Vertical profiling of greenhouse gas mixing ratios above a coastal marsh using a laser heterodyne radiometer

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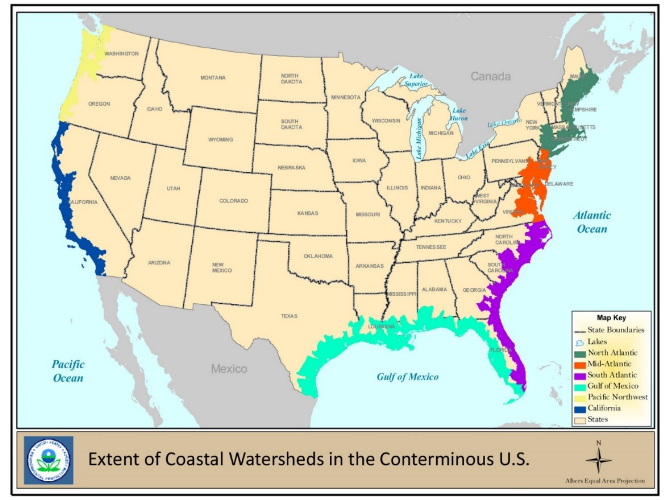
DoE DE-SC0019543
(Atmospheric Radiation Measurement)

Atmospheric Diagnostics

- Many options for "Point Sensors"
  - Ground: good temporal resolution, lousy spatial coverage
  - Aircraft: good temporal, slightly better spatial
- LIDAR, microwave sounding, TCCON
- Satellites
  - Typically report column averages
- Reliance on modeling to fill in the holes

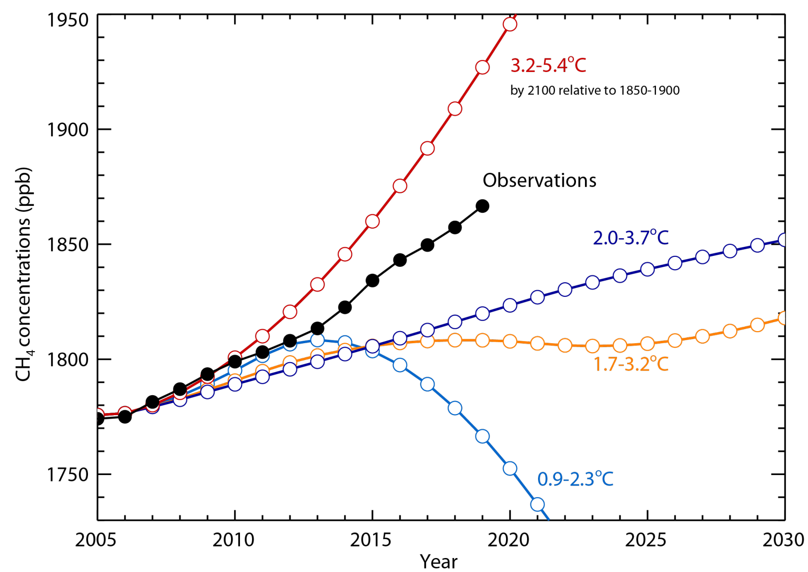
Wetlands and Carbon



- *Inland* wetlands: largest natural source of CH_4 emissions – 15-45%
  - Negligible contribution from ***coastal*** wetlands

- ***Coastal*** wetlands: net carbon sinks
  - ~300–600 Gt stored carbon
  - 5.1 °C Temp increase ⟶ >2x ***coastal*** wetland emissions

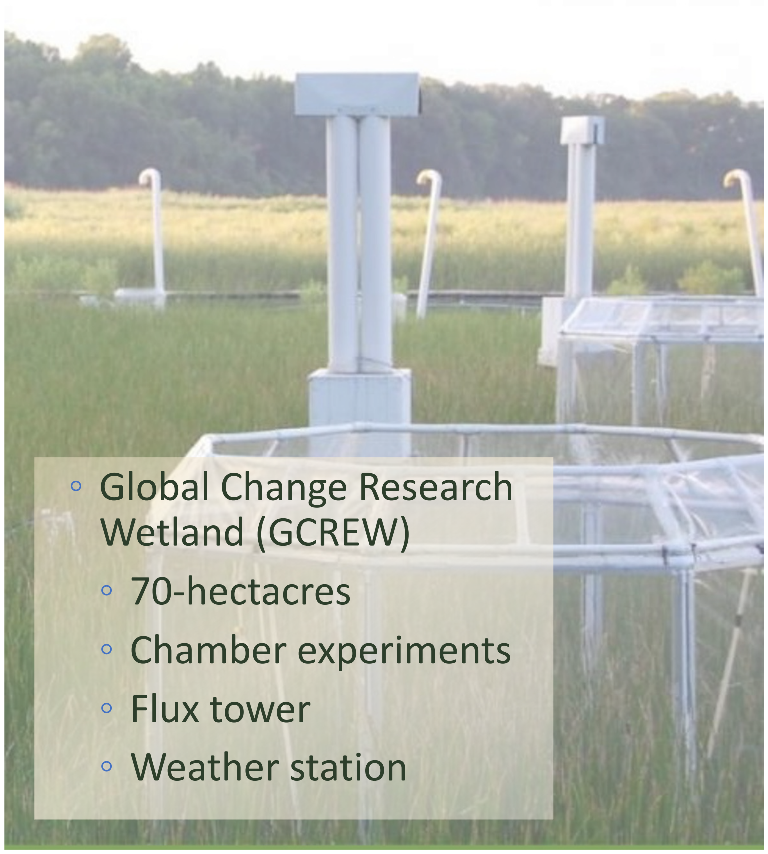
- Large uncertainty in land-air exchange
  - Complicated by carbon cycle
  - Data used in models are difficult to scale up



Global Carbon Project (2022). *Global Methane Budget, 2022.* [Updated from Saunois, *et al.* 2016, ERL].

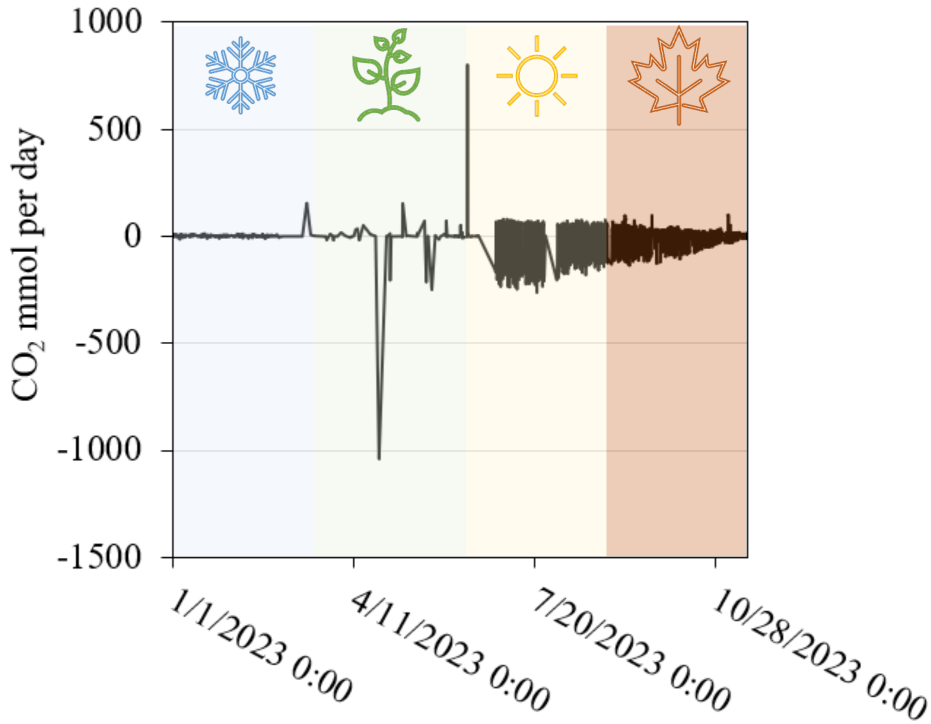
Smithsonian
Environmental Research Center

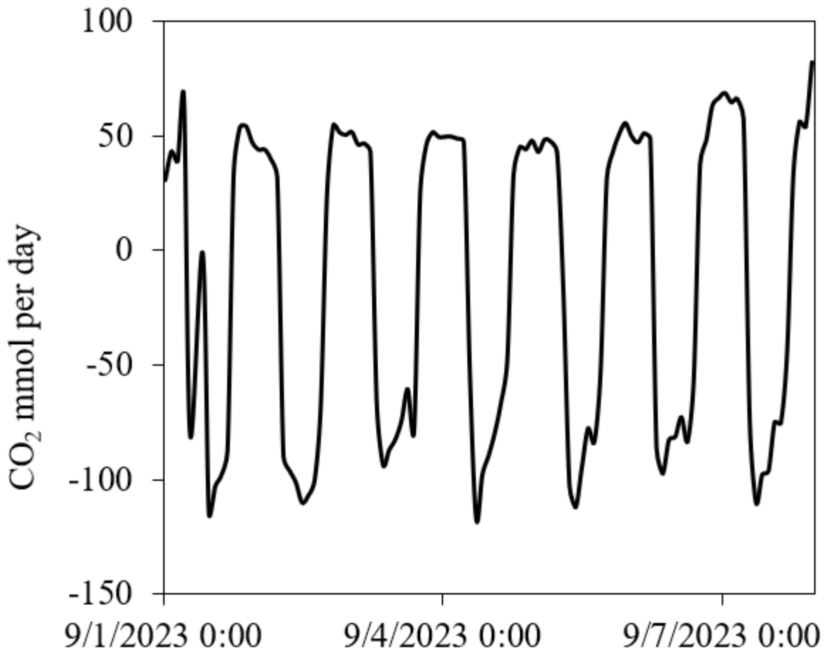
Smithsonian Environmental Research Center (SERC)



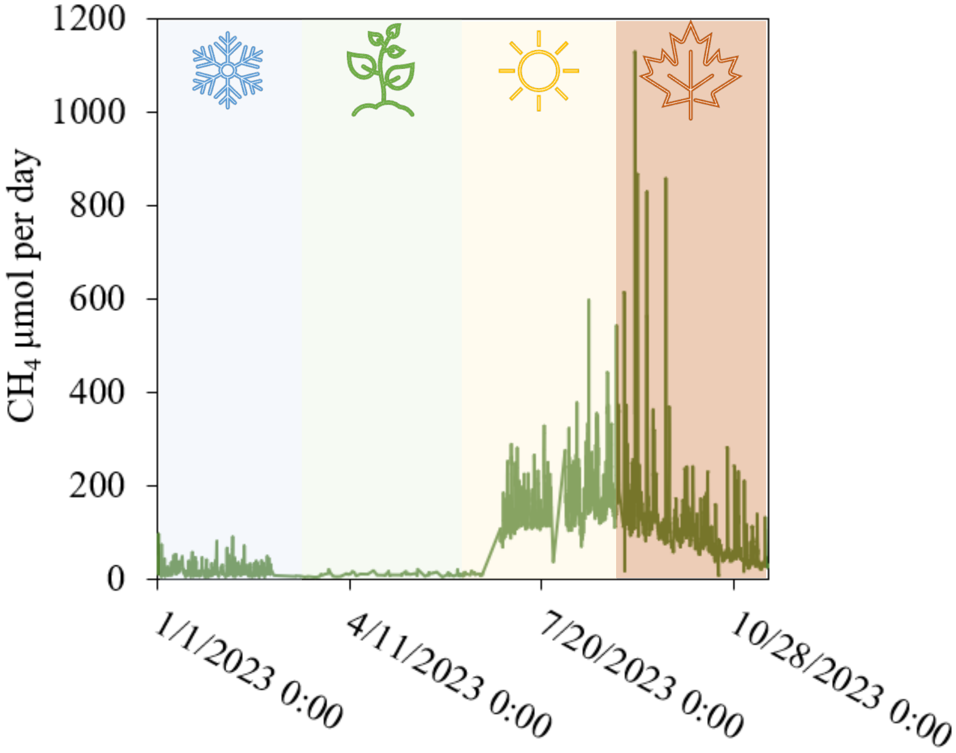
- Global Change Research Wetland (GCREW)
  - 70-hectacres
  - Chamber experiments
  - Flux tower
  - Weather station

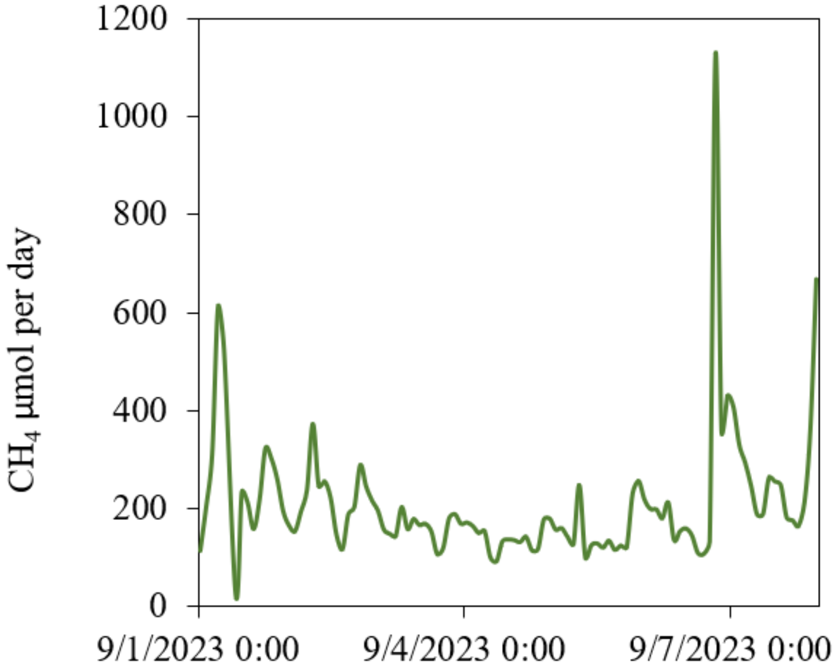
GCREW CO_2 Chamber Flux Data



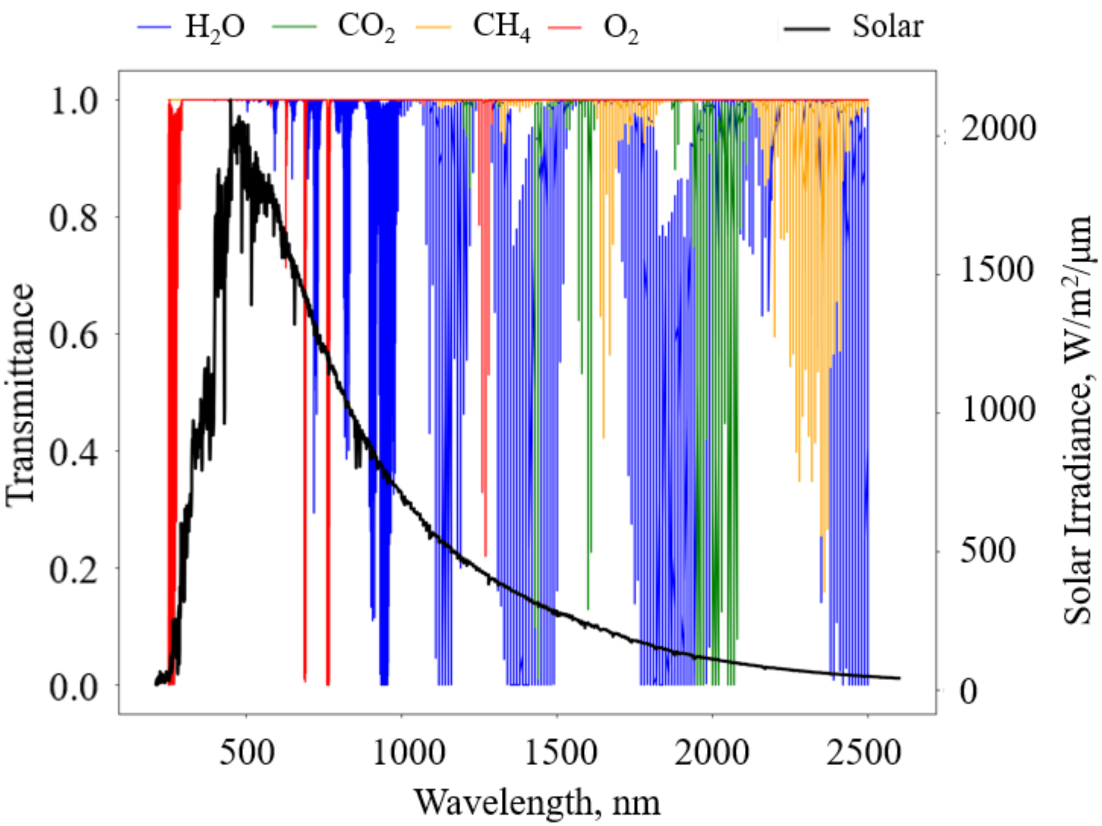


GCREW CH_4 Chamber Flux Data

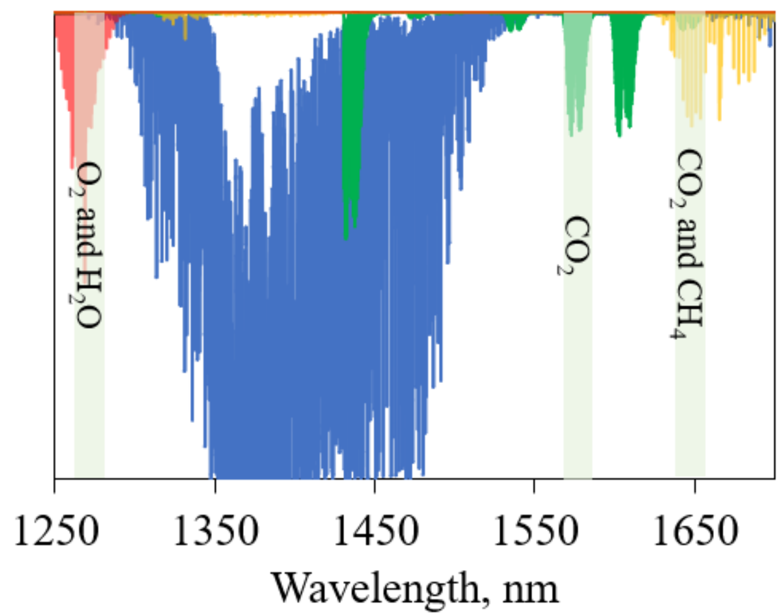




Greenhouse Gas Absorption Spectroscopy

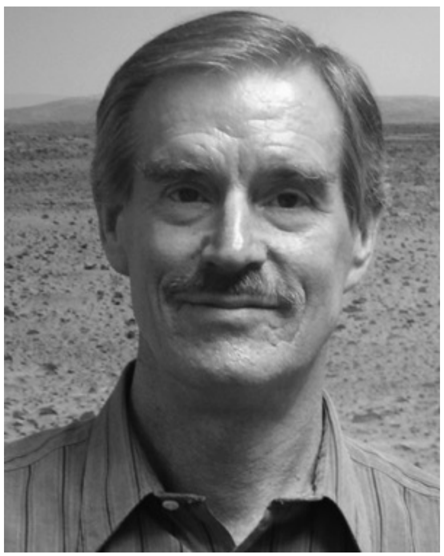


Near-IR spectral regions of interest



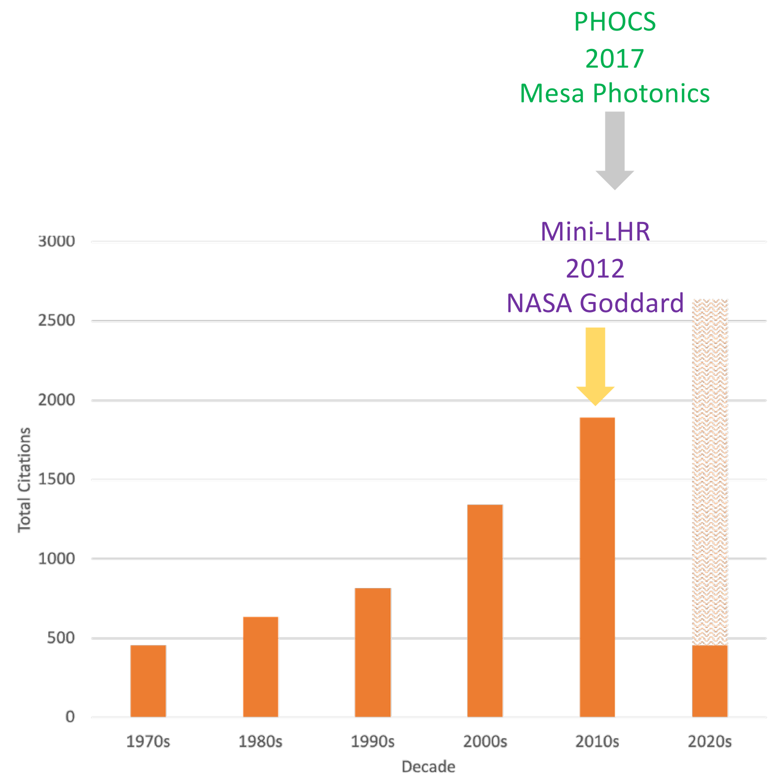
Laser heterodyne radiometry (LHR)
(a very brief history)

Robert Menzies
(1970s)



- “Remote sensing with infra-red heterodyne radiometers”, Opto-electronics volume 4, pages179–186 (1972).
- “Remote detection of SO_2 and CO_2 with a heterodyne radiometer“, Appl. Phys. Lett. 22, 592 (1973).
- “Laser heterodyne detection techniques.” in Laser Monitoring of the Atmosphere, pp 297–353 (1976).

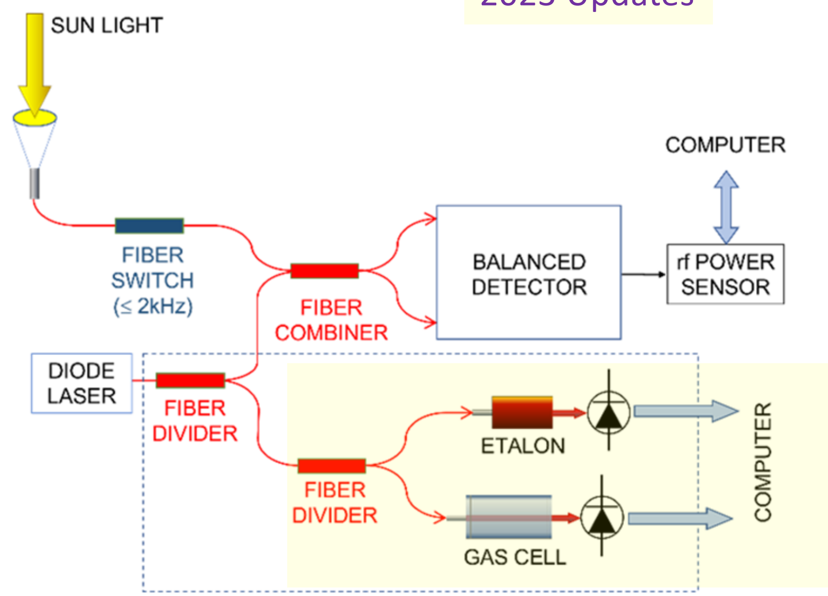
NASA Jet Propulsion Laboratory
California Institute of Technology



Laser heterodyne radiometry (LHR)

- Adapted from and analogous to radio receiver technology.
- Incoming light is combined with light from a narrow-band laser source (the local oscillator or LO) on a photodetector.
- The detector output contains AC electronic signals at the (optical) difference frequencies.
- PHOCS heterodyne signals are proportional to the solar spectrum at the LO wavelength.
- When the LO coincides with an optical absorbance, the heterodyne signal intensity will drop by an amount proportional to the absorbance.

2023 Updates



Laser hete  radiometry (LHR)

- It is an atmospheric absorption technique measuring the sun light intensity as a function of light frequency at the surface.

- There are lasers involved, but no light laser light leaves the instrument.
  - *“PASSIVE” laser technique*.
  - High spectral resolution of the laser and radiofrequency electronics enable vertical profiling.

- The characteristics of light absorption depend on pressure and temperature which change along the path through the atmosphere.
  - *We need a detailed model of atmospheric structure to interpret the spectra.*

LHR installation at SERC/GCREW

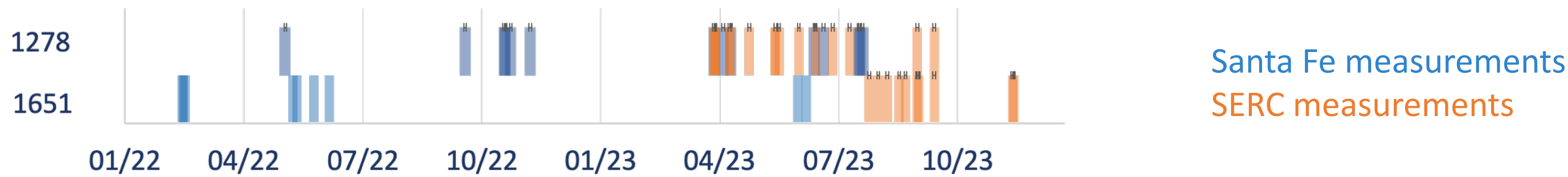
0.6 m Rack Components:

1. Power distribution & USB subsystems
2. Solar tracker electronics
3. CO_2/CH_4
4. O_2/H_2O
5. (Future?) Open Path Instrument

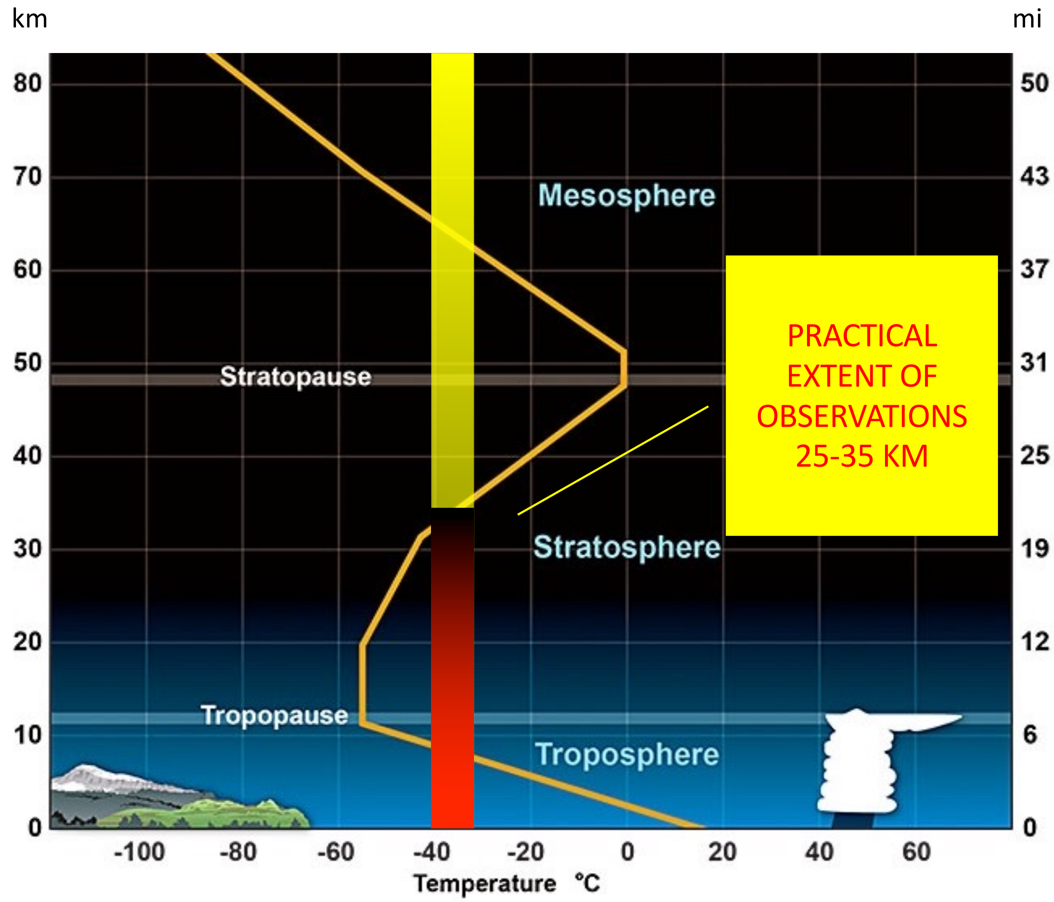
LHR at SERC/GCREW

Not with out some bumps in the road…

- The Plague
  - Access limitations at GW or SERC.
  - Supply chain: 14-month delay in delivery of dome from the UK
  - Some assembly required.
- First deployed instrument was a “Franken-Fox” combination of parts from GW, NASA, and Mesa Photonics.
- First new heterodyne unit (at 1278 nm) delivered in Spring 2023
- Second (1651 nm) delivered in Summer 2023

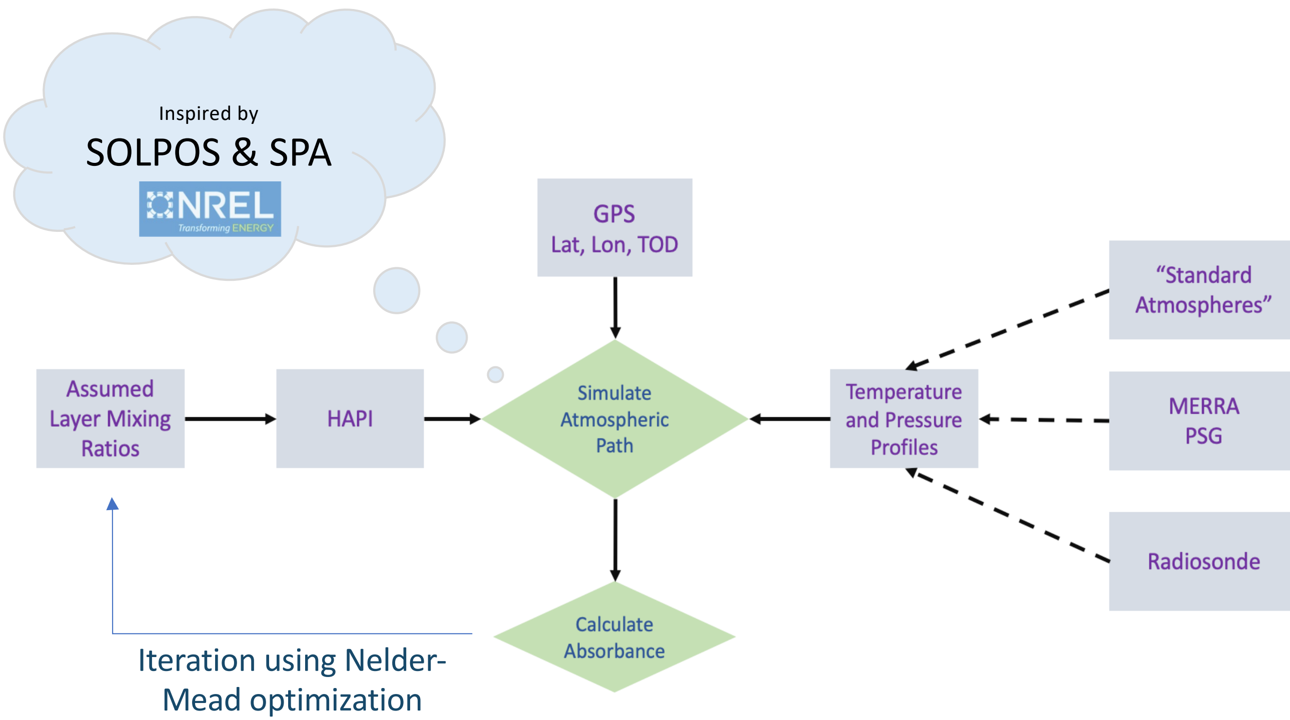


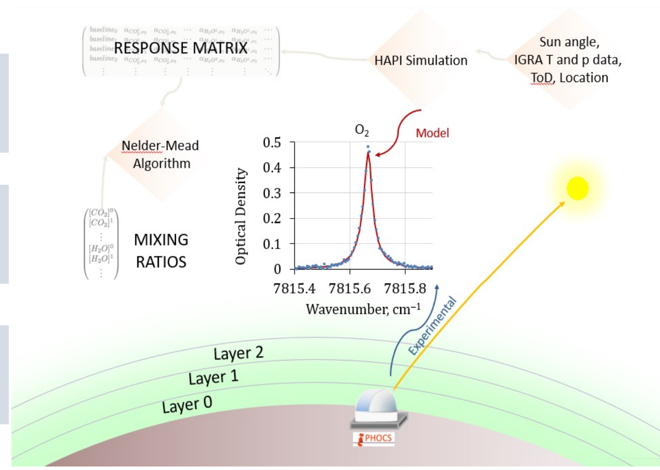
The Atmosphere



https://www.weather.gov/jetstream/layers

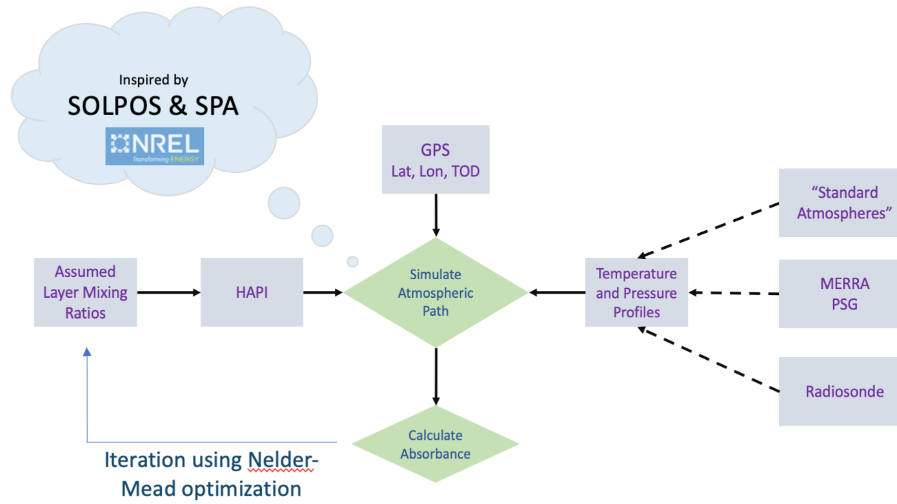
Vertical Profiling Method





1651 nm Retrieval (redux)

1. Raw Transmission Spectra
2. Calibration
3. Absorbance Spectra
4. Isolate features from CO_2 and CH_4
5. Refine Calibration Using *LahetraSim*
6. Calculate spectrum-specific absorption path coefficient matrix
7. Fit using Nelder-Mead or Truncated Newton Method



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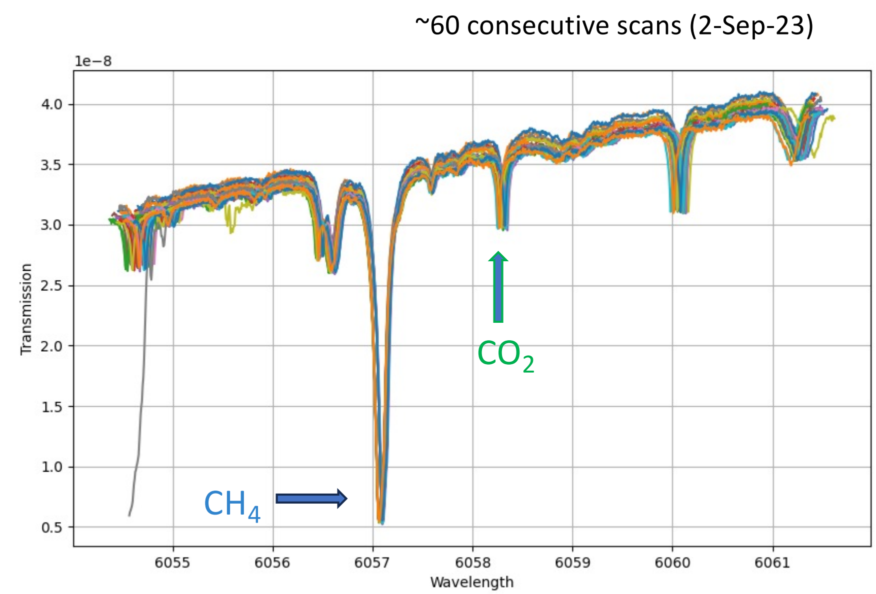

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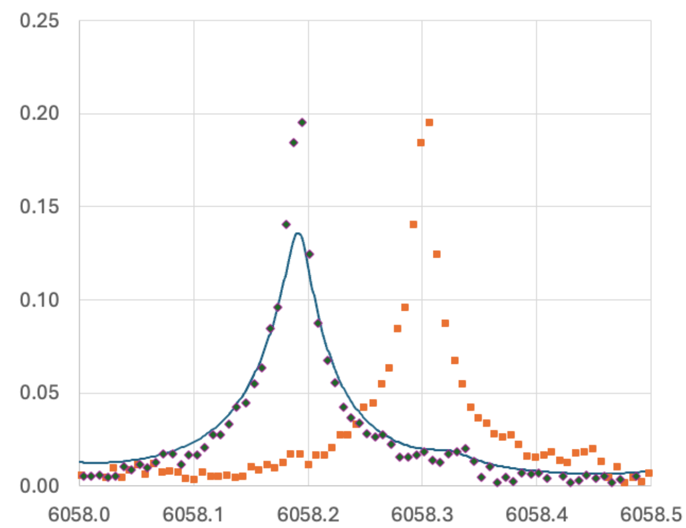

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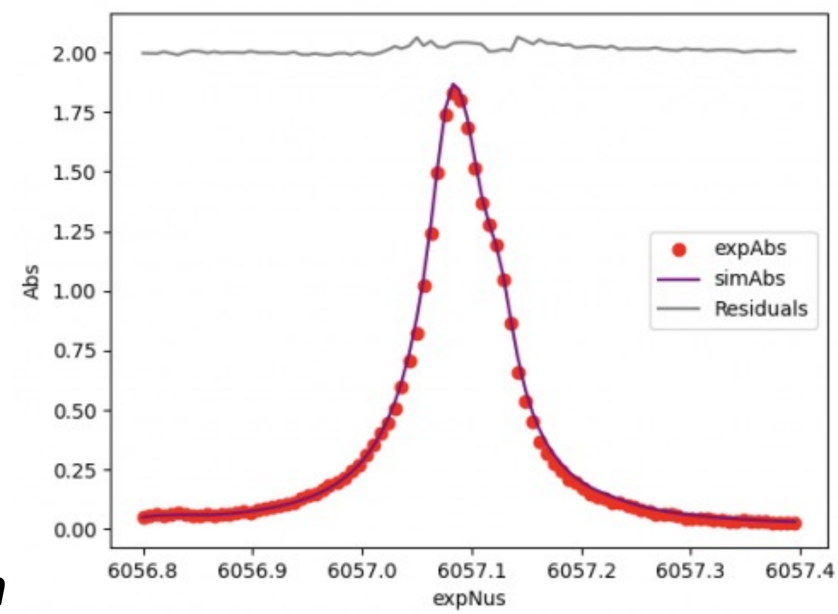

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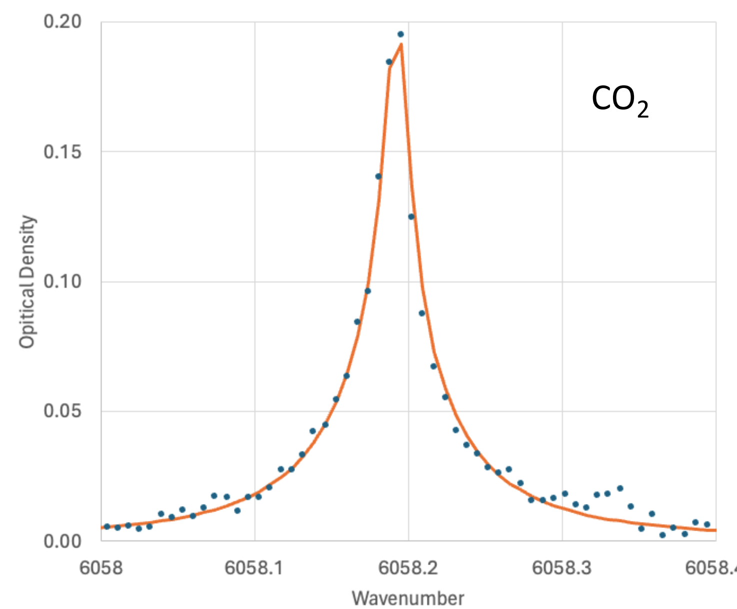

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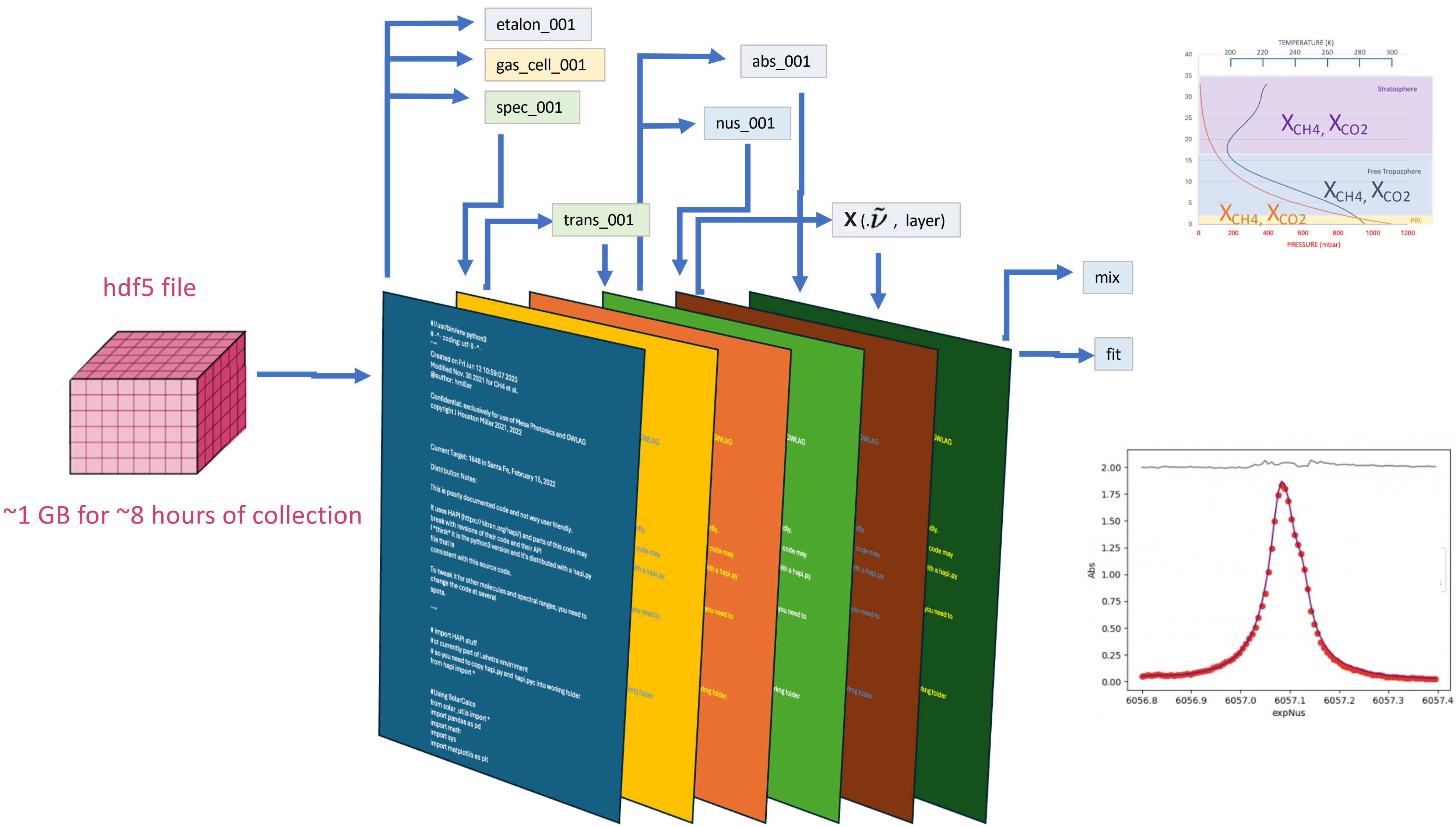
Where are we (and where are we going)?

The Good

- Arguably (one of) the best performing LHR instrument we are aware of.
  - Good performance (SNR > 100) at 100 MHz (0.0033 cm^{-1}) spectral resolution

The not so Good

- Current data record is temporally sparse and difficult to draw many meaningful scientific inferences
  - We need to do better in moving to autonomous operation
- Retrieval is still too cumbersome.


hdf5 file
~1 GB for ~8 hours of collection
etalon_001
gas_cell_001
spec_001
trans_001
abs_001
nus_001
X (.ν̃ , layer)
mix
fit
TEMPERATURE (K)
Stratosphere
Free Troposphere
PBL
PRESSURE (mbar)
XCH4, XCO2
Abs
expNus

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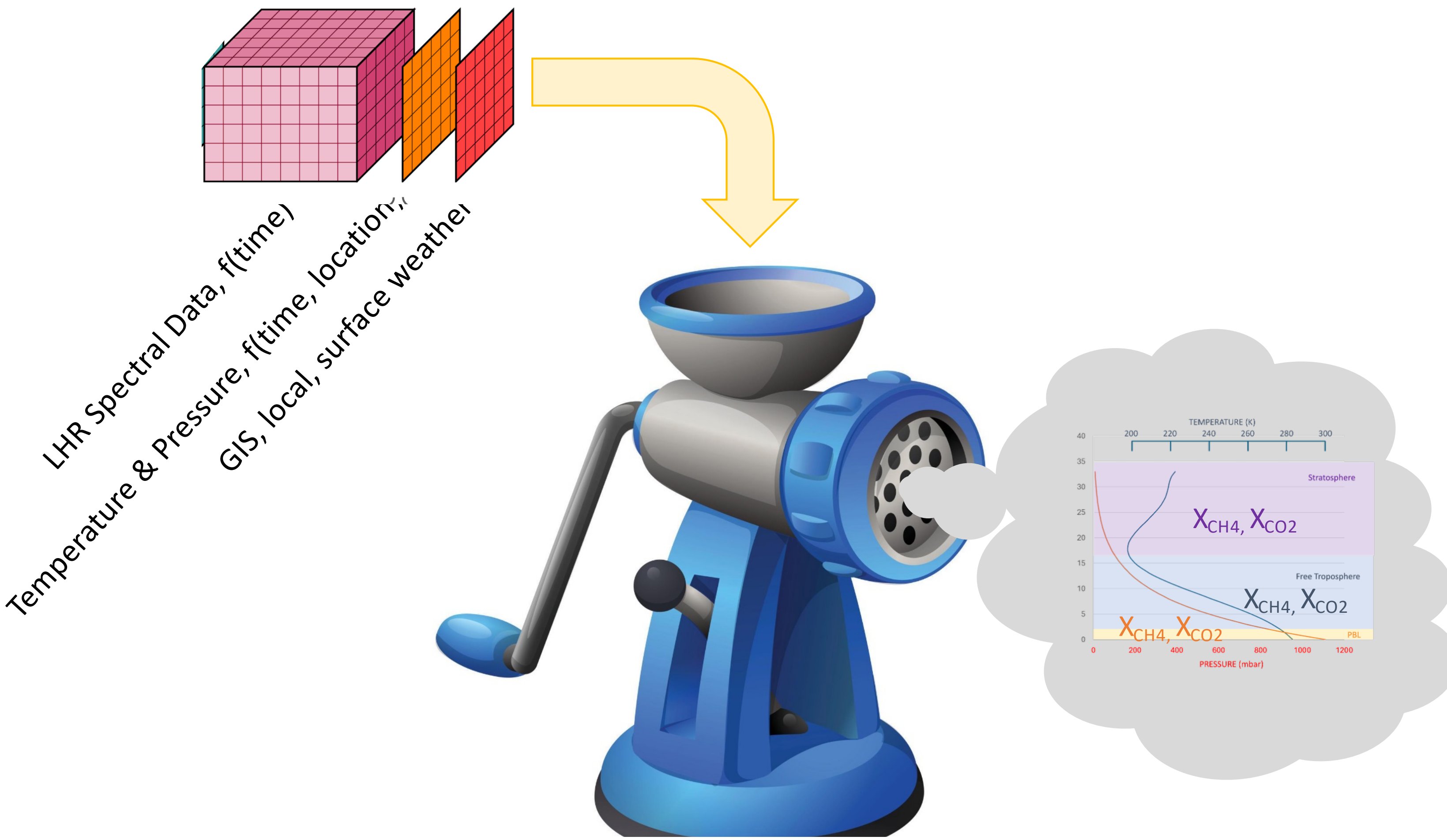
LHR Spectral Data, f(time)
Temperature & Pressure, f(time, location
GIS, local, surface weathe
TEMPERATURE (K)
200 220 240 260 280 300
40 35 30 25 20 15 10 5 0
Stratosphere
X_{CH4}, X_{CO2}
Free Troposphere
X_{CH4}, X_{CO2}
X_{CH4}, X_{CO2}
PBL
0 200 400 600 800 1000 1200
PRESSURE (mbar)

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- Retrieval is still too cumbersome.
  - The goal is *Drag and Drop* individual data records into a program queue
  - We don't yet fully understand the uncertainty in the retrievals: How sensitive are the fits to individual layer mixing ratios?
  - Absolutely, we need to constrain layer mixing ratios to deliver meaningful results and useful "priors" are difficult to come by.
  - Not as sensitive to (very near) surface emissions as we would like.
    - Averaging over the boundary layer
    - Co- location with one or more mixing ratio and/or flux *point* experiments would add valuable insight.

What we didn't have time to talk about

- Santa Fe, New Mexico!
  - Lower humidity (1278 nm data) and higher elevation
- A novel way to refine temperature and pressure value using a trio of O_2 features (1278 nm data)
- Hydrogen Fluoride detection in the stratosphere (1278 nm data).

Acknowledgements

- Smithsonian Environmental Research Center
  - Roy Rich
- Mesa Photonics and GWU were supported under a joint Small Business Technology Transfer grant from the Department of Energy, DE-SC0019543.

GW LASER ANALYTICS MesaPhotonics Smithsonian Environmental Research Center U.S. DEPARTMENT OF ENERGY