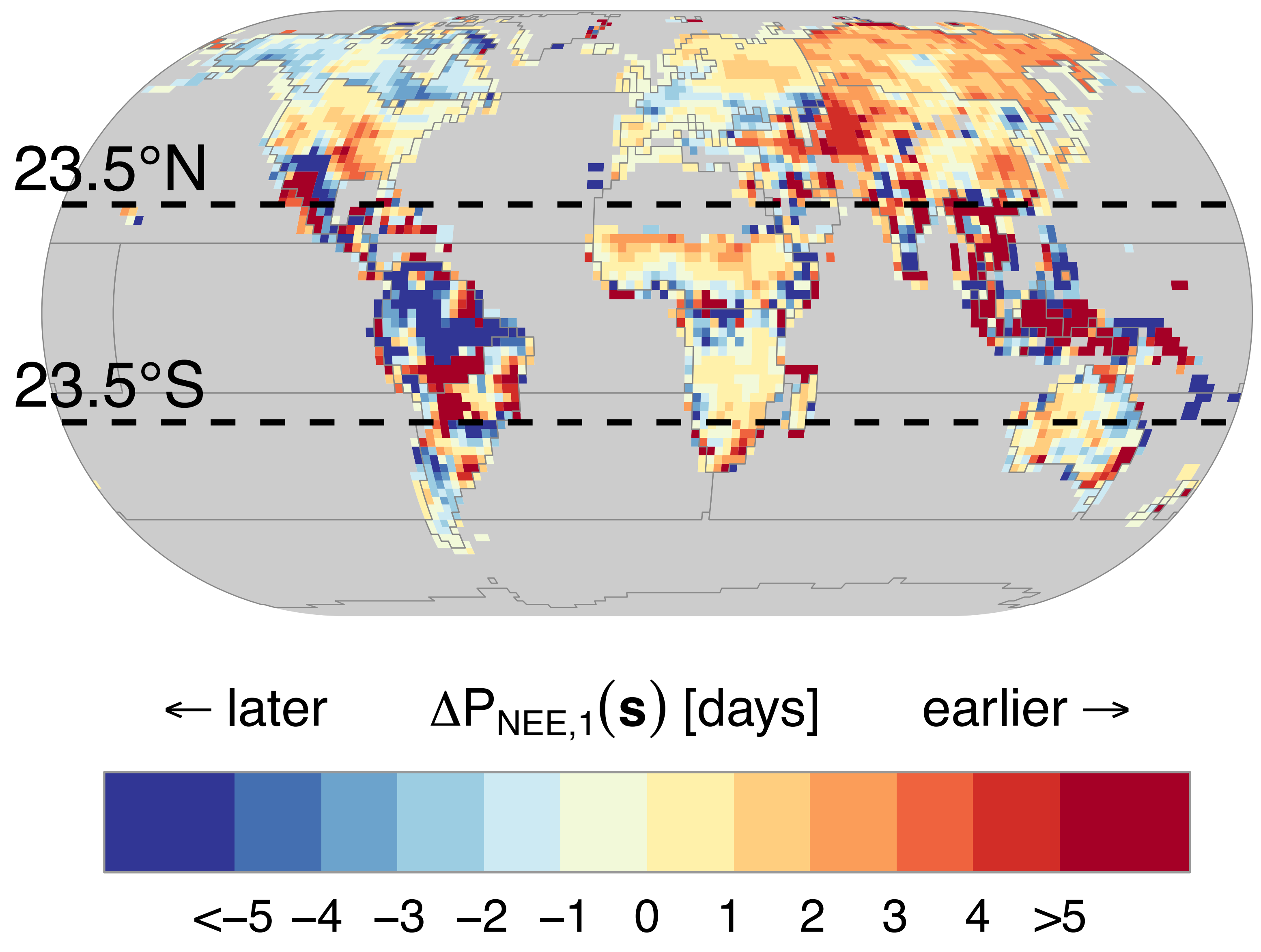
Estimating the trend, seasonality, and variability of global and regional CO_2 fluxes with a Bayesian flux-inversion framework



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Key members (location, discipline):

- Michael Bertolacci (UOW, statistics)
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- Jenny Fisher (UOW, atmospheric chemistry)
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- Andrew Schuh (CSU, atmospheric chemistry)
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- Yi Cao (UOW, IT)
- Noel Cressie (UOW, statistics)

Valuable input/feedback:

Several others including Anita Ganesan, Matt Rigby, Ann Stavert, Peter Rayner, Ian Baker, Sara Mikaloff-Fletcher, and members of the OCO-2 Flux Group.

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Motivation and overview

- The seasonal cycle of natural CO_2 fluxes is changing
- This is driven by changes to other processes such as surface temperatures
- For example, Park et al. (2019) find that the timing of peak photosynthesis in northern regions is coming earlier
- We extended the WOMBATv1 flux-inversion framework (Zammit-Mangion et al., 2022) to address this problem
- The new system is called WOMBATv2

Note: WOMBAT stands for WOllongong Methodology for Bayesian Assimilation of Trace-gases

WOMBAT v2 flux model

- We model fluxes using the decomposition

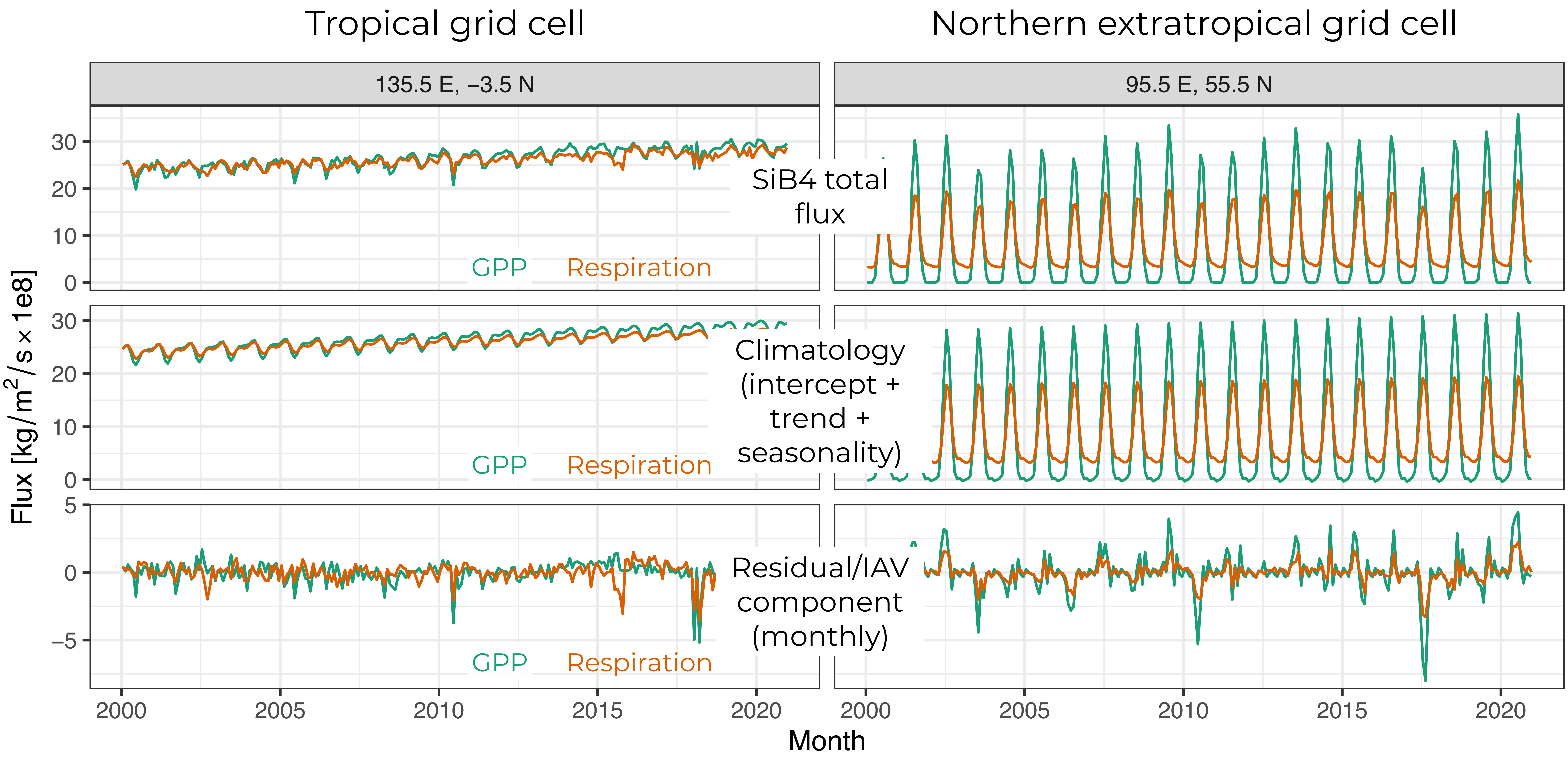
$$\text{flux} = \text{intercept} + \text{trend} + \text{seasonality} + \text{residual/IAV}$$

- Mathematically:

$$X(\mathbf{s}, t) = \beta_0(\mathbf{s}) + \beta_1(\mathbf{s})t + \boxed{\sum_{k=1}^{K} (\beta_{2,k}(\mathbf{s}) + \beta_{3,k}(\mathbf{s})t)\cos(2\pi kt/365.25) + \sum_{k=1}^{K} (\beta_{4,k}(\mathbf{s}) + \beta_{5,k}(\mathbf{s})t)\sin(2\pi kt/365.25)} + \boxed{\epsilon(\mathbf{s}, t)}$$

Flux at location **s** and time t

β's and ϵ are unknown and estimated as part of the inversion



These fluxes are from SiB4, not posterior estimates. Fluxes shown are monthly, the underlying inventory is hourly. Climatology uses K = 3 harmonics. Rows have different scales.

Time-varying phase and amplitude

- The seasonal component of flux can be written as

$$\sum_{k=1}^{K} \underbrace{\boxed{A_k(\mathbf{s}, t)}}_{\substack{\text{Seasonal}\\ \text{cycle}\\ \text{amplitude}}} \cos(2\pi k t/365.25 + \underbrace{\boxed{P_k(\mathbf{s}, t)}}_{\substack{\text{Seasonal}\\ \text{cycle phase}}})$$

where

$$\boxed{A_k(\mathbf{s}, t)} \equiv \sqrt{(\beta_{2,k}(\mathbf{s}) + \beta_{3,k}(\mathbf{s})t)^2 + (\beta_{4,k}(\mathbf{s}) + \beta_{5,k}(\mathbf{s})t)^2}$$

$$\boxed{P_k(\mathbf{s}, t)} \equiv \tan^{-1}\left(-\frac{\beta_{4,k}(\mathbf{s}) + \beta_{5,k}(\mathbf{s})t}{\beta_{2,k}(\mathbf{s}) + \beta_{3,k}(\mathbf{s})t}\right)$$

- This means that we estimate a time-varying phase and amplitude

Flux inversion

System details:

- Covers the 6-year period from January 2015 to December 2020
- Uses a fully-Bayesian hierarchical framework with uncertainty quantification
- Scaling factors for 12 land and 11 ocean regions (based on the TRANSCOM regions)

Observations:

- Orbiting Carbon Observatory-2 (OCO-2) retrievals of column-average CO_2 concentration (land retrievals only)
- *In situ* and flask measurements of CO_2 concentrations

Details

Inventories

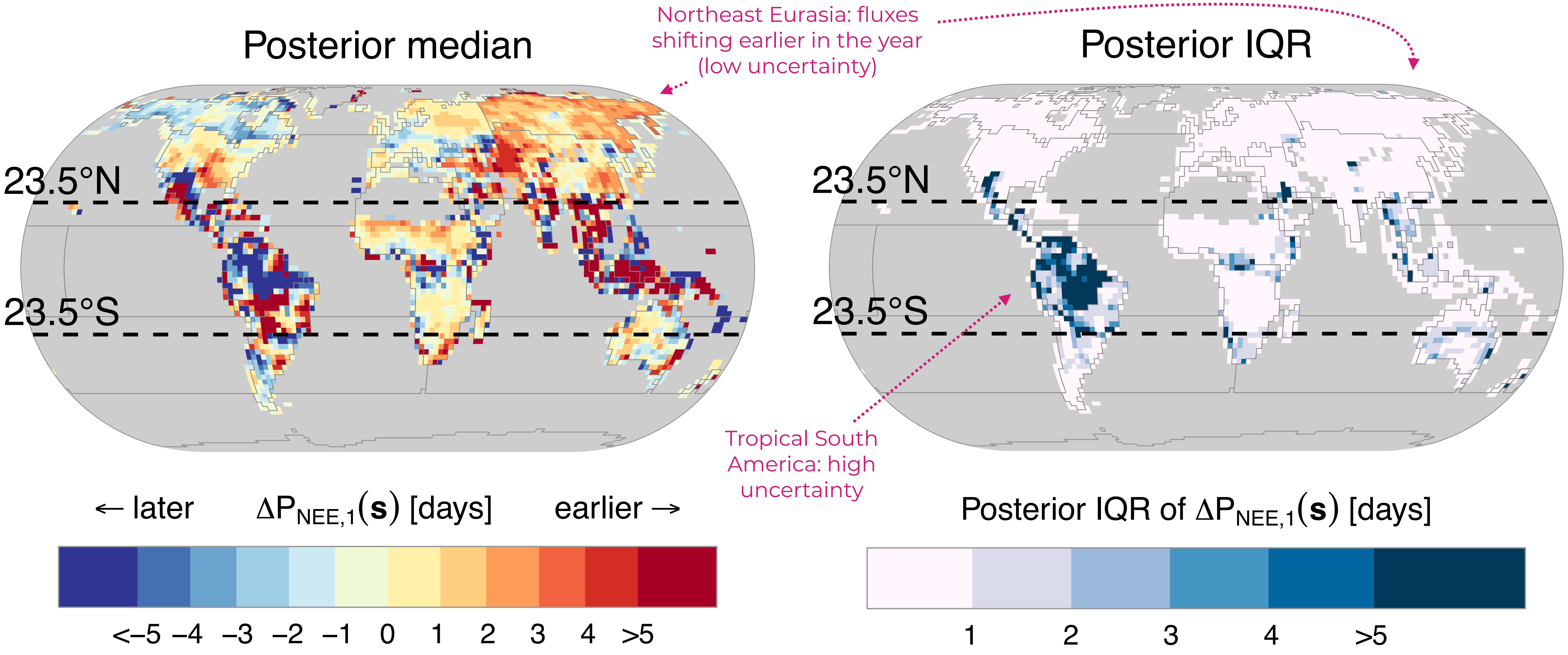
Fossil	ODIAC + TIMES
Biofuels	Yevich and Logan (2003)
Biosphere	SiB4
Ocean	Landschutzer et al. (2016)
Fires	GFED4

Fossil fuel, fire, and biofuel fluxes assumed known

Transport

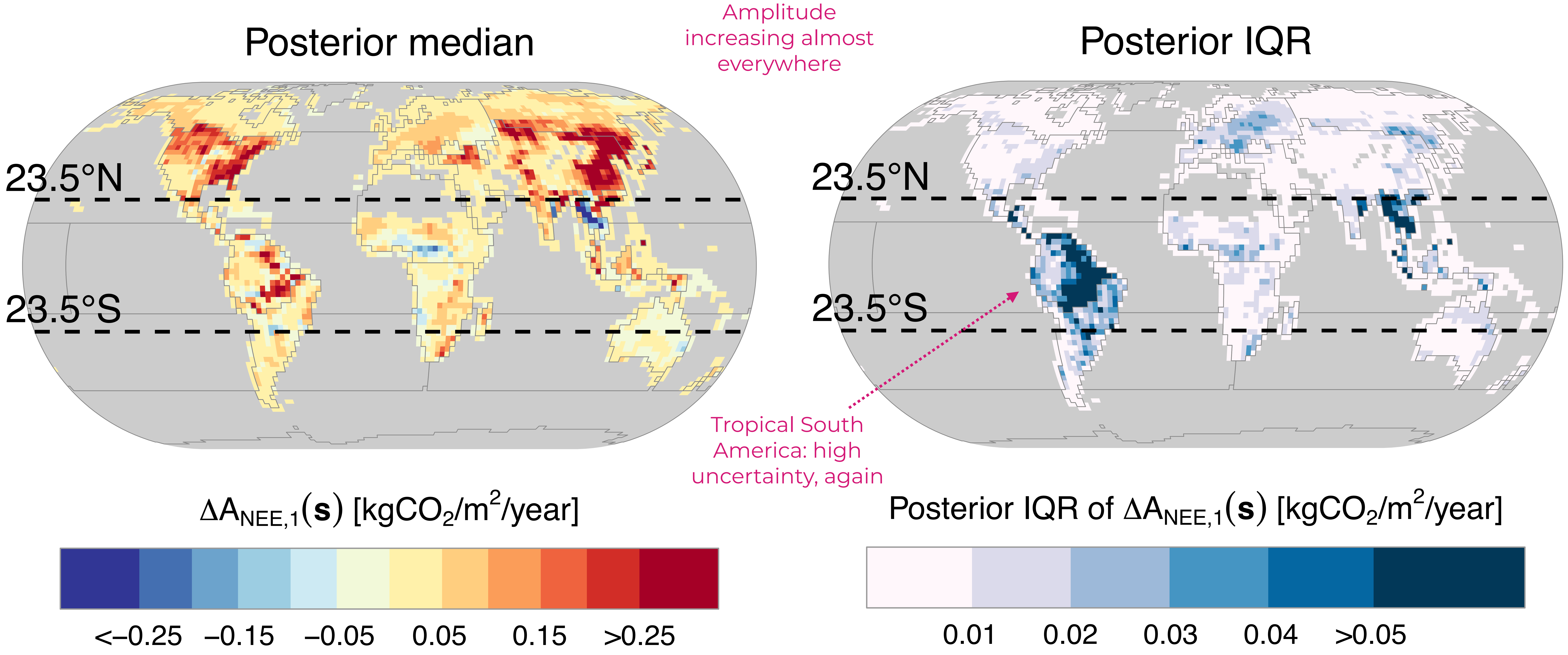
Model	GEOS-Chem 12.3.2
Grid	2x2.5 (lat x lon)
Met.	MERRA2

Estimated phase shift in net ecosystem exchange (NEE) seasonal cycle from January 2015 to December 2020



Note: values are for k = 1 component (period of 12 months). Colour scales are truncated to maximum values. IQR = interquartile range

Estimated amplitude change of net ecosystem exchange (NEE) seasonal cycle from January 2015 to December 2020



Note: values are for k = 1 component (period of 12 months). Colour scales are truncated to maximum values. IQR = interquartile range

Summary

- We built a flux-inversion system that can estimate changes to seasonal cycles of natural fluxes
- Demonstrates the feasibility of doing this using data on atmospheric CO_2 concentrations
- Results demonstrate global changes in CO_2 flux natural cycles, including increasing amplitude of cycle almost everywhere

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