Integrated Global GHG Information System (IG³IS): Evidence Based Policy Support and Evaluation: Paris Agreement on Climate Change

Phil DeCola
Sigma Space
University of Maryland

Oksana Tarasova
WMO

James Butler
NOAA GMD

Kevin Gurney
Arizona State Univ.

Riley Duren, NASA JPL

Alistair Manning, UK Met Office

Stefan Reimann, Empa

and the IG³IS Team
International IG³IS Planning Team Members

Chair: Phil DeCola

Why do we have a UNFCCC?
Atmospheric GHGs – Primary Driver of Climate Change – But questions remain

- Atmospheric CO$_2$ continues to increase every year
  - The trend is largely driven by fossil fuel emissions

- Methane growth rate also significant but unknown variability
  - 80 times more forcing than CO$_2$

- The Earth System continues to capture 50% of emissions
  - Despite the increase in emissions
  - How long can we depend on this “benefit” and how will it change with time?

Can science-based, evidence-based information help to guide us along solution pathways?

“YOU CAN'T MANAGE WHAT YOU DON'T MEASURE.”
- W. Edward Deming

“to measure is to know – if you cannot measure it, you cannot improve it”
- Lord Kelvin
Paris Agreement and GHG Monitoring: Evolving from Top-Down versus Bottom-Up Paradigm

Then (2009)

Binding Multi-national Treaty Commitments

“we will verify your reported emissions”

A grand top-down GHG Information System

Advocates: Science Community!!!

Now (2016)

Nationally Determined Contributions

“we will help you improve your data”

Federation of focused monitoring systems

Advocates: WMO (191 countries), UNEP, Cities (eg, C40), NGOs, Industry (eg, Oil Companies)
**Figure 2**
Comparison of global emission levels in 2025 and 2030 resulting from the implementation of the intended nationally determined contributions and under other scenarios.
Conference of the Parties
Twenty-second session
Marrakech, 7–18 November 2016
Item X of the provisional agenda

Aggregate effect of the intended nationally determined contributions: an update
Figure 1
Types of mitigation target communicated in the intended nationally determined contributions

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute</td>
<td>32%</td>
</tr>
<tr>
<td>Business-as-usual</td>
<td>45%</td>
</tr>
<tr>
<td>Intensity target</td>
<td>4%</td>
</tr>
<tr>
<td>Peaking target</td>
<td>2%</td>
</tr>
<tr>
<td>Policy and actions</td>
<td>20%</td>
</tr>
<tr>
<td>Other</td>
<td>1%</td>
</tr>
</tbody>
</table>

Note: The percentages shown are percentages of the Parties that submitted an INDC by 4 April 2016.
GHG monitoring and reporting in 2010: atmospheric “top-down” and inventory “bottom-up”

Can atmospheric measurements and models “verify” inventories?
Paris Agreement and GHG Monitoring: Evolving from Top-Down versus Bottom-Up Paradigm

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  - Advocates: Science Community!!!

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- Nationally Determined Contributions
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  - Federation of focused monitoring systems
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Carbon trackers could help bolster climate vows
Projects lay groundwork for a global greenhouse monitoring system

By Warren Cornwall

In May, China’s statistical agency quietly raised estimates of how much coal the nation has burned since 2000. That little bit of bookkeeping had big implications. It amounted to as much as 900 million metric tons of additional carbon dioxide (CO₂) emitted annually in recent years, more than the total yearly emissions of Germany. It also underscored the challenge of knowing what many countries are really pumping into the atmosphere.

After negotiators left Paris last week with vows to curb the world’s climate pollution (see box, p. 1451), officials will want to know whether countries are living up to their promises. The Paris meeting addressed part of the puzzle: greenhouse gas accounting, including mechanisms for auditing emissions reports. But scientists are also in the early stages of deploying systems they hope could buttress international agreements by closely tracking greenhouse gas emissions in the air, rather than on paper.

Space-borne sensors are watching the ebb and flow of carbon around the globe, and a few experimental, city-scale monitoring systems are up and running. Ultimately, a network of instruments on satellites, commercial jets, smokestacks, and communications towers could deliver a detailed, nearly instantaneous picture of emissions in a country, city, or even a neighborhood: a global weather system for greenhouse gases.

“A carbon weather service is probably the best example of where we probably ought to get in the future,” says Riley Duren, an engineer at NASA’s Jet Propulsion Laboratory in Pasadena, California. He heads the Megacities Carbon Project, which is building a first-generation system in Los Angeles, California. The idea got a boost earlier this year when the United Nations World Meteorological Organization (WMO) endorsed the creation of the Integrated Global Greenhouse Gas Information System, to promote networks for tracking greenhouse gases.

Today, the clearest data on CO₂ are the atmospheric concentrations measured at more than 40 stations around the world. Emissions for countries or cities are estimated by adding up reams of statistics about fuel consumption, deforestation, electricity generation, and other activities.

Many developed countries have honed these inventories over years of practice under the Kyoto, Japan, climate treaty. But much less is known about emissions in the developing world, which today account for an estimated 60% of climate pollution. In October, the European Union’s earth observation agency, Copernicus, warned that such uncertainties “could undermine the credibility and the stability of future climate agreements.”

The projects now underway in the skies and on the ground could eventually help officials determine whether their neighbors are meeting their promises and whether their own strategies are producing results.

“Our goal is to say: ‘Your emission reduction policies seem to be consistent with what we see in the atmosphere, although it looks like your efforts in transportation are having a bigger impact than the energy sector,’” says James Whetstone, a scientist and manager at the National Institute of Standards and Technology in Gaithersburg, Maryland, which is helping fund several of the U.S. projects.

Los Angeles illustrates both the potential and the challenges. Today, 13 devices mounted high on tall buildings and cellphone and radio towers constantly measure CO₂ across an area of 17,000 square kilometers. Some also track methane, a potent heat-trapping gas. Atop nearby Mount Wilson, a device scans the basin every 90 minutes, detecting the gases’ infrared signature. Airplanes zero in on hot spots identified by the stationary instruments. NASA’s Orbiting Carbon Observatory-2 (OCO-2) satellite periodically surveys the city for a big-picture snapshot.

Carbon trackers could help bolster climate vows, however:

“...don’t want....another grand research strategy for the circular file of posterity,”

PARIS2015
JN CLIMATE CHANGE CONFERENCE
COP21·CMP11

Science 18 Dec 2015:
W Cornwall, Vol. 350, Issue 6267, pp. 1450-1451
DOI: 10.1126/science.350.6267.1450
The Role of the World Meteorological Organization (WMO)

- Ensure high quality, consistent, continuous GHG and other observations of atmospheric composition
- Develop high quality atmospheric transport and data inversion models
- Coordinate global atmospheric measurements; improve models and analysis
- Leverage capabilities across programs and nations
- Build capacity in developing nations
The patterns in observed surface concentrations are distinctly opposite to the daily variations of emissions fluxes from human activity.

Surface concentrations of CO$_2$ maximize at nighttime when the nocturnal PBL is shallow, but PBL height and rush hour emissions are increasing in the morning.

*Must understand atmospheric transport and dynamics to quantify emissions fluxes from atmospheric concentration measurements*
The IG$^3$IS Goals and Principles

**Goal:** Support the success of post-COP21 actions of nations, sub-national governments, and the private sector to reduce climate-disrupting GHG emissions through a sound-scientific, measurement-based approach that:

- reduces uncertainty of national emission inventory reporting,
- identifies large and additional emission reduction opportunities, and
- provides nations with timely and quantified guidance on progress towards their emission reduction strategies and pledges (e.g., NDCs)

**Principles**

- IG$^3$IS will serve as an international coordinating mechanism and establish and propagate consistent methods and standards.
- Diverse measurement and analysis approaches will fit within a common framework.
- Stakeholders are entrained from the beginning to ensure that information products meet user priorities and deliver on the foreseen value proposition.
- Success-criteria are that the information guides additional and valuable emission-reduction actions.
- IG$^3$IS must mature in concert with evolution of technology and user-needs / policy.
Near-term IG$^3$IS Objectives (3-5 year horizon)

Support of Paris Agreement:

- Timely and quantified trend assessment of NDCs in support of “Global Stocktaking”
- Improved national inventory reporting by making use of atmospheric measurements for all countries

Key sub-national efforts and new mitigation opportunities:

- GHG monitoring in large urban source areas (megacities)
- Detection and quantifying large unknown CH$_4$ emissions
An integrated multi-tool approach for national inventories -

Updates to the IPCC TFI 2006 IPCC guidelines

- IPCC guidelines/guidance provide broad international calculation methods:
  - Assists development of inventories that are transparent, documented, consistent over time, complete, comparable, assessed for uncertainties, subject to quality control and quality assurance, and efficient in the use of resources

- **Country-driven** multi-tool approach includes:
  - National QA/QC plans
  - Internal QC checks
  - Independent QA & review
  - Reporting, documentation & archiving
  - Verification through comparison with independent data sets & atmospheric measurements

- Planned 2019 Methodological Update to improve guidance for countries on a portfolio QA/QC & verification procedures
  - Establish link with WMO/IG3IS effort to make it easier for countries to use measurement & modeling information to improve inventory estimates
ISSUE Verification guidance is outdated (especially the guidance on comparisons with atmospheric measurements and new datasets are available)

Guidance to Authors
1) There is a need to discuss various ways to verify emission estimates in the context of the latest science with case examples:
   i) atmospheric concentration data;
   ii) independent monitoring of carbon stocks and fluxes: remote-sensing of activity data.

The refinement work should not be focused on developing detailed methods, but reference more detailed examples that have been published elsewhere. Also, other uses of these data should be discussed, for example, direct emission measurements to prepare better emission factors where other information is limited, describe circumstances where this is possible and the limitations (link to data collection chapter)

2). Guidance on the reporting of the use of such data. It was noted that there might be a need for some follow-up in the sectoral guidance about the use of atmospheric data and other data. Outline how this can be used to improve inventories. Examples. This will be advisory not mandatory. (Use IPCC workshop report on use of concentration data).
The main agenda items of the Forty-Fourth Session of the IPCC will be to consider the outline for the IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, and to consider the outline of the Methodology Report(s) to refine the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The Panel will also address other items that require consideration and decision by the Panel.
All Kyoto gases

- CO₂, CH₄, N₂O, SF₆

Except NF₃
Use the NAME transport model driven by 3-D meteorology to understand the recent (3-4 weeks) history of the air arriving at measurement stations

Two stage process:
- Estimate long-term Northern Hemisphere baseline concentrations using Mace Head observations.
- Estimate regional emissions through inversion modelling (InTEM).

Mace Head air history maps are generated for each 2-hour period between 1989 and 2015.
• Significant mismatch throughout the entire time-series of emissions, approximately inversion is 50% lower than inventory.

• Investigated the refrigeration model used by inventory compilers, key variables to be re-considered by DECC:
  • Refill rate
  • Uptake rate

Example from UK report to UNFCCC: HFC-134a
Example from UK report to UNFCCC: Methane

- Early (1990s) mismatch with the inventory.
- Difficult to understand, most likely cause is landfill emissions but retrospectively challenging to investigate.
- Inspired DECC to expand the network from 1 to 4 stations.
$^{14}\text{CO}_2 : ^{12}\text{CO}_2 \ (\Delta^{14}\text{C})$ is a robust tracer for fossil fuel fluxes: atmospheric $\Delta^{14}\text{C}$ looks just like fossil $\text{CO}_2$.

$\Delta^{14}\text{C}_{\text{ff}} = -1000$ per mil (i.e. zero $^{14}\text{C}$)

Scaling: $-2.7$ per mil $\Delta^{14}\text{C} = 1$ ppm CO$_2$-fossil

Predominantly fossil fuel, but includes small effects from ecosystems, oceans, nuclear power, cosmic rays

Includes only fossil fuel

Miller et al, 2012
$^{14}$CO$_2$ History

$\Delta^{14}C = \left[\frac{(14C/C)_{\text{sample}}}{(14C/C)_{\text{standard}}} - 1\right] \times 1000\%$,
Mount Wilson Observations of $^{14}$C and CO2

Nov – Feb (2011, 2012)
$<C_{bio}/C_{tot}> = 15\%$ (median)
Ultrasensitive radiocarbon detection

Radiocarbon is rare, forming no more than one part per trillion of the total carbon content of the atmosphere. An optical method allows radiocarbon to be detected at roughly 25-fold lower levels than this, opening up fresh avenues of research.

Richard N. Zare

Most isotope-ratio measurements are carried out using mass spectrometry, in which ions of carbon dioxide containing $^{12}$C and $^{13}$C, but the low concentration of $^{14}$C has made its measurement in carbon dioxide extremely difficult. Using an ultrasensitive technique called saturated-absorption cavity ring-down spectroscopy, Galli et al. have now succeeded in measuring the ratio of $^{14}$C to total carbon at values well below radiocarbon's natural abundance in carbon dioxide.

In their technique, the authors placed a gas sample between two or more highly reflecting mirrors that form an optical cavity. Infrared light that is incident on the cavity continually circulates within it, so that it takes many round trips. This effectively increases the optical path length of the light, allowing infrared absorption measurements of $^{14}$C.

Molecular Gas Sensing Below Parts Per Trillion: Radiocarbon-Dioxide Optical Detection

I. Galli, S. Bartalini, S. Borri, P. Cancio, D. Mazzotti, P. De Natale, and G. Giusfredi

Istituto Nazionale di Ottica-CNR (INO-CNR) and European Laboratory for Non-Linear Spectroscopy (LENS) Via N. Carrara 1, I-50019 Sesto Fiorentino, Italy

(Received 17 May 2011; published 30 December 2011)

Radiocarbon ($^{14}$C) concentrations at a 43 parts-per-quadrillion level are measured by using saturated-absorption cavity ringdown spectroscopy by exciting radiocarbon-dioxide ($^{14}$C$^{16}$O$_2$) molecules at the 4.5 $\mu$m wavelength. The ultimate sensitivity limits of molecular trace gas sensing are pushed down to attobar pressures using a comb-assisted absorption spectroscopy setup. Such a result represents the lowest pressure ever detected for a gas of simple molecules. The unique sensitivity, the wide dynamic range, the compactness, and the relatively low cost of this table-top setup open new perspectives for $^{14}$C-tracing applications, such as radiocarbon dating, biomedicine, or environmental and earth sciences. The detection of other very rare molecules can be pursued as well thanks to the wide and continuous mid-IR spectral coverage of the described setup.

DOI: 10.1103/PhysRevLett.107.270802

PACS numbers: 07.07.Df, 33.20.Ea, 42.62.Eh, 87.64.km
Optical Measurements of $^{14}$CO$_2$

- $^{14}$CO$_2$ transitions are shifted relative to $^{12}$CO$_2$
  - Allows for spectroscopic measurements of $^{14}$CO$_2$ in the mid-infrared
  - Natural abundance – 1.2 ppt of the total CO$_2$ (~400 ppm) in atmospheric samples

- Due to the ultralow abundance of $^{14}$CO$_2$ in atmospheric samples, optical detection at ambient levels has only been demonstrated by an Italian research group
- NIST has demonstrated preliminary optical detection of biogenic samples containing $^{14}$CO$_2$ using a significantly less complex benchtop optical method*
- Future efforts will investigate methods to reduce the detection limits of the ultra-sensitive CRDS system used in these measurements.

*AGU Annual Mtg. Presentation, 2015, D. A. Long
When the SLAC linac and microwave klystron were invented they were revolutionary developments.

Klystron invented 1937

Microwave linac invented 1948

“only” 3 feet long!

2 MV/m
Shortly after lasers were invented it was suggested to use them to accelerate particles.


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.
Can we do for particle accelerators what the microchip industry did for computers?

ENIAC, early computer

Micro-accelerator fabricated at Stanford

integrating circuit CPU

NLCTA accelerator at SLAC
First gradients observed were 10 times higher than the main SLAC linac...

IG³IS Objectives –
Develop for each objective

Near-term end-to-end demonstrations (3-5 year) and,

Methodology standards (long-term implementation plans)

Support of Paris Agreement:

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Key sub-national efforts and new mitigation opportunities:

- GHG monitoring in large urban source areas (megacities)
- Detection and quantifying large unknown CH$_4$ emissions
Carbon emissions from cities and their support systems represent the single largest human contribution to climate change.

The Megacity Project provides a strategy, methodology and roadmap for an international framework to assess directly the carbon emission trends of the world’s megacities.

http://megacities.jpl.nasa.gov
Relevance: cities matter

> 70% of global fossil-fuel CO$_2$ (about half of that from megacities)

Source: *Cities and Climate Change: an urgent agenda*, World Bank, 2010
Cities are demonstrating the political will for climate action and increasingly possess the needed economic strength.

A network of large cities from around the world committed to implementing meaningful and sustainable climate-related actions locally that will help address climate change globally.
Urgency: cities are changing rapidly

Both with Stabilization
- Green LA Plan (2007)
  - 35% (vs 1990) by 2030
- Paris Climate Plan (2007)
  - 25% (vs 2004) by 2020

and Growth
- Global urbanization will **double** by 2050
- Explosive growth in developing megacities
  - population >4%/year
  - emissions >10%/year
Pragmatic: monitoring cities is a tractable problem

\[ \text{CO}_2 \text{ at local (human) scales is more intense than at larger scales} \]

Right: Gridded annual fossil fuel CO2 emissions from a medium-size city (Indianapolis) show distinct gradients at different spatial scales. Right: CDIAC 2006 emissions for the CONUS plotted on a 1° (~100 km) show avg flux 200-600 gC/m2/yr. Middle: Vulcan 2002 emissions for the ~10,000 km2 area centered on Indianapolis on a 10 km grid. Left: Hestia 2002 emissions for the urban core on a 1 km grid. The Vulcan and Hestia plots use log-normal scales (typically >20,000 gC/m2/yr).
Multilevel observation and simulation design

Total Column Tomography
urban dome CH$_4$, CO$_2$, CO

Surface Network CH$_4$, CO$_2$, CO

Meteorology

Emission Inventories

Atmospheric model

Mini MPL

Northeast Corridor Urban Dome Sensor Network and Model Framework

Validated, Hi-Resolution Simulation tool for pollution, exposure

Urban Emissions CH$_4$, CO$_2$, CO from Metro Boston

Societal issues

Societal issues
WRF-STILT Urban GHG Modeling Approach

- STILT modeling: Lagrangian Particle Dispersion Model (LPDM)
  - Compute backward trajectories and influence regions ("footprints") for measurement sites (in units of ppb/(μmoles m^-2 s^-1))
  - Couple with background concentration and surface flux estimates for comparison with observations
- Weather Research and Forecasting Model (WRF) - nested domains down to 1.33 km grids
  - Initialize LPDM with winds, temperature moisture, surface pressure, and geopotential height
Airborne methane remote measurements reveal heavytail flux distribution in Four Corners region,

The Hestia Project: Quantifies all fossil fuel CO2 emissions at building and street scale.
Hot off of the presses:
Last week campaign in Los Angeles
GOSAT Observations Demonstrate Space-based Detection of Megacity XCO2

Selecting observations over LA & ‘Background’ Location

Persistent, robust enhancement = 3.2 ± 1.5 ppm
Near-term IG$^3$IS Objectives (3-5 year horizon)

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Methane from Oil and Gas Supply Chain
USA Texas (Barnett Shale) Example
Atmospheric composition plus enhanced bottom-up activity data

EDF COORDINATED CAMPAIGN

PRODUCTION
- NOAA/CU/Michigan Scientific Aviation/Penn State
- Purdue University

GATHERING/PROCESSING
- Picarro/Duke University

TRANSMISSION/STORAGE
- Sander Geophysics
- Princeton/University of Texas - Dallas
- West Virginia University
- Washington State University

LOCAL DISTRIBUTION

TRUCKS AND STATIONS
- UC Irvine/University of Cincinnati (Air Samples)
- Aerodyne
- University of Houston
A tiered strategy for monitoring methane leaks in the US

Tier 1: Satellite detects hotspot region

Tier 2 (Blue boxes): Aircraft spectrometers estimate local fluxes & attributes source sectors

Tier 3: Plume Imaging aircraft map point sources

Tier 4 (not shown): Surface observations

Enhanced Activity Data

Tier 2 (Blue boxes):

- Kern River oil field
- Taft dairies
- Elk Hills oil field

Tier 3:

- Bakerfield

Pixel size 1.5m
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How will Society know it is reducing Greenhouse Gas Emissions??

- Develop IG$^3$IS System
- Enhance IG$^3$IS System
- Maintain IG$^3$IS System
- Establish Baselines

Critical Period for detection of progress toward global emission reductions

Higher fidelity info to track and fine-tune progress

Percent of 2016 Emissions vs Time
Paris Agreement “Global Stocktaking”:
A combination of top-down and bottom-up methods can deliver higher-frequency, lower-latency assessments of national emission trends and with rigorously quantified uncertainties.
Analogous to the development of numerical weather prediction and its architecture of observations and models, IG³IS has a long-term vision for “GHG weather” analyses and forecasts.

The system incorporates multiple coordinated satellites in low Earth orbit (LEO) and geostationary orbit (GEO), aircraft, balloon, and ground observing systems in a true system of systems.
Future with geostationary sounders, low-Earth orbiting mapping systems and data assimilation
Conclusion

Build systems for future services that will meet society’s evolving needs to reduce GHG emissions:

- Define the detailed implementation plan
- Prepare statement of work and budgets
- Actively entrain partners, users, and sponsors through all stages of development
- Coordinate with UNFCCC, IPCC, GCOS, GFCS, GEO Carbon Flagship, WCRP and others.
BACK UP SLIDES
What if we start with no CO$_2$ difference and add a “typical” anthropogenic source …

In one hour (if no advection), the CO$_2$ difference is up to 20 ppm.

If, instead, the boundary layer depth is half …

Or, double …

Consider advection also

170,000 mol km$^{-2}$ hours$^{-1}$
PBL Depth of 400 meters
Los Angeles Megacity Monitoring: Mini MPL Mobile Study

1.63km from point A to point B
Los Angeles Megacity Monitoring: Mini MPL Mobile Study

400 meter PBL height change in only 1.6 km

Coastal stationary

Small Hill- Pacific Coast Highway

Julian Day

Topography
**The IG³IS Overarching Goals**

**Goal:** Support the success of post-COP21 actions of nations, sub-national governments, and the private sector to reduce climate-disrupting GHG emissions through a sound-scientific, measurement-based approach that:

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- provides nations with timely and quantified guidance on progress towards their emission reduction strategies and pledges (e.g., NDCs)
I. INTRODUCTION

Research on line broadening, though often regarded as pedestrian and unlikely to lead to new fundamental insights, is nonetheless inspired by a vision. One dreams that in a distant star or in some other inaccessible region filled with matter a few atoms, perhaps hydrogen atoms, emit lines whose structure can be analyzed in terrestrial laboratories. These lines carry in many cases information we have already learned to understand: red shifts revealing masses, Doppler shifts revealing motions, and sometimes Doppler widths revealing temperatures. It is clear that in principle all physical properties of the medium containing the radiating atoms are somehow reflected in the line structure, since they affect the forces between the radiating atom and its neighbors, the distances over which these forces are exerted, and the times during which they act. One hopes, therefore, that when the language of the spectral lines has been fully learned, a radiating atom in a distant material environment can serve as a noninterfering probe conveying significant data regarding pressure, temperature, or, more generally, the distribution of molecular speeds, and states of ionization in the surrounding medium. Such hope is now far from fulfillment, and this article attempts but a modest contribution to its realization.
ACS Symposium: Vibrational Spectroscopy
as a Probe of Biomolecular Structure and Dynamics

2007 ACS Symposium to honor the career of my Ph.D. Advisor
Prof. Robin Main Hochstrasser http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3677431/
Deliver data to characterize and quantify the “missing” terrestrial carbon sink

Mission strategy optimized to deliver accurate, global XCO2

Orbiting Carbon Observatory (OCO-2)
Observations of Reflected NIR Sunlight
Quantum mechanical details of the spectral lineshapes for CO\textsubscript{2} and O\textsubscript{2} to understand the macroscopic details of Earth’s carbon cycle

Physical chemists thought we knew everything about the spectra of diatomic molecules
Carbon Dioxide and the Global Carbon Cycle Science

- Human activities currently add ~10 Gt of carbon to the atmosphere each year.
- Less than half of this CO$_2$ stays in the atmosphere. The rest is absorbed by natural “sinks” at the Earth’s surface.
- Current measurement networks:
  - Can quantify the atmospheric CO$_2$ buildup on global scales.
  - Provide insufficient coverage and resolution to accurately quantify sources and sinks of CO$_2$.
- Fundamental questions:
  - Where is the missing sink? land / ocean.
  - Why does the sink strength vary dramatically from year to year?
  - Will the nature, location and strength of CO$_2$ sinks change in the future?

Annual fossil fuel emissions, the major anthropogenic CO$_2$ source, increase smoothly over time.

The accumulation rate of atmospheric CO$_2$ varies dramatically from year to year due to variation in the fundamental processes responsible for land and ocean sinks.