Global Monitoring Division

Theme 1- Climate Forcing,

and

Common Elements

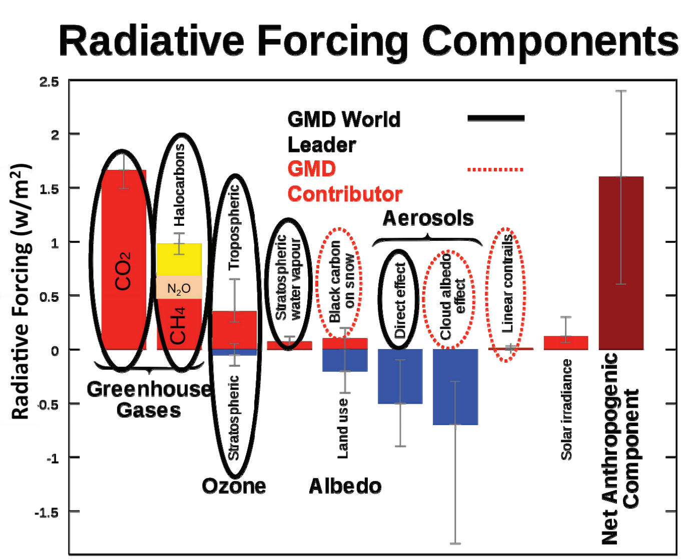
Contents:

- 13 Presentations on Climate Forcing
- 3 Presentations on Common Elements

Overview of Climate Research at GMD

John B. Miller

GMD makes the observations necessary to calculate the majority of radiative forcing



Following IPCC Fourth Assessment

→ *GMD conducts research to understand present-day and historical processes, to better enable predictions of radiative forcing in the future.*

GMD Climate Forcing Research is Motivated by Fundamental Scientific Questions

1. How are atmospheric levels of GHGs changing and what are their impacts on Radiative Forcing (RF)?
2. What are the anthropogenic and natural sources and sinks of long-lived GHGs and how are they changing over time?

A. Long-lived Greenhouse Gases

3. How sensitive are the large reservoirs of arctic and tropical terrestrial carbon to rising temperatures?
4. What are the historic, present, and future drivers of upper tropospheric, lower stratospheric (UTLS) water vapor abundances?

B. Water Vapor

5. *How do the means, variability, and trends of climatically important aerosol optical properties vary as a function of location, time and atmospheric conditions?*

C. Aerosols

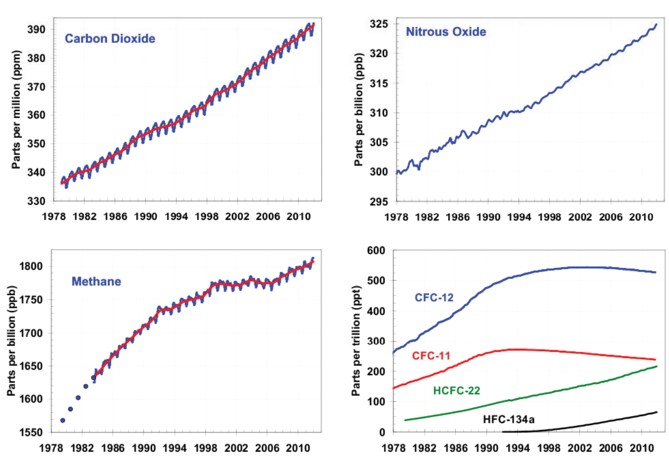
6. What changes in the worldwide radiation budget are we detecting at Earth's surface and what are the causes?

D. Radiation

1. How are atmospheric levels of GHGs changing and what are their impacts on Radiative Forcing (RF)?

→ *See talk by Montzka*

Relevance: Long-lived GHGs like CO_2, CH_4, N_2O and halogenated gases are the most important contributors to global climate change.



- In 2011, CO_2 is ~ 2/3 of RF
- Since 1990, forcing has increased by 30%.
- 80% of that is due to CO_2.

1. How are atmospheric levels of GHGs changing and what are their impacts on Radiative Forcing (RF)?

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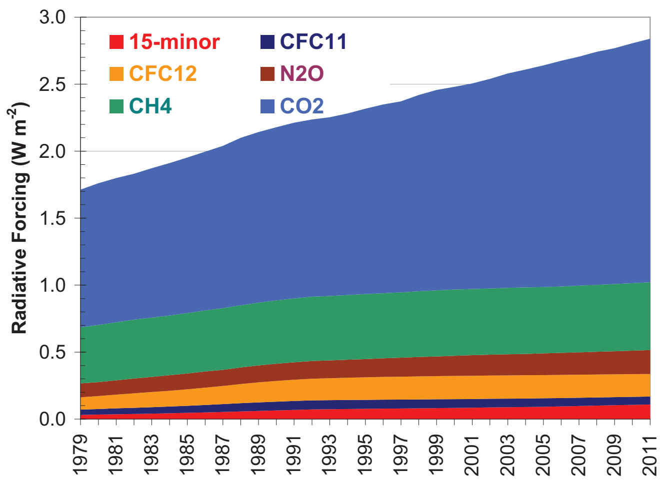
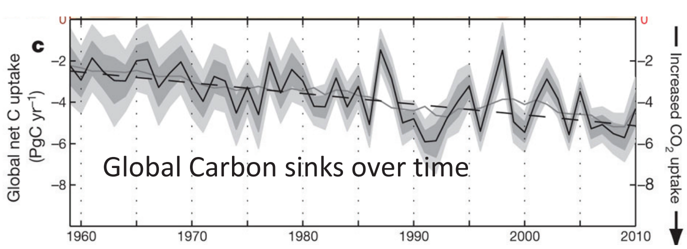


- In 2011, CO_2 is ~ 2/3 of RF
- Since 1990, forcing has increased by 30%.
- 80% of that is due to CO_2.

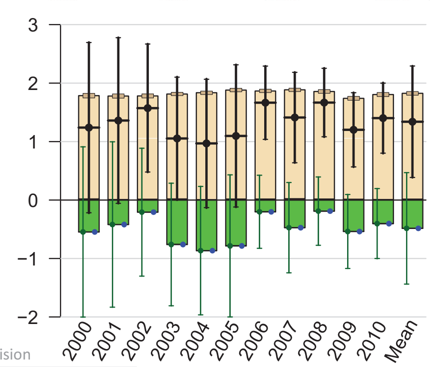
2. What are the anthropogenic and natural sources and sinks of long-lived GHGs and how are they changing over time?

→ *See talks by Tans, Miller, Jacobson, Dlugokencky and Bruhwiler*

Relevance: Understanding past variations in sources and sinks of greenhouse gases is fundamental to any attempt at emission management and future predictions.



- Global CO_2 sinks keep increasing.
- North America takes up ~1/4 of its emissions

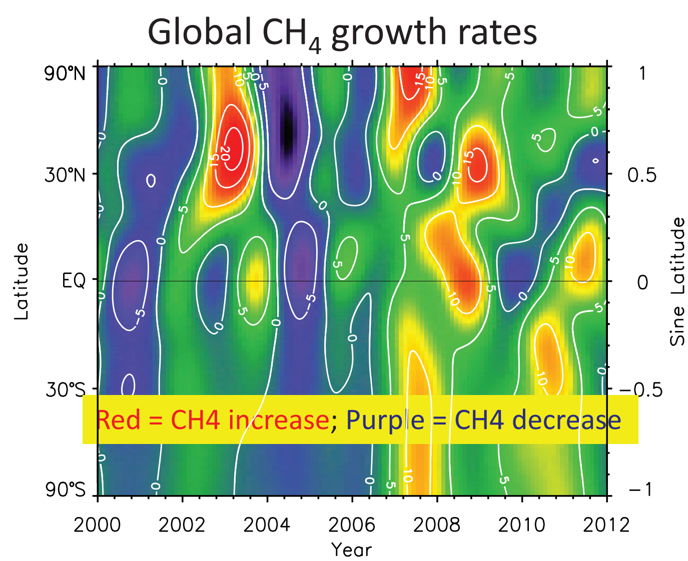


North American sinks and sources since 2000.

3. How sensitive are the large reservoirs of arctic and tropical terrestrial carbon to rising temperatures?

→ See talks by Dlugokencky and Bruhwiler

Relevance: **Carbon-climate feedbacks are a major uncertainty in predicting future climate.** A Better understanding of these reservoirs is critical for improving climate prediction.

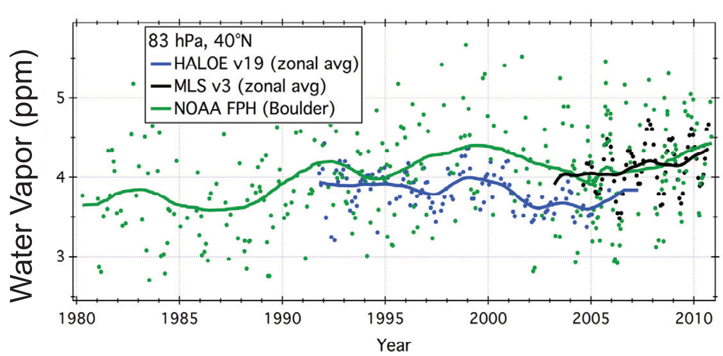


- Contrary to local-scale studies, Arctic methane sources have not been increasing.
- Amazonian CO2 fluxes show large climate sensitivity

4. What are the historic, present, and future drivers of upper tropospheric, lower stratospheric (UTLS) water vapor abundances?

→ See talk by Hurst

Relevance: UTLS water vapor has both strong sensitivity to and impact on Earth's climate.

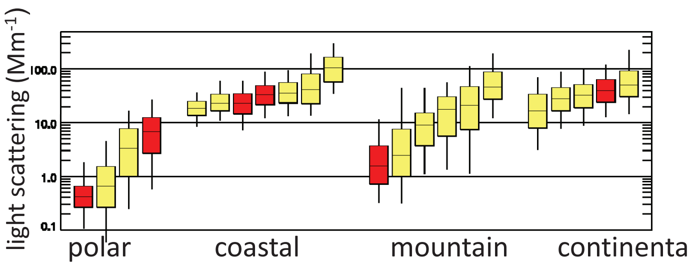


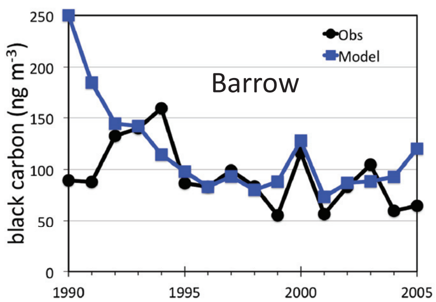
- Strong trend in the past 30 years: large impact but not easily explained.
- An example of long-term measurements used to help link and 'calibrate' shorter satellite time series.

5. How do the means, variability, and trends of climatically important aerosol optical properties vary as a function of location, time and atmospheric conditions?

→ *See talks by Ogren, Augustine; poster by B. Andrews*

Relevance: The contribution of aerosol scattering and absorption remains one of the largest uncertainties in determining radiative forcing.



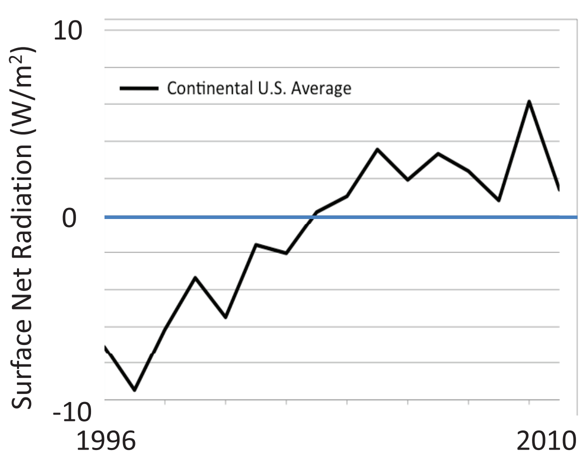


- Aerosol scattering and absorption (i.e. black carbon) are both high uncertainty elements of the global radiative forcing budget.
- Both are measured and assessed by GMD.

6. What changes in the worldwide radiation budget are we detecting at Earth's surface and what are the causes?

→ *See talk by Michalsky*

Relevance: Changes in Earth's radiation budget reflect the integrated influence of all direct and indirect climate forcing.



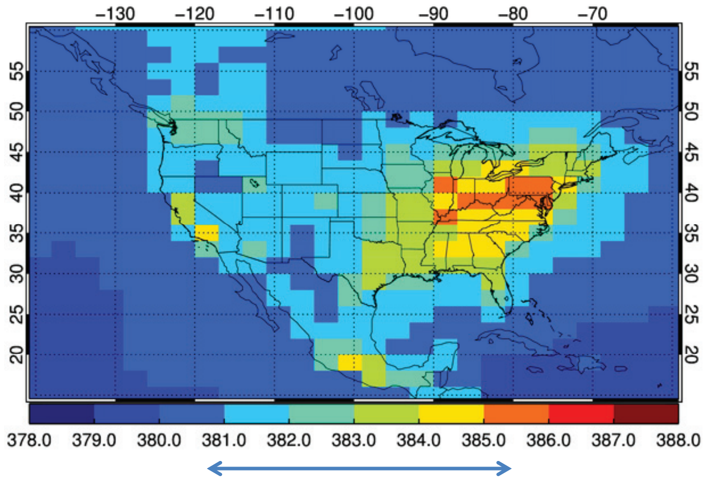
- Large increase in CONUS surface net radiation in the past 15 years.
- GHGs and aerosols can not explain this.

7. Final Note: Importance of highly calibrated data

→ *See talks by Tans, Hall and Masarie*

Relevance: Measured gradients must be real and not artifacts of inaccurate calibrations.

Annual Average CarbonTracker Boundary Layer CO_2

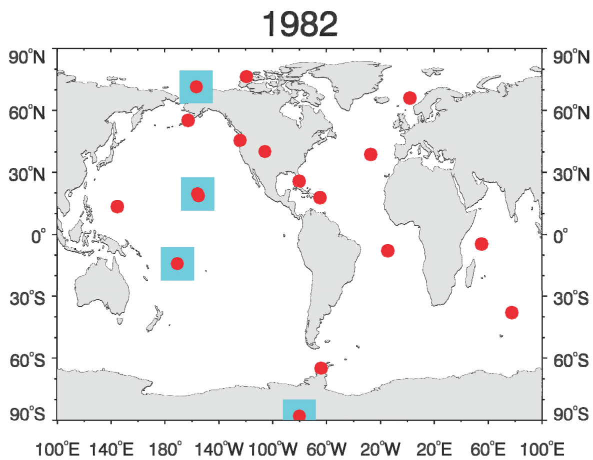


- Annual net fluxes are sensitive to small calibration errors: 0.5 ppm error in the E-W gradient would result in a flux error similar to the size of the N. American sink.

Development of the Global Greenhouse Gas Reference Network

"Science-driven monitoring of the atmosphere, responding to societal needs"

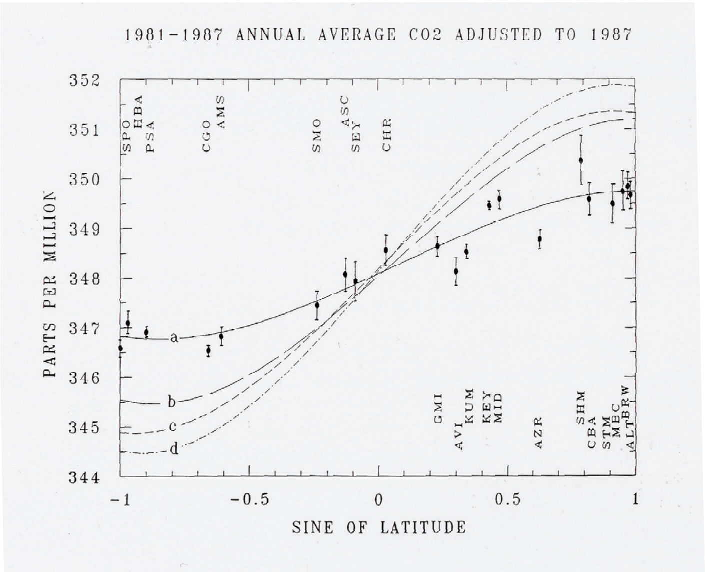
Pieter Tans



- flask sampling site (weekly)
- observatory (continuous)

5000 flask samples/year analyzed, CO_2 only.

Goal:
Create well documented record of the global increase of atmospheric CO_2.



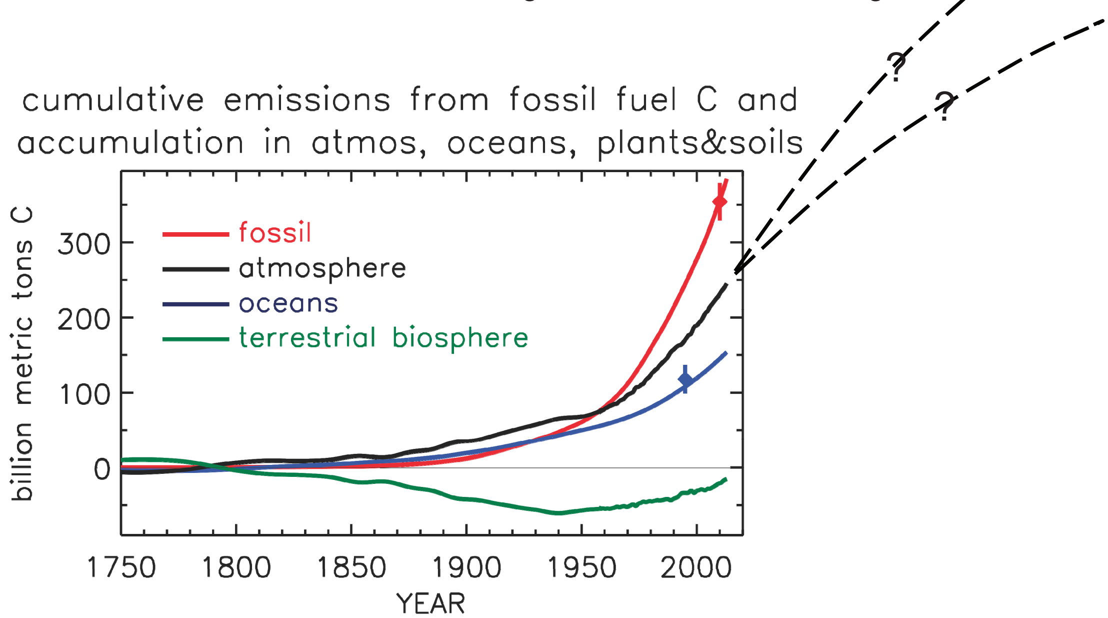
Tans, Fung and Takahashi, Science 1990.

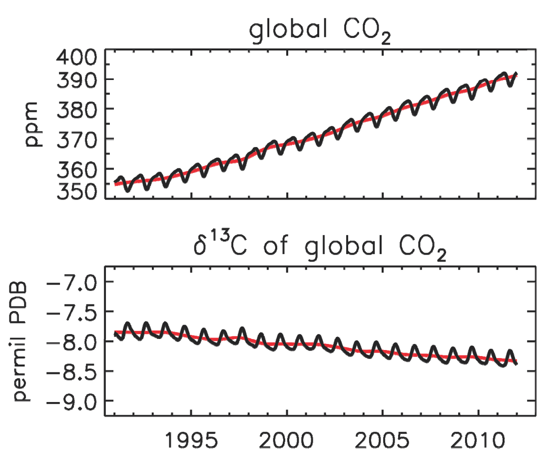
Conclusion:

Modeled gradients can be reconciled with observed CO_2 when a mid-latitude *terrestrial* sink of 2-3 PgC yr^{-1} is assumed.

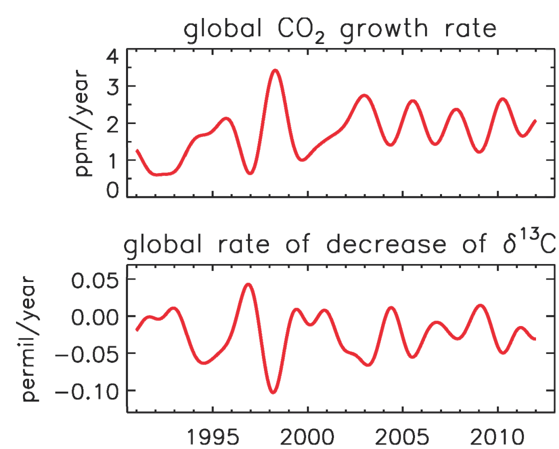
Added goal:
Quantify the terrestrial CO_2 sink at temperate northern latitudes and discover the mechanisms.

Overarching questions for CO2:
What happened to past emissions, and how will the carbon cycle respond to continued emissions, human management, and climate change?





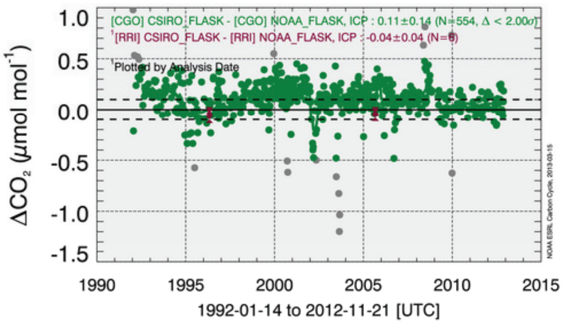
Add isotopic ratio measurements…..



In collaboration with
Stable Isotope Laboratory,
U. of Colorado/INSTAAR

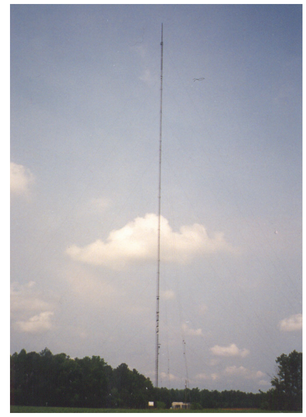
THE GLOBAL GREENHOUSE GAS REFERENCE NETWORK IN THE 1990s

Difference CSIRO (Australia) minus NOAA



- comparison of reference gas cylinders
- comparison of sampled air in flasks

…and add measurements over land in the vertical on tall towers and aircraft

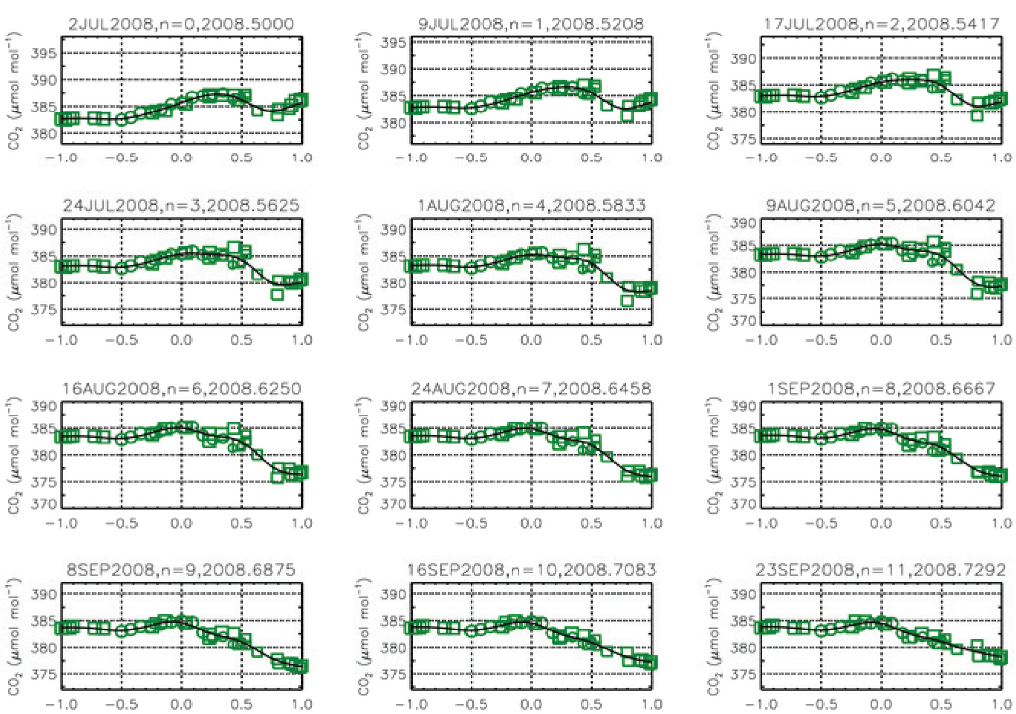


1992
First tall tower
North Carolina

1992
First aircraft sampling

THE GLOBAL GREENHOUSE GAS REFERENCE NETWORK IN THE 1990s

Marine boundary layer reference surface (time, sine of latitude)



Masarie **et** al., JGR 1995

Goals:

Create *unassailable* and well documented record of the global increase of atmospheric CO_2 and *other greenhouse gases*.

Quantify *large-scale sources and sinks of greenhouse gases* and discover the mechanisms.

Necessary attributes:

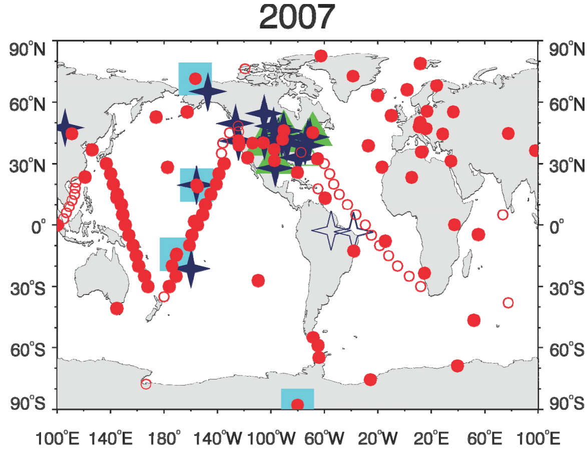
Ongoing traceability by calibrations and overall quality control of the entire measurement process.

Complete transparency by full and prompt disclosure of all data and metadata.

Make the international effort hang together, coordinated by the World Meteorological Organization/Global Atmosphere Watch program.

1999 The U.S. Carbon Cycle Science Plan
2002 follow up: The North American Carbon Program (NACP)

2007



- flask site
- observatory
- aircraft profiles
- tall tower

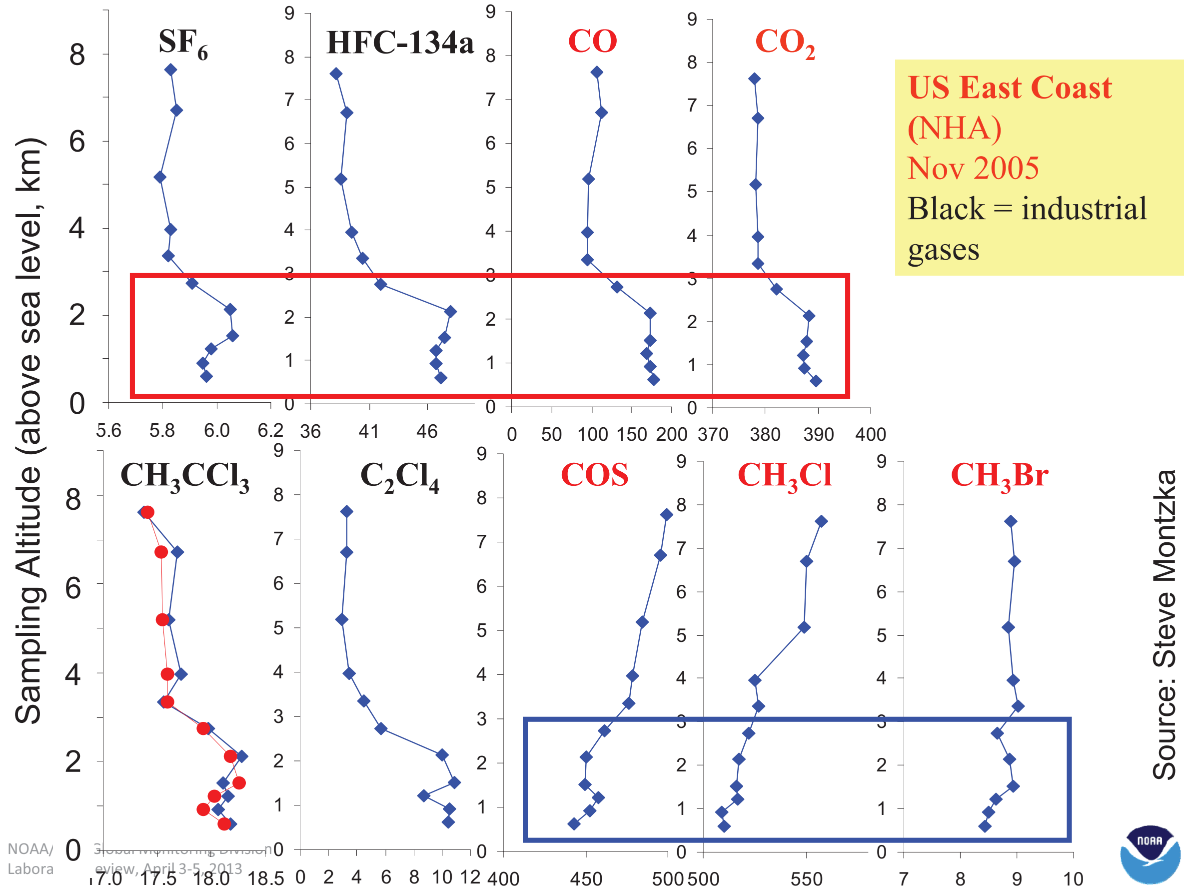
open symbol: discontinued

Enabled by NOAA NACP funds:

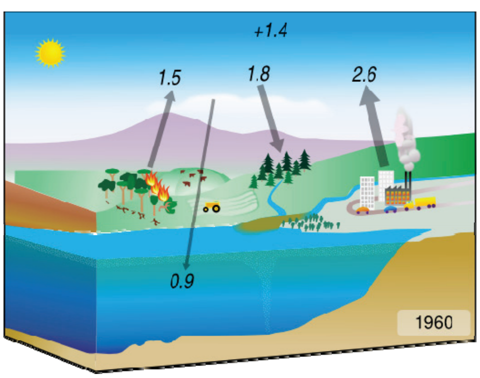
8 tall towers (Arlyn Andrews)

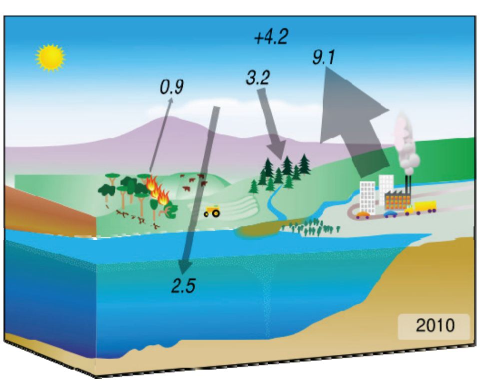
15-23 aircraft sites (Colm Sweeney)

~200 programmable flask sampling packages



THE GLOBAL GREENHOUSE GAS REFERENCE NETWORK IN THE 2000s

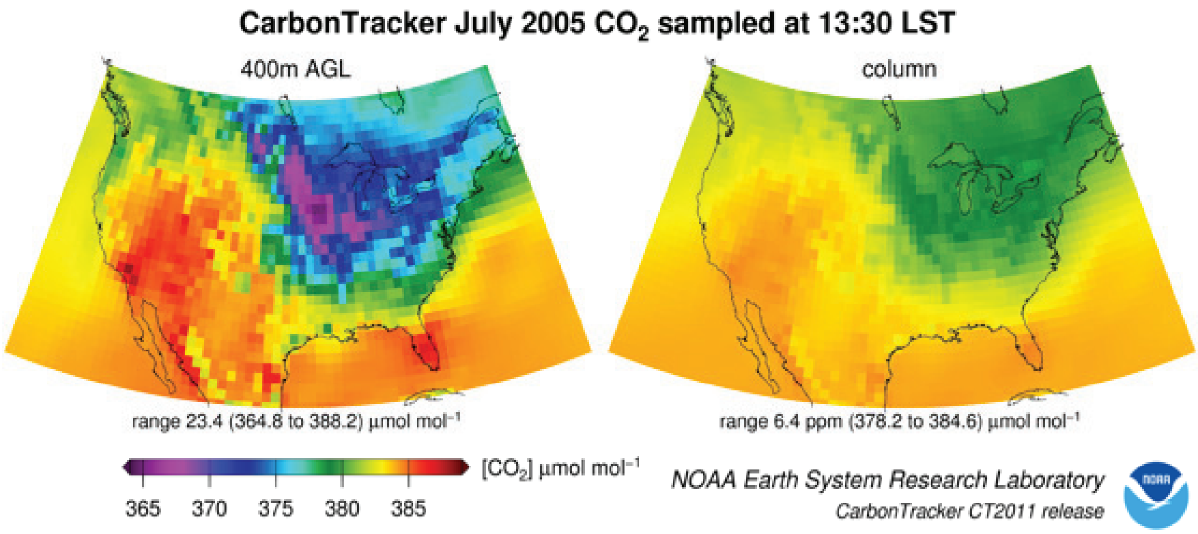




Carbon-14 measurements quantify the component of CO_2 due to recent fossil fuel burning.

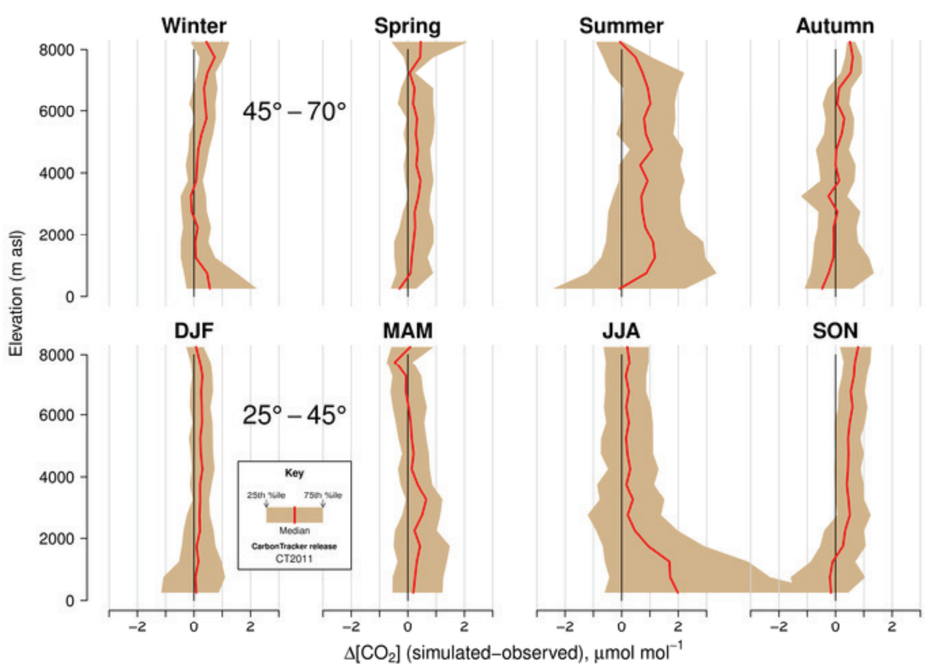
Single measurement precision 0.7 ppm fossil

Collaboration with Scott Lehman (CU/INSTAAR) and UC-Irvine

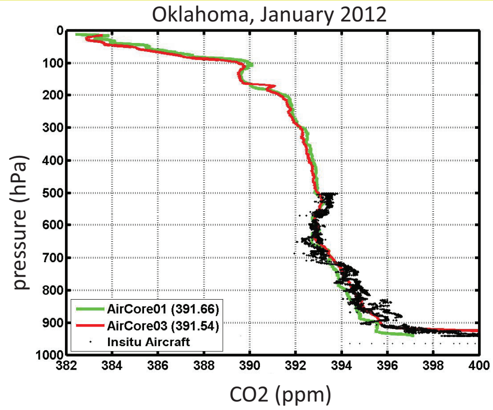


Mass balance estimate:
1 PgC/year source of CO_2 in the USA causes the total column average to increase by ~0.5 ppm.

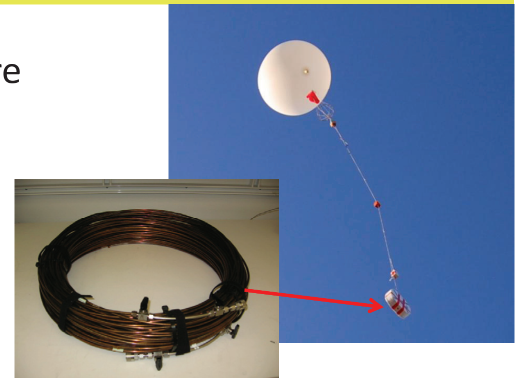
Vertical profiles modeled by CarbonTracker minus observed profiles over North America

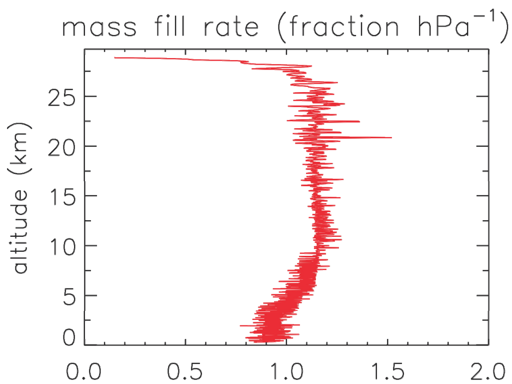


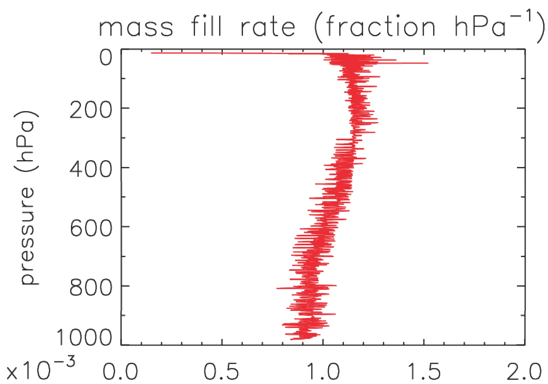
CALIBRATED MEASUREMENTS ARE THE BASIS OF OBSERVING SYSTEMS



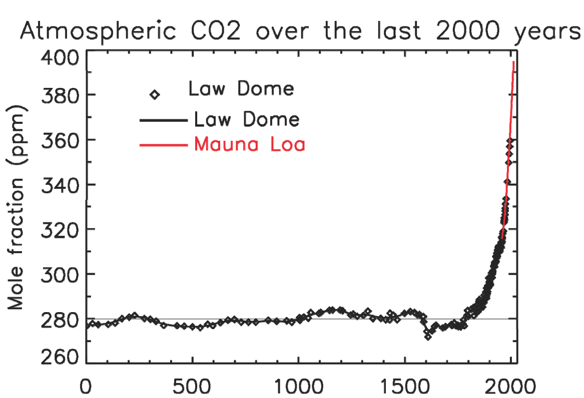
AirCore

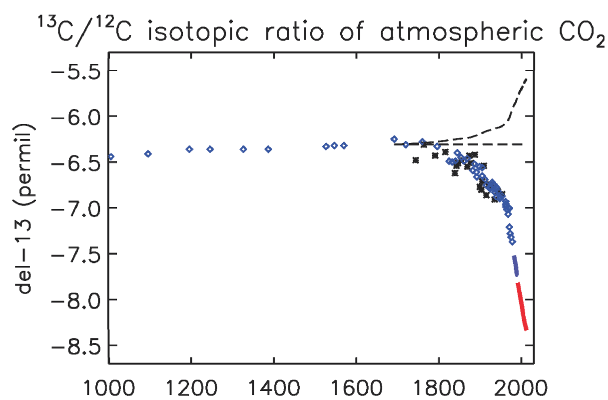


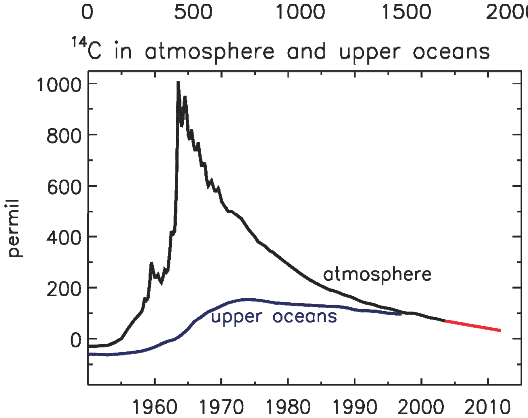


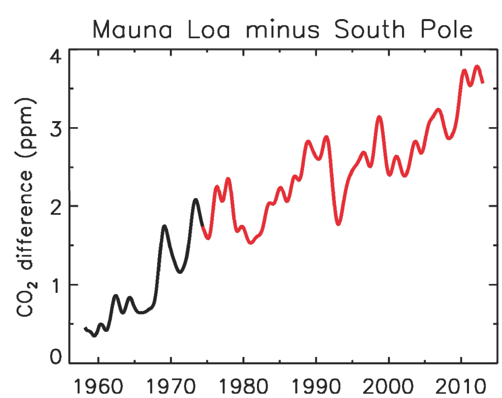


DIRECT DATA ANALYSIS: BURNING OF FOSSIL FUELS CAUSES THE INCREASE OF CO2









Summary:

We are creating an unassailable and well documented record of greenhouse gases.

Global Greenhouse Gas Reference Network

Calibrated measurements are the foundation of any long-term observing system.

We try to help society deal with the climate problem:

Create a quantitative record of climate forcing.

Quantify and diagnose the response of the natural carbon cycle and greenhouse gas budgets to climate change.

Evaluate potential "surprises" and give early warning if warranted.

Support mitigation by providing objective and transparent verification of emissions.

The Carbon Cycle and Anthropogenic Carbon Emissions

John B. Miller

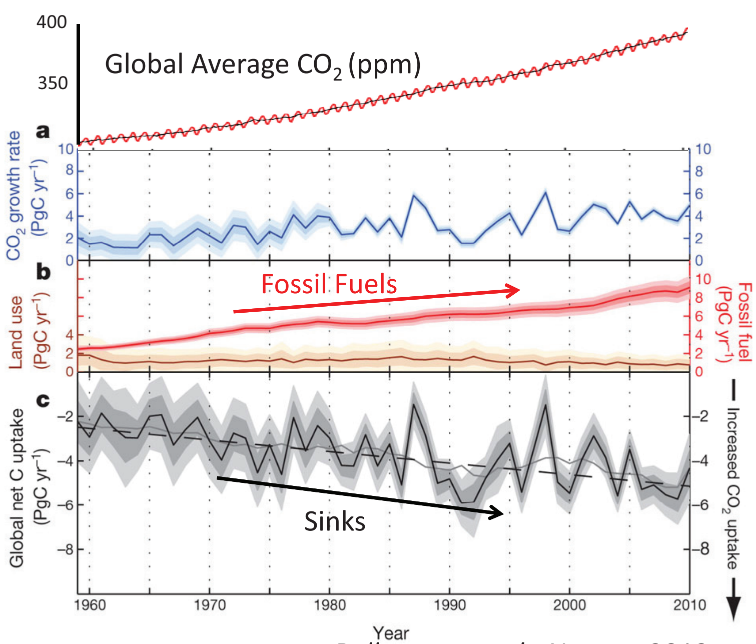
Outline and Summary

1. GMD makes measurements of CO_2 through which sources and sinks at global, continental and regional scales are constrained.

   (For these calculations, fossil fuel-CO_2 emissions are assumed, not measured)
2. $^{14}CO_2$:$^{12}CO_2$ is a robust atmospheric tracer for fossil fuel emissions.
3. Measurements of $^{14}CO_2$:$^{12}CO_2$ partition *total* flux into fossil and biosphere components.
4. Fossil-CO_2 can be correlated with enhancements of other anthropogenic gases in order to calculate their emissions.

Global carbon sinks are increasing.

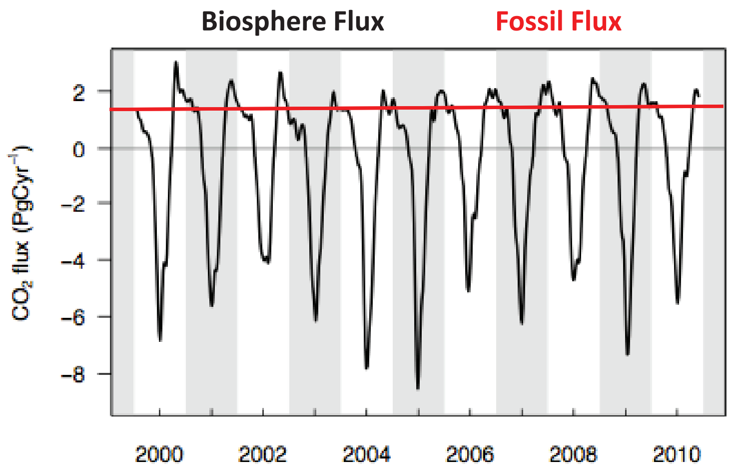
(despite regional and modeling studies implying the opposite)



Ballantyne et al., Nature, 2012

- Carbon sinks keep increasing as fossil fuels keep rising. Global C uptake now ~ 4 PgC/yr.
- 50% of fossil fuel emissions are still taken up by sinks.
- Fossil Fuel emissions uncertainty is now the biggest uncertainty in sinks.

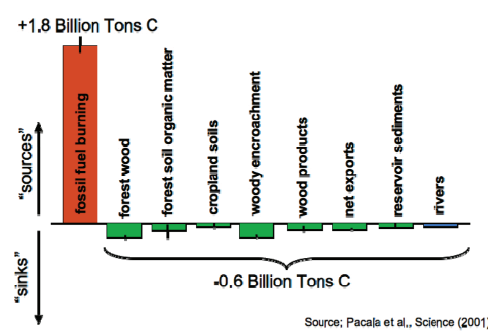
CarbonTracker shows large inter-annual variability in North American fluxes

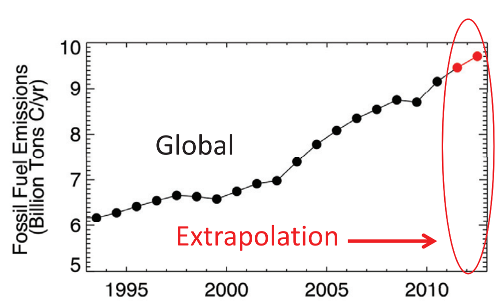


- Summertime net photosynthesis shows large year to year variability.
- Wintertime net respiration is relatively constant.
- Annually, ~1/4 of N. American fossil fuel emissions are absorbed by the biosphere.

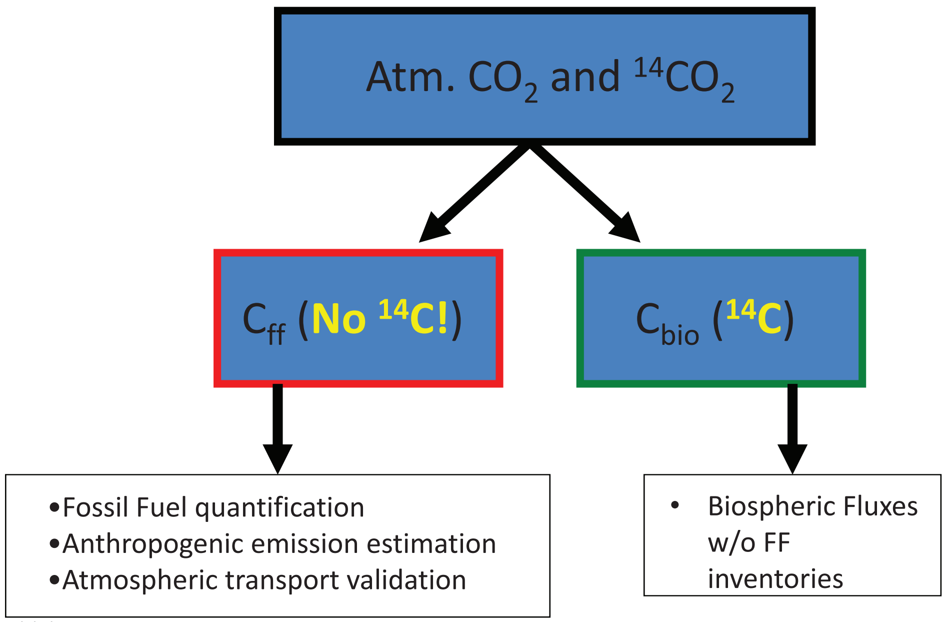
Fossil Fuel are the biggest ***annual*** fluxes globally and in N. America …

1. …but, at many time scales ecosystem fluxes are bigger, which makes FF hard to identify
2. Inventories are good; why check them?
   a. They have spatio-temporal biases at the state/monthly and smaller scales.
   b. Generally, for up to date inversions, we need to extrapolate inventories.



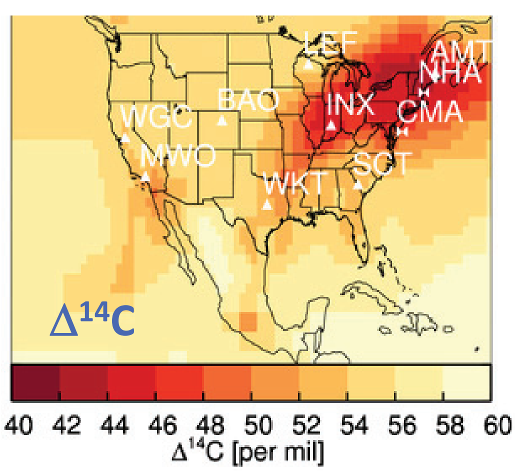


CO_2 PBL enhancements (or depletions) can be partitioned into Ecosystem and Fossil fractions.

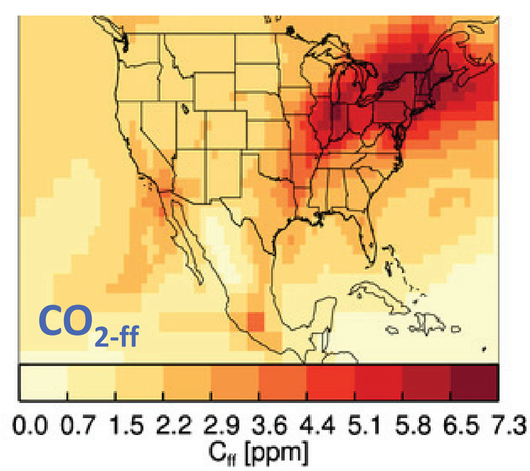


$^{14}CO_2$:$^{12}CO_2$ ($\Delta^{14}C$) is a robust tracer for fossil fuel fluxes. Atmospheric $\Delta^{14}C$ looks just like fossil CO_2.

$\Delta^{14}C_{ff}$ = -1000 per mil (i.e. zero ^{14}C)
Scaling: -2.7 per mil $\Delta^{14}C$ = 1 ppm CO_2-fossil



Includes ecosystems, oceans, nuclear power, cosmic rays, fossil fuel.



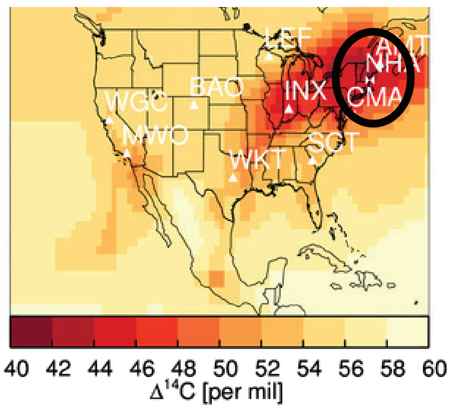
Includes only fossil fuel

$^{14}CO_2$ measurements are made at background, regional and urban scales.

→ National Research Council recommends a large increase in $^{14}CO_2$ measurements to verify emissions reductions. At 750/yr now; eventually 5000.

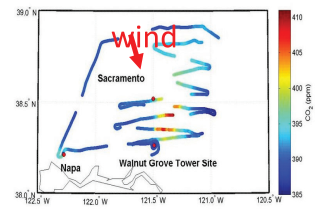
Made as part of a cooperative program with Scott Lehman at U. of Colorado.

Regional monitoring

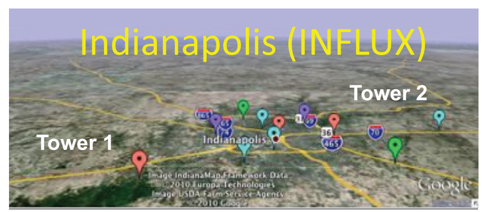


U.S. Tower and Aircraft
East Asian (not shown)

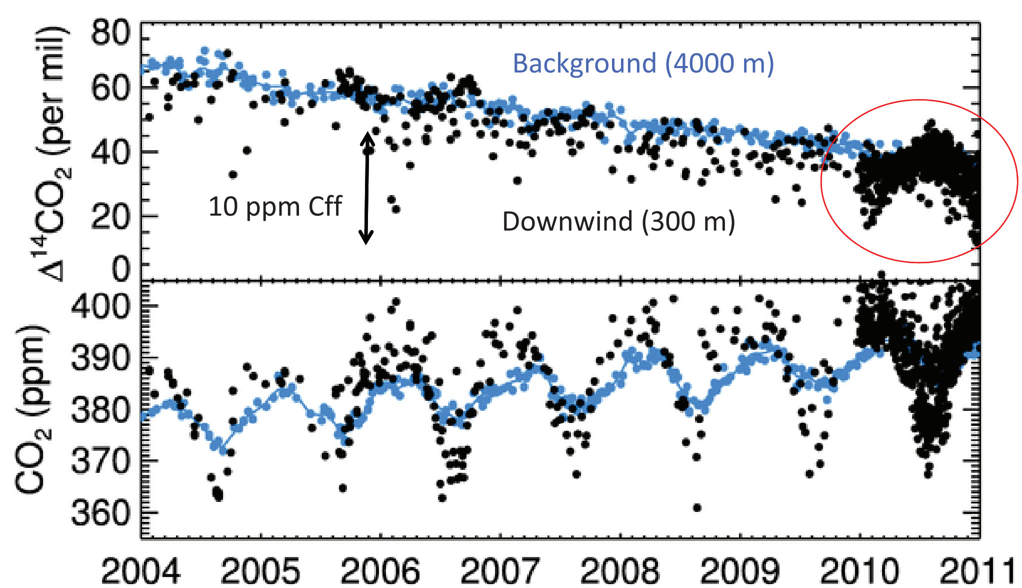
Urban Campaigns



Sacramento, 2009 (*Turnbull et al, 2011*)

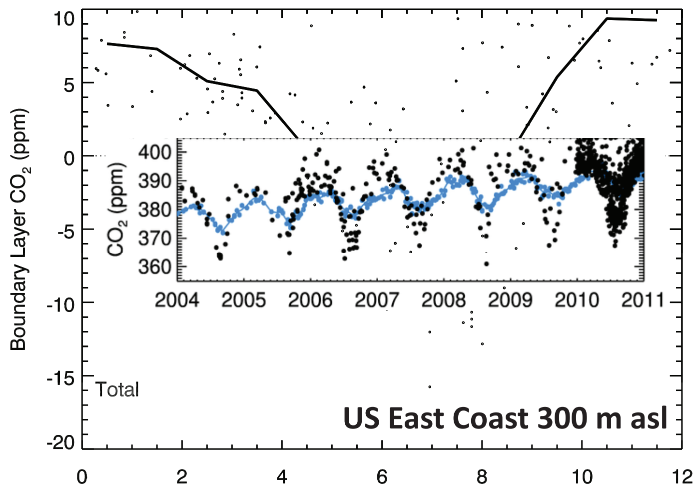


U.S. lower atmosphere data show expected depletions of ^{14}C



Fossil CO_2 masks the true extent of Ecosystem CO_2

"Total CO_2" = Boundary Layer minus Background



- → Ecosystem-CO_2 large even in winter (~60% of total winter-time enhancement) despite urban/industrial observational footprint
- → CO_2-only methods (tower, satellite, etc.) can not assume enhancements are due just to Fossil-CO_2

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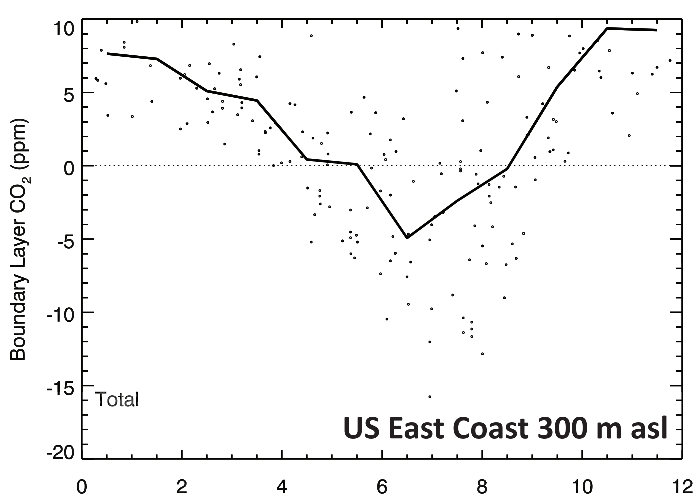

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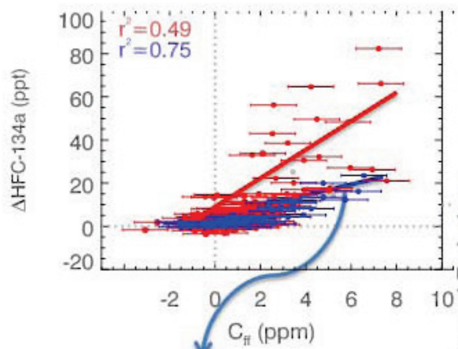
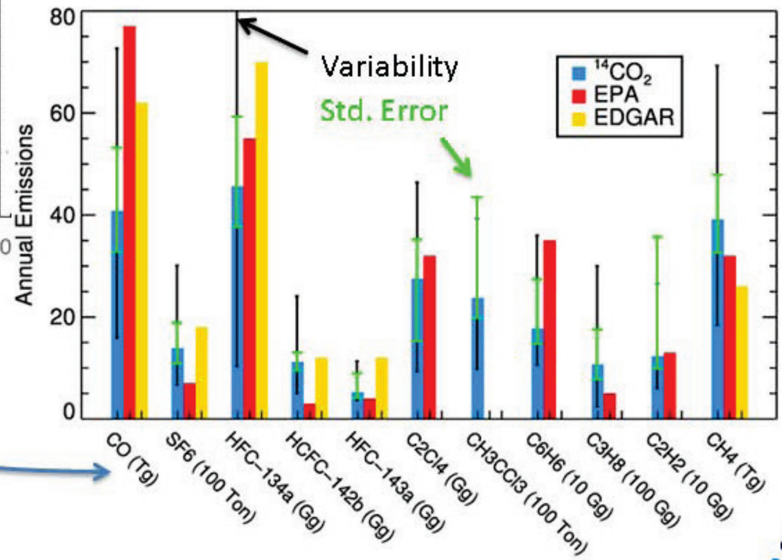
Fossil Fuel-CO_2 is correlated with anthropogenic gas enhancements and can be used to quantify emissions.

→ *See Montzka poster for more on correlation of CO_2-ff with anthropogenic gases.*



$$E_{gas} = (\Delta_{gas}/C_{ff}) \times E_{ff}$$



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Outline and Summary

1. GMD makes measurements of CO_2 through which sources and sinks at global, continental and regional scales are constrained.

   (For these calculations, fossil fuel-CO_2 emissions are assumed, not measured)

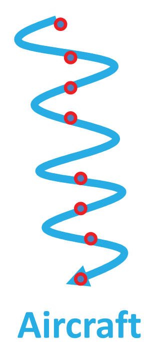
2. $^{14}CO_2$:$^{12}CO_2$ is a robust atmospheric tracer for fossil fuel emissions.
3. Measurements of $^{14}CO_2$:$^{12}CO_2$ partition *total* flux into fossil and biosphere components.
4. Fossil-CO_2 can be correlated with enhancements of other anthropogenic gases in order to calculate their emissions.

Main Points

1. **Unique Network: No other aircraft network has been designed to answer specific scientific questions and lasted as long as this network**
2. **Independent flux estimate: Less dependent on vertical transport.**
3. **Validation of models and remote sensing methodologies.**
4. **Background: In situ aircraft profiles are a key source of validation for background conditions.**

Automated Flask Sampling from Aircraft:

- One twelve-pack per flight
- Typical profile from 500 m AGL to 8000 m ASL
- Species: CO_2, CO, CH_4, N_2O, SF_6,
  stable isotopes, halocarbons, COS,
hydrocarbons…
  $^{14}CO_2$ on a limited number of samples



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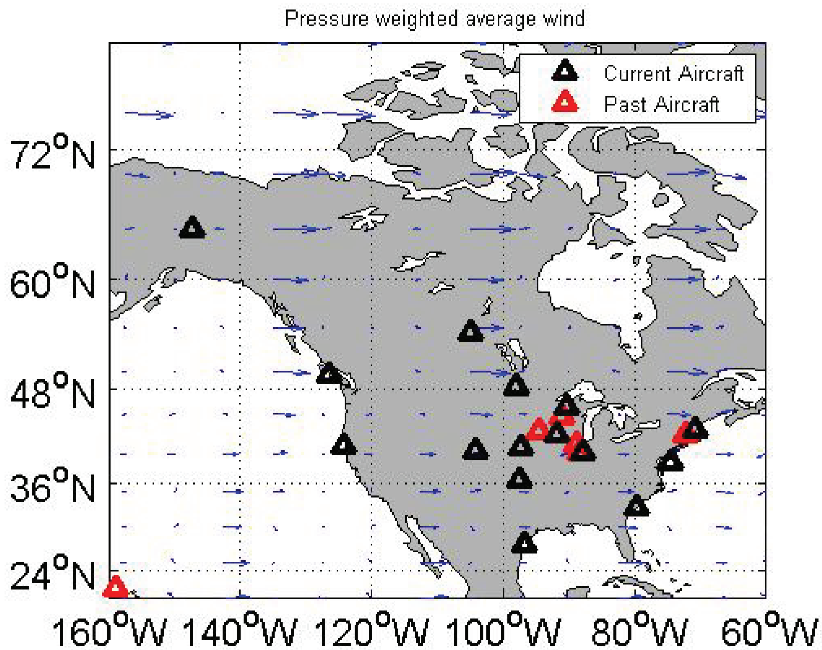
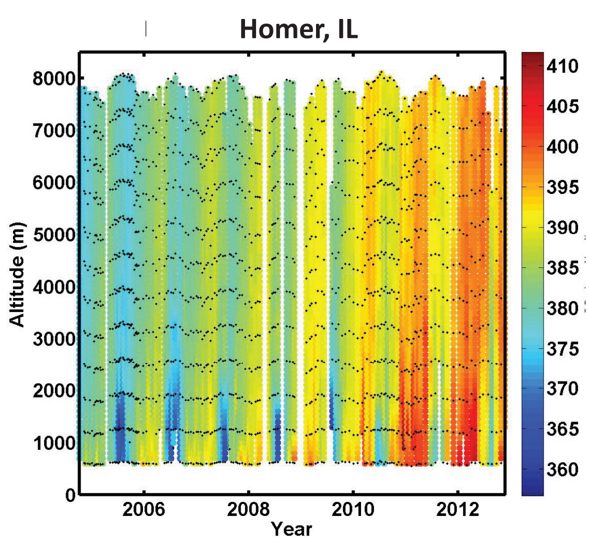
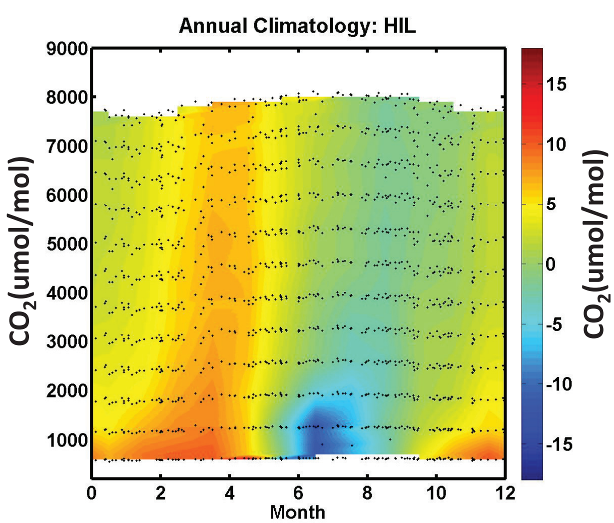
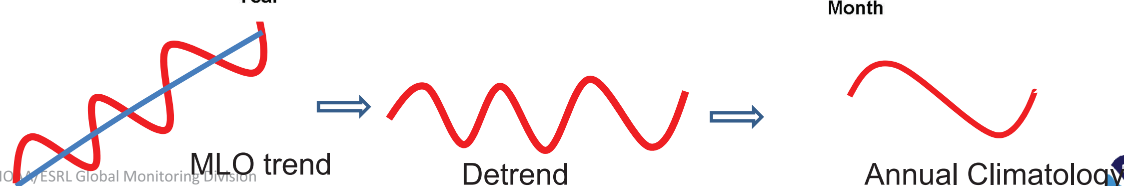
Current NOAA/GMD aircraft network



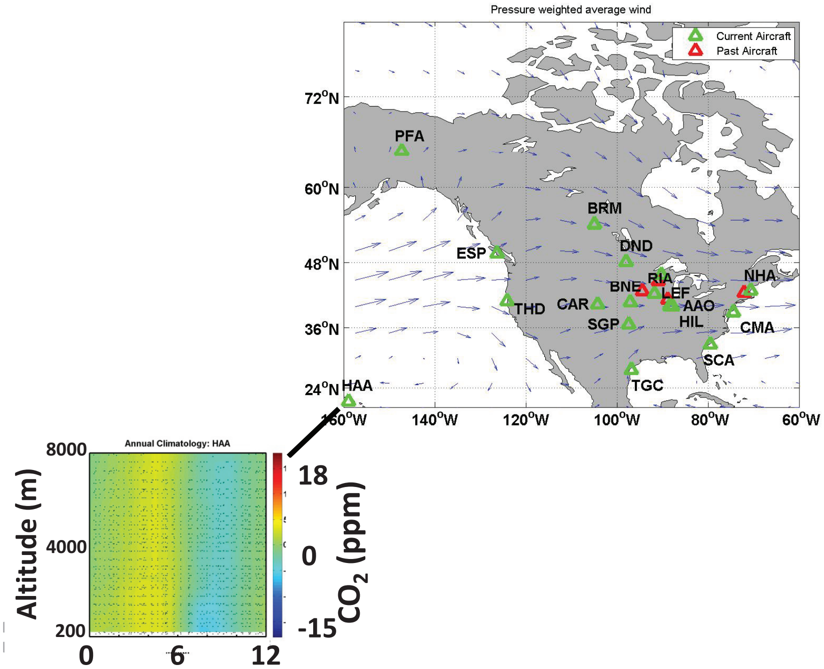
Annual Climatology







CO_2 seasonal cycle



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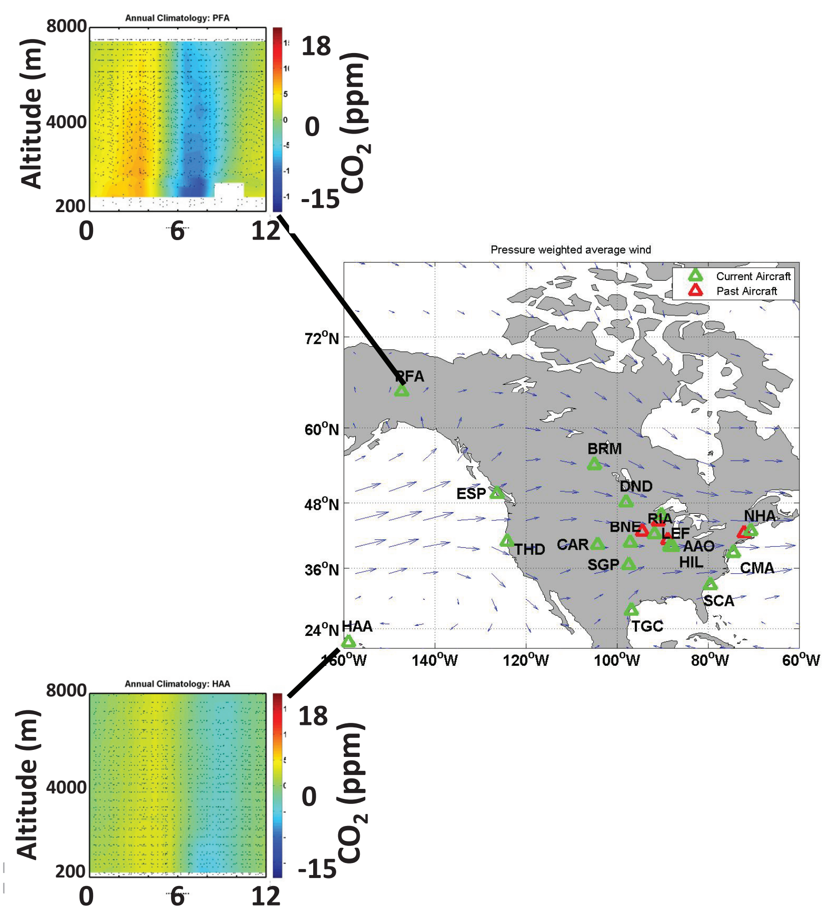

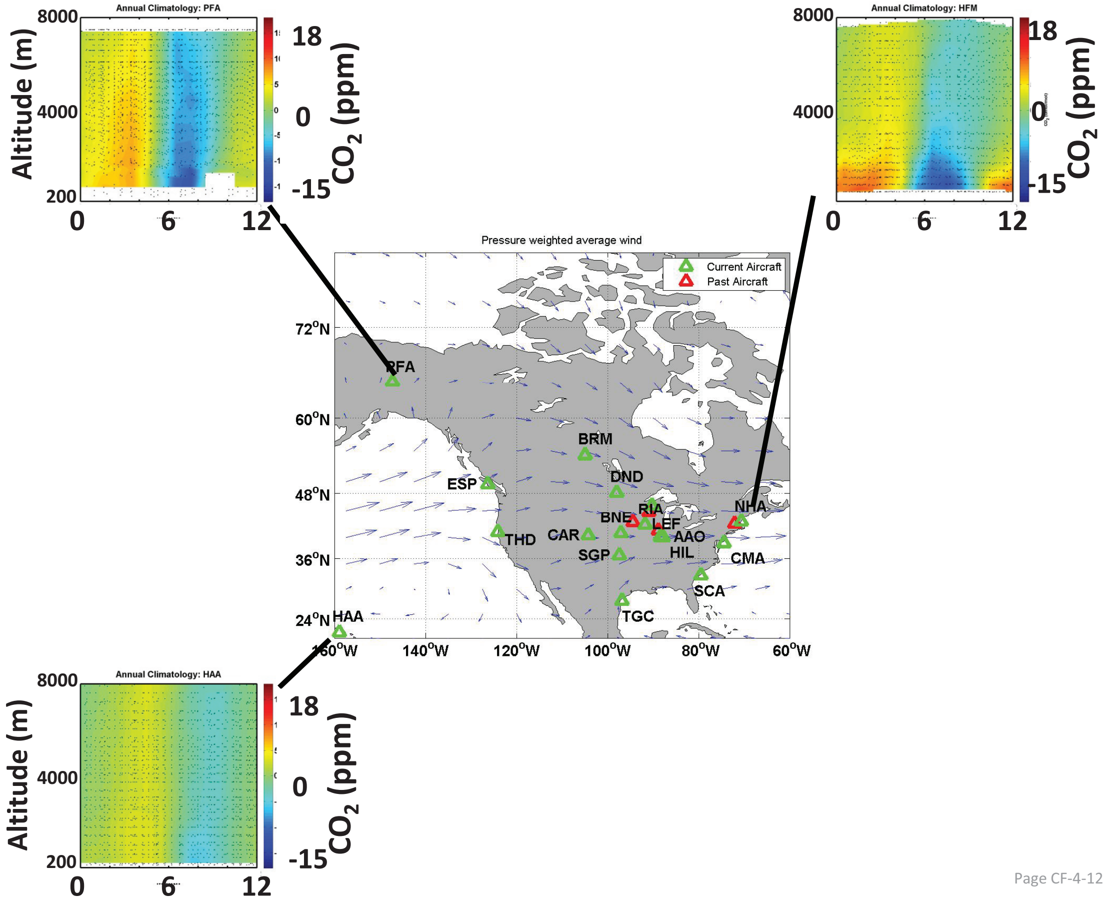

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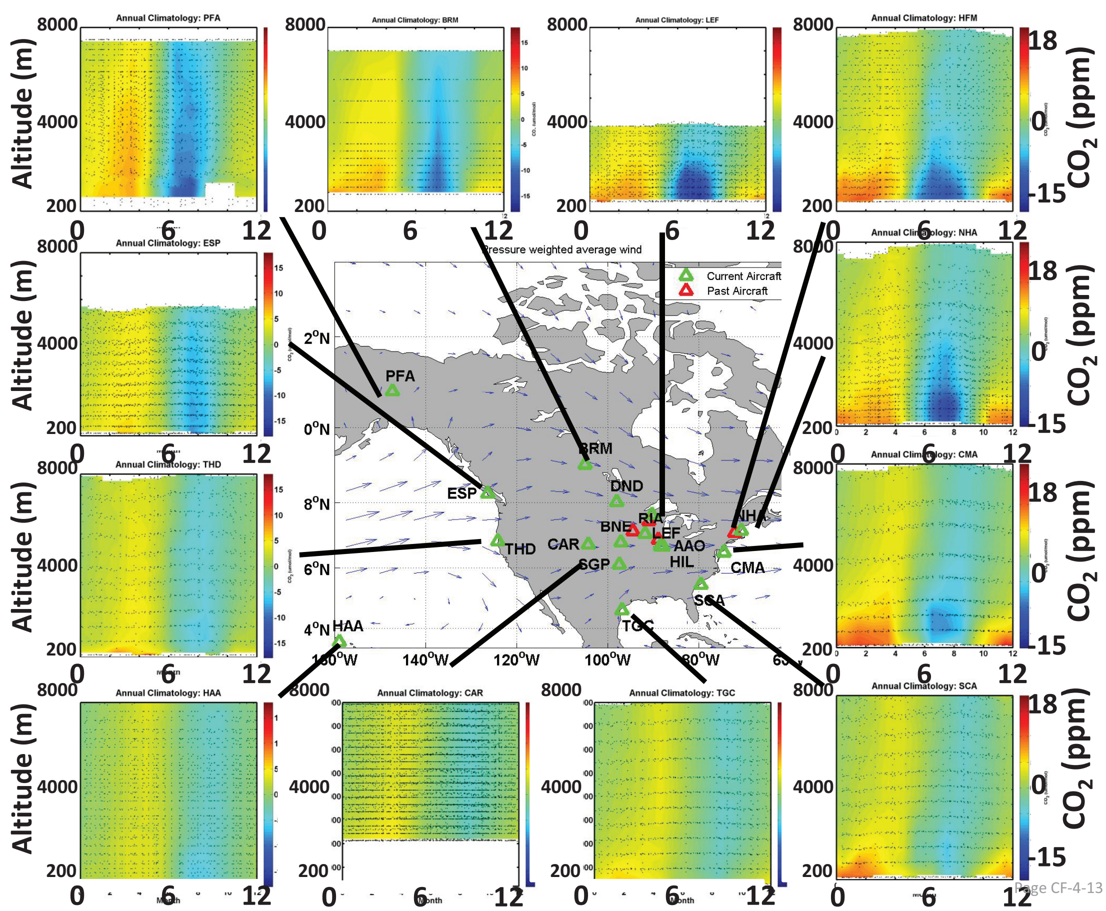

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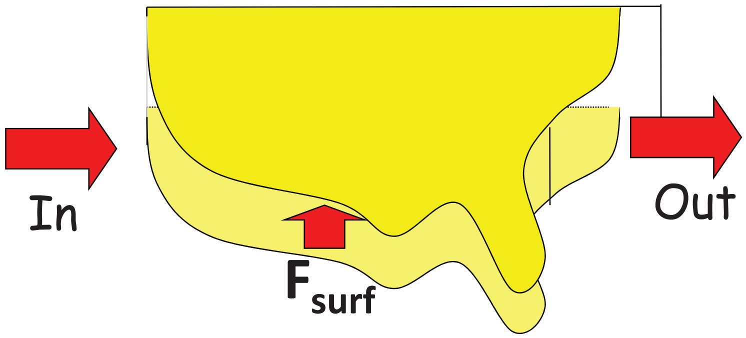


F_{surf} → 1.22 GtC.yr^{-1}

Fossil fuel emission → 1.73 GtC.yr^{-1}

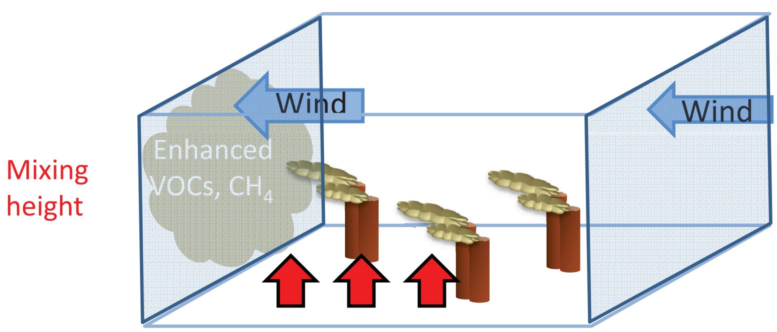
North American sink: → -0.5 ± 0.4 GtC.yr^{-1}

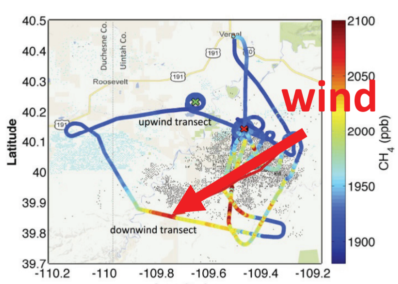
✓The uncertainty is derived from the kriging estimate of interpolation error and temporal and spatial biases.

✓A potential bias comes from the convective flux, even if small, at 8 km.

✓Simulations with atmospheric transport models give an estimated bias of -0.1 GtC.yr^{-1}, mainly in the South East during summer (June-August).

Crevoisier and Sweeney et al. 2010

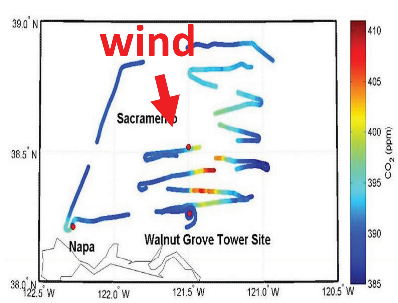




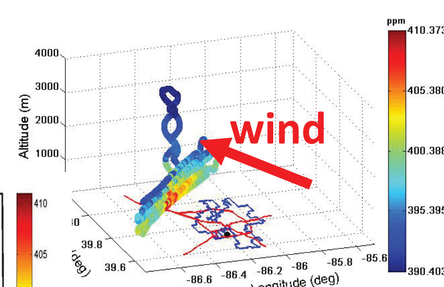
Uintah Basin Utah

Karion and Sweeney et al. 2013

Sacramento, CA



Turnbull et al. 2010



Indianapolis, IN

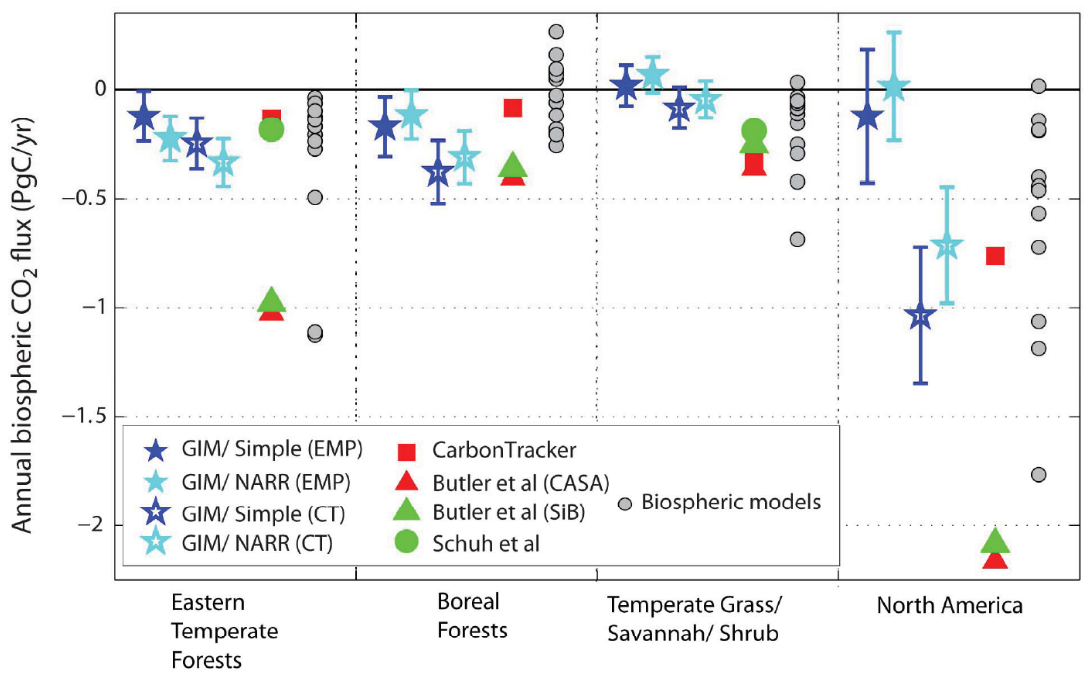
Mays et al. 2009

Background CO_2

Flux = (obs – background) * transport
transport = (365/5 * 5*10^{19}g)/29
Obs – Background = 1 ppm
Flux = 1.5 Gt C/yr

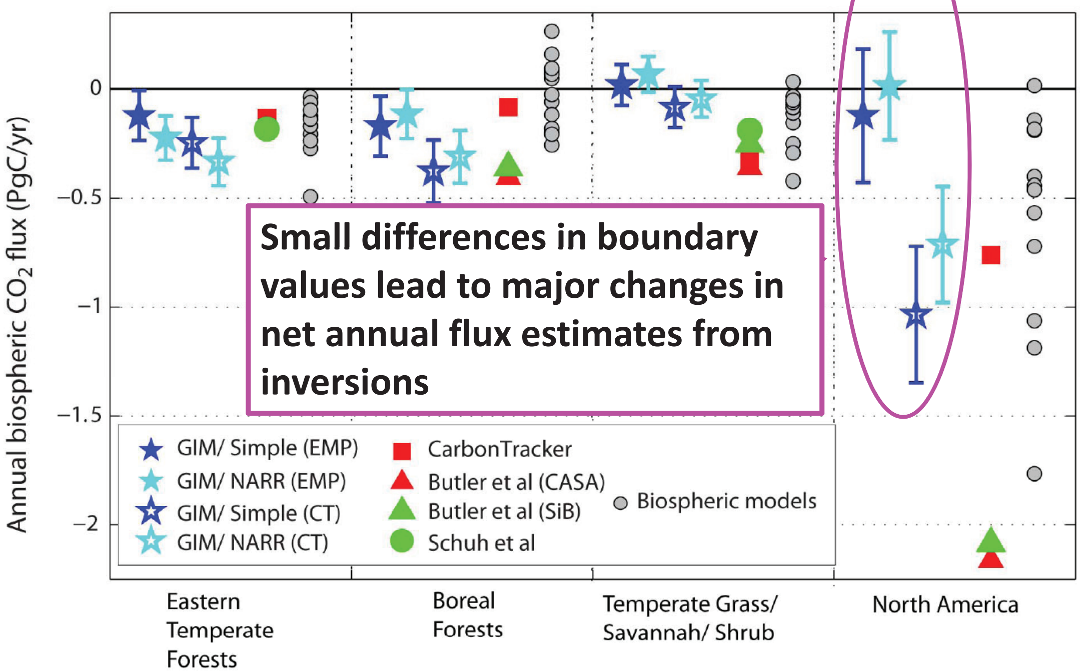
The bottom 50% of the atmospheric column will change by **1 ppm** due to fossil fuel emissions (1.5 Gt/yr) given an average transport time of 5 days over the US continent. **Extremely accurate background measurements are needed to detect changes in these emissions.**

Background CO_2



Gourdji et al. 2012

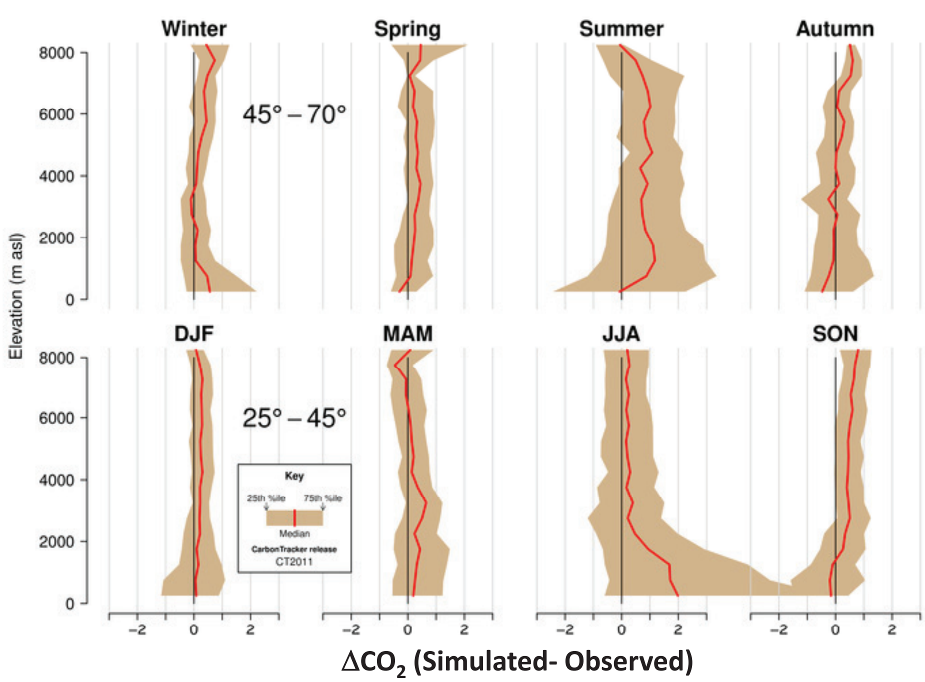
Background CO_2



Gourdji et al. 2012

Ground truth for models

CarbonTracker



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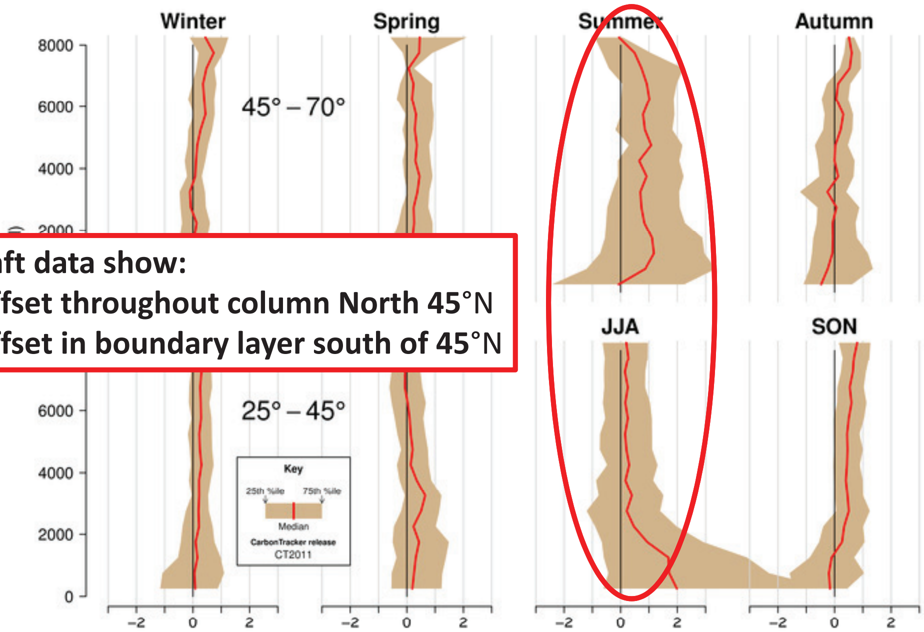
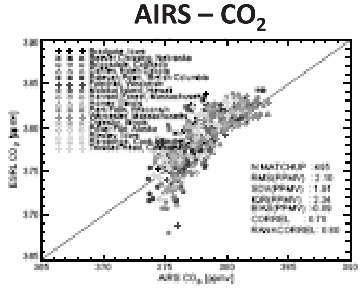


Aircraft data show:
- Offset throughout column North 45°N
- Offset in boundary layer south of 45°N

ΔCO_2 (Simulated- Observed)

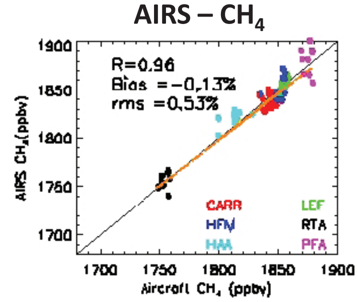
Ground truth for remote sensing

AIRS – CO_2



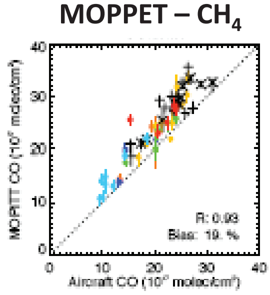
Maddy et al. (2007)

AIRS – CH_4



Xiong et al. (2008)

MOPPET – CH_4



Emmons et al. (2009)

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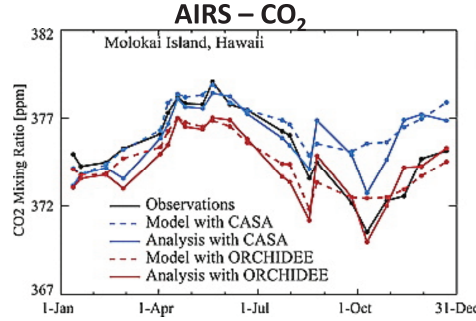

Engelen et al. (2009)

Conclusion

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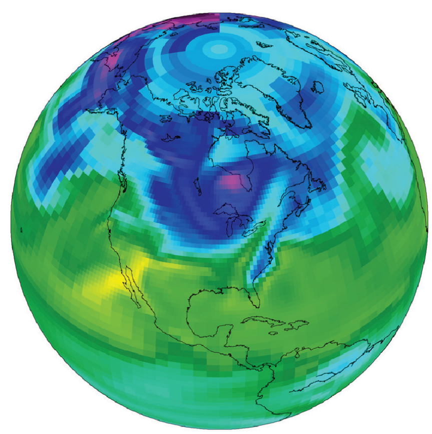
CarbonTracker

Modeling of Greenhouse Gases at GMD

Andy Jacobson



1. A brief history of CarbonTracker
2. Why have models in a measurement program?
3. How is our product used?
4. Plans for the future

CarbonTracker overview

- A global atmospheric CO_2 model using data assimilation to estimate optimal surface fluxes.
- Initial release in February 2007, with quasi-annual updates
- A hybrid operational product and research tool
- Completely open
  - extensive web presence
  - source code, fluxes, 4-D CO_2 fields, input data
- Reviewed three times in 2008, including a dedicated science review
- N. American Carbon Program science goals:

  carbon cycle diagnosis, attribution, prediction, and decision support

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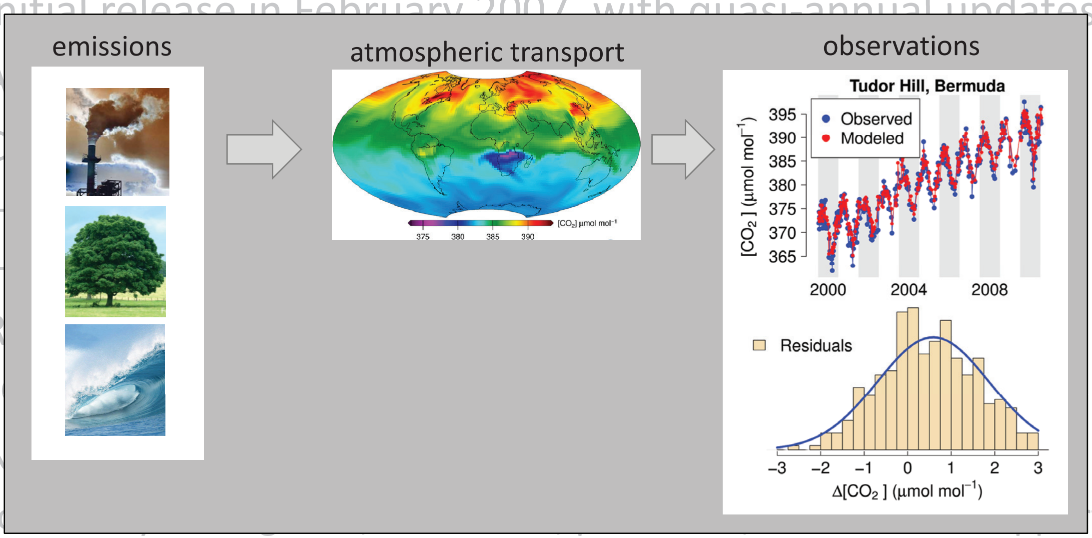

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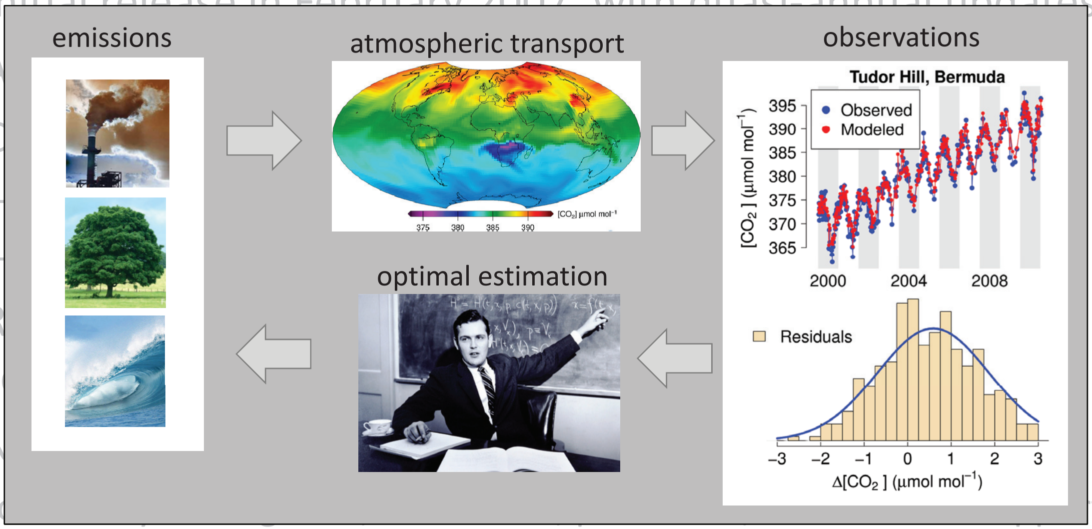

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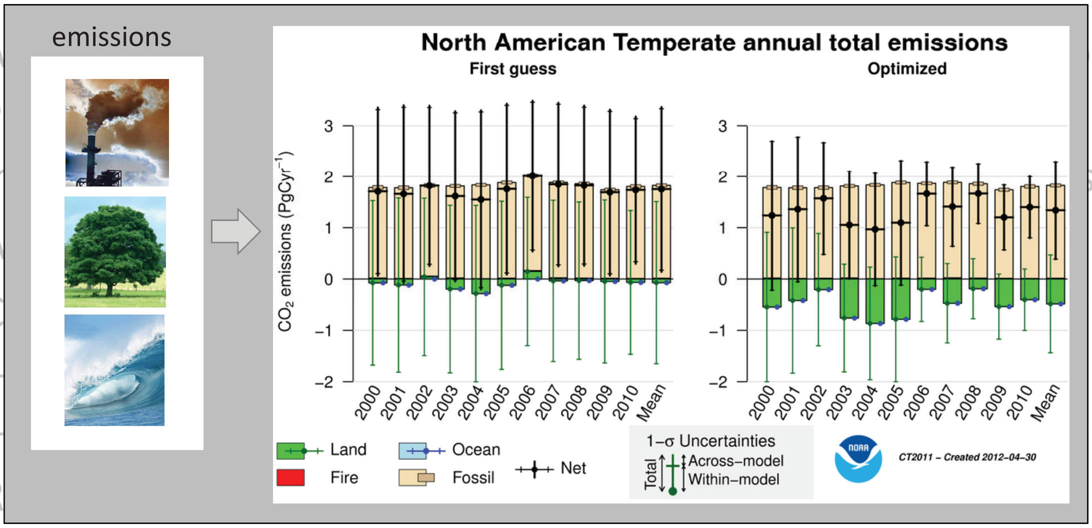

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A *complete* observing system includes modeling

- At the measurement level
  - "Last step in quality control" –P. Tans
  - Beyond statistics of total CO_2 variations; accounts for emissions and transport
- At the network level
  - Understand strengths and weaknesses of network
  - Participate actively in interpretation of measurements
  - Evaluate whether we can answer carbon cycle questions

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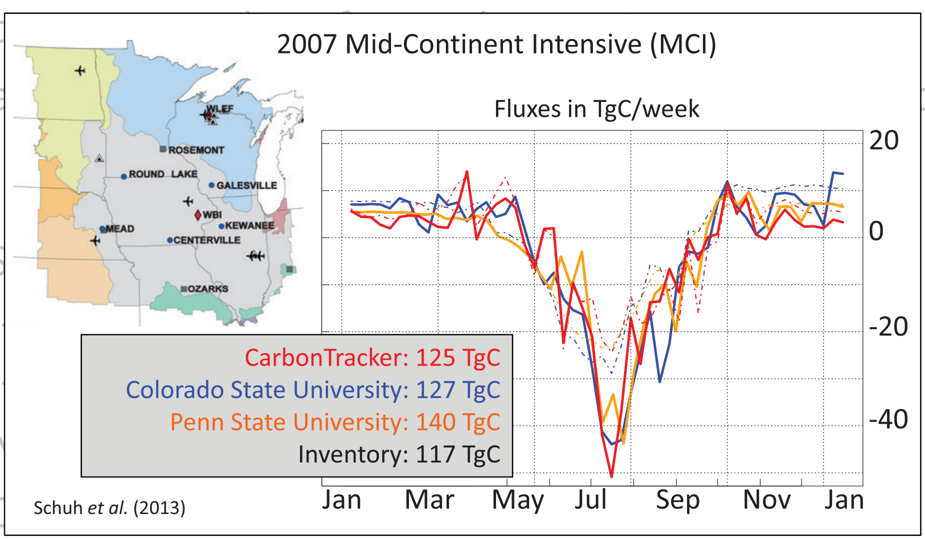
How is CarbonTracker used by others?

- as boundary conditions for regional and local analyses
- as a benchmark for land and ocean flux products



Schuh *et al.* (2013)

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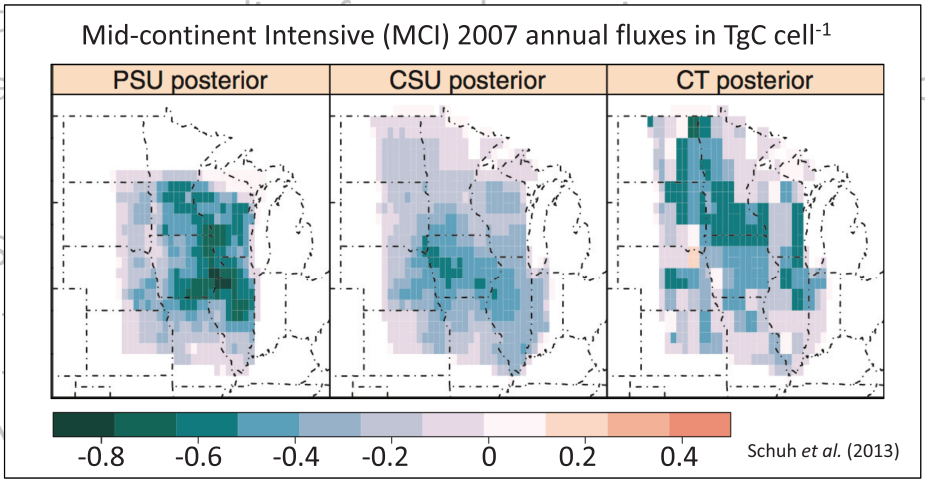

- S
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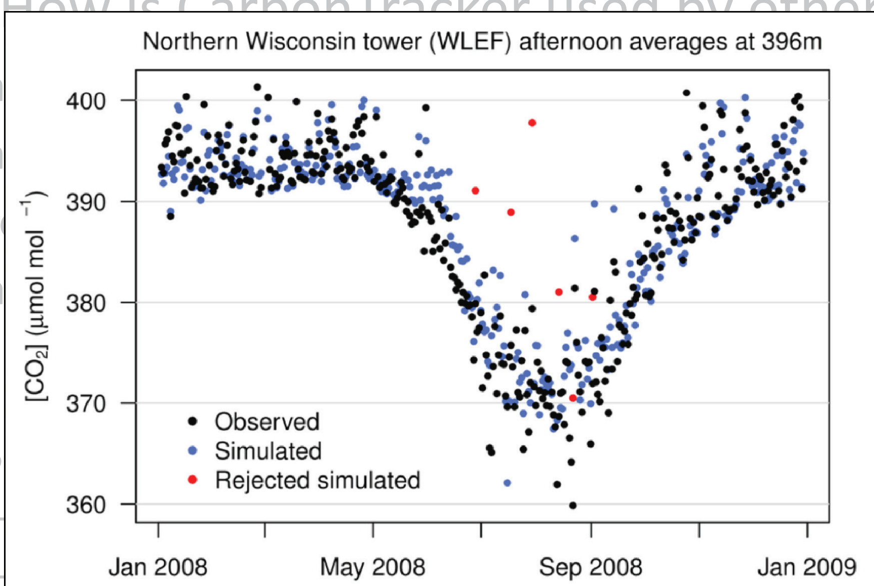

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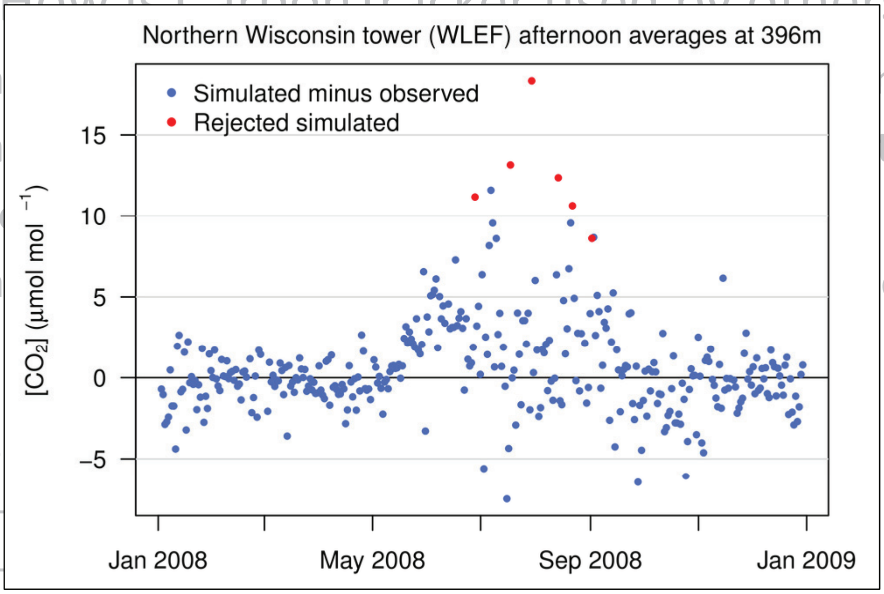

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Plans for the future

- New optimization framework, specifically for use of aircraft, TCCON[1], and satellite data
- Multiple transport models, higher resolution
- Multiple tracers
  - CarbonTracker Methane
  - ^{14}C constraints for fossil emissions
  - other hydrocarbons, like ethane
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- Forecasts and near-real time

[1] Total Carbon Column Observing Network

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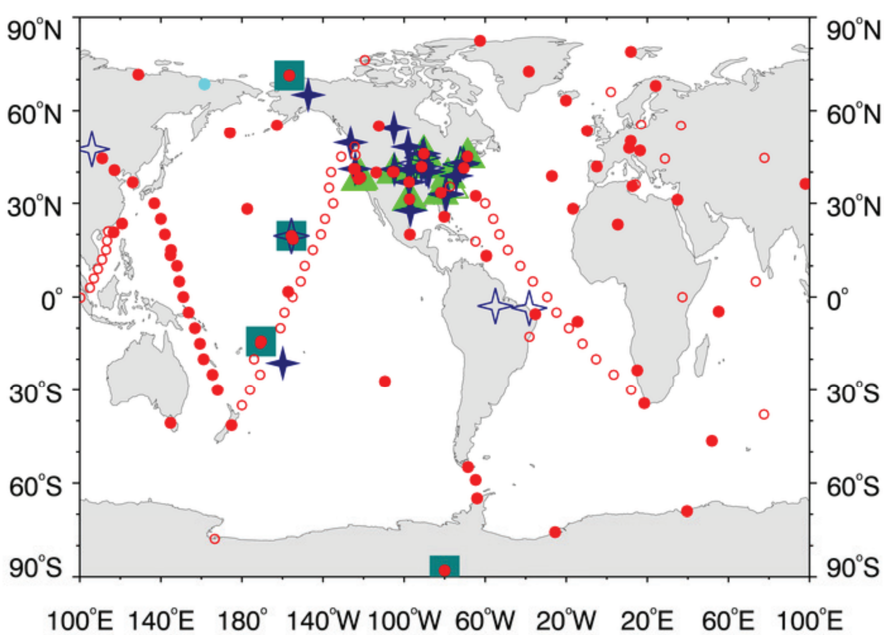
[1] Total Carbon Column Observing Network

Methane

Ed Dlugokencky

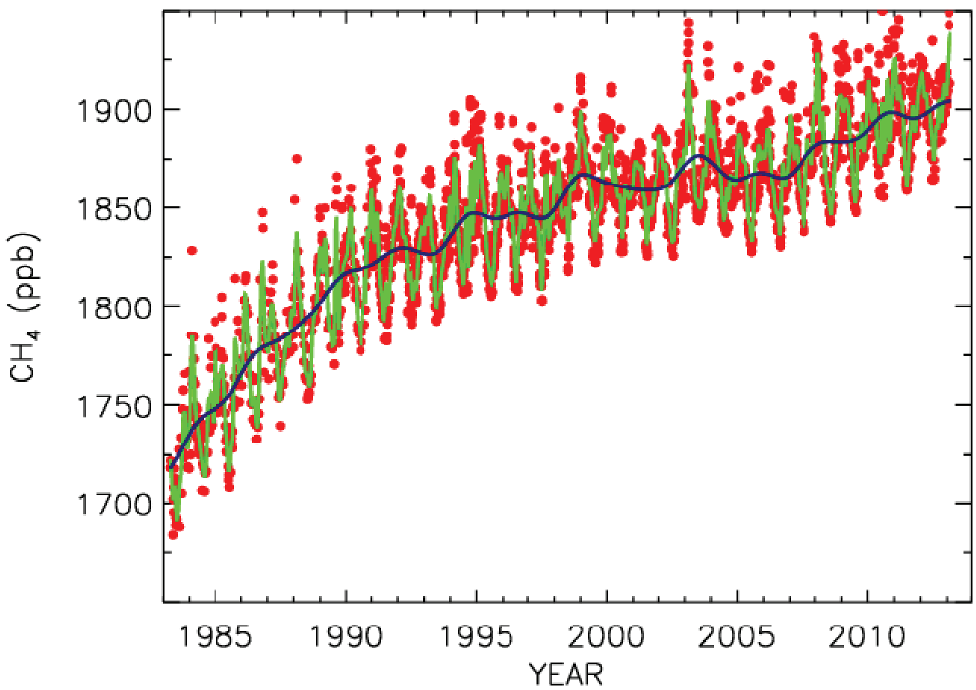
Constraints on the Global CH_4 Budget from NOAA's Global Cooperative Air Sampling Network

GMD Global Cooperative Air Sampling Network



Crotwell poster: applications to CO_2, SF_6, CO, and CH_4

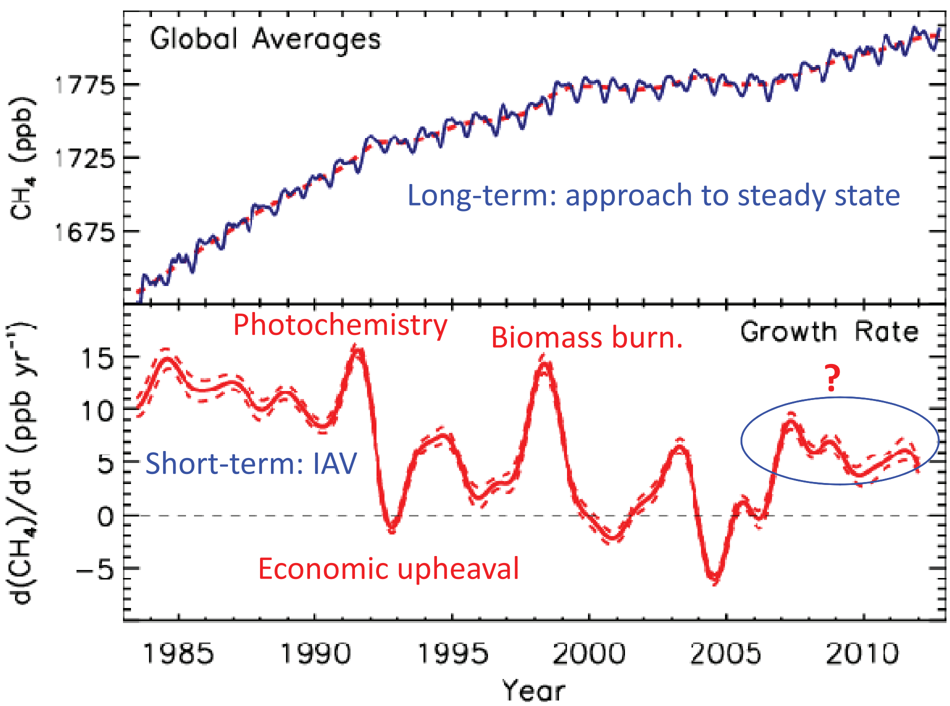
Barrow, Alaska



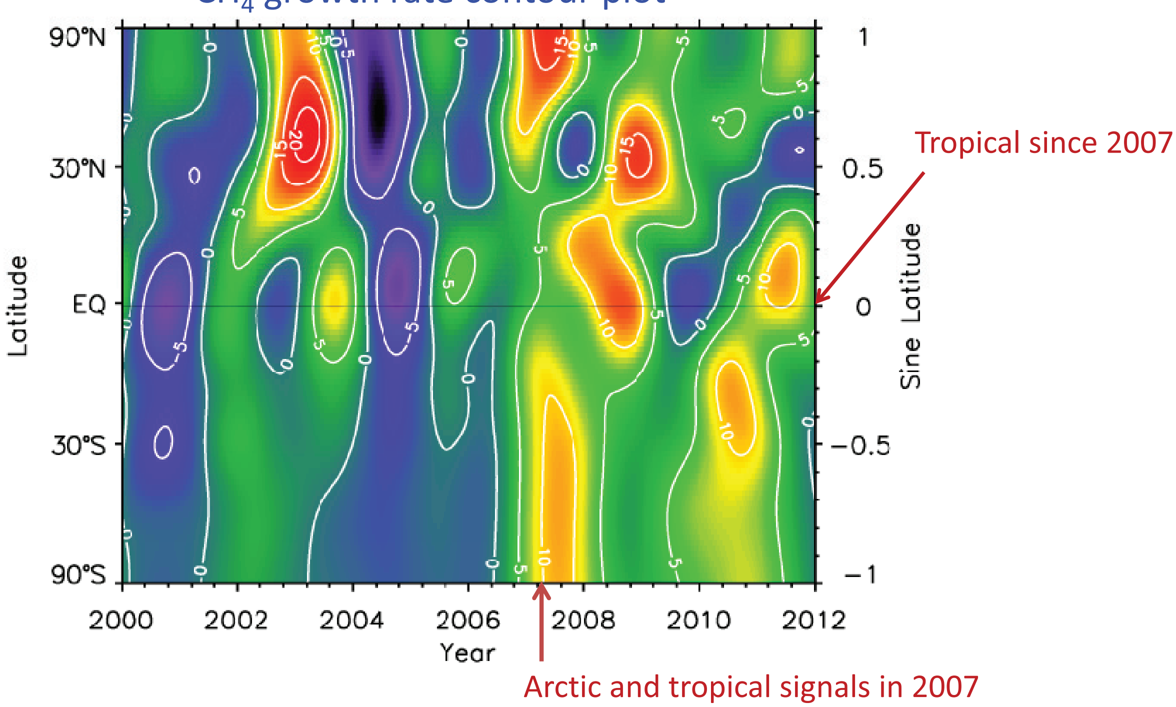
Uses of the CH_4 data

- Global mean - calculation of radiative forcing
- Forward and inverse model studies
  - E.g., CarbonTracker – CH_4
- Regional studies
  - Provide boundary conditions
- Satellite retrievals of CH_4 column abundance
  - Validation and bias corrections (up to 40 ppb)
- Large-scale process understanding
  - Exploiting "anomalies" in growth rate

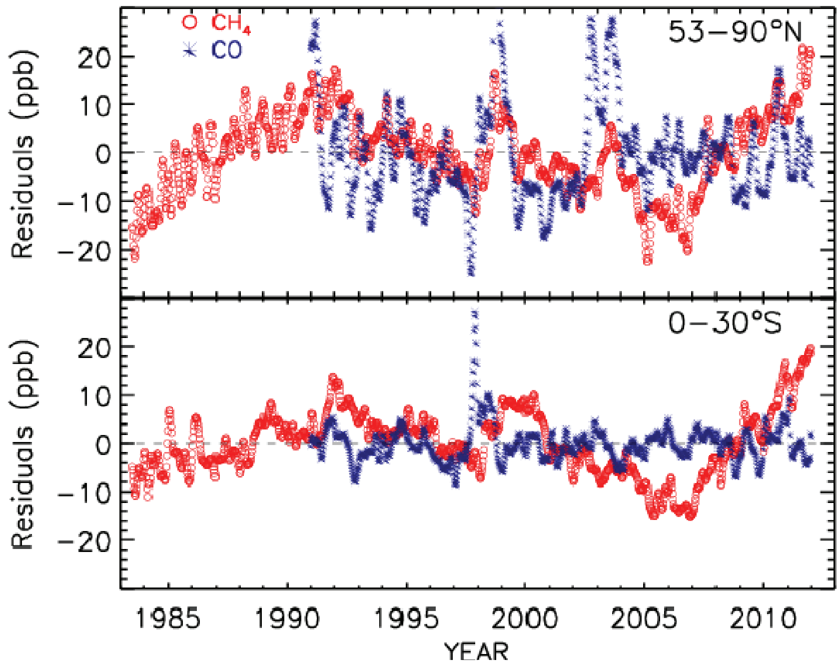
Globally averaged CH_4 and its growth rate



CH_4 growth rate contour plot

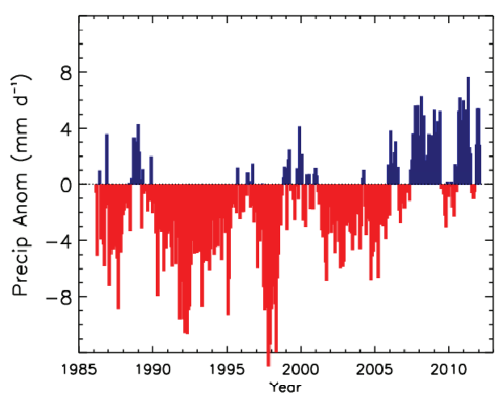


Potential causes: biomass burning? NO

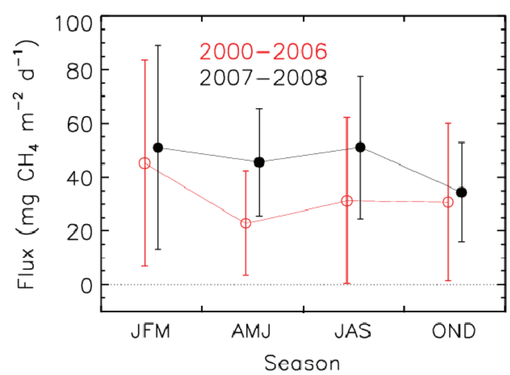


$\delta^{13}C$ in CH_4 also not consistent with biomass burning.

Potential causes: wetlands? YES

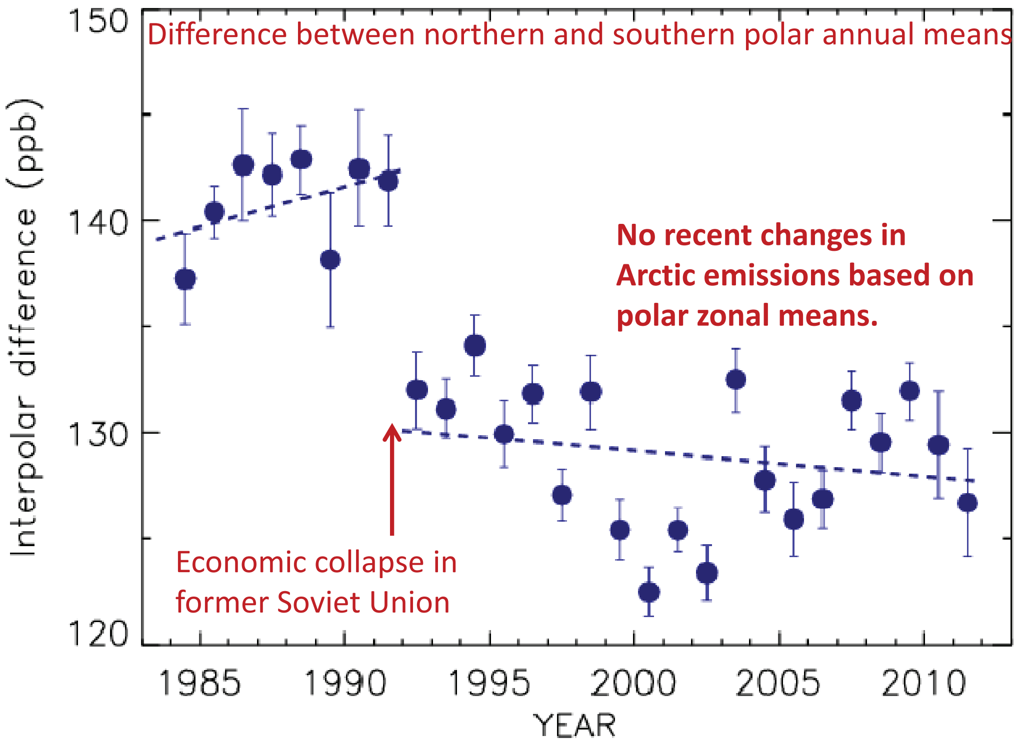


Precipitation anomalies in tropical wetlands.



Increased CH_4 fluxes in wet years.
(Collaboration with Brazil)

Potential causes: Arctic wetlands and clathrates? Only 2007



Permanent increase in Arctic emissions not observed.

Summary

- Long-term CH_4 measurements are the basis for understanding the global CH_4 budget
- Information about processes inherent in anomalies
- Provide voice of reason for claims about Arctic
- Continue observations, expanding sampling when and where possible, and cultivate collaborations
  - Arctic (Carbon in Arctic Reservoirs Vulnerability Experiment, US Coast Guard flights – Bruhwiler presentation)
  - Tropics (Nuclear and Energy Research Institute, Brazil)
  - N. America (Numerous collaborators)

Detection and Monitoring of Changing Methane Emissions in the Arctic

Lori Bruhwiler

The Arctic: Issues and Concerns

- The fastest increases in temperature in the world:
  > 0.6 C per decade since 1980
  (Global: *0.13 C/decade over 50 years)*
- Rapidly melting ice on sea and land
- Probable expansion of human activities
  (e.g. fossil fuel/mineral extraction and transportation)
- ~1700 PgC stored in permafrost soils
  Several times the amount of carbon already emitted by fossil fuel combustion
- ~215 PgC- 380 PgC may thaw by 2100 (Harden et al, 2012)
  (enough to raise atmospheric CO_2 would by 100-180 ppm)

Could Emissions Have Been Changing Already?

- Meta-Analysis of Arctic Tundra Emissions Based on Flux Measurements and Process Models (McGuire et al., 2012)

CO_2

1990s:	0.138 (-0.102,0.378) PgC/yr
2000s:	-0.202 (-0.628,0.224) PgC/yr

CH_4

1990s:	13 (-1,29) $TgCH_4$/yr
2000s:	26 (15,68) $TgCH_4$/yr

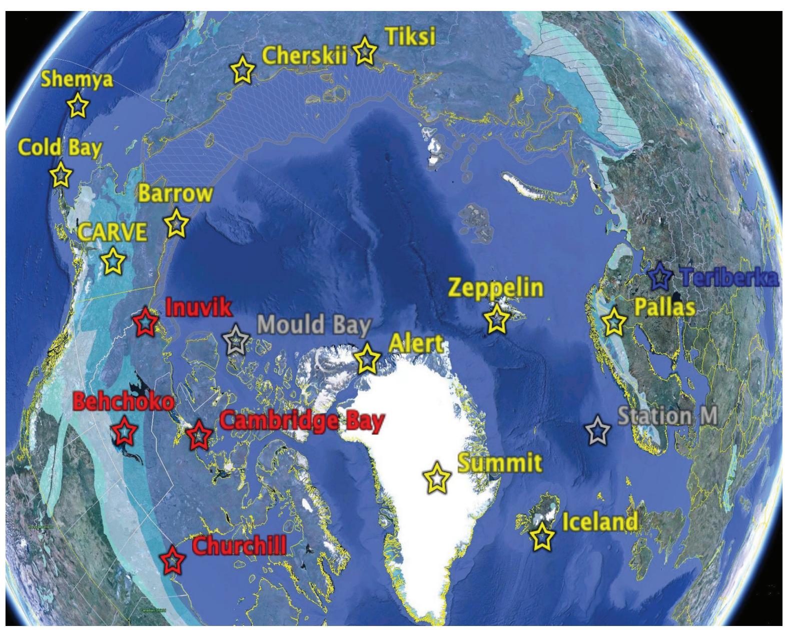
(Note: $1Tg=10^{12}g=10^{-3}Pg$)

NOAA GMD's Role in The Arctic

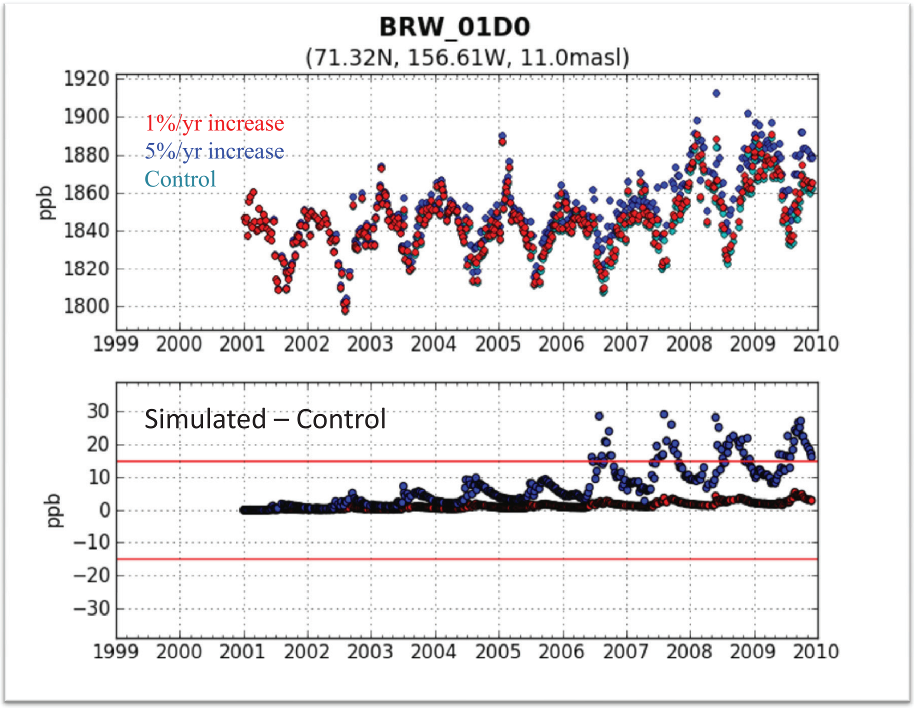
- Collaborate with Other Arctic Nations

Environment Canada
Finnish Met Inst.
Icelandic Met. Office
Norway Met. Inst.
Russian HydroMet Inst./NE Observatory

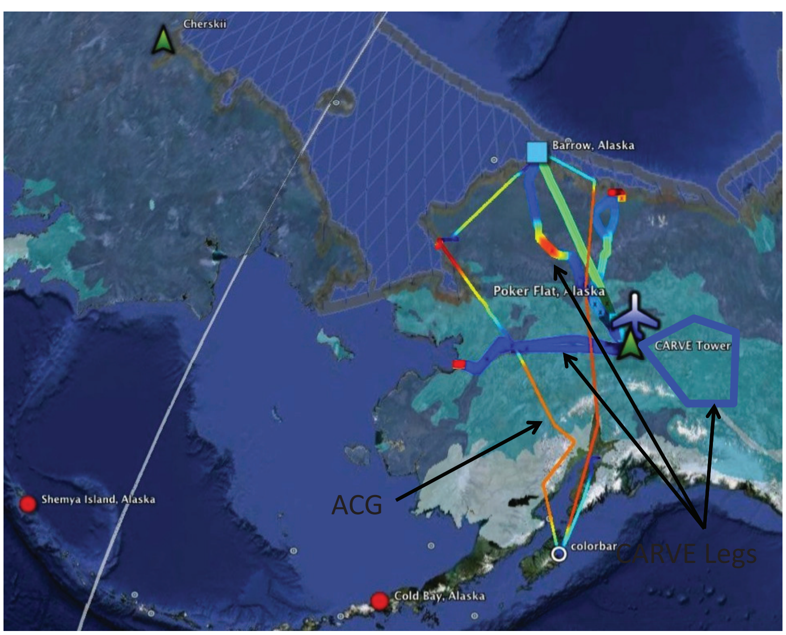
- Help Ensure Data Quality and Data Compatibility Between Institutions
- Modeling and Data Analysis to Further our Understanding of Arctic GHG Budgets
- Commitment to Long-Term Observations



Why We Need Long Observational Records



Regional Studies:
NOAA and CARVE GHG Observations



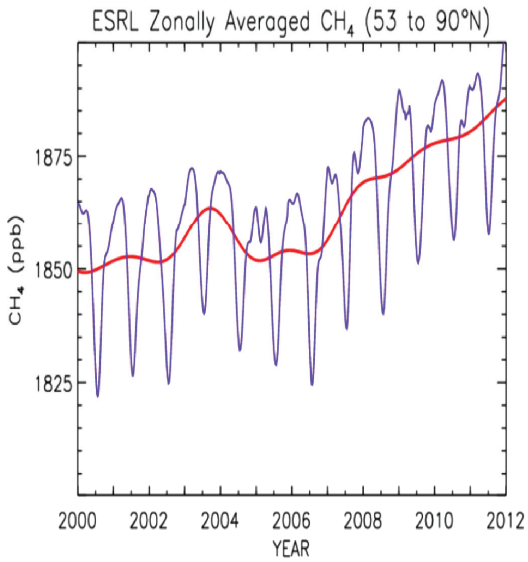
<u>Towers:</u>

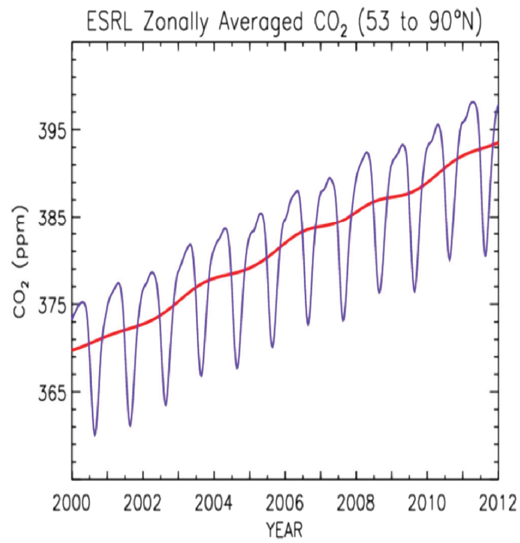
Cherskii, Russia
CARVE, Alaska

<u>Aircraft:</u>

Alaska Coast Guard
CARVE Aircraft Campaign

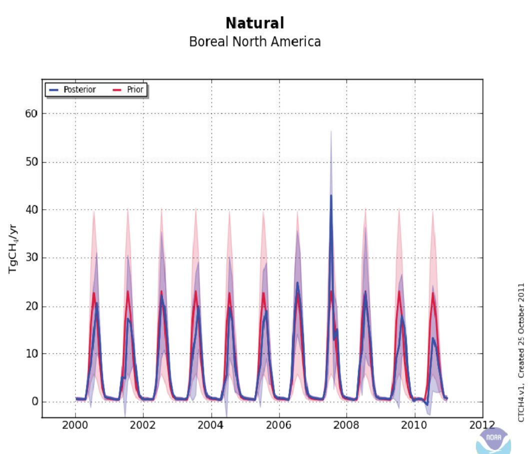
How Do Get From Here….

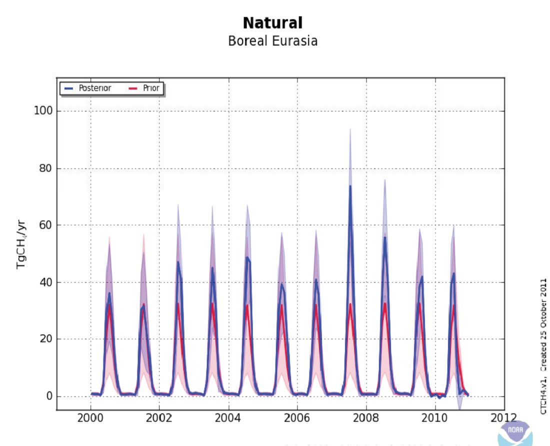


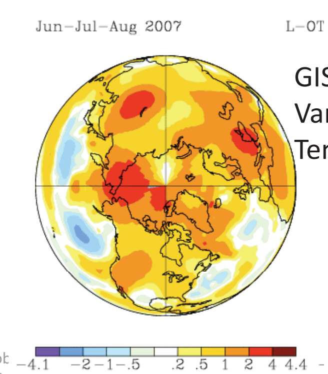


……To Arctic Emissions? *(Hint: Use Models!)*

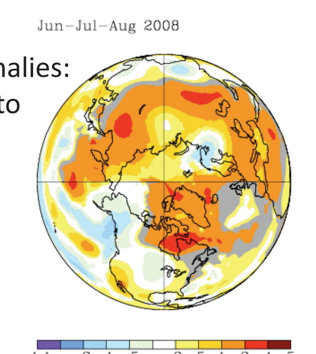
CarbonTracker-CH_4: Inter-Annual Variability, No Trend





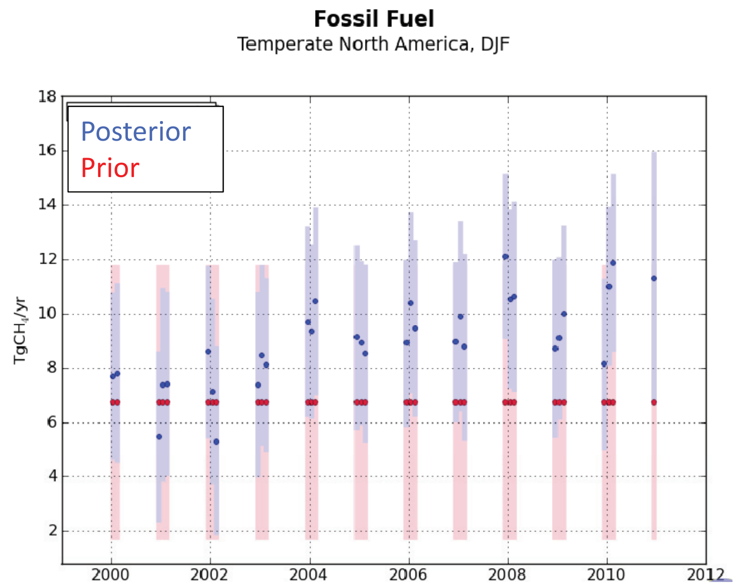


GISS Surface Temperature Anomalies: Variability in Emissions Related to Temperature Variability



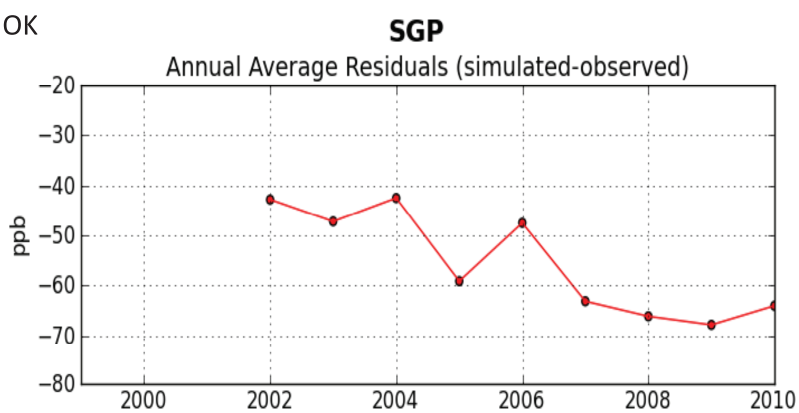
But Some CarbonTracker-CH_4 Do Show Changes in Emissions….

Biogenic Emissions
Are Small During Winter



The Sites that CarbonTracker-CH4 Has Trouble Fitting are Near Regions with Fossil Fuel Development

Example:
Southern Great Plains, OK

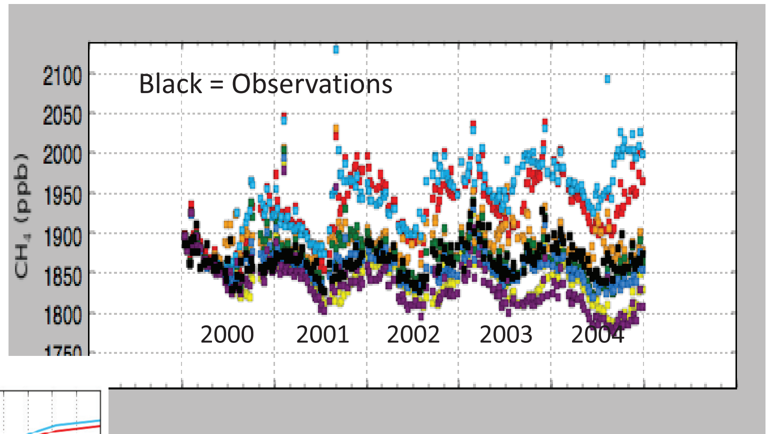


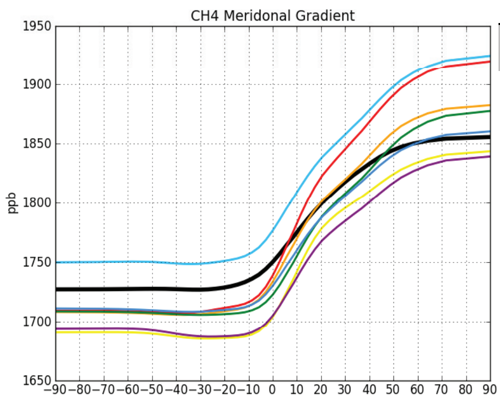
The prior flux estimate is too low, this problem becomes worse over time.

Improving Prediction of Future Emissions

Observational Metrics

Seasonal Cycle
Meridional Gradient
Regional Spatial Variation
Trends

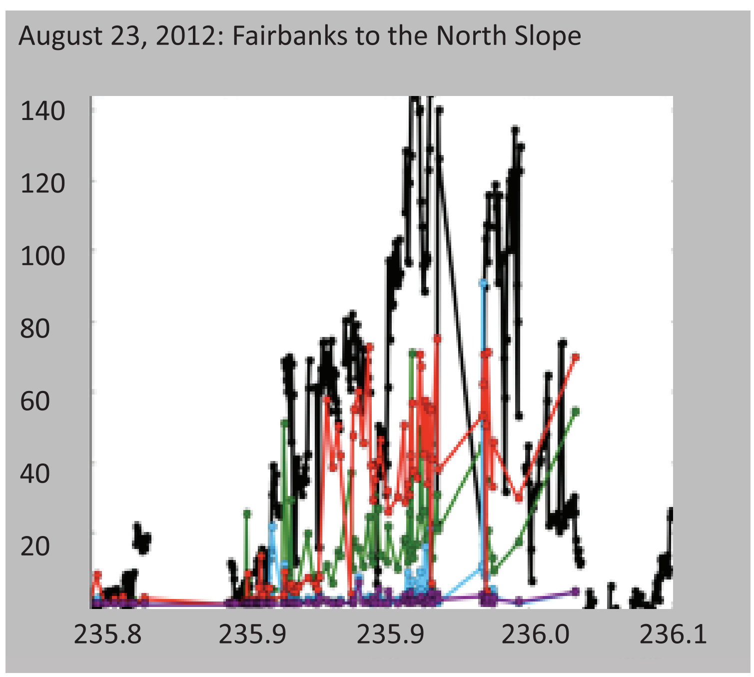




Note: Many of These Models are Being Used in Coupled Climate Models (!!!)

Improving Prediction of Future Emissions

Can We Learn About Regional Emissions and Apply to Pan-Arctic Scales?



Black – CARVE Airborne Observations

Colors- Wetland Models

Can We Use Δ^{14}C to Keep Track of Permafrost Carbon Entering the Atmosphere?

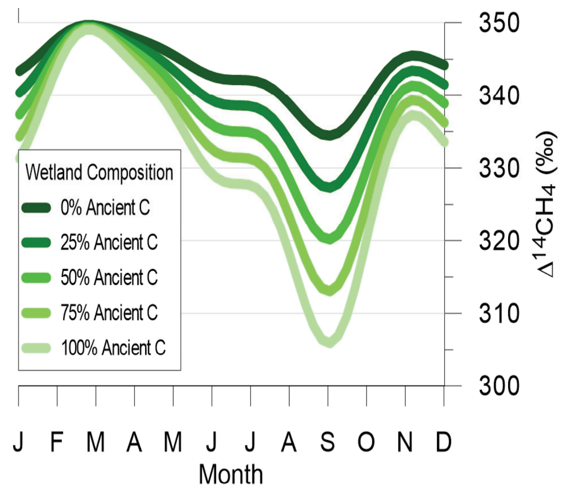


Figure Courtesy of Logan Mitchell

Lower Values Reflect Older Carbon

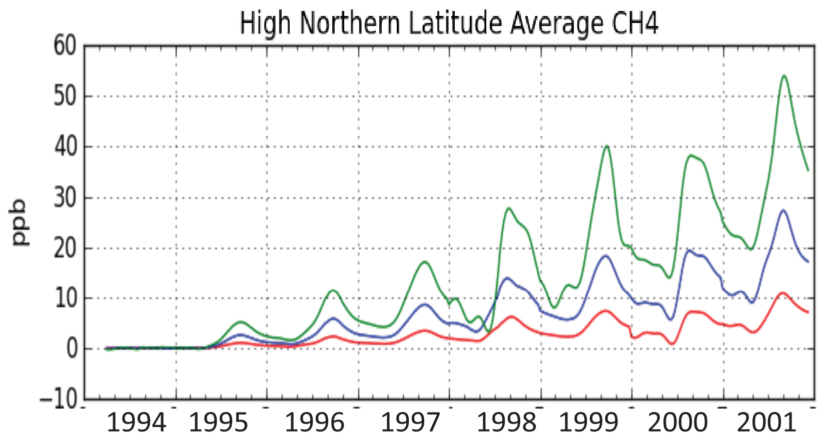
Maximum Input from Wetlands is During Late Summer

Measurements Being Made as Part of CARVE in collaboration with CU/INSTAAR

Summary

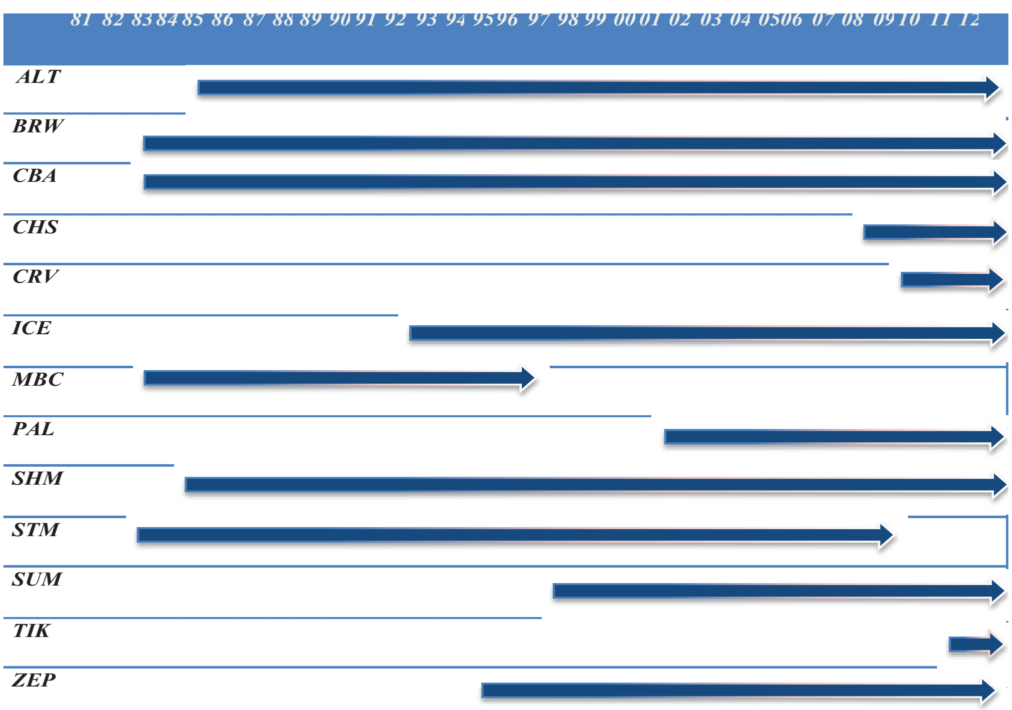
- If we want to know whether Arctic carbon emissions are changing we need to preserve the existing long-term data records.
- Expanding the network throughout the Arctic and placing sites near productive regions will help us to monitor and track changing emissions.
- We do not detect significant changes in Arctic carbon budgets yet – *why not*?

Why We Need Long Observational Records



Red: 2%/yr Increase in Arctic Wetlands Emissions
Blue: 5%/yr Increase
Green: 10%/yr Increase

Commitment to Long-Term Observations



Greenhouse Gas Measurement Program Future Directions

Arlyn Andrews

Designing an Optimal Network for Research Quality GHG Monitoring

Measurement requirements are driven by scientific and policy needs:

- Arctic and tropical carbon sensitivities
- North American carbon sink magnitude, mechanisms, drivers of variability, potential for saturation
- Fossil fuel emissions tracking

Designing an Optimal Network for Research Quality GHG Monitoring

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- Arctic and tropical carbon sensitivities
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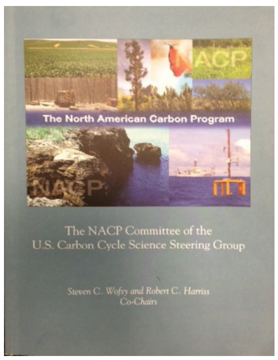


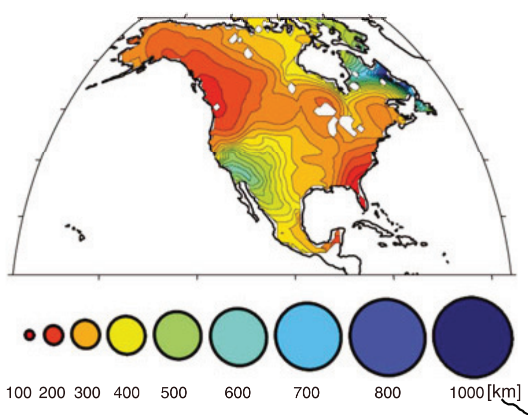
North American Carbon Program Plan, 2002

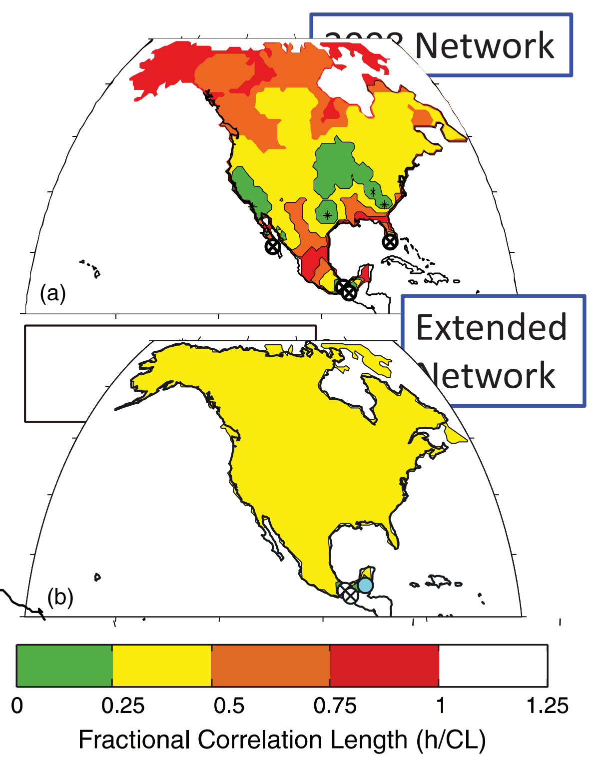
*"Consider uptake of CO_2 due to woody encroachment… 0.12 GtC/yr… spread out over an area the size of Texas, the annual mean decrease of CO_2 in the column would be 0.11 ppm/day…The associated depletion in atmospheric CO_2 over 1000 km could be 0.6 ppm in the lowest 3 km, comparable to the CO_2 from fossil fuels…**A total of 30 sites for North America are anticipated…Vertical profiles should be obtained at frequency of every other day…**"*

- 0.1 ppm measurement comparability to resolve the signal of important processes

Network Design

Designing a network to capture the expected variability:





Y. P. Shiga, A. M. Michalak, S. R. Kawa, R. J. Engelen, "In-situ CO_2 monitoring network evaluation and design: A criterion based on atmospheric CO_2 variability", JGR, 2012

Adapting to New Developments

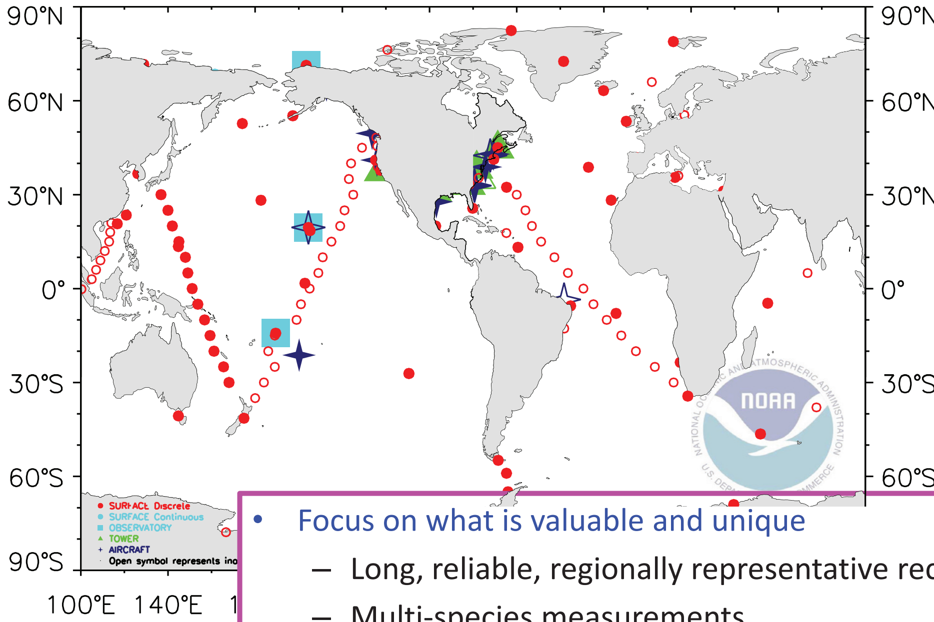
- What is technically possible?
  - Always changing (e.g. satellite and ground-based column CO_2, low-maintenance continuous measurements, boundary layer structure, commercial aircraft GHGs)

Earth Networks' New Greenhouse Gas Network

- Private GHG network inconceivable circa 2004
  - Can potentially fulfill surface monitoring requirements for NACP
- Will data be available for research?
- What can we do to ensure data quality?
  - Reference gases purchased from GMD
  - Ongoing comparison at Lewisburg, PA started March 2013
- Several ongoing collaborations among GMD and EN scientists, some of which are funded through competitive research programs

Goal: Create a Global Greenhouse Gas Reference Network

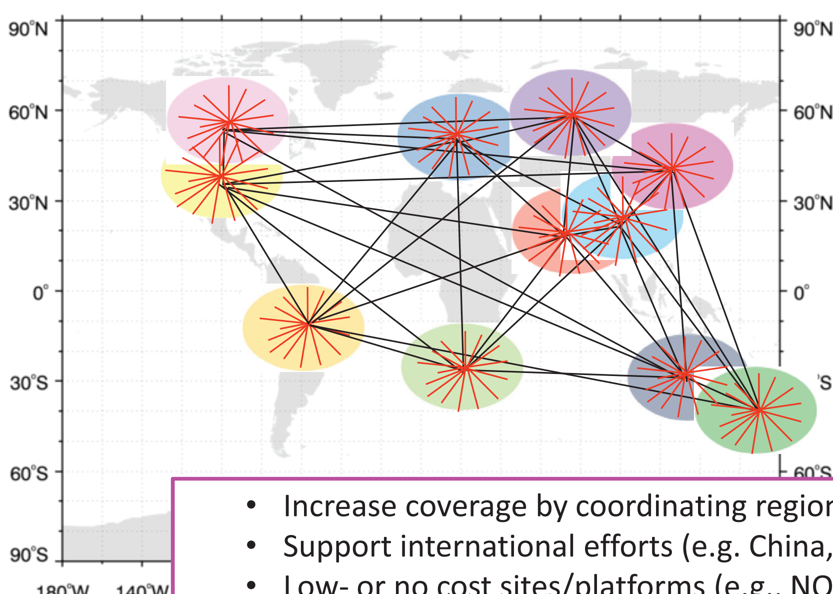
1) Maintain and strengthen core capabilities



- Focus on what is valuable and unique
  - Long, reliable, regionally representative records
  - Multi-species measurements
  - Vertical profiles

Goal: Create a Global Greenhouse Gas Reference Network

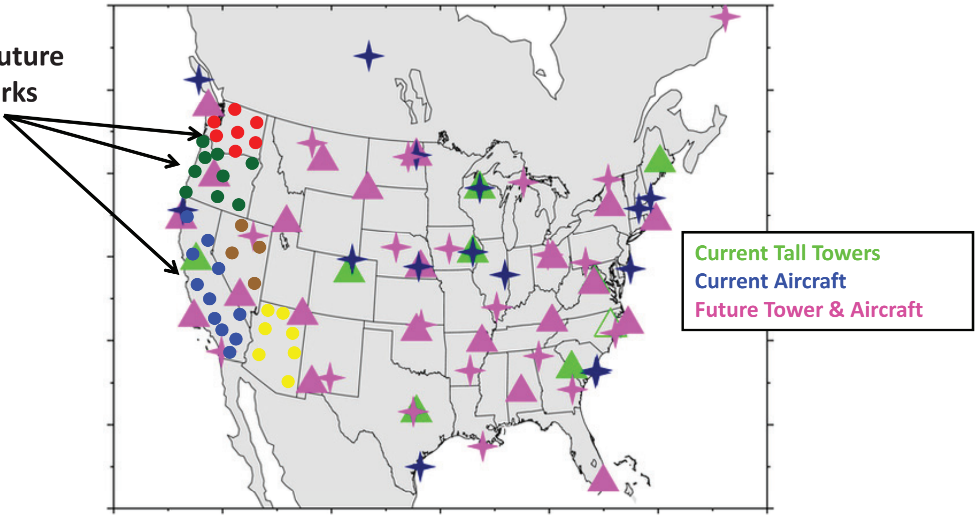
2) Maintain and Develop Partnerships



- Increase coverage by coordinating regional networks
- Support international efforts (e.g. China, Brazil)
- Low- or no cost sites/platforms (e.g., NOAA ships)

Partnerships: Regional and Local Networks

Hypothetical future partner networks



- Regional monitoring efforts underway now: California Air Resources Board CO_2/CH_4, Earth Networks, NEON, Ameriflux, academic regional networks (e.g. Oregon State University, Penn State University
- Site evaluation and QA/QC services

Goal: Create a Global Greenhouse Gas Reference Network

3) Super-sites for Greenhouse Gas Monitoring





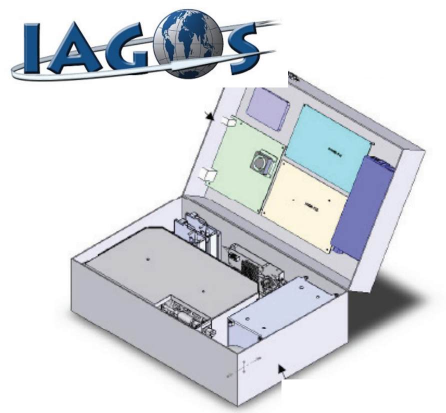
- Automated, continuous measurements
  - CO_2, CH_4 CO, *N_2O, O_3, aerosols, radiation*
- Daily or alternate day flask samples
  - 40+ species
  - Radiocarbon ~3x per week
- Meteorological measurements
  - Wind, temperature, humidity on a tall tower
  - Energy budget
  - Boundary layer profiling
    - Doppler lidar and/or Microwave profiler
  - *Tropopause height*
- Upward looking spectrometers
  - TCCON or TCCON-lite
- Routine vertical profiles
  - aircraft and aircore

Maintain and augment existing super-sites such as LEF (Park Falls, WI), ARM/SGP(Lamont, OK), and Poker Flats and establish new super-sites


Goal: Create a Global Greenhouse Gas Reference Network

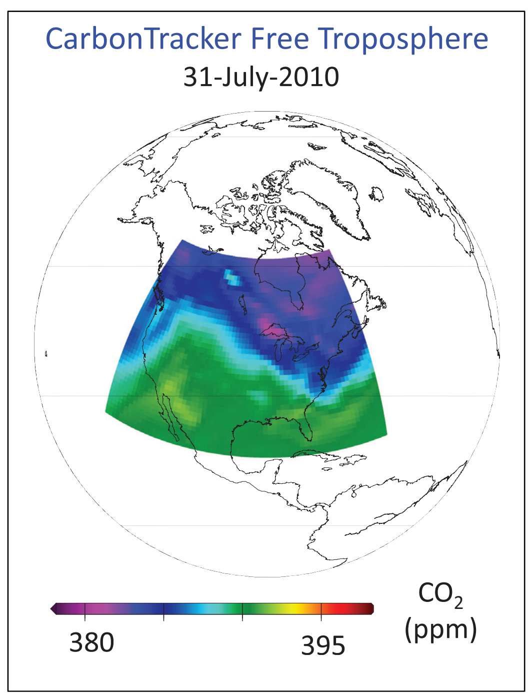
4) CO_2 and CH_4 Monitoring from Commercial Aircraft

- Build on existing programs
  - CARIBIC (EU), IAGOS (EU) and CONTRAIL (Japan)
  - National Weather Service meteorological sampling
- Technically feasible due to advances in spectroscopy and communications



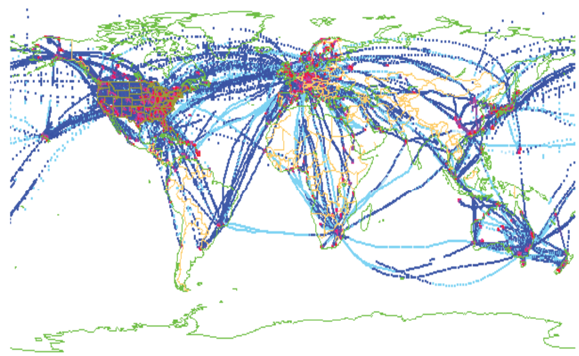
Commercial Aircraft GHG Measurements

- Correlation lengths in the troposphere are 100s of km
  - Capture the variability with a modest program ~10 aircraft
- Initial focus on N. America (tropics to Arctic)to simplify logistics and enable dense sampling
  - Robust flux estimation
  - Rigorous satellite retrieval evaluation
- Support OCO-2 and GOSAT evaluation if accomplished quickly
- Need to identify partners, develop a white paper



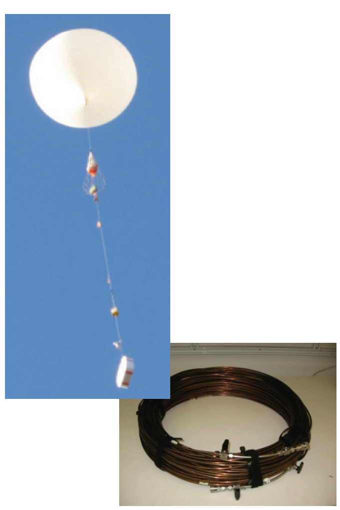
Water Vapor Sensing System-2: a model for GHG monitoring from commercial aircraft within NOAA

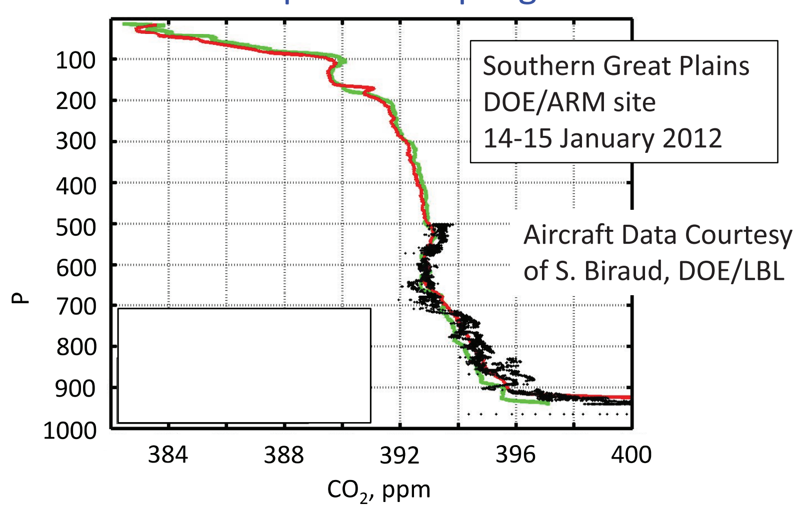
- High-quality Tunable Diode Spectrometers measuring H_2O for weather forecasting
- Currently flying on 57 UPS and Southwest Planes
  - Contract in place to expand to 92 aircraft
  - 757-200PF, 737-300, 737-700
- Data management and assimilation already resident at NOAA (via airlines and AIRINC)
  - 60,000 obs per day
  - 920 profiles per day



Goal: Create a Global Greenhouse Gas Reference Network

5) Deploy AirCore for Surface to Stratosphere Sampling





- Aircore patented by P. Tans and described by A. Karion et al., *JAOT,* 2010.
- Two Aircores on separate balloons achieved maximum altitude >27 km
- Launch/recovery team of 4 people—location monitored by telemetry
- Mass fill rate is nearly invariant to >25 km
- Currently analyzed for CO_2, CH_4, CO, other gases possible.
- Under 6 pounds does not require FAA approval.

GMD GHG Monitoring Priorities

Overarching Goal: Create and sustain a Global Greenhouse Gas Reference Network

- Maintain and strengthen core capabilities
  - Long, reliable, regionally representative records
  - Multi-species measurements
  - Aircraft network
- Maintain and develop partnerships
  - More comparisons (e.g., Earth Networks, NEON, Ameriflux)
  - Support international efforts (e.g. China, Brazil)
  - Low- or no cost sites/platforms (e.g., NOAA ships)
  - Site evaluations and QA/QC services
  - Support satellite evaluation
- Create continental supersites
  - Surface, column and profile GHG measurements
  - Boundary layer structure
- Pursue commercial aircraft CO_2/CH_4
  - Network design study
  - White paper
  - Identify partners
- Aircore
  - Surface to stratosphere sampling
  - "Transfer standard" for satellite and TCCON retrievals

Thank You

Climate Forcing Gases and the Annual Greenhouse Gas Index

Steve Montzka
NOAA

GMD's tracking of trace-gas climate forcing

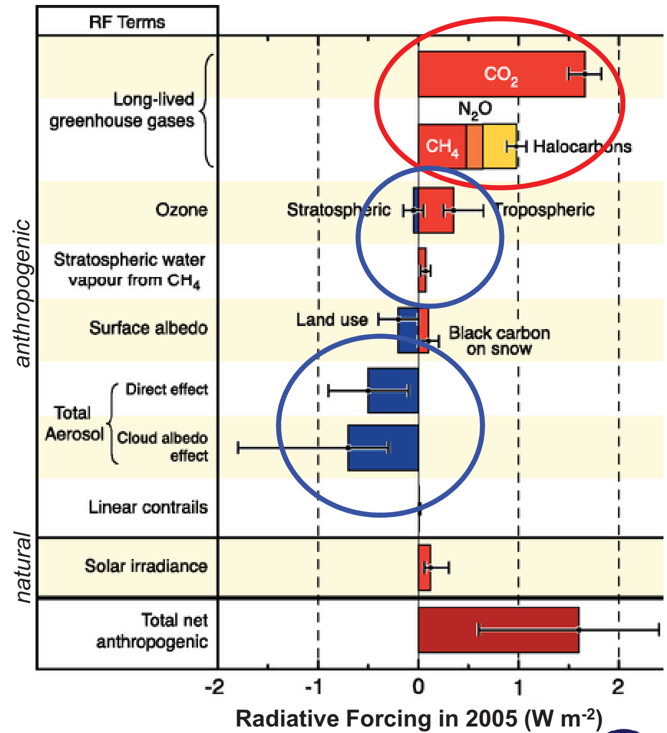
A) We measure tropospheric changes for long-lived greenhouse gases ***with high precision and accuracy***
- GMD's Global and North-American sampling networks

B) We quantify climate forcing from long-lived trace gases and communicate results to others
- NOAA's Annual Greenhouse Gas Index

C) We strive to understand the causes of recent atmospheric change
- Deriving global and regional emissions
  - quantifying anthropogenic and natural contributions
- Understanding loss process magnitudes and variability
- Improving our predictive understanding of trace gases

Human factors influencing climate forcing

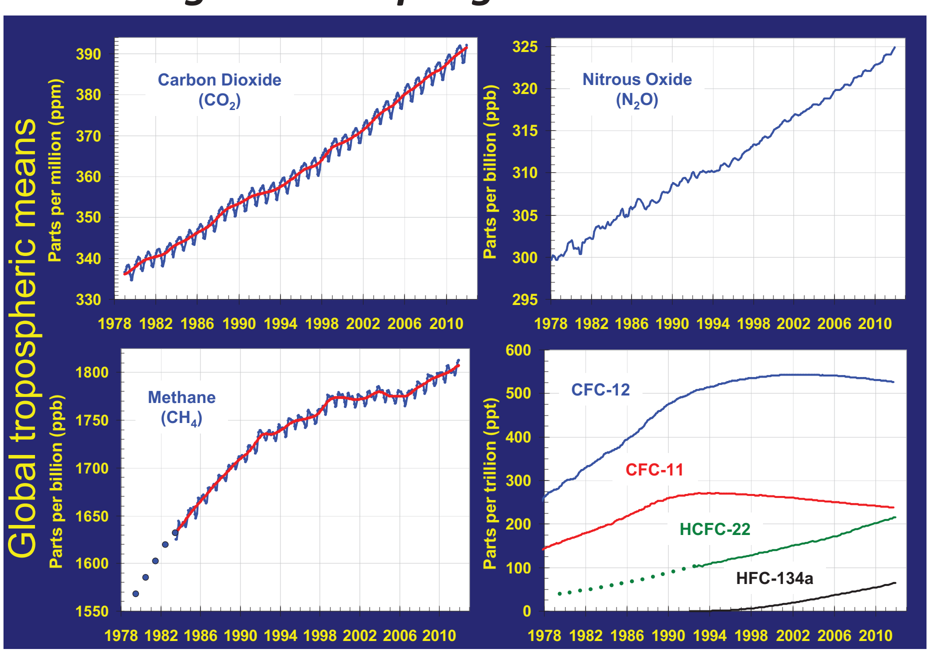
- ***Many different anthropogenic activities influence climate:***
- *Long-lived greenhouse gases*:
  - Contribute substantially to radiative forcing
  - Alter forcing on global scales for decades to millenia after being emitted
- *Short-lived substances* (ozone and aerosols):
  - Also make important contributions, but are the subject of other talks.



IPCC (2007)

A) Measuring tropospheric changes at GMD

- ***Measurements of long-lived greenhouse gases from the GMD global sampling network:***



GMD global observations are:

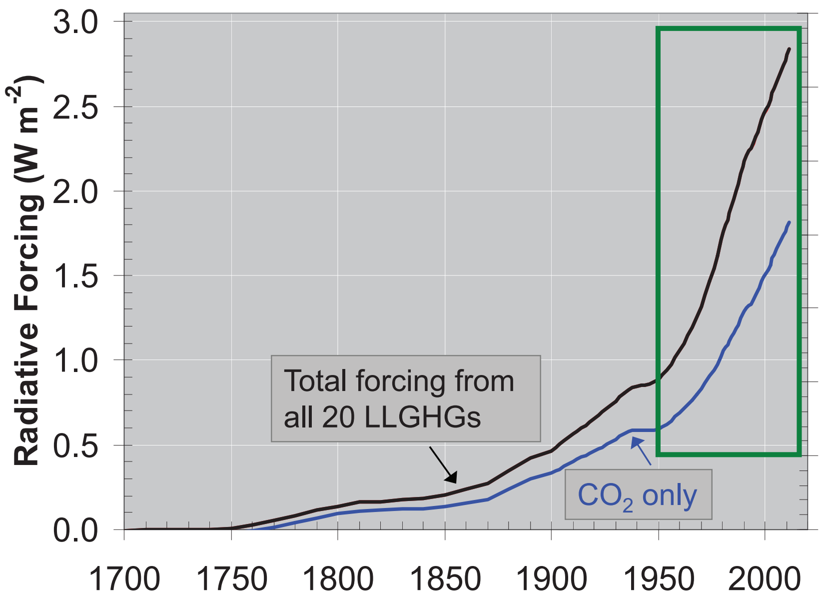
**derived* from the world's most extensive global sampling network.

**maintained* with long-term internal consistency and accuracy

**comprehensive* as they account for >99% of radiative forcing from all long-lived greenhouse gases

B) Quantifying climate forcing from long-lived greenhouse gases (LLGHGs)

- ***Long-term changes in radiative forcing:***
  - From ice cores, firn air, and ongoing GMD measurements:



Ice-core data from Etheridge et al.

B) Quantifying climate forcing from long-lived greenhouse gases (LLGHGs)

- ***Long-term changes in radiative forcing:***
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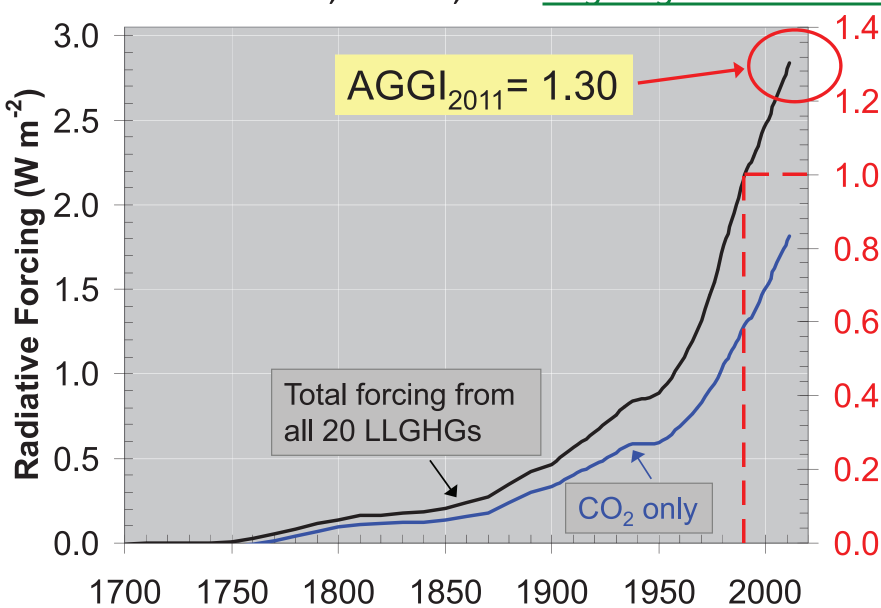


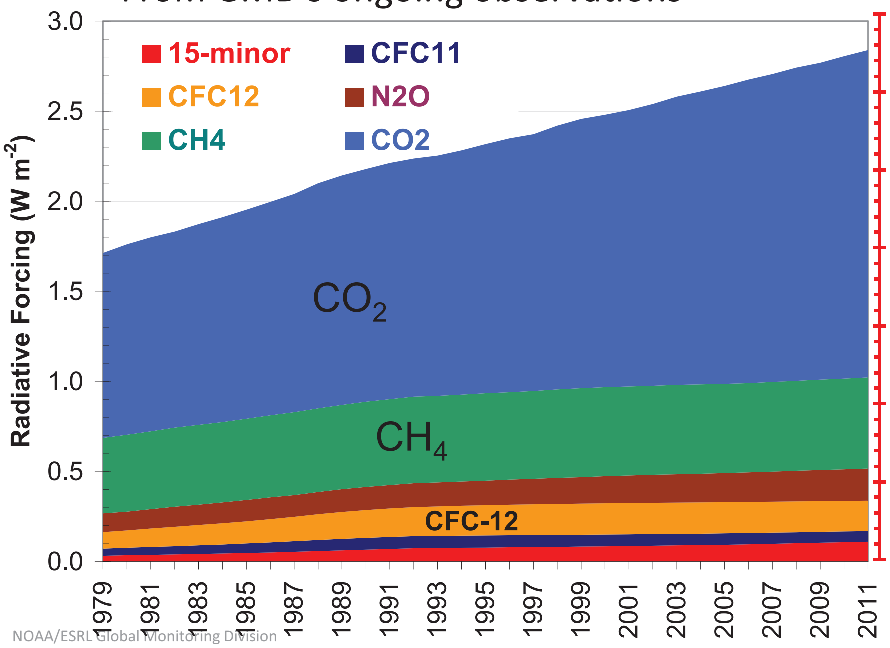
NOAA's **Annual Greenhouse Gas Index** =

Total forcing in any year relative to 1990

Hofmann et al., 1996; Ice-core data from Etheridge et al.

B) Quantifying climate forcing from long-lived greenhouse gases (LLGHGs)

- ***Quantifying contributors to recent changes***
  – From GMD's ongoing observations



AGGI

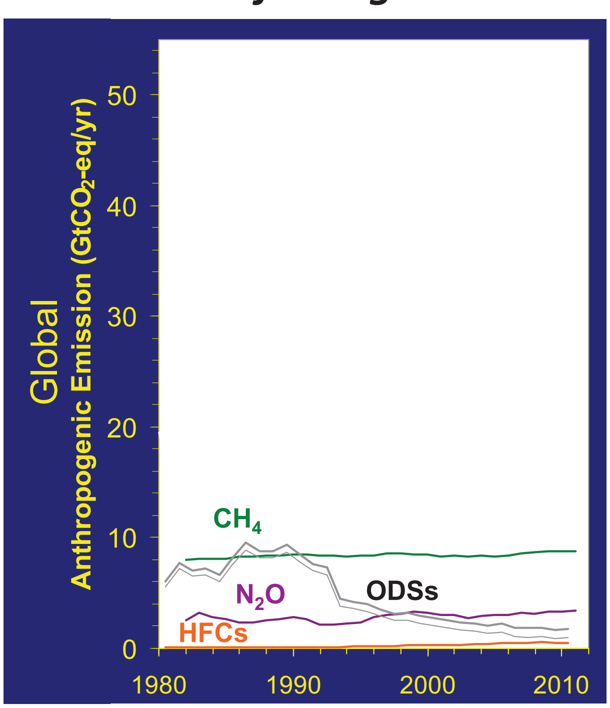
CO_2:
→ Largest contributor
→ Largest recent increase

Non-CO_2:
→ Accounted for 36% of total forcing in 2011

15-minor:
HCFCs, CFC-113, CCl_4, HFCs, SF_6, Halons, & CH_3CCl_3

C) Understanding causes of recent change

- ***Emissions represent our main control knob on future radiative forcing***
  – **Global emissions are derived with global GMD data**

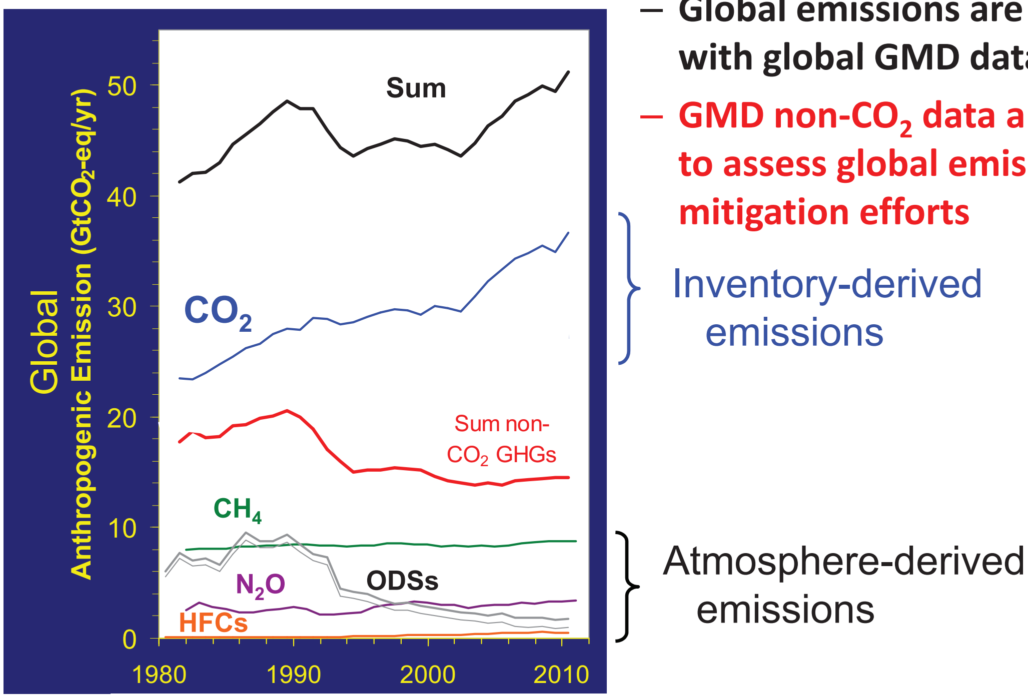


Inventory-derived emissions

Atmosphere-derived emissions

C) Understanding causes of recent change

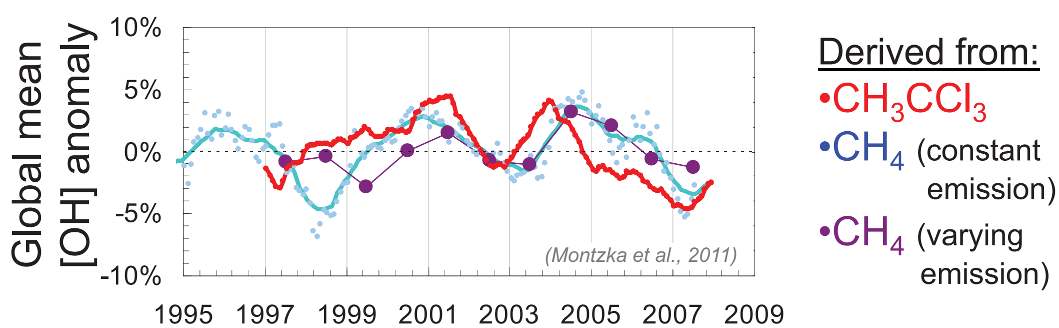
- ***Emissions represent our main control knob on future radiative forcing***



- **Global emissions are derived with global GMD data**
- **GMD non-CO_2 data allow us to assess global emission mitigation efforts**

C) Improving our predictive understanding

- ***Delineating changes in natural* vs. *anthropogenic emissions***
  - provides an understanding natural system feedbacks *(CO_2, CH_4, N_2O)*
- ***Quantifying US emissions of greenhouse gases (see posters)***
- ***Understanding variability in loss processes (lifetimes):***
  - *In the stratosphere (N_2O, CFCs, SF_6)*
  - *In the troposphere from OH (CH_4, HCFCs, HFCs):*



Summary:

- ***GMD's measurements of Long-Lived Greenhouse Gases:***
  - ***Quantify the contributions of CO_2 and non-CO_2 gases*** to current climate forcing and its change over time
  - ***Are annually summarized*** in a single, robust, unit-less number by **NOAA's Annual Greenhouse Gas Index**
  - ***Allow an assessment of current human activities*** (emissions) on future climate forcing (national to global scales) and sink processes
  - ***Improve our predictive understanding*** of future GHG concentrations and radiative forcing to policy options and natural system feedbacks

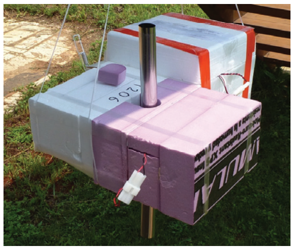
Long-Term Monitoring of Water Vapor in the Upper Troposphere and Lower Stratosphere

GMD's Frost Point Hygrometer Program

Dale Hurst

Boulder Water Vapor Record

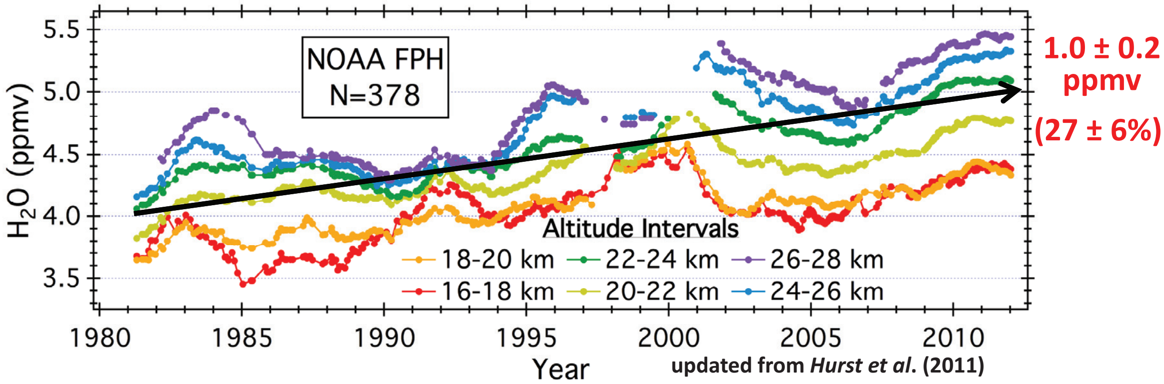
Longest continuous UTLS water vapor record in existence



NOAA Frost Point Hygrometer (FPH)

Mastenbrook and Oltmans

Boulder Launch Site



Mastenbrook and Oltmans (1983); *Oltmans and Hofmann* (1995); *Oltmans et al*. (2000); *Scherer et al*. (2008); *Hurst et al*. (2011)

Why Monitor Water Vapor in the Upper Troposphere and Lower Stratosphere (UTLS) ?

"… UTLS water vapor is an important driver of decadal global surface climate change"

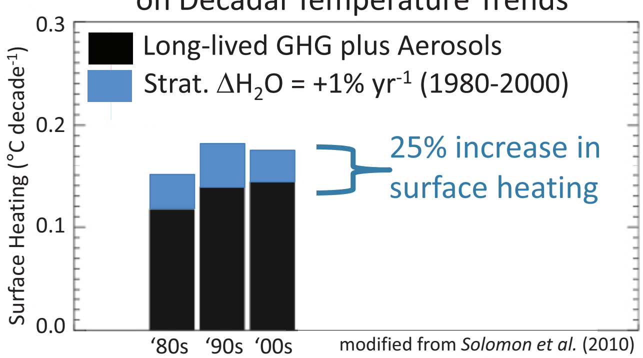
Solomon et al., Science (2010)

Changes in UTLS water vapor influence:

- tropospheric and stratospheric temperatures

  water vapor increase warms the troposphere and cools the stratosphere
- many other important atmospheric processes

Impact of Stratospheric H_2O Changes on Decadal Temperature Trends



modified from *Solomon et al.* (2010)

Halogen activation (HOx)

O_3 reaction rates (T)

Polar O_3 chemistry (PSCs)

Lifetimes of GHGs and ODS (OH, T)

Cirrus cloud microphysics

GMD's UTLS Water Vapor Sounding Sites

Support: NOAA Base Funding, NOAA Climate Program Office, US Global Climate Observing System (GCOS), NASA Upper Atmosphere Research Program

● Boulder, Colorado 40° N (Apr 1980 -)

● Hilo, Hawaii 20° N (Dec 2010 -)

● Lauder, New Zealand 45° S (Aug 2004 -)

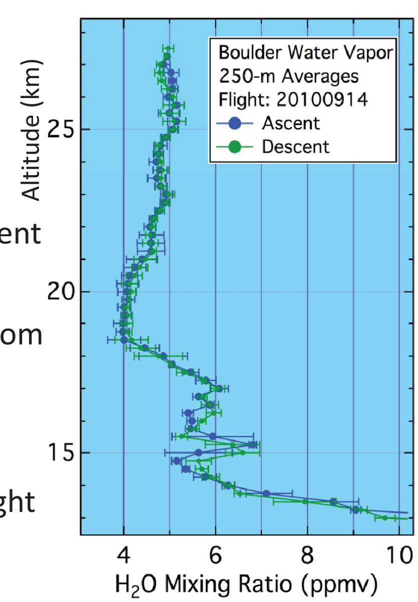
Objective: one high-quality sounding per month at each site with NOAA FPH

Maintaining Long-Term Calibration Stability

The accurate determination of long-term trends in UTLS water vapor requires that the measurement calibration be stable over decades

Advantages of Frost Point Hygrometry

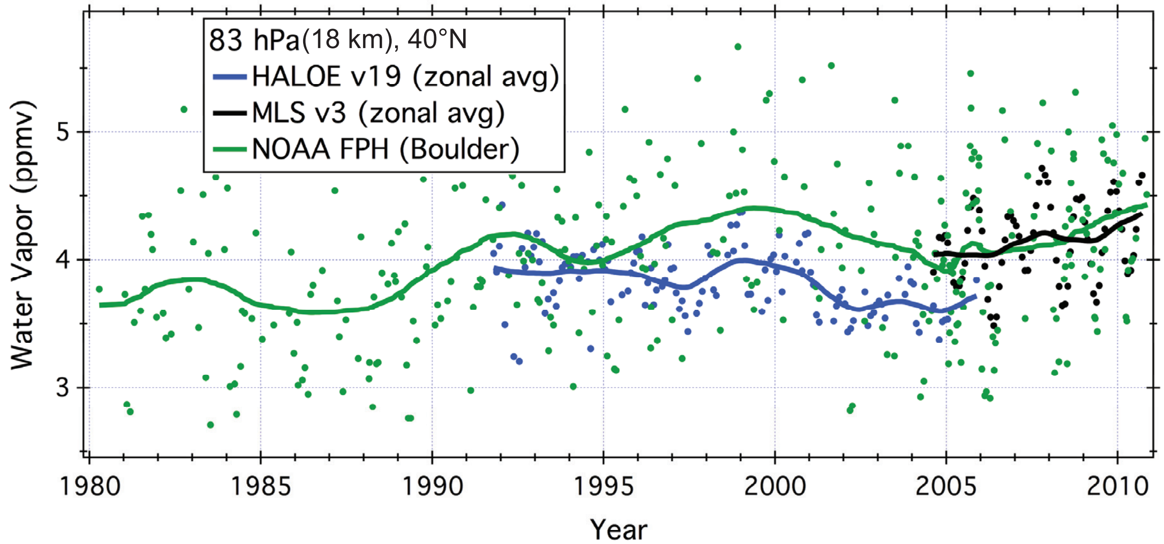
- no calibration standards or scale for water vapor are required (very difficult to maintain)
- FP hygrometry is essentially a temperature measurement
- mirror thermistors are batch calibrated using a NIST-traceable standard probe and several thermistors from previous batches



Measurement quality is routinely assessed by

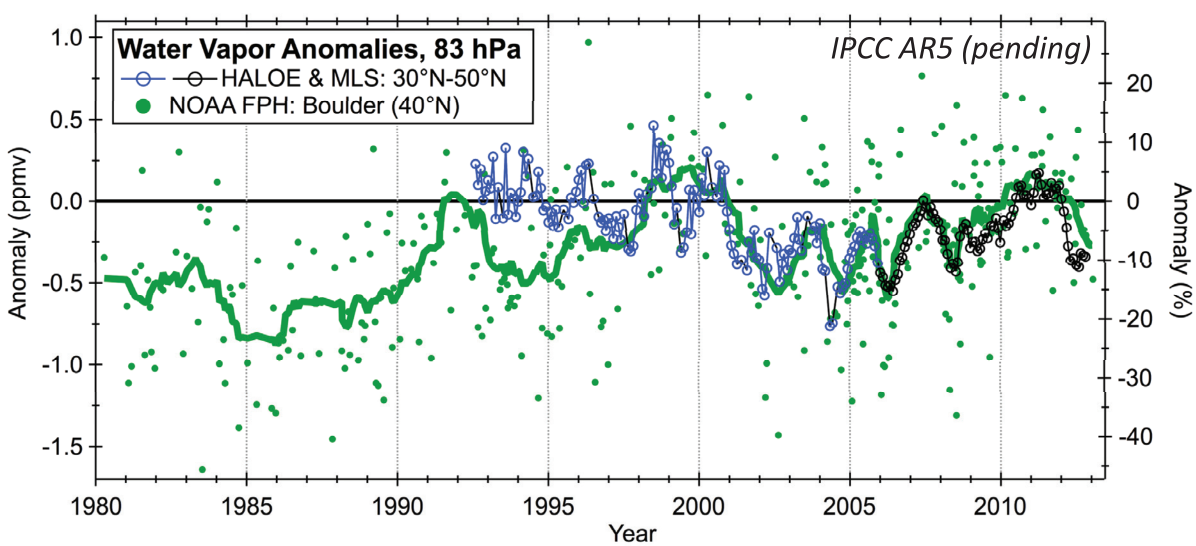
- Comparing ascent/descent measurements for each flight
  stratospheric profiles should be the same
- Comparisons with other in situ and remote sensors

Calibration/Validation of Satellite-Based Water Vapor Sensors by the NOAA FPH



- HALOE v19 retrievals differ from FPH and MLS by an average of 0.3 ppmv (8%)
- Balloon-borne NOAA FPH soundings validate Aura MLS stratospheric retrievals (differences are <3% for 135 coincidences over Boulder)

Calibration/Validation of Satellite-Based Water Vapor Sensors by the NOAA FPH



- Anomalies remove the offset between HALOE and MLS
- Very good coherence of anomalies 1998 - 2012
- Poor coherence of anomalies 1993 – 1997 (not understood)

GRUAN GCOS Reference Upper Air Network

GRUAN is an international reference observing network designed to meet climate requirements and fill a major void in the current global observing system.

GRUAN will make long-term, high-quality observations (with uncertainties) to

- create measurement records required for climate studies
- constrain and validate data from space-based remote sensors
- provide accurate data for studies of atmospheric processes

GRUAN Essential Climate Variables (ECVs)

Priority 1:
Water Vapor
Temperature
Pressure

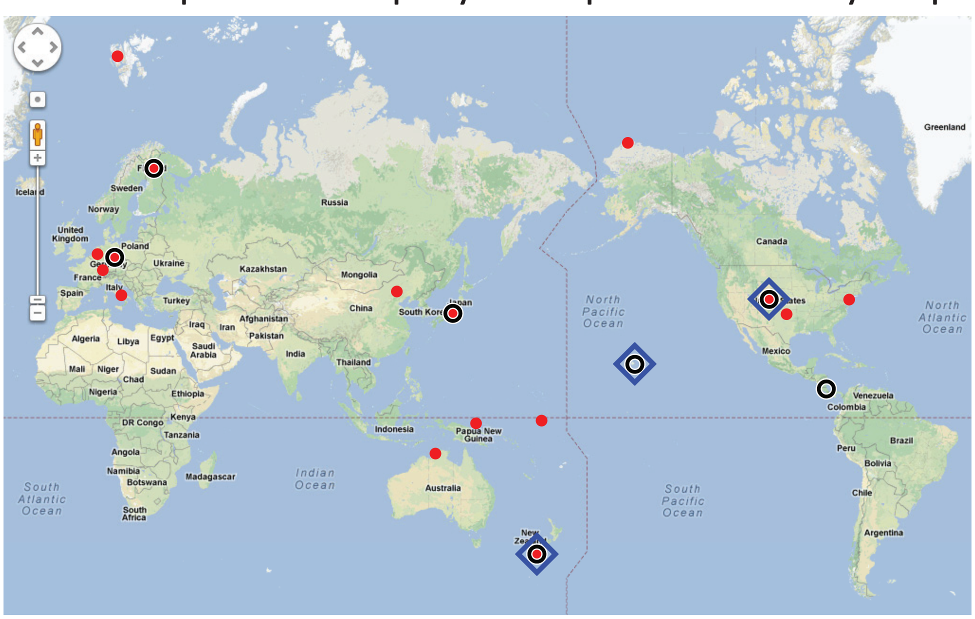
Priority 2:	
Ozone	Surface Radiation
Methane	AOD
Winds	Cloud Observations

GRUAN 16 GRUAN Sites (as of Jan. 2013)

● are making P, T and RH measurements with best-quality radiosondes

Radiosonde RH measurements in UTLS must be corrected for dry bias and response lag

GRUAN requires reference-quality water vapor measurements by frost point hygrometers



○ Sites w/ Routine FPH Soundings (N=7)

◇ GMD FPH Sites

Summary

- GMD monitors UTLS water vapor to detect trends that can significantly impact Earth's radiation budget
- The 1% per year increase in stratospheric water vapor over Boulder since 1980 increased surface warming by well-mixed GHGs by 25%
- Frost point hygrometry benefits the long-term stability of measurement calibration
  Temperature calibration is easier to consistently perform and maintain
- Retrievals from satellite-based water vapor sensors are calibrated and validated by routine NOAA FPH soundings
- GMD's water vapor monitoring program is critical to GRUAN's proposed global network of reference-quality UTLS water vapor measurements

Aerosol Direct Climate Forcing

John A. Ogren

on behalf of
GMD Aerosol Group

Objective

Improve climate and air quality assessments and predictions...

through measurements and analysis of the spatio-temporal distribution of aerosol properties for up to multi-decadal time scales

WMO Global Atmosphere Watch, Aerosol Program, Baltensperger et al., 2003

Strategy

How to tackle the problem with the largest error bars in IPCC assessment of radiative forcing with the smallest group in GMD?

#1: Focus tightly

- Long-term, in-situ measurements
- Aerosol direct forcing

#2: Enlist partners

- Expand spatial scope
- Expand measurements
- Apply data to models and remote sensing

Aerosol Measurements

Core system

- Light scattering and backscattering (3-λ)
- Light absorption (3-λ)
  - Equivalent Black Carbon
- Particle number concentration
- Aerosol optical depth (Augustine talk tomorrow)

Partners enable additional climate-relevant measurements:

- Cloud condensation nuclei (U.S. Dept. of Energy, salary support)
- Hygroscopic growth (U.S. Dept. of Energy, salary support)
- Chemical composition (NOAA Pacific Marine Environmental Lab.)
- Black carbon (U. Tokyo, Japan)
- Size distribution (Inst. for Tropos. Res., Leipzig, Germany)

NOAA Federated Aerosol Network

GMD provides …

Sampling system design

- Drawings on web
- Help with building and operating

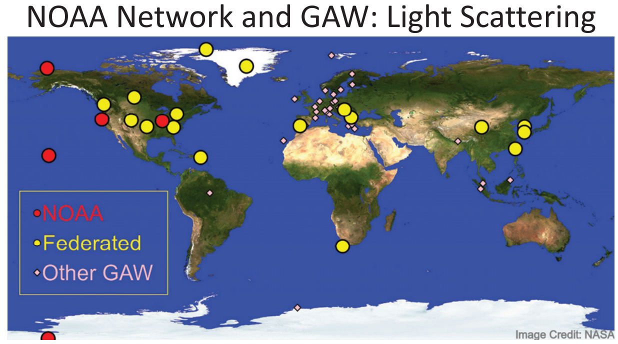
Software

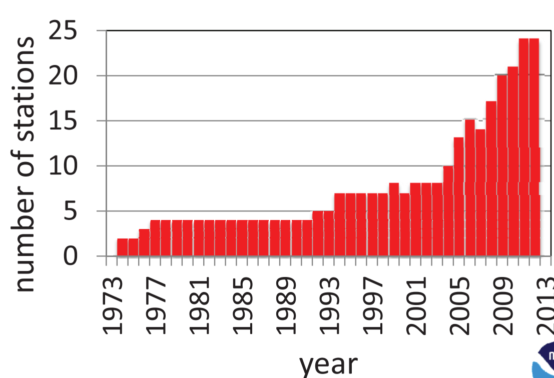
- Data acquisition
- Routine processing on GMD servers
- Data viewing, QC editing, and archiving (Masarie talk tomorrow)

Knowledge

- Workshops on aerosol monitoring techniques
- Int'l coordination through WMO/GAW Science Advisory Group for Aerosols (Chair)

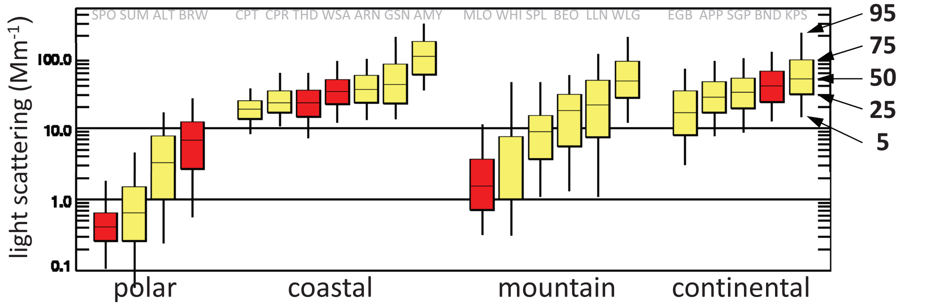
NOAA Network and GAW: Light Scattering





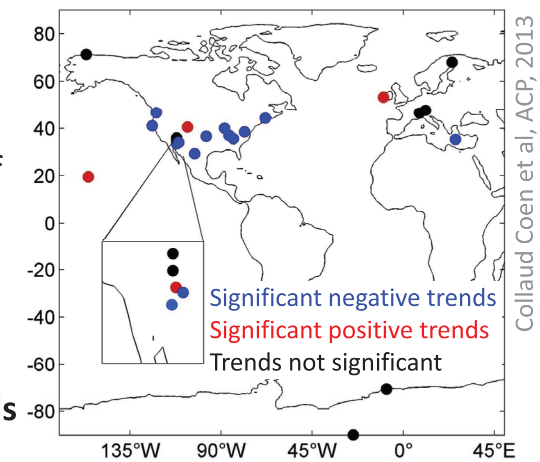
Climatology and Trends

Climatology spans nearly four orders of magnitude across network



Trends in light scattering

- WMO/GAW and US/IMPROVE networks
- Stations with at least 10 years of data submitted to World Data Center for Aerosols
- 2-3 %/yr significant negative trend across US



A rich data set for evaluating models

Black Carbon Measurements

Reporting "BC" data

- Light absorption coefficient (equivalent BC)
- Elemental Carbon (chemical)
- Refractory BC (laser incandescence)
- Petzold et al, ACPD, 2013

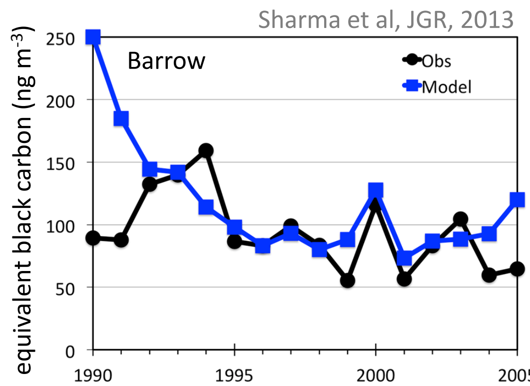
Improved methods

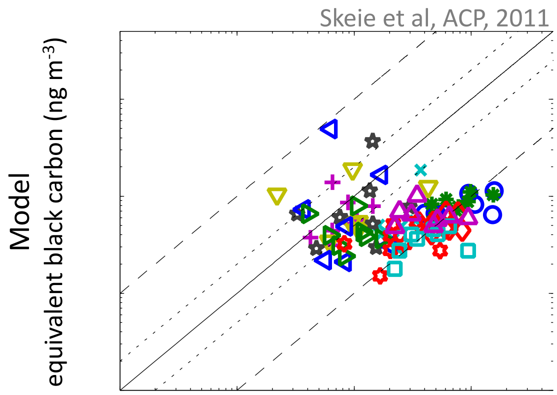
- New absorption photometer now at ~20 sites worldwide
- New correction scheme for method artifacts (Constrained Two-Stream)
- Müller et al, AMTD, 2013

NOAA Continuous Light Absorption Photometer

Black Carbon Model Evaluation

NIES (Canada) model ⇒ reproduces long-term, wintertime-average trend at Barrow





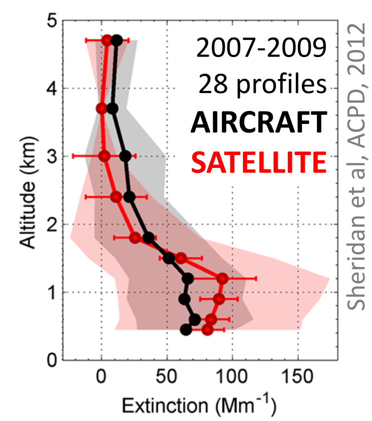
⇐ Oslo CTM2 model is biased low and has less variability than observations (monthly averages, 2001-2008)

Aerosol Vertical Profiles

Light aircraft profiling

– 1073 flights, over stations in Oklahoma (2000-2007) and Illinois (2006-2009)

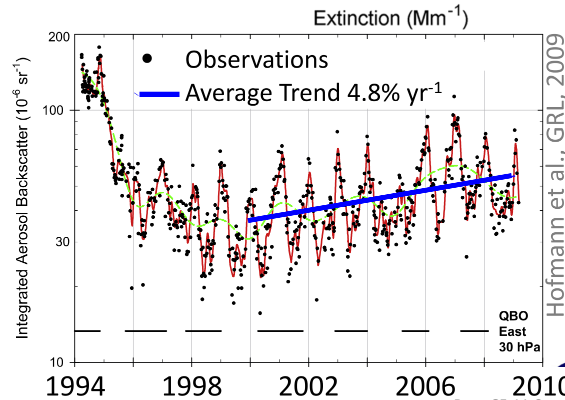
– Comparison reveals likely problems with cloud-screening algorithm for data from NASA's CALIPSO satellite at around 1 km altitude



Lidar profiling

– GMD operates lidars at seven stations

– Trend in stratospheric aerosols over Mauna Loa (20-25 km alt.) is attributed to mid-size volcanoes



Summary and Conclusions

Strategy for enlisting partners is working

- contributing measurements at GMD sites
- using software and hardware developed and supported by GMD
- submitting data to WMO World Data Center for Aerosols

Data are being used by GMD and others

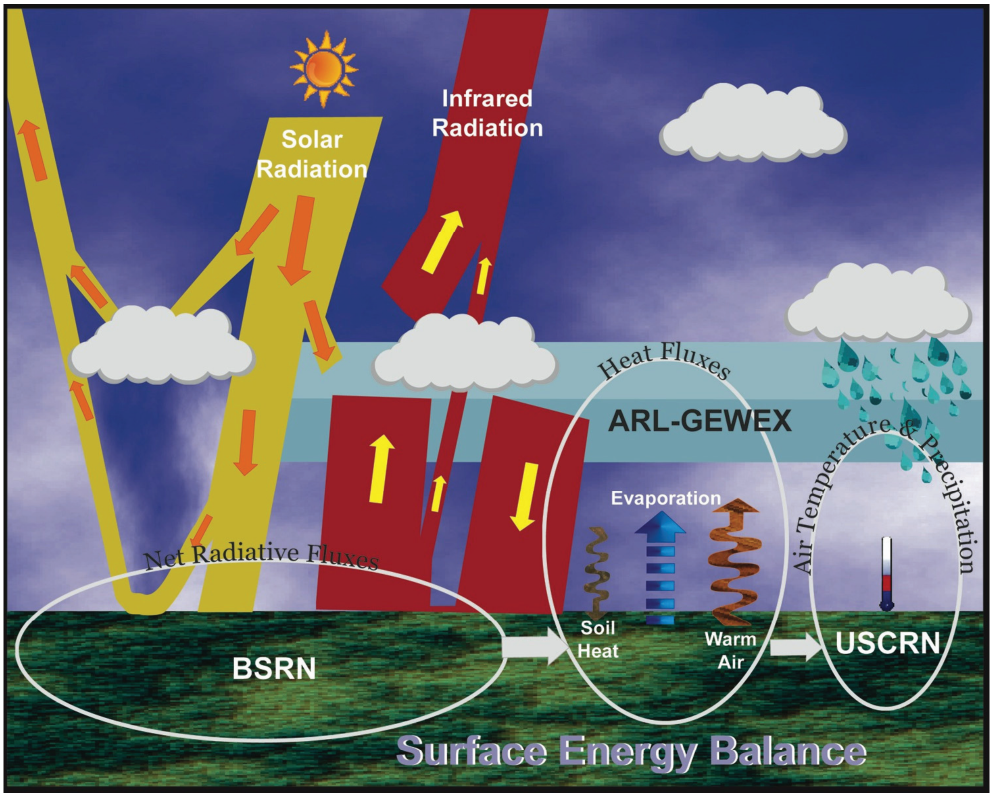
- Determine means, variabilities, and trends of key aerosol optical and microphysical properties
- Evaluate remote-sensing retrievals of aerosol optical properties, both satellite and ground-based
- Evaluate modeled means, variabilities, and trends of aerosol light scattering, absorption, and number concentration

Radiation Contributions to Climate Forcing, Ozone, and Air Quality

Joseph Michalsky

GMD Radiation Group

Changes in trace gases and aerosols, which include changes in ozone and air quality, result in long-term changes in the solar and infrared radiation budgets at the surface that can be measured if one has sufficient accuracy and sufficient time for changes to occur.


Infrared
Radiation
Solar
Radiation
Heat Fluxes
ARL-GEWEX
Evaporation
Air Temperature & Precipitation
Net Radiative Fluxes
Soil
Heat
Warm
Air
USCRN
BSRN
Surface Energy Balance


Global
Diffuse
Direct Beam
Albuquerque, NM (ISIS site)

Radiation Networks Operated by GMD

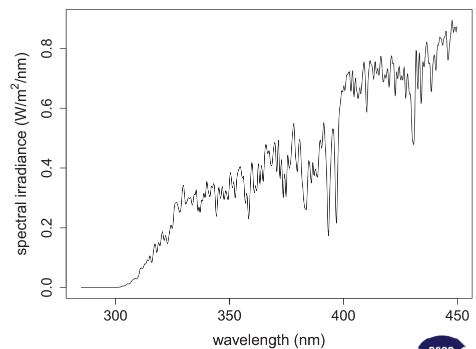
- Ells Dutton managed the Baseline Surface Radiation Network (**BSRN**); a project of the World Climate Research Program; **GMD operates 12 of 52 worldwide sites**
- **7 U.S.** Surface Radiation (SURFRAD) network sites measure SW↑, SW↓, LW↑, LW↓ plus sky imager, aerosol optical depth; adding spectral albedo; and building two mobile SURFRAD stations (NESDIS and DOE)
- **5 global** sites – SPO, BRW, BAO (Colorado) (NOAA base); Kwajalein, Bermuda (downwelling only) (NASA)
- 7 U.S. Integrated Surface Irradiance Study (ISIS) sites measure downwelling solar/UVB (DOE for solar energy prospecting and siting)

Antarctic UV – 3 sites with UV spectrometers

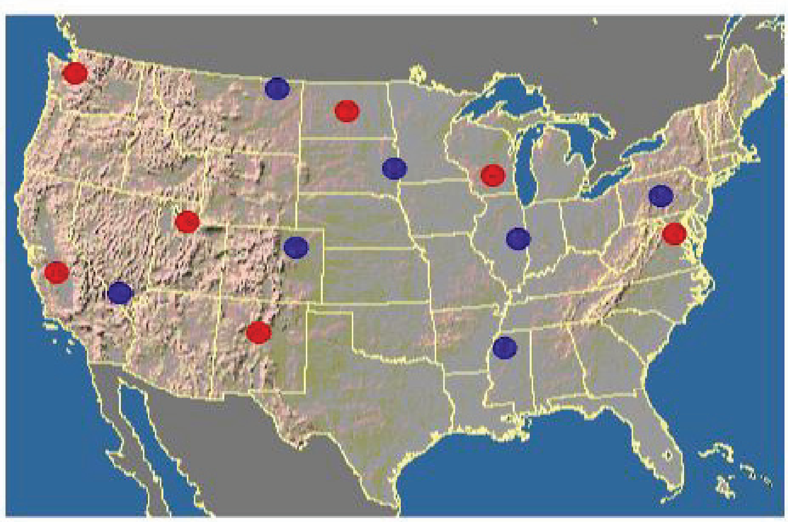
(NSF ran for 22 years; NOAA has operated since 2009)

NOAA/EPA Ultraviolet Brewer (NEUBrew) network

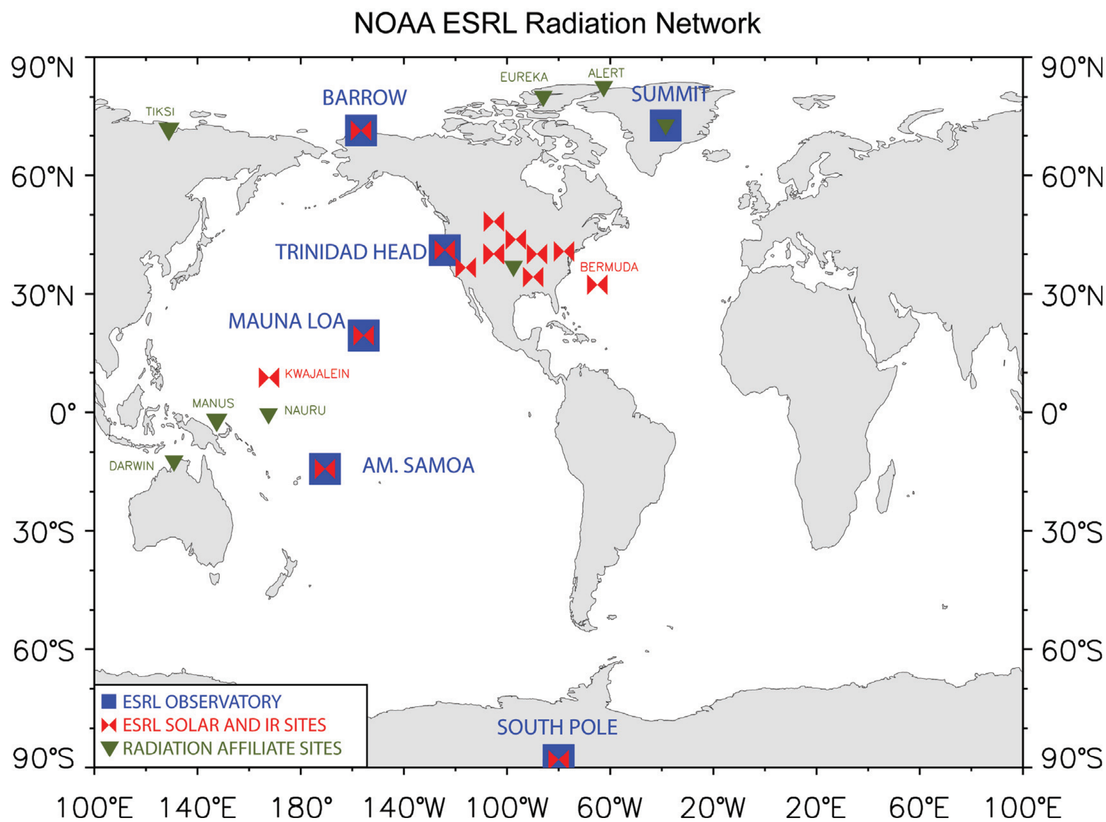
6 ultraviolet UV spectrometers (EPA, NOAA)



The SURFRAD and ISIS Networks



- ISIS (Solar, UV)
- SURFRAD (Solar, IR, UV, PAR)

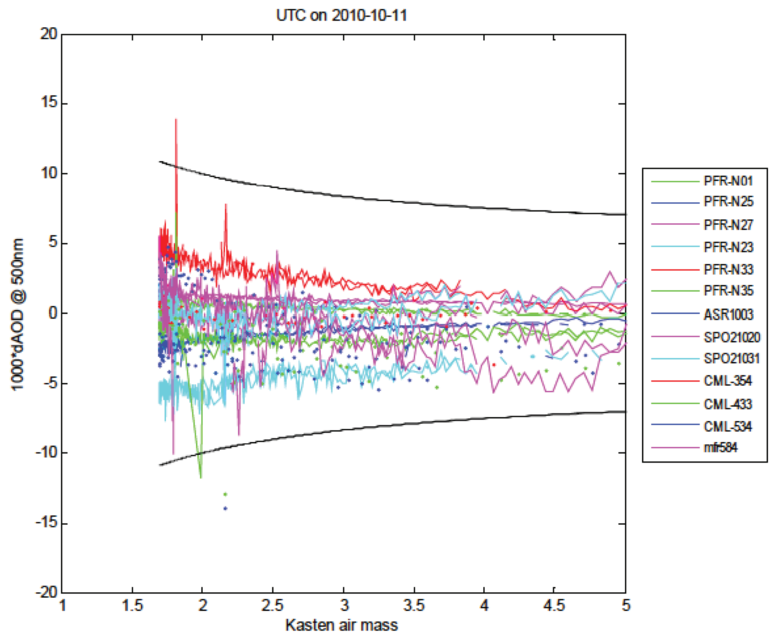


BSRN Measurement Improvements (95% Uncertainties)

- Solar direct beam (20 years ago and now ± 0.35%; field measurements were ± 2.0%, now at ± 0.7%)
- Solar diffuse on horizontal (2.2% of reading + 0.2 W/m^2)
- Solar irradiance on horizontal from summing two components
- Broadband infrared (uncertainty 10% to 2%)
- Aerosol optical depth (WMO/GAW Experts Workshop at Davos, Switzerland, in 2004 specified 0.005 +/- 0.01/m; before this acceptable uncertainty was not set)

Uncertainty of Acceptable Aerosol Optical Depth Measurements

500nm



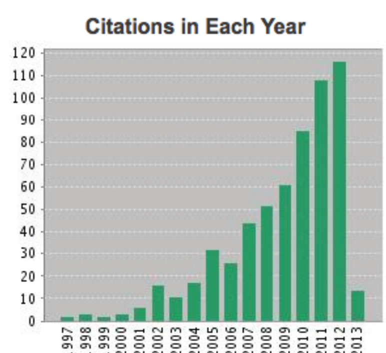
Applications of NOAA Radiation Data

- **Satellite product evaluation and improvement**
- **Climate and weather model evaluation and improvement**
- **Climate change research – trends & variations**
- Air quality model evaluation
- Domestic solar energy, including architectural applications
- Ultraviolet exposure and model validation (most sites)
- Agricultural, ecological, and tourism interests

NOAA Radiation Data Users

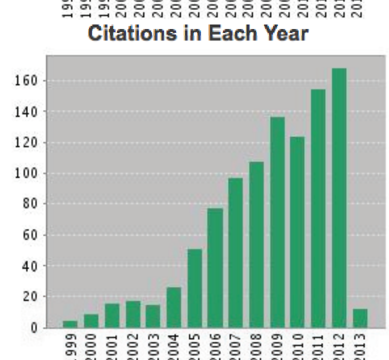
NCEP&GFDL (NOAA Modeling)	**Surface physics validation, RUC model surface irradiance validation, ETA and GCM validation**
NESDIS (Satellite)	**GOES surface irradiance validation**
NASA	**EOS/CERES, SRB, ISCCP, MODIS, ASTER validation**
ECMWF	**Modeled irradiance validation**
OAR	Climatology, model testing, radiative closure
NWS	UV index verification
DOD	AGROMET and radiation model validation
USGS	Hydrology modeling validation
DOE	ARM, U.S. solar data base
MS Canada	Effects of clouds on the SRB
Universities	Validate SW retrievals from satellite
	Validate MODIS and CERES albedo models
	Validate LW fluxes in hydrology model
	MODIS snow algorithm
	Effects of Asian dust on U.S. solar resource
	Solar energy studies
WMO	WCRP, GAW, WRDC, GCOS, baseline measurements

SURFRAD & BSRN Citations



SURFRAD

Results found:	39
Sum of the Times Cited [?] :	598
Sum of Times Cited without self-citations [?] :	527
Citing Articles[?] :	450
Citing Articles without self-citations [?] :	415
Average Citations per Item [?] :	15.33
h-index [?] :	14



BSRN

Results found:	45
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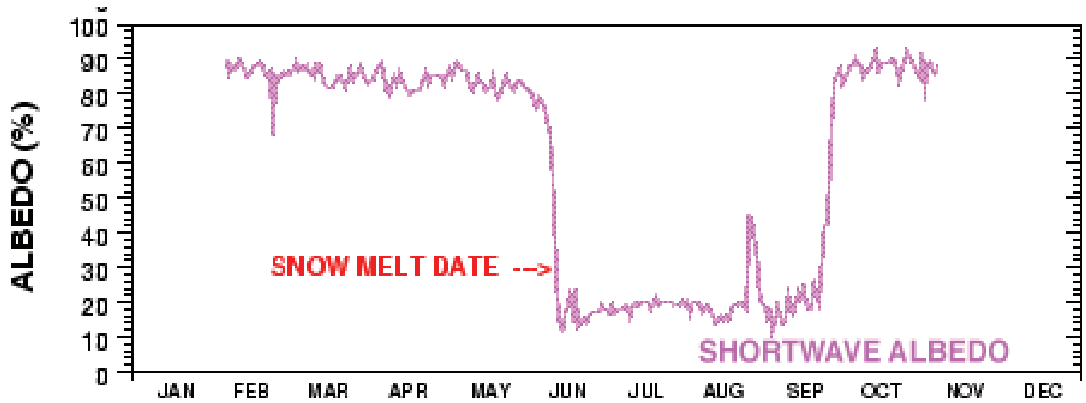
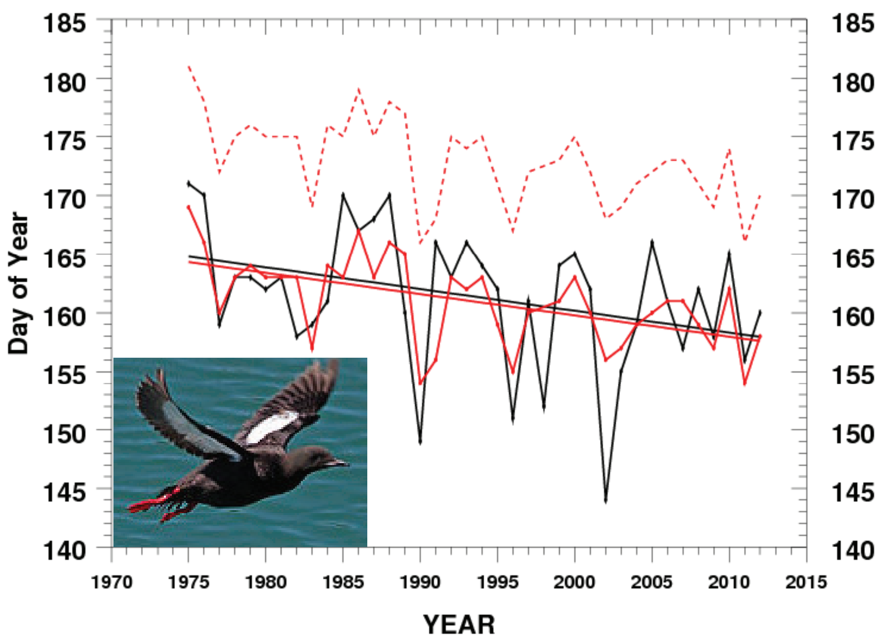
Sum of Times Cited without self-citations [?] :	934
Citing Articles[?] :	811
Citing Articles without self-citations [?] :	775
Average Citations per Item [?] :	22.64
h-index [?] :	13

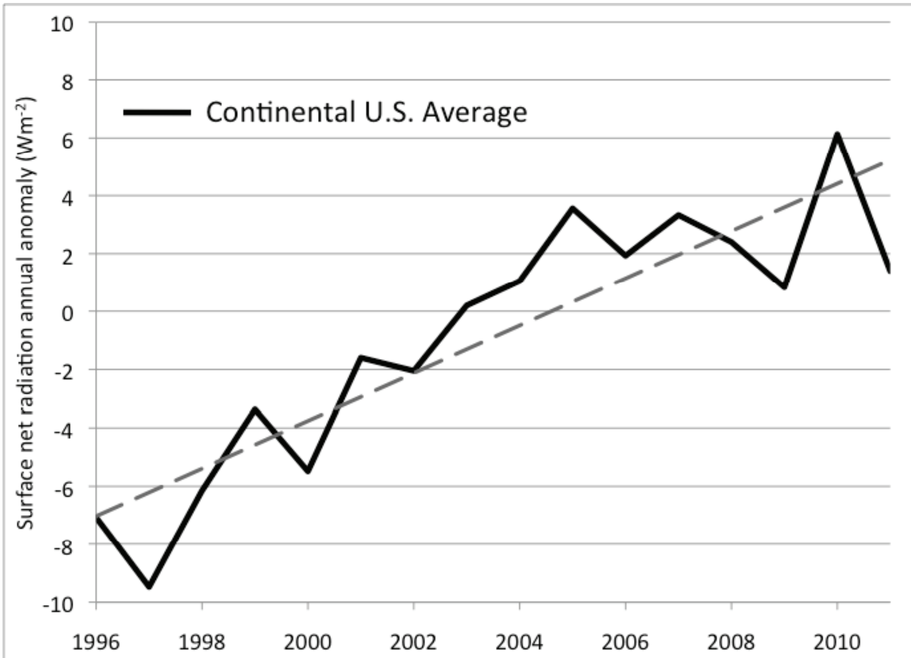
Barrow Snowmelt Date



Correlated BRW snow melt and appearance of First Egg



Radiation Trends – Regional

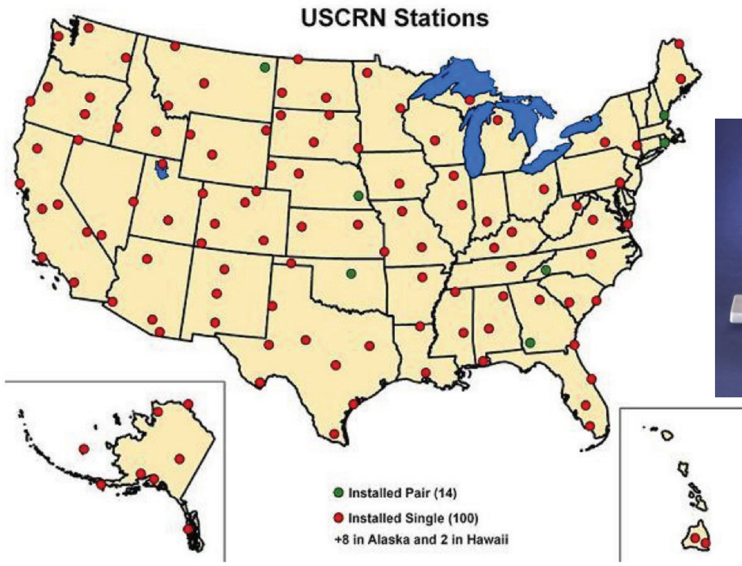


Augustine, J. A. and E. G. Dutton, Variability of the surface radiation budget over the United States from 1996 through 2011 from high quality measurements, *J. Geophys. Res. Atmos.* ,118, 43–53.

Planned Additions/Improvements

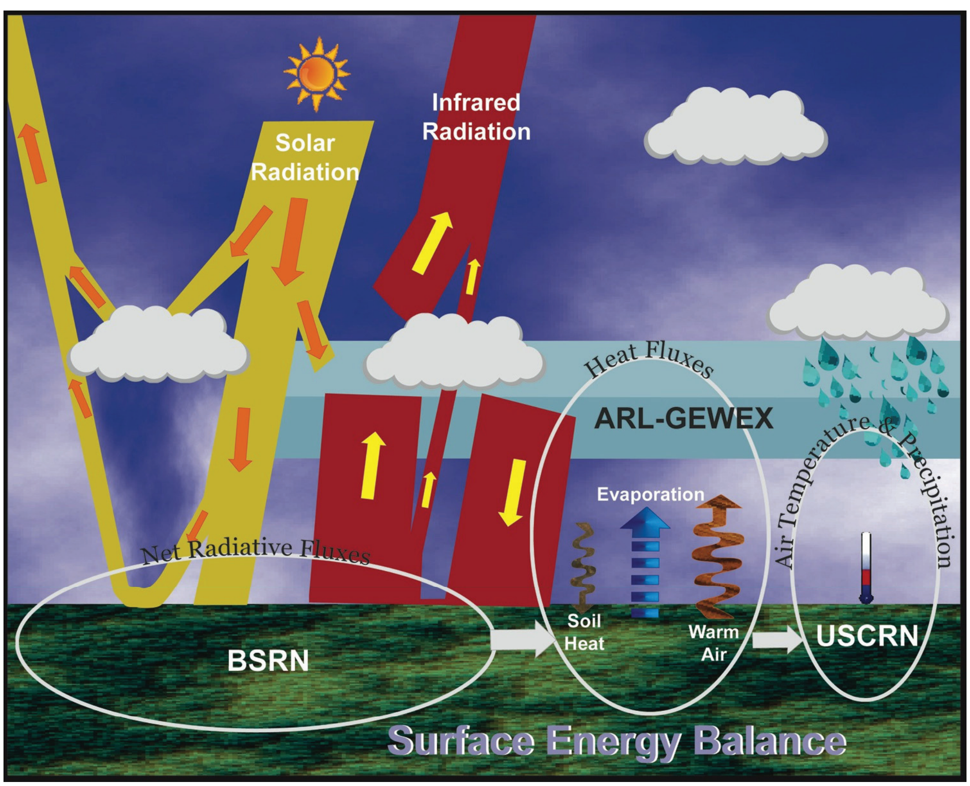
- Adding spectral albedo measurements and changing a spectral channel to 1625 nm
  - Improve aerosol size and absorption retrievals
  - Enable retrieval of cloud optical depth and effective radius
  - Indirectly improve satellite retrievals
- Direct irradiance measurement will be upgraded to from uncertainty of 1.8% to 0.7% with higher accuracy instrumentation

Solar Energy Network Proposal

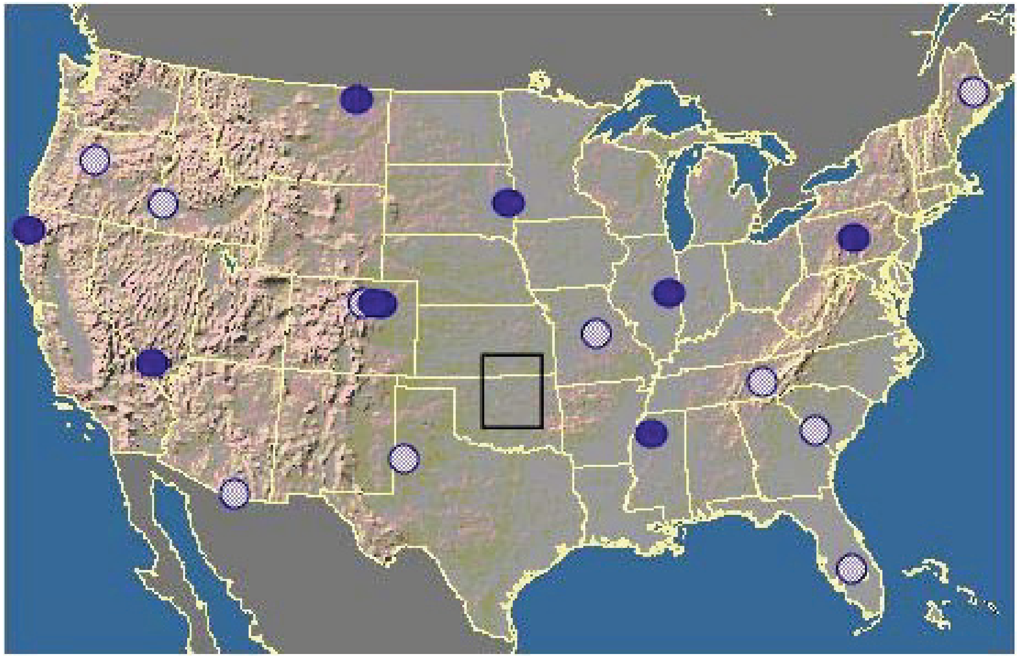


Unprecedented Spatial and First-Time Spectral Coverage

Surface Energy Budget Network Proposal



Surface Energy Budget Network Proposal



Main Points

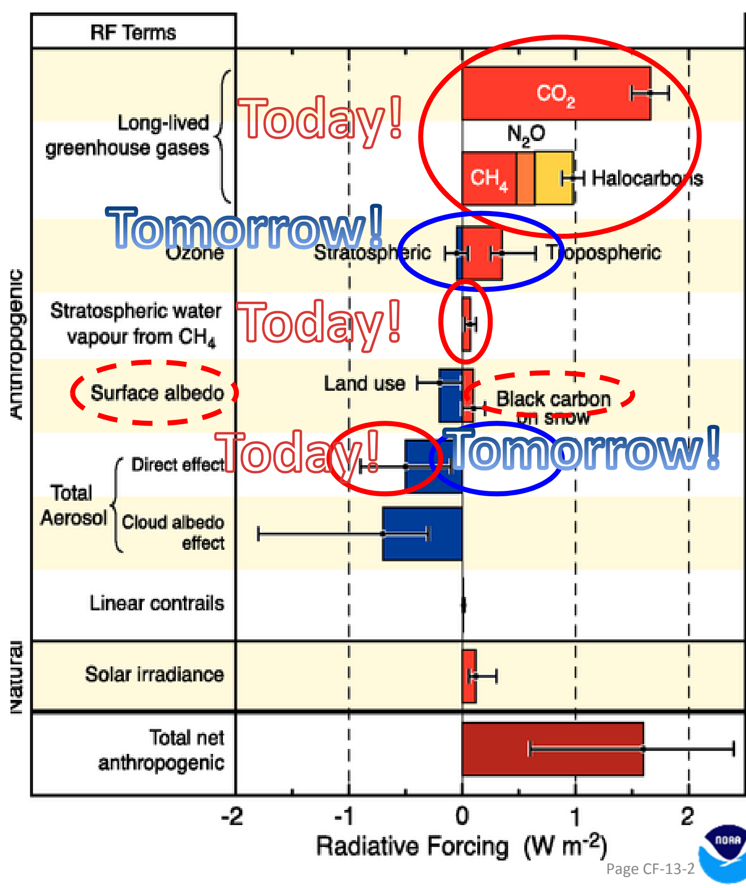
- Eighteen year+ radiation budget and aerosol optical depth records at ~ 15 sites
- Significant improvements in accuracy of all radiation and aerosol optical depth measurements
- Widely-used measurement set for satellite and model development and evaluation plus other uses
- Statistically significant radiation and aerosol optical depth trends have been detected over CONUS
- Upgrades will improve radiation and, thereby, trend detection; enable useful aerosol and cloud retrievals

Climate Forcing Summary

James Butler

Radiative Forcing

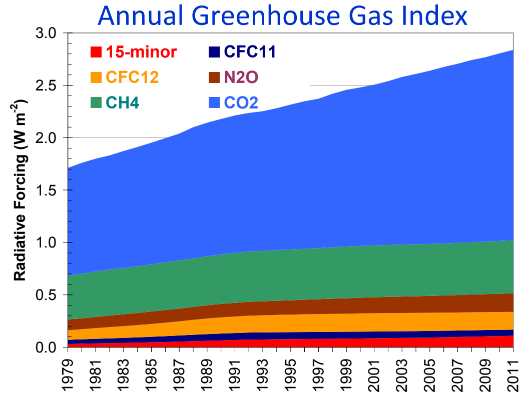
- GMD monitors constituents contributing to ~95% of radiative forcing
- Many were shown today, more tomorrow as part of the ozone and air quality sessions

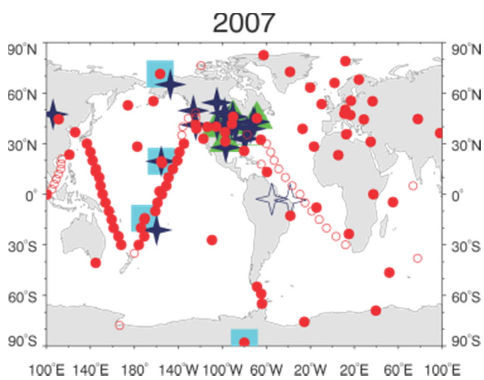


Long-lived Greenhouse Gases

- NOAA's monitoring program captures >99% of the radiative forcing from long-lived gases.
- It allows assessments of human activities on radiative forcing
- It improves the predictive understanding of climate.

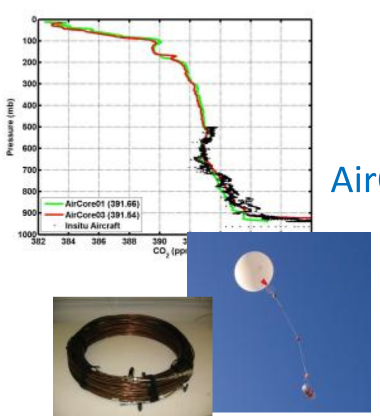
Annual Greenhouse Gas Index





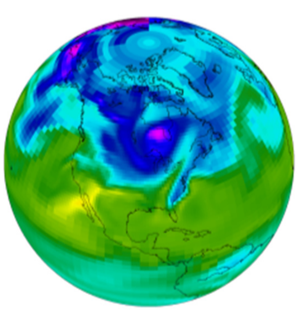
- Global Greenhouse Gas Reference Network
  - 6-10 gases per site
  - Very high quality measurements
  - Global trends and distributions
  - Vertical profiling capability
  - Isotopic signatures
  - Continental-scale fluxes of CO_2, CH_4

Innovation



AirCore

- Innovation shows in much of what we do
- It is what makes our observing systems better
- It is what allows us to interpret our data effectively

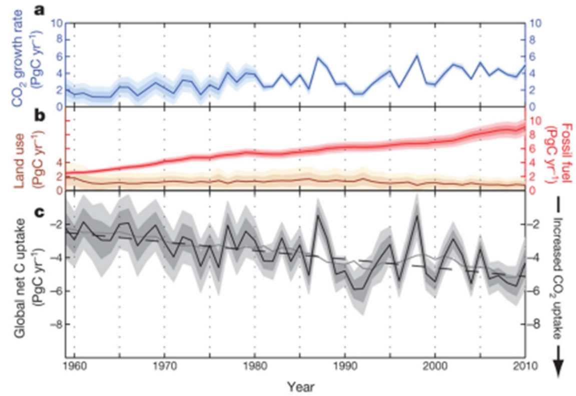


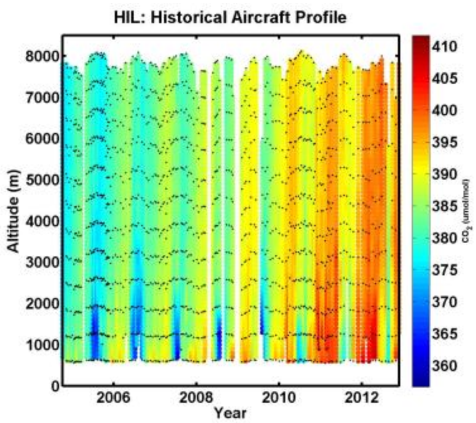
CarbonTracker

Portable Flask Package (PFP)

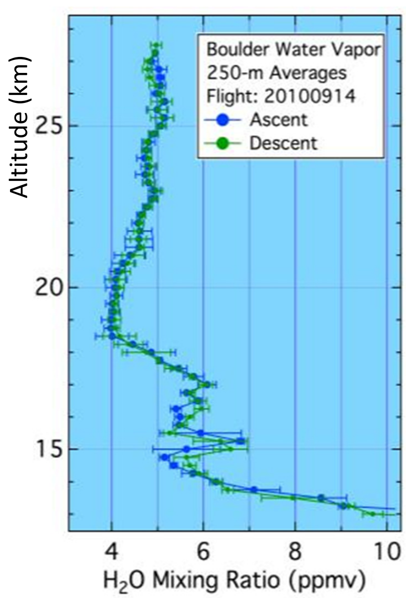
Breakthroughs

- Making use of ALL of our data allows us to draw clear distinctions



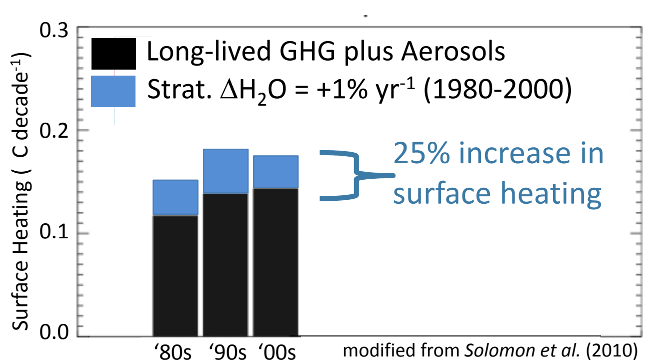


- Our observations take us much closer to separating human from natural sources



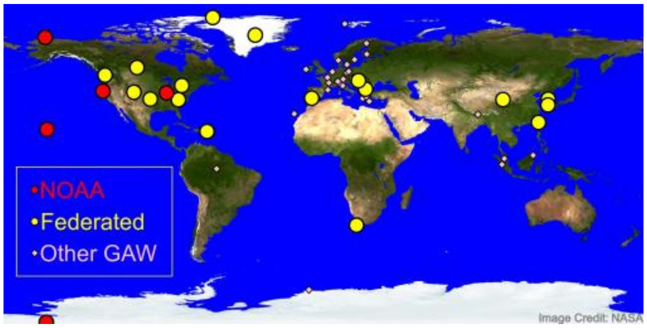
Stratospheric Water Vapor

- GMD trends of stratospheric water vapor demonstrate a major contribution to the increase in radiative forcing.



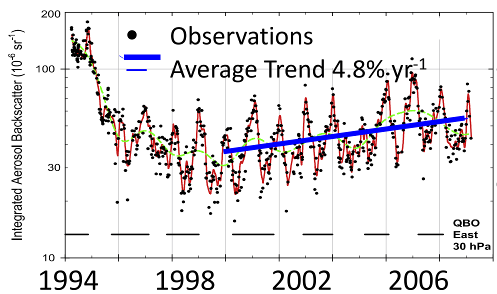
modified from *Solomon et al.* (2010)

Aerosol Properties, Black Carbon



- NOAA Federated Network
- New instrument for black carbon
- Climatologies of aerosol properties
- Satellite validation
- Stratospheric trends

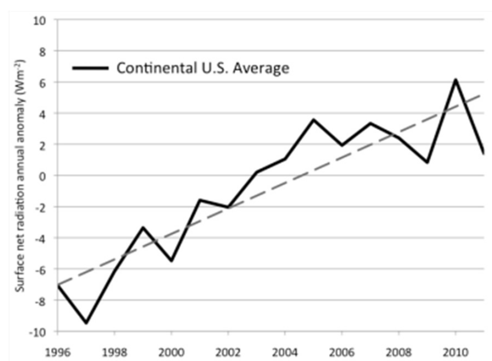
Continuous light absorption photometer



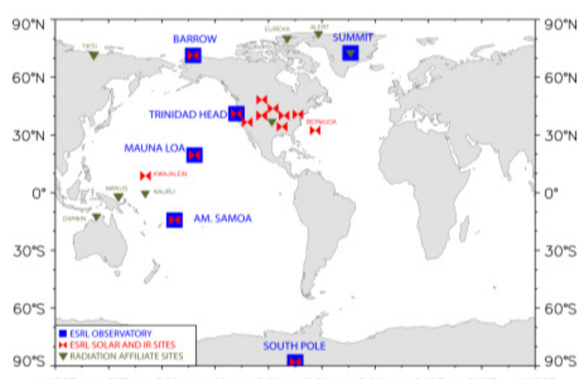
Hofmann et al., GRL, 2009

Surface Radiation

- Radiation budget and aerosol optical depth records at ~ 15 sites
- Leveraged capability through the WCRP/GEXEX Baseline Surface Radiation Network
- Widely used for evaluation and validation of satellite retrievals and models
- High quality records

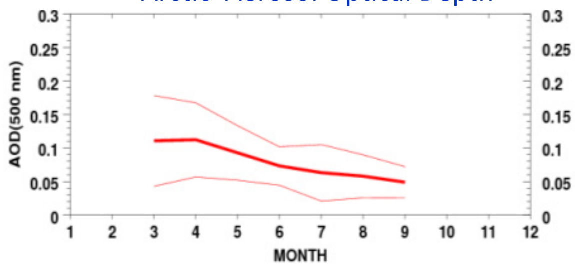


Solar “Brightening” over the US

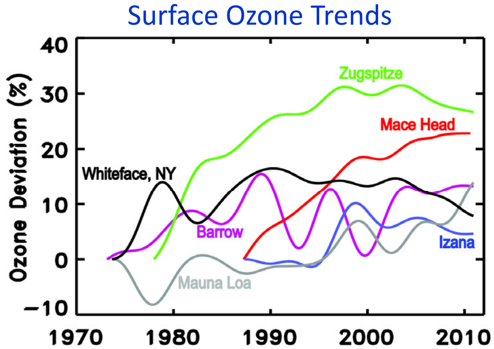


And there is more tomorrow . . .

Arctic Aerosol Optical Depth



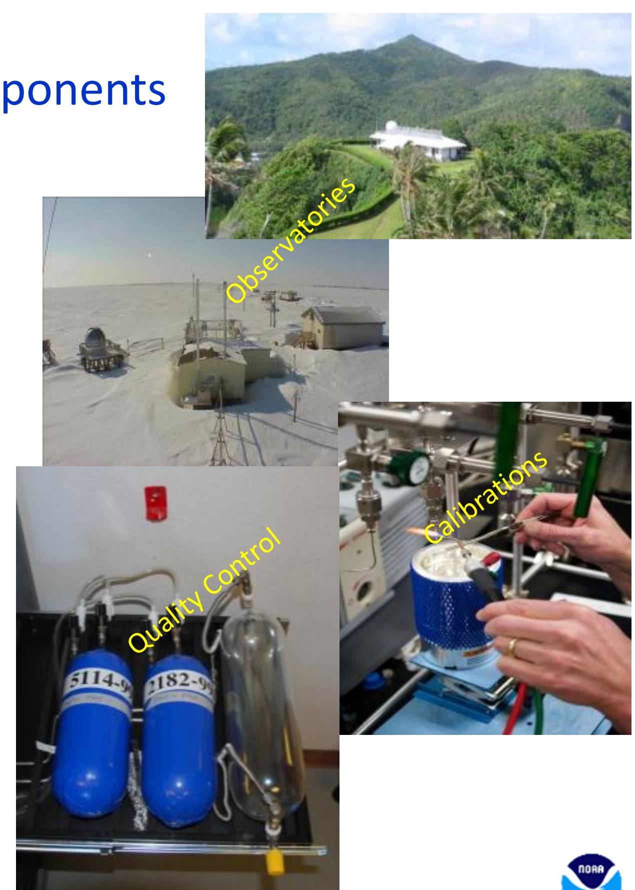
Surface Ozone Trends

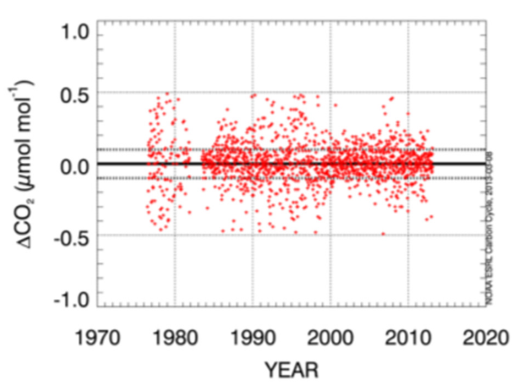


- Tomorrow contains sessions on ozone depletion and air quality
- Atmospheric substances have several properties and influences
- Their roles often overlap into climate forcing – GMD themes are not independent

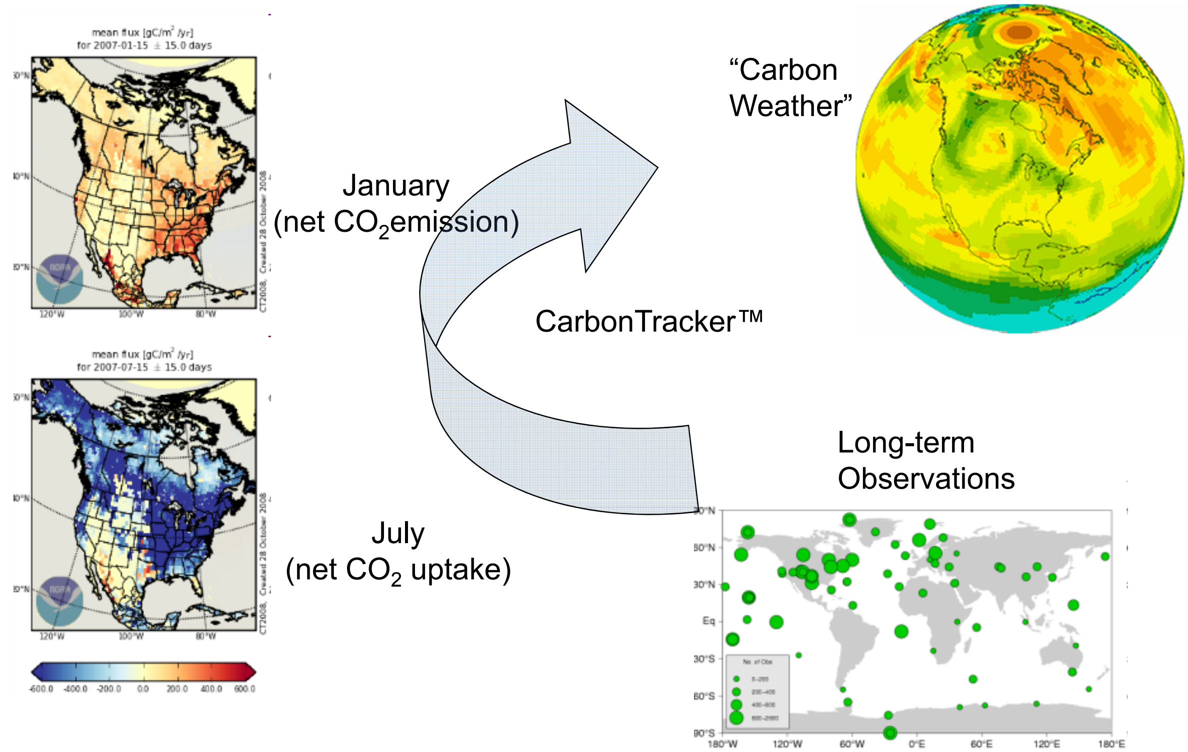
Also Tomorrow - Core Components

- Observatories form the backbone of our observing networks
- Calibrations are essential in all areas
- Comparison, quality control, and data management are at the core of all we do





Questions?



mean flux [gC/m² /yr]
for 2007-01-15 ± 15.0 days
mean flux [gC/m² /yr]
for 2007-07-15 ± 15.0 days
-600.0 -400.0 -200.0 0.0 200.0 400.0 600.0
January
(net CO_2 emission)
July
(net CO_2 uptake)
CarbonTracker™
“Carbon
Weather”
Long-term
Observations
180°W 120°W 60°W 0°E 60°E 120°E 180°E

Global Monitoring Division

Common Elements

Contents:

- 3 Presentations on Common Elements

Global Monitoring Division
Observing Facilities and Operations

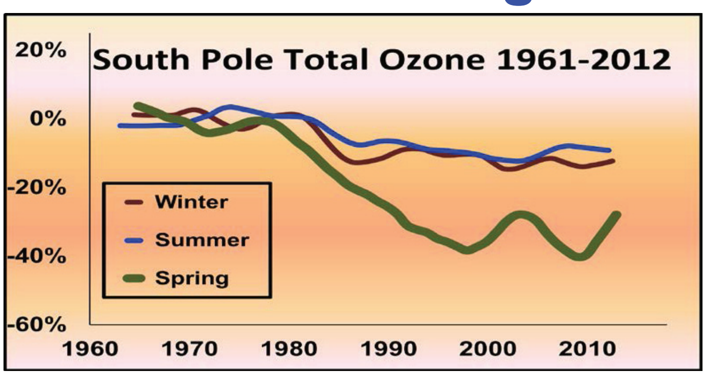
Russ Schnell

The Global Monitoring Division (GMD) conducts "sustained observations and research related to global distributions, trends, sources and sinks of atmospheric constituents that are capable of forcing change in the climate of the Earth".

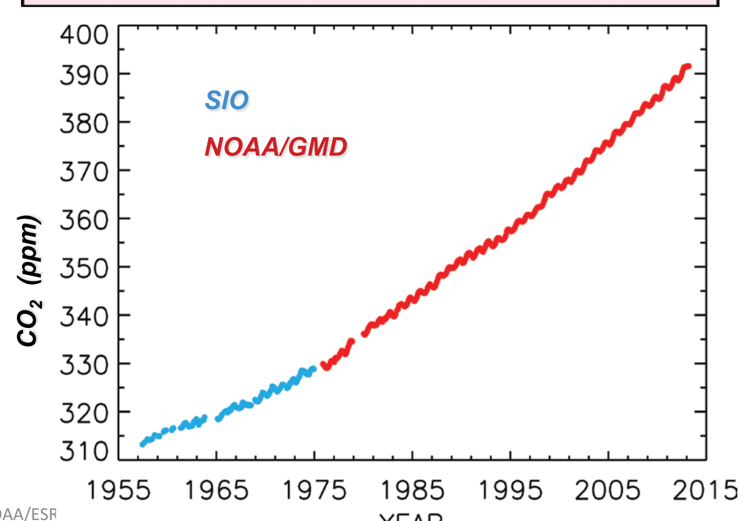
To fulfill this mandate, GMD conducts:

- Up to 250 different types of well calibrated measurements,
- At 239 different locations,
- Encompassing all 7 continents,
- From land, sea and air,
- With some measurement series spanning 56 years.

GMD is Long-Term Monitoring

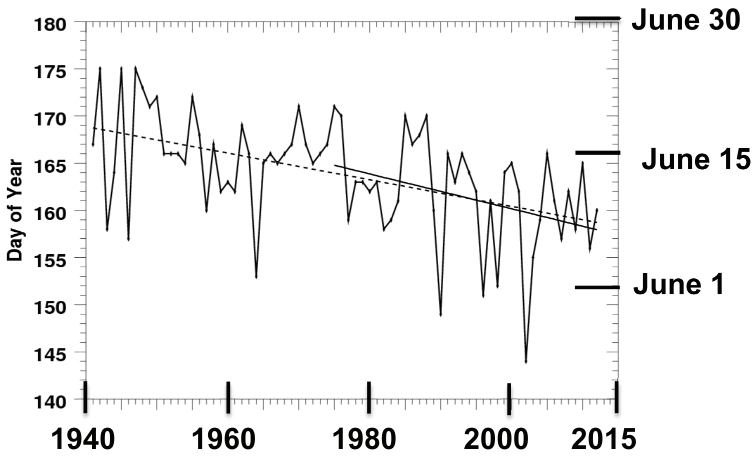


Depletion of ozone in the Antarctic stratosphere is not just a springtime event.

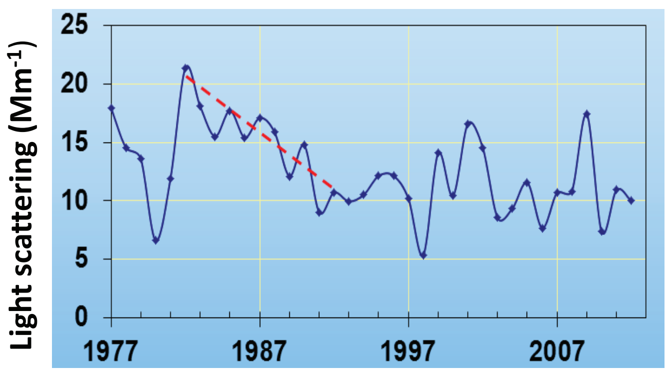


The South Pole CO2 record is longer than the Mauna Loa record by over one year

GMD is Long-Term Monitoring

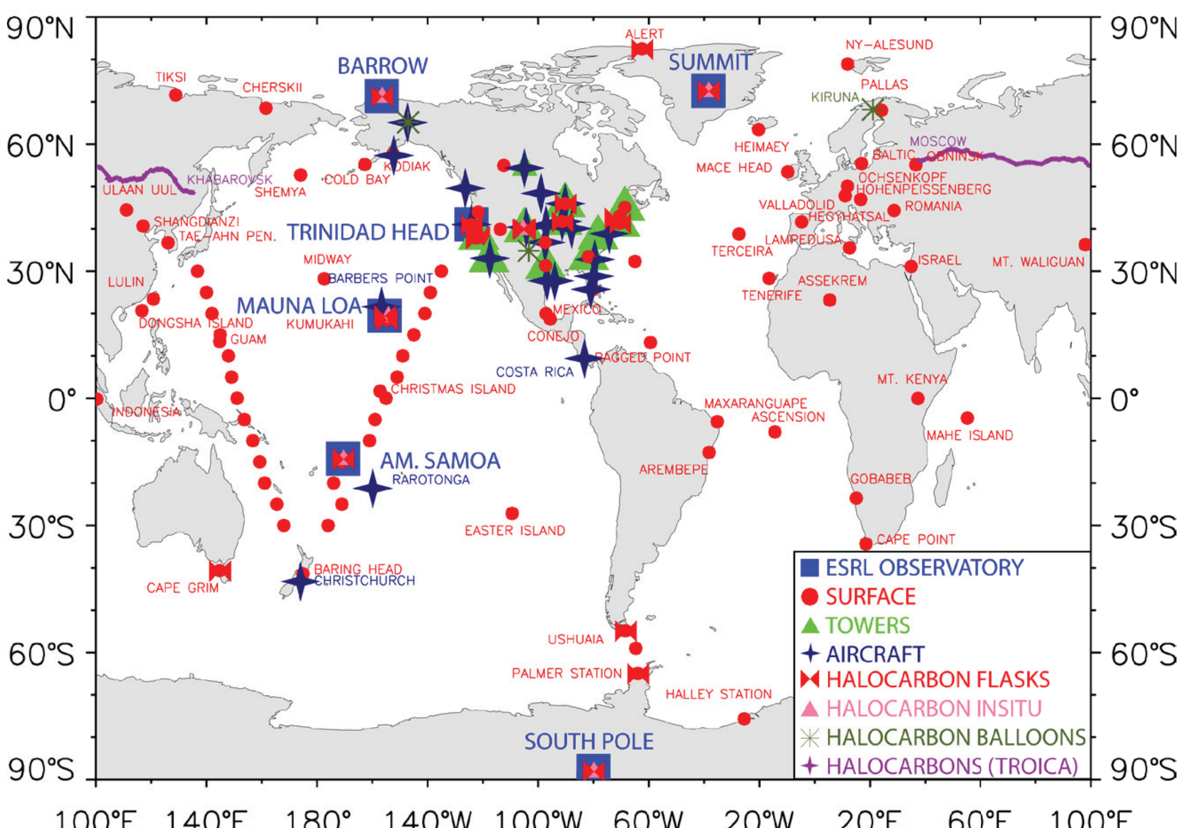


Snowmelt date at Barrow, Alaska, has advanced ~12 days from 1940 to 2012 extending the snow free period by ~16%.
Data courtesy Bob Stone, GMD/CIRES.

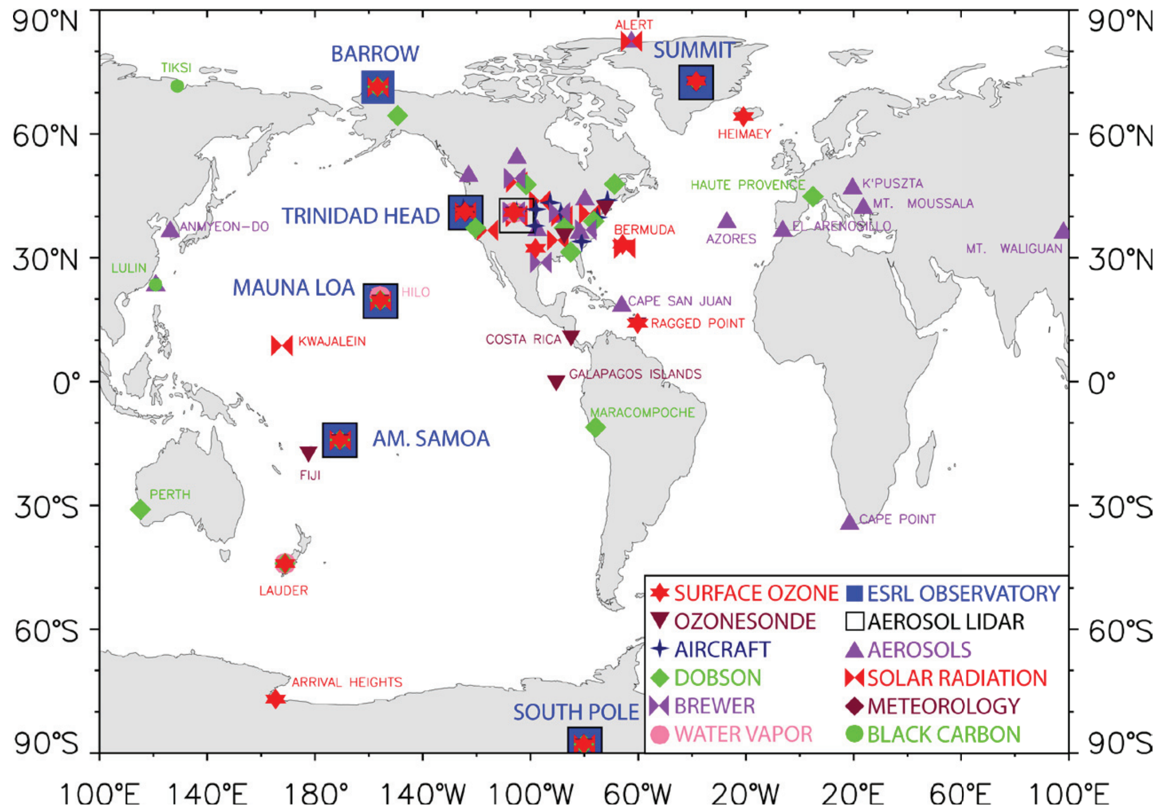


Arctic Haze (Eurasian air pollution) April averages, 1977 to 2012. The red line decrease (2x) is attributed to the collapse of industry in the former Soviet Union.

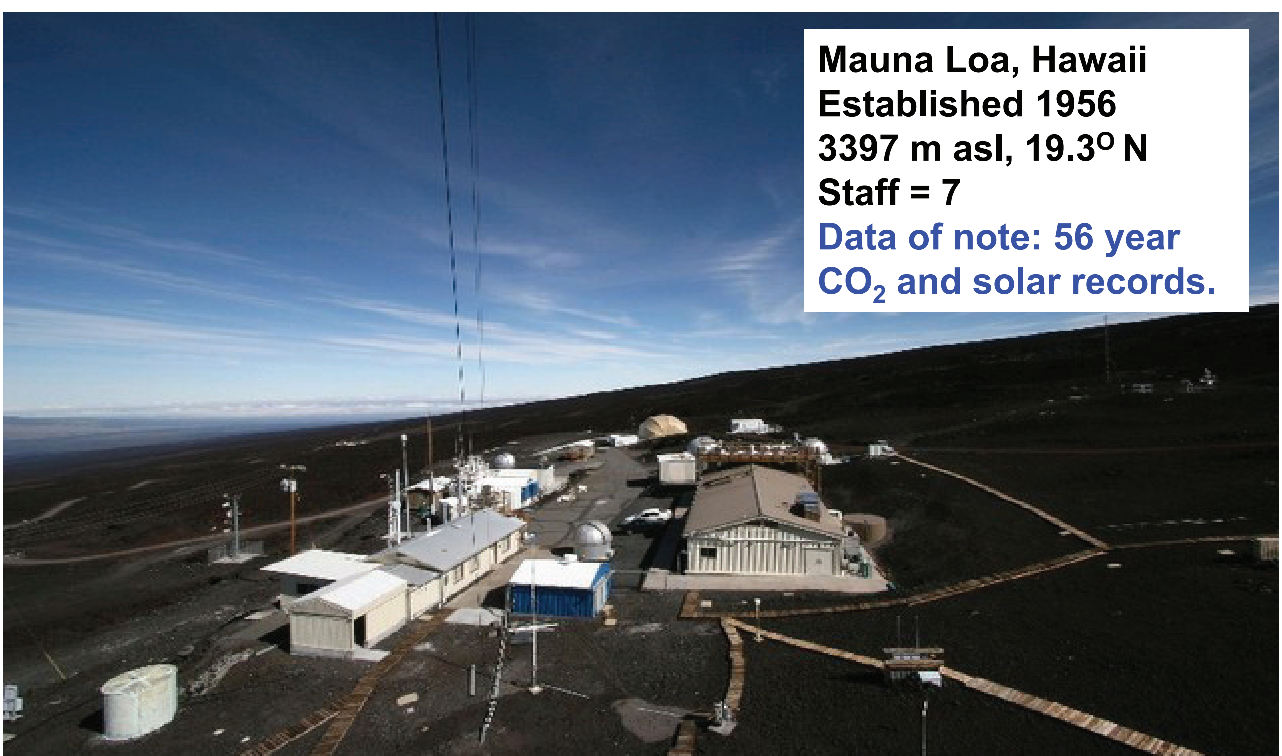
GMD Carbon Cycle and Halocarbon Gases



GMD Aerosols, Solar, Meteorology, Black Carbon and Ozone

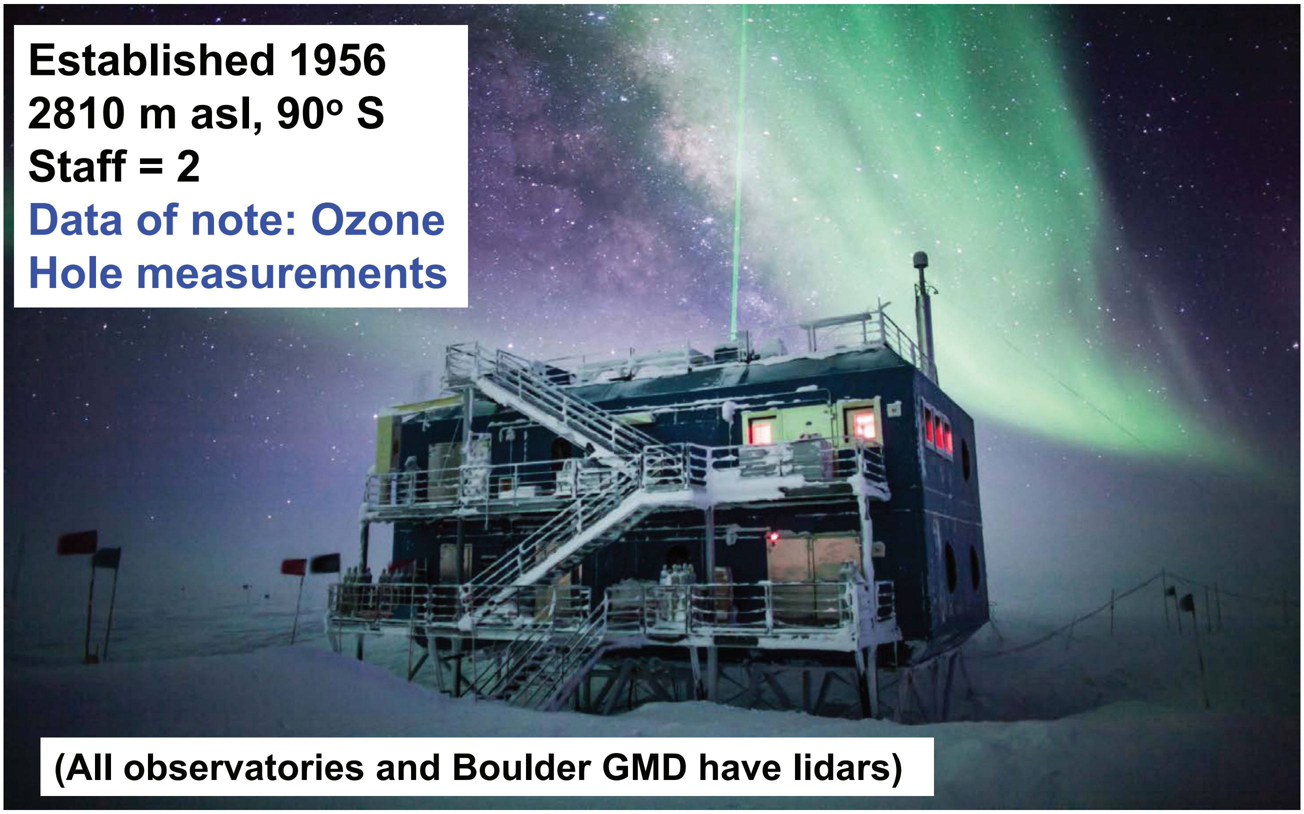


The Backbone of the Global Measurements are Manned Atmospheric Baseline Observatories



South Pole, Antarctica

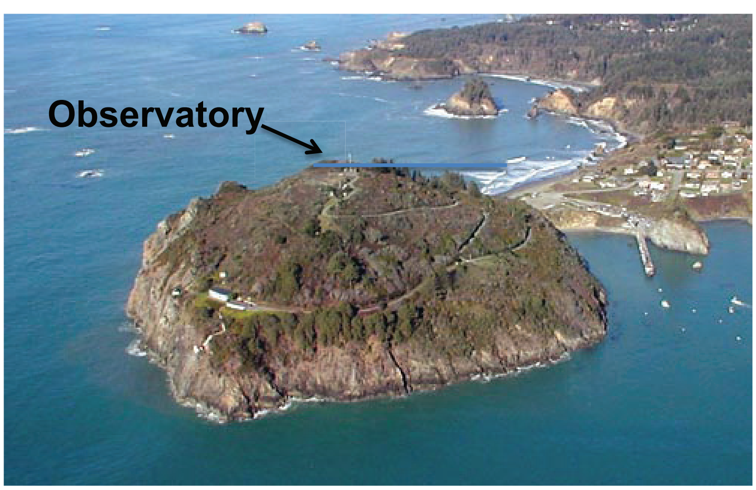
Established 1956
2810 m asl, 90^o S
Staff = 2
Data of note: Ozone Hole measurements



(All observatories and Boulder GMD have lidars)

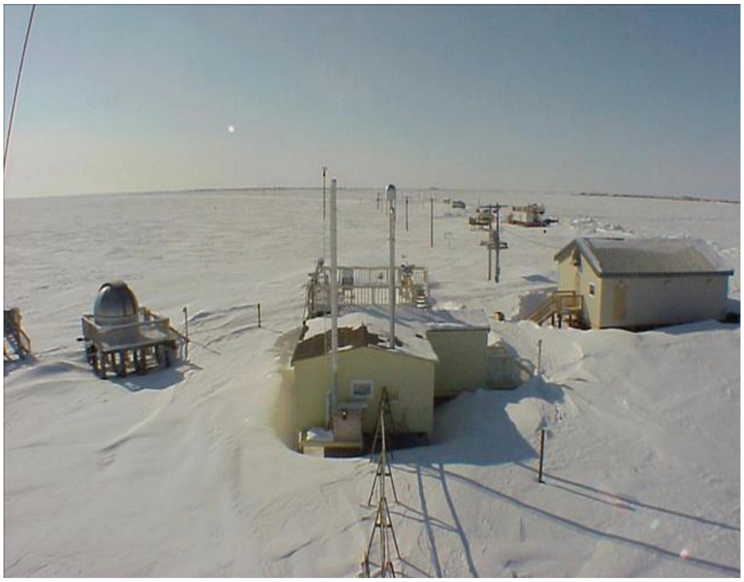
American Samoa

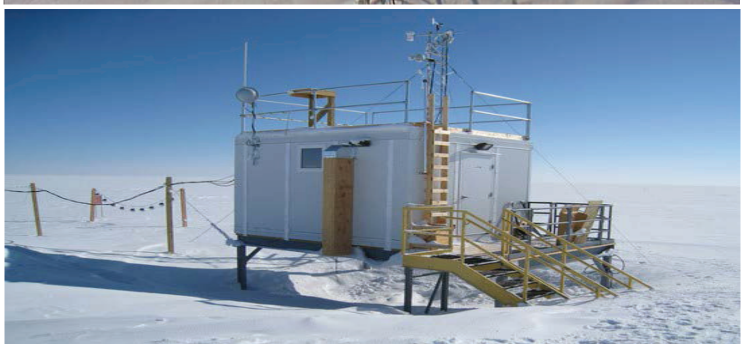
Established 1974
30 m asl, 20^0S
Staff = 2
Data of Note: NOAA and AGAGE halocarbon 22 year data overlap.



Trinidad Head, CA

Established 2004
107 m asl, 41^0 N
Staff = 1
Data of Note: Asian air pollution entering the Western U.S.





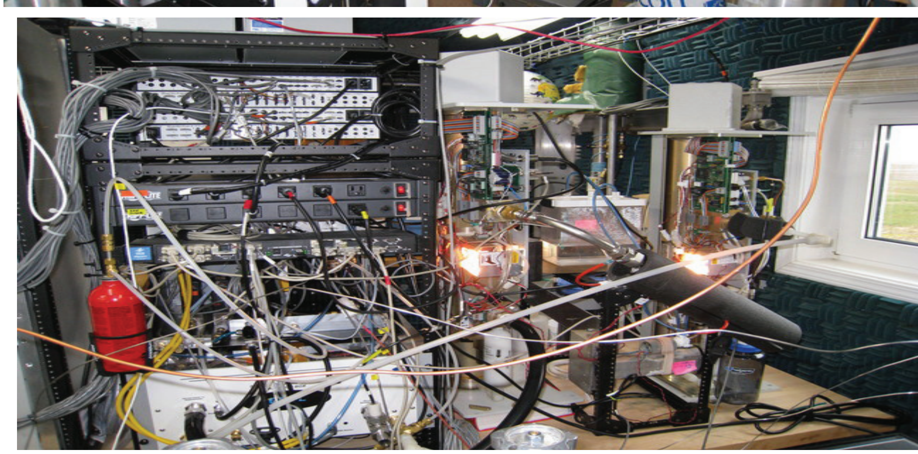
Barrow, AK

Established 1973
11 m asl, 71^0 N
Staff = 2
Data of note: Boundary layer ozone destruction in spring .

Summit, Greenland

Established 1997
3209 m asl, 72^0 N
Staff = 2
Data of note: Stratospheric aerosol measurements

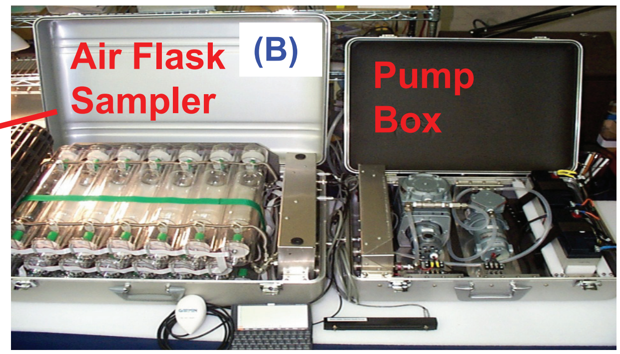
Interior of an observatory. **Instruments are checked at least once, and up to six times a shift.**



Rear view of an aerosol rack. **Note the numerous air inlets, and power and signal cables.**

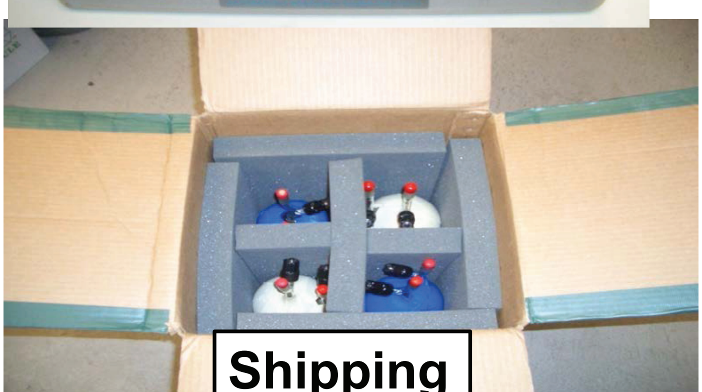
(A) Looking down from the 300 m "tall tower" equipped for gas measurements begun in 1992. Now total of 9.

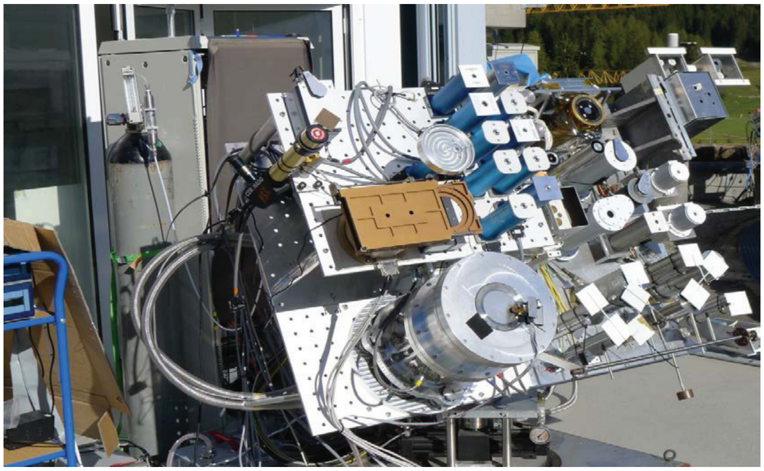
(B) Aircraft glass bottle (flask) air sampling system. 14 rented aircraft conduct weekly to tri-weekly sampling profiles to 20,000 ft.



Air Flask System

(Up to 60 different gases are measured in a flask)





Calibrations are key to long-term data intercomparability and data integrity.

World Radiometric Reference for solar measurements, Davos, Switzerland.

Dobson total column ozone instrument intercomparison in Buenos Aires. The WMO World Standard is maintained by GMD in Boulder, CO.

GMD Inventory is >1,600 cylinders

Reliable standards are essential for high quality monitoring. GMD maintains WMO primary standards for CO_2, CH_4, CO, SF_6, N_2O and the NOAA halocarbon standards.

(U) Moving gas cylinders into the CO_2 calibration laboratory.

(L) Step in preparing a standard by sealing a known amount of gas into a glass capillary tube.

(R) Gas added to cylinders is weighed to milli- and microgram levels.

Summary

- The Global Monitoring Division conducts 1,000s of atmospheric composition and related measurements around the globe.
- These measurements require accuracy, repeatability and comparability over century scales.
- The data from these measurements must be maintained in accessible form and have transparent metadata and QA/QC information.
- The following 2 presentations address these issues:

  Brad Hall: Standards and calibrations.
  Ken Masarie: Data management and quality control.

Calibration and Standards Activities

Brad Hall

Trace Gases

Solar and Infrared Radiation

GMD Calibration Activities

Dobson Column Ozone

Aerosol Network

Trace Gases

Solar and Infrared Radiation

Common Aspects

- Commitment to Consistency
- Regional/Global Scope
- R&D: Improving Methods
- Scientific Outreach
- Transparency/Accessibility

Dobson Column Ozone

Aerosol Network

Trace Gases

Solar and Infrared Radiation

Goals

- Maintain Consistent Scales
- Maintain Traceability
- Improve Methods
- Understand Differences
- Participate in Working Groups

Dobson Column Ozone

Aerosol Network

Trace Gases

Primary Standard: Gas mixture with known mole fractions

1) by mass (gravimetric)
2) by analysis of P, T, V (manometric)

GLOBAL ATMOSPHERE WATCH

CO_2
CH_4
CO
N_2O
SF_6

WMO- Global Atmosphere Watch Central Calibration Laboratory (CCL)

40 halocarbons	(e.g. CFCs)
10 hydrocarbons	(propane, benzene)
5 other	(carbonyl sulfide)

Internal NOAA scales – adopted by others

Trace Gases

CO_2
CH_4
CO
N_2O
SF_6

WMO/GAW
Central Calibration Laboratory
(CCL)

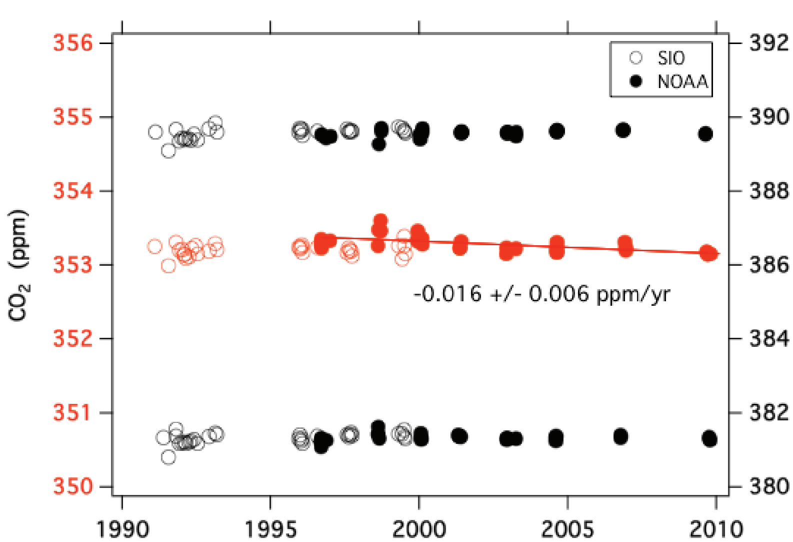
CCL Responsibilities

1. Maintain WMO mole fraction scales.
2. Establish traceability to primary reference materials or fundamental quantities (SI).
3. Carry out comparisons with independent primary scales.
4. Transparency: Provide complete and prompt disclosure, including uncertainties.
5. Distribute reference gases to WMO/GAW participants.

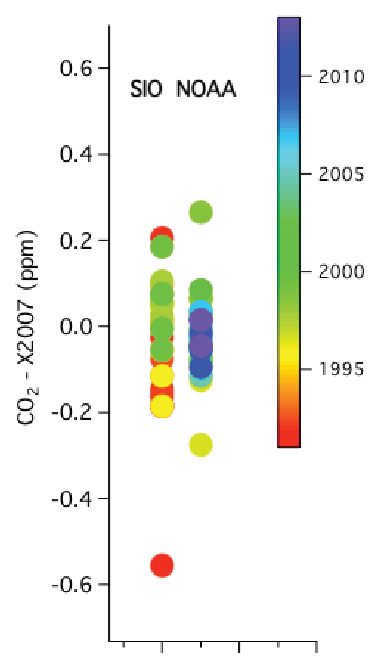
GMD Manometer

- Absolute measure of the CO_2 mole fraction in dry air

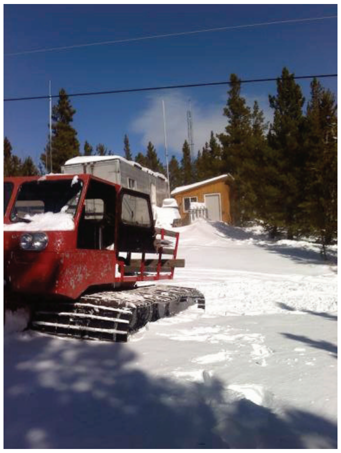
- Cannot assume that mole fractions are constant

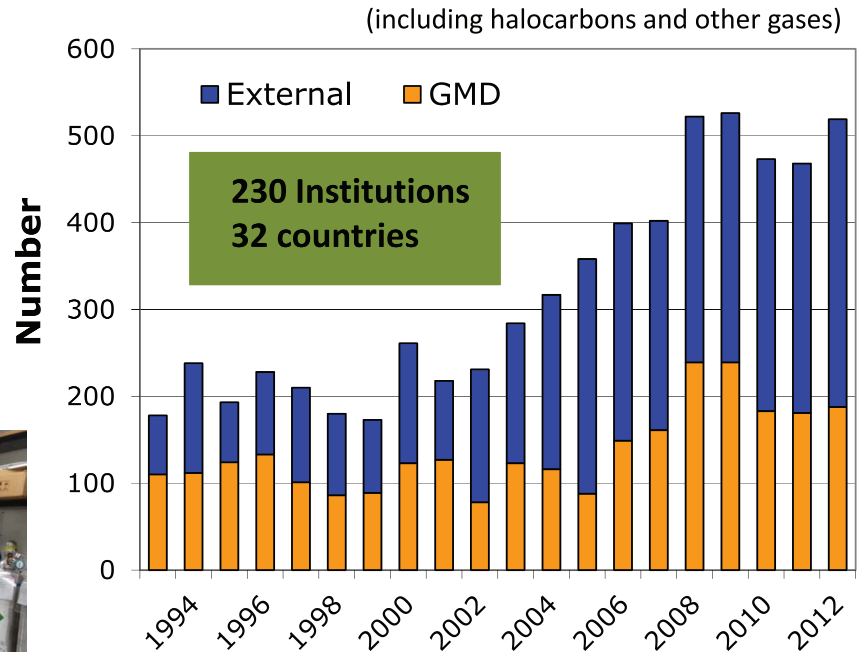


Primary 381



Natural Air Gas Standards



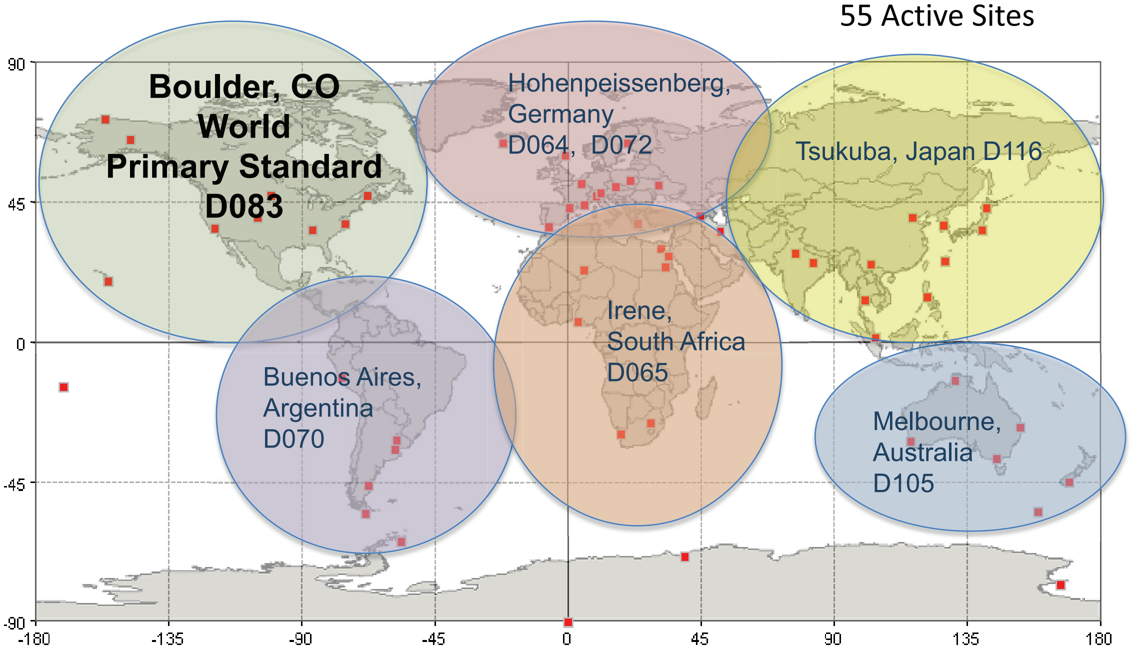


see poster: Duane Kitzis

Dobson Column Ozone

World and Regional Calibration Centers

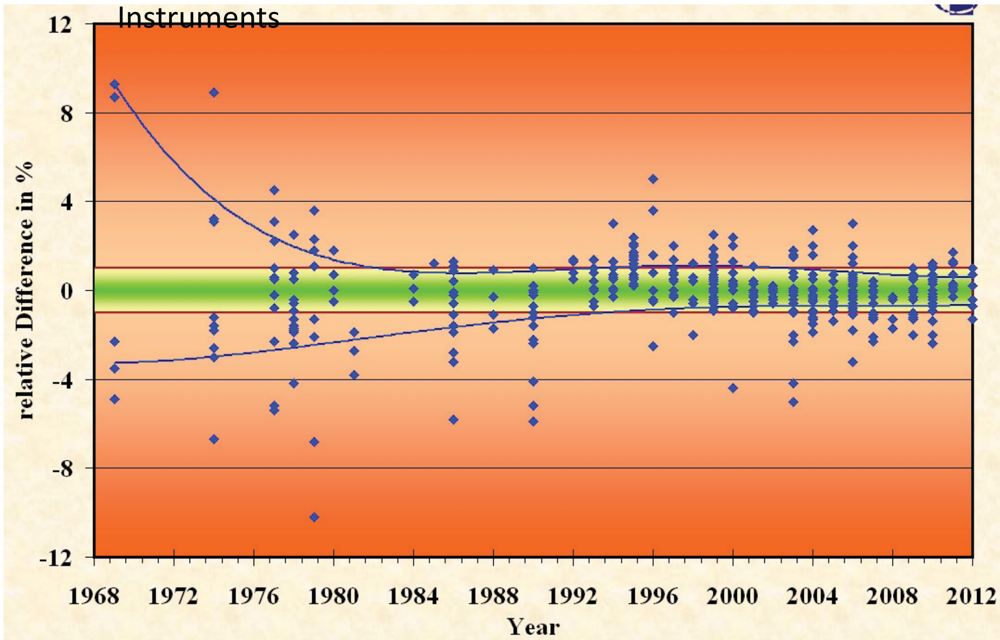
55 Active Sites



see poster: Bob Evans

Dobson Column Ozone

Dobson Comparisons: Relative to Reference Instruments

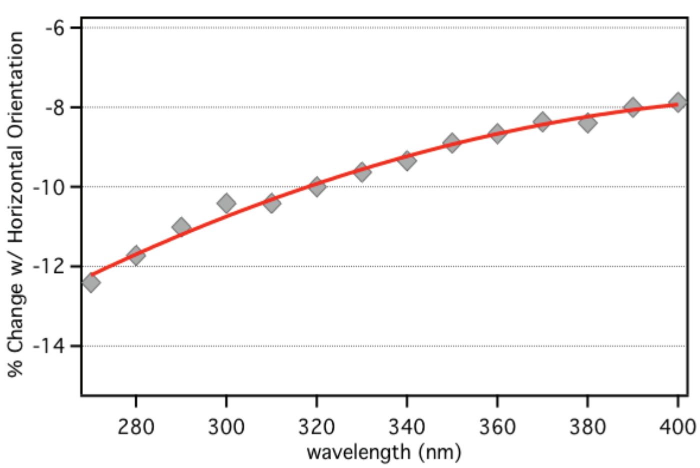


courtesy Köhler Ulf

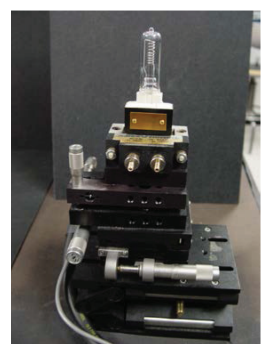
Central Ultraviolet Calibration Facility (CUCF)

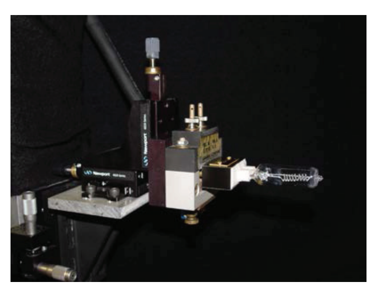
The CUCF is the only facility in the world to distribute horizontally-calibrated 1000 watt FEL-type quartz-tungsten-halogen standard lamps

% Change in Irradiance



Normal NIST calibration orientation.

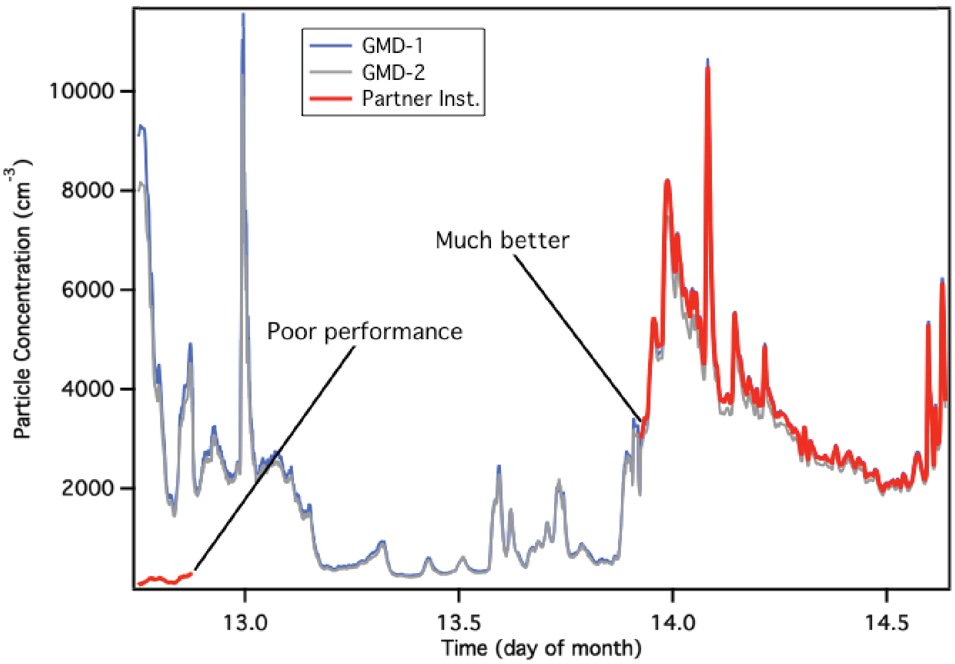




The CUCF horizontal orientation is necessary to calibrate upward viewing UV monitoring instruments.

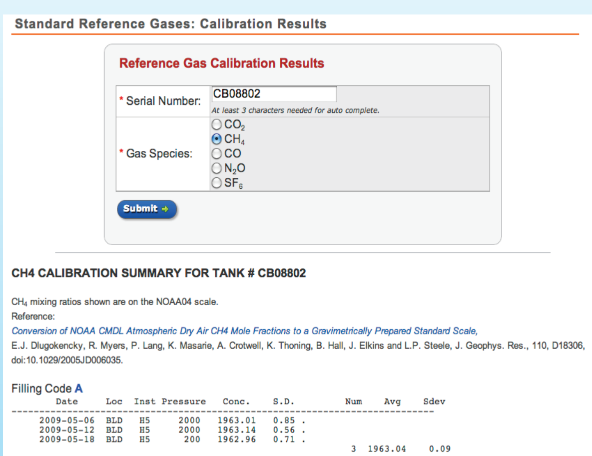
Scientific Outreach: Helping others improve their measurements

Particle Counter Comparison (2010)



Transparency/Accessibility

Trace Gas Calibration Results Available on Website



Standard Reference Gases: Calibration Results

Reference Gas Calibration Results

* Serial Number: CB08802
At least 3 characters needed for auto complete.

* Gas Species: CO_2 / CH_4 / CO / N_2O / SF_6

Submit

CH4 CALIBRATION SUMMARY FOR TANK # CB08802

CH_4 mixing ratios shown are on the NOAA04 scale.
Reference:
Conversion of NOAA CMDL Atmospheric Dry Air CH4 Mole Fractions to a Gravimetrically Prepared Standard Scale,
E.J. Dlugokencky, R. Myers, P. Lang, K. Masarie, A. Crotwell, K. Thoning, B. Hall, J. Elkins and L.P. Steele, J. Geophys. Res., 110, D18306, doi:10.1029/2005JD006035.

Filling Code A

Date	Loc	Inst	Pressure	Conc.	S.D.	Num	Avg	Sdev
2009-05-06	BLD	H5	2000	1963.01	0.85 .			
2009-05-12	BLD	H5	2000	1963.14	0.56 .			
2009-05-18	BLD	H5	200	1962.96	0.71 .			
						3	1963.04	0.09

Quality System

ISO 17025: International management standard for calibration and measurement

- WMO-BIPM Mutual Recognition Agreement
- Full Documentation
- Internal Audits
- External Assessments

Publications

Calibration Methods and Uncertainties

Zhao and Tans, 2006; Dlugokencky et al., 2004
Hall et al., 2007; Novelli et al., 2003,
WMO TD No. 1456; Early et al., 1998.

Summary

Calibration and Standards Activities

- Trace Gases
- Dobson Column Ozone
- Solar and Infrared Radiation
- Aerosols

Common Aspects

- Commitment to Consistency
- Regional/Global Scope
- R&D: Improve Methods, Compatibility
- Scientific Outreach
- Transparency/Accessibility

Data Management & Quality Control

Ken Masarie
Carbon Cycle Group

The GMD Mission is a long-term proposition

- **Long-term records are critical for questions with long time horizons**
  - Assessments of Climate Forcing, Ozone Depletion, and Baseline Air Quality
  - Development and testing of diagnostic and prognostic models designed to improve understanding of budgets and natural processes
  - Keeping the public, policymakers, and scientists current on the state of our chemical and radiative atmosphere

- **Signals may be subtle …**
  - Small systematic biases matter
  - Measurements must be precise, accurate, and consistent over decades
  - Tools to help detect problems soon after they develop (minimize data gaps)

- **Some questions require many, many more observations …**
  - GMD fosters close collaboration with partners
  - GMD plays a leading role in efforts to build defensible cooperative networks

Data Management and Quality Control

Also a long-term proposition …

Quality Control

- How well do our measurements compare with those from independent sources?
- Can we identify potential errors in our methodology to provide useful estimates of measurement uncertainty?
- What do our measurements represent? How are they influenced?

Data Management

- Does our system support **Consistency**, **Automation**, **Documentation**, **Exploration**, **Transparency**, **Preservation**, and **Distribution**?
- Do users have ready access to all data (good and bad)?
- Do we manage all appropriate data and metadata?

Managing information about measurements

Migrating to electronic logs to improve Transparency, Consistency, and Preservation

metadata

The Carpenter's Hammer

Services
- Near-real time Data Viewer
- Near-real time Data Distribution
- Central Calibration (Brad Hall)
- OutReach (tutorials, FAQs, movies)

Data Products
- GHG/Ozone Index (Steve Montzka)
- CarbonTracker (Andy Jacobson)
- ObsPack/GLOBALVIEW
- CO_2 Trends
- SURFRAD (John Augustine)
- BARROW Snowmelt

Data Distribution
- NOAA GMD FTP
- World Data Centers

Quality Control
- Calibration (Brad Hall)
- Rule-based Algorithms
- Complementary measurements
- Comparison Experiments

Exploration
- Interpretation
- Discovery

Data Access Tools → support many languages and empower researchers

Data and Information Management System

AERO DB System

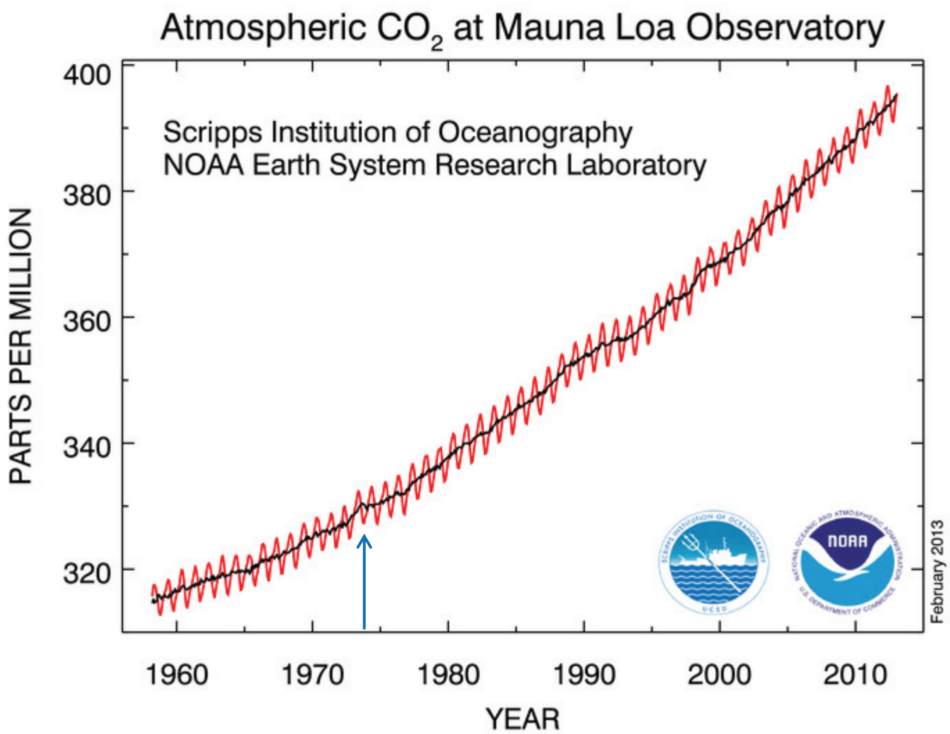
CCGG DB System

OBOP and OZWV (testing)
Used at ~20 national/international stations

INSTAAR and HATS measurements of CCGG samples
Shared with France, China, Brazil

The historic Mauna Loa CO_2 record

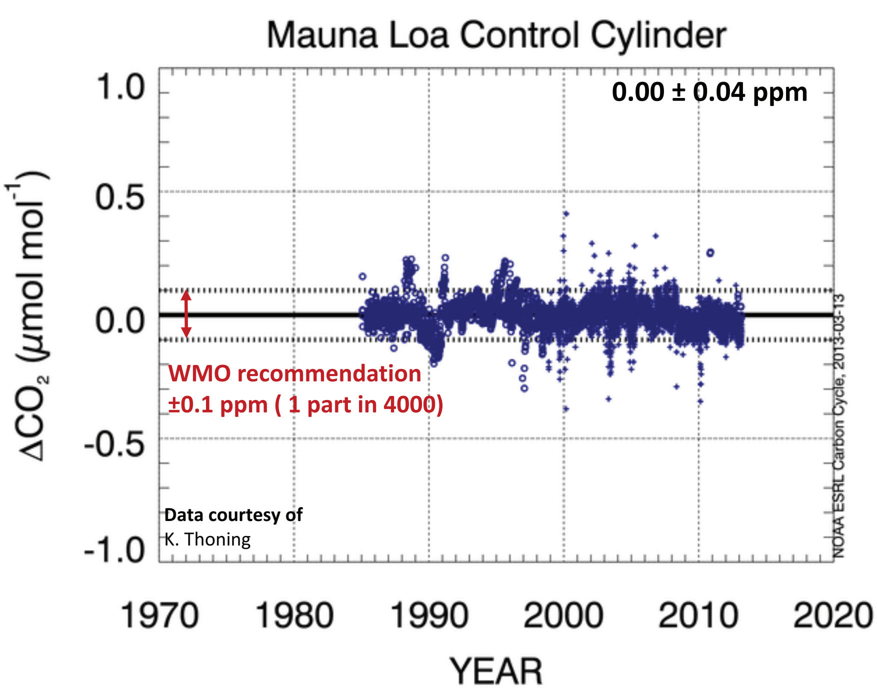
How do we assess the quality of this record?



parts per million (ppm) ≡ µmol mol^{-1}

Routine measurement of control cylinders

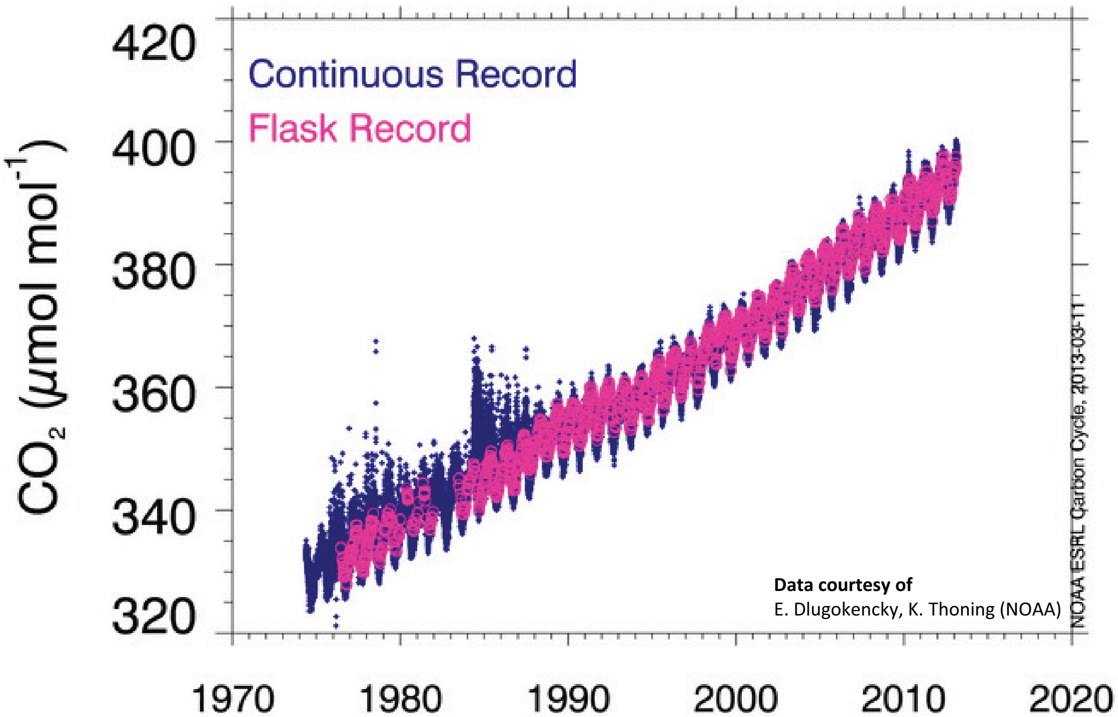
Propagation of laboratory scale and measurement reproducibility at Mauna Loa



parts per million (ppm) ≡ µmol mol^{-1}

Compare co-located measurements at Mauna Loa

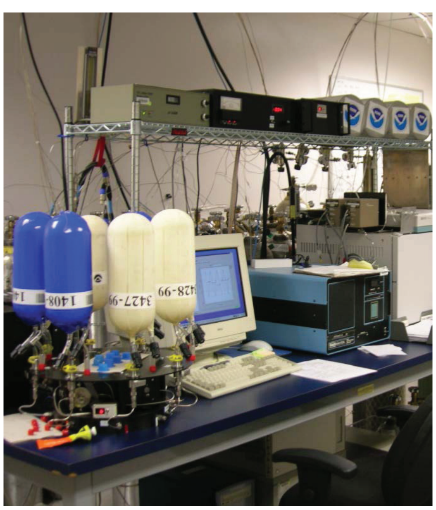
Before doing so, we first must estimate uncertainty in flask measurements

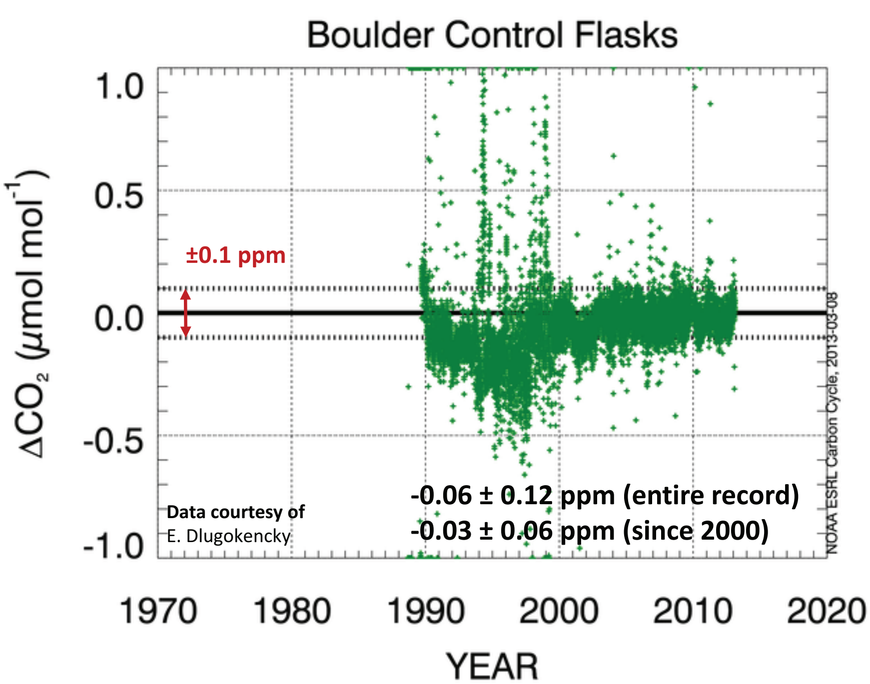


parts per million (ppm) ≡ µmol mol^{-1}

Analysis of air filled from a well-calibrated cylinder

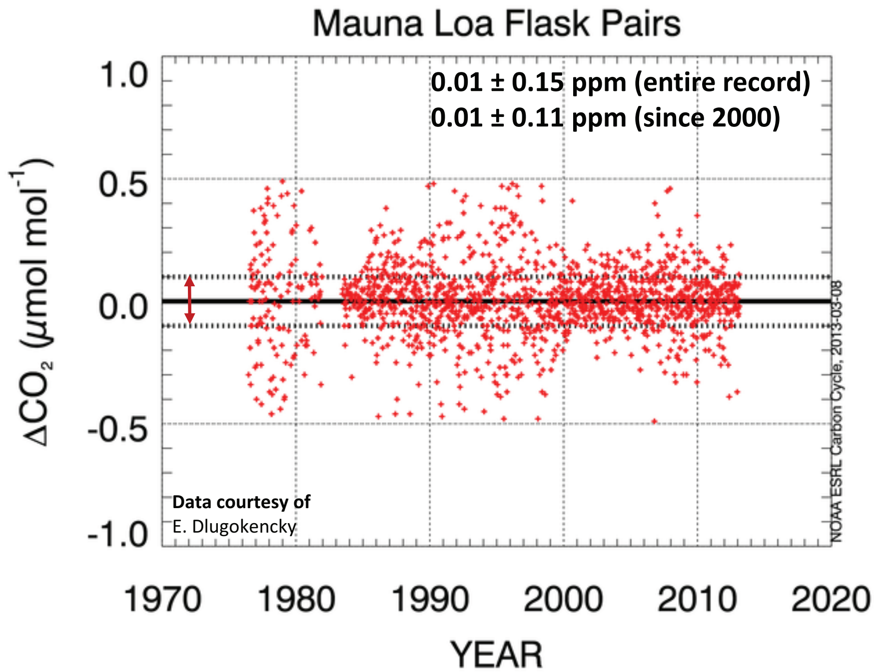
Propagation of laboratory scale and measurement reproducibility in Boulder





How well do we collect and store air in a glass flask?

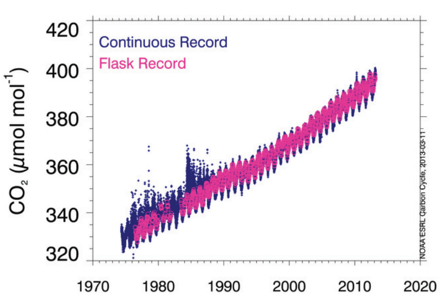
Routine comparison of flask pair measurements

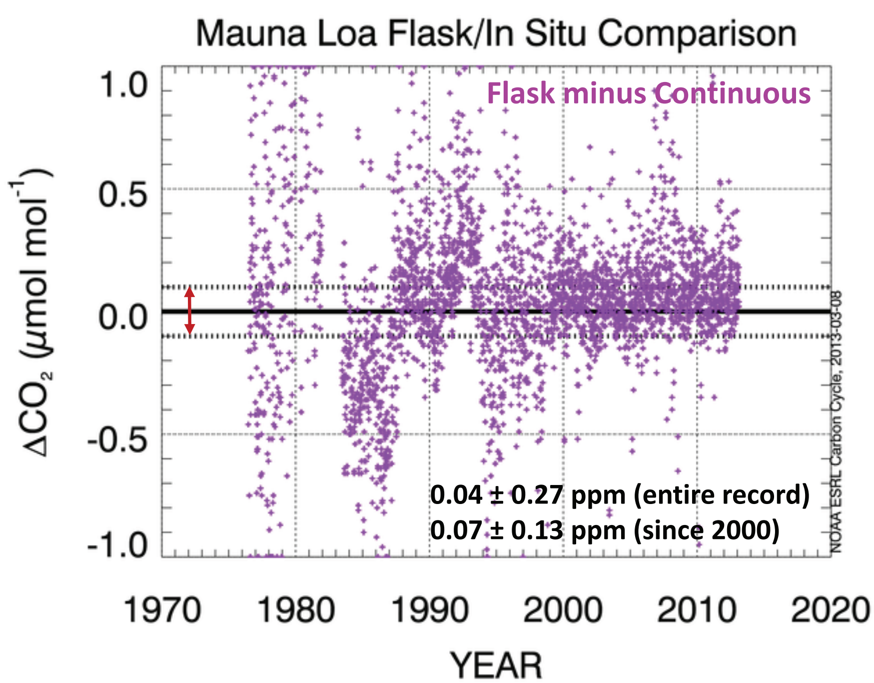


parts per million (ppm) ≡ µmol mol^{-1}

A realistic estimate of measurement uncertainty

Co-located GMD comparison at Mauna Loa



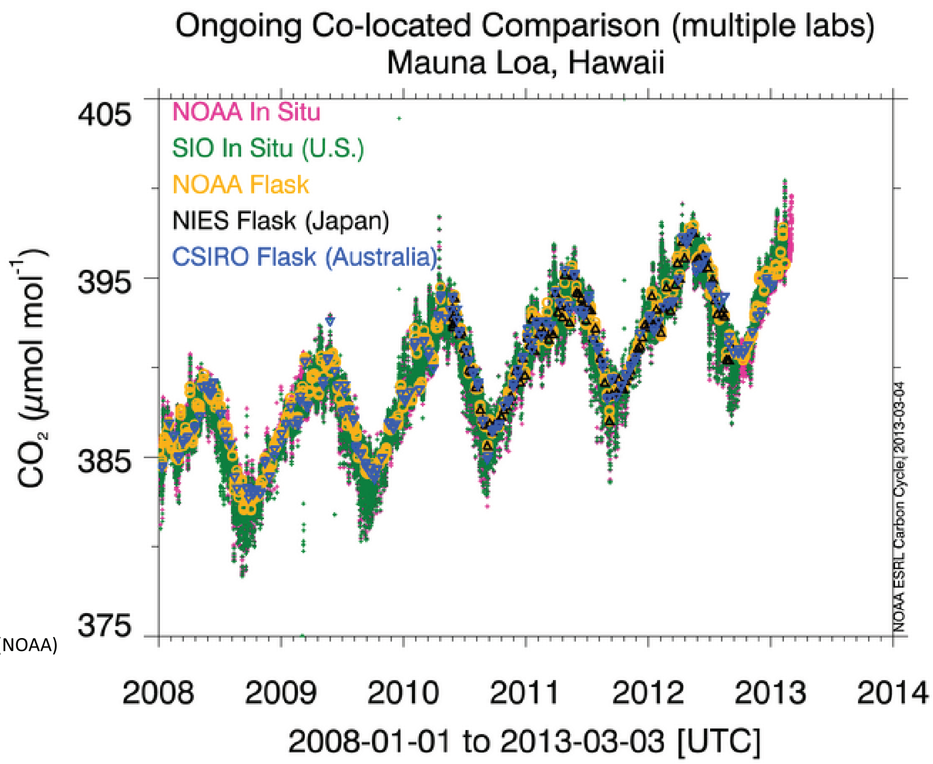


Data courtesy of
E. Dlugokencky, K. Thoning (NOAA)

parts per million (ppm) ≡ µmol mol^{-1}

Measurement compatibility between 4 laboratories

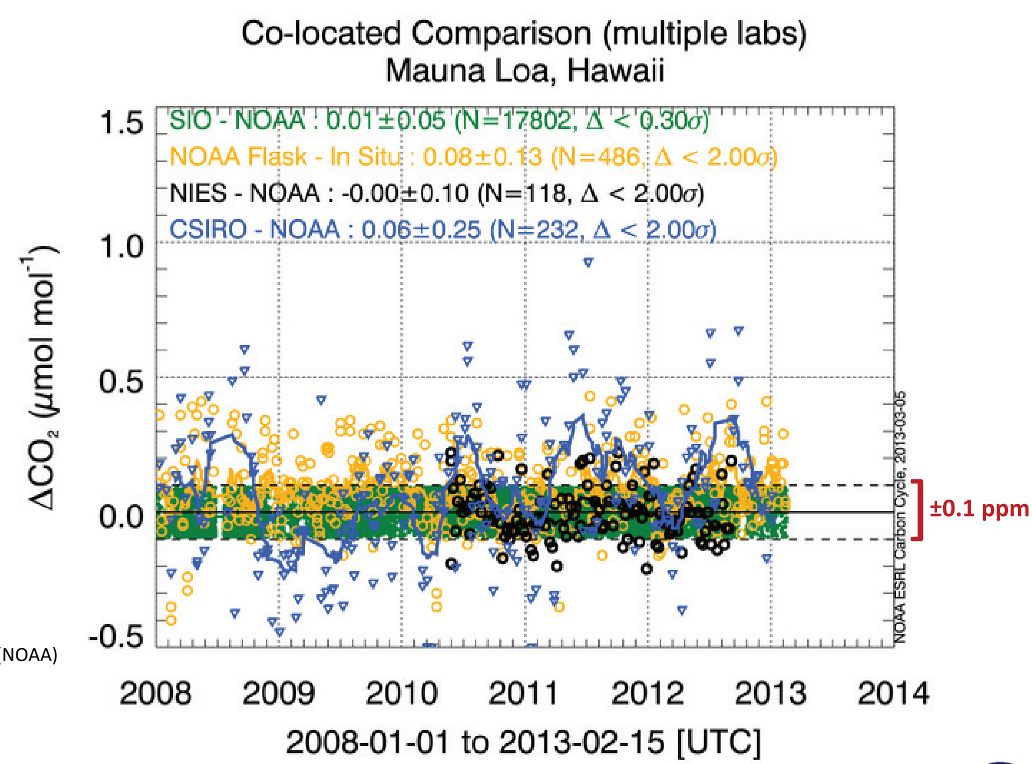
Multi-laboratory comparison at Mauna Loa



Data courtesy of
E. Dlugokencky, K. Thoning (NOAA)
R. Keeling (SIO)
H. Mukai (NIES)
P. Krummel (CSIRO)

A realistic estimate of uncertainty

Do parallel programs give comparable results?

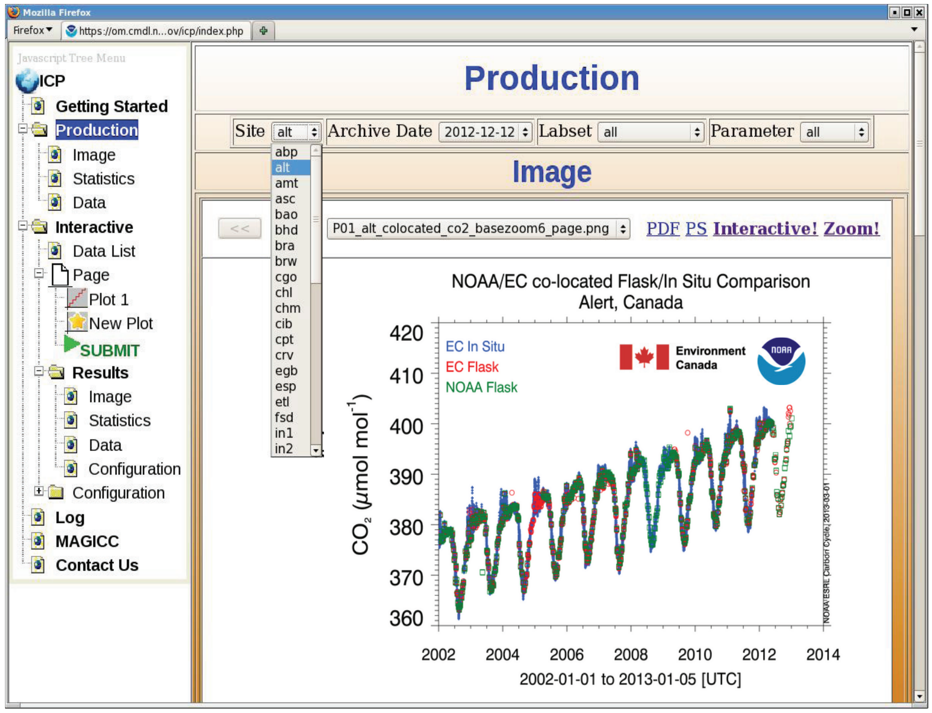


Data courtesy of
E. Dlugokencky, K. Thoning (NOAA)
R. Keeling (SIO)
H. Mukai (NIES)
P. Krummel (CSIRO)

Ongoing comparisons at 43 sites with 20 partners

Tools that improve our ability to detect problems soon after they develop

- Near real-time access
- Underlying database
- Automation
- Frequent comparison
- Anywhere access

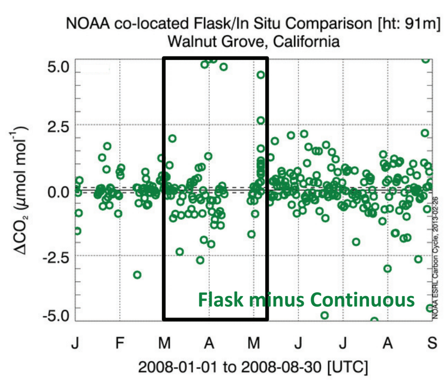


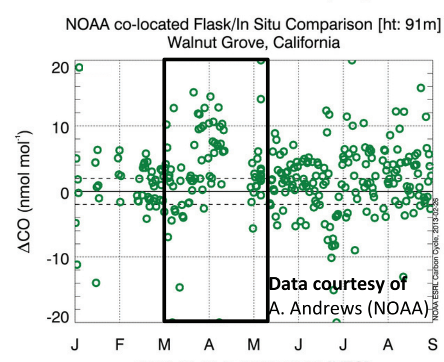
➢ This effort has improved the quality of our measurements as well as those of our partners

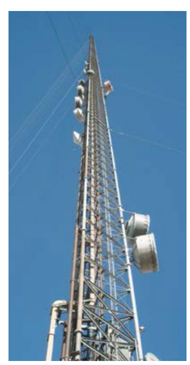
Note: Comparison results are informational ONLY !

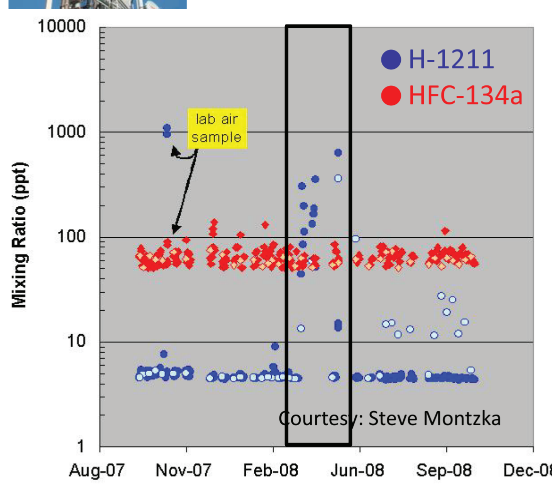
Automated and complementary comparisons

Detecting problems soon after they develop



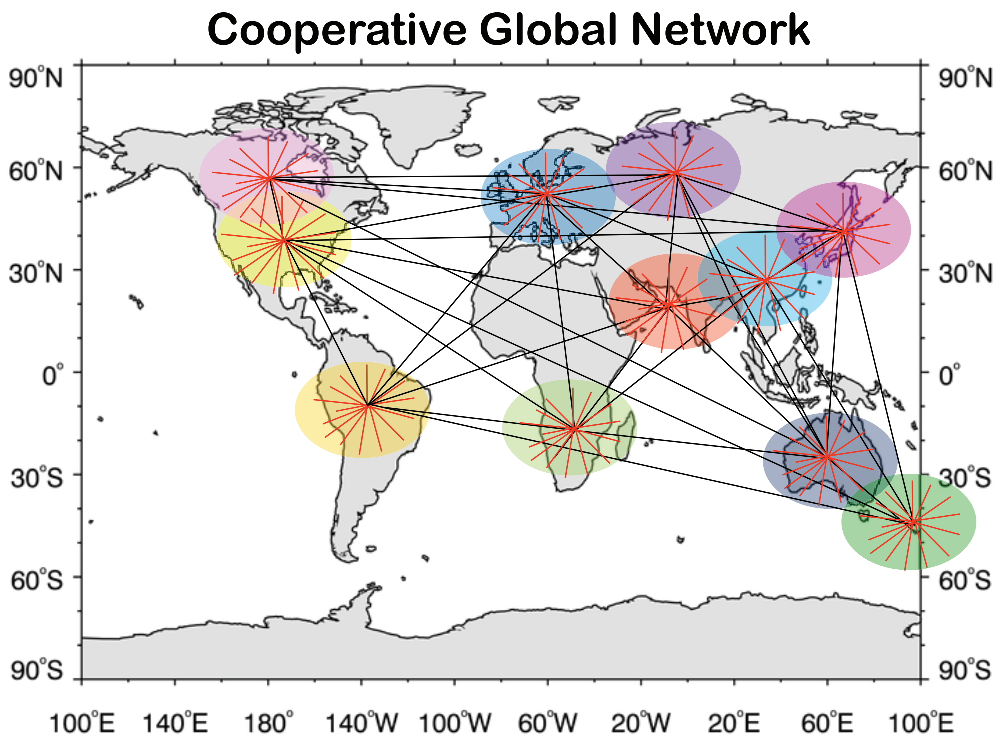






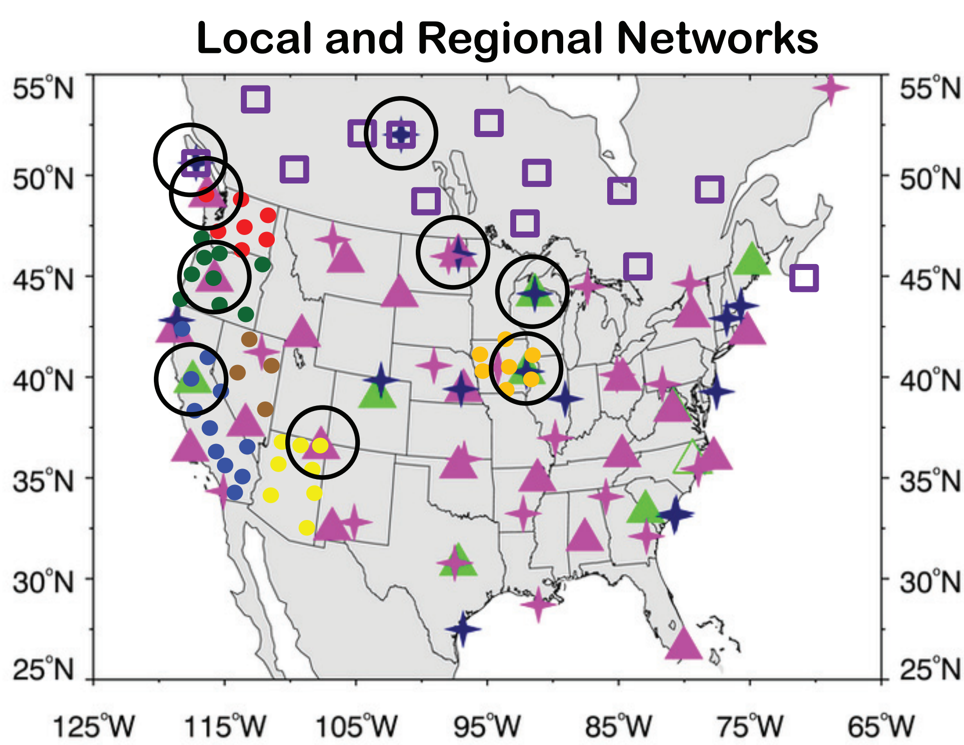
Some questions require many more observations

Conceptual Cooperative Global Network



Building a continental scale cooperative network

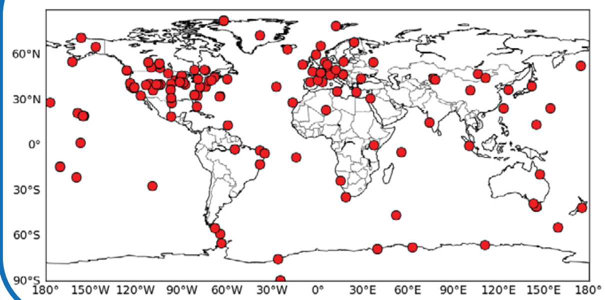
Conceptual Network



Creating defensible value-added data products

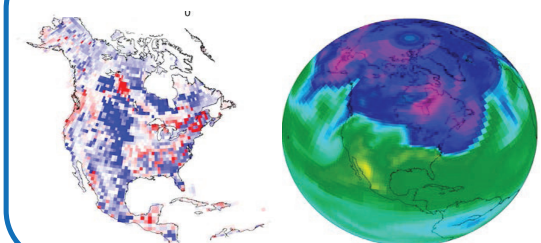
Using comparison results from independent measurements

ObsPack



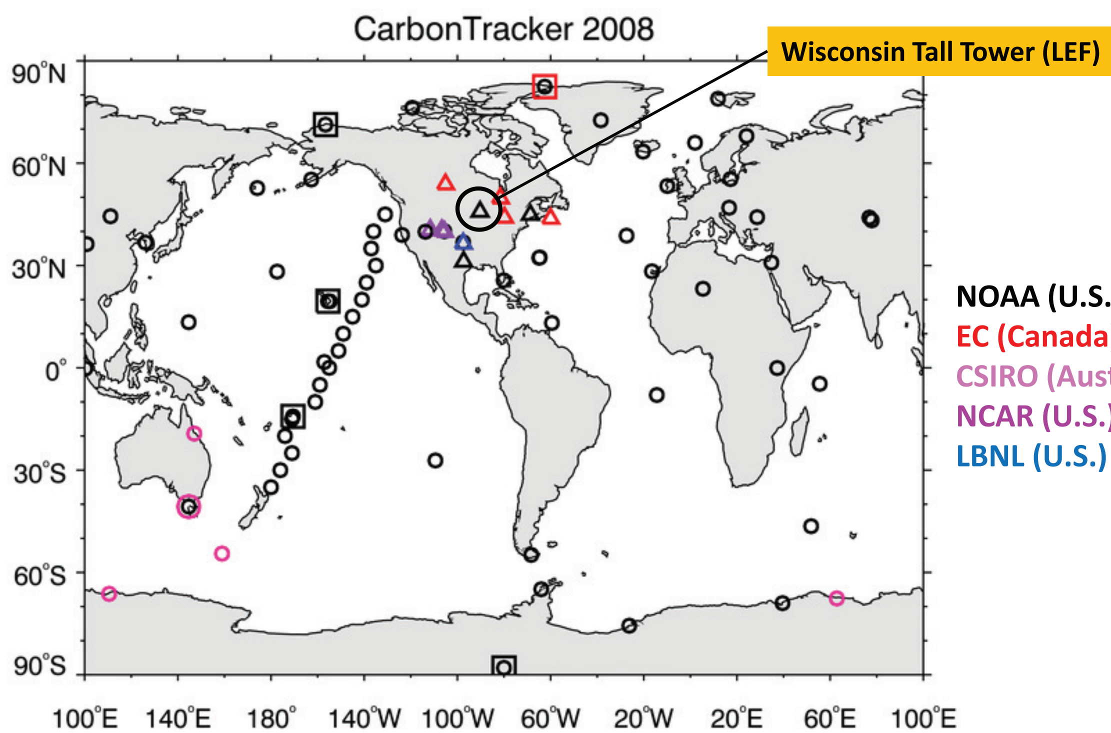
Australia
Brazil
Canada
Finland
France
Germany
Hungary
Japan
Netherlands
South Africa
Spain
Switzerland
United States

CarbonTracker



How sensitive is CarbonTracker to measurement bias?

Introduce constant measurement bias for one year at a single North American site

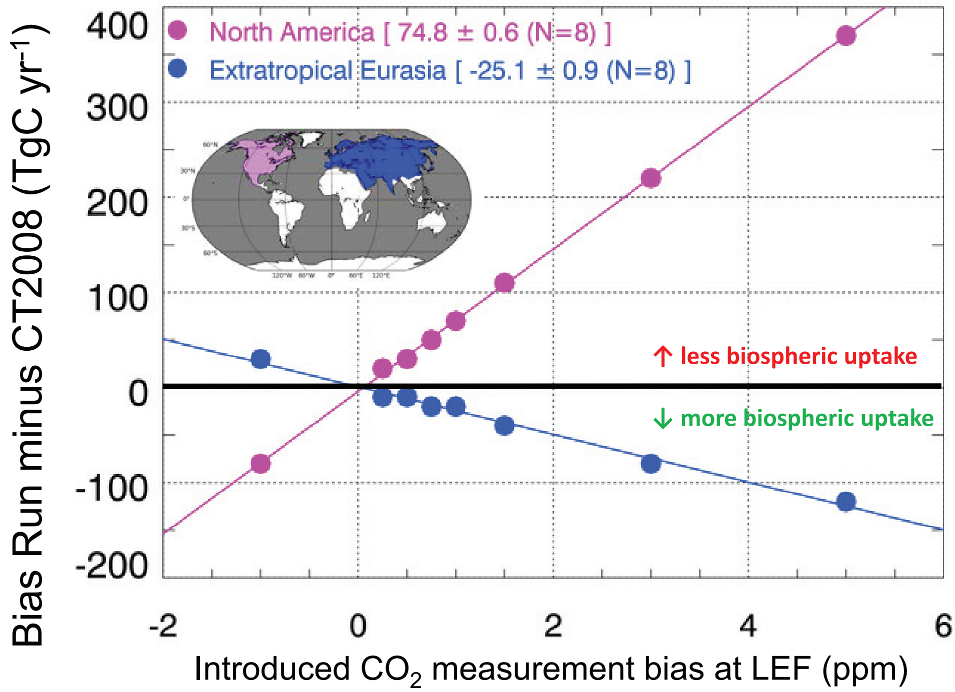


NOAA (U.S.)
EC (Canada)
CSIRO (Australia)
NCAR (U.S.)
LBNL (U.S.)

Masarie et al., 2011 (JGR, doi:10.1029/2011JD016270, 2011)

How does bias impact annual net CO_2 surface fluxes?

Introduced bias at a single site in North America impacts fluxes globally



Masarie et al., 2011 (JGR, doi:10.1029/2011JD016270, 2011)

Summary

- **Data and Information Management is GMD's "hammer"**
  - Supports consistency, automation, documentation, transparency, preservation
  - Facilitates quality control, interpretation, distribution, services, data products
  - Promotes exploration and evaluation
- **Quality Control processes address "How well are we doing?"**
  - Rule-based algorithms
  - Complementary measurements
  - Co-located Comparison Experiments
- **Comparison experiments are critical to our operations**
  - assess long-term measurement compatibility with partners
  - potential to detect experimental problems soon after they develop
  - provide honest estimates of measurement uncertainty
- **Comparison results help us to create defensible cooperative products**
  - e.g., ObsPack and GLOBALVIEW (not discussed)
  - Surface flux estimates using data assimilation systems **will** be challenged!