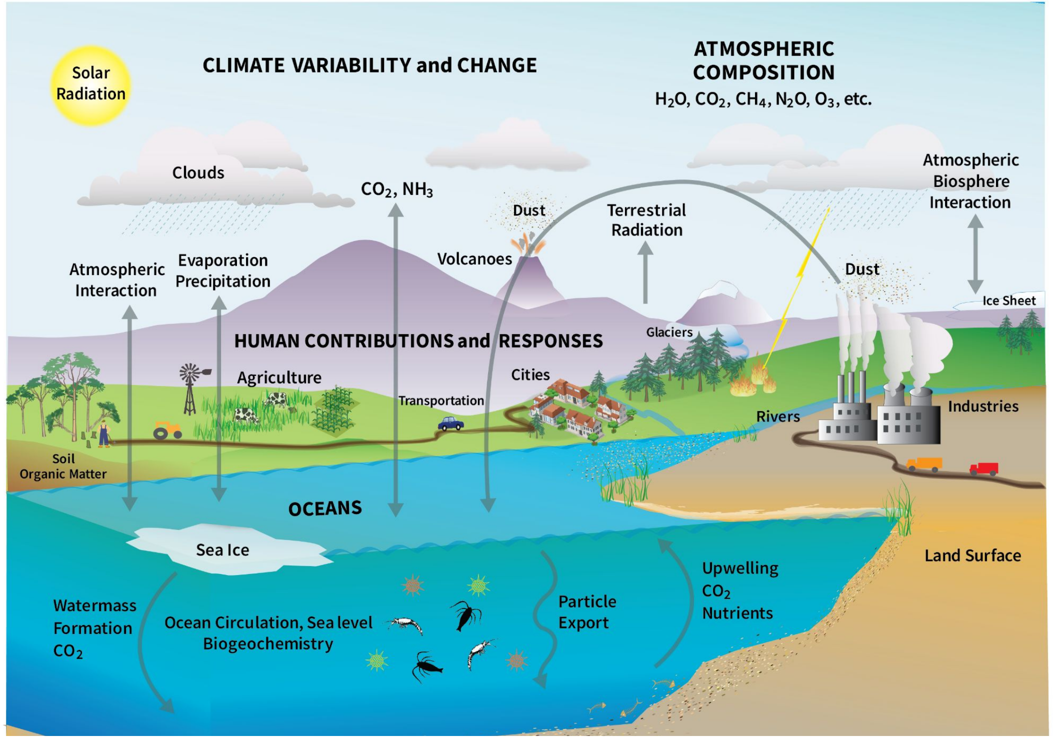
Earth System Interactions and Processes: Understanding, Predictions and Projections

John Dunne

Q2: Concerning NOAA's key mission element of understanding, predicting, and projecting changes in the Earth System, how can GFDL drive further advances in these areas, including extremes and environmental hazards, through scientific innovation based on observations, theory, and modeling? Where are the strengths, gaps, and new frontiers?

GFDL models the complex Earth system representing fundamental processes and interactions, including contributions from across the lab for GFDL-ESM4.1

Dunne, Horowitz, Adcroft, Ginoux, Held, John, Krasting, Malyshev, Naik, Paulot, Shevliakova, Stock, Zadeh, Balaji, Blanton, Dunne, Dupuis, Durachta, Dussin, Gauthier, Griffies, Guo, Hallberg, Harrison, He, Hurlin, McHugh, Menzel, Milly, Nikonov, Paynter, Ploshay, Radhakrishnan, Rand, Reichl, Robinson, Schwarzkopf, Sentman, Underwood, Vahlenkamp, Winton, Wittenberg, Wyman, Zeng, Zhao (2020, GMD)



The best performing model, GFDL-ESM4, has about 4 times more influence than it would have without weighting” Brunner et al., ESD, 2020)

Contributions to IPCC Multimodel Assessment include **Historical climate** and **Scenario Projections** of temp., precip., overturning and sea level rise; Estimation of **Transient Climate Response**, **Equilibrium Climate Sensitivity**, **Transient Climate Response to cumulative Emissions**, **Zero Emission Commitment**, Remaining Carbon budgets; Changing Short-Lived Climate Forcers (**SLCF**s) and overall radiative forcing

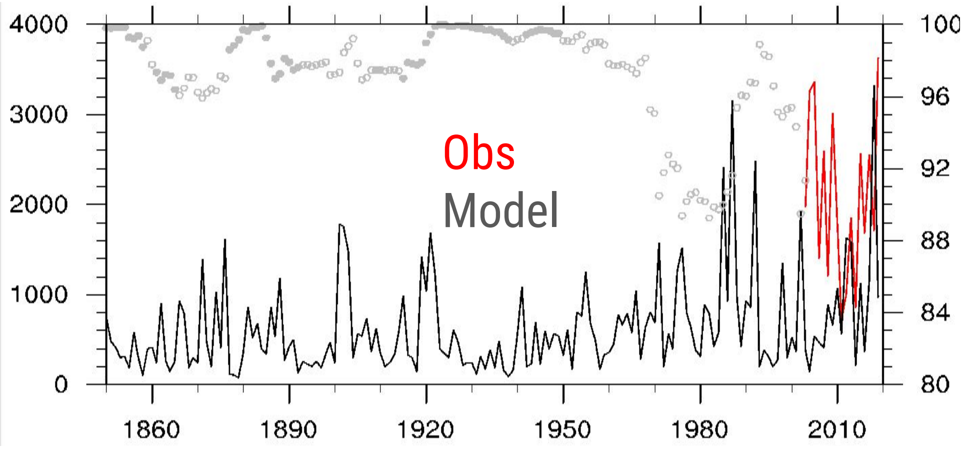
Lead author: Lee, J-Y, J Marotzke, G Bala, L Cao, S Corti, **J P Dunne**, et al., 2021: Future Global Climate: Scenario-based Projections and Near-term Information In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, pp. 553–672, doi:10.1017/9781009157896.006553-672.

Coordinating lead author: Szopa, S., **V. Naik**, et al. 2021: Short-Lived Climate Forcers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press,, pp. 817–922, doi: 10.1017/9781009157896.008.

See prerequisite slides on GFDL’s participation in Assessments and MIPs for more information

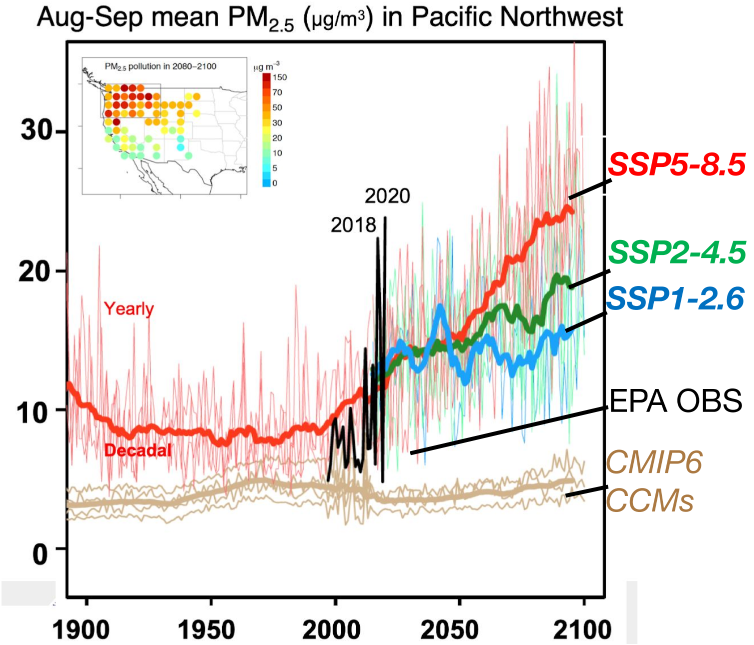
Past and Future Increase in North American Wildfire

ESM4.1 identified an increased risk of fires in Alaska from a climate-mediated increase in fuel Statistically significant difference during 2003-2019



The grey circles represent percentile of 2019-like event in 17-year window and likelihood that the 2019 extreme event falls outside of the historical statistical distribution. (Y. Yu, et al., 2021, BAMS)

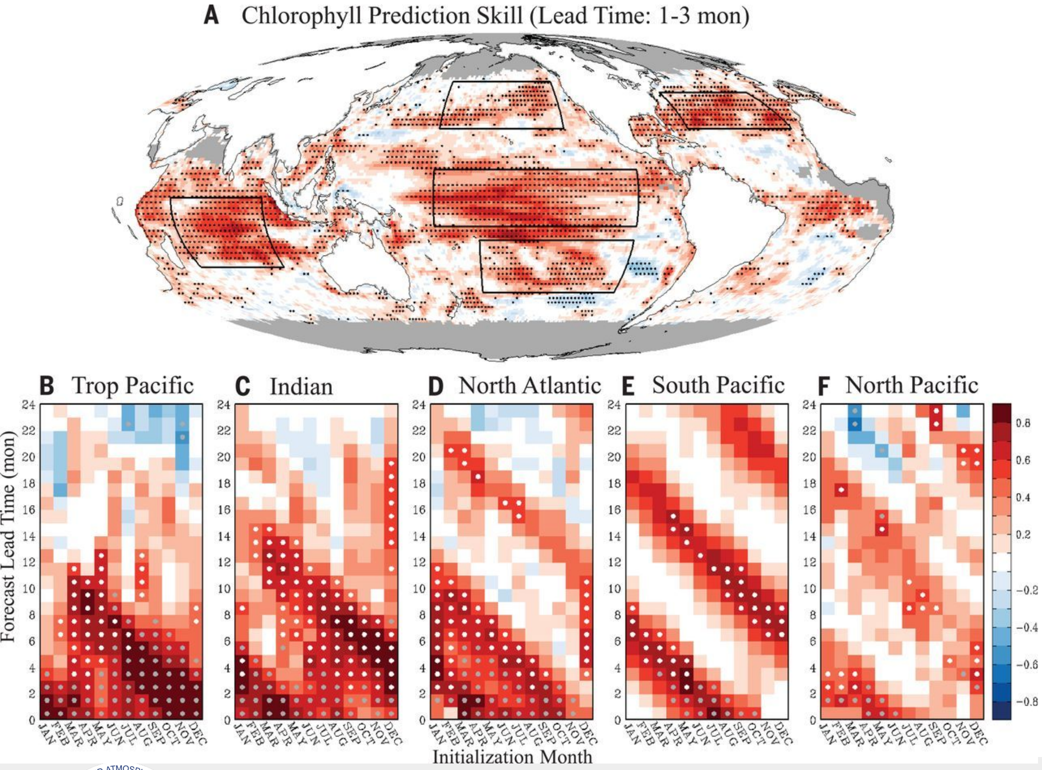
North American wildfire impacts on air quality extremes

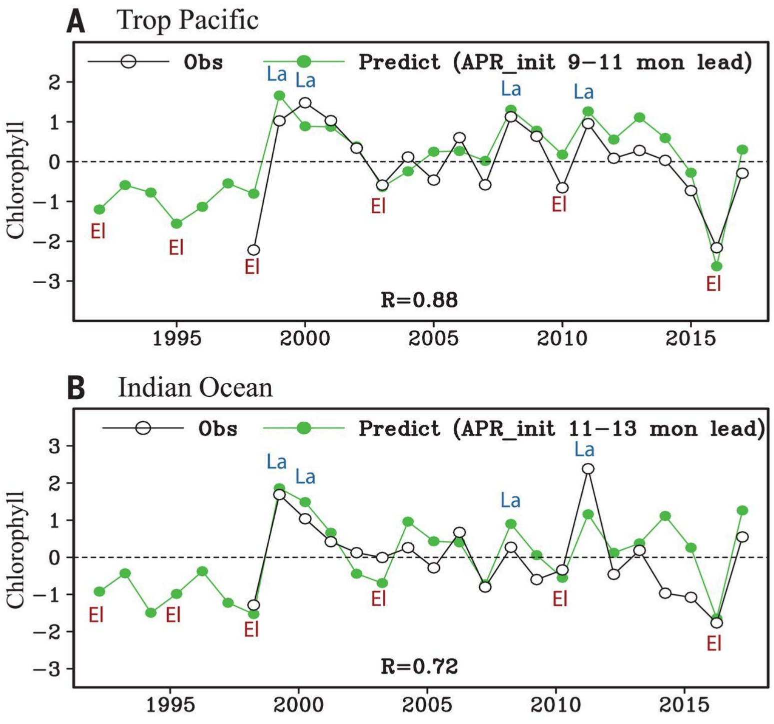


Projected scenarios suggest Pacific Northwest wildfire smoke may triple in a warming climate; 2020/2023 new norm (Xie et al., 2022, PNAS)

Ocean Biogeochemical Predictability and Prediction

Park et al., 2019, Seasonal to multiannual marine ecosystem prediction with a global Earth system model, Science





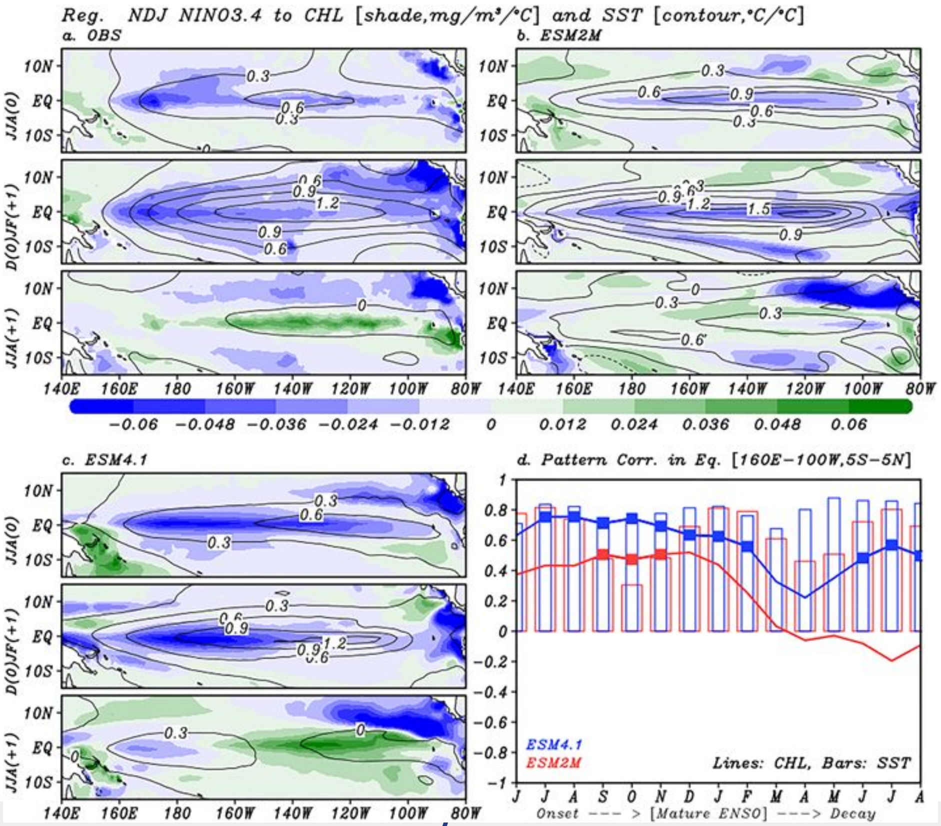
Representation of post-El Niño Chlorophyll Rebound

The observed post-El Niño chlorophyll anomaly, "chlorophyll rebound," in the equatorial Pacific is successfully simulated in GFDL-ESM4.1

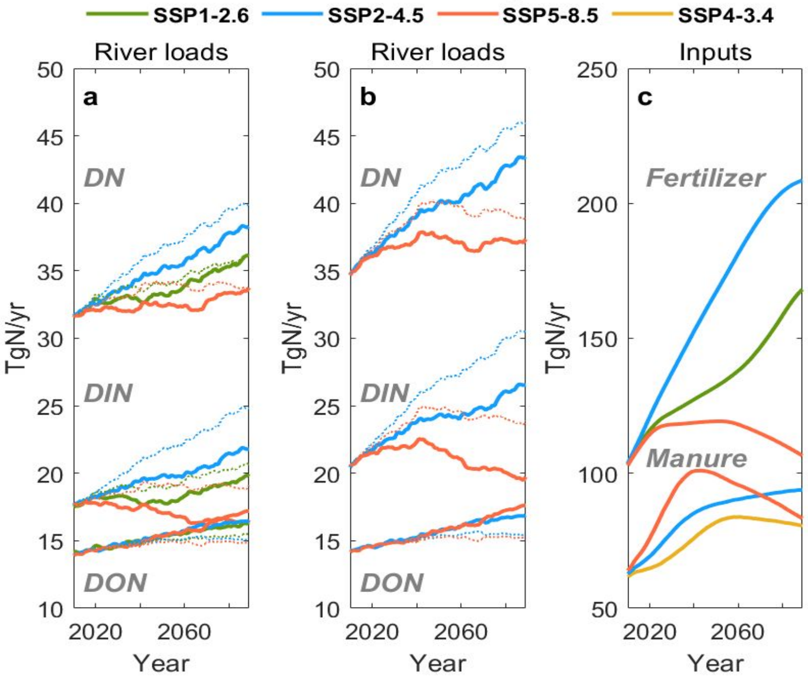
This rebound is primarily driven by surfacing high iron anomalies propagated from western Pacific via Equatorial Undercurrent

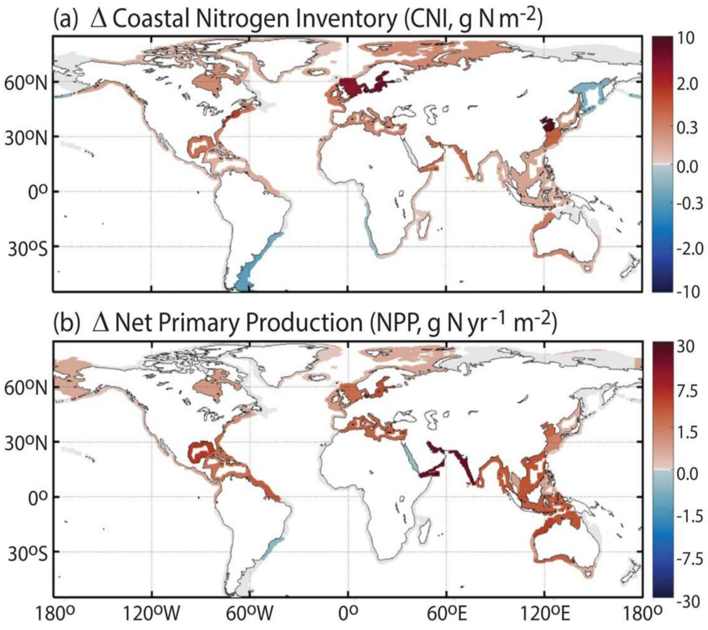
Contrary to previous theory, this chlorophyll rebound does not depend on La Niña following El Niño.

Lim et al., Oceanic and Atmospheric Drivers of Post-El-Niño Chlorophyll Rebound in the Equatorial Pacific. Geophysical Research Letters, 49, 5, 2022, DOI:10.1029/2021GL096113



Past and future of nitrogen pollution from land to oceans (LM3-TAN)





Lee et al., ERL, 2021

Liu et al., GRL, 2021

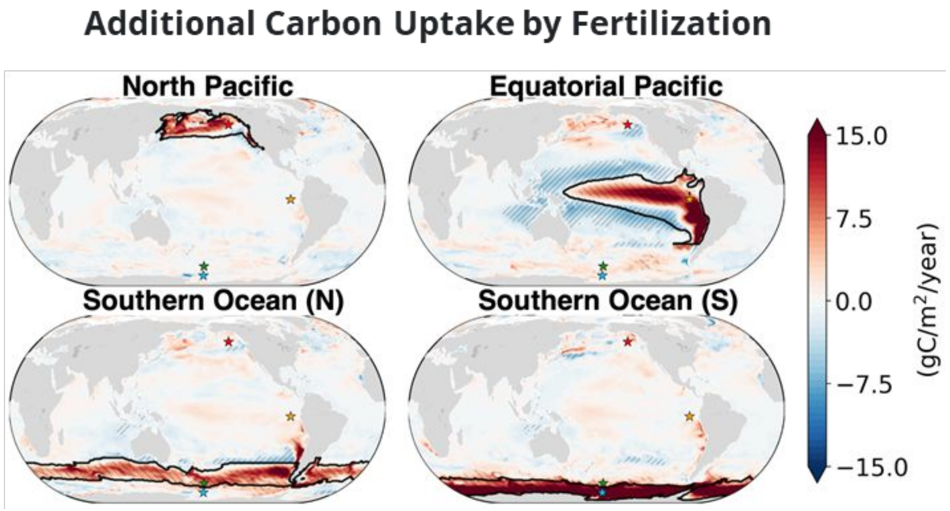
Lee et al., GMD, 2024

Unintended consequence of land-based carbon mitigation -> increased N coastal pollution, mostly in developing countries.

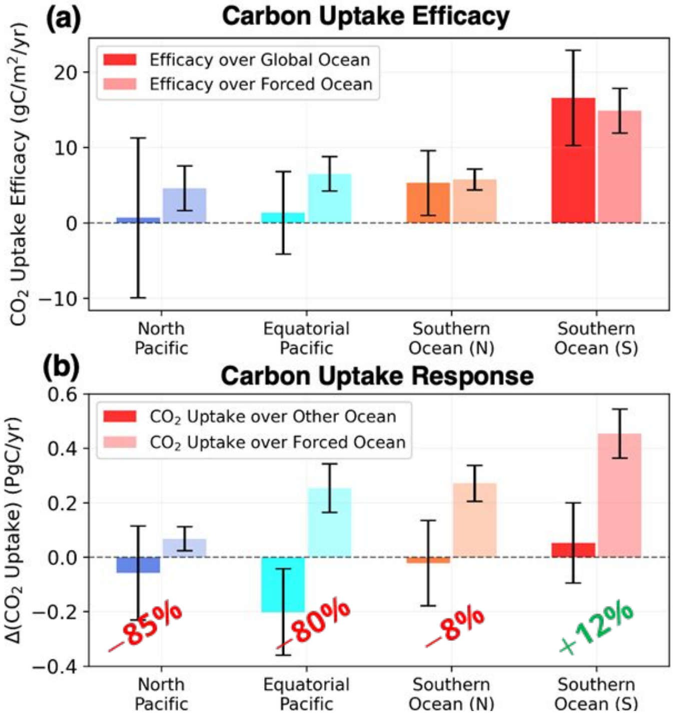
River N loads to coastal systems are increasing (1960-2010)

Coastal ecosystem responses to increasing river N loads vary considerably across the globe

Carbon uptake under Iron Fertilization largely compensated outside the Southern Ocean

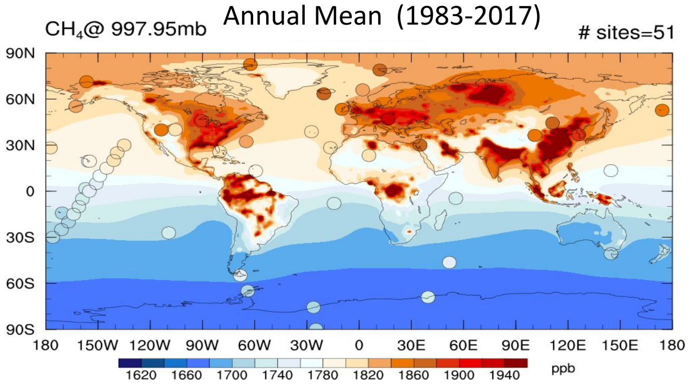


- Carbon uptake efficacy highest in the Southern Ocean
- Carbon uptake mostly compensated elsewhere, meaning little "additionality" (Noh et al., submitted)

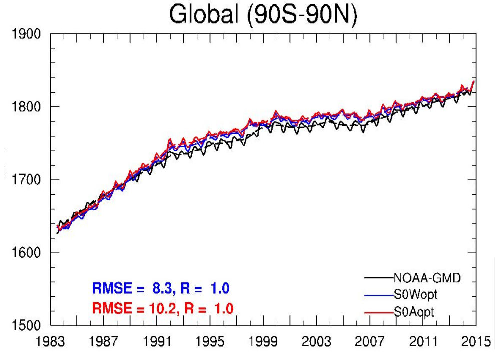


Understanding and attributing changes in SLCFs for improved predictions of AQ and Climate responses

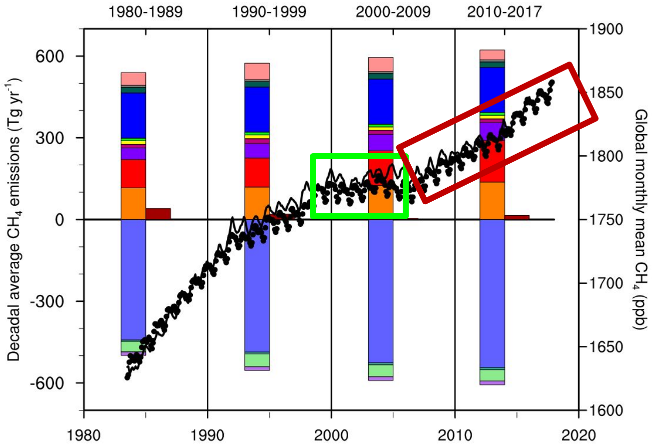
CH_4 emission-driven AM4 is able to capture observed methane latitudinal variation, trend, and variability



CH_4 (ppbv)



Renewed CH_4 growth is likely due to increasing methane sources rather than reduced sinks



He et al., *ACP*, 2020

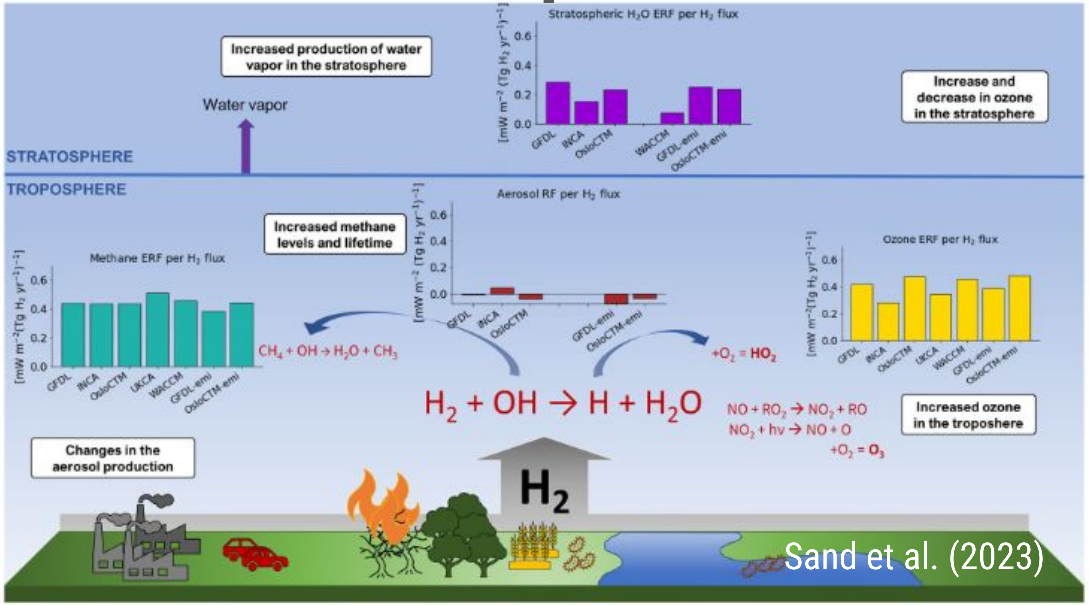
Pause in growth due to increasing methane sources balanced by increasing sinks

also see Stevenson et al. (2020), He et al (2021), and Chua et al. (2023) for attribution of trends in hydroxyl, sink for methane

Quantifying the environmental implications of an "H_2 economy"

ESM4.1 represents the impact of H_2 oxidation on CH_4 lifetime, O_3, and stratospheric water

- **H_2 ERF** (Paulot et al., *IJHE*,2021; Chua et al., *in prep*) and **H_2 GWP** (Sand et al., *CEE*, 2023) - collaboration with CICERO
- **H_2 and AQ** (Chua et al., in prep)
- **H_2-CH_4 coupling** (Bertagni et al., *Nature Com*, 2022)) - collaboration with Princeton University
- **Climate implications of greater H_2 usage** (Hauglustaine et al., *CEE*, 2022) - collaboration with IPSL



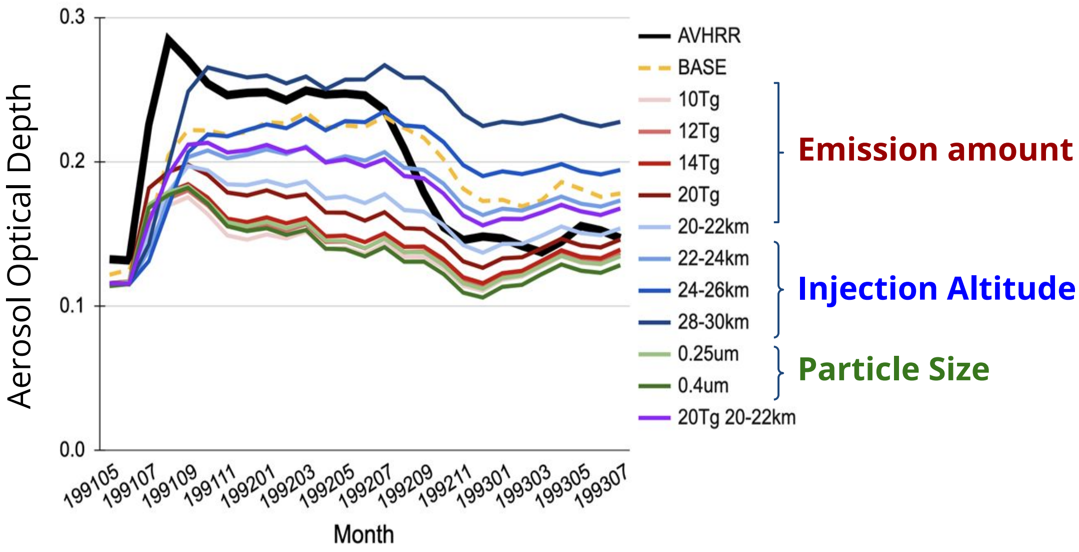
Sand et al. (2023)

- H_2 GWP (indirect) is ~12 (2-3x greater than assessments)
- Green H_2 offers clear benefits in terms of radiative forcing. H_2 produced using CH_4 (grey/blue) is much less advantageous from a radiative standpoint
- Need for additional research on land sink/natural sources

Fabien Paulot, Glen Chua

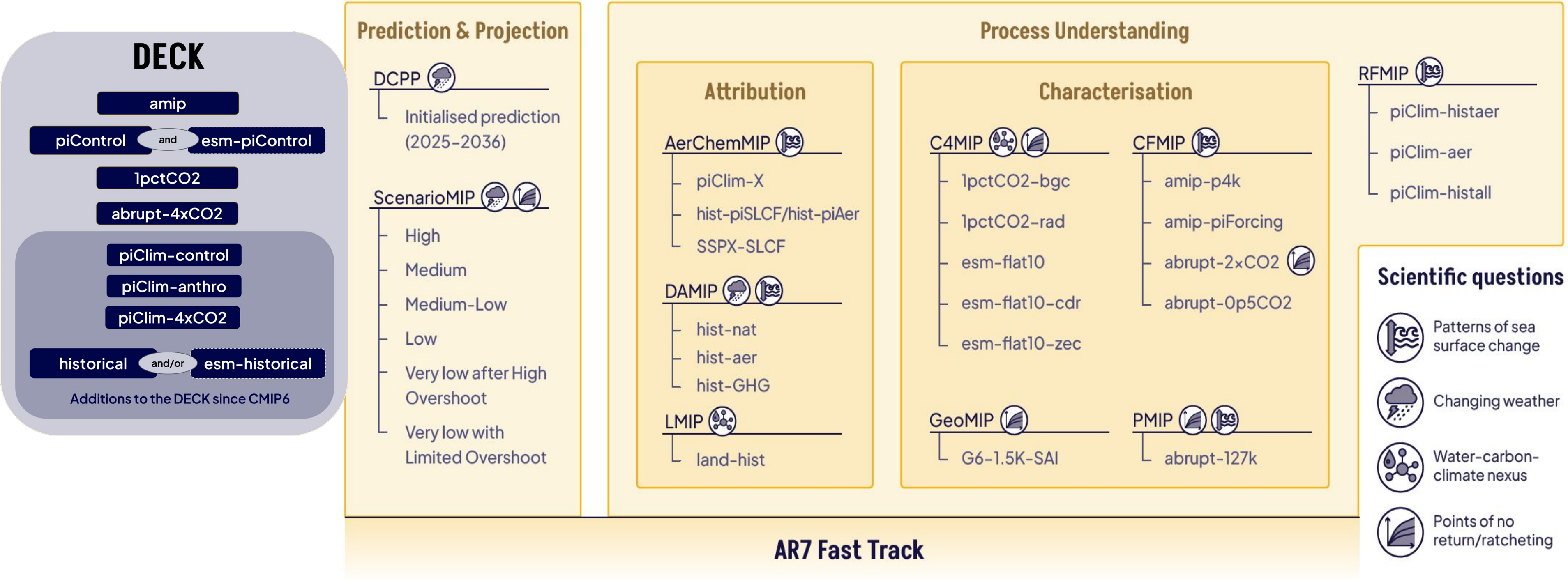
GFDL-ESM Representation of Natural and Human Stratospheric Aerosol Injection

- Important to assess response to:
  - Volcanic eruptions such as Pinatubo (Gao et al., 2023)
  - Climate intervention strategies (see also *Mahfouz et al., 2023*)
- Highlight the need for improved aerosol process representation



Comparison of observed (**black**) Aerosol Optical Depth (AOD) with GFDL AM4.1 simulations with different assumptions of sulfur dioxide emissions amount & injection altitude, and aerosol particle size for the **Mt. Pinatubo eruption** (*Gao et al., JAMES 2023*)

GFDL-ESM4.5 in Coupled Model Intercomparison Project Phase 7



Dunne et al., submitted GMD

GFDL's Next Generation ESM4.5: "Fast Track" supporting IPCC/AR7 Science and Service

A. **Historical Earth System Changes:** Faithfully represent historical climate change, CO_2 responses and chemistry-climate interactions driven by emissions to assess changes in the Earth System.

B. **Climate Risks and Tipping Points:** Determine risks associated with stabilization at various global warming levels, including the likelihood of a wide range of tipping points (e.g. TIPMIP).

C. **Climate-Ecosystem Interactions:** Evaluate implications of too much or too little water for managed and unmanaged ecosystems, including at the sub-grid stakeholder relevant scale.

D. **Climate Mitigation and Intervention:** Evaluate the viability and implications of climate change mitigation strategies including climate intervention techniques (e.g., CDR, SRM).

Merge recent GFDL successes in climate and Earth system fidelity; Snow-dust-albedo interactions and snow physics improvements; Improved surface turbulent exchanges, Sea salt emissions; Reproduce historical temperature and CO_2 record.

Global coastal/shelf/slope marine ecosystems with expanded biodiversity and improved physiology and chemistry; Land management complexity; Improved soil carbon-microbial interactions and processes.

Interactive fire emissions; Sub-grid hydrological heterogeneity; Treeline parameterization for high latitudes and altitudes; Next generation soil microbial carbon representation

Improved representation of plant biogeography and land and ocean carbon sinks; Improvements to natural and anthropogenic aerosol and chemistry interactions; Applications with CO_2 emissions and removal forcing.

GFDL-ESM4 Addresses OAR Societal Challenges

Confronting Challenges from our Changing Climate

- Understanding past and projecting future climate and Earth System evolution
- ESM4 applications to coupled carbon-chemistry-climate, including emission projections and climate mitigation options

Protecting against extreme weather events and environmental hazards

- Application of regional refinement to atmospheric composition and air quality
- Fire, dust, SO_4, ozone, and air quality modeling under compound extremes (e.g., heat/drought)
- Eutrophication modeling

Managing too much and too little water

- Vegetation and hydrology modeling for drought and flood

Sustaining a healthy environment and economy

- Characterizing environmental change and impacts including air/water quality and acidification
- Supporting climate services of regional downscaling and impacts studies