NOAA Efforts in Chemical Data Assimilation and Inverse Modeling

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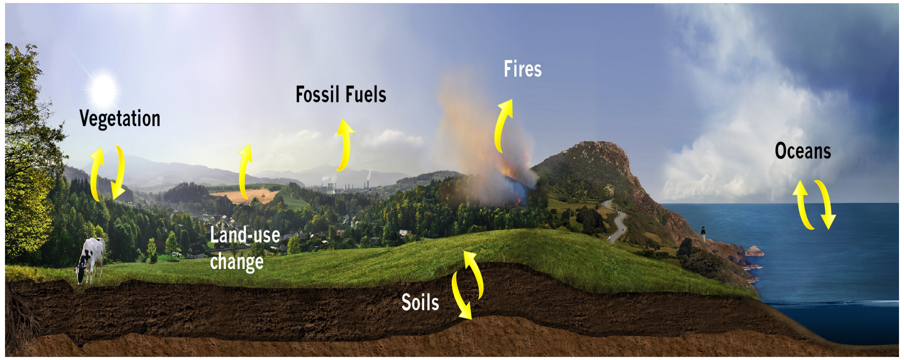
Atmospheric Carbon Data Assimilation and Flux Inversion

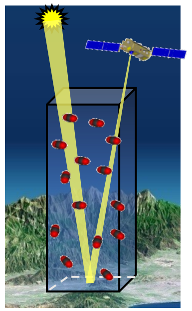
$$L_s = (\mathbf{H}s - z)^T \mathbf{R}^{-1} (\mathbf{H}s - z) + (s - s_p)^T \mathbf{Q}^{-1} (s - s_p)$$

Prior Flux Models



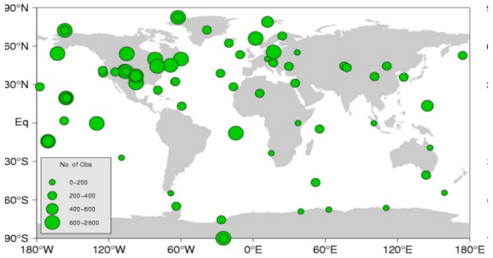
Credit: NASA/Jenny Mottar and Abhishek Chatterjee

Remotely- Sensed Column Data

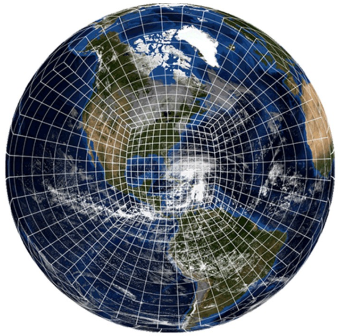


Profiles from aircraft

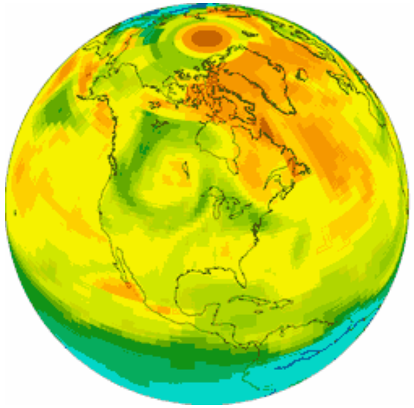
In Situ Surface Network Data

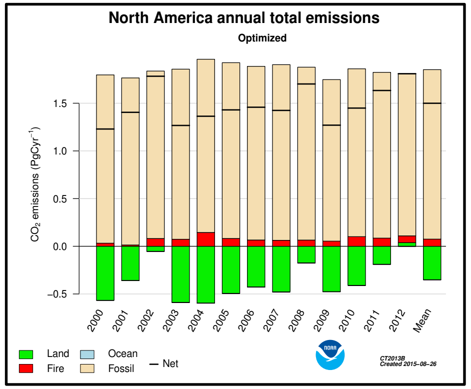


Atmospheric Transport Model+ DA/Inversion Techniques



Analyses



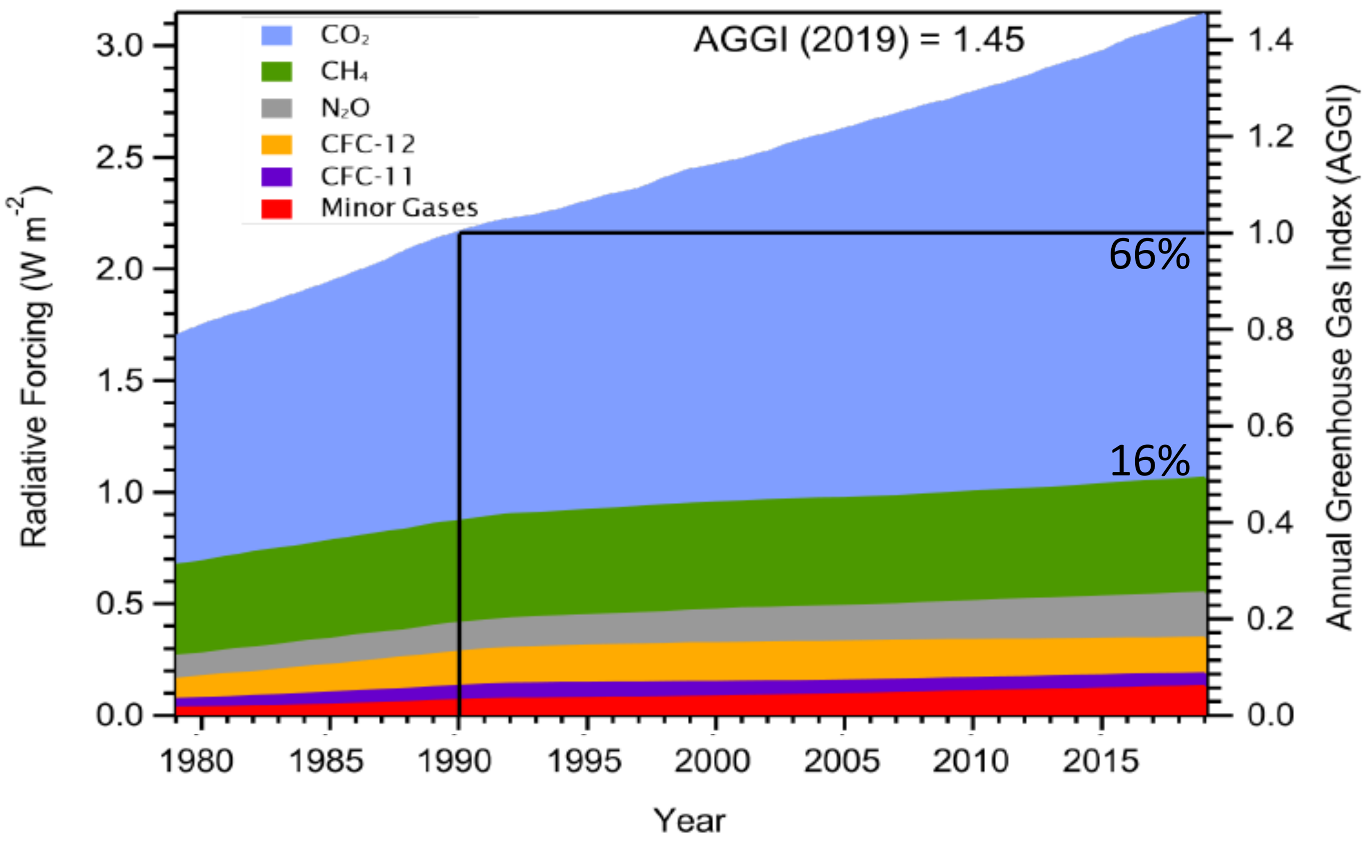


Estimated Fluxes

www.esrl.noaa.gov/gmd/ccgg/carbontracker/

www.esrl.noaa.gov/gmd/ccgg/carbontracker-ch4/

The Earth's Energy Budget



- *Radiative Forcing = human impact on Earth's energy budget since pre-industrial times. Units are Watts/meter^2. Based on NOAA network measurements.*

www.esrl.noaa.gov/gmd/aggi

The CO_2 contribution is rapidly increasing.

The GWP-100 of CH_4 is 28-36, but there is less of it in the atmosphere.

Using Climate-Chemistry Models (IPCC):

ΔT (CO_2) = 0.75 (0.25 – 1.25) ºC

ΔT (CH_4) = 0.5 (0.25 – 0.8) ºC **

****Includes chemical effects on other radiative forcers. CH_4 has an atmospheric lifetime of ~9-10 yrs.**

The Paris Agreement 5-Year Global Stocktake

Feedback between carbon cycle science and policy

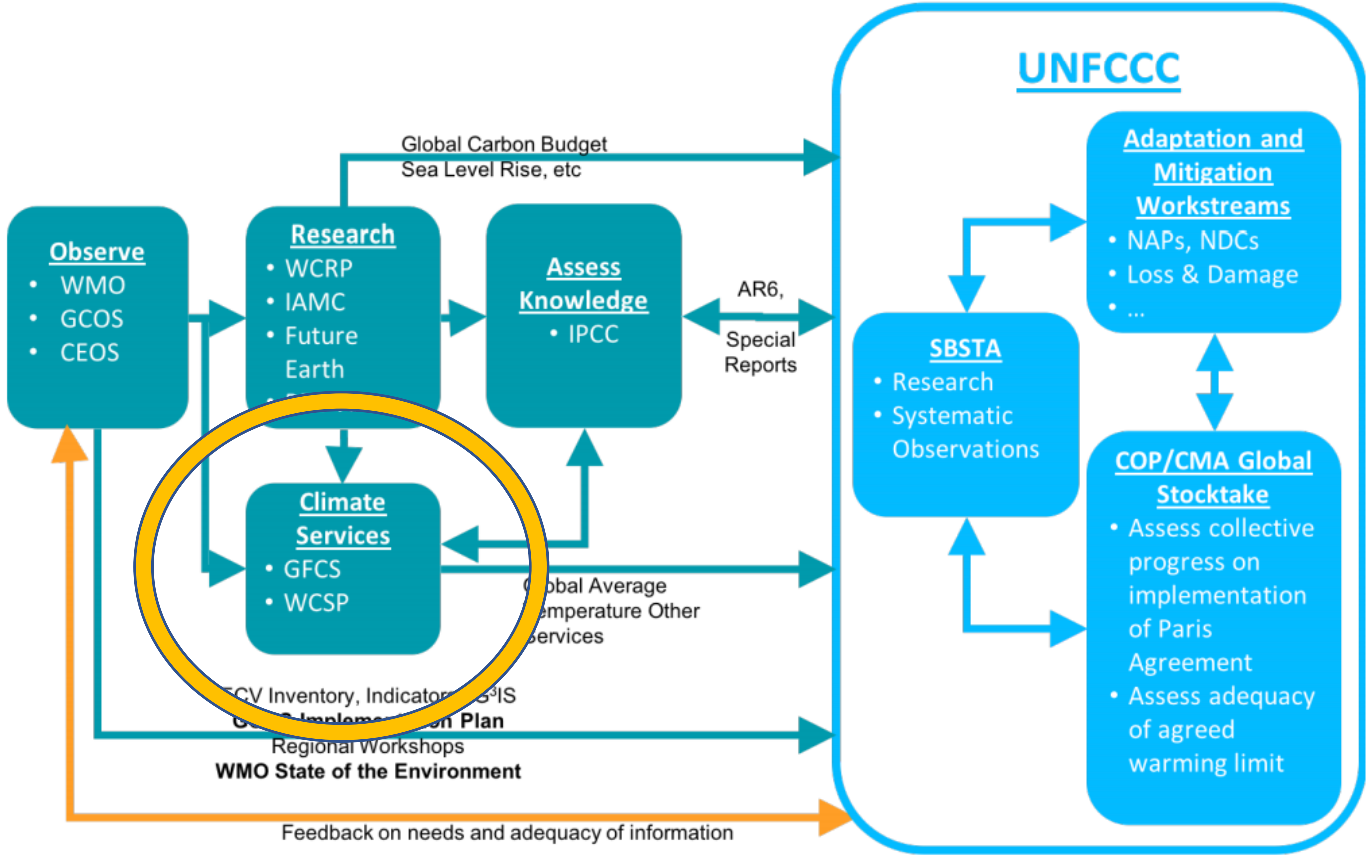


Figure 2 How science can drive climate policy and climate policy drive science. Note: the figure presents the main topics that have been considered at SBSTA 47 in Bonn (e.g. GCOS – IP and climate indicators, CEOS - ECV inventory, WMO - Regional Climate Centres).

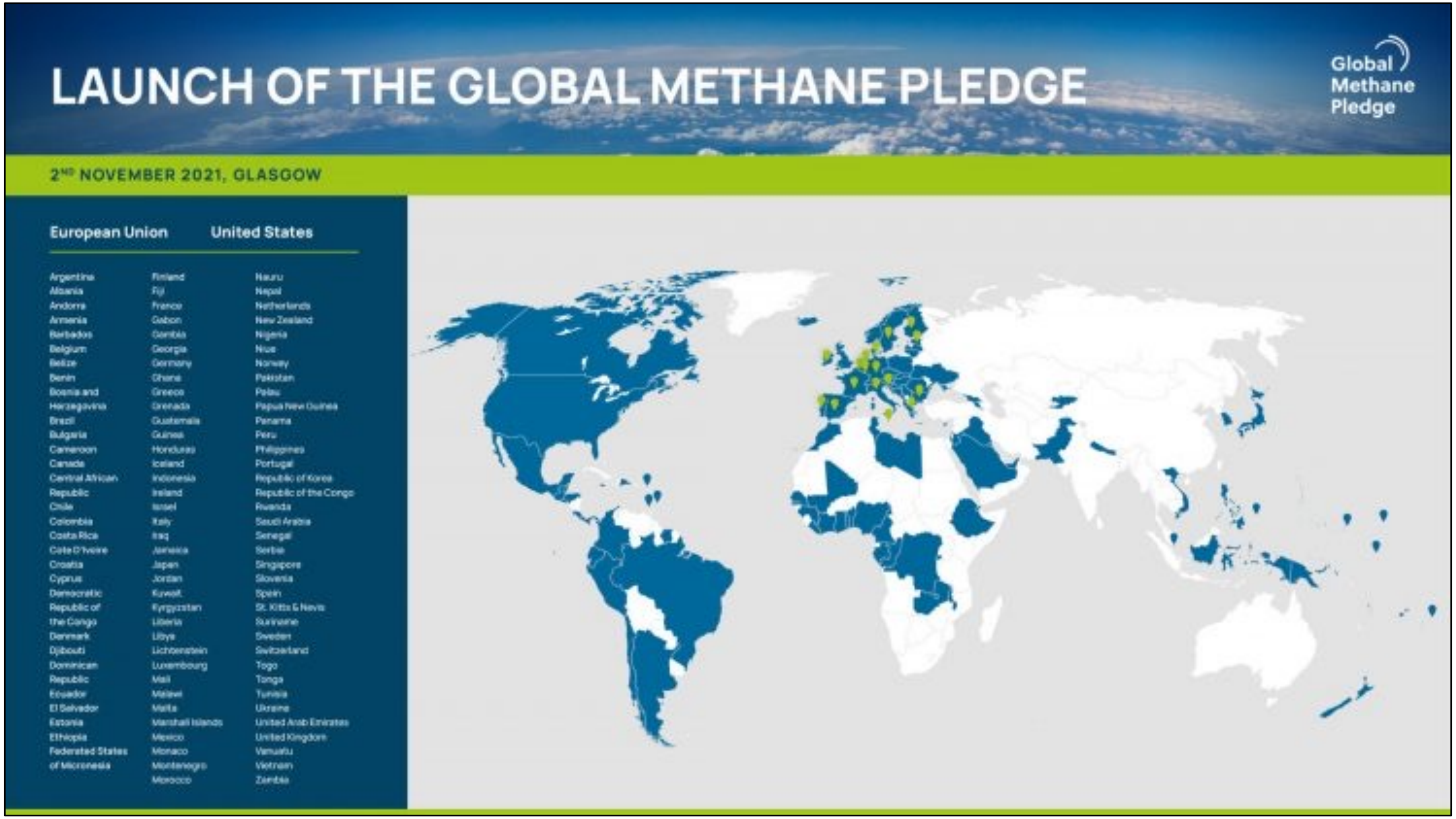
Source: GCOS Planning Document, https://library.wmo.int/doc_num.php?explnum_id=5417

Stocktake every 5 years to assess progress towards climate goals, and to inform more ambitious nationally determined contributions (NDCs) for the next 5 years.

An Issue: Lateral Fluxes, Distribution of Agricultural Products

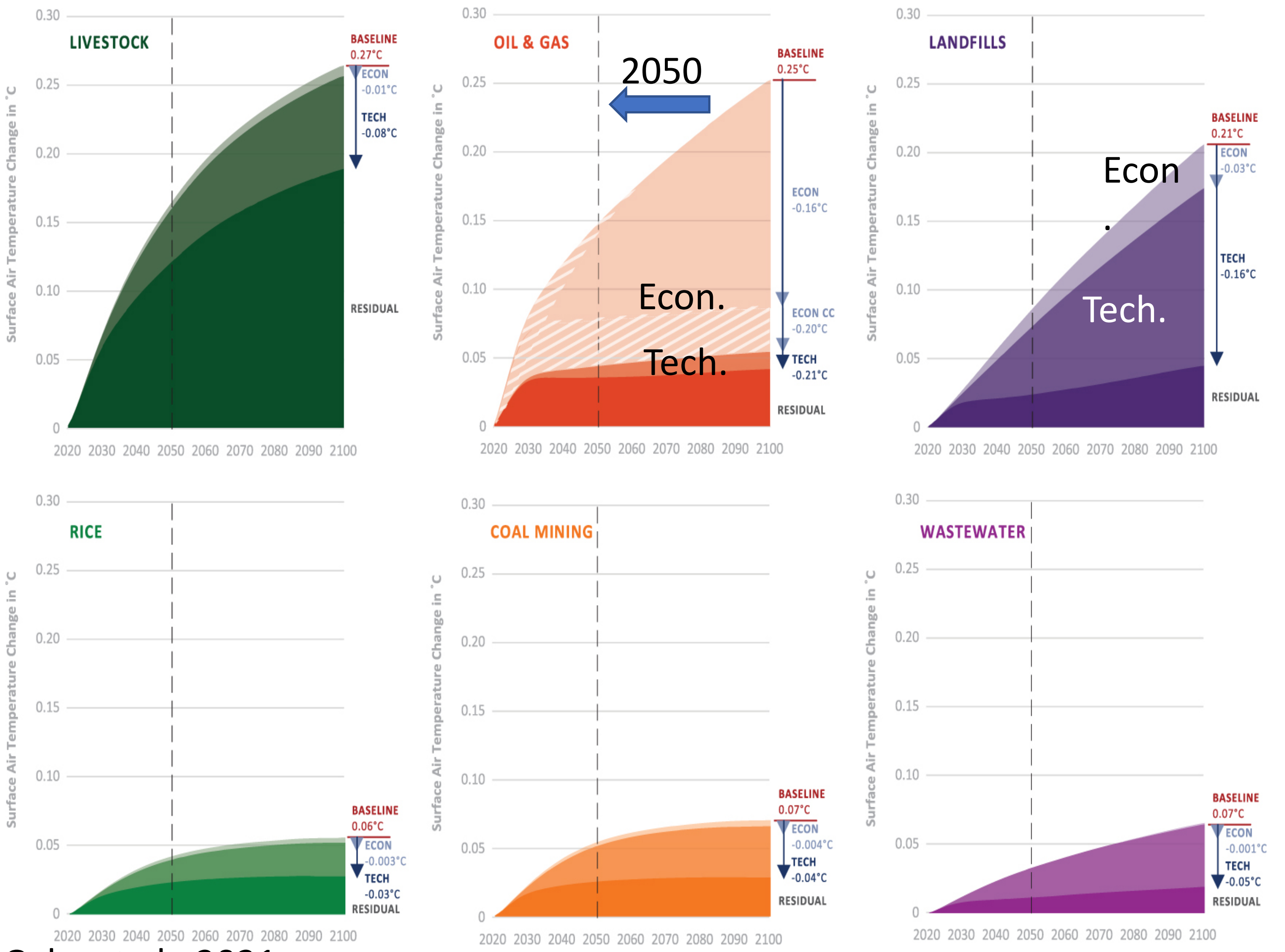
The Global Methane Pledge

Reduce Anthropogenic Emissions of CH_4 by 30% below 2020 levels by 2030



Some Major CH_4 Emitting Countries have not joined pledge

Most of the Reductions Will Need to Come From Oil & Gas



Ocko et al., 2021

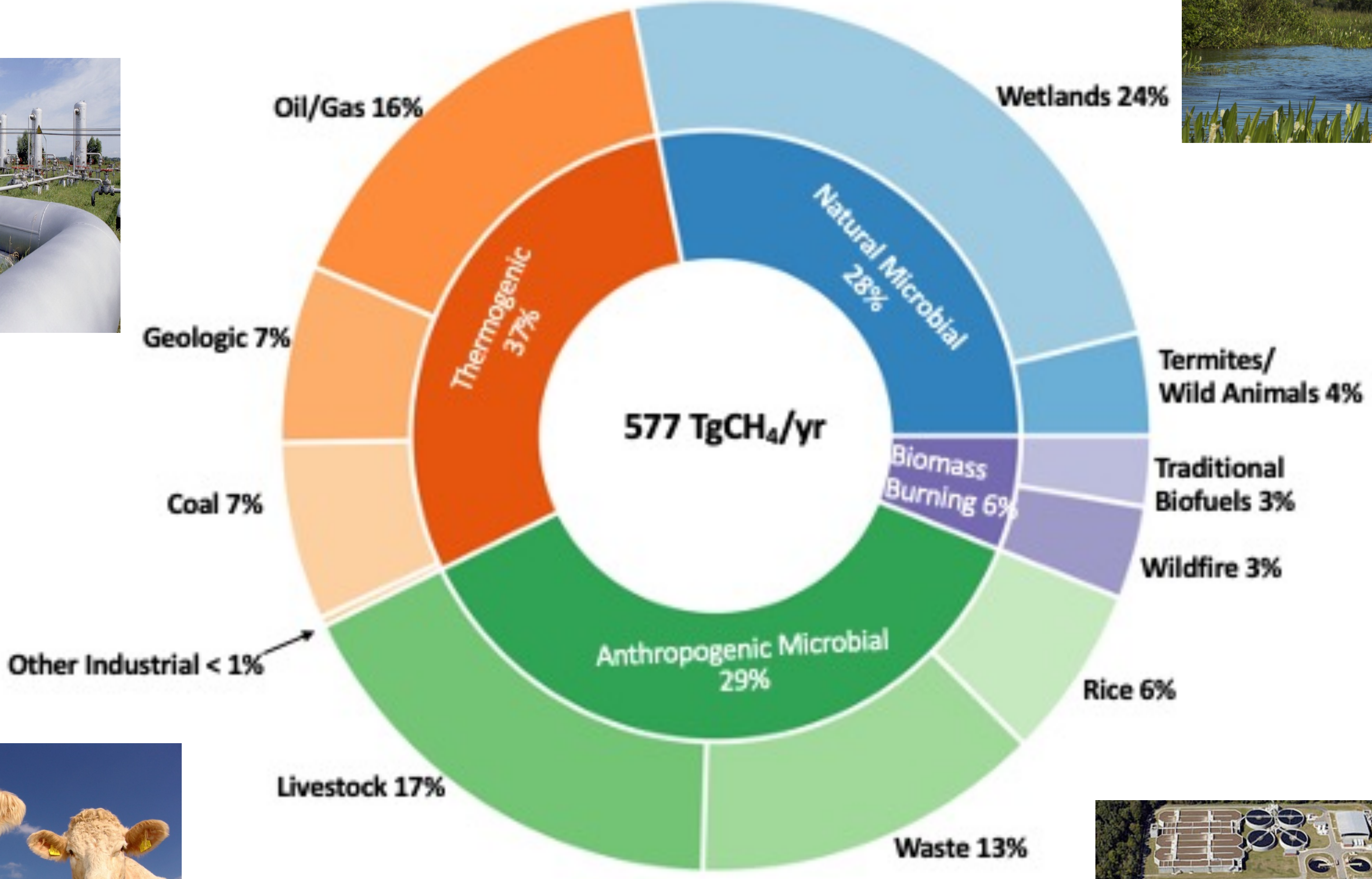
Most Reductions Have to Come From Oil and Gas

How Much Could Be Mitigated?

50-77% Relative to 2030 (Ocko et al., 2021)
45% Below Present (IEA)

A Wide Range of Human and Natural Activities Emit CH_4

A Plausible CH_4 Budget ca. 2015



Sources ≈ Chemical Destruction (Mostly Reaction with OH)

<u>Anthropogenic Emissions</u>
$TgCH_4$/yr

400 (69%)

Fossil = 215 (37%)

Microbial = 185 (32%)

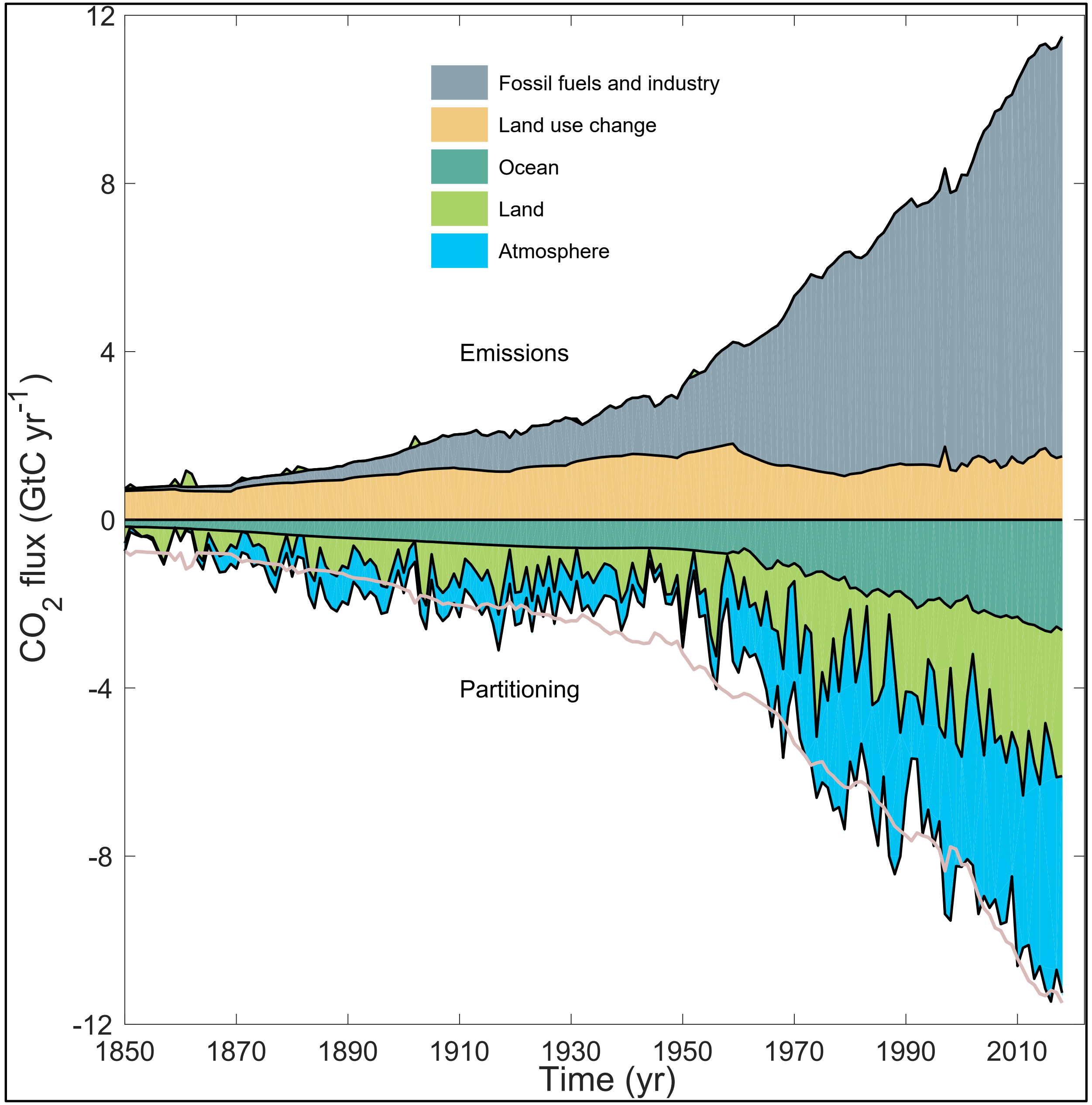
Methane Pledge Cuts = 120

(only about ½ of Fossil Emissions can be cut with current methane pledge signatories)

Earth System Services: For How Long?

Currently the oceans and terrestrial biosphere take up about ½ of the CO_2 emitted, and the rest accumulates in the atmosphere.

What will the implications be for productivity? How acidic will the oceans become?



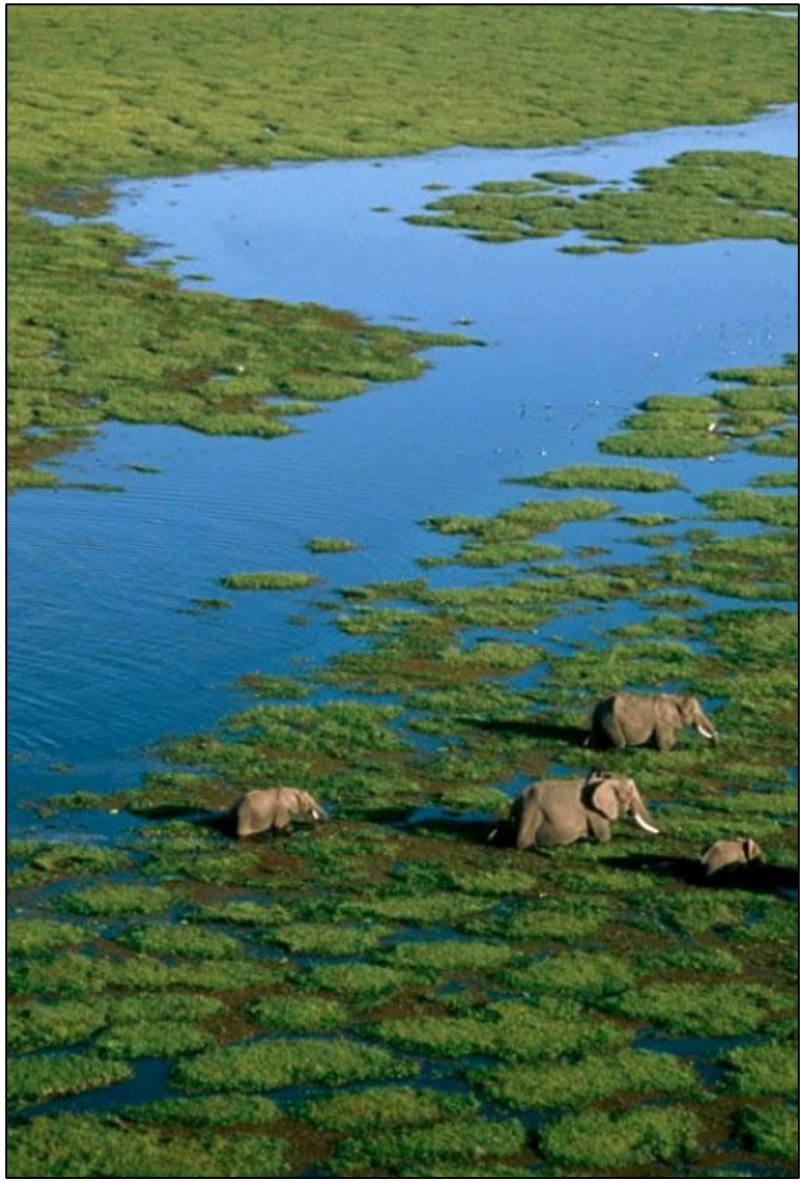
Friedlingstein et al, 2019

Methane - Climate Feedbacks

The amount of carbon in Arctic permafrost soils is ~4x what humans have already emitted.

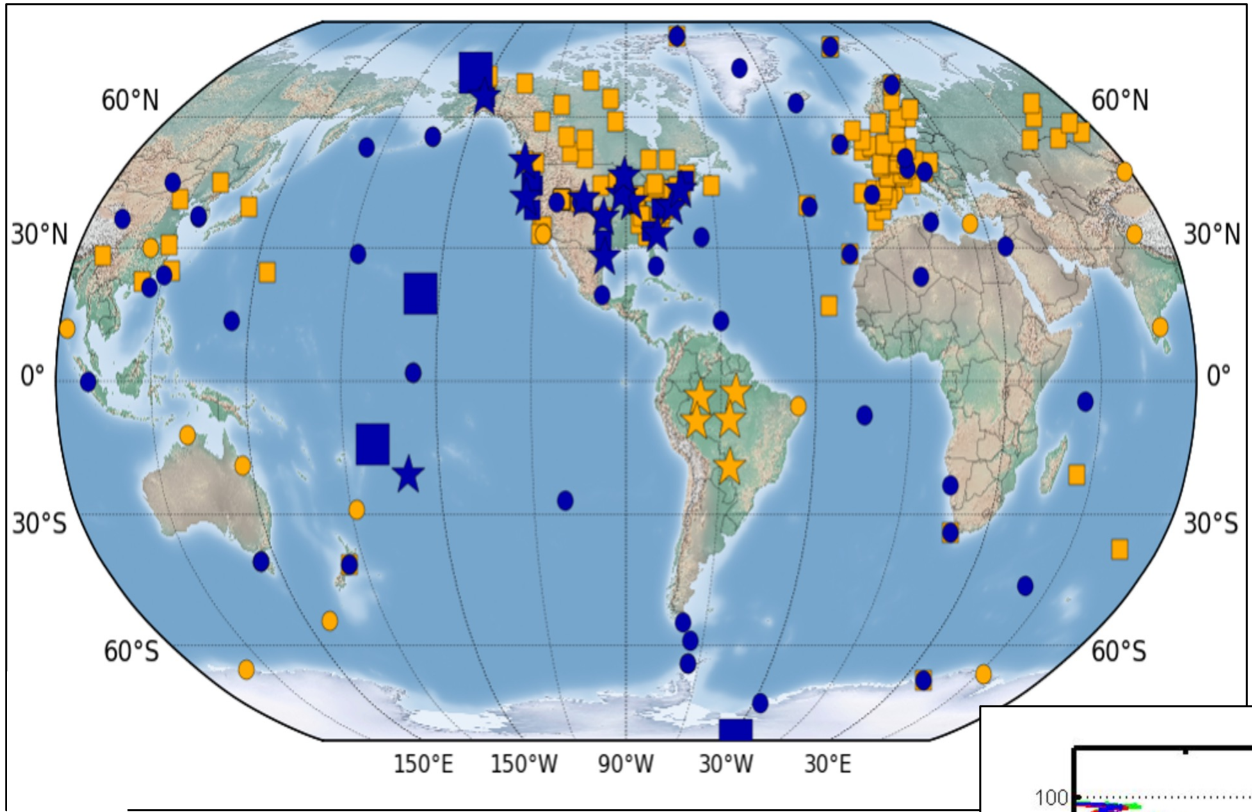
Arctic CH_4 emissions could double over this century with accelerating increases next century.

Monitoring observations suggest large emission increases are not happening……yet.

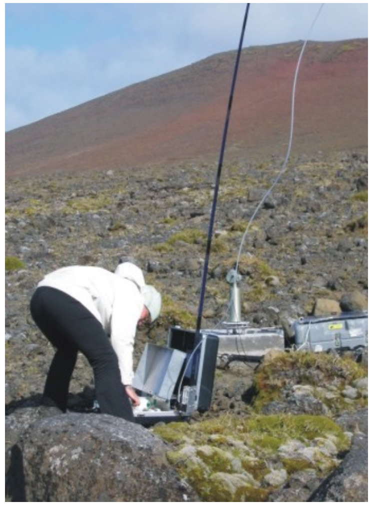


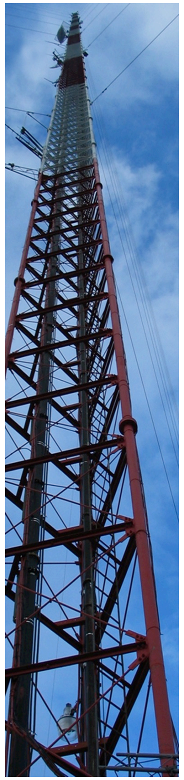
Are tropical wetlands drying up or expanding?

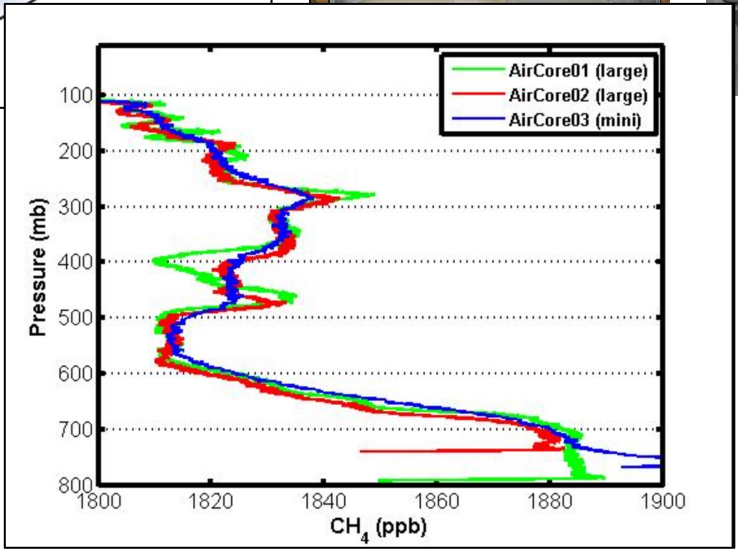
Monitoring Atmospheric GHGs: In Situ Measurements



- NOAA Continuous
- NOAA Flask
- NOAA Aircraft
- Non-NOAA Continuous
- Non-NOAA Flask
- Non-NOAA Aircraft

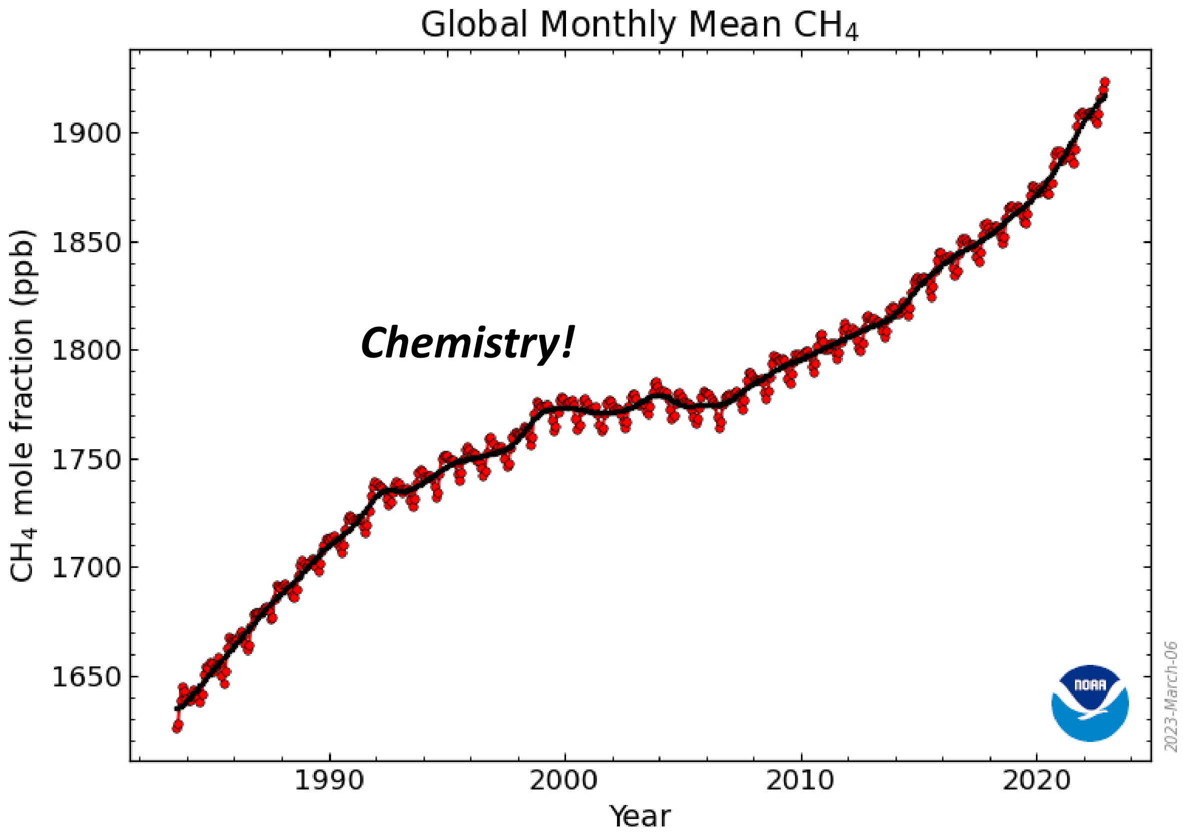


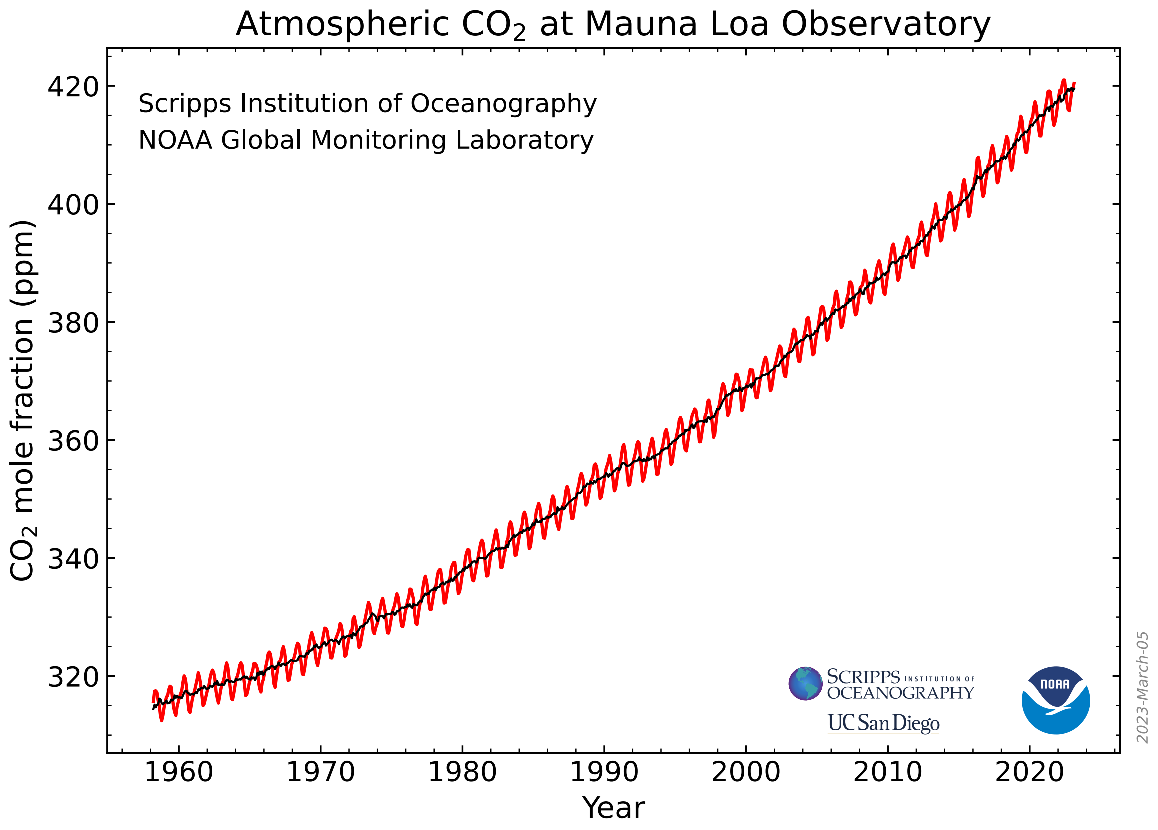




Detailed Vertical Profiles from balloon-borne air samples (The AirCore)

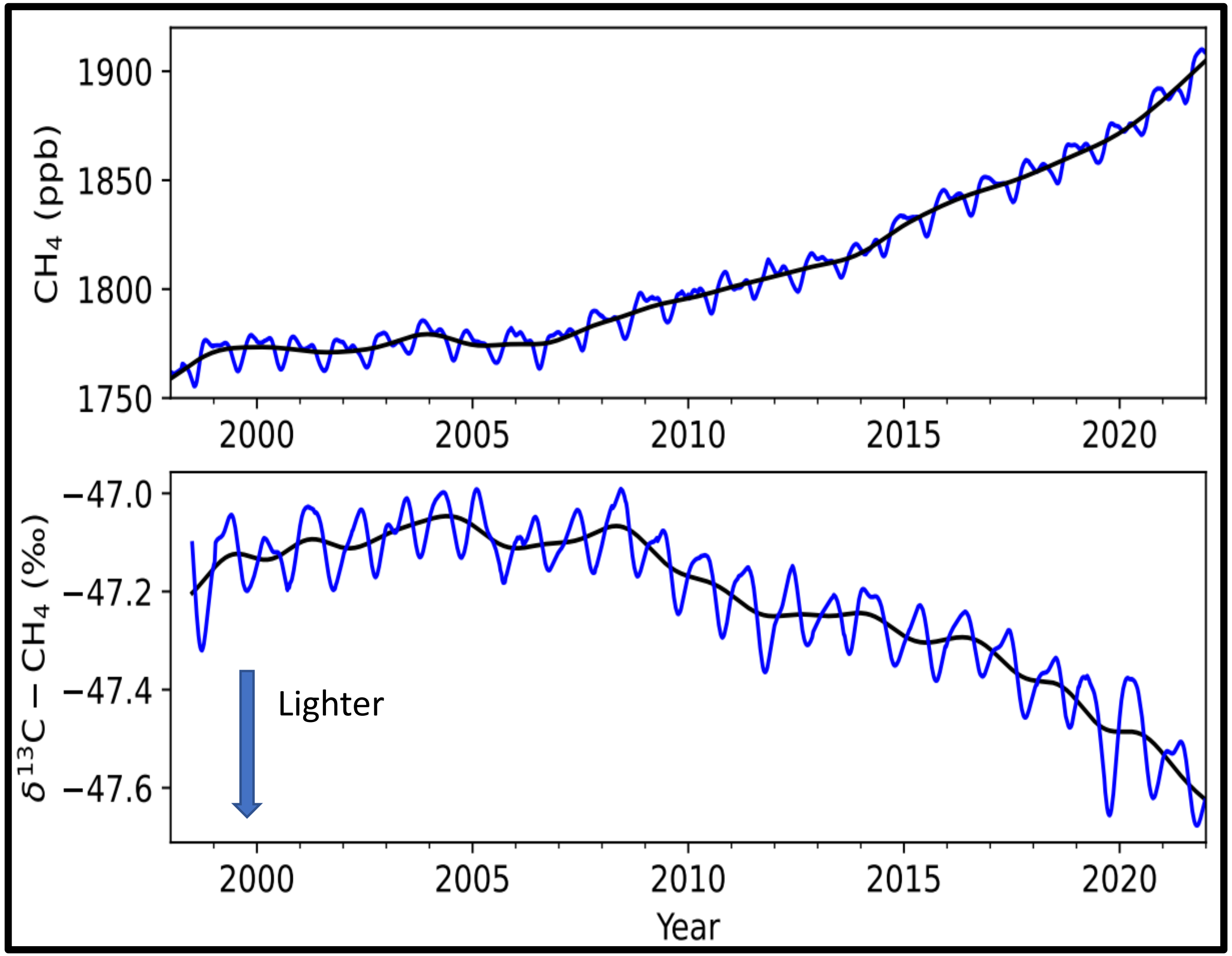
Monitoring Related Atmospheric Species Can Help Us to Understand the Methane Budget.





https://gml.noaa.gov/ccgg/

Monitoring Related Atmospheric Species Can Help Us to Understand the GHG Budgets.



$^{13}CH_4$ observations could help us separate fossil fuel and microbial emissions.

What do isotopes tell us?

1) **Fossil fuel emissions are larger than estimates from bottom-up inventories (but…. uncertainty!)**

2) **Most of the growth in atmospheric CH_4 is due to microbial sources**

Other possible constraints:

Ethane, $^{14}CH_4$, Methyl Chloroform

https://gml.noaa.gov/ccgg/

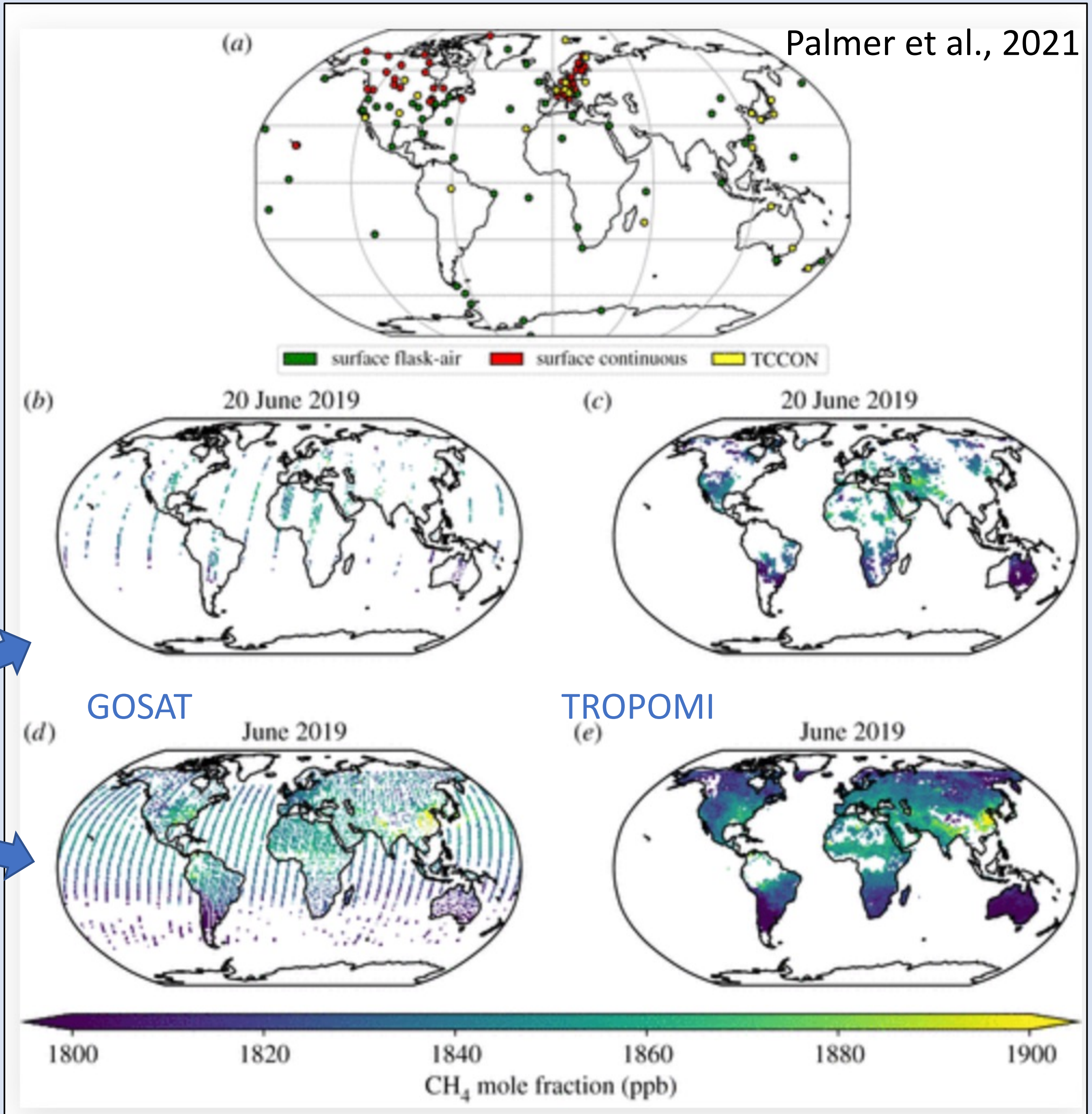
Satellite and In situ Data are Complementary

<u>Satellite Retrievals:</u>
High Spatiotemporal resolution but Lower Precision, Possible Biases

<u>In Situ Data:</u>
Low Spatiotemporal Resolution but High Precision, Arctic Coverage, High Surface Sensitivity

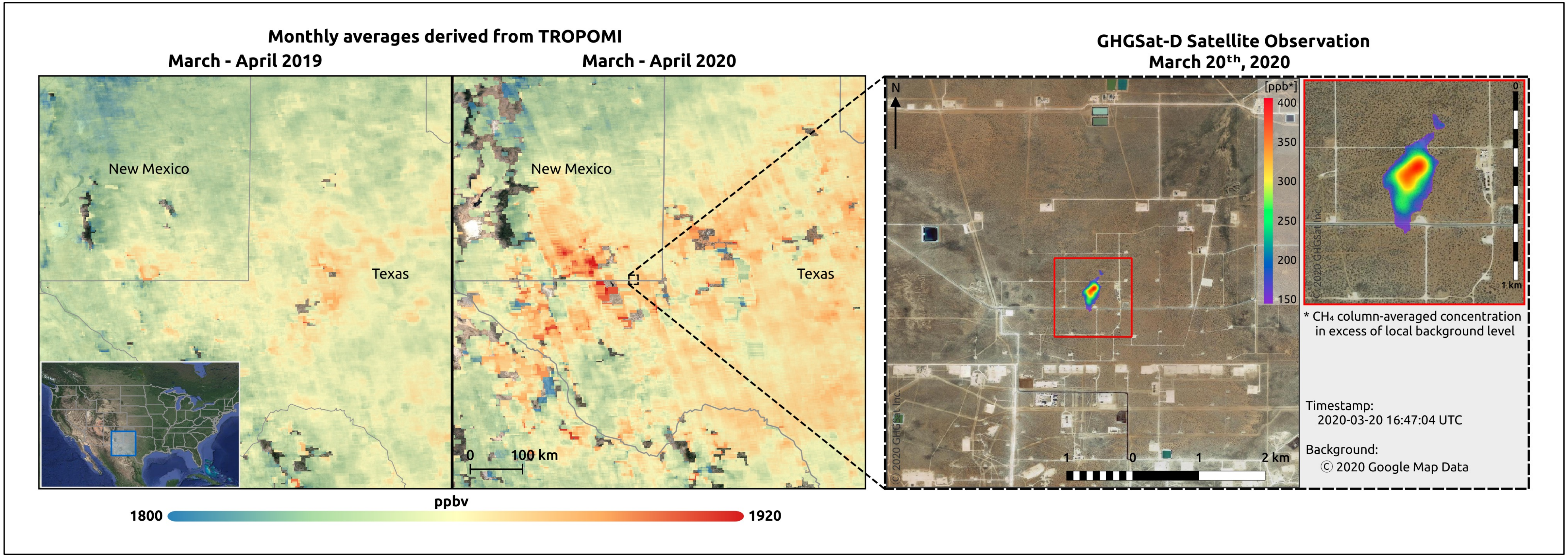
1 Day

1 Month



Methane Observations From Space

High resolution space-based data can help us to identify strong-emitters.



But we need to know something about winds to get emissions from this data.

http://www.tropomi.eu/data-products/methane
https://www.ghgsat.com/en/

Uncertainty: The other half of the answer!

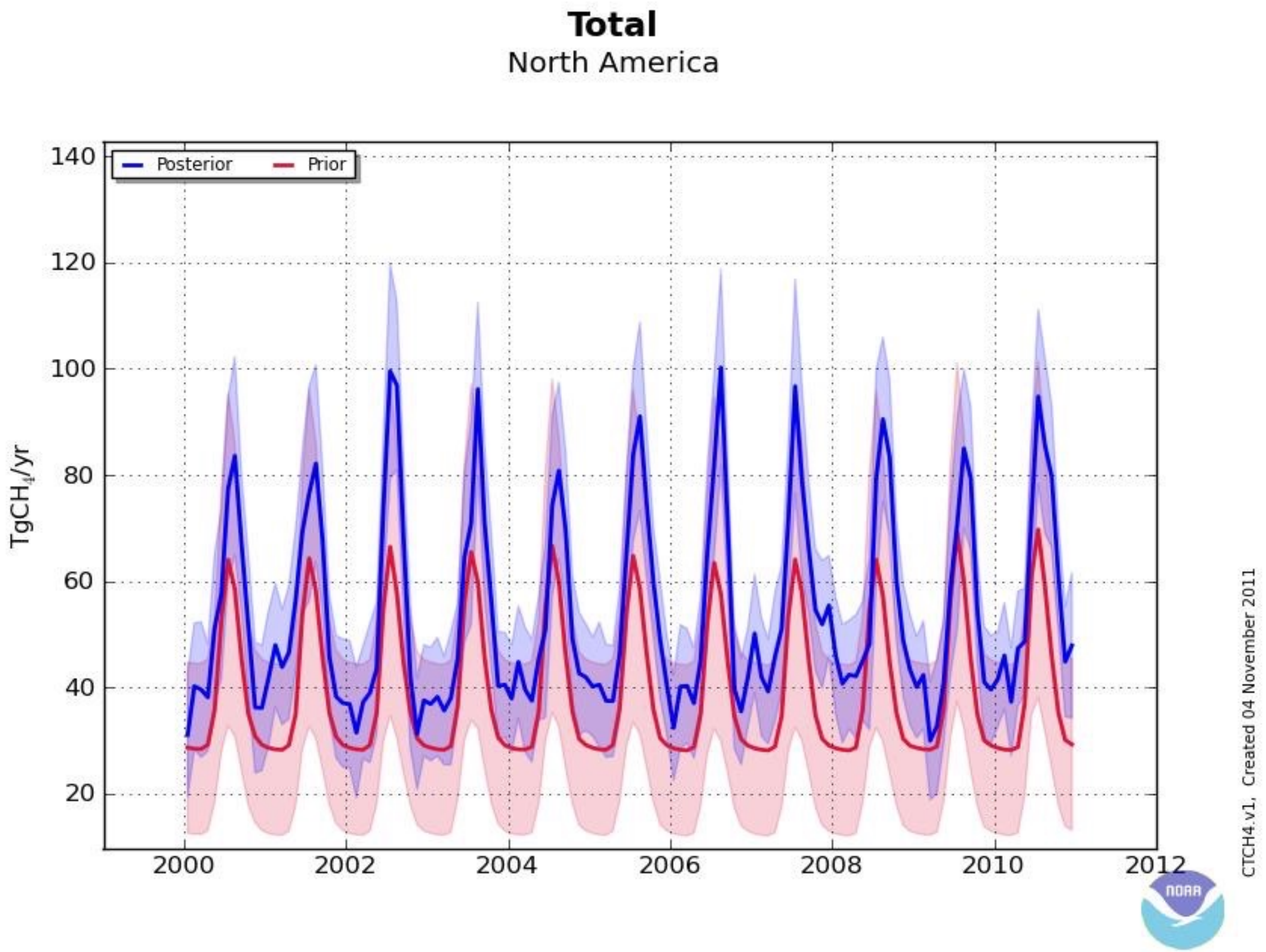
Internal Uncertainty

Gives us information about how observations changed prior estimates and reduce prior uncertainty

External Uncertainty

We don’t know some parameters, so we make assumptions rather than estimating them.

Estimated Internal Uncertainty (EnKF with In Situ Observations)



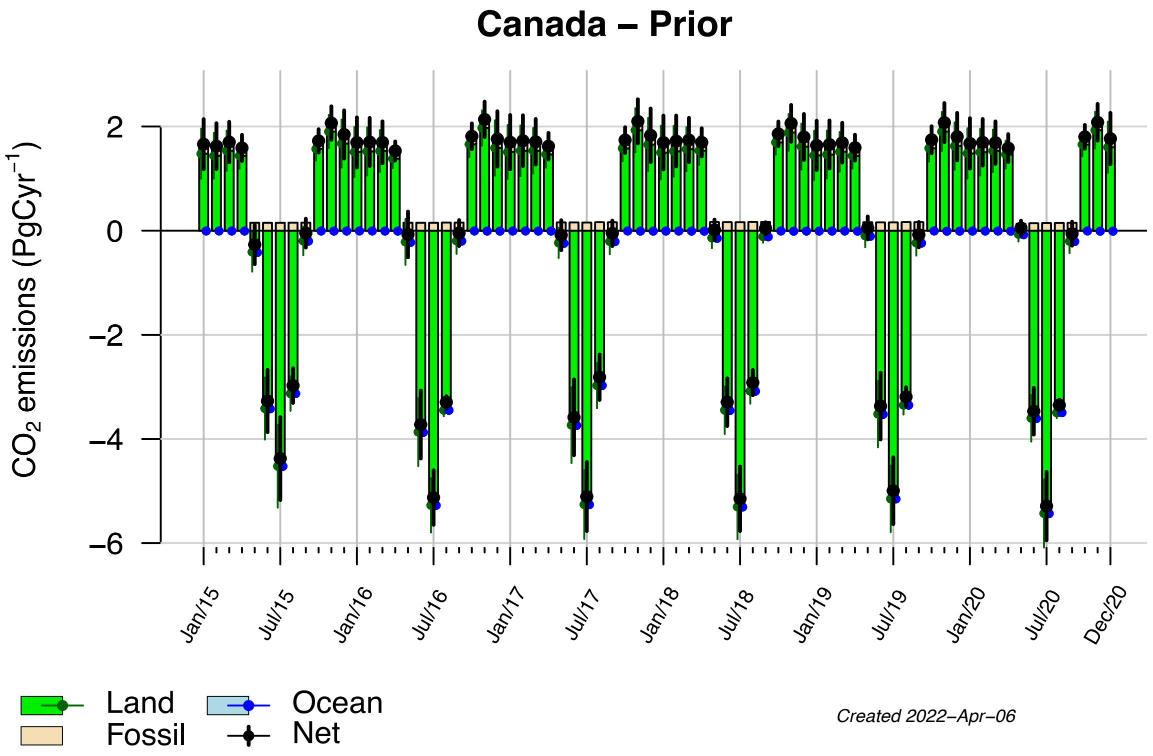
1) The posterior mean estimate is higher than the prior.

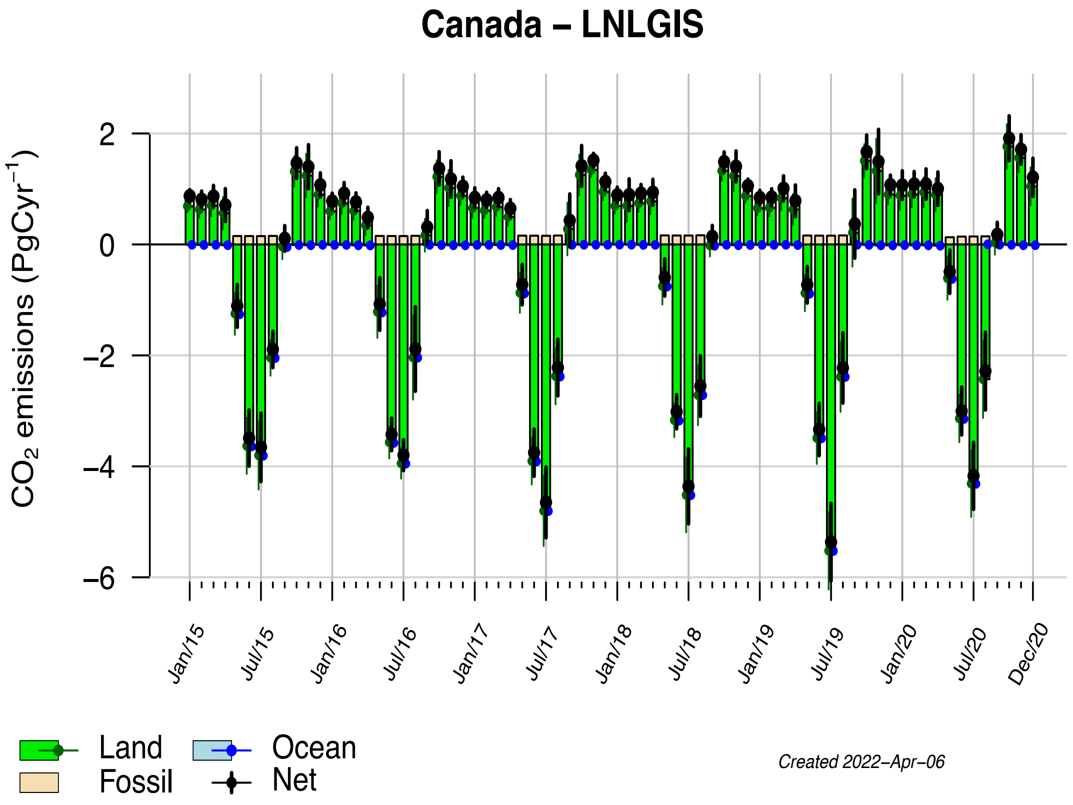
2) Estimates have larger interannual variability.

3) Estimated posterior 1-σ values are reduced compared to the prior.

The OCO-2 MIP (log-likelihood weighted)

Fossil Fuel Emissions not estimated
Bars are model ranges reflecting different transport, priors, errors etc. (e.g. External Uncertainties)
Comparisons with prior estimates give insights into internal uncertainty

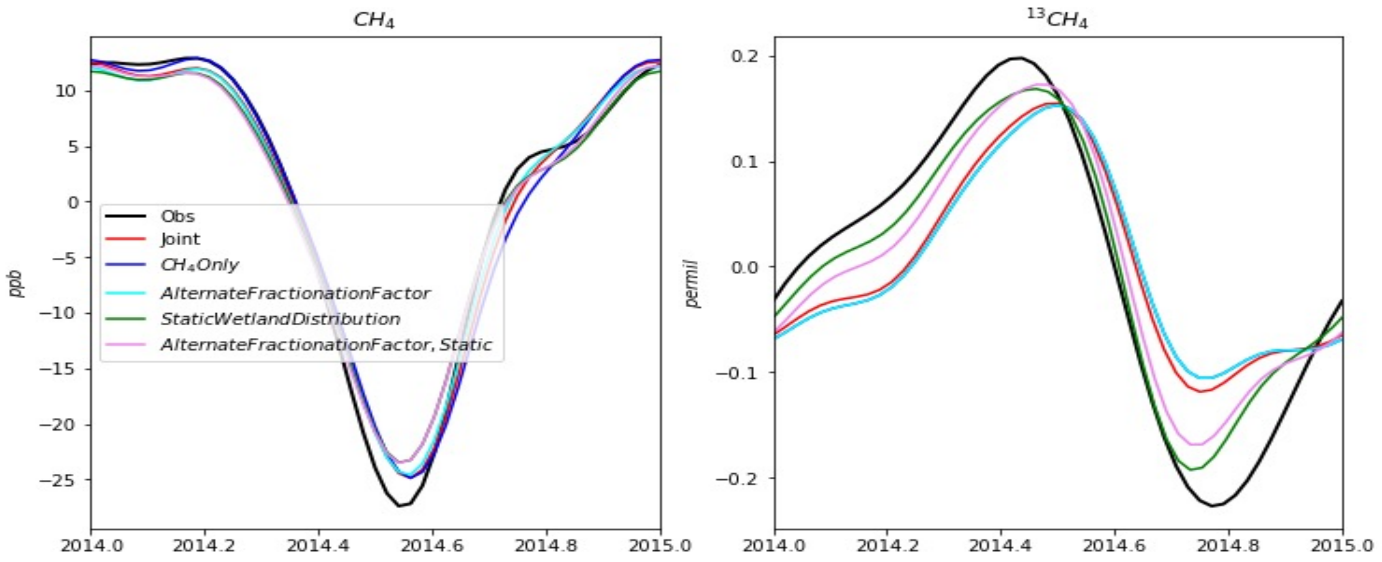




Uncertainties Associated with the use of $^{13}CH_4$ in CH_4 Flux Inversions

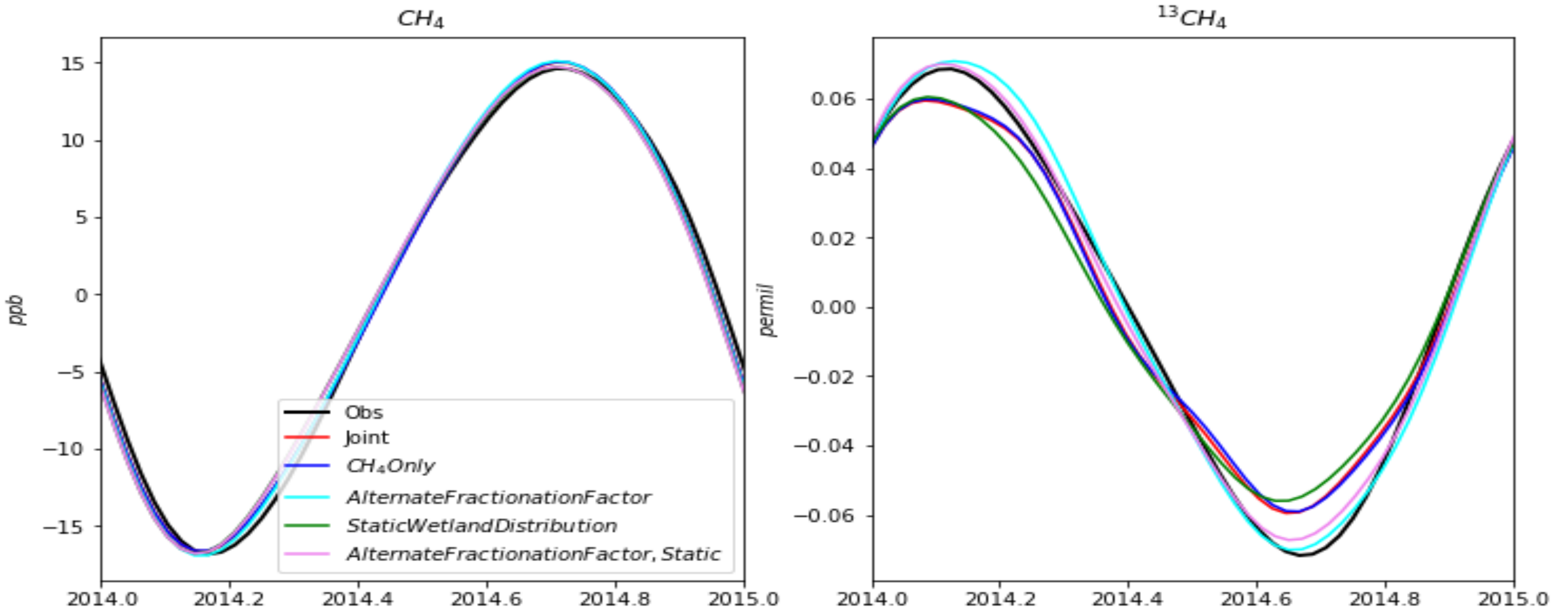
- **Source Signatures and their spatial variability are imperfectly known**
- **Significant uncertainty in the distribution of natural CH_4 producing environments (e.g. wetlands)**
- **Atmospheric chemical sinks fractionate - how well do we know the distributions of OH and Cl?**
- **Large range in fractionation factor of the OH loss, how well do we know the Cl fractionation factor?**

Can we reduce external uncertainty using observations?
Example: The Average High Latitude Annual Cycle of CH_4

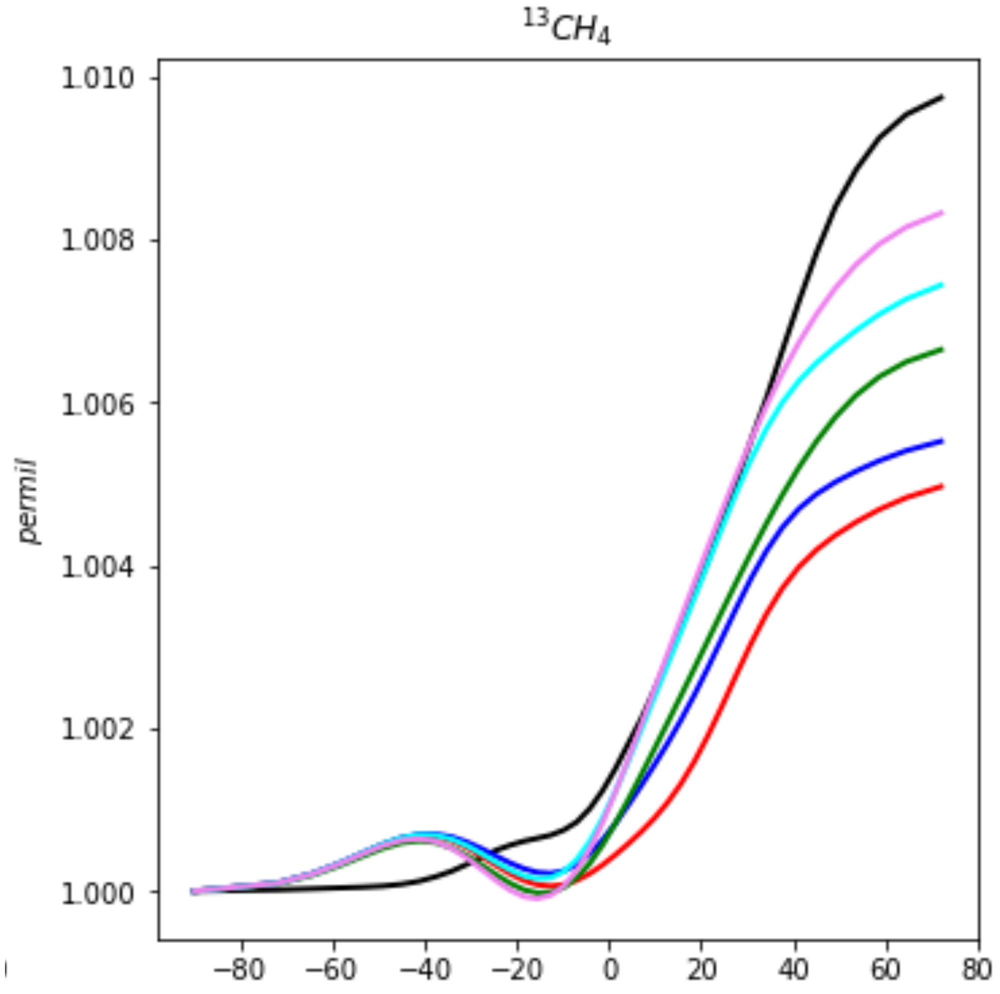


Using the "Static" wetland map (green, pink) improves the posterior seasonal cycle for the high-latitude NH

Using the "Alternate Fractionation Factor"(cyan, pink) improves the posterior seasonal cycle for high-latitude SH



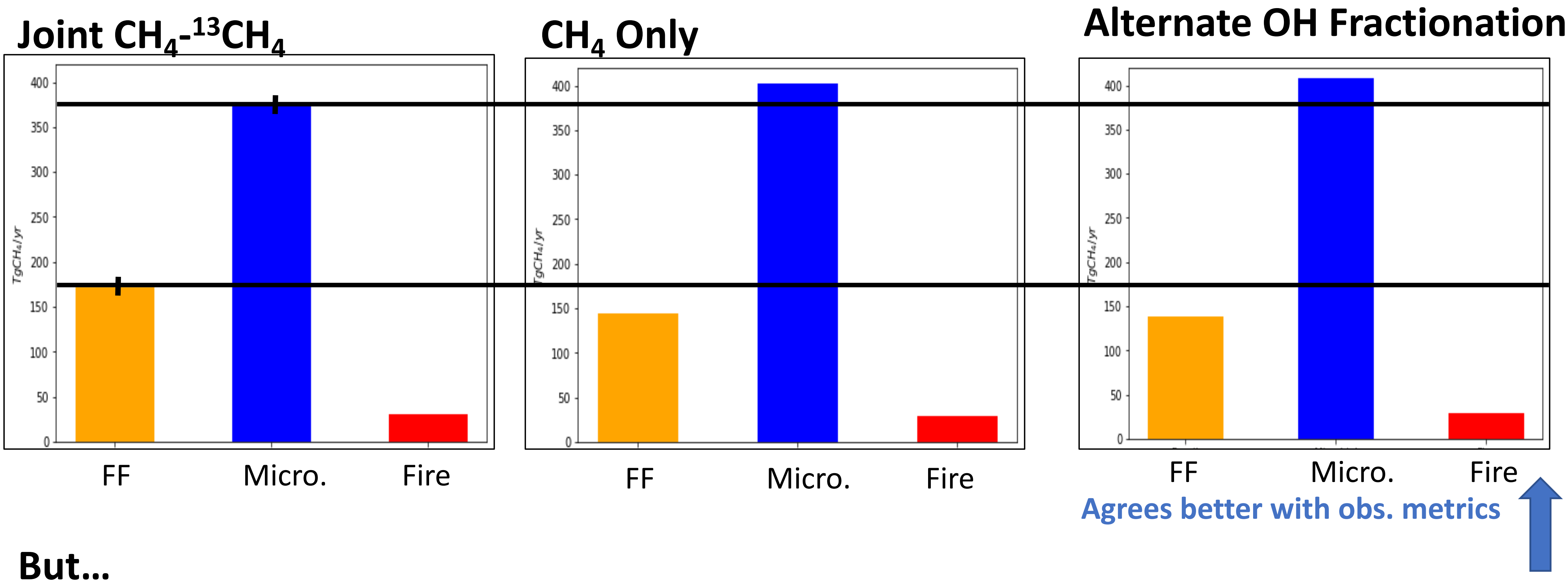
Another Example: The Latitudinal Gradient



It's difficult to match the observed N-S gradient of $^{13}CH_4$.

A combination of the "Static" wetland distribution and the "Alternate" OH fractionation factor may produce the best match with the observed N-S gradient.

Uncertainty in Partitioning Between Fossil and Microbial Emissions Using CarbonTracker-CH_4



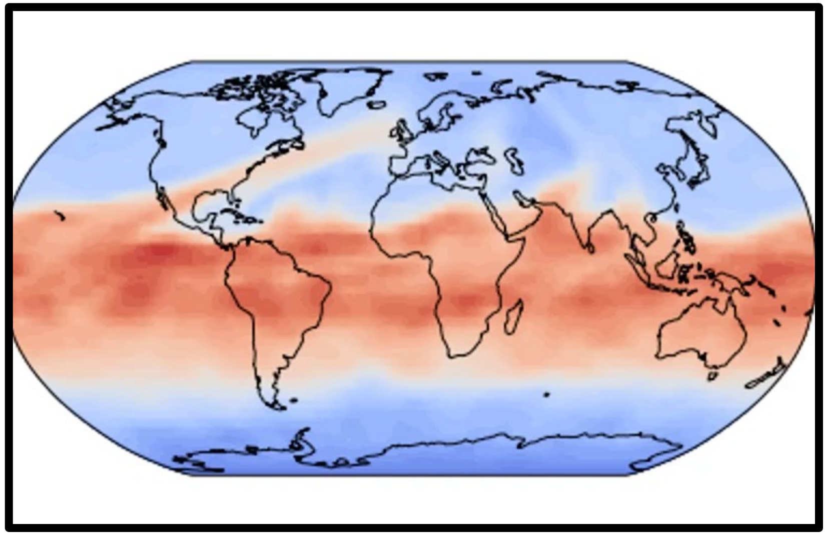
But…

1) **If tropospheric Cl is less than we've assumed, then fossil emissions will be higher and microbial emissions lower**
2) **The wetland prior can also affect the partitioning**

Advancing Transport Model Simulations

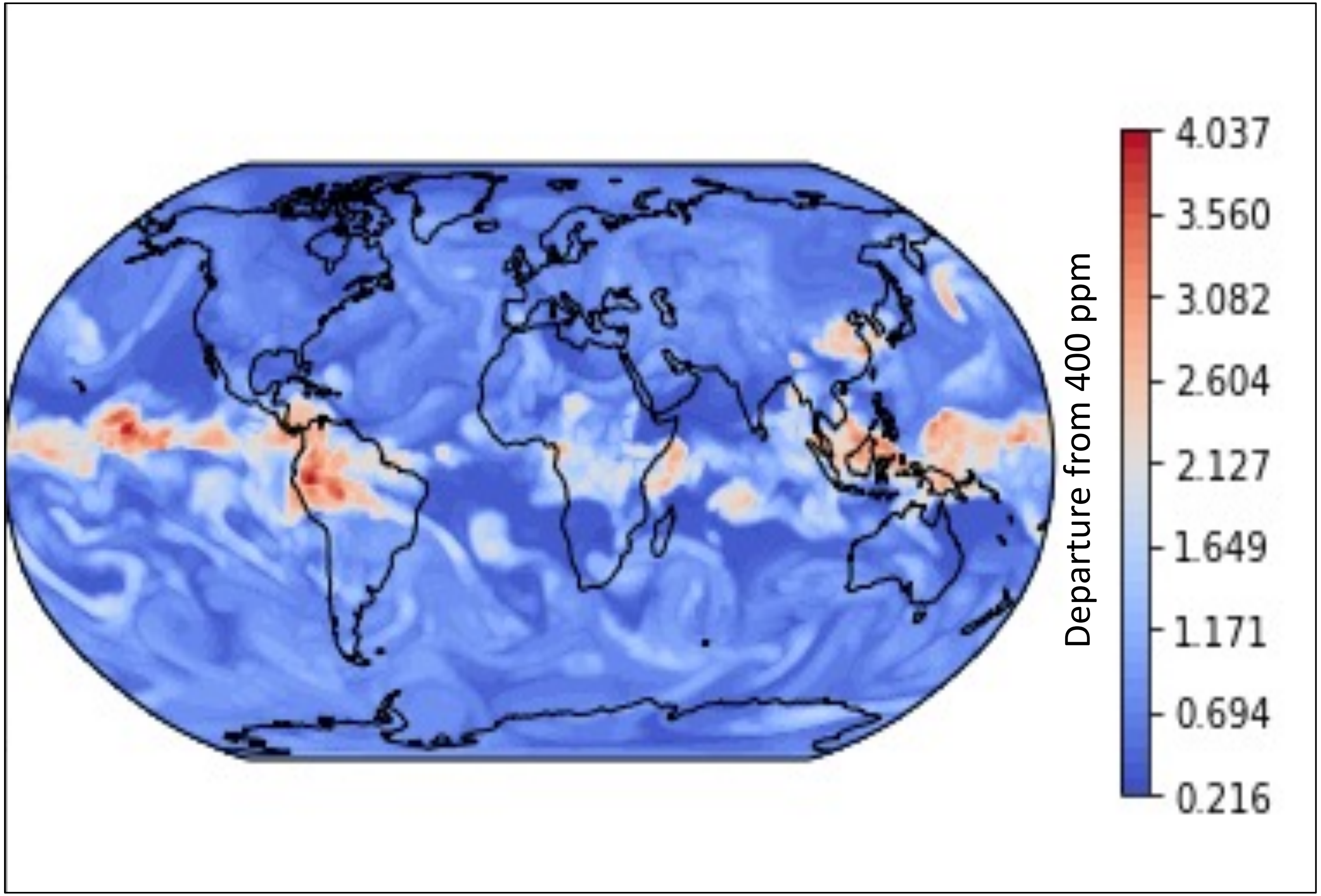
- **Is the NOAA UFS (driven with the GEFSv12 reanalysis) a good model for studying the budgets of GHGs?**
    - **Does it simulate observed spatial and temporal variability?**
- **Does increased spatiotemporal resolution can help us to better simulate GHG observations?**
- **Can we use the GEFSv12 reanalysis ensemble to better estimate transport model error?**
- **Can we use the UFS DA tools estimate the atmospheric states and fluxes of CO_2 and CH_4?**
- **What benefits would there be if we integrate a LSM with a detailed treatment of vegetation and carbon exchanges to the UFS?**

CH_4 050120



A CH_4 "forecast"

500 hPa, 1 week



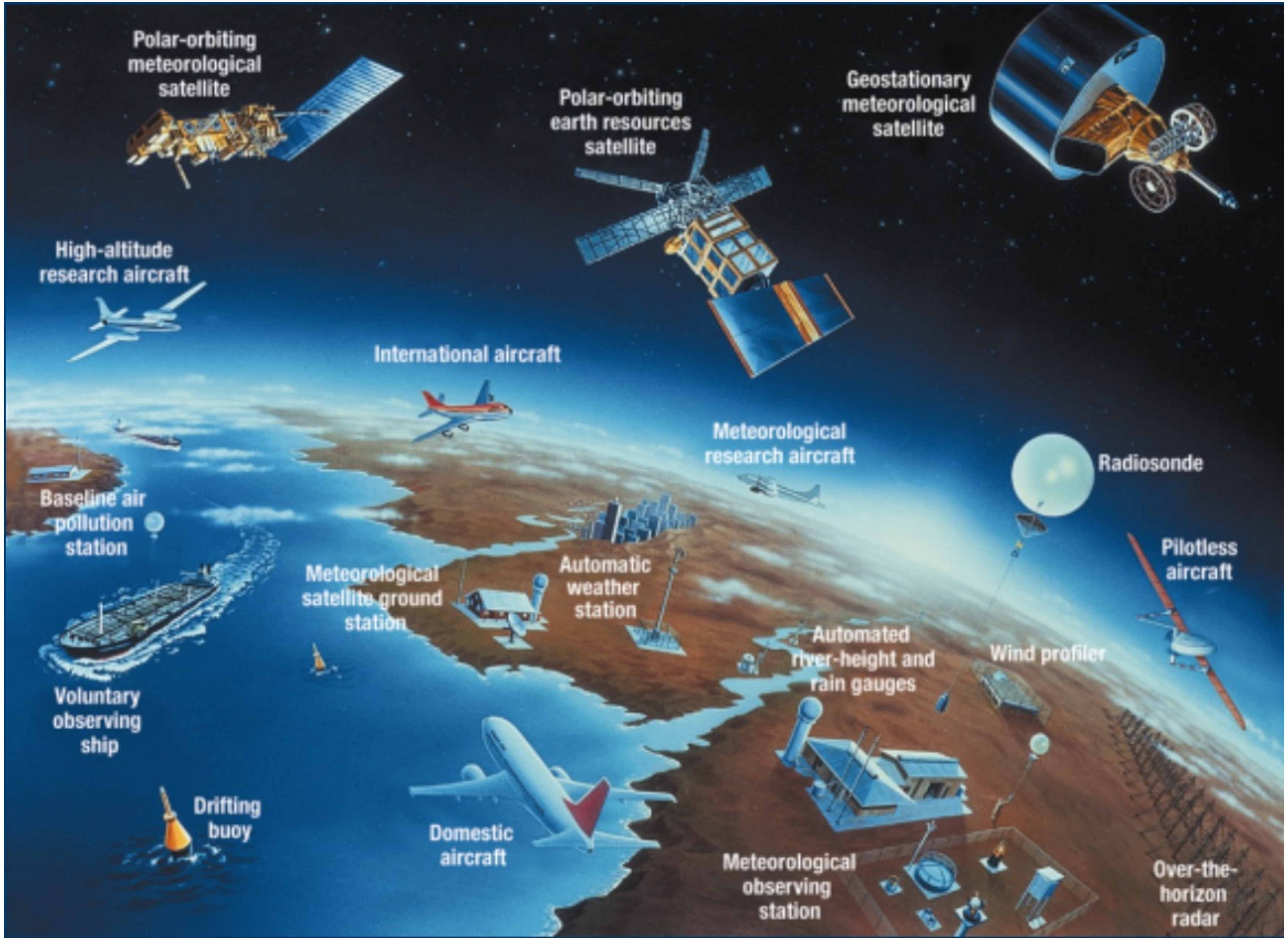
The Experiment:

Constant CO_2 field (400 ppm)
No sources/sinks/deposition

These errors are similar to the gradients we hope to use to learn about emissions.

Could this affect AQ simulations also?

The Global Observing System (WMO)



10K weather stations!

Application to Predictability at S2S Timescales

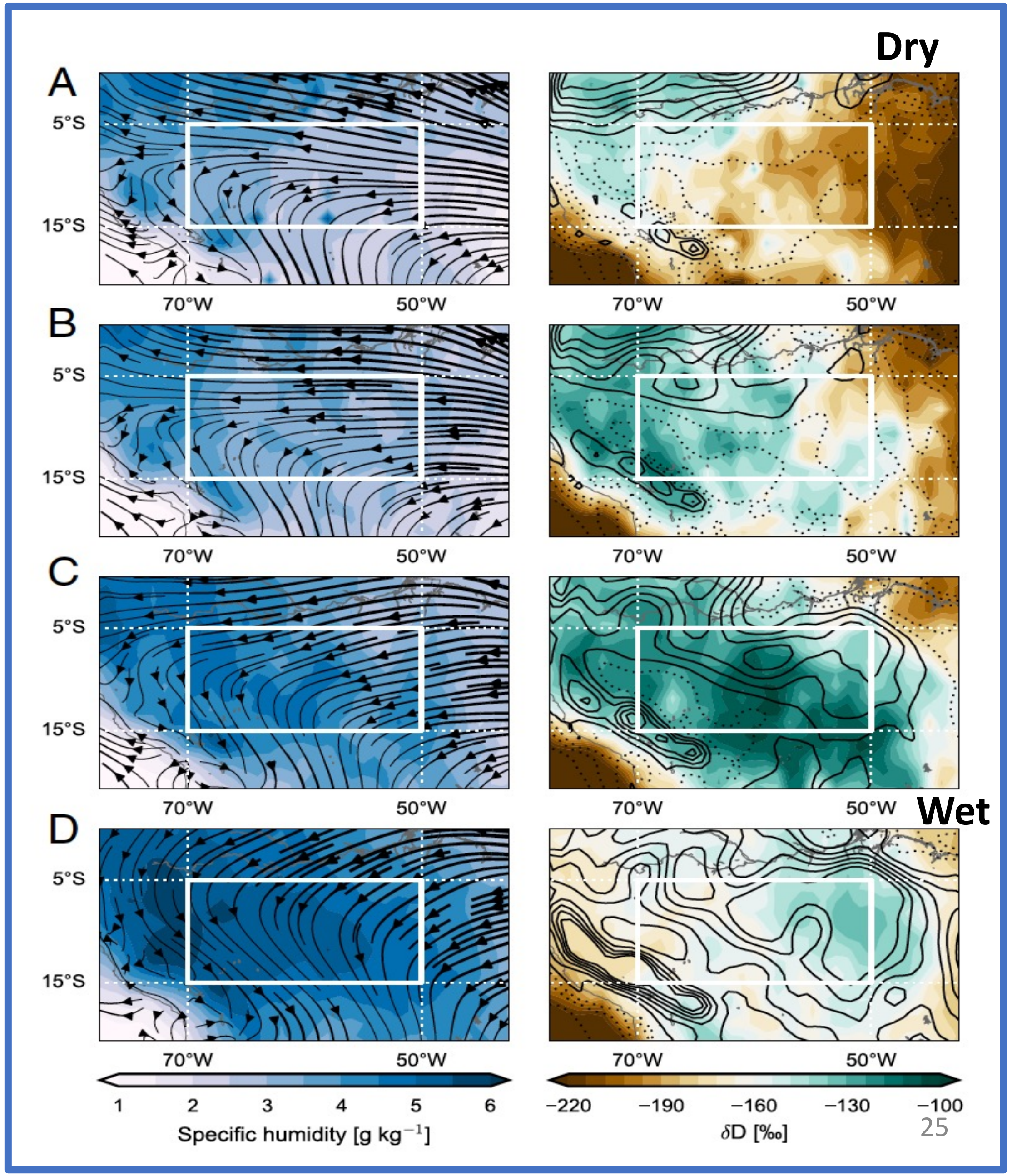
Rainforest-initiated wet season onset over the Southern Amazon, Wright et al., PNAS, 2017

What controls the onset of the rainy season in the Amazon?

The onset of the rainy season occurs 2-3 months before the southward migration of the ITCZ.

Answer: The Biosphere!

Late dry season transpiration pumps moisture into the atmosphere, initiating deep convection and moisture transport from the tropical Atlantic.



RH, δD: TES
850 hPa winds, moisture flux convergence (kg $m^{-2}d^{-1}$): ERA-I

Thanks for your attention!