, Raoudha Mougou, Marc Voltz: Assessing the consistency of eddy covariance measurements under conditions of sloping topography within a hilly agricultural catchment. *Agr. Forest Meteorol.*, 164, 123-135, 2012.

BIOGRAPHICAL SKETCH FOR ANKUR R DESAI

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(A) PROFESSIONAL PREPARATION

Oberlin College (Ohio) B.A., Environmental Studies and Computer Science (double major), 1997

University of Minnesota, M.A., Geography, 2000

Pennsylvania State University, Ph.D., Meteorology, 2006

National Center for Atmospheric Research (Colorado), ASP Postdoctoral Fellow, 2006-2007

(B) APPOINTMENTS

2016- Professor, Dept. of Atmospheric & Oceanic Sciences, U. Wisconsin

- 2017- Faculty affiliate, Civil and Environmental Engineering

2011-2016 Associate Professor, Dept. of Atmospheric & Oceanic Sciences, U. Wisconsin

- 2014 MICMoR Visiting Scientist, KIT IMK-IFU, Garmisch-Partenkirchen, Germany

2007-2011 Assistant Professor, Dept. of Atmospheric & Oceanic Sciences, U. Wisconsin

- 2009- Faculty affiliate, Freshwater and Marine Sciences
- 2008- Faculty affiliate, Sustainability and Global Environment (SAGE)
- 2008- Faculty affiliate, Center for Climatic Research (CCR), Nelson Institute

2006-2007 Postdoctoral Fellow, Advanced Study Program, NCAR

2002-2006 Graduate Research Assistant, Dept. of Meteorology, Pennsylvania State U.

2000-2001 Research Fellow, Dept. of Forest Resources, University of Minnesota

1998-2000 ICGC MacArthur Scholar Fellow, Dept. of Geography, University of Minnesota

(C) PRODUCTS

FIVE RELEVANT PUBLICATIONS AND PRODUCTS (BOLD DEONTES DESAI LAB AUTHORS)

Bagley, J.E., **Desai, A.R.**, Harding, K.J., Snyder, P.K., and Foley, J.A., 2014. Drought and deforestation: Has land cover change influenced recent precipitation extremes in the Amazon? *J. Climate*, 27, 345-361,doi:10.1175/JCLI-D-12-00369.1.

Desai, A.R., 2014. Influence and predictive capacity of climate anomalies on daily to decadal extremes in canopy photosynthesis. *Photosynthesis Research*, 119, 31-47,doi:10.1007/s11120-013-9925-z.

Desai, A.R., **Xu, K.**, Tian H., Weishampel, P., **Thom, J.**, Baumann, D., Andrews, A.E., Cook, B.D., King, J.Y., and Kolka, R., 2015. Landscape-level terrestrial methane flux observed from a very tall tower. *Agricultural and Forest Meteorology*, 201, 61-75, doi:10.1016/j.agrformet.2014.10.017.

Xu, K., Metzger, S., **Desai, A.R.**, 2017 Surface-atmosphere exchange in a box: Space-time resolved storage and net vertical fluxes from tower-based eddy covariance. *Agricultural and Forest Meteorology*, in press, doi:10.1016/j.agrformet.2017.10.011.

Xu, K., Metzger, S., **Desai, A.R.**, 2017. Upscaling tower-observed turbulent exchange at fine spatio-temporal resolution using environmental response functions. *Agricultural and Forest Meteorology*, 232:10-22, doi:10.1016/j.agrformet.2016.07.019

FIVE OTHER PUBLICATIONS AND PRODUCTS (BOLD DEONTES DESAI LAB AUTHORS)

Becknell, J.M., **Desai, A.R.**, Dietze, M.C., Schultz, C.A., Starr, G., Duffy, P.A., Franklin, J.F., Pourmokhtarian, A., Hall, J., Stoy, P.C., Binford, M.W., Boring, L.E., and Stuadhammer, C.L., 2015. Assessing interactions among changing climate, management, and disturbance in forests: A macrosystems approach. *Bioscience*, 65:263-274, doi:10.1093/biosci/biu234

Dietze, M.C., Serbin, S.P., Davidson, C., **Desai, A.R.**, Feng, X., Kelly, R., Kooper, R., LeBauer , D., Mantooth, J., McHenry , K., and Wang, D., 2014. A quantitative assessment of a terrestrial biosphere model's data needs across North American biomes. *J. Geophys. Res-G*, 119, 286–300, doi:10.1002/2013JG002392.

Kenny, W.T., Bohrer, G., Morin, T.H., Vogel, C.S., Matheny, A.M., and **Desai, A.R.**, 2017. A Numerical Case Study of the Implications of Secondary Circulations to the Interpretation of Eddy-Covariance Measurements Over Small Lakes. *Boundary-Layer Meteorol.*, 165, 311–332, 10.1007/s10546-017-0268-8.

Novick, K.A., Biederman, J.A., **Desai, A.R.**, Litvak, M.E., Moore, D.J.P., Scott, R.L., and Torn, M.S., 2017. The AmeriFlux Network: A Coalition of the Willing. *Agricultural and Forest Meteorology*, in press, doi:10.1016/j.agrformet.2017.10.009.

Wolf, S., Keenan, T.F., Fisher, J.B., Baldocchi, D.D., **Desai, A.R.**, Richardson, A.D., Scott, R.L., Law, B.E., Litvak, M.E., Brunsell, N.A., Peters, W., and van der Laan-Luijkx, I.T., 2016. Warm spring reduced carbon cycle impact of the 2012 US summer drought. *Proc. Natl Acad Sci*, 113, 5880-5885, doi:10.1073/pnas.1519620113.

(D) SYNERGISTIC ACTIVITIES

- Journal of Geophysical Research, Biogeosciences, Editor, 2015-, Associate Editor, 2011-2014
- Earth Educator Rendezvous, On the Cutting Edge: Preparing for an Academic Career in the Geosciences, Workshop Lead Organizer, Madison, WI, Jul 18-20 2016
- Chair, American Meteorological Society (AMS), Agricultural and Forest Meteorology, Science Technical and Advisory Committee (STAC), 2010-2016
- Member, Science, Technology and Education Advisory Committee, National Ecological Observatory Network, Batelle Ecology, 2016-
- AMS Clarence Leroy Meisinger Award and AMS Early Career Achievement Award, 2016

BIOGRAPHICAL SKETCH FOR STEFAN METZGER

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PROFESSIONAL PREPARATION

University of Bayreuth (Germany), Diplom (MSc equivalent), Geo-ecology, 2007
University of Bayreuth (Germany), Dr. rer. nat. (PhD equivalent), Micrometeorology, 2013
National Ecological Observatory Network (Boulder, CO, U.S.A.), Postdoctoral Researcher, 2011-2014

APPOINTMENTS

2016-	Team Lead – Surface-Atmosphere Exchange, Battelle Ecology, Boulder, CO, U.S.A.
2014-2016	Staff Scientist, National Ecological Observatory Network, Boulder, CO, U.S.A.
2011-2014	Postdoctoral Researcher, National Ecological Observatory Network, Boulder, CO, U.S.A.
2007-2011	Research Fellow, Chinese Academy of Sciences IAP, Beijing, China
2002-2007	Research Assistant, University of Bayreuth, Germany

FIVE RELEVANT PUBLICATIONS AND PRODUCTS

Metzger, S.: Surface-atmosphere exchange in a box: Making the control volume a suitable representation for in-situ observations, Agric. For. Meteorol., doi:10.1016/j.agrformet.2017.08.037, 2017.

Xu, K., **Metzger, S.**, and Desai, A. R.: Surface-atmosphere exchange in a box: Space-time resolved storage and net vertical fluxes from tower-based eddy covariance, Agric. For. Meteorol., doi:10.1016/j.agrformet.2017.10.011, 2017.

Metzger, S., Durden, D., Sturtevant, C., Luo, H., Pingintha-Durden, N., Sachs, T., Serafimovich, A., Hartmann, J., Li, J., Xu, K., and Desai, A. R.: eddy4R 0.2.0: a DevOps model for community-extensible processing and analysis of eddy-covariance data based on R, Git, Docker, and HDF5, Geosci. Model Dev., 10, 3189-3206, doi:10.5194/gmd-10-3189-2017, 2017.

Xu, K., **Metzger, S.**, and Desai, A. R.: Upscaling tower-observed turbulent exchange at fine spatio-temporal resolution using environmental response functions, Agric. For. Meteorol., 232, 10-22, doi:10.1016/j.agrformet.2016.07.019, 2017.

Metzger, S., Junkermann, W., Mauder, M., Butterbach-Bahl, K., Trancón y Widemann, B., Neidl, F., Schäfer, K., Wieneke, S., Zheng, X. H., Schmid, H. P., and Foken, T.: Spatially explicit regionalization of airborne flux measurements using environmental response functions, Biogeosciences, 10, 2193-2217, doi:10.5194/bg-10-2193-2013, 2013.

FIVE OTHER PUBLICATIONS AND PRODUCTS

Kohnert, K., Serafimovich, A., **Metzger, S.**, Hartmann, J., and Sachs, T.: Strong geologic methane emissions from discontinuous terrestrial permafrost in the Mackenzie Delta, Canada, Scientific Reports, 7, 5828, doi:10.1038/s41598-017-05783-2, 2017.

Vaughan, A. R., Lee, J. D., Shaw, M. D., Misztal, P. K., **Metzger, S.**, Vieno, M., Davison, B., Karl, T. G., Carpenter, L. J., Lewis, A. C., Purvis, R. M., Goldstein, A. H., and Hewitt, C. N.: VOC emission rates over London and South East England obtained by airborne eddy covariance, Faraday Discuss., 200, 599-620, doi:10.1039/c7fd00002b, 2017.

Metzger, S., Burba, G., Burns, S. P., Blanken, P. D., Li, J., Luo, H., and Zulueta, R. C.: Optimization of an enclosed gas analyzer sampling system for measuring eddy covariance fluxes of H_2O and CO_2, Atmos. Meas. Tech., 9, 1341-1359, doi:10.5194/amt-9-1341-2016, 2016.

Smith, D., **Metzger, S.**, and Taylor, J. R.: A transparent and transferable framework for tracking quality information in large datasets, PLoS One, 9, e112249, doi:10.1371/journal.pone.0112249, 2014.

Metzger, S., Junkermann, W., Mauder, M., Beyrich, F., Butterbach-Bahl, K., Schmid, H. P., and Foken, T.: Eddy-covariance flux measurements with a weight-shift microlight aircraft, Atmos. Meas. Tech., 5, 1699-1717, doi:10.5194/amt-5-1699-2012, 2012.

SYNERGISTIC ACTIVITIES

- Convener and/or Chair of several sessions during AGU, AmeriFlux and NACP annual meetings
- Main Developer of eddy4R flux processor and environmental response function software: An algorithm that enables quantitatively extracting the hidden relationships between observations of environmental drivers and responses
- Host of environmental response function annual user workshop and eddy4R software tutorial > 50 participants, since 2014
- Manuscript Reviewer for various periodicals including Advances in Science and Research, Agricultural and Forest Meteorology, Atmospheric Chemistry and Physics, Atmospheric Measurement Techniques, Biogeosciences, Boundary-Layer Meteorology, Climatic Change, Journal of Applied Remote Sensing, Journal of Geophysical Research - Atmospheres Journal of Geophysical Research - Biogeosciences, Journal of Atmospheric and Oceanic Technology, Meteorologische Zeitschrift, Plant and Soil, Theoretical and Applied Climatology, Water Resources Research
- Proposal Reviewer for various panels including NSF Division of Environmental Biology, NSF Major Research Instrumentation Program

BIOGRAPHICAL SKETCH: GRANT PETTY

I. Professional Preparation

University of Washington, Seattle Washington

Ph.D. 1990 Atmospheric Science

University of California at Davis, Davis, California

B.S. 1984 Applied Physics with emphasis in Atmospheric Physics

II. Appointments

2000–present *University of Wisconsin-Madison*:

2003–present: Professor

2013–2016: Department Chair

2000–2003: Associate Professor

1990–2000 *Purdue University*:

1995–2000: Associate Professor

1990–1995: Assistant Professor

III. 10 Most Relevant Publications

Petty, G.W., and K.B. Katsaros, 1992: The response of the Special Sensor Microwave/Imager to the marine environment. Part I: An analytic model for the atmospheric component of observed brightness temperatures. *J. Atmos. Ocean. Tech.*, **9**, 746–761

Petty, G.W., 1994: Physical retrievals of over-ocean rain rate from multichannel microwave imagery. Part I: Theoretical characteristics of normalized polarization and scattering indices. *Meteorol. Atmos. Phys*., **54**, 79–100

Petty, G.W., and K.B. Katsaros, 1994: The response of the SSM/I to the marine environment. Part II: A parameterization of the effect of the sea surface slope distribution on emission and reflection. *J. Atmos. Ocean. Tech.* , **11**, 617–628

Petty, G.W. 2001: Physical and microwave radiative properties of precipitating clouds. Part 1. Principal component analysis of observed multichannel microwave radiances in tropical strati- form rainfall. *J. Appl Meteor*., **40**, 2105–2114.

Petty, G.W. 2001: Physical and microwave radiative properties of precipitating clouds. Part 2. A parametric 1-D rain cloud model for use in microwave radiative transfer simulations. *J. Appl Meteor.*, **40**, 2115–2129

Petty, G.W, 2002: Area-average solar radiative transfer in three-dimensionally inhomogeneous clouds: the Independently Scattering Cloudlets model. *J. Atmos. Sci*., **59**, 2910–2929.

Petty, G.W., and W. Huang, 2010: Microwave backscatter and extinction by soft ice spheres and complex snow aggregates. *J. Atmos. Sci*., **67**, 769–787

Petty, G. W., 2013: Dimensionality reduction in Bayesian estimation algorithms. *Atmos. Meas. Tech.*, **6**, 2267–2276

Petty, G. W. and Bennartz, R., 2017: Field-of-view characteristics and resolution matching for the Global Precipitation Measurement (GPM) Microwave Imager (GMI), *Atmos. Meas. Tech*., **10**, 745-758

Petty, G. W., 2017: On some shortcomings of Shannon entropy as a measure of information content in indirect measurements. Conditionally accepted, *J. Atmos. Ocean. Tech*.

IV. Synergistic Activities

a. Textbooks

Petty, G.W., *A First Course in Atmospheric Radiation* (2nd. Ed.), Sundog Publishing, 2006, 452 pp., ISBN: 978-0-9729033-1-8. [Recipient of an *Outstanding Academic Title* designation by *CHOICE Magazine*. Over 5,000 copies in circulation.]

Petty, G.W., *A First Course in Atmospheric Thermodynamics*, Sundog Publishing, 2008, 352 pp., ISBN: 978-0-9729033-2-5. [Over 4,000 copies in circulation.]

b. Teaching innovations

Petty, G.W., 2015: Integrative/immersive learning of Python in an undergraduate atmospheric thermodynamics course. Oral presentation at the 95th American Meteorological Society Annual Meeting, Phoenix, AZ; abstract and recording available at https://ams.confex.com/ams/95Annual/webprogram/Paper270030.html

c. Selected professional highlights

1993–2002: Associate Editor, *Journal of Applied Meteorology*.

1996: Editors Award, American Meteorological Society. "For exceptionally careful and insightful reviews in the area of satellite remote sensing for the *Journal of Applied Meteorology*."

1996: Co-chair, AMS 8th Conference on Satellite Meteorology and Oceanography.

d. Other activities

2016–present: Led a UW-Madison initiative to acquire a manned ultralight airplane for meteorological research; built and first flew the aircraft in July–August 2017.

2016-2017: Built a large fixed wing unmanned aerial vehicle (UAV) for use as a measurement platform in support of an undergraduate *Meteorological Measurements* field course.

Mark Donald Schwartz

Professional Preparation

Institution	Location	Major/Area	Degree and Year
Mich. State Univ.	(E. Lansing)	Earth Science, Lyman Briggs College	B.S. 1980 (w/honor)
Mich. State Univ.	(E. Lansing)	Geography	M.S. 1982
Univ. of Kansas	(Lawrence)	Geography	Ph.D. 1985

Appointments

2010-present	*Distinguished Professor*, Geography, UW-Milwaukee
2002-2010	*Professor*, Geography, UW-Milwaukee
1996-2002	*Associate Professor*, Geography, UW-Milwaukee
1992-1996	*Assistant Professor*, Geography, UW-Milwaukee
1987-1992	*Lecturer*, Geography/*Assistant Research Scientist* (1989-1992), San Francisco State University
1985-1987	*Assistant Professor*, Geography, San Francisco State University

Five Most Related Publications

Book

Schwartz, M. D. (editor), 2013: *Phenology: An Integrative Environmental Science, 2nd Ed.*, Springer, Netherlands, 610 pp.

Referred Journal Articles

Ault, T. R., **Schwartz, M. D.**, Zurita-Milla, R., Weltzin, J. F., & J. L. Betancourt, 2015: Trends and Natural Variability of North American Spring Onset as Evaluated by a New Gridded Dataset of Spring Indices. *Journal of Climate* **28**(21): 8363-8378.

Liu, L., Liang, L., **Schwartz, M. D.**, Donnelly, A., Wang, Z., Schaaf, C. B., & L. Liu, 2015: Evaluating the Potential of MODIS Satellite Data to Track Temporal Dynamics of Autumn Phenology in a Temperature Mixed Forest. *Remote Sensing of Environment* **160**(1): 156-165.

Schwartz, M. D., Ahas, R., & A. Aasa, 2006: Onset of Spring Starting Earlier Across the Northern Hemisphere. *Global Change Biology* **12**(2): 343-351.

Schwartz, M. D., Ault, T. R., & J. L. Betancourt, 2013: Spring Onset Variations and Trends in the Continental USA: Past and Regional Assessment Using Temperature-Based Indices. *International Journal of Climatology* **33**(11): 2917-2922.

Five Other Significant Publications (*all referred Journal Articles*)

Liang, L., **Schwartz, M. D.**, & S. Fei, 2011: Validating Satellite Phenology through Intensive Ground Observation and Landscape Scaling in a Mixed Seasonal Forest. *Remote Sensing of Environment* **115**(1): 143-157.

Schwartz, M. D. 1998: Green-wave phenology. *Nature* **394** (6696): 839-840.
Schwartz, M. D., & T. R. Karl, 1990: Spring Phenology: Nature's Experiment to Detect the Effect of "Green-up" on Surface Maximum Temperatures. *Monthly Weather Review* **118**(4): 883-890.
Schwartz, M. D., & J. M. Hanes, 2009: Intercomparing Multiple Measures of the Onset of Spring in Eastern North America. *International Journal of Climatology* **30**(11): 1614-1626.
Schwartz, M. D., Hanes, J. M., & L. Liang, 2013: Comparing Carbon Flux and High-resolution Spring Phenological Measurements in a Northern Mixed Forest. *Agricultural and Forest Meteorology* **169**: 136-147.

Synergistic Activities

Co-founder, **USA-National Phenology Network** (USA-NPN), http://www.usanpn.org
PI, **NSF Research Coordination Network** (RCN) USA-NPN **grant** IOS-0639794 (2007-2014)
Developer of the "**Spring Indices**" **models**, which process daily max-min air temperature data from selected sites or gridded data into values comparable to the onset of spring plant growth and development at local to global scales. Used by Environmental Protection Agency (EPA) and U.S. Global Change Research Program National Climate Assessment as climate change indicators. Near-real time products available at https://www.usanpn.org/data/spring
Chair of Organizing Committee and Host for **Phenology 2012 Conference**, http://www.phenology2012.uwm.edu

Biographical Sketch - Philip A. Townsend

Professor, Department of Forest & Wildlife Ecology
Email: ptownsend@wisc.edu

(a) Professional Preparation

University of Virginia, Charlottesville	B.A.	1985-1989
University of North Carolina, Chapel Hill	Ph.D.	1992-1997

(b) Appointments

2005- Associate then Full (2010) Professor, Forest & Wildlife Ecology, UW-Madison
- Vilas Distinguished Achievement names professorship, 2014-present
- Joint appointment, Department of Entomology, 2013-present
- Graduate Chair, Forest & Wildlife Ecology, 2012-present

1998-2005 Assistant then Associate (2003) Professor, University of Maryland Center for Environmental Science, Appalachian Laboratory

1997-1998 Assistant Professor, Geography, Texas A&M University

(c.i) Five Related Products

Garcia, ME, and **PA Townsend**, 2016. Recent climatological trends and potential influences on forest phenology around western Lake Superior, USA. *JGR - Atmosphere*s 121: 13,364–13,391.

Madritch, MD, CC Kingdon, A Singh, KE Mock, RL Lindroth and **PA Townsend**, 2014. Imaging spectroscopy links aspen genotype with belowground processes at landscape scales. *Philosophical Transactions of the Royal Society B* 369:20130194, 10.1098/rstb.2013.0194.

Serbin, SP, A Singh, AR Desai, SG Dubois, AD Jablonski, CC Kingdon, EL Kruger and **PA Townsend**, 2015. Remotely estimating photosynthetic capacity, and its response to temperature, in vegetation canopies using imaging spectroscopy. *Remote Sensing of Environment* 167:78-87.

Singh, A, SP Serbin, CC Kingdon, BE McNeil and **PA Townsend**, 2015. Imaging spectroscopy algorithms for mapping canopy foliar chemical and morphological traits and their uncertainties. *Ecological Applications* 25: 2180-2197.

Townsend, PA, SP Serbin, EL Kruger and JA Gamon, 2013. Disentangling the contribution of biological and physical properties of leaves and canopies in imaging spectroscopy data. *Proceedings of the National Academy of Sciences* 110:E1074-E1074, doi:10.1073/pnas.1300952110.

(c.ii) Five Other Significant Products

Cotrozzi, L, JJ Couture, J Cavender-Bares, CC Kingdon, B Fallon, G Pilz, E Pellegrini, C Nali, **PA Townsend**, 2017. Using foliar spectral properties to assess the effects of drought on plant water potential. *Tree Physiology*, 37: 1582-1591, doi:10.1093/treephys/tpx106.

Fisher, JB., F Melton, E Middleton, C Hain, M Anderson, R Allen, MF McCabe, S Hook, D Baldocchi, **PA Townsend**, *et al.*, 2017. The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural

management, and water resources. *Water Resour. Res*. 53:2618–2626, doi:10.1002/2016WR020175.
Schimel, D, R Pavlick, JB Fisher, GP Asner, S Saatchi, **PA Townsend**, C Miller, C Frankenberg, K Hibbard and P Cox, 2015. Observing terrestrial ecosystems and the carbon cycle from space. *Global Change Biology* 21:1762-1776, 10.1111/gcb.12822.
Serbin, SP, A Singh, BE McNeil, CC Kingdon and **PA Townsend**, 2014. Spectroscopic determination of leaf morphological and biochemical traits for northern temperate and boreal tree species. *Ecological Applications* 24:1651-1669, 10.1890/13-2110.1.
Yuan, M, JJ Couture, **PA Townsend**, MD Ruark and WL Bland, 2016. Estimation of leaf nitrogen concentration and leaf mass per area in sweet corn and snap bean using narrowband reflectance spectroscopy. *Agronomy Journal*: 108: 2519-2526, 10.2134/agronj2016.05.0260.

(d) Synergistic Activities

1. Aldo Leopold Leadership Program Fellow (2008)
2. European Union COST Action ES903 – Eurospec, External Evaluator (2013-2014)
3. NASA HyspIRI (satellite) Mission Science Study Team (2009-present)
4. Developer of the EcoSIS (ecosis.org) open-source, online database for spectral data, metadata and associated trait measurements; co-developer of SDAL ("Spectral Data Abstraction Library") an open-source Python software library for processing of environmental spectroscopy data
5. Oak Ridge National Laboratory Distributive Active Archive Center for Biogeochemical Dynamics (ORNL-DAAC), Advisory Committee (2013-present)

Data Management Plan

CHEESEHEAD aims to provide a public database of the highest density sub-mesoscale surface energy balance observations and models simulations for years to come. We strive to provide open-access, curated, long-term archived data with rapid turnaround and broad publicity. Below we describe the products, standards, archival, and access plans. We intend to rely on the data ingest, harmonization, and archival services provides by UCAR/NCAR EOL Lower Atmosphere Observing Facilities (LAOF) data services. We will follow all requirements of EOL's data policy. Preliminary and processed data, metadata, quality control information will be provided to all researchers, regardless of affiliation with the project, as soon as it is available, freely, on a public website. Science progresses fastest when data are free.

What is produced?

Ameriflux tall tower and flux tower observations of raw turbulent and time series of momentum, heat, moisture, and greenhouse gases are collected continuously and uploaded hourly to Desai lab servers at University of Wisconsin, which are then immediately placed online in ASCII or binary formats for download by anyone. Each night, fluxes are processed from our public flux processing code and CSV files are uploaded to the Dept. of Energy (DOE) Lawrence Berkeley Lab (LBL) Ameriflux Project office and also made available immediately on Desai lab servers. Every 3 months, QA/QC processing is applied and Level 2 Ameriflux products are produced and made available on the DOE LBL DAAC. We request EOL to mirror these observations for the project period as part of the field project merged repository.

Up to 20 FluxPAM towers will be deployed from the EOL Integrated Surface Flux System. Both raw (10-20 Hz) and processed (5-minute statistics and half-hourly averages) meteorological (temperature, humidity, winds), radiation (net radiation, incoming and outgoing shortwave and longwave), flux (water, CO_2, momentum, heat) and soil (temperature, moisture, heat) observations will be collected and archived by EOL. Similarly, EOL Integrated Sounding System observations including wind profiler, RASS, and atmospheric sondes will be similarly archived and made available by EOL. Any mobile deployments from Ameriflux or NEON will also be submitted to this repository.

University of Wyoming King Air, Wyoming Cloud LiDAR, and Compact Raman LiDAR observations of airborne 10 Hz turbulent meteorology (winds, temperature, humidity, CO_2), 1 s metrology and radiation, and LiDAR returns will be archived for analysis at EOL.

The SSEC Portable Atmospheric Research Center (SPARC) observations will be processed by University of Wisconsin SSEC staff and include retrieved profiles of virtual temperature and humidity from AERI, raw AERI output, HALO scanning wind LiDAR 1-s wind retrievals, HSRL 532 and 1064 scattering and depolarization profiles, and sondes. These will be archived locally at SSEC and provided to EOL as part of a field project combined archive. Quicklook generation and automated subset tools are already available for several of these instruments at part of the SSEC atmospheric instruments portal. KIT Raman/DIAL LiDAR will be processed by KIT collaborators (Mauder) and provided to UW for archival and submission to EOL within 2 months of collection.

Phenology, ground cover, and vegetation observations collected by University of Wisconsin-Milwaukee will be entered using clear metadata protocols and provided in CSV or Spreadsheet format, served both at Desai lab servers and sent to EOL within six months of collection.

UW spectrometer hyperspectral data will be collected once during the project. Georectified maps of surface will be produced by co-PI Phil Townsend, archived at the EcoSIS repository and also sent to EOL within three months of collection. UW ultralight data of could include 1 second temperature, humidity, pressure, winds, thermal radiation, and GPS position and will be archived locally and shared with EOL after post-processing.

Models include Large Eddy Simulation (LES) numerical output and Environmental Response Function scaled fluxes and driver data will be made available locally with investigators. ERF algorithms are already located in a GitHub repository. Additional documentation, developer's guide, and R and Python source code will all be published on a separate public GitHub repository. LES algorithms are available from the investigator. All ERF scaling driver data (meteorology, land surface remote sensing) are already publicly available. Harmonized LES output and ERF scaled fluxes will be provided to EOL for the combined archive within two months of production and analysis.

We have requested EOL to collect ancillary observations of NWS sondes in Green Bay, WI and Minneapolis, MN and 0Z and 12Z forecast model output from the NOAA NCEP 3km HRRR numerical weather prediction model for the north central US domain for LES boundary condition.

Presentations, manuscripts, and reports will all be made publicly available as soon as presented or accepted for publication. Open-access journals will be preferred wherever possible, and all articles will also be placed in a University repository.

Who is responsible?

Ankur Desai will be responsible for overall data management, timely access to algorithms, and publications. NCAR EOL staff will be responsible for LAOF archival and integration of Ameriflux and ancillary data with ISS, ISFS, and King Air observations. LES model code, model output, and KIT LiDAR will be responsibility of Matthias Mauder, working closel. Phil Townsend is responsible for spectrometer observations. Mark Schwartz is responsible for phenology and vegetation observations. Grant Petty is responsible for the ultralight observatiosn.

Where will it be archived?

All investigators provided data will be stored locally on the Desai lab servers where possible. Desai lab has 40 TB available for the project in a RAID that is backed up regularly at the UW Center for Climatic Research. A THREDDS-based webpage will be created to allow for quick download of all data products

Long-term archival data services will be provided by EOL data services, and include LAOF and King Air observations, and also serve as a second archive for campaign specific observations from Ameriflux, DTS, LES model output, ERF fluxes, and SPARC observations. SPARC observations are also archived in the SSEC general data repository and provided in NetCDF. Spectrometer data will be submitted to the EcoSIS repository in HDF5. Flux tower processed flux and meteorology data and raw observations will be archived at DOE Ameriflux repository in CSV, which can be queried by website or JSON-based API.

When will it be freely available?

All data will be made publicly accessible as soon as produced. The code repository will contain a real-time snapshot of the algorithms in development. Initial, raw investigator-specific data may be made available only by email request to project PIs, but in all cases made freely available in less than 6 months of collection or model experiment. We strive to make all publications open-access, and where not possible, pre-prints will be placed online on Desai's website and the University repository. Talks and posters are generally placed online on Desai's website within one week of presentation. Publicity on this will be made in the core experiment paper for BAMS, through an experiment blog, and announced through major listservs, including Fluxnet and Ecolog. All investigator permissions and requirements will be met prior to sharing data publicly. However, we do not anticipate any significant intellectual property, ethical, or privacy issues. We have developed a code sharing policy based on a standard open-source license (Creative Commons) and authorship policy based on the Vancouver Protocol.

Post-Doctoral Mentoring Plan

Desai is committed to high quality, hands-on mentoring of the two post-doctoral researchers (PDR) to be funded on this project. A PDR's appointment is viewed as an apprenticeship—a professional training or transitional employment that will prepare that person to excel in a long-term academic, industrial, governmental, or other full-time research career in atmospheric or related sciences. The objective of our mentoring is to provide the tools and opportunities for the PDR to become a leader in the discipline through the unique field and modeling experiences provided here.

The PDR, as early career scientists, are essential to the project's mission and through this project gain key skills in project management during the field experiment, leadership through co-mentoring of students during and after the field experiment, and scholarship by building research expertise and publications in energy balance, scaling, and atmospheric science. One PDR will be hired at the start of the project and focus on leading the field project, remote sensing, and observational data analysis. The second PDR will be hired to overlap with the first PDR, but start later and focus on modeling and synthesis activities.

We will recruit broadly for the PDR, including international listservs search as the Earth Science Women's Network (ESWN) ES_JOBS_LIST. Desai places a high emphasis on recruiting broad thinkers and also on improving representation of women and underrepresented minorities in our field. Desai will use the National Postdoctoral Association mentoring plan to develop a mentoring and goal setting document with the PDR on initial hire and follow up with a review meeting every 6 months. Office space will be provided on the same floor as Desai at University of Wisconsin.

Following guidelines of the NPA, the mentoring plan will provide i) a clear statement of the terms of their appointment (e.g., salary, roles and responsibilities, benefits, evaluation policy, intellectual property policy and agreement, etc.), ii) a structured timeline of goals and review meetings, iii) career planning assistance, and iv) outline priority of opportunities to learn career development skills such as writing, guided instruction on protocols, methodology and techniques, effective problem-solving strategies, mentoring of students, and critical interpretation of project data. The PDRs will also have opportunities to participate in and will be encouraged to lead, write and review journal papers.

One PDR will be expected to provide on the ground field support during the entire field project and for set up and breakdown (four months total), living at a nearby field station, which is well set up for long-term visiting arrangements. This project will provide funding for lodging, vehicles, and meals during this period for the PDR in addition to other visits and conferences. We will also cover all time and costs for safety training and provide opportunity for the PDR to gain mentoring skills by working with the project graduate and undergraduate students. This PDR will lead processing of remote sensing and ultralight aircraft data. The second PDR will work with the PI and graduate students on modeling analysis, working with the team in Germany on Large Eddy Simulations. Together the PDRs will lead a Bulletin of the AMS manuscript on the overall project. Both PDRs will also be given broad latitude to develop additional manuscripts on research areas of interest in the areas of energy balance, micrometeorology, modeling, or scaling, and help co-supervise graduate and undergraduate thesis research depending on PDR interest and overlap. Both PDRs will be given opportunity to participate in education and outreach in collaboration with Collaborator Pertzborn.

Desai runs weekly lab meetings, and bi-weekly individual meetings with all research staff, including the PDRs. The PDRs will also participate and help initiate all weekly teleconference calls with the project team and also, depending on research direction, be provided access, travel, and funding to work with co-PIs or Collaborators Petty, Townsend, Metzger, Schwartz, Mauder, or Stoy.

THE UNIVERSITY *of* WISCONSIN MADISON

31 October 2016

Physical & Dynamic Meteorology Program
National Science Foundation
201 Wilson Boulevard
Arlington VA 22230

Dear Review Panel,

Kemp Natural Resources Station supports the research proposal submitted by Dr. Ankur R. Desai entitled, *"Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors."*

Kemp Station is a University of Wisconsin-Madison research and teaching facility located in north-central Wisconsin. Each year the station supports more than 50 research projects; hosts numerous field courses; and implements dozens of outreach events. The station is well positioned to implement its mission, having been awarded two NSF Field Station and Marine Laboratory grants that significantly expanded and enhanced station infrastructure. Specifically, Kemp Station has fully equipped analytical and computer laboratories; classroom and meeting room facilities; broadband, wireless internet access; and on-site living accommodations for 60 people. In addition to this on-site capacity, the station provides convenient access to a diverse range of aquatic and terrestrial ecosystems relevant to Dr. Desai's research proposal.

Kemp Station welcomes the opportunity to collaborate with Dr. Desai on this project – it is a mutually beneficial partnership in which the resources of Kemp Station can assist Dr. Desai in the pursuit of this important research.

By signing below, I acknowledge that I am listed as a supporting facility on the proposal entitled *"Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors"* with Ankur R. Desai as the Principal Investigator. I agree to undertake the tasks associated with me as described in the project description of this proposal, and/or commit to provide or make available the resource designated in the proposal.

Sincerely,

Scott Bowe

Scott Bowe
Professor and Director, Kemp Natural Resources Station

Kemp Natural Resources Station
University of Wisconsin 9161 Kemp Road Woodruff, Wisconsin 54568
715–358–5667 Fax: 715–356–3669 Email: kemp@cals.wisc.edu kemp.wisc.edu

November 7, 2016

To: NSF Physical and Dynamic Meteorology

From: Linda Parker, Forest Ecologist, Chequamegon-Nicolet National Forest

Dear NSF,

By signing below, I acknowledge that I am listed as a supporting collaborator on the proposal entitled "Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors," with Ankur R Desai as the Principal Investigator. I agree to commit to provide or make available the resources designated in the proposal. These include support in permitting and enabling access for potential flux tower and field experiment sites at and near the very tall tower.

Sincerely,

Linda R. Parker

Linda Parker
Forest Ecologist
Chequamegon-Nicolet National Forest

SPACE SCIENCE AND ENGINEERING CENTER

UNIVERSITY of WISCONSIN – MADISON
1225 West Dayton Street
Madison, Wisconsin 53706-1695

15 November 2016

This letter is to express the collaboration, commitment, and support of the University of Wisconsin-Madison, Space Science and Engineering Center (SSEC) for the SSEC Portable Atmospheric Research Center (SPARC) to participate in the NSF proposal, "Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors" including SSEC personnel and SPARC instrumentation.

By signing below (or transmitting electronically), I acknowledge that the SPARC facility is committed to participate as detailed within the proposal entitled "Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors" with Professor Ankur R. Desai as the Principal Investigator. I agree to undertake the tasks associated with me as described in the project description of this proposal, and/or commit to provide or make available the resources designated in the proposal

Sincerely,

Wayne F. Feltz

Wayne F. Feltz
Executive Director-Science
Space Science and Engineering Center
University of Wisconsin-Madison

Karlsruhe Institute of Technology

KIT-Campus Alpin
IMK-IFU: Atmospheric Environmental Research

Institute of Meteorology and Climate Research
Atmospheric Environmental Research (IMK-IFU)
Head: Prof. Dr. H.P. Schmid

Kreuzeckbahnstr. 19
82467 Garmisch-Partenkirchen, Germany

Phone: +49 8821-183-XXX
Fax: +49 8821-735 73
Email: matthias.mauder@kit.edu
Web: www.imk-ifu.kit.edu

From the desk of: Dr. Matthias Mauder
Date: 2017-11-21

KIT-Campus Alpin | IMK-IFU |Kreuzeckbahnstr. 19 | 82467 Garmisch-Partenkirchen, Germany

Prof. Ankur Desai
Ned P. Smith Professorship of Climatology
Dept of Atmospheric and Oceanic Sciences
University of Wisconsin – Madison

UNITED STATES OF AMERICA

Letter of collaboration

Dear Prof. Ankur Desai,

We intend to collaborate with you on the proposed project "Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors" to address questions of crossing scales in heterogeneous terrain and the energy balance closure problem. Firstly, KIT intends to contribute our expertise in large-eddy simulation with the aim of conducting virtual tower measurements in order to quantify those horizontal and vertical flux contributions that cannot be measured. Secondly, KIT intends to contribute ground-based remote sensing of temperature and water vapor throughout the boundary layer by means of a newly developed lidar instrument with full scanning capabilities and two additional Halo Photonics Streamline Doppler lidars in order to determine the 3D wind at arbitrary positions without the assumption of horizontal homogeneity at that height. These activities will be led by Dr. Matthias Mauder and Dr. Hannes Vogelmann. Funding for these important contributions will be requested from the German Science Foundation (DFG), including means for transportation of the instruments, travel, and two PhD positions. The corresponding DFG-proposal will be submitted in parallel to the NSF-proposal coordinated by Prof. Desai. Since the sabbatical of Prof. Desai at KIT-Campus Alpin, a collaboration has developed already on other related topics (e.g. Desai at al., Environ. Res. Lett. 2016), and we look forward to continued successful collaboration.

Yours sincerely,

Matthias Mauder

Dr. Matthias Mauder, Dr. Hannes Vogelmann

SSEC

SPACE SCIENCE AND ENGINEERING CENTER
University of Wisconsin-Madison

20 December 2017

Professor Ankur R. Desai
Ned P. Smith Professorship of Climatology
Department of Atmospheric and Oceanic Sciences
University of Wisconsin-Madison
1225 W. Dayton Street
Madison, WI 53706

RE: NSF Program Announcement: PD 98-1522

Dear Professor Desai,

On behalf of the Wisconsin Global Learning and Observations to Benefit the Environment (GLOBE) Partnership, we are delighted to participate in your proposed NSF project entitled "Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors."

As discussed, the Wisconsin GLOBE Partnership team (myself and Dr. Sanjay Limaye) will provide GLOBE training for up to three school districts in the Butternut, WI region that are proximal to the location for your proposed research efforts. In addition to training and planning for GLOBE protocals, we will also provide follow-up support to the participating teachers and schools to insure successful GLOBE implementation as well as active participation in support of your research. As you are aware, I have established a very good relationship with the science teachers from the Butternut, WI school districts and they are very enthusiastic about the prospect of participating in this unique science educational experience with their students and community.

Thank you for including the Wisconsin GLOBE Partnership in your project. We sincerely look forward to working with you and your team on this exciting opportunity.

Best regards,

Rosalyn A. Pertzborn

Rosalyn A. Pertzborn
Wisconsin GLOBE Partnership Lead
Outreach Program Manager, SSEC

Cc: Dr. Sanjay Limaye

BATTELLE

1 December 2017

Ankur R. Desai, Professor
Ned P. Smith Professorship of Climatology
Atmospheric and Oceanic Sciences
University of Wisconsin – Madison
225 W. Dayton Street
Madison, WI 53706

Dear Dr. Desai:

On behalf of Battelle and the NEON Project, I am writing in regard to your NSF Physical Dynamic Meteorology proposal entitled *"Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors"*. NEON plans to collect extensive observations across the United States that may be relevant to this topic. NEON plans to establish observations at 81 terrestrial and aquatic sites with remote sensing capabilities and data resources to extend from the sites to regional and national scales, including several close to your proposed field experiment location.

Battelle would work together with your proposed effort through a sub-award to Battelle Ecology, Inc. Dr. Metzger will specify combinations of experimental design and hardware requirements that optimize the scientific return on investment of the CHEESEHEAD project. The work will be performed during the planning stage of the CHEESEHEAD field campaign, among others based on existing field and Large Eddy Simulation datasets. Dr. Metzger will develop the foundation for cost-efficient design of this and future measurement campaigns and routine observations. This will be accomplished by evaluating the trade-space "how many towers are enough to observe unbiased surface-atmosphere exchange", with and without invoking the ERF-VCV concept on the CHEESEHEAD dataset. Dr. Metzger will also deliver an ERF-VCV open-source library that permits users of CHEESEHEAD, NEON and other datasets to perform unbiased fusion of ground-based, airborne and satellite-based observations, and to extract their joint information content.

Our estimated cost for this effort is $138,306, inclusive of labor, travel and consumables. Additional details on the budget justification are provided under separate cover. Our NEON technical point of contact is Dr. Stefan Metzger. Our financial and contractual point of contact is Ms. Mary Kaiser. Note that Battelle does not own the property on which NEON infrastructure and observational plots are located. Rather, Battelle obtains rights of access to circumscribed property to develop and maintain NEON's infrastructure and observational plots as defined in formal Land Use Agreements with site hosts. As such, if you require access to any NEON sites, you will need to obtain any required research permits from the site hosts; however, NEON personnel are available to facilitate this process as needed. Please contact Ms. Mary Kaiser for additional information.

Feel free to reach out to Dr. Metzger or Ms. Kaiser if you require further information or assistance. We look forward to working with you.

Sincerely,

Richard Farnsworth, PhD
NEON Program Manager

Stefan Metzger, Ph.D.
Team Lead – Surface-Atmosphere Exchange
National Ecological Observatory Network (NEON)

Adjunct Assistant Professor
Dept. of Atmospheric and Oceanic Sciences, University of Wisconsin

BATTELLE

Date: 2017-12-09

To: NSF PDM

From: Stefan Metzger, Ph.D.

Subject: Letter of collaboration

By signing below (or transmitting electronically), I acknowledge that I am listed as a Co-Investigator on the proposal entitled "Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors (CHEESEHEAD)," with Ankur R Desai as the Principal Investigator. I agree to undertake the tasks associated with me as described in the project description of this proposal, and/or commit to provide or make available the resources designated in the proposal.

Signed: Stefan Metzger Digitally signed by Stefan Metzger Date: 2017.12.09 10:16:00 -06'00'

Organization: Battelle Ecology

From: "Bauder, Steve M - ECB" <Steve.Bauder@ecb.org>
Subject: RE: Support letter request for WLEF research project
Date: December 9, 2016 at 1:41:55 PM CST
To: 'Ankur Desai' <desai@aos.wisc.edu>
Cc: "Baun, Terry M - ECB" <Terry.Baun@ecb.org>, "Ayers, Jeff D - ECB" <Jeff.Ayers@ecb.org>, "Strand, Roger I - ECB" <Roger.Strand@ecb.org>, "Siroin, Doug A - ECB" <DougA.Siroin@ecb.org>, "Guy, Glenn T - ECB" <Glenn.Guy@ecb.org>, "Hoenecke, Mark R - ECB" <Mark.Hoenecke@ecb.org>
Resent-From: desai@aos.wisc.edu

Sorry for the delay, here you go Dr. Desai:

ECB is willing to collaborate with NOAA and the UW on this project. Conditions include:

· meet our site grounding requirements for equipment located outside of the building/tower grounding system, including a local grounding electrode at each facility and a direct grounding connection to site grounding system with a minimum #6 bare copper that is direct buried between the locations (this usually runs with any power conductors);
· pay the cost for power consumed;
· clean up the site and remove all above ground conductors and temporary equipment on the tower;
· Installation and removal of the shielded fiber optic line and temperature sensor to be performed under the direct supervision of ECB personnel and in accordance with industry standard installation and attachment methods;
· Tower contractor must provide insurance certificate and be approved by ECB prior to commencement of work;
· Failure to remove tower appurtenances and on-ground facilities by October 31, 2018 will result in a negotiated penalty
· Temporary rent increase to be negotiated

Steve Bauder
Director of Field Engineering
Wisconsin Public Broadcasting
Educational Communications Board

Madison, WI
Office: 608-264-9674
Cell: 715-556-0823

UWMILWAUKEE

Office of Sponsored Programs

3203 N. Downer Ave.
Mitchell Hall 273
P.O. Box 340
Milwaukee, WI.
53201-0340
414 229-3332 phone
414 229-5000 fax
http://uwm.edu/officeofresearch/osp/

October 16, 2017

Ankur R. Desai, Professor
Ned P. Smith Professorship of Climatology
Atmospheric and Oceanic Sciences
University of Wisconsin - Madison
1225 W. Dayton Street
Madison, WI 53706

RE: UWM Proposal Number 113722-DH

Dear Dr. Desai:

This serves as confirmation that the University of Wisconsin-Milwaukee (UWM) is willing to collaborate with the University of Wisconsin-Madison in a joint proposal entitled, "Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors" that will be submitted to the National Science Foundation. Dr. Mark D. Schwartz, UWM Department of Geography, will serve as Principal Investigator at UWM.

The proposed project covers the period July 1, 2019 through June 30, 2020 with the sub-award budget totaling $80,274. This budget includes indirect costs calculated at 52.0% of MTDC based on the UWM's DHHS rate agreement dated June 26, 2017.

The University of Wisconsin-Milwaukee's participation is hereby endorsed on behalf of the Board of Regents of the University of Wisconsin System. The appropriate programmatic and administrative personnel of UWM involved in this grant application have reviewed our participation and are prepared to establish the necessary inter-institutional agreement(s) consistent with our status as a public university of the State of Wisconsin.

If you have any technical questions, please contact Dr. Schwartz at (414) 229-3740 or mds@uwm.edu. Any contractual questions may be addressed to Dave Harris at (414) 229-5667 or dnh@uwm.edu.

Sincerely,

Dorothy Johnson

Dorothy Johnson
Associate Director

Cc: Dr. Mark D. Schwartz

Chequamegon
Class ACT
Charter School

Chequamegon School District, 420 North 9th St, Park Falls, WI 54552
Phone: 715-762-2474 ext 2264
classactcharterschool.weebly.com

Nov. 30, 2016

To: NSF Physical and Dynamic Meteorology

Dear NSF,

By signing below, I acknowledge that I am listed as a supporting outreach partner on the proposal entitled "Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors," with Ankur R Desai as the Principal Investigator

Class ACT Charter school, a charter high school within the Chequamegon School district is located in the city of Park Falls, or about 11 miles from the core experiment sight. As a Project Based Learning School, Class ACT students often engage in hands on research and experiments as part of their learning and will will arrange for our teachers and students to be available to cooperate with Prof. Desai as we gain experience and training during our involvement with his project.

We look forward to collaborating with Prof. Desai and "getting our hands dirty" as we learn by doing throughout this project.

Sincerely,

Travis Augustine
Teacher/Advisor
Class ACT Charter School
715-762-2474 ext 2264
taugustine@csdk12.net

2015-12-17

NORTHLAND COLLEGE

THINK DIFFERENTLY LIVE DIFFERENTLY

To: NSF PDM

From: Dr. Jonathan G. Martin, Assistant Professor of Natural Resources/Forestry: Northland College
Leslie Alldritt, Vice President of Academic Affairs, Dean of Faculty: Northland College

Northland College is proud to serve as a collaborator with Ankur R Desai on the attached proposal. This endeavor with not only provide critical data in support of understanding the role of diverse forest types in the flow of energy and water but it will also serve as an unparalleled educational and mentorship experience for the diverse undergraduates in the meteorology and natural resource programs at Northland College.

By signing below (or transmitting electronically), I acknowledge that I am listed as a collaborator on the proposal entitled "Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors (CHEESEHEAD)," with Ankur R Desai as the Principal Investigator. I agree to undertake the tasks associated with me as described in the project description of this proposal, and/or commit to provide or make available the resources designated in the proposal. In particular, we will assist Dr. Desai in selection and mentoring support of undergraduate students interested in participating in the field experiment.

Sincerely,

2015/12/17

Jonathan G. Martin, PhD
Assistant Professor of Natural Resources/Forestry
Northland College
1411 Ellis Avenue
Ashland, WI 54806
jmartin@northland.edu
715-682-1270

Leslie D. Alldritt

Leslie Alldritt
Vice President of Academic Affairs
Dean of Faculty
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1411 Ellis Avenue
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