Integrating observations & inventories to improve emission estimates: a global framework for synthesis

“Leakage Issue” illustrated with estimated interregional fluxes of emissions embodied in trade (Mt CO2 y$^{-1}$) from dominant netexporting countries (blue) to the dominant net importing countries (red). Davis & Calderia, Consumption-based accounting of CO2 emissions, PNAS, 2010.

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Motivation & Scope

• Uncertainties carbon stocks and fluxes represent risks to the global economy and to policies intended to stabilize GHG emissions

• Risks could be mitigated by a global, sustained monitoring system offering actionable information on policy-relevant scales

• National Research Council (NRC) study: *Verifying GHG emissions: methods to support international climate agreements* (Pacala et al., 2010)
  – Strengthening national GHG inventories
  – Independently and *remotely* estimate national FF CO2 Emissions
  – Accurate estimates of national CO₂/CH₄/N₂O emissions & CO₂ removals/sinks from AFOLU¹ & independently check reported CO₂ emissions from forest changes

• So taking an end-to-end look at a possible integrated response...

¹Agriculture, Forestry, & Other Land Use
Complementary roles of inventories & observations

Independent Review

“MRV&V”

Verification of Specific Actions

National level reporting: Emission Inventories & audits

Validation of Overall Effects

Observationally-derived, spatially resolved data

Inter-comparison (consistency testing)

Improved constraints on models (diagnostic & prognostic)
Can we test emission inventories with top-down observational methods on regional scales?

Yes, for selected gases….

Europe CH$_4$ annual emission (2001), nested 1°x1°, 56 element surface network and TM5 transport model

Global CO annual emission (2004), 4°x5° using MOPITT, AIRS, & SCIAMACHY satellite observations & GEOS-Chem transport model

ratio between the observationally-derived and reported emissions (factor of 2+ difference in some regions)

Bergamaschi et al., Atmos. Chem. Phys., 2005

Kopacz et al., Atmos. Chem. Phys., 10, 855–876, 2010

….but 3 major challenges must be addressed to estimate the emissions of longer-lived GHGs (e.g., CO$_2$) for most countries
Challenge #1: large/poorly quantified flux uncertainties on regional scales
(but what’s a “regional scale” and an “acceptable” level of uncertainty?)

One definition of “regional scale”*: GHG fluxes at 100km resolution should resolve the emissions of most countries…

EU-25: 400 cells
Japan: ~ 40 cells

US & China: 900 cells each

LA county & Paris aire urbaine: 1 cell each

...including contributions from their EEZs (Coastal Oceans).

*clearly, “regional” becomes 1-10 km if evaluating emissions at local/city scales

source: EDGAR, 2007

source: SOCCR, 2007
“Acceptable” levels of flux uncertainty (for CO₂)?
(country-level detectability and 2σ emission uncertainty at 100km resolution, 2008)

And a caution – what’s the true uncertainty associated with models? (TRANSCOM)
Uncertainty quantification remains a challenge

1After Chevallier et al., 2007, GRL and Canadell et al., 2000, Ecosystems
Challenge #2: Scope (CO₂ & CH₄ example) useful comparisons of inventories & observations?

Atmospheric observations “see” TOTAL net emission (combination of all sources and sinks)

National Inventories “see” COVERED net emission (most, but not all, sources & sinks)


CH₄: Enteric Fermentation, Landfills, Natural Gas Systems, Coal Mining, Manure Management, Forest Land Remaining Forest Petroleum Systems, Wastewater Treatment, Stationary Combustion. Rice Cultivation. Abandoned Underground Coal Mines., and many others...

•Known exclusions (or, *included in IPCC guidelines but not universally reported):
  •CO₂ emissions from
    •Burning Coal Deposits & Waste Piles
    •Natural Gas Processing*
    •Shale Oil Production*
    •Industrial Waste Combustion*
    •CH₄ emissions from wetlands not affected by humans
    •Wetlands Creation or Destruction*
    •Petroleum Coke Production*

•Volcanic eruptions
•CO₂ exchange with oceans
•Natural forest fires*
•Unmanaged forests

•Unknown exclusions → ?

Observations can’t resolve all individual sectors – but can decouple the primary categories: FF, LUCF/AFOLU, & oceans (sources and sinks) and perhaps selected sources within each…..
Challenge #3: Source attribution (CO$_2$ & CH$_4$ example) how can we separate anthropogenic from natural activity?

Long-lived GHG flux products (CO$_2$, CH$_4$)

\[ F_{\text{net}} = \sum\{F_a(t), F_n(t)\} \]

Annual net emission \( F_{\text{net}} \)

**Anthropogenic Flux** \( F_a(t) \)

**Natural Flux** \( F_n(t) \)

- **Fossil Fuel Fluxes** \( F_{\text{ff}}(t) \)
- **Chemical Fluxes** \( F_{\text{c}}(t) \)
- **Biogenic Fluxes** \( F_{\text{bio}}(t) \)
- **Carbon Cycle Fluxes** \( F_{\text{cc}}(t) \)

**National inventories**

**Tracer flux products** \((^{14}\text{C}, \text{CO}, \text{NO}_2, \text{etc})\)

**Synthesis of a tiered set of observations** should help provide source attribution within the major categories (e.g., specific FF combustion processes, forest carbon & CH$_4$ (and perhaps N$_2$O) associated with selected agricultural and other land-use processes, etc)
Putting it all together: a **notional** synthesis framework

**Tracer gas Observations** (CO, $\Delta^{14}$C, NO$_2$, etc)

**Direct Land Flux Observations** (CO$_2$)

**Tracer gas Data assimilation**

**Tracer fluxes, uncertainties**

**Atmo Model(s)**

**GHG Observations** (CO$_2$, CH$_4$, N$_2$O, etc)

**GHG Data assimilation**

**Total fluxes, uncertainties**

**Attribution filtering**

**LULUCF Flux estimate**

**Fluxes (Total, FF, LULUCF & Ocean), uncertainties**

**Comparison & Reconciliation**

**Land & Ocean Source/Sink fluxes (priors)**

**Terrestrial carbon Model(s)**

**Ocean carbon Model(s)**

**Emission Factors**

**Biomass Upscaling (stocks/change)**

**Vegetation type, $\Delta$area, etc**

**LULUCF Models**

**FF Models**

**CEM**

**Surveys of Forests, soils, etc**

**Ecosystem structure**

**Ocean color, pCO$_2$, etc**

**VI, LAI, FPAR, fire, etc**

**Ocean color, pCO$_2$, etc**

**Ecosystem structure**

*comparison of multiple models is needed for cross-validation for each area (beyond internal consistency)*
Priorities for improvement
(to enable top-down/bottom-up reconciliation)

Synthesis framework
(GHGIS)

Best-effort non-NEI Inventory (IPCC TGU task)

Improvements in Atmo, Land, & Ocean flux estimation (GHGIS)

\[
S_{\text{NEI}} \leftrightarrow S'_{\text{NEI}} = S_{\text{atmo}} - S_{\text{terr}} - S_{\text{nonNEI}}
\]

Duren, Miller, DeCola 2010, GRL, submitted
Towards a global Greenhouse Gas Information System (GHGIS)

**Ancillary Data**
- Land/ocean surface T, P, winds, ocean salinity, etc

**Models**
- (Atmo transport & Ecosystem/Ocean/Fire/FF carbon)

**Synthesis System**
- (Data Assimilation, Uncertainty Quant, Top-down/bottom-up Reconciliation)

**Carbon/GHG Observing Systems**
- (space/air/land/ocean)
- Carbon/GHG Measurements
  - Atmospheric GHG data
  - Land carbon data (cover, biomass, soil)
  - Ocean carbon data

**Archive/Exchange System**
- GHGIS Data Products
  - Retrieved flux & stock maps
  - Attribution (tracer) maps
  - Original data sets
  - Calibrated/validated data sets
  - Metadata and uncertainties

**Decision Support System**
- GHGIS Analysis Products
  - Inventory reconciliation
  - Flux & Stock projections
  - Carbon-stock sensitivity functions

**GHGIS Analysis Products**
- Inventories
- Registries
- Energy Activity (lights, grid, etc)

**Analysts/Assessors**
- (Auditors, IPCC, Climate Services, etc)

**Decision/Policy Makers**

**Requirements**
- pre-decisional discussion material
Conclusions

1. Observations have the potential to complement inventories and improve emission estimates of country-level totals & major categories (FF, AFOLU, etc).

2. Current observational (& modeling) capabilities are significant & improving - but they were designed for scientific research, not decision support (not “operational”).

3. No single observational or modeling method can offer a reliable & practical way to test inventories: synthesis of tiered observations will be critical for attribution, for example:
   - Total fluxes of CO$_2$, CH$_4$, N$_2$O, etc over a range of spatial scales
   - Concurrent tracer fluxes ($^{14}$C, CO, NO$_2$, etc)
   - Improved constraints on terrestrial ecosystem & ocean fluxes

1. Challenges are formidable – but not insurmountable. Good potential for integrating observations and inventories – if a comprehensive and sustained effort is made to:
   - Reduce uncertainties on regional scales → measurement density & model improvements
   - Provide a common framework to compare inventories and observations
   - Avoid critical data gaps (satellites and sustain ground networks)
   - Continue/expand data availability and transparency

A dual-pronged approach might involve near-term pilot projects leveraging existing capabilities in parallel with a more strategic, optimal design effort.
End-to-End integration will be common to other climate services

Observations

Modeling & Analysis

Geophysical data, models

Climate Data Production & Exchange

Assessable Information

Integrated Assessment

Actionable Information

Stakeholders & decision makers

Greenhouse gases/carbon

Sea-level & ice

Freshwater

Ecosystems

Socio Economics

Natural Hazards
Backup material
Motivation & Scope

• Uncertainties in GHG & carbon data represent risks to the global economy and to policies intended to stabilize GHG emissions

• Risks could be mitigated by a global monitoring system that:
  – Supports independent assessment of policy compliance and efficacy
  – Quantifies baselines and tracks disturbances in terrestrial carbon stocks
  – Provides early-warning of abrupt GHG release events
  – Improves accuracy of GHG/carbon models (diagnostic & prognostic)

• National Research Council (NRC) study: *Verifying GHG emissions: methods to support international climate agreements (Pacala et al., 2010)*
  – Strengthening national GHG inventories
  – Independently and *remotely* estimate national FF CO2 Emissions
  – Accurate estimates of national CO$_2$/CH$_4$/N$_2$O emissions & CO$_2$ removals/sinks from AFOLU$^1$ & independently check reported CO$_2$ emissions from forest changes

$^1$Agriculture, Forestry, & Other Land Use
Where’s China?

FF emission trajectories after Marland, 2010
Terrestrial flux after Canadell et al., 2007
By “observations”, we mean observations + models (because we do not have perfect spatio-temporal sampling)

Generic inverse modeling approach for CO₂
Current observations of GHGs from the surface/air

**Concentrations → flux inversions**

**Carbon Tracker**
- NOAA
- AGAGE NASA & partners (from Switzerland, Italy, Norway, Japan, Korea, and China)
- TCCON NASA
- HIPPO NSF/NOAA
- MAMAP IUP/GFZ
- CAMS DOE

**Direct fluxes**
- FluxNet WMO, DOE, NSF, DOC, USDA, NASA
Current observations of GHGs from satellites

**Currently Operational Missions**

<table>
<thead>
<tr>
<th>Measurement Method</th>
<th>Instrument</th>
<th>CO₂ Measurement</th>
<th>CO₂ Product Precision*</th>
<th>Down-track Sampling</th>
<th>Other gases retrieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflected Sunlight</td>
<td>SCIAMACHY</td>
<td>Total Column</td>
<td>3-10 ppm</td>
<td>60 km</td>
<td>CH₄, N₂O, CO, O₃, NO₂, H₂O, SO₂, others</td>
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<tr>
<td></td>
<td>GOSAT/IBUKI</td>
<td>Total Column</td>
<td>4 ppm</td>
<td>10.5 km</td>
<td>CH₄, O₃, O₅, H₂O</td>
</tr>
<tr>
<td>Thermal Emission</td>
<td>AIRS</td>
<td>Mid-Trop</td>
<td>1 – 2 ppm</td>
<td>45 km</td>
<td>CH₄, CO, O₃, H₂O, SO₂</td>
</tr>
<tr>
<td></td>
<td>IASI-A</td>
<td>Mid-Trop</td>
<td>2 ppm</td>
<td>100 km</td>
<td>CH₄, N₂O, CO, O₃, H₂O, others</td>
</tr>
<tr>
<td></td>
<td>TES</td>
<td>Mid-Trop</td>
<td>~5 ppm</td>
<td>~50 km</td>
<td>CH₄, N₂O, CO, O₃, H₂O, HNO₃</td>
</tr>
</tbody>
</table>

*CO₂ products often have different precision and spatial scale than for individual samples

**Source:** Chahine et al., 2008

**Source:** Buchwitz et al., 2007

Current satellite & surface observations of other gases: “concurrent tracers” could help source attribution for combustion activity

XCO₂/XCO Correlation Coefficients - GEOS-Chem model

Observations from OMI satellite show 50% reduction in NO₂ in Beijing following strict traffic restrictions in preparation for the Olympic games.

January: strong correlation (+1.0) between CO₂ and CO due to the predominance of the FF combustion signal; July: CO₂ and CO are almost perfectly anti-correlated (-1.0) since biological activity dominates the CO₂ signal while CO is still due to FF combustion.

Δ¹⁴CO₂ surface observations & models as FF tracers (&/or to "calibrate" CO)
Examples of current observations of land/ocean carbon

**Surface-based &/or fusion with satellite data**
- Forest & Soil Carbon inventories (FIA & NRI) *USDA*
- Ocean color/photosynthetic activity: MODIS
- Ecosystem Structure/biomass: ALOS PALSAR
- Forest Biomass from satellite imaging & airborne lidar *Carnegie*

**Satellites**
- Vegetation greenness, health and productivity: Landsat-7, MODIS, AVHRR, EO-1
- Deforestation (Landsat) *Source: NASA/USGS/UMD*
- Global Biosphere Productivity (MODIS/SeaWIFS) *Source: NASA*
The Future (planned): some highlights of GHG observations

**Orbiting Carbon Observatory (OCO)**

**Planned Missions 2013-2010**

<table>
<thead>
<tr>
<th>Measurement Method</th>
<th>Instrument</th>
<th>CO₂ Measurement</th>
<th>CO₂ Product Precision*</th>
<th>Down-track Sampling</th>
<th>Other gases retrieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflected Sunlight</td>
<td>OCO-2</td>
<td>Total Column</td>
<td>1 ppm</td>
<td>2.3 km</td>
<td>O₂</td>
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<td></td>
<td>pre-Sentinel-5</td>
<td>Total Column</td>
<td>tbd</td>
<td>10km</td>
<td>CH₄, CO, O₃, NO₂, SO₂</td>
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<tr>
<td></td>
<td>Sentinel-5</td>
<td>Total Column</td>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
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<tr>
<td>Thermal Emission</td>
<td>IASI-B</td>
<td>Mid-Trop</td>
<td>2 ppm</td>
<td>100 km</td>
<td>CH₄, N₂O, CO, O₃, H₂O, others</td>
</tr>
<tr>
<td></td>
<td>IASI-C</td>
<td>Mid-Trop</td>
<td>2 ppm</td>
<td>100 km</td>
<td>CH₄, N₂O, CO, O₃, H₂O, others</td>
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<tr>
<td></td>
<td>JPSS CrIS</td>
<td>Mid-Trop</td>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
</tr>
<tr>
<td>Active (LIDAR)</td>
<td>ASCOPE</td>
<td>Lower-trop</td>
<td>2 – 4 ppm</td>
<td>~100 km</td>
<td>CO</td>
</tr>
<tr>
<td></td>
<td>ASCENDS</td>
<td>Lower-trop</td>
<td>2 – 4 ppm</td>
<td>~100 km</td>
<td>CO</td>
</tr>
</tbody>
</table>

*CO₂ products often have different precision and spatial scale than for individual samples

**Integrated Carbon Observation System (ICOS)**

Will integrate existing & new observations in Europe with a common data system

**NOAA Aircore (GHG vertical profiles)**

Source: Tans, 2010

**DOE CAMS**

increase in 14C throughput

OCO animation http://www.nasa.gov/mission_pages/oco/multimedia

Source: Ciais et al., 2009
The Future (planned): highlights of Land/ocean carbon observations

Vegetation greenness, health and productivity: HyspIRI, LDCM, JPSS (VIIRS), Sentinel-2

Ocean color/photosynthetic activity: GEOCAPE

Freeze-Thaw, Land Photosynthetic activity: SMAP

Ecosystem Structure & Biomass: DESDynl, ICESAT-2, Sentinel-1, BIOMASS

Boreal land-atmosphere CO2 exchange (NEE) derived from SMAP & MODIS

Mapping project-level biomass through synthesis of satellite/aircraft observations, field surveys, & models

ACTIVE sensors


Source: S. Saatchi, R. Houghton. et al 2007

Source: S. Saatchi, R. Houghton. et al 2007

Terminology

- AFOLU: Agriculture, Forestry, and Other Land Use
- AIRS: Atmospheric Infrared Sounder (NASA)
- ALOS: Advanced Land Observation Satellite (JAXA)
- AGAGE: Advanced Global Atmospheric Gases Experiment (NASA)
- ASCENDS: Active Sensing of CO2 Emissions over Nights, Days, and Seasons (NASA)
- CAMS: Center for Accelerator Mass Spectrometry (DOE LLNL)
- ESA: European Space Agency
- FF: Fossil Fuels
- FIA: Forest Inventory & Analysis (USDA)
- GAW: Global Atmosphere Watch (WMO)
- GEO: Group on Earth Observations (international consortium)
- GOSAT: Greenhouse gases Observing Satellite aka Ibuki (JAXA)
- IASI: Infrared Atmospheric Sounding Interferometer (ESA)
- ICOS: Integrated Carbon Observing System (EU)
- IUP/GFZ: Institute of Environmental Physics/Bremen & Geoforschungszentrum Potsdam
- JPSS: Joint Polar Satellite System (NASA/NOAA – formerly NPOESS/NPP)
- LDCM: Landsat Data Continuity Mission (NASA/USGS)
- LULUCF: Land Use, Land Use Change, & Forestry
- MODIS: Moderate Resolution imaging Spectrometer (NASA)
- NRI: National Resource Inventory (USDA)
- OCO: Orbiting Carbon Observatory (NASA)
- SCIAMACHY: SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (ESA)
- TCCON: Total Carbon Column Observing Network (NASA)
- TES: Thermal Emission Spectrometer (NASA)
- VIIRS: Visible Infrared Imager Radiometer Suite (NOAA)
- WMO: World Meteorological Organization (UN)
Observations are necessary but not sufficient
(other attributes of a robust monitoring system)

• Driven by Policy Needs
  – Must support timely decision-making & mitigation/adaptation assessment
  – Convert data to policy-relevant information on appropriate spatio-temporal scales

• Actionable Products
  – Must distinguish anthropogenic from natural background
  – Carbon forecasts (prognostics as well as diagnostics)

• Global Coverage
  – Detect “leakage”
  – No denied territory
  – Carbon stocks and flows in terrestrial biosphere & ocean (not just atmosphere)

• Transparent, Unassailable, & Objective
  – Traceability and public availability of data, models, & products
  – Relentless attention to bias/errors (regular calibration & validation)

• Sustained, Flexible, & Scalable
  – Initially measure CO₂, followed by CH₄ & other Kyoto gases
  – Learn (iterate) as we go
  – Continued operation over decades

Source: GHG Information System collaboration between DOE labs, NASA centers, NOAA and series of interagency workshops and meetings involving ~30 organizations