

Interactive Atmospheric Composition Emulation for Next-Generation Earth System Models

Mohammad H. Erfani^{1,3}, Kara D. Lamb², Susanne E. Bauer³, Kostas
Tsigaridis^{1,3}, Marcus van Lier-Walqui^{1,3}, and Gavin Schmidt³

¹Center for Climate Systems Research, Columbia University

²Department of Earth and Environmental Engineering, Columbia University

³NASA Goddard Institute for Space Studies

Define the problem

NASA GISS ESMs (ModelE)

Atmospheric Composition Module

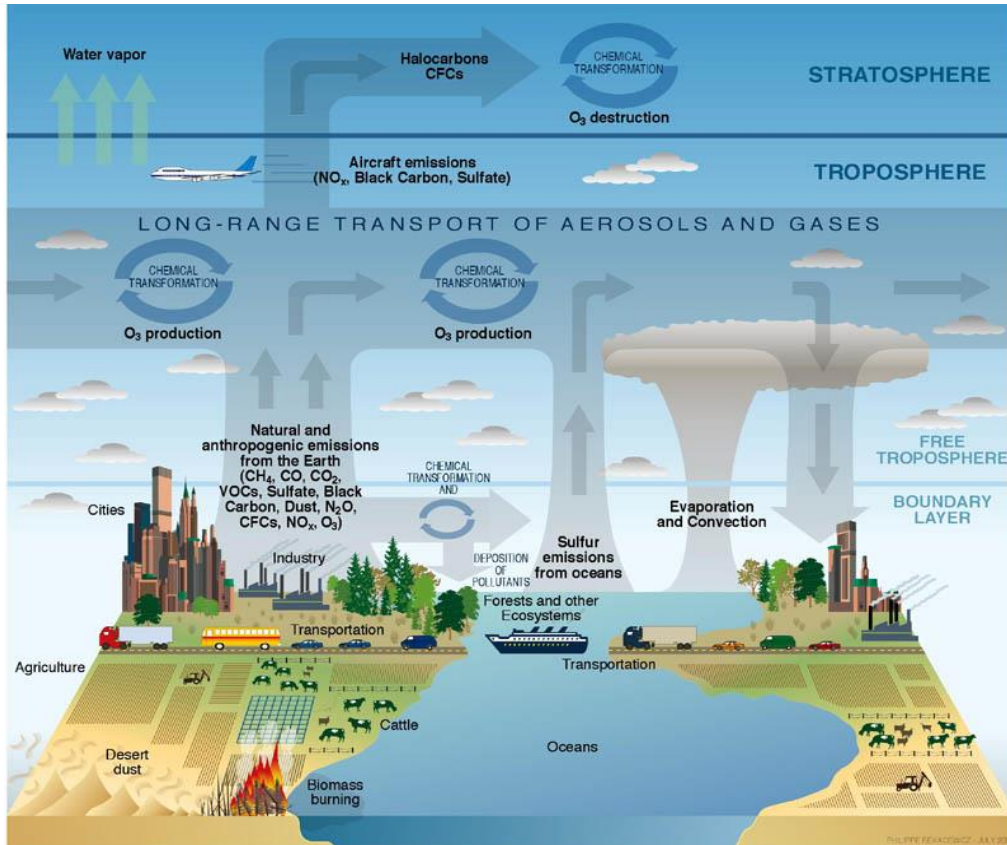


Image credit: Susanne E. Bauer

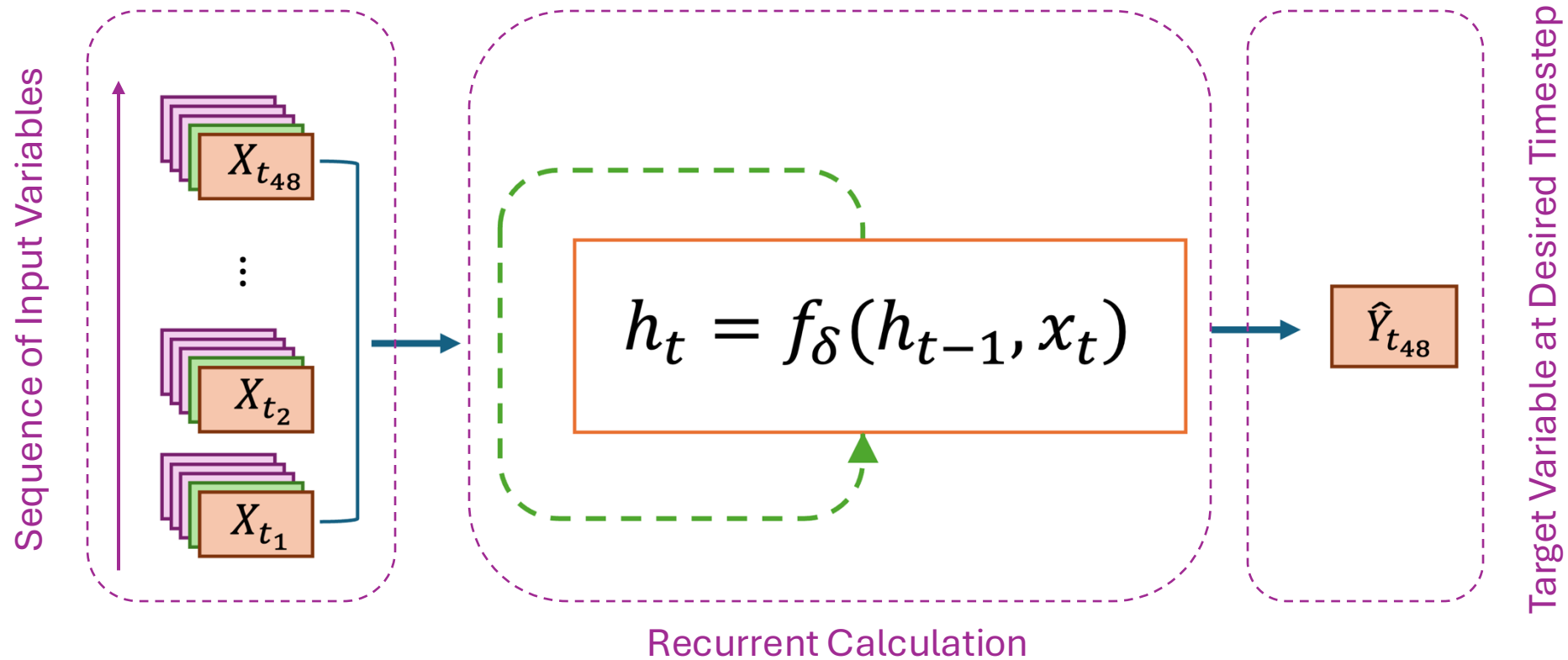
Atmospheric Transport Model

$$\underbrace{\frac{d\mu}{dt} + u \frac{d\mu}{dx} + v \frac{d\mu}{dy}}_{\text{Horizontal Advection}} + \underbrace{w(\omega, T, q, z) \frac{d\mu}{dz}}_{\text{Vertical Convection}} = \underbrace{\Sigma}_{\text{Sink/Source terms}}$$

Benson, V., Bastos, A., Reimers, C., Winkler, A.J., Yang, F. and Reichstein, M., **2025. Atmospheric transport modeling of CO₂ with neural networks.** *Journal of Advances in Modeling Earth Systems*, 17(2), p.e2024MS004655.

Model Conceptualization

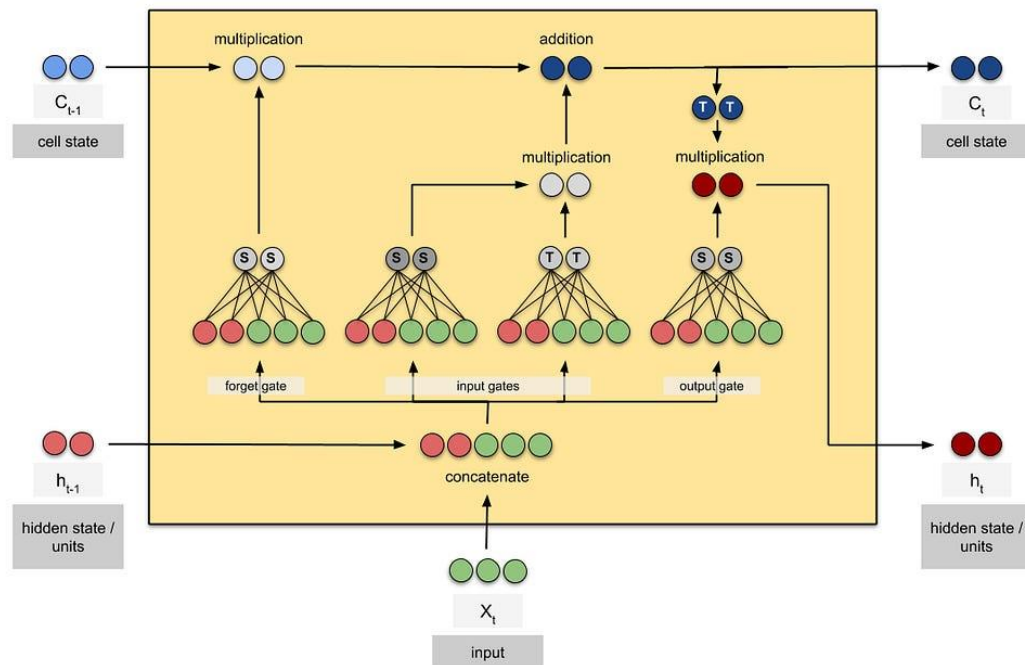
Spatio-temporal Machine Learning



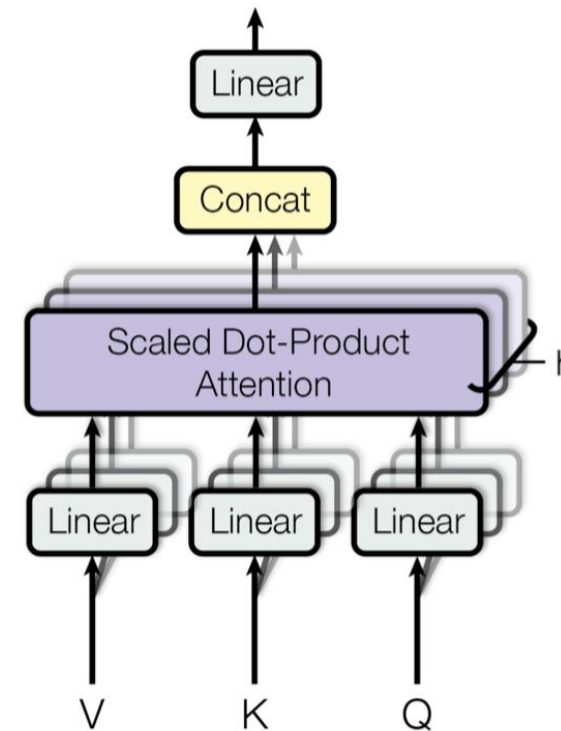
Capture Temporal Dependencies

Short-term Patterns / Long-term Trends

Long short-term memory (LSTM)



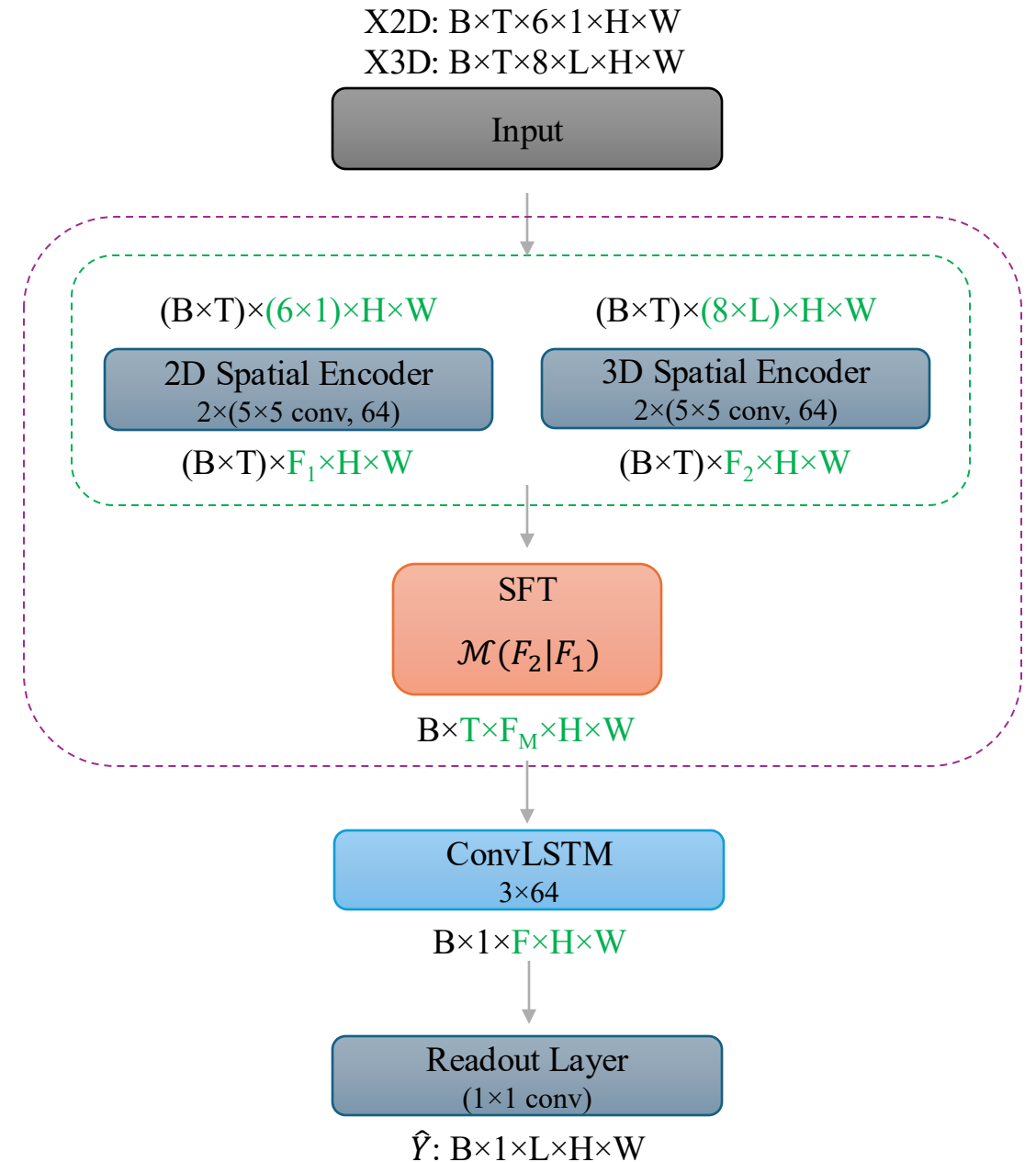
Attention Mechanism



Model Architecture

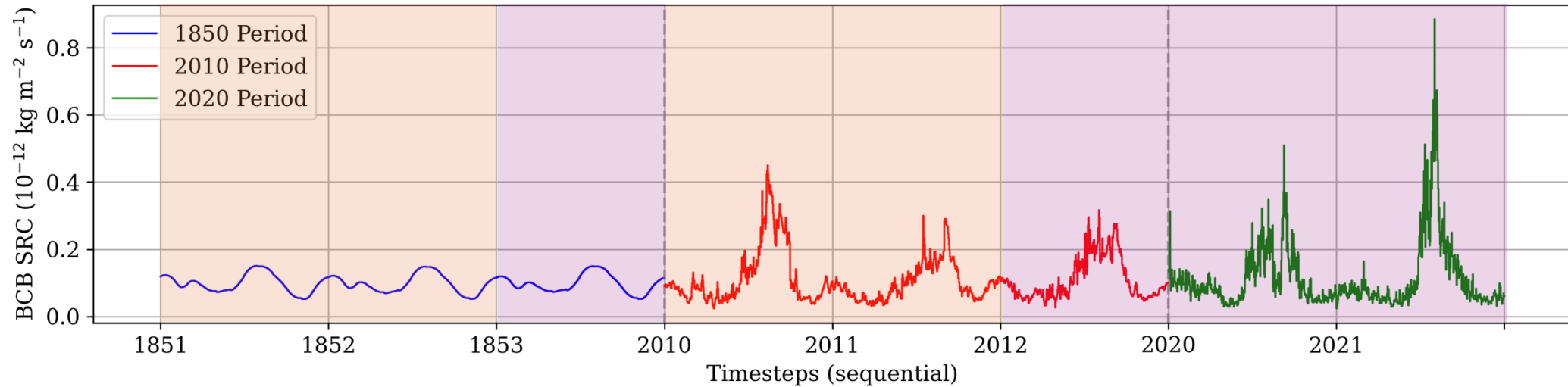
Profile-Guided Fusion Module (PGFM)

- 1) Gao, Zhangyang, et al. "Simvp: Simpler yet better video prediction." *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*. 2022.
- 2) Tan, Cheng, et al. "Temporal attention unit: Towards efficient spatiotemporal predictive learning." *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*. 2023.
- 3) Wang, Xintao, et al. "Recovering realistic texture in image super-resolution by deep spatial feature transform." *Proceedings of the IEEE conference on computer vision and pattern recognition*. 2018.



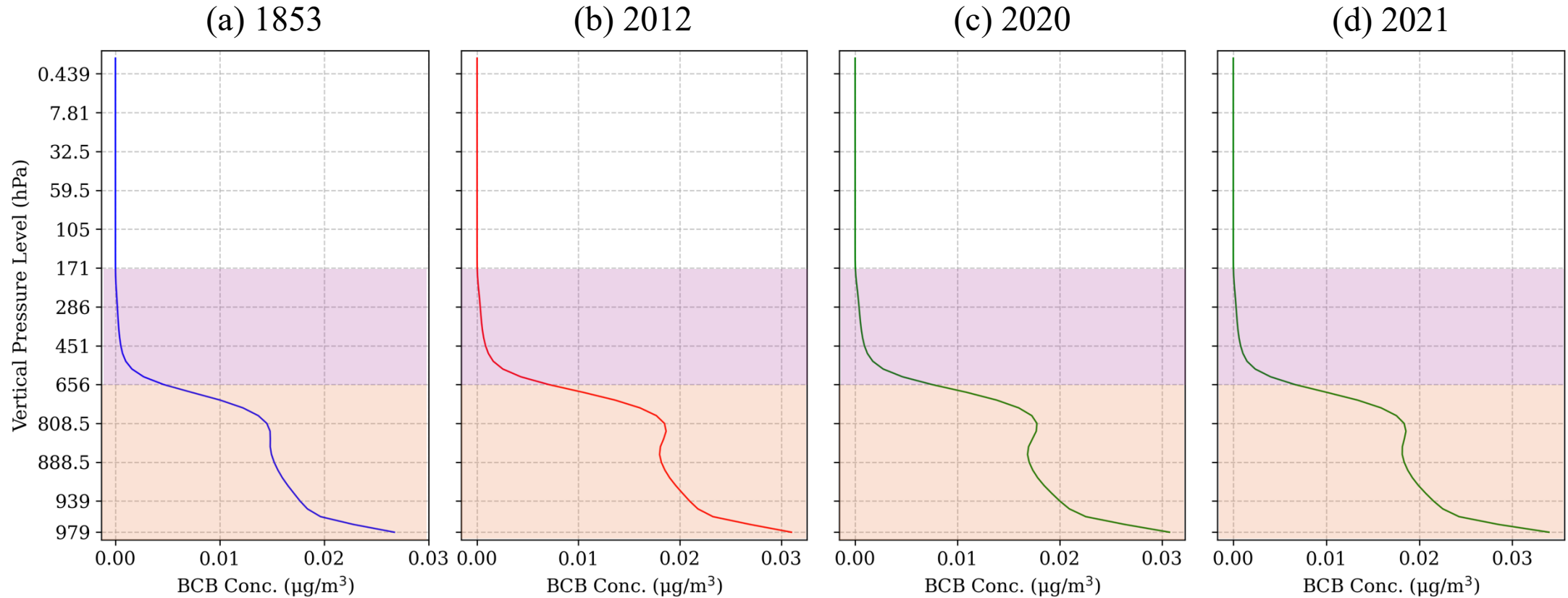
BCB Emission Sources

Global Daily average



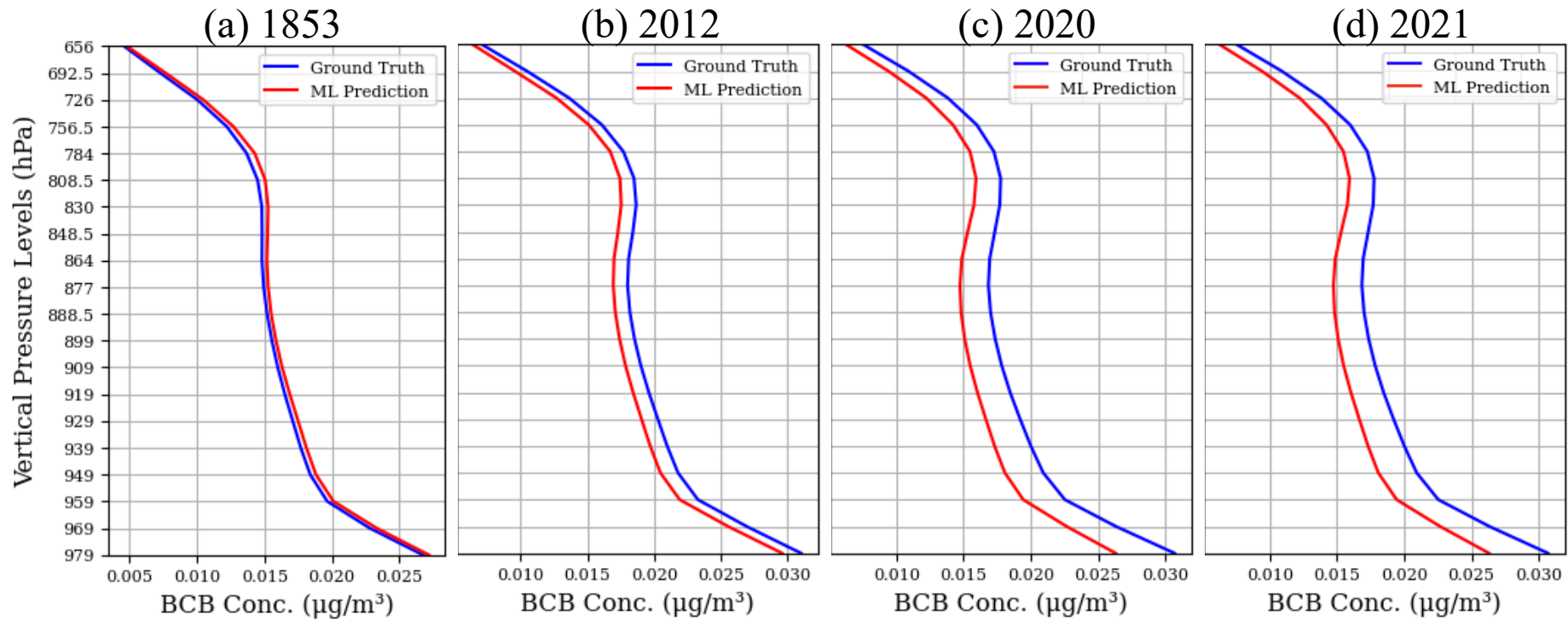
Vertical profiles of BCB Conc.

62 Atmospheric Levels



Vertical profiles of BCB Conc.

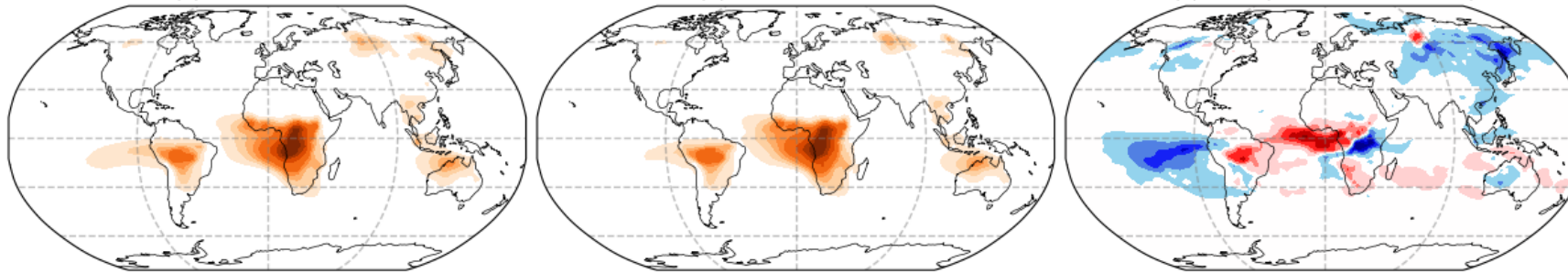
20 Atmospheric Levels



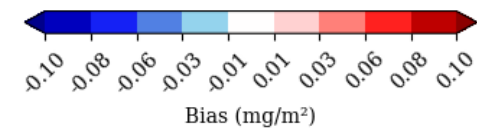
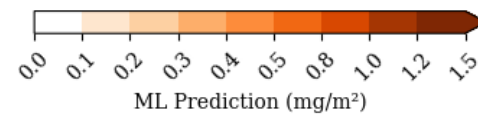
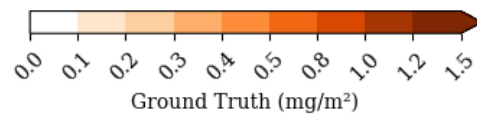
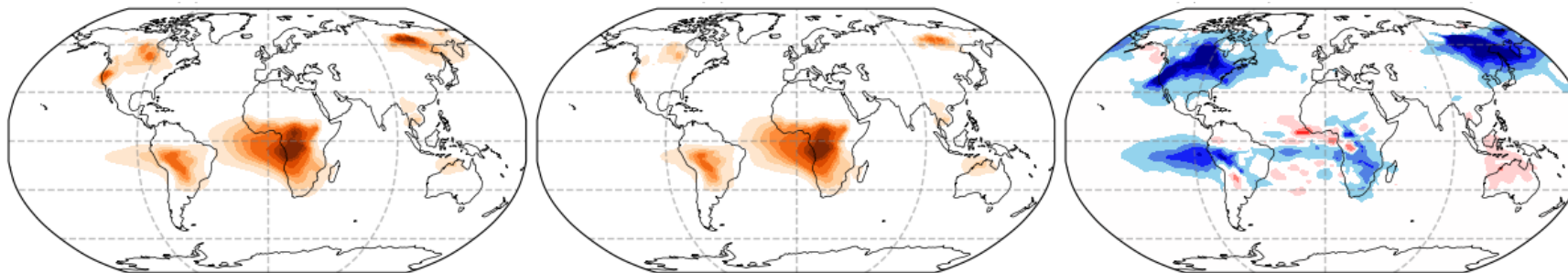
BCB Column Burden

Annual Average

2012



2021



Conclusion

- Architectural provisions
 - Temporal evolution
 - Vertical atmospheric coupling
- Climate modeling
 - Stable performance over long-term projection

Preprint: <https://arxiv.org/abs/2510.10654>