A pilot top-down CO_2 budget based on the v10 OCO-2 MIP

B. Byrne[1], D. F. Baker[2], S. Basu[3,4], M. Bertolacci[5], K. W. Bowman[1,6], A. Chatterjee[1], F. Chevallier[7], P. Ciais[7], N. Cressie[5], D. Crisp[1], S. Crowell[8], F. Deng[9], Z. Deng[10], A. Eldering[1], L. Hu[11], A. R. Jacobson[11,12], S. Jeong[13], M. S. Johnson[14], D. B. A. Jones[9], J. Liu[1,15], J. B. Miller[11], S. M. Miller[16], T. Oda[17], C. O'Dell[2], P. K. Patra[18], H. Peiro[8], S. Philip[19], B. Poulter[3], A. Schuh[2], C. Sweeney[11], H. Tian[20], J. R. Worden[1], Y. Yao[20], J. Yun[13], A. Zammit-Mangion[5] + many more

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA; [2]Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, USA; [3]NASA Goddard Space Flight Center, Global Modeling and Assimilation Office, Greenbelt, MD, USA; [4]Earth System Science Interdisciplinary Center, College Park, MD, USA; [5]School of Mathematics and Applied Statistics, University of Wollongong, Australia; [6]Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, CA, USA; [7]Laboratoire des Sciences du Climat et de L'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, 91198 Gif-sur-Yvette, France; [8]University of Oklahoma, Norman, OK, USA; [9]Department of Physics, University of Toronto, Toronto, Ontario, Canada; [10]Department of Earth System Science, Tsinghua University, Beijing, China; [11]NOAA Global Monitoring Laboratory, Boulder, CO, USA; [12]Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA; [13]Department of Environmental Planning, Graduate School of Environmental Studies, Seoul National University, Seoul, Republic of Korea; [14]NASA Ames Research Center, Moffett Field, CA, USA; [15]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA; [16]Department of Environmental Health and Engineering, Johns Hopkins University, Baltimore, MD 21218, United States of America; [17]Goddard Earth Sciences Technology and Research, Universities Space Research Association, Columbia, MD, USA; [18]RCGC/IACE, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, 236-0001, Japan; [19]Indian Institute of Technology Delhi, New Delhi, India; [20]International Center for Climate and Global Change Research, School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL 36832, USA

contact: brendan.k.byrne@jpl.nasa.gov

Goals

- **Contribute to Global Stocktake (GST) Activities of the Paris Agreement**
  - GST to monitor Paris agreement implementation (e.g., emissions and removals of CO_2)
  - GST to evaluate the collective progress made in achieving goals.

- **Goal of the pilot dataset**: Start a conversation.
  - Provide a pilot product of emissions and removals of CO_2
  - Illustrate the type of dataset we can provide.
  - Identify current limits of our approach and where research is needed.
  - Inform development of Monitoring and Verification System

- **Long term goal**:
  - Provide countries with precise and accurate carbon budgets to track AFOLU (Agriculture, Forestry and Other Land Use) and unmanaged lands. Complement bottom-up datasets.

What is in our dataset?

- **Quantities provided:**
  - Net carbon exchange (net surface-atmosphere CO_2 flux)
  - Change in terrestrial carbon stocks (ΔC_{loss}).
  - Fossil fuel emissions and lateral C fluxes
  - And their uncertainties!

- **Spatiotemporal scale:**
  - Annual net fluxes over (2015-2020)
  - Country totals and as 1^o x 1^o degree.

Methods - CO_2 flux inversions

v10 OCO-2 Model Intercomparison Project (MIP)

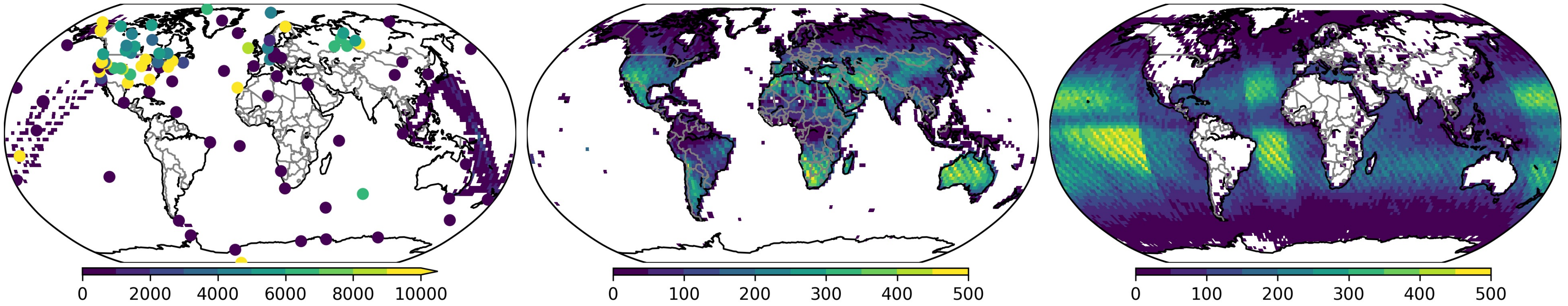
- 12 flux inversion models from 5 countries (multiple models helps quantify systematic errors)
- Follow protocol with common data assimilated and fossil fuel emission inventory.
  Each group free to choose prior NBE and ocean fluxes

Includes four MIP experiments that use different datasets:

- In situ (IS)
- Land nadir + land glint (LNLG)
- Land nadir + land glint + in situ (LNLGIS)
- Land nadir + land glint + ocean glint + in situ (LNLGOGIS)

Data coverage over 2015-2020

In situ CO2 measurements | OCO-2 land X_{CO2} retrievals | OCO-2 ocean X_{CO2} retrievals



Methods - CO_2 flux inversions

Data Quality ←——→ **Data Quantity**

IS | **LNLG** / **LNLGIS** | **LNLGOGIS**

IS:

- In situ data undergoes direct validation and has high accuracy and precision.
- Observations are sparse over much of globe (outside North America and Europe).

LNLG:

- OCO-2 land data is less precise and accurate than IS data but is generally high quality (remaining regional biases may be present).
- Global land coverage (particularly during the summer), but seasonal data gaps.

LNLGIS:

- Combined information of in situ and OCO-2 land data, which betters fills observational gaps.
- Main concern is intercalibration errors between IS and LNLG datasets.

LNLGOGIS:

- Combines all data providing very dense observation constraints.
- Still significant concerns about OCO-2 ocean data which means great caution is needed.

Methods - CO_2 flux inversions

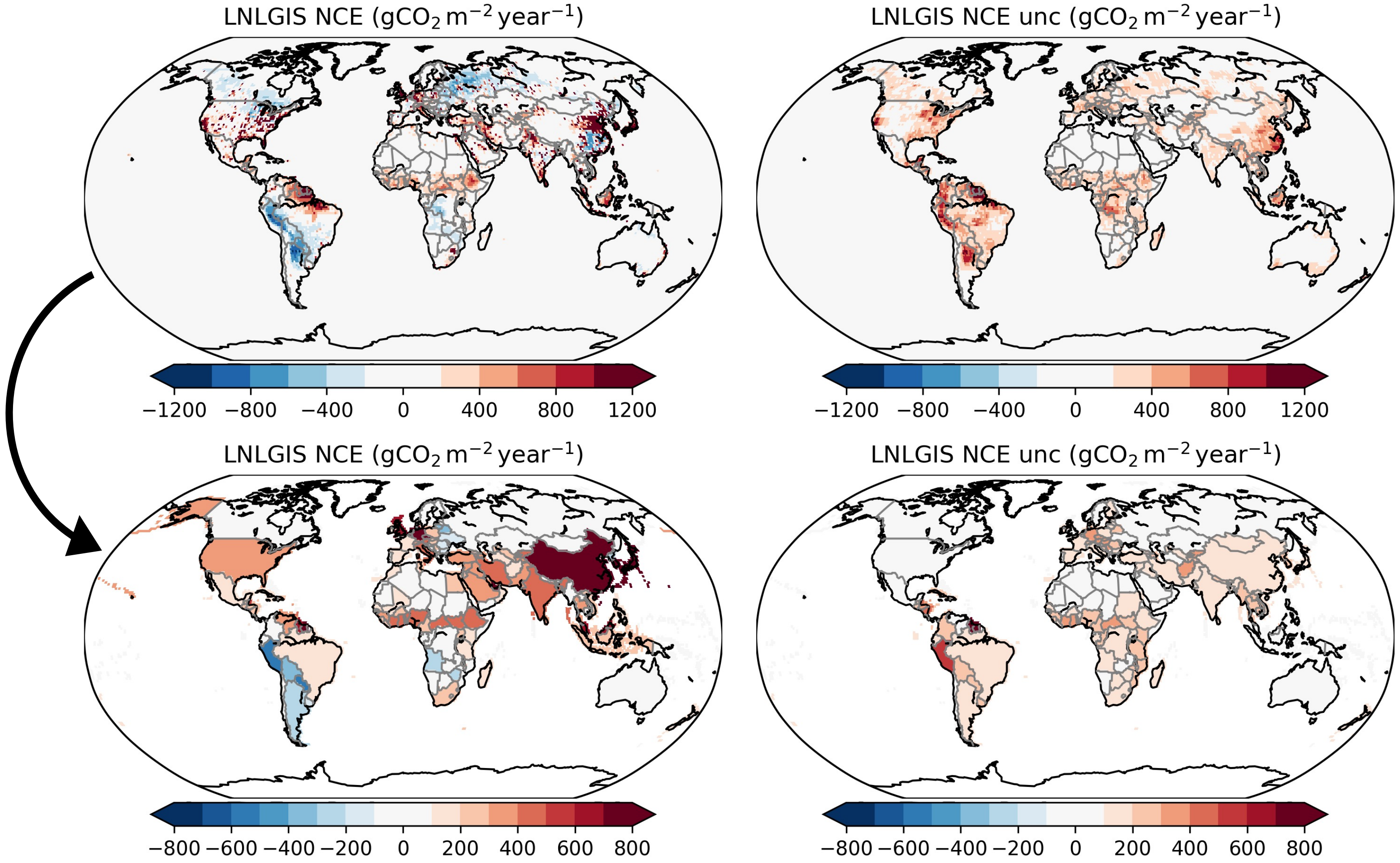
Each modeling group estimates the **Net Carbon Exchange (NCE) = Fossil Fuel + Net Biosphere Exchange**

- Estimates provided on a 1° x 1° grid.
- We aggregate to country totals.
- Take model median as best estimate.
- Uncertainty is estimated as the standard deviation across model estimates.

Net Carbon Exchange (NCE) for 2015–2020

Median **Uncertainty**

NCE fluxes Aggregated to Country Totals



Methods – Carbon stockchange

Enabling Comparisons with Inventories

- The global stocktake examines changes in land carbon stocks (for AFOLU sector).
- **Land carbon stock loss (ΔC_{loss})** estimated by combining top-down NCE with other carbon flux datasets.
- Calculate:

$$\Delta C_{loss} = NCE - FF - F_{crop\ trade} - F_{wood\ trade} - F_{rivers\ export}$$

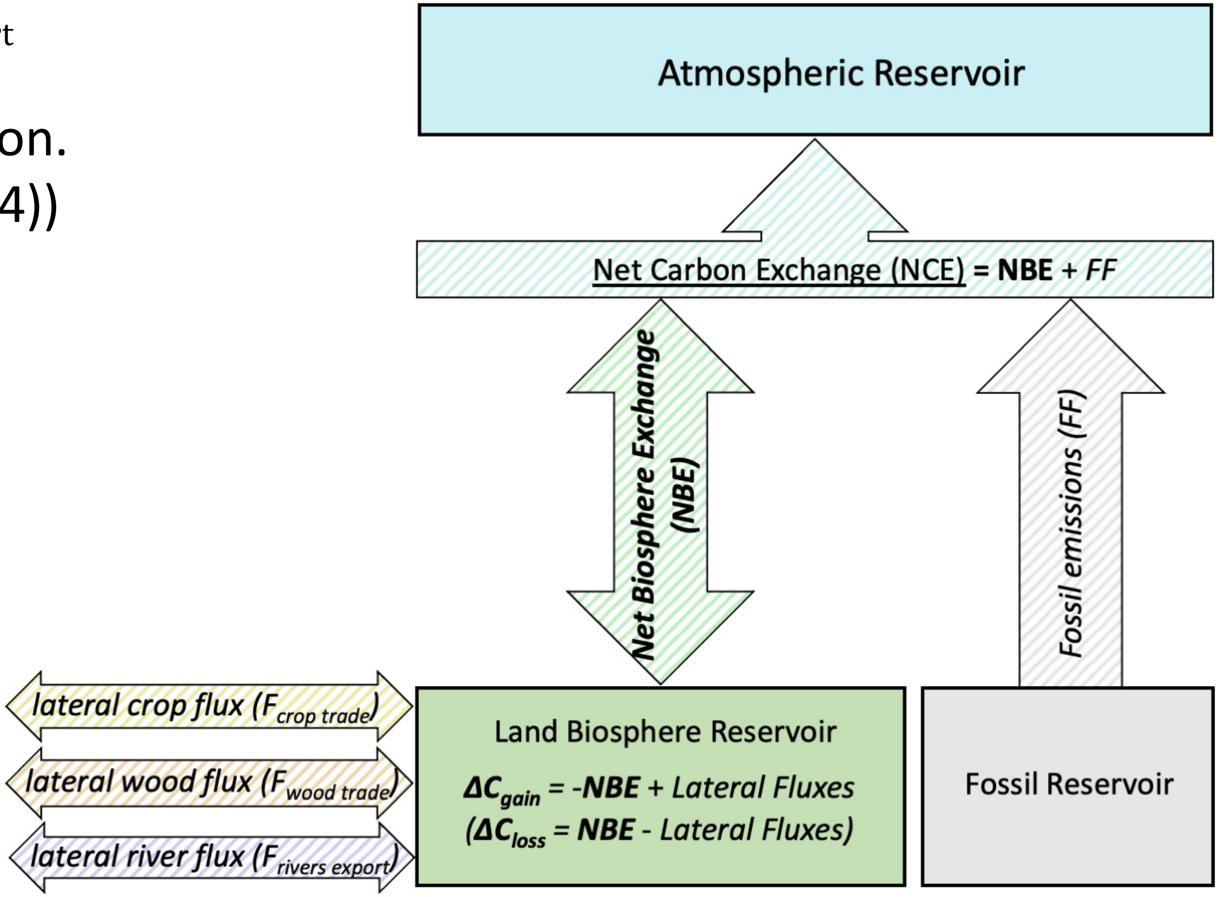
FF: CO_2 emissions from fossil fuels and cement production. (ODIAC w/ fractional uncertainties of Andres et al. (2014))

$\mathbf{F_{crop\ trade}}$: lateral flux of carbon due to farming (Deng et al. 2022, assume std = 30%).

$\mathbf{F_{wood\ trade}}$: lateral flux of carbon due to wood harvesting. (Deng et al. 2022, assume std = 30%).

$\mathbf{F_{rivers\ export}}$: lateral flux of carbon due to rivers. (mean of Deng et al. 2022 and DLEM, Uncertainty = absolute difference)

Carbon fluxes for a given land region



Andres et al. (2014), Tellus B, https://doi.org/10.3402/tellusb.v66.23616
Deng et al. (2022), ESSD, https://doi.org/10.5194/essd-14-1639-2022

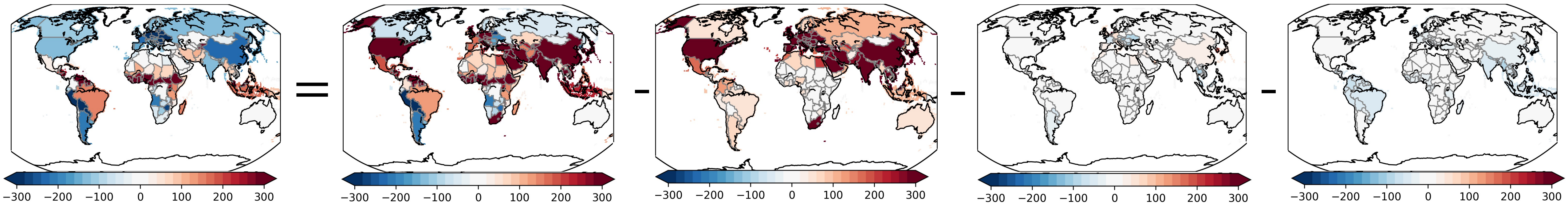
Methods – Carbon stockchange

Calculation of Land Carbon Stock Loss (ΔC) and Uncertainties

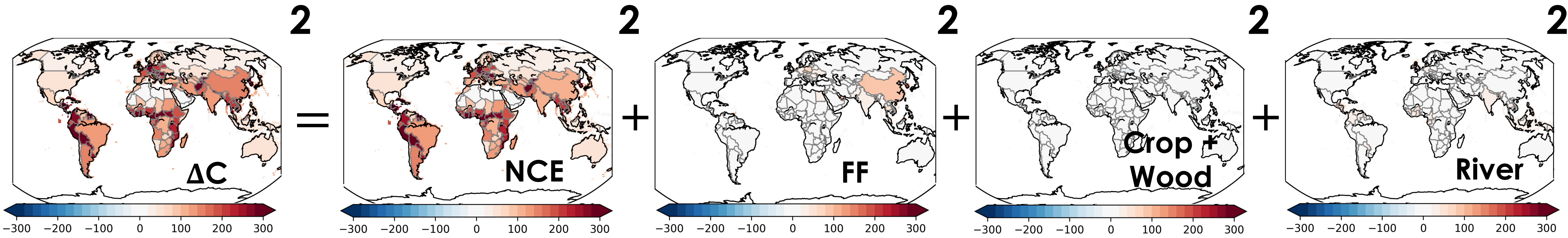
$$\Delta C_{loss} = \mathrm{NCE} - \mathrm{FF} - F_{crop\ trade} - F_{wood\ trade} - F_{rivers\ export}$$

Best Estimate of ΔC_{loss} for LNLG Experiment

LNLG ΔC_{loss} ($gCO_2\ m^{-2}\ year^{-1}$) | Model medial LNLG NCE ($gCO_2\ m^{-2}\ year^{-1}$) | FF ($gCO_2\ m^{-2}\ year^{-1}$) | $F_{crop\ trade} + F_{wood\ trade}$ ($gCO_2\ m^{-2}\ year^{-1}$) | $F_{rivers\ export}$ ($gCO_2\ m^{-2}\ year^{-1}$)



Uncertainty in ΔC_{loss} for LNLG Experiment



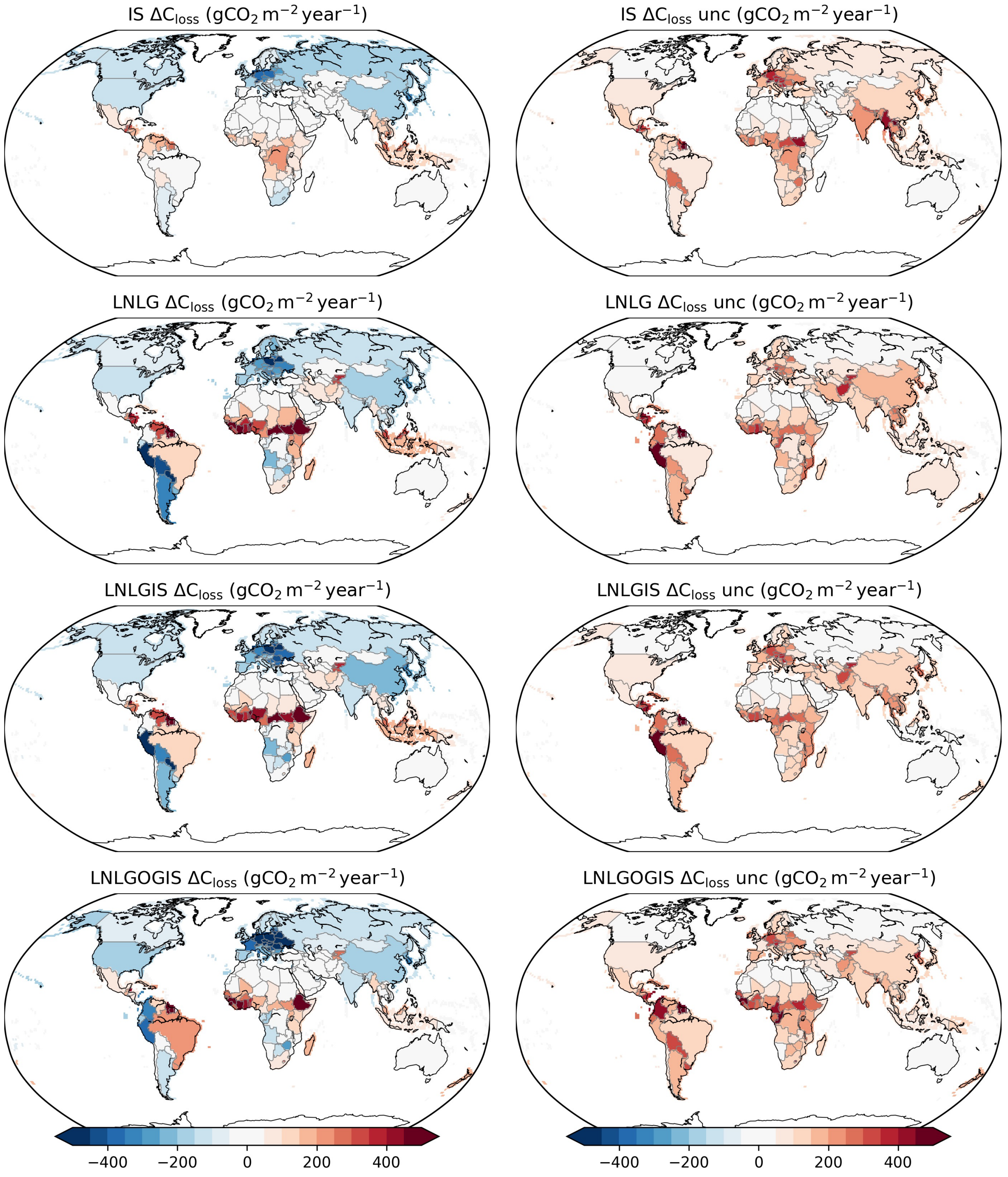
Results – Carbon stock loss

2015 – 2020 ΔC_{loss} for Each MIP Experiment

- ΔC_{loss} shows many consistent signals across the experiments.
    - Negative (land carbon gain) across northern high latitudes
    - Positive (land carbon loss) across tropics.

- However, some important differences appear
    - OCO-2 vs IS differences in tropics
    - Factors driving differences:
        - Lack of in situ data
        - Retrieval biases in OCO-2 XCO_2 retrievals

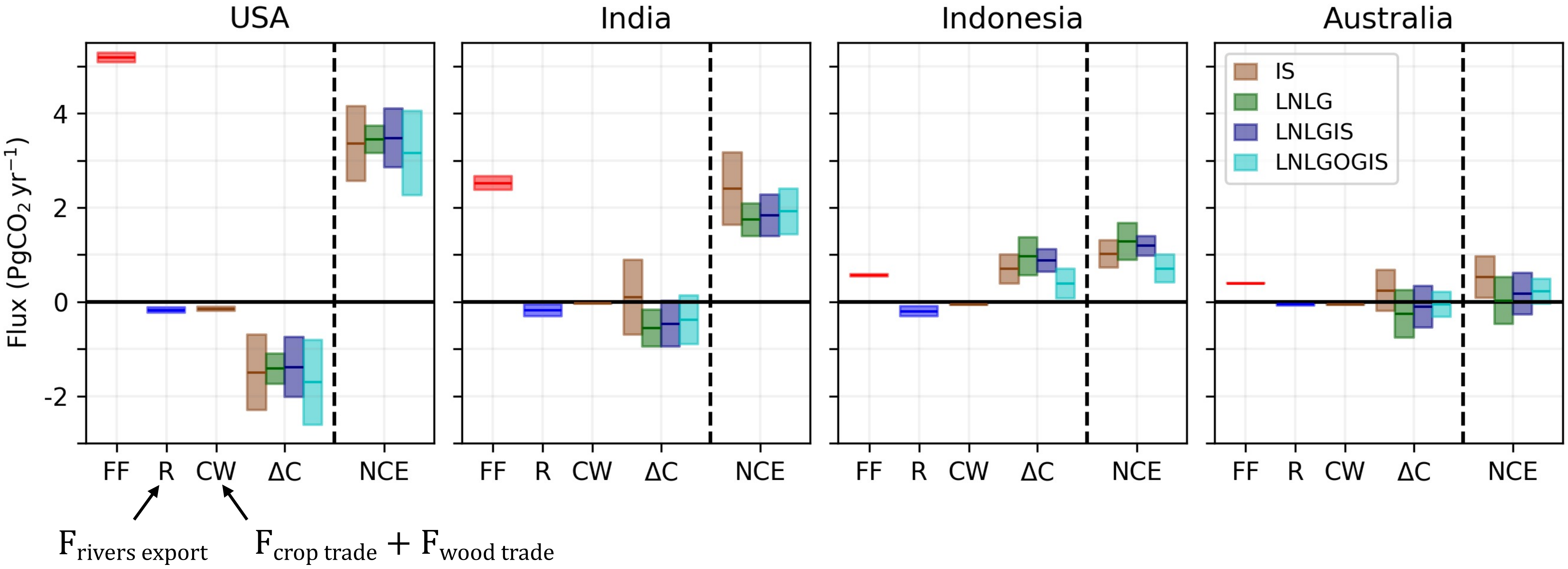
- We have the highest confidence in ΔC_{loss} estimates when they are consistent across all experiments (excluding LNLGOGIS).



2.1.4 Carbon Stock Loss

Example 2015–2020 Carbon Budgets for Four Countries

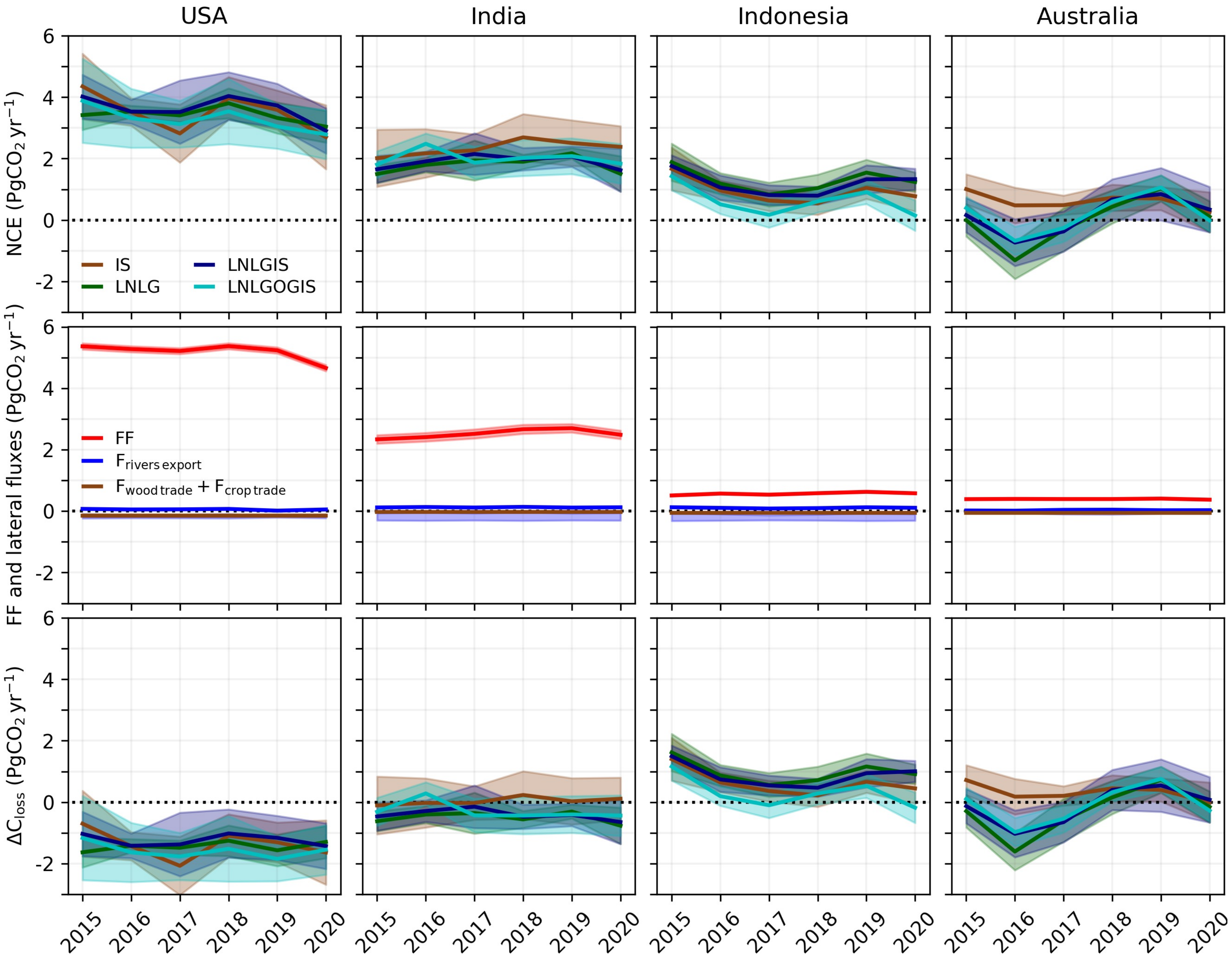
- Recall: $FF + F_{\text{crop trade}} + F_{\text{wood trade}} + F_{\text{rivers export}} + \Delta C_{\text{loss}} = NCE$
- Figure below shows how each component contributes to the NCE for a few specific countries, constrained by atmospheric CO_2 measurements.
- Increasing land carbon stocks decrease NCE relative to FF emissions for USA, but the opposite occurs for Indonesia.



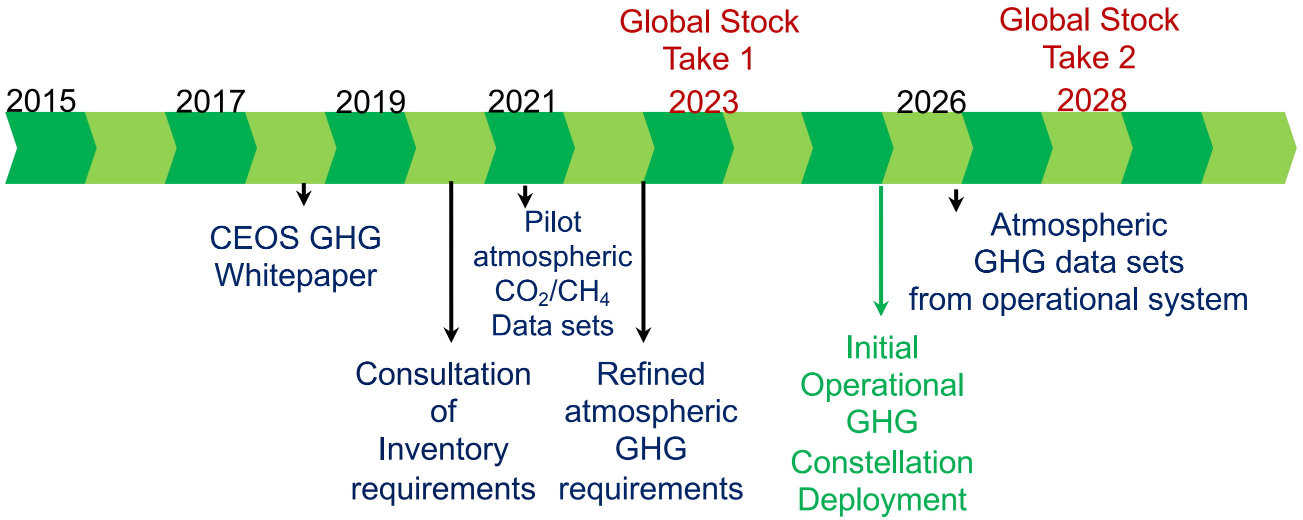
2.1.4 Carbon Stock Loss

Example Carbon Budget Time Series for Four Countries

- Provide annual net fluxes for six years covering 2015 through 2020.
- Interannual variations in NCE are driven primarily ΔC_{loss} due to climate variability and trends in FF.
- Droughts reduce carbon uptake by the ecosystem. Variability associated with El Niño in the tropics is a strong driver of variability in ΔC_{loss}.



Lessons learned and path forward



Lots of Obs in pipeline

- Data-dense GeoCarb, CO2M and GOSAT-GW
- Regional expansions of in situ measurements.

Keys to future success:

- **Increased ground-based and aircraft-based CO_2 measurements in poorly sampled regions will identify retrieval biases and improve confidence.** Some regions show substantial differences between OCO-2 and in situ inversions that are not well understood. Need more independent CO_2 data in tropics.
- **Uncertainty quantification should incorporate Bayesian uncertainties.** Spread between flux inversion ensemble members largely captures systematic errors (model transport, inversion set-up) but not Bayesian component.
- **Refine inversions systems.** Including adding missing processes (e.g., atmospheric CO_2 production).

Acknowledgments

The research carried out at the Jet Propulsion Laboratory, California Institute of Technology, was under a contract with the National Aeronautics and Space Administration.