Final Report

Project Title: "Confronting Models with Regional CO_2 Observations"

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This final report is divided into six sections

- A summary of objectives, goals, and accomplishments
- A summary of CLM4.5 modeling efforts in forest ecosystems and publication products
- A summary of modeling efforts to take our continuously monitored CO2 data form mountain peaks and invert these data into regional carbon fluxes and publication products
- A summary of urban CO2 observations and publication products
- data collection, model development and simulations, group meetings, additional collaborations, publications, and plans for the upcoming year.

1.0 Summary

This research addressed an important DOE science area: *the role of natural disturbances in carbon cycling*. Our project included both (a) modeling and field measurements and (b) strengthened ties between DOE national laboratories and universities which continue after the project was completed. Our focus was on understanding the consequences of *drought and emissions (fire and urban)* to atmospheric trace gas composition (carbon dioxide, carbon monoxide, and methane), including both concentration and stable isotope composition. Measurements of these atmospheric gases were used to infer the spatial and temporal patterns of both sources and sinks in the carbon cycle. As part of this effort, we maintained two long-term monitoring networks along a geographic gradient in Utah and Colorado that spans montane forests, urban regions, and oil/gas fields. In this research, we expanded on a well-accepted atmospheric model (STILT-WRF) as a tool to evaluate fluxes in CLM/CESM-related models. We used the STILT model to provide a strong linkage between point atmospheric measurements and the surface parameterizations/emissions that are part of the CLM/CESM models. Overall, this project *benefited and supported the DOE Long Term Mission and Goals* in four distinct ways: (a) testing of carbon cycle models, (b) testing and evaluating model mechanisms whereby factors in CLM influence trace gas composition in CESM, (c) acquiring high-quality, long-term data on concentrations of carbon dioxide in western USA ecosystems, and (d) by reducing uncertainties associated with the representation of climate-carbon feedbacks in Earth System models through the development of new methods for evaluating model performance. One postdoctoral associate (Henrique Duarte) and one Ph.D. student (Darek Malia) were trained with this support. Nine peer-reviewed publications and 14 poster presentations were produced with support from this project.

This proposal addresses a specific science area in the RFP: ***the role of natural disturbances in carbon cycling***. In particular, we will focus on the consequences of ***drought and fire*** at landscape to regional scales for atmospheric trace gas concentration and stable isotope composition (CO_2, CO, and CH_4). We seek to expand on the well accepted atmospheric Stochastic Time-Inverted Lagrangian Transport (STILT) model coupled to the Weather Research and Forecasting (WRF) model as a tool to evaluate stable isotope fluxes in CLM/CESM-related models through existing, long-term data sets and field campaigns where high-precision trace gas concentration and isotope measurements can be made along gradients and transects. Given the confounding impacts of anthropogenic trace gas emissions on landscape-to-regional atmospheric observations, we will also measure and parameterize isotopic characteristics of CO_2, CO, and

CH_4 from anthropogenic or forest sources in order to allow us the opportunity to partition atmospheric trace gases into natural and anthropogenic sources.

2.0 Project objectives and goals

Project objectives: The objectives of the proposed research were to

- Incorporate carbon isotope fluxes into STILT-WRF so that different biosphere-atmosphere fluxes from drought, fire, and urban emissions can be appropriately partitioned into source components.
- Test existing parameterization of isotopes and fluxes in CLM4 through long-term observations and field campaign measurements (biogeochemical, photosynthesis, soil respiration processes).
- Apply STILT as a bridge between ecosystem scale models and global models (e.g., CESM); serve to constrain interpretations; use STILT to provide strong linkage between point atmospheric measurements to surface parameterizations/emissions.
- Develop the tools/products that will allow us to partition changes in CO_2 fluxes in CESM into natural (drought and fire related) and anthropogenic components
- Predict with CLM spatial patterns of trace gases and test predictions using transect trace-gas observation that describe patterns between long-term measurement sites.

Project approaches: We will use these approaches:

- Data collection - continue ongoing continuous atmospheric CO_2 measurements at long-term sites and supplement with campaign-focused CO_2, CO, and CH_4 transect measurements.
- Modeling - add isotope simulation capacity to STILT-WRF so that regional flux inversions and source partitioning are possible. Improve existing isotope capabilities in CLM4 where necessary to connect with the available observational data.
- Model testing - use STILT as a connection/testing approach to link land ecosystem and atmospheric model components of CESM.
- Synthesis - link data with models to improve our understanding of the role of drought, urban emissions, and fire impacts on the terrestrial carbon cycle.

3.0 Data collections

A critical element of this project was to continue long-term atmospheric carbon dioxide measurements in the Rocky Mountain and Intermountain West regions. Four CO2 observatories were maintained throughout the course of the DOE support; three remain operational today and complement other observatories in the Intermountain West network maintained by co-PI John Lin in Atmospheric Sciences at the University of Utah (http://air.utah.edu). Continuous carbon dioxide collections continued along the transect as described in the original proposal and as shown below in Figure 1.

The Salt Lake Valley urban CO2 observatory is the longest-running, continuously-operational observatory in the United States today (Mitchell et al., 2016; Lin et al., 2018). Data are available

online at http://air.utah.edu. The data sets were critical to the regional carbon cycle modeling studies completed during this project and summarized in the next sections.

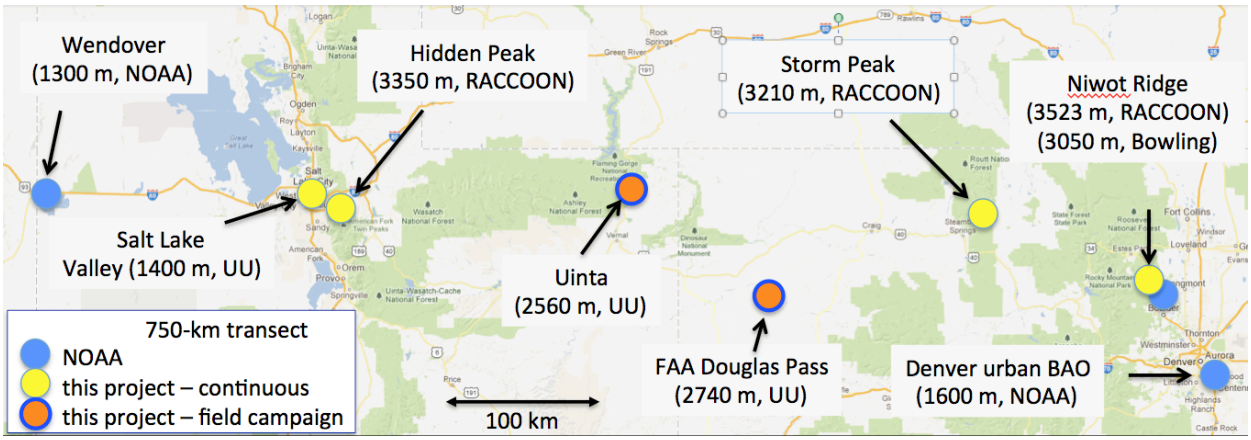

Figure 1. Shown are the 4 continuous CO_2 observation sites in this study (yellow), 2 campaign mode measurement sites (orange), and 3 NOAA-maintained CO_2 measurement sites (blue).

4.0 CLM modeling

A major goal of this project was to (a) incorporate carbon isotopes into CLM4.5 as a constraint on model predictions and (b) to explore regional carbon cycle predictions for ecosystems exposed to drought, fire, and urban emissions. A summary of that effort follows from Duarte et al. (2017).

Droughts in the western United States are expected to intensify with climate change. Thus, an adequate representation of ecosystem response to water stress in land models is critical for predicting carbon dynamics. The goal of the Duarte et al (2016) study was to evaluate the performance of the Community Land Model (CLM) version 4.5 against observations at an old-growth coniferous forest site in the Pacific Northwest region of the United States (Wind River AmeriFlux site), characterized by a Mediterranean climate that subjects trees to water stress each summer. CLM was driven by site-observed meteorology and calibrated primarily using parameter values observed at the site or at similar stands in the region. Key model adjustments included parameters controlling specific leaf area and stomatal conductance. Default values of these parameters led to significant underestimation of gross primary production, overestimation of evapotranspiration, and consequently overestimation of photosynthetic 13C discrimination, reflected in reduced 13C/12C ratios of carbon fluxes and pools. Adjustments in soil hydraulic parameters within CLM were also critical, preventing significant underestimation of soil water content and unrealistic soil moisture stress during summer. After calibration, CLM was able to simulate energy and carbon fluxes, leaf area index, biomass stocks, and carbon isotope ratios of carbon fluxes and pools in reasonable agreement with site observations. Overall, the calibrated CLM was able to simulate the observed response of canopy conductance to atmospheric vapor pressure deficit (VPD) and soil water content, reasonably capturing the impact of water stress on ecosystem functioning. Both simulations and observations indicate that stomatal response from water stress at Wind River was primarily driven by VPD and not soil moisture. The calibration

of the Ball–Berry stomatal conductance slope (mbb) at Wind River aligned with findings from recent CLM experiments at sites characterized by the same plant functional type (needleleaf evergreen temperate forest), despite significant differences in stand composition and age and climatology, suggesting that CLM could benefit from a revised mbb value of 6, rather than the default value of 9, for this plant functional type. Conversely, Wind River required a unique calibration of the hydrology submodel to simulate soil moisture, suggesting that the default hydrology has a more limited applicability. The Duarte et al (2016) study demonstrated that carbon isotope data can be used to constrain stomatal conductance and intrinsic water use efficiency in CLM, as an alternative to eddy covariance flux measurements. It also demonstrated that carbon isotopes can expose structural weaknesses in the model and provide a key constraint that may guide future model development.

Two additional peer-reviewed publications on this topic resulted from DOE support, resulting in three solid contributions. In addition, 14 posters were presented at national meetings and conferences (see Section 7).

- Duarte HF, Raczka BM, Ricciuto DM, Lin JC, Koven CD, Thornton PE, Bowling DR, Lai C-T, Bible KJ, & Ehleringer JR (2017) Evaluating the Community Land Model (CLM 4.5) at a coniferous forest site in northwestern United States using flux and carbon isotope measurements. *Biogeosciences* 14: 4315–4340. https://doi.org/10.5194/bg-14-4315-2017
- Raczka B, Duarte HF, Koven CD, Ricciuto D, Thornton PE, Lin JC, & Bowling DR (2016) An observational constraint on stomatal function in forests: Evaluating coupled carbon and water vapor exchange with carbon isotopes in the Community Land Model (CLM 4.5). *Biogeosciences* 13: 5183–5204. https://doi.org/10.5194/bg-13-5183-2016
- Raczka B, Duarte HF, Koven CD, Ricciuto D, Thornton PE, Lin JC, & Bowling DR (2016) An observational constraint on stomatal function in forests: evaluating coupled carbon and water vapor exchange with carbon isotopes in the Community Land Model (CLM 4.5). *Biogeosciences Discussions*. https://doi.org/10.5194/bg-2016-73

5.0 Evaluating carbon cycle sink strength through regional CO_2 observations

A major carbon cycle modeling effort revolved around sustained, high-precision CO_2 observations globally of the kind sustained through DOE support of this project (see Section 3). In this project, several studies were conducted to estimate regional carbon fluxes based on CO_2 observations and then to evaluate patterns of regional and global changes in CO_2 associated with drought. These studies resulted in three peer-reviewed publications.

- Duarte HF, Raczka BM, Bowling DR, Wang A, & Lin JC (2018) How can biosphere models grow enough vegetation biomass in the mountains of western United States? Implications of meteorological forcing. Submitted to the *Journal of Geophysical Research: Biogeosciences*.
- Lin, JC, Mallia DV, Wu D, Stephens BB (2017) How can mountaintop CO_2 observations be used to constrain regional carbon fluxes? Atmospheric Chemistry and Physics 17:5561-5581. Doi:10.5194/acp-17-5561-2017.

- Peters W, van der Velde IR, van Schaik E, Miller JB, Ciais P, Duarte HF, van der Laan-Luijkx IT, van der Molen MK, Scholze M, Schaefer K, Vidale PL, Verhoef A, Wårlind D, Zhu D, Tans PP, Vaughn B, & White JWC (2018) Increased water-use efficiency and reduced CO_2 uptake by plants during droughts at a continental scale. *Nature Geoscience* 11: 744–748. https://doi.org/10.1038/s41561-018-0212-7

6.0 Carbon cycle source and sink relationships in urban ecosystems

Although there has been a historical tendency for DOE to focus on natural ecosystems instead of managed or urban ecosystems, this project nevertheless included a component to evaluate drivers of carbon sources and sinks from urban systems based on trace gas concentration and stable isotope ratio measurements. Mitchell et al (2018) synthesized the results of long-term CO_2 observations on fluxes in different urban forms, providing a strong foundation where it becomes possible to link urban and natural ecosystem observations. Below is a summary from Mitchell et al (2018).

Cities are concentrated areas of CO_2 emissions and have become the foci of policies for mitigation actions. However, atmospheric measurement networks suitable for evaluating urban emissions over time are scarce. Mitchell et al (2018) presented a unique long-term (decadal) record of CO_2 mole fractions from five sites across Utah's metropolitan Salt Lake Valley. They examined "excess" CO_2 above background conditions resulting from local emissions and meteorological conditions. Mitchell et al. (2018) ascribed CO_2 trends to changes in emissions, since we did not find long term trends in atmospheric mixing proxies. Three contrasting CO_2 trends emerged across urban types: negative trends at a residential-industrial site, positive trends at a site surrounded by rapid suburban growth, and relatively constant CO_2 over time at multiple sites in the established, residential, and commercial urban core. Analysis of population within the atmospheric footprints of the different sites revealed approximately equal increases in population influencing the observed CO_2, implying a nonlinear relationship with CO_2 emissions: Population growth in rural areas that experienced suburban development was associated with increasing emissions while population growth in the developed urban core was associated with stable emissions. Four state-of-the-art global-scale emission inventories also have a nonlinear relationship with population density across the city; however, in contrast to the Mitchell et al (2018) observations, they all have nearly constant emissions over time. The Mitchell et al (2018) results indicate that decadal scale changes in urban CO_2 emissions are detectable through monitoring networks and constitute a valuable approach to evaluate emission inventories and studies of urban carbon cycles.

The studies focusing on carbon source/sink relationships in urban systems resulted in three peer-reviewed publications:

- Gorski, G., C. Strong, S.P. Good, R. Bares, J.R. Ehleringer, and G.J. Bowen. 2015. Vapor hydrogen and oxygen isotopes reflect water of combustion in the urban atmosphere. Proceedings of the National Academy of Sciences USA 112:3247-3252. Doi:10.1073/pnas.1424728112.

- Lin, J., L. Mitchell, E. Crossman, D. Mendoza, M. Buchert, R. Bares, B. Fasoli, D. Bowling, D. Pataki, D. Catherine, C. Strong, K. Gurney, R. Patarasuk, M. Baasandorj, A. Jacques, S. Hoch, J. Horel, and J.R. Ehleringer. 2018. CO_2 and carbon emissions from cities: linkages to air quality, socioeconomic activity and stakeholders in the Salt Lake City urban area. Bulletin of the American Meteorological Society doi:10.1175/BAMS-D-17.0037.1
- Mitchell, L.E., J.C. Lin, D.R. Bowling, D.E. Pataki, C. Strong, A.J. Schauer, R. Bares, S.E. Bush, B.B. Stephens, D. Mendoza, D. Mallia, L. Holland, K.R. Gurney, and J.R. Ehleringer. 2018. Long-term urban carbon dioxide observations reveal spatial and temporal dynamics related to urban characteristics and growth. Proceedings of the National Academy of Sciences USA 115:2912-2917. DOI:10.1073/pnas.1702393115

7.0 Publications and presentations arising from this research

Articles (9)

Duarte HF, Raczka BM, Bowling DR, Wang A, & Lin JC (2018) How can biosphere models grow enough vegetation biomass in the mountains of western United States? Implications of meteorological forcing. Submitted to the *Journal of Geophysical Research: Biogeosciences*.

Duarte HF, Raczka BM, Ricciuto DM, Lin JC, Koven CD, Thornton PE, Bowling DR, Lai C-T, Bible KJ, & Ehleringer JR (2017) Evaluating the Community Land Model (CLM 4.5) at a coniferous forest site in northwestern United States using flux and carbon isotope measurements. *Biogeosciences* 14: 4315–4340. https://doi.org/10.5194/bg-14-4315-2017

Gorski, G., C. Strong, S.P. Good, R. Bares, J.R. Ehleringer, and G.J. Bowen. 2015. Vapor hydrogen and oxygen isotopes reflect water of combustion in the urban atmosphere. Proceedings of the National Academy of Sciences USA 112:3247-3252. Doi:10.1073/pnas.1424728112.

Lin, JC, Mallia DV, Wu D, Stephens BB (2017) How can mountaintop CO_2 observations be used to constrain regional carbon fluxes? Atmospheric Chemistry and Physics 17:5561-5581. Doi:10.5194/acp-17-5561-2017.

Lin, J., L. Mitchell, E. Crossman, D. Mendoza, M. Buchert, R. Bares, B. Fasoli, D. Bowling, D. Pataki, D. Catherine, C. Strong, K. Gurney, R. Patarasuk, M. Baasandorj, A. Jacques, S. Hoch, J. Horel, and J.R. Ehleringer. 2018. CO_2 and carbon emissions from cities: linkages to air quality, socioeconomic activity and stakeholders in the Salt Lake City urban area. Bulletin of the American Meteorological Society doi:10.1175/BAMS-D-17.0037.1

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Peters W, van der Velde IR, van Schaik E, Miller JB, Ciais P, Duarte HF, van der Laan-Luijkx IT, van der Molen MK, Scholze M, Schaefer K, Vidale PL, Verhoef A, Wårlind D, Zhu D, Tans PP, Vaughn B, & White JWC (2018) Increased water-use efficiency and reduced CO_2 uptake by

plants during droughts at a continental scale. *Nature Geoscience* 11: 744–748. https://doi.org/10.1038/s41561-018-0212-7

Raczka B, Duarte HF, Koven CD, Ricciuto D, Thornton PE, Lin JC, & Bowling DR (2016) An observational constraint on stomatal function in forests: Evaluating coupled carbon and water vapor exchange with carbon isotopes in the Community Land Model (CLM 4.5). *Biogeosciences* 13: 5183–5204. https://doi.org/10.5194/bg-13-5183-2016

Raczka B, Duarte HF, Koven CD, Ricciuto D, Thornton PE, Lin JC, & Bowling DR (2016) An observational constraint on stomatal function in forests: evaluating coupled carbon and water vapor exchange with carbon isotopes in the Community Land Model (CLM 4.5). *Biogeosciences Discussions*. https://doi.org/10.5194/bg-2016-73

Presentations at Professional Meetings (14)

Duarte HF, Lin JC, Mallia DV, Wu D, Stephens BB, Raczka BM, Ricciuto DM, Koven CD, Thornton PE, Bowling DR, & Ehleringer JR (2017) Confronting the Community Land Model against atmospheric CO_2 and biospheric datasets in the western U. S. In: *U.S. Department of Energy's 2017 Environmental System Science (ESS) PI Meeting*, 25–26 April 2017, Potomac, MD. *[poster presentation]*

Duarte HF, Lin JC, Mallia DV, Wu D, Stephens BB, & Ehleringer JR (2016) Constraining modeled biospheric CO_2 fluxes in the Rocky Mountains with atmospheric observations: a WRF-STILT-CLM framework. In: *American Meteorological Society's 3rd Conference on Biogeosciences/32nd Conference on Agricultural and Forest Meteorology/22nd Symposium on Boundary Layers and Turbulence*, 20–24 June 2016, Salt Lake City, UT. *[oral presentation]*

Duarte HF, Lin JC, Mallia DV, Wu D, Stephens BB, Raczka BM, Ricciuto DM, Koven CD, Thornton PE, Bowling DR, & Ehleringer JR (2016) Scaling biospheric CO_2 fluxes in the Western U.S. from site to region using the Community Land Model. In: *U.S. Department of Energy's 2016 Environmental System Science (ESS) PI Meeting*, 26–27 April 2016, Potomac, MD. *[poster presentation]*

Raczka B, Duarte HF, Koven C, Ricciuto D, Thornton P, Lin JC, & Bowling DR (2016) An observational constraint on stomatal function in forests: evaluating coupled carbon and water vapor exchange with carbon isotopes in the Community Land Model (CLM 4.5). In: *U.S. Department of Energy's 2016 Environmental System Science (ESS) PI Meeting*, 26–27 April 2016, Potomac, MD. *[poster presentation]*

Raczka B, Duarte HF, Koven C, Ricciuto D, Thornton P, Lin JC, & Bowling DR (2016) An observational constraint on stomatal function in forests: evaluating coupled carbon and water vapor exchange with carbon isotopes in CLM 4.5. In: *CESM Joint Land Model and Societal Dimensions Working Group Meeting*, 8–10 February 2016, Boulder, CO. *[oral presentation]*

Duarte HF, Raczka BM, Koven CD, Ricciuto DM, Lin JC, Bowling DR, & Ehleringer JR (2015) Assessing ecosystem drought response in CLM 4.5 using site-level flux and carbon-isotope measurements: results from a Pacific Northwest coniferous forest. In: *2015 American*

Geophysical Union Fall Meeting, 14–18 December 2015, San Francisco, CA. *[poster presentation]*

Raczka BM, Duarte HF, Koven CD, Ricciuto DM, Thornton PE, Lin JC, & Bowling DR (2015) Simulating photosynthetic ^{13}C fractionation at a western subalpine forest for seasonal and multi-decadal time periods with the Community Land Model (CLM 4.5). In: *2015 American Geophysical Union Fall Meeting*, 14–18 December 2015, San Francisco, CA. *[poster presentation]*

Raczka B, Duarte HF, Koven C, Lin J, Ricciuto D, Stephens B, Thornton P, & Bowling D (2015) Testing the Community Land Model (CLM 4.5) 13C isotope simulations against high resolution observations within a subalpine forest at Niwot Ridge, Colorado. In: *U.S. Department of Energy's 2015 Environmental System Science (ESS) PI Meeting*, 28–29 April 2015, Potomac, MD. *[poster presentation]*

Duarte HF, Lin JC, Ehleringer JR, Raczka BM, Bowling DR, & Ricciuto DM (2015) Evaluating the performance of the Community Land Model (CLM4.5) for a western US coniferous forest under annual drought stress. In: *CESM Land Model and Biogeochemistry Working Group Meetings*, 2–4 March 2015, Boulder, CO. *[poster presentation]*

Raczka B, Duarte HF, Koven C, Lin J, Ricciuto D, Stephens B, Thornton P, & Bowling D (2015) Testing the Community Land Model (CLM4.5) C13 isotope simulations for a subalpine forest at Niwot Ridge, Colorado. In: *CESM Land Model and Biogeochemistry Working Group Meetings*, 2–4 March 2015, Boulder, CO. *[poster presentation]*

Duarte HF, Lin JC, Ehleringer JR, Raczka BM, Bowling DR, Ricciuto DM (2015) Evaluating the performance of the Community Land Model (CLM4.5) for a western US coniferous forest under annual drought stress. In: *5th NACP PI Meeting & Ameriflux PI Meeting*, 26–29 January 2015, Washington, DC. *[poster presentation]*

Lin J, Stephens B, Mallia D, Duarte HF, Urbanski S, Ehleringer J, & Wu D (2015) How can we constrain regional carbon fluxes in the American Rockies from atmospheric measurements? In: *5th NACP PI Meeting & Ameriflux PI Meeting*, 26–29 January 2015, Washington, DC. *[poster presentation]*

Raczka B, Duarte HF, Koven C, Lin J, Ricciuto D, Stephens B, Thornton P, & Bowling D (2015) Testing the Community Land Model (CLM 4.5) ^{13}C isotope simulations against high resolution observations within a sub-alpine forest at Niwot Ridge, Colorado. In: *5th NACP PI Meeting & Ameriflux PI Meeting*, 26–29 January 2015, Washington, DC. *[poster presentation]*

Duarte HF, Lin JC, & Ehleringer JR (2014) Evaluating the performance of the Community Land Model (CLM4.5) for a western US coniferous forest under annual drought stress. In: 2014 *American Geophysical Union Fall Meeting*, 15–19 December 2014, San Francisco, CA. *[poster presentation]*