The Final Report for the Project

Using the GoAmazon-CHUVA measurements to understand what causes the biases in the onset of the rainy season in Amazonia in climate models

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1. Objectives and Proposed Tasks of the Project

This project aims to clarify the underlying causes of the underestimation of changes of the rainy season onset over the Amazon and its sensitivity to anthropogenic forcing. The main hypothesis is that such a model bias is due to an inadequate representation of the types of convection, especially related to convective anvils and shallow convection, ~~(i.e., maritime versus continental)~~ and ~~their relationships to~~the influences of aerosols and land surface on convection and its diabatic heating. Three tasks are proposed as described below.

- Task-1: Develop working hypotheses for the analysis of upcoming GoAmazon and CHUVA data
- Task-2: Understand the processes that control the impacts of land surface, aerosols, and large-scale atmospheric circulation on the frequency, type, intensity, and life cycle of the convective systems using GoAmazon and CHUVA data
- Task-3: Use CESM/BESM model experiments to establish sensitivities to model structure

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Summary of the activities and accomplishment: With the support of this DOE project, this investigation team has published 19 peer reviewed papers, one book chapter, participated in 4 DOE PI meetings. The PI has given 28 invited and keynote presentations and seminars based on the results of this project. The PI has also served on the Committee of Visitors for DOE Climate and Environmental Sciences Division, review panels for DOE proposals.

2. Publications from This Project

We have published 19 peer reviewed papers with the support from this project, including three papers in PNAS and two in GRL and one in the Frontier of Ecology and the Environment. Wright et al. (2017, PNAS) showed unequivocally that moisture during the early dry to wet transition comes from plants, but not from oceans in the PI's corresponding author paper (Wright et al. 2017), through innovative use of satellite measurements of atmospheric water vapor deuterium, solar induced fluorescence, along with climate measurements of clouds, surface radiation, rainfall, and a water isotope mixing model. The journal *Science* (August 4, 2017) reported this work as a "smoking gun" and "a clear fingerprint" for the contribution of plants to monsoon processes.

One of the main challenges for validating the hypothesis that aerosols can delay precipitation and thus increase cloud lifetime, the foundation for the aerosol second indirect effect on clouds, is lack of adequate observations that connect aerosols with cloud lifetime at climate scale. Dr. Fu co-located a suite of polar-orbital satellite observations with the convective tracking data for thousands of convective systems over tropical continents, and combined four different sensors (CloudSat, Aura/MLS,

CALIPSO, and TRMM) to capture changes of small, medium and large ice particles in convective cores and anvils. Based on this novel approach, she and her students demonstrated that, on climate scale, precipitation delay and ice presence increase in convective anvils prolong the mature and decay phases of the convective life cycle, and substantially increase total rainfall during the convective lifetime (Chakraborty et al. 2016, PNAS, 2018 GRL). As commented by Daniel Rosenfeld, a reviewer of the paper "This study is the first that I am aware of that quantifies the impact of aerosols on the longevity of deep tropical convective storms, almost three decades after Albrecht (1989) did the same for shallow marine clouds. This is a significant advancement."

With the support of this project, we have clarified the environmental conditions central for shallow to deep convection transition using the GoAmazon data (Zhuang et al. 2016; Wright et al. 2017, Marengo et al. 2017). We have further broadened our analysis to six DOE ARM field sites/campaigns to evaluate the changes of environmental conditions for deep convection across different climate zones in the tropics and subtropics (Zhuang et al. 2018). We have also identified the causes of the dry and diurnal cycle biases of rainfall over the Amazon using six versions of CAM5/SPCAM5 simulations with different treatments of cloud physics and aerosols-cloud interaction and atmospheric boundary layer in collaboration with Drs. Steve Ghan and Ruby Leung at the DOE Pacific North Laboratory. We have also tested the influences of different vegetation types on rainfall over Amazonia (Gu et al. 2016, Alves et al. 2017). The publications from this project are listed below:

Papers published:

1. Shi, M. J., J. J. Liu, J. R. Woden, A. A. Bloom, S. Wong, **R. Fu**, 2019: Can the vegetation legacy effects of Amazonian droughts delay the dry to wet seasonal transition? A case study of the 2005 Amazonian drought, In Press, *GRL*.
2. Costa, M. H., L. C. Fleck, A. S. Cohn, G. M. Abrahão, P. M. Brando, M. T. Coe, **R. Fu**, D. Lawrence, G. F. Pires[1], R. Pousa, B. S. Soares-Filho, 2018: Climate risks to Amazon agriculture raise awareness to conserve local forests, Frontier of Ecology and the environment, Accepted
3. Chakraborty+, S., **R. Fu**, S. T. Massie, D. Rosenfeld, J. Marengo, 2018: Can aerosols enhance the total rainfall of the mesoscale convective systems? *GRL*, 45, 13,099-13,106, **https://doi.org/10.1029/2018GL080371**.
4. Chakraborty+, S., K. Schiro, R. Fu, D. Neelin, 2018: On the role of aerosols, humidity, and vertical wind shear in the transition of shallow to deep convection in the Green Ocean Amazon, ACP, 18, 11135-11148, https://doi.org/10.5194/acp-18-11135-2018.
5. Zhuang Y*, **Fu R**, Wang H. How do environmental conditions influence vertical buoyancy structure and shallow-to-deep convection transition across different climate regimes?. *J. Atmo. Sci*, 75, 1909-1932, *https://doi.org/10.1175/JAS-D-17-0284.1*.
6. Zhao B, Liou K.N., Gu Y., Jiang J.H., Li QB, Q.B. Li, **Fu R**., Huang L., Liu X.H., Shi X.G., Su H., C. L. He. 2018: Impact of aerosols on ice crystal size. Atmospheric Chemistry and Physics. 18, 1065-1078.

7. Zhang*, K., **R. Fu**, M. J. Shaikh, S. Ghan, M. H.Wang, R. Leung, R. E. Dickinson, J. Marengo, 2017: Influence of superparameterization and a higher-Order turbulence closure on rainfall bias over Amazonia in Community Atmosphere Model Version 5, JGR-Atmos. Vol. 122, Iss. 18, 9879-9902. 10.1002/2017JD026576.
8. Bowerman A.R., **R. Fu** (Corresponding author), L. Yin, D. N. Fernando, P. A. Arias, and R. E. Dickinson, 2017, An influence of southern hemispheric cold surge on the North Atlantic through a shallow atmospheric circulation. JGR-atmo. Vol 122, Iss 19, 10,135-10,148.
9. Wright, J. S., **R. Fu** (corresponding author), J. Worden, S. Chakraborty, N. Clinton, C. Risi, Y. Sun, & L. Yin, 2017: A rainforest-initiated wet season over the southern Amazon, *PNAS*, July 20, doi.org/10.1073/pnas.1621516114
10. Marengo, J., G. F. Fisch, L. M., Alves, N. V. Sousa, **R. Fu**, Y. Z., Zhang, 2017: Meteorological context of the onset and end of the rainy season in Central Amazonia during 2014-15 Go-Amazon Field Experiment, *ACP*, Vol 17, Iss. 12, 7671-7681.
11. Zhuang*, Y. Z., **R. Fu**, J. A. Marengo and H. Q. Wang, 2017: seasonal variation of shallow-to-deep convection transition and its link to the environmental conditions over central amazon, *JGR-Atmo.*, vol 122, iss 5, 2649-2666, doi: 10.1002/2016jd025993.
12. Alves, L., Marengo, J. , Fu, R. and Bombardi, R. (2017) Sensitivity of Amazon Regional Climate to Deforestation. *American Journal of Climate Change*, **6**, 75-98. doi: 10.4236/ajcc.2017.61005.
13. Gu, Yu, K. N. Liou, J. H. Jiang, **R. Fu**, Sarah Lu, and Y. Xue. 2016 "A GCM investigation of impact of aerosols on the precipitation in Amazon during the dry to wet transition." *Climate Dynamics*, 1-12.
14. Chabraborty, S.*, **R. Fu**, S. Massie, G. Stephens, 2016: "Relative influence of the meteorological conditions and aerosols on the lifetime of the mesoscale convective systems", *PNAS*, doi/10.1073/pnas.1601935113.
15. Bi, J, Knyazikhin Y, S. Choi, T. Park, J. Barichivich, P. Ciais, **R. Fu**, S. Ganguly, F. Hall, T. Hilker, A. Huete, M. Jones, J. Kimball, A. I. Lyapustin, M. Mõttus, R. R. Nemani, S. Piao, B. Poulter, S. R. Saleska, S. S. Saatchi, L. Xu, L.M. Zhou, and R. B. Myneni, 2014: "Sunlight mediated seasonality in canopy structure and photosynthetic activity of Amazonian rainforests" *Environ Res. Lett*., 10.6 (2015): 064014.
16. Gao H+. L. S. Zhang, **R. Fu**, W. H. Li, R. E. Dickinson, 2015: Inter-annual variation of the surface temperature of tropical forests from satellite observations, *Advances in Meteorology*, Article ID 564126.
17. **Fu, R**., 2015: An Accelerated Drying in the Tropics by Global Warming, *PNAS,*| March 24, 2015 | vol. 112 | no. 12 | 3593–3594.
18. Arias, P. A.*, **R. Fu,** C. Vera, M. Rojas, 2015: A correlated shortening of the North and South American monsoon seasons in the past few decades, *Climate Dynamics*. **45,** Issue 11 (2015), Page 3183-3203 (10.1007/s00382-015-2533-1).
19. Yin, L.*, **R. Fu**, Y. F. Zhang, P. A. Arias, D. N. Fernando[a], W.H. Li, K. Fernandes, A. R. Bowerman, 2014: What controls the interannual variation of the wet season onsets over the Amazon? *J. Geophys. Res. Atmos*., 119, 2314–2328, doi:10.1002/2013JD021349