Advance in understanding of the changes in the carbon cycle and its linkage to the water cycle during the 2023-2024 El Niño in Amazon region

Wenli Zhao[1], Jianing Fang[1], Kevin Bowman[2], Pierre Gentine[1]

1: Columbia University in the city of New York, New York, USA
2: Jet Propulsion Laboratory, California Institute of Technology

Presented by Kevin Bowman

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Contact: wz2481@Columbia.edu

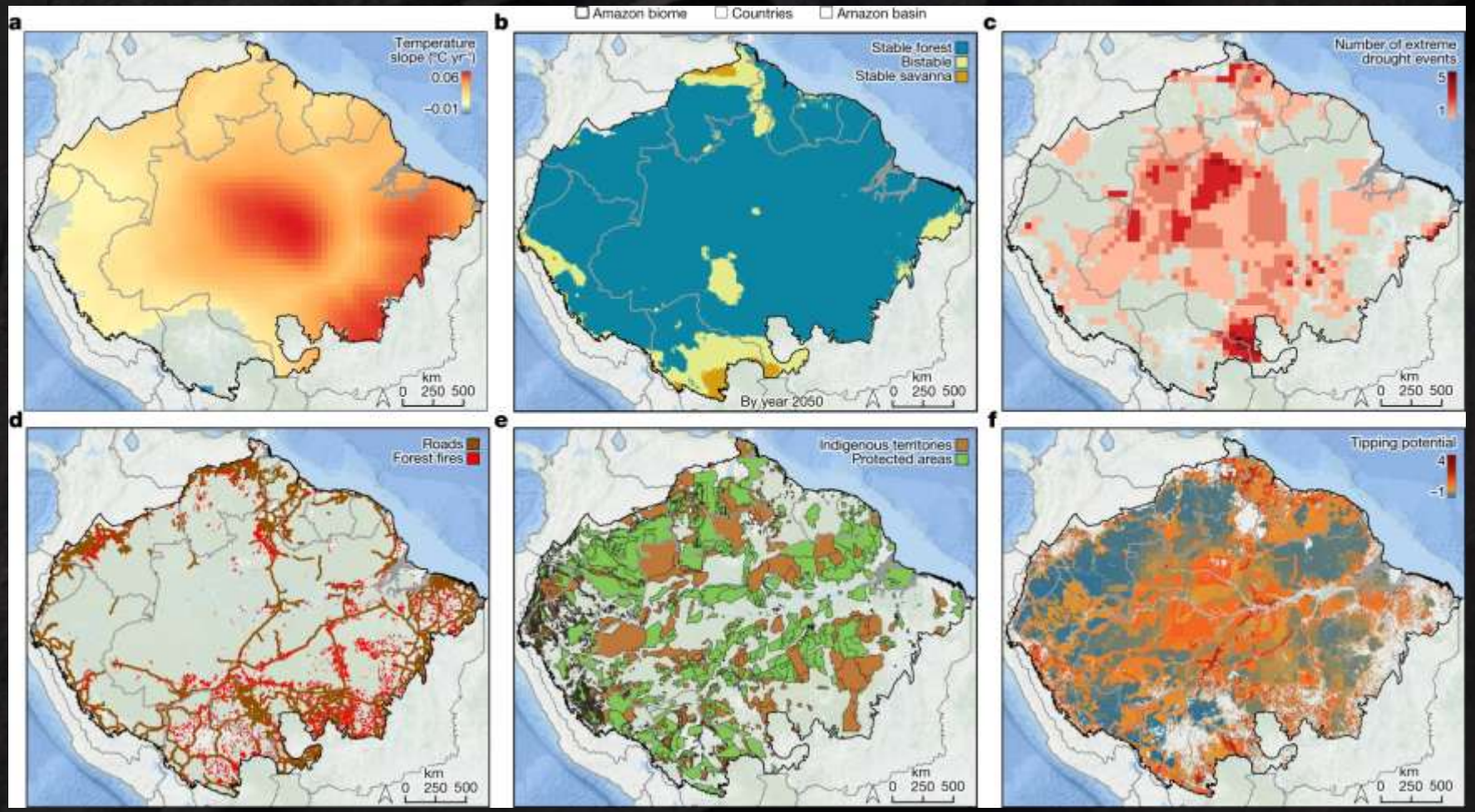
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

NASA Jet Propulsion Laboratory
California Institute of Technology

Motivation

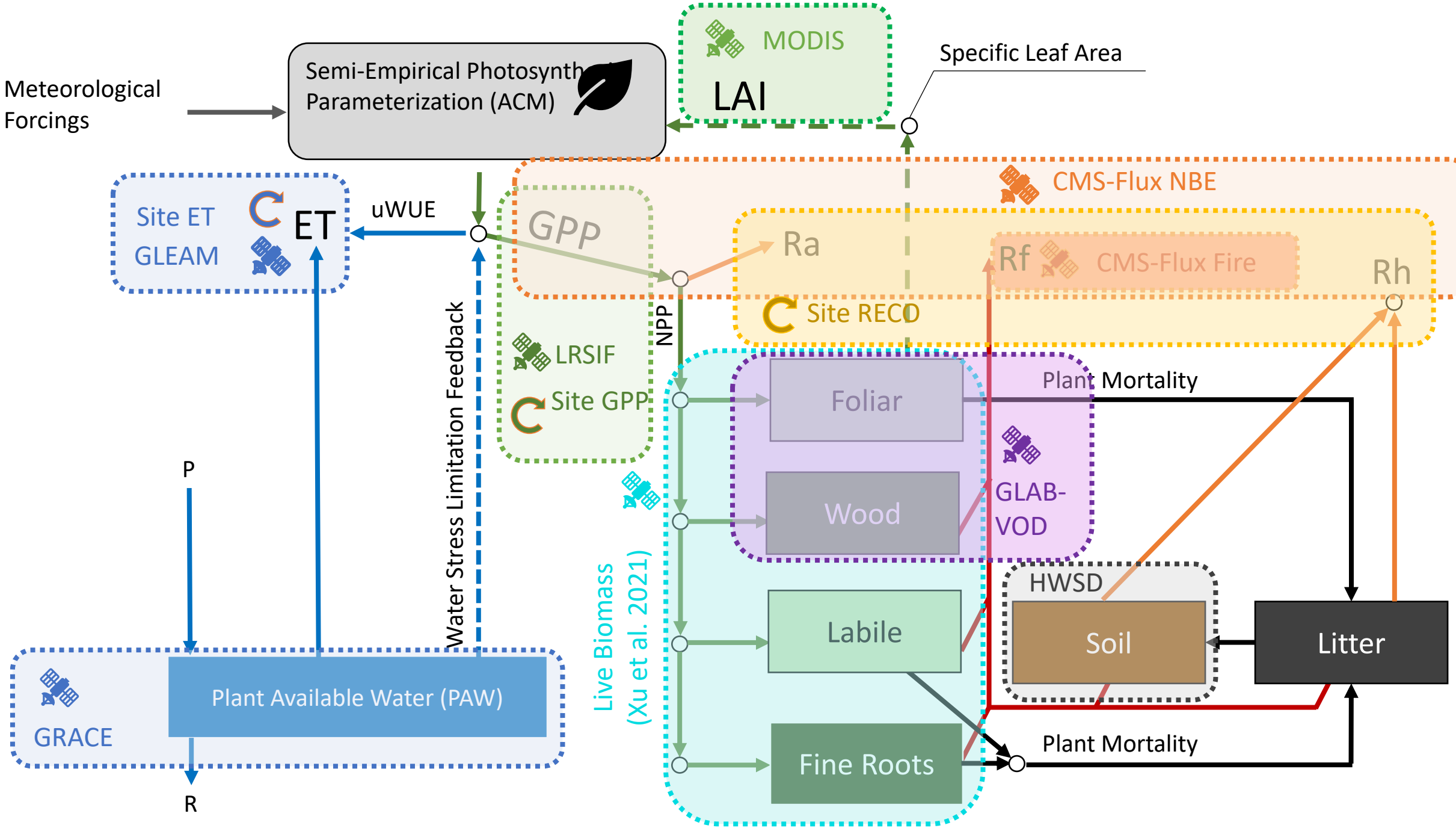
- The Amazon plays a pivotal role in the global carbon cycle, and is highly sensitive to both human and climate-induced disturbances.
- The Amazon may be approaching a tipping point, raising global concerns about potential large-scale forest collapse.
- The 2023–2024 El Niño is accelerating CO_2 growth, yet regional drivers remain uncertain due to complex carbon–water–energy coupling and spatial heterogeneity.

Critical transitions in the Amazon forest system
(adapted from Flores et al., 2024)



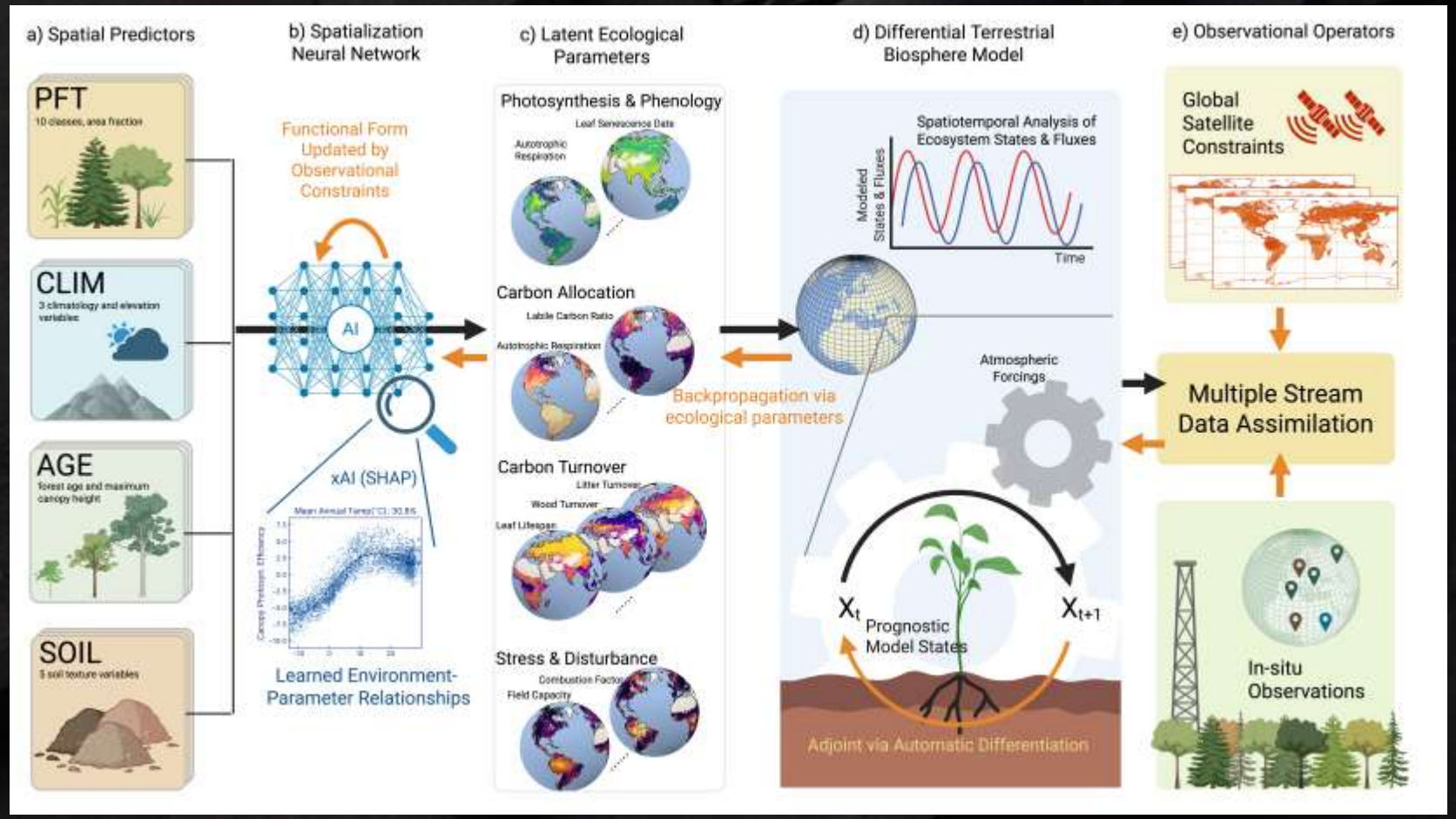
(Flores et al., 2024)

Source: IPCC AR6 WGI Fig. SPM1


Meteorological Forcings
Semi-Empirical Photosynth
Parameterization (ACM)
MODIS
LAI
Specific Leaf Area
CMS-Flux NBE
Site ET
GLEAM
ET
uWUE
GPP
Ra
Rf
CMS-Flux Fire
Rh
Site RECO
LRSIF
Site GPP
NPP
Water Stress Limitation Feedback
Plant Mortality
Foliar
Wood
GLAB-
VOD
Live Biomass
(Xu et al. 2021)
HWSD
Soil
Litter
Labile
Fine Roots
Plant Mortality
P
GRACE
Plant Available Water (PAW)
R

Motivation

DifferLand: A hybrid machine learning framework that exploits spatial gradients in climate, forest age, and soil properties to enhance predictions of vegetation responses to external forcings—especially under the extreme conditions of the 2023–2024 “super” El Niño.

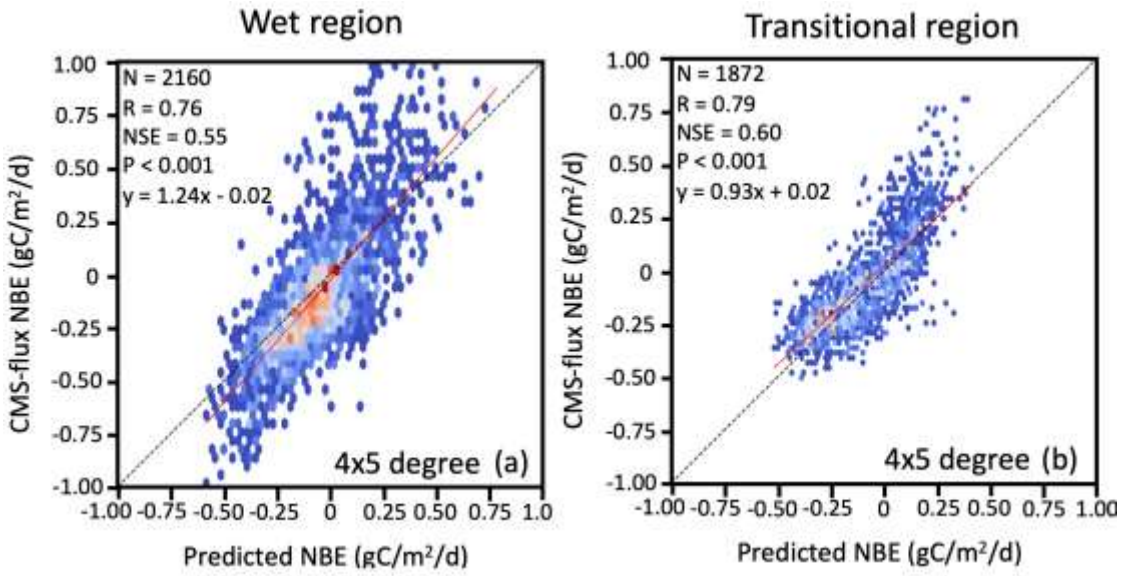


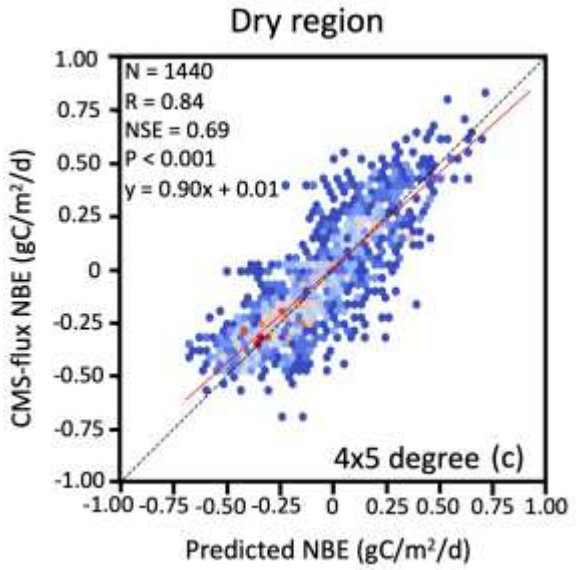
DifferLand: A Hybrid-ML Land Data Assimilation Framework

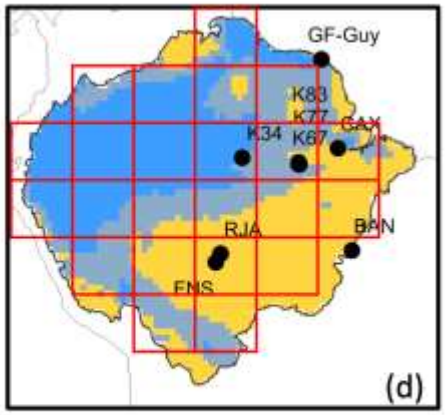
Fang et al., 2024.

Results: Model Performance

1. Hybrid machine learning performs quite well across Amazon Region.
2. Model performance in the wet region could be further improved.







CMS-flux grid for validation

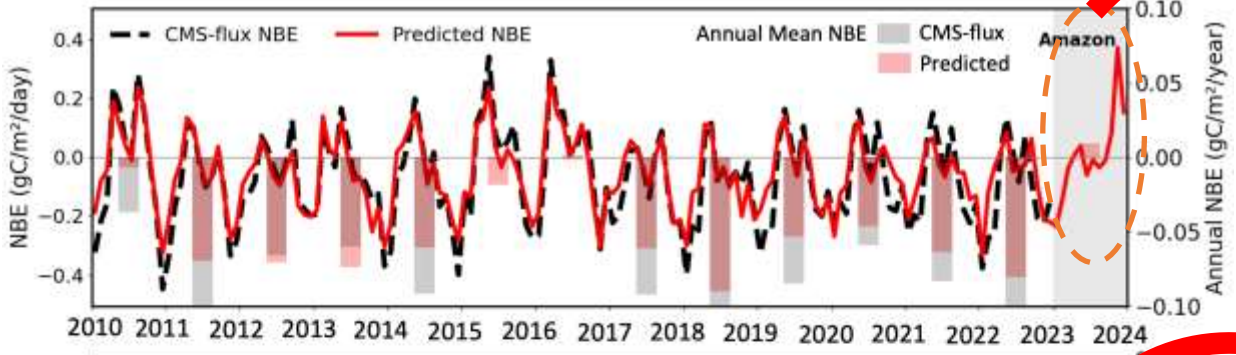
Monthly Evaluation: DifferLand vs. CMS-Flux GCP NBE (Liu et al., 2023)

Wet: SDC ≤ 3.5

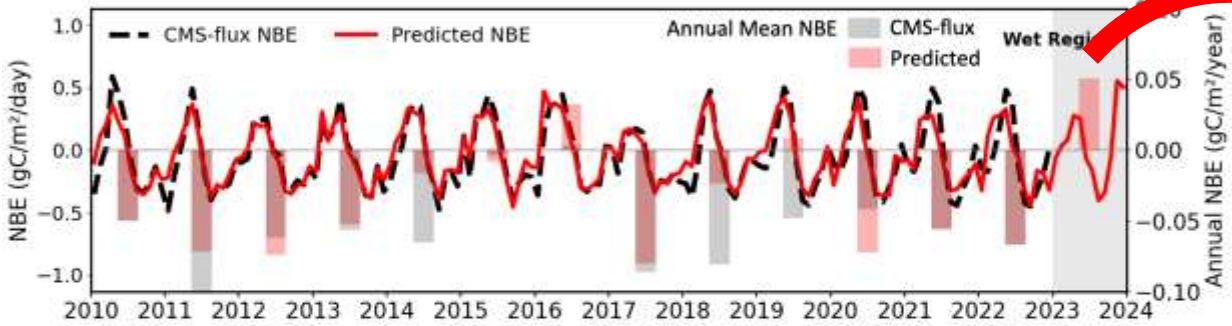
Seasonally dry: SDC ≥ 7

Transitional: 3.5 < SDC < 7

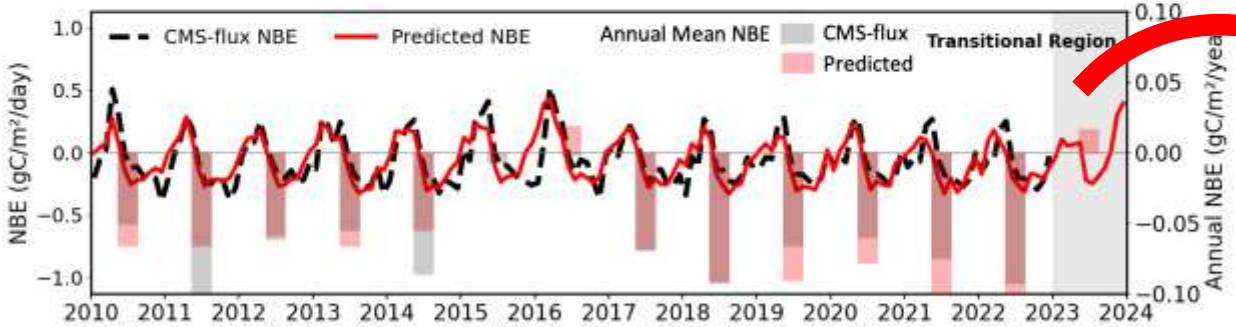
SDC: the ratio of cumulative rainfall of the three wettest months to that of the three driest ones. *Adapted from Figure S1 in Lian et al., 2024.*



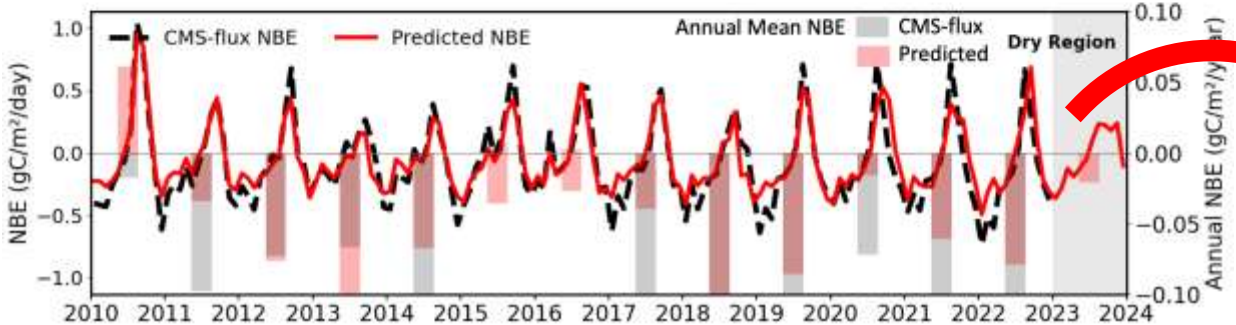
Amazon region shifts from sink to source during 2023–2024 El Niño, with changes emerging mid-2023



Wet region shifts from sink to source during 2023–2024 El Niño



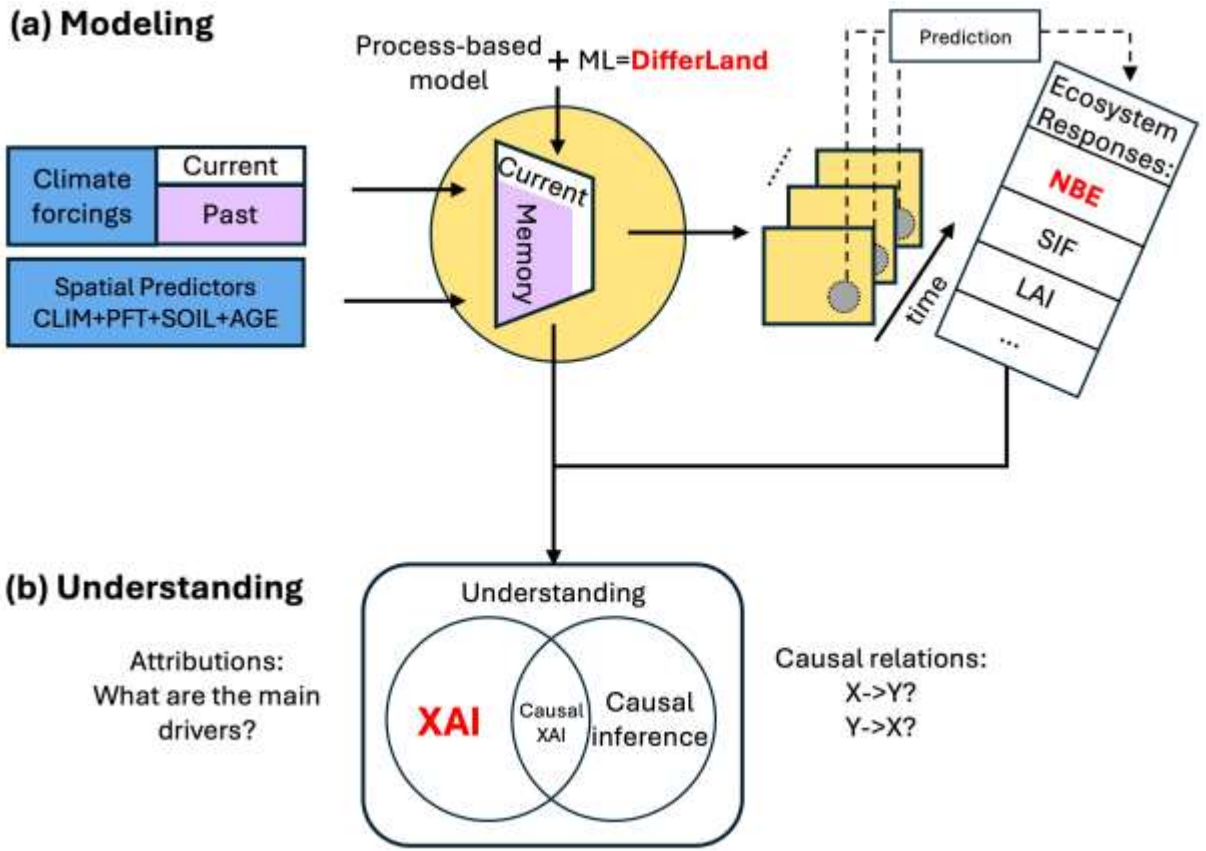
Transitional region shifts to source during 2023–2024 El Niño, though the signal was weaker than in the wet region.



Dry region remains a carbon sink

How to understand the regional drivers and controlling processes?

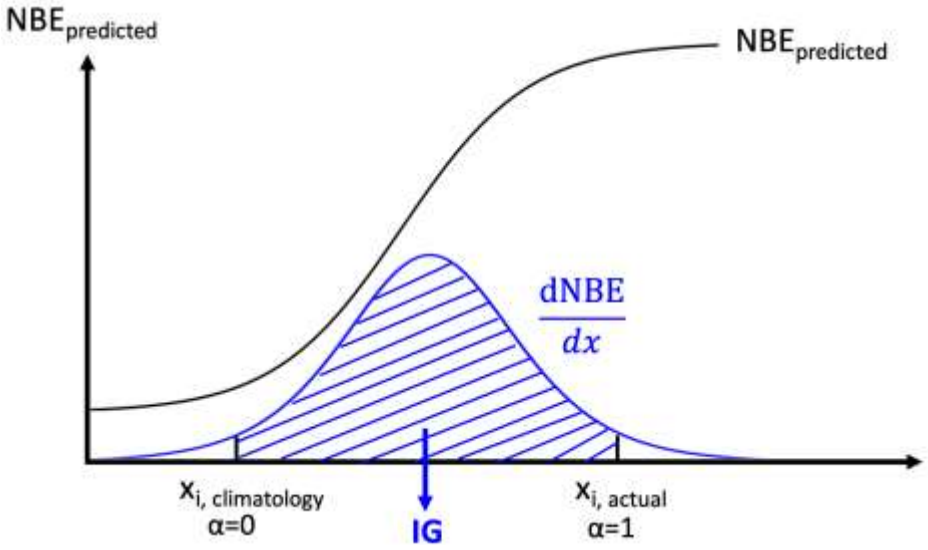
DifferLand + XAI



XAI: Integrated Gradients (IG)

Integrated Gradients (IG) quantify the contribution of meteorological anomalies to NBE, conditioned on the dynamics of carbon and water fluxes, thereby revealing the underlying processes modelled by DifferLand.

$$\text{IntegratedGrads}_i(x) ::= (x_{i,actual} - x_{i,clim}) \times \int_{\alpha=0}^{1} \frac{\partial NBE_{predicted}(x_{clim} + \alpha \times (x_{actual} - x_{clim}))}{\partial x_i} d\alpha$$



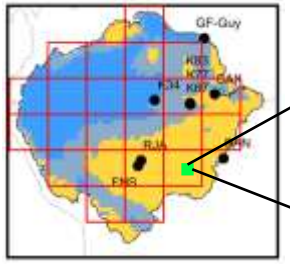
DifferLand + XAI supports event-level climate anomaly analysis

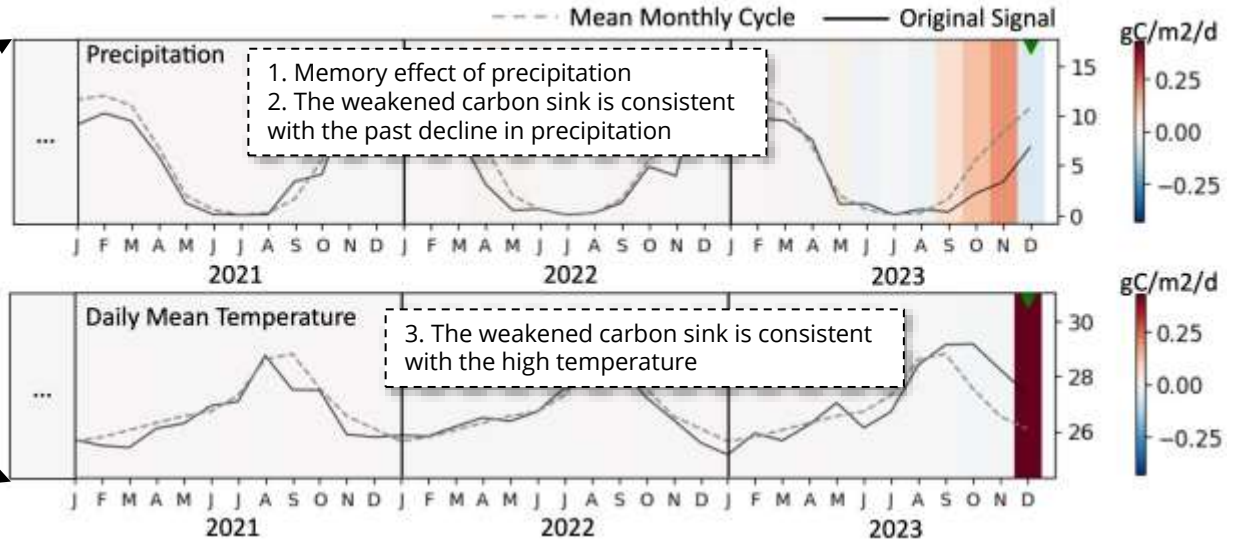
- The framework can reveal event- and sub-grid-scale mechanisms underlying NBE in specific instances.

IG > 0, weakens carbon sink

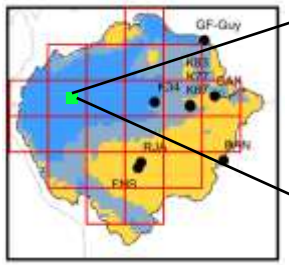
IG < 0, Strengthens carbon sink

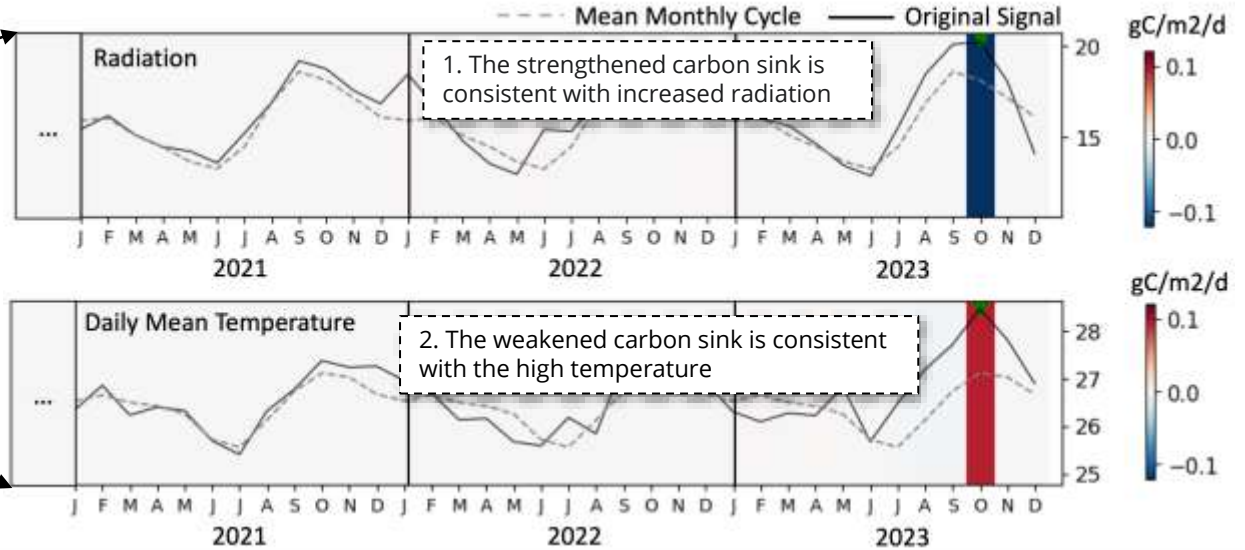
Dry region pixel example





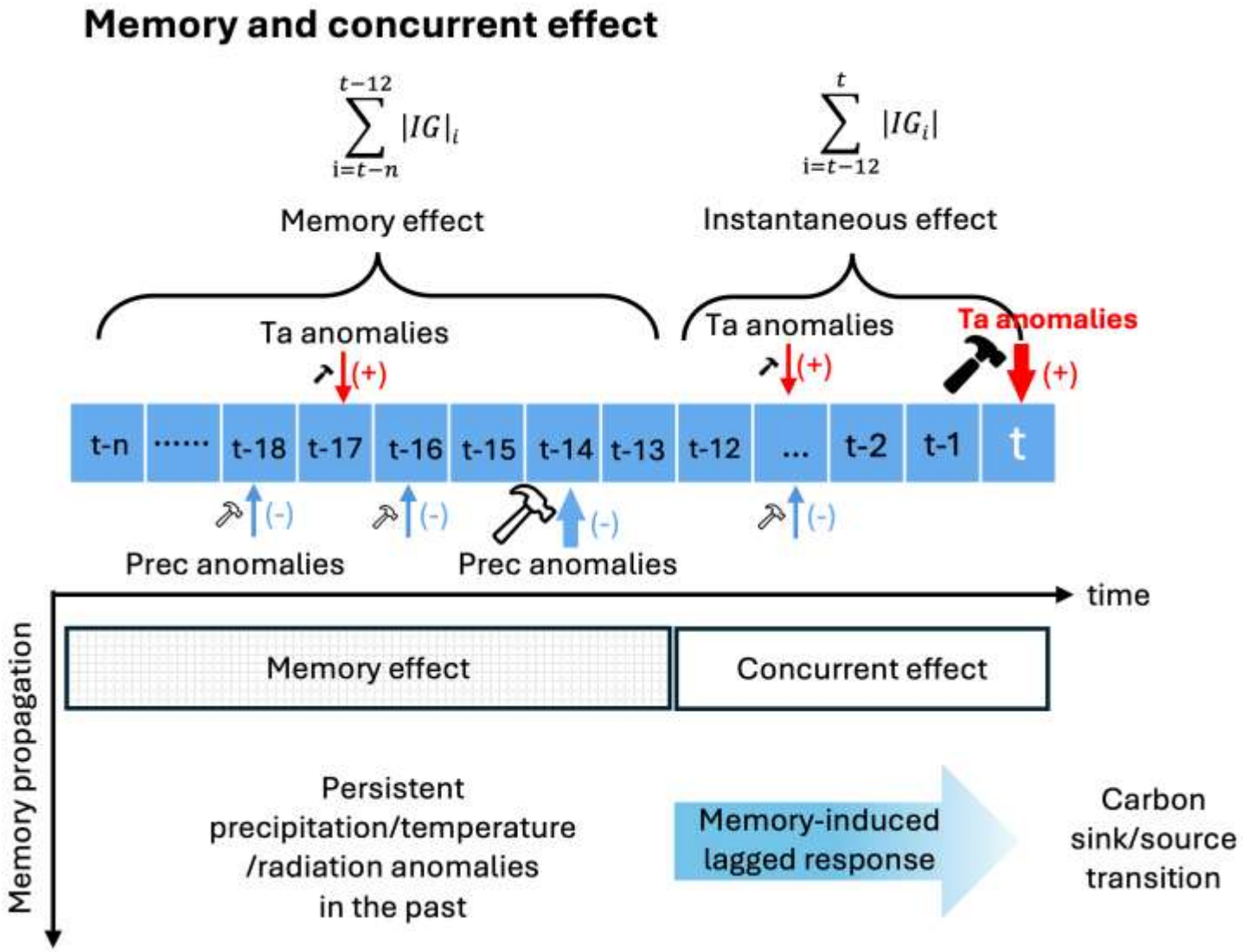
Wet region pixel example





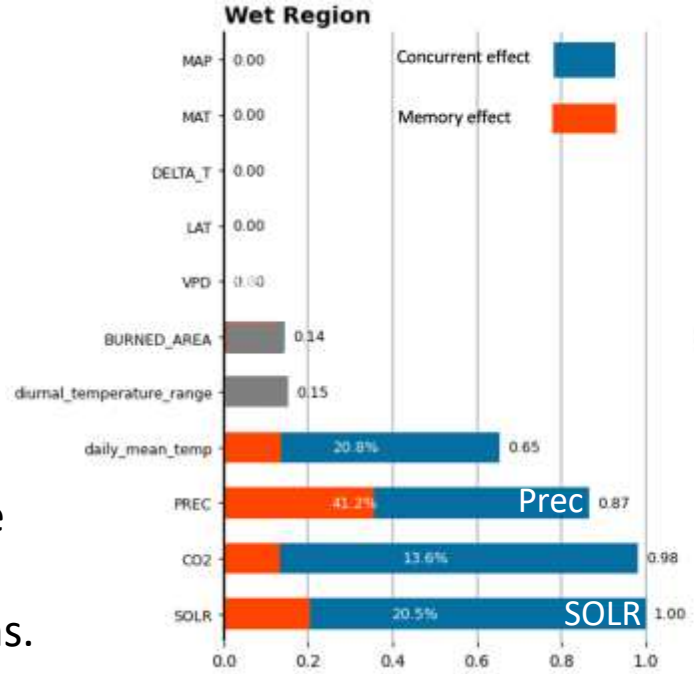
Results: summarized by concurrent and memory effects

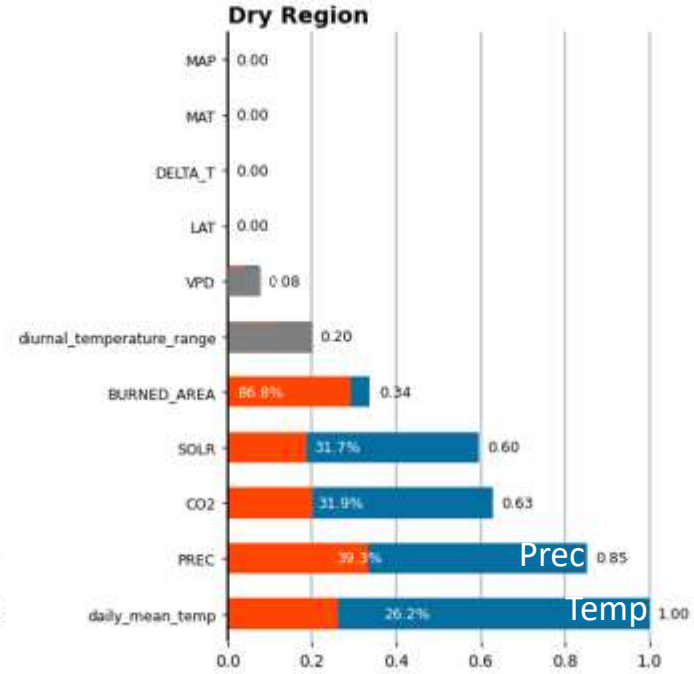
- Event-level analysis
- The concurrent effect is defined as the fraction of absolute IGs from the most recent 12 months relative to the full input period.
- The memory effect is defined as the fraction of absolute IGs from all prior periods excluding the concurrent year, relative to the total over the full input period.

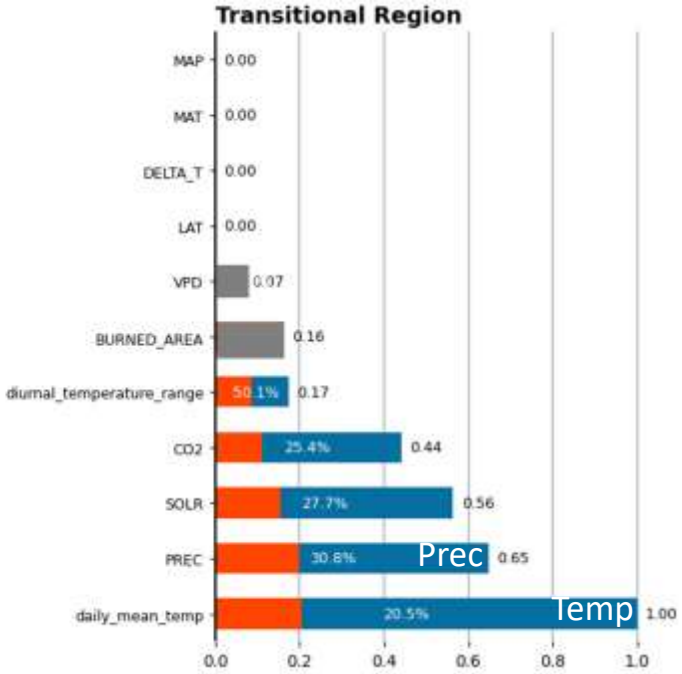


2023 El Niño
NBE

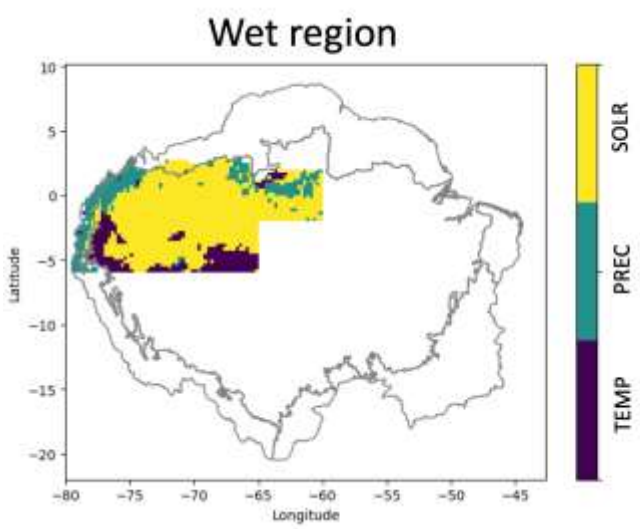
- Radiation and precipitation dominate in wet regions, while temperature and precipitation drive both dry and transitional regions.

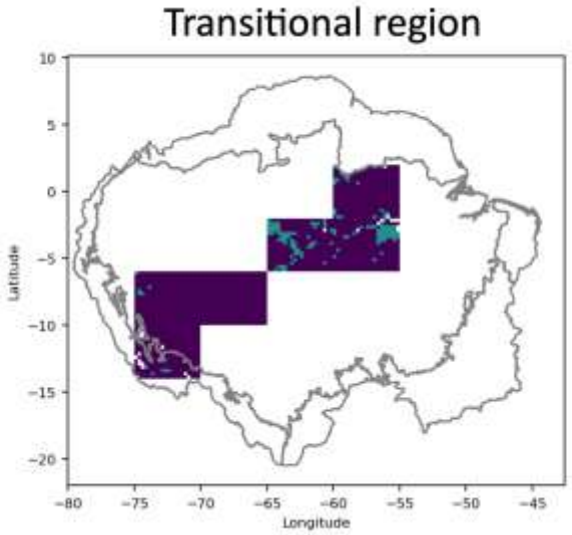


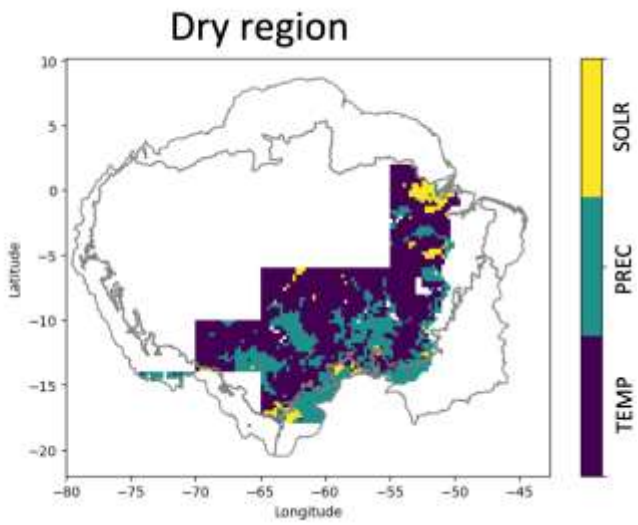




- The strong concurrent effect in 2023 is due to pronounced climate anomalies, whereas weaker anomalies in other years tend to enhance memory effects.







Take home messages

1. Training our hybrid ML model, **DifferLand**, on satellite observations in the Amazon yielded high Nash-Sutcliffe Efficiency scores, especially for net biome exchange (NBE). **The model captures the 2023/2024 El Niño impact, showing the Amazon as a weak carbon source.**

2. Explainable AI (XAI) using integrated gradients revealed distinct carbon–climate interactions during **2023**: **radiation dominating in wet regions, while precipitation and temperature controlling dry-region dynamics.**

3. XAI further separated memory effects (lagged responses) from concurrent effects (real-time responses), showing that **the strong 2023 concurrent effect stemmed from pronounced climate anomalies**, while weaker anomalies in other years would enhance memory effects.

References

1. Flores, B. M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R. A., et al. (2024). Critical transitions in the Amazon forest system. *Nature*, *626*(7999), 555–564. https://doi.org/10.1038/s41586-023-06970-0
2. Liu J., et al. (2023). https://cmsflux.jpl.nasa.gov/get-data/gcp-2023
3. Fang, J., Bowman, K., Zhao, W., Lian, X., & Gentine, P. Differentiable Land Model Reveals Global Environmental Controls on Ecological Parameters.
4. Liu, J., Baskaran, L., Bowman, K., Schimel, D., Bloom, A. A., Parazoo, N. C., et al. (2021). Carbon Monitoring System Flux Net Biosphere Exchange 2020 (CMS-Flux NBE 2020). *Earth System Science Data*, *13*(2), 299–330. https://doi.org/10.5194/essd-13-299-2021
5. Liu, J., Bowman ,Kevin W., Lee ,Meemong, Henze ,Daven K., Bousserez ,Nicolas, Brix ,Holger, et al. (2014). Carbon monitoring system flux estimation and attribution: impact of ACOS-GOSAT XCO2 sampling on the inference of terrestrial biospheric sources and sinks. *Tellus B: Chemical and Physical Meteorology*, *66*(1), 22486. https://doi.org/10.3402/tellusb.v66.22486
6. Lian, X., Morfopoulos, C., & Gentine, P. (2024). Water deficit and storm disturbances co-regulate Amazon rainforest seasonality. *Science Advances*, *10*(36), eadk5861. https://doi.org/10.1126/sciadv.adk5861

Thank you!

Q & A?

Contact: wz2481@Columbia.edu

Check our DifferLand paper