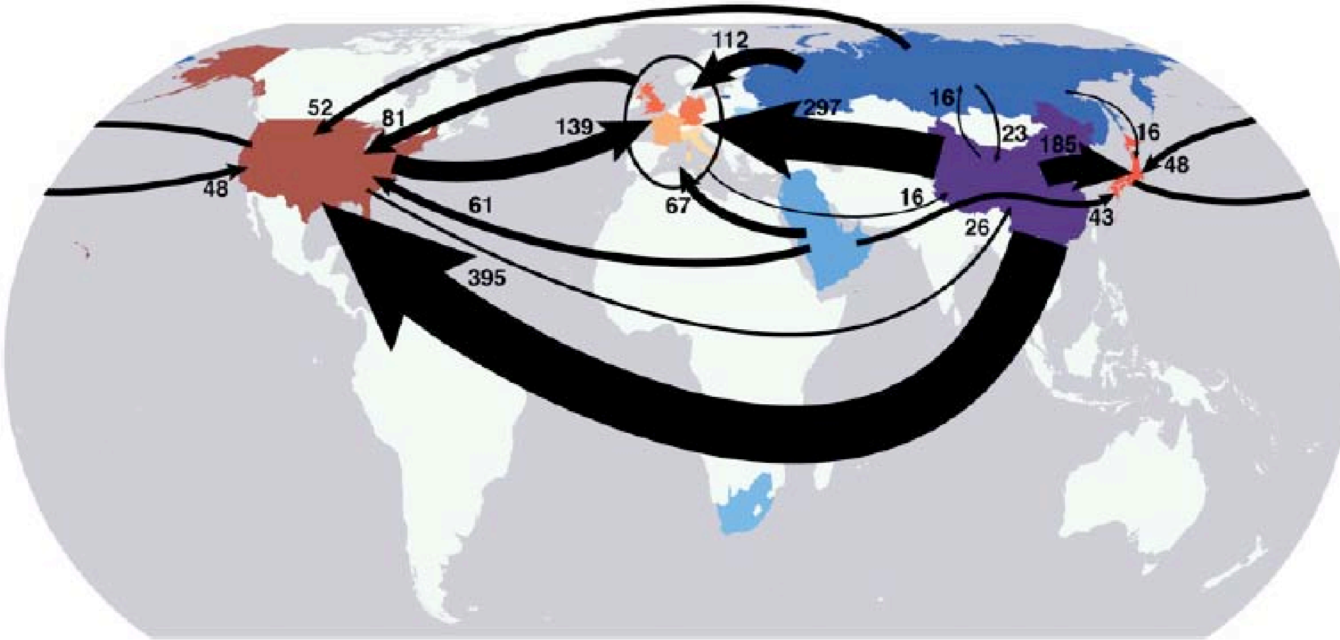
Integrating observations & inventories to improve emission estimates: a global framework for synthesis



"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.

Riley Duren

Jet Propulsion Laboratory

California Institute of Technology

With thanks to many collaborators at NASA, NOAA, DOE labs, EPA, OSTP and the GHGIS, NASA CMS, & ICOS teams

Motivation & Scope

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

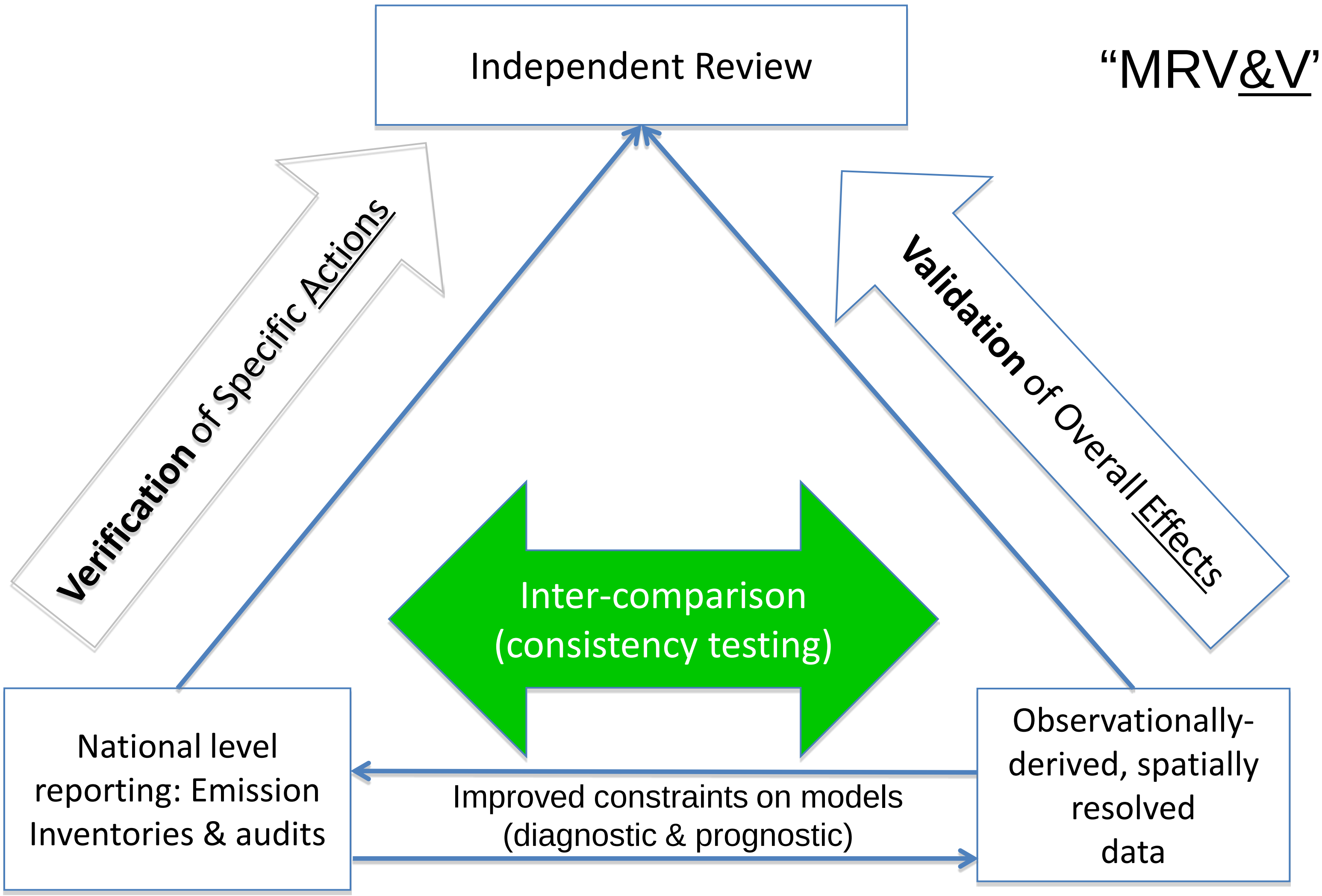
- Risks could be mitigated by a global, sustained monitoring system offering actionable information on policy-relevant scales

- 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 CO_2/CH_4/N_2O emissions & CO_2 removals/sinks from AFOLU[1] & independently check reported CO_2 emissions from forest changes

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

[1]Agriculture, Forestry, & Other Land Use

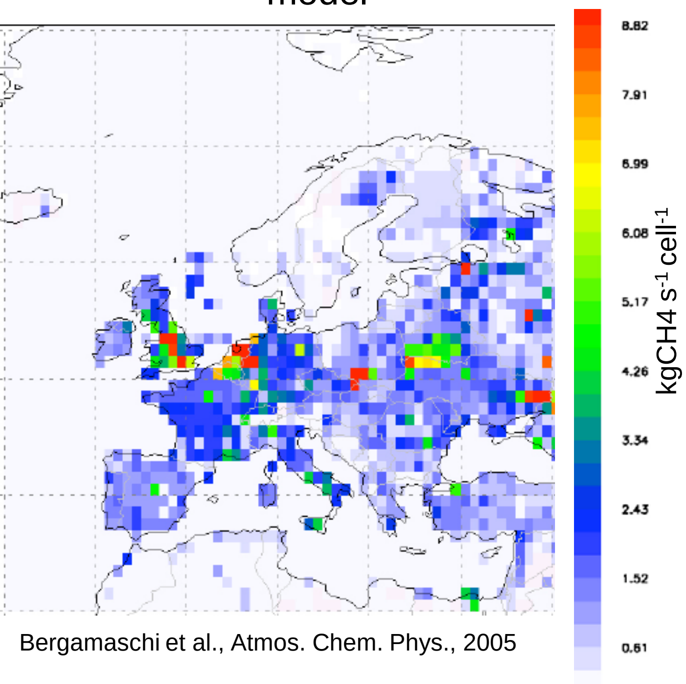
Complementary roles of inventories & observations



Can we test emission inventories with top-down observational methods on regional scales?

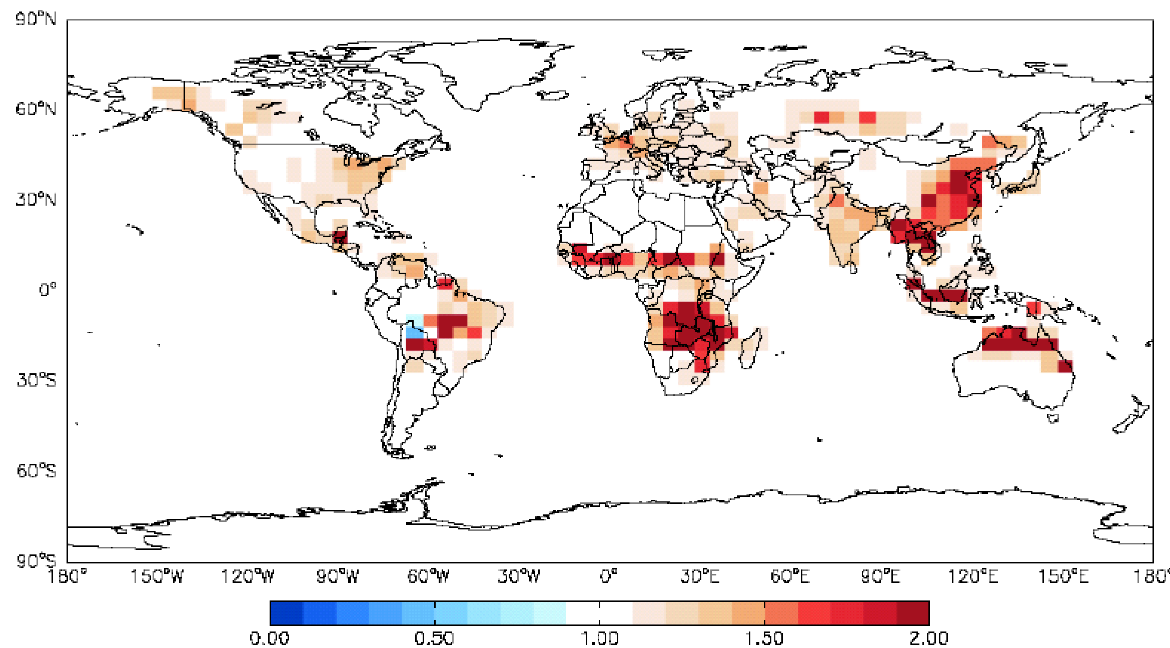
Yes, for selected gases….

Europe CH_4 annual emission (2001), nested 1°x1°, 56 element surface network and TM5 transport model



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

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)

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

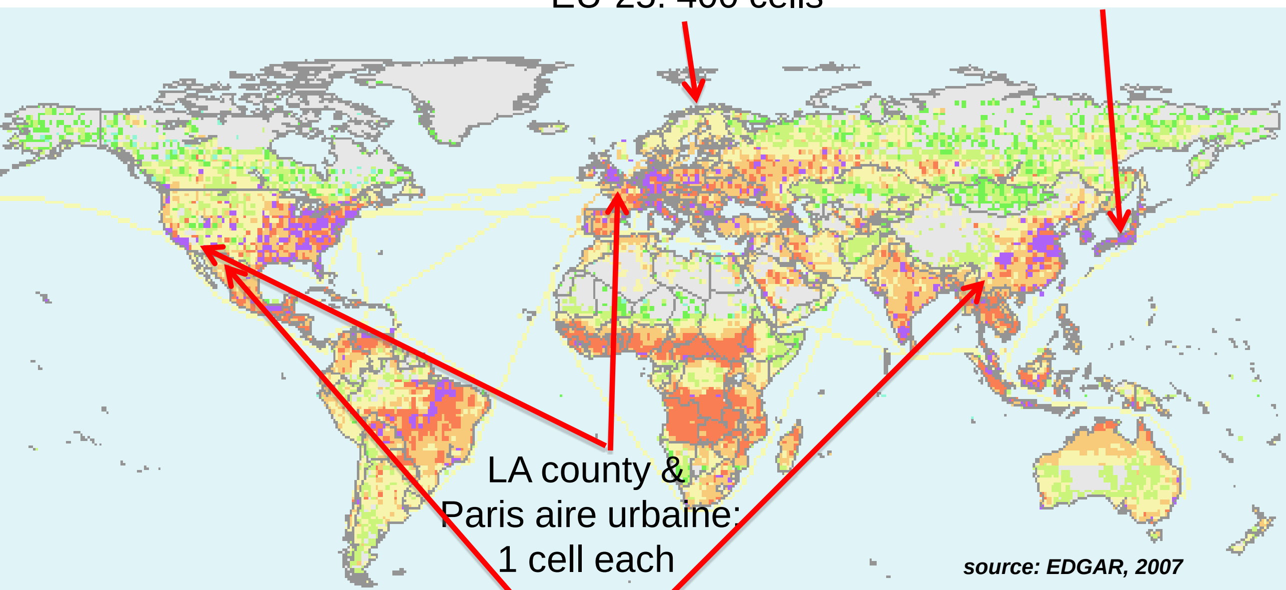
Challenge #1: large/poorly quantified flux uncertainties on regional scales

(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…

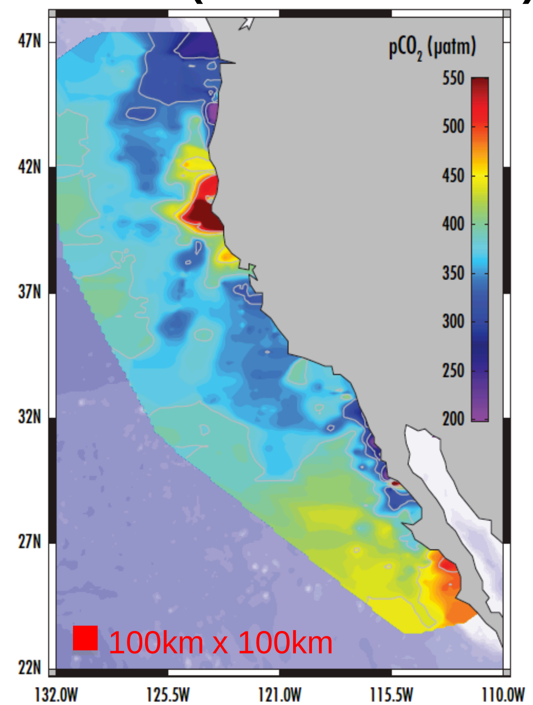
EU-25: 400 cells

Japan: ~ 40 cells



US & China: 900 cells each

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

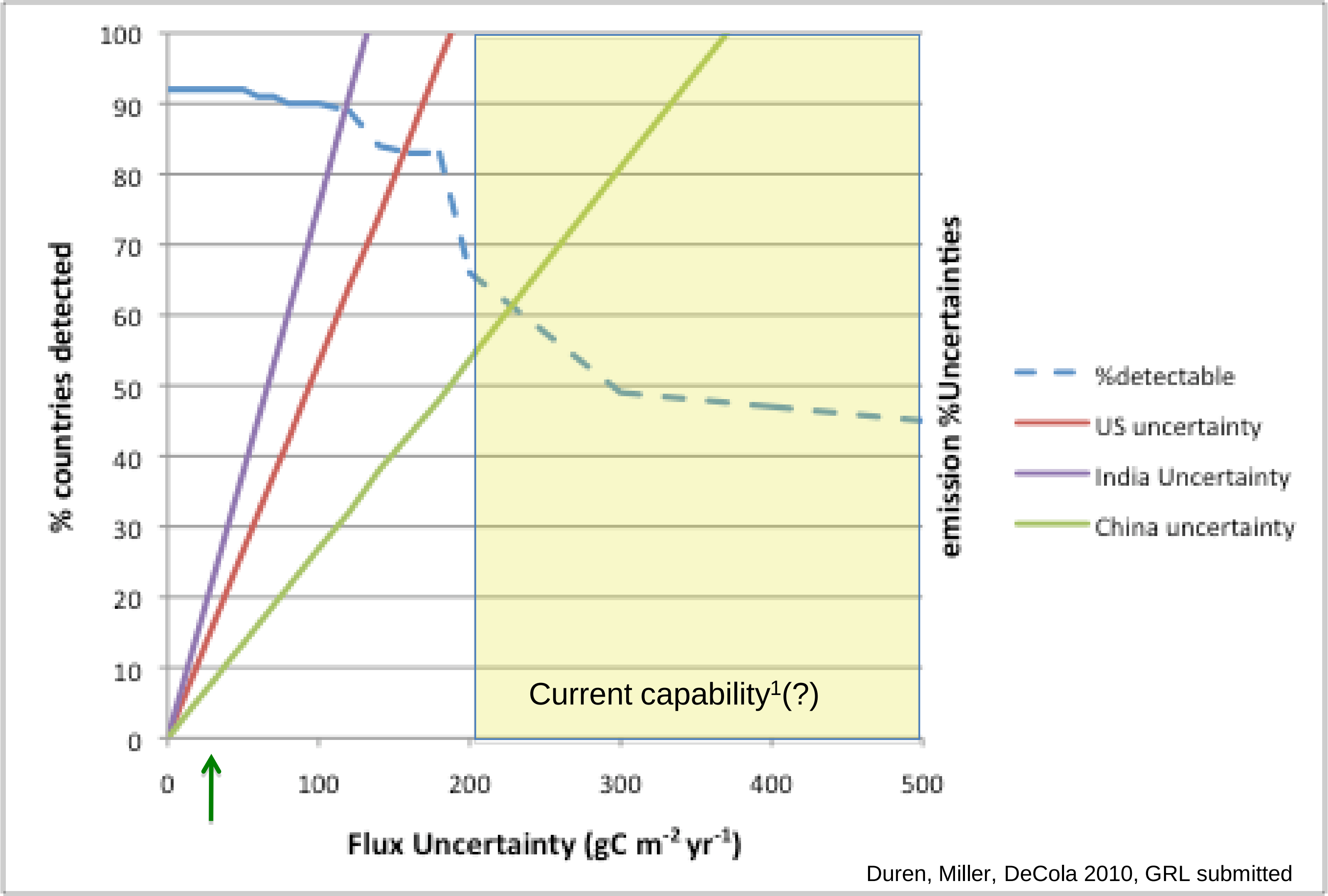


source: SOCCR, 2007

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

"Acceptable" levels of flux uncertainty (for CO_2)?

(country-level detectability and 2σ emission uncertainty at 100km resolution, 2008)



[1]After Chevallier et al., 2007, GRL and Canadell et al., 2000, Ecosystems

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

Challenge #2: Scope (CO_2 & CH_4 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)

CO_2: Electricity Generation, Transportation, Industrial, Residential, Commercial. Non-Energy Use of Fuels, Iron and Steel Production & Metallurgical Coke Production, Cement Production, Natural Gas Systems, Incineration of Waste, Lime Production, Ammonia Production and Urea Consumption. Cropland. Limestone and Dolomite Use. Aluminum Production, Wetlands. Zinc Production. Petroleum Systems, Lead Production, Silicon Carbide Production and Consumption . *Land-Use Change, and Forestry (Sink), Biomass—Wood, Biomass – Ethanol,* **and many others…**

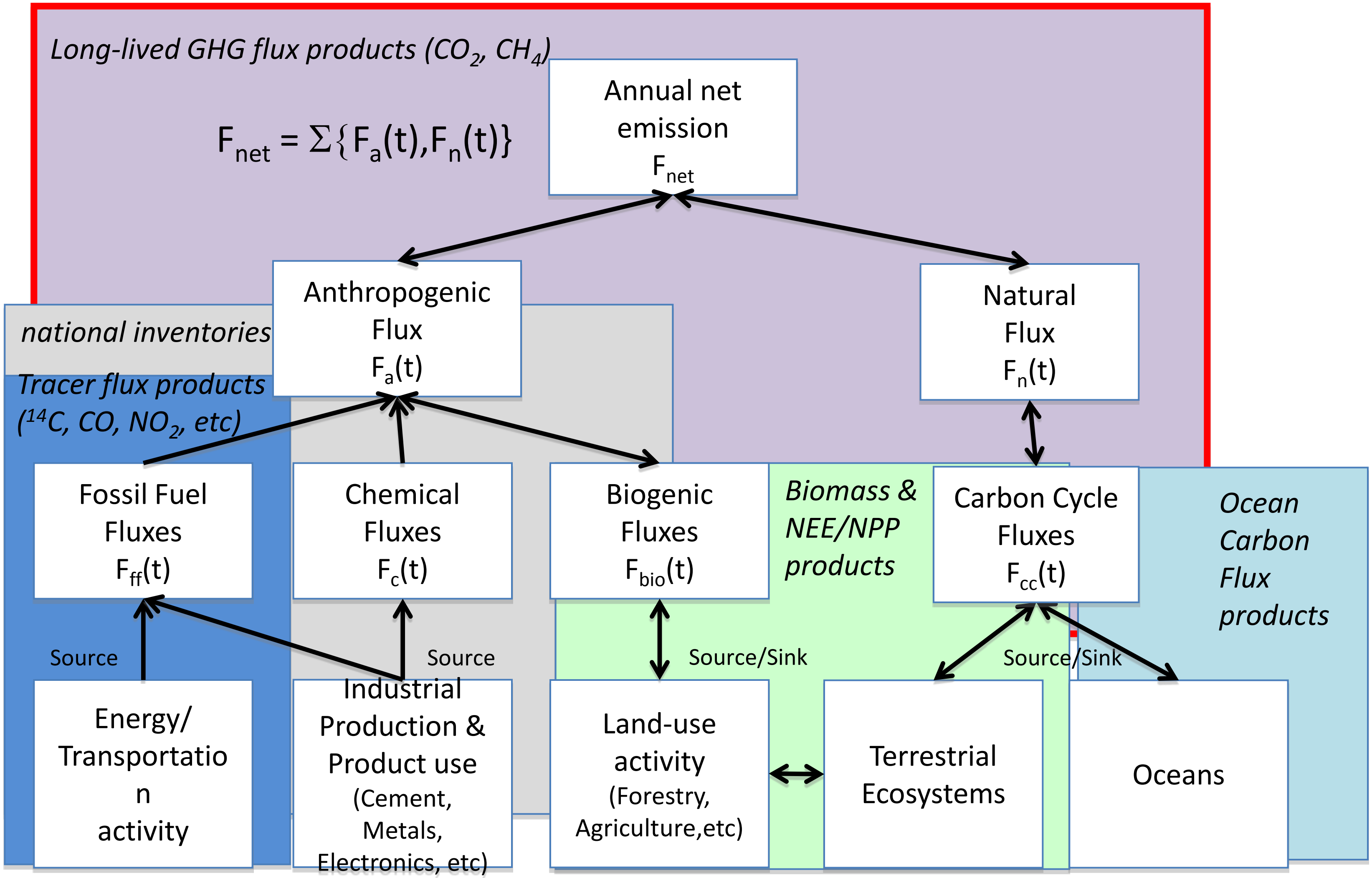
CH_4: Enteric Fermentation, Landfills, Natural Gas Systems, Coal Mining, Manure Management, Forest Land Remaining Forest Petroleum Systems, Wastewater Treatment, Stationary Combustion. Rice Cultivation Abandoned Underground Coal Mines,, **and many others…**

International bunker fuels

- Known exclusions (or, *included in IPCC guidelines but not universally reported):
  - CO_2 emissions from
    - Burning Coal Deposits & Waste Piles
    - Natural Gas Processing*
    - Shale Oil Production*
    - Industrial Waste Combustion*
    - CH_4 emissions from wetlands not affected by humans
    - Wetlands Creation or Destruction*
    - Petroleum Coke Production*
  - Volcanic eruptions
  - CO_2 exchange with oceans
  - Natural forest fires*
  - Unmanaged forests
- Unknown exclusions → ?

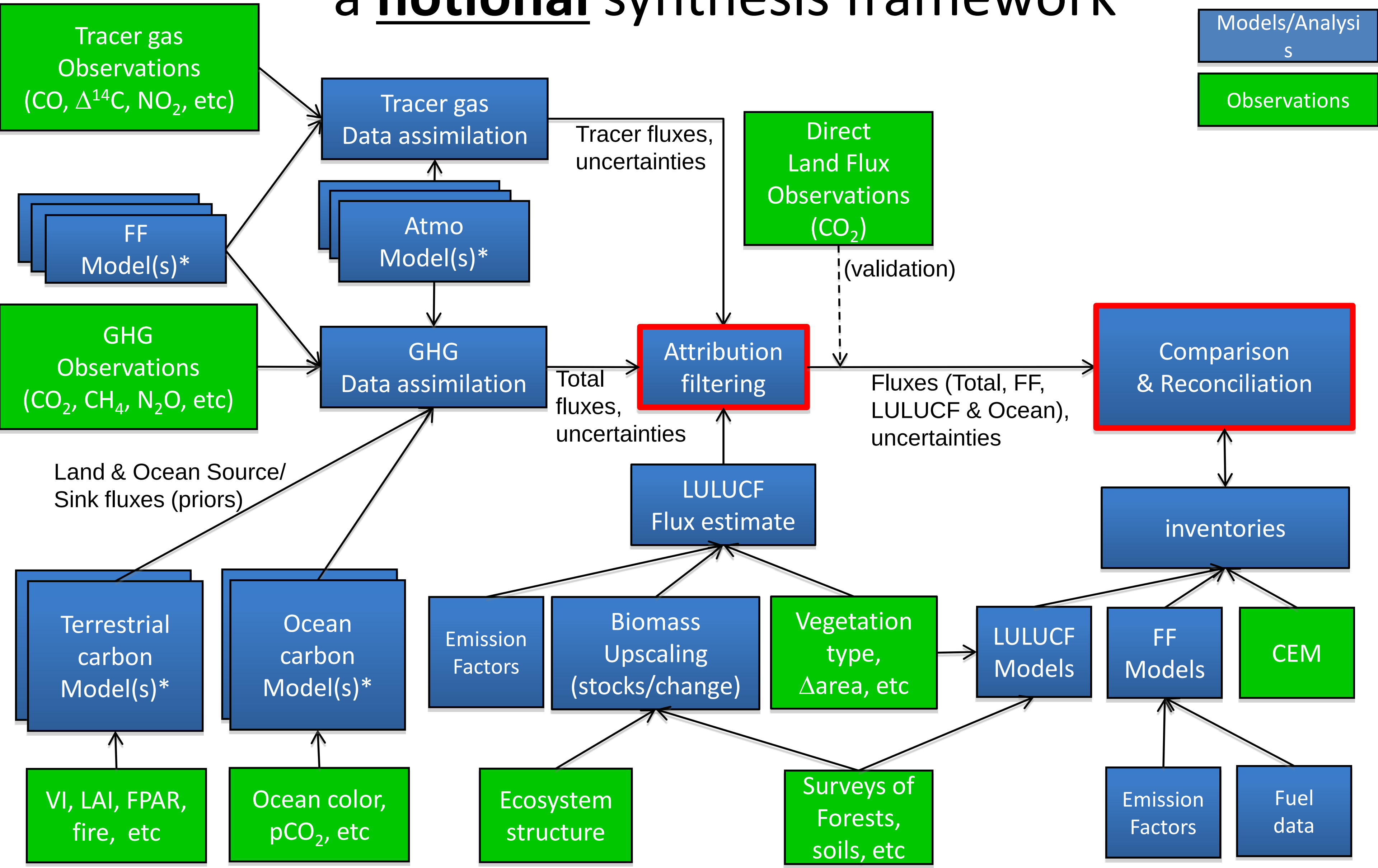
Observations can't resolve all individual sectors – but can decouple the primary categories: FF, LUCF/AFOLU, & oceans (sources <u>and</u> sinks) and perhaps selected sources within each…..

Challenge #3: Source attribution (CO_2 & CH_4 example)
how can we separate anthropogenic from natural activity?



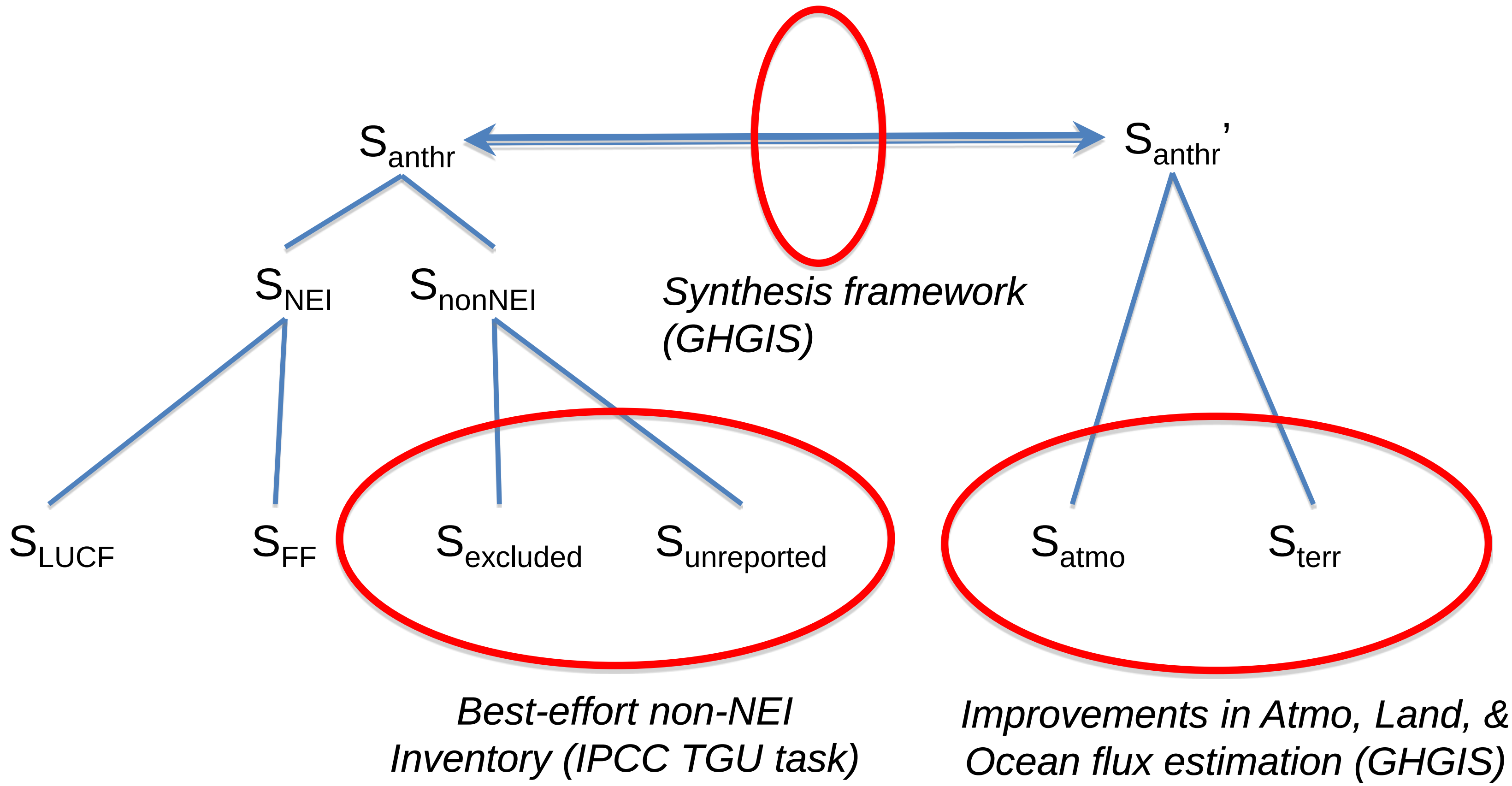
Synthesis of a **tiered set of observations** should help provide source attribution within the major categories (e.g., specific FF combustion processes, forest carbon & CH_4 (and perhaps N_2O) associated with selected agricultural and other land-use processes, etc)

Putting it all together: a **notional** synthesis framework



*comparison of multiple models is needed for cross-validation for each area (beyond internal consistency)

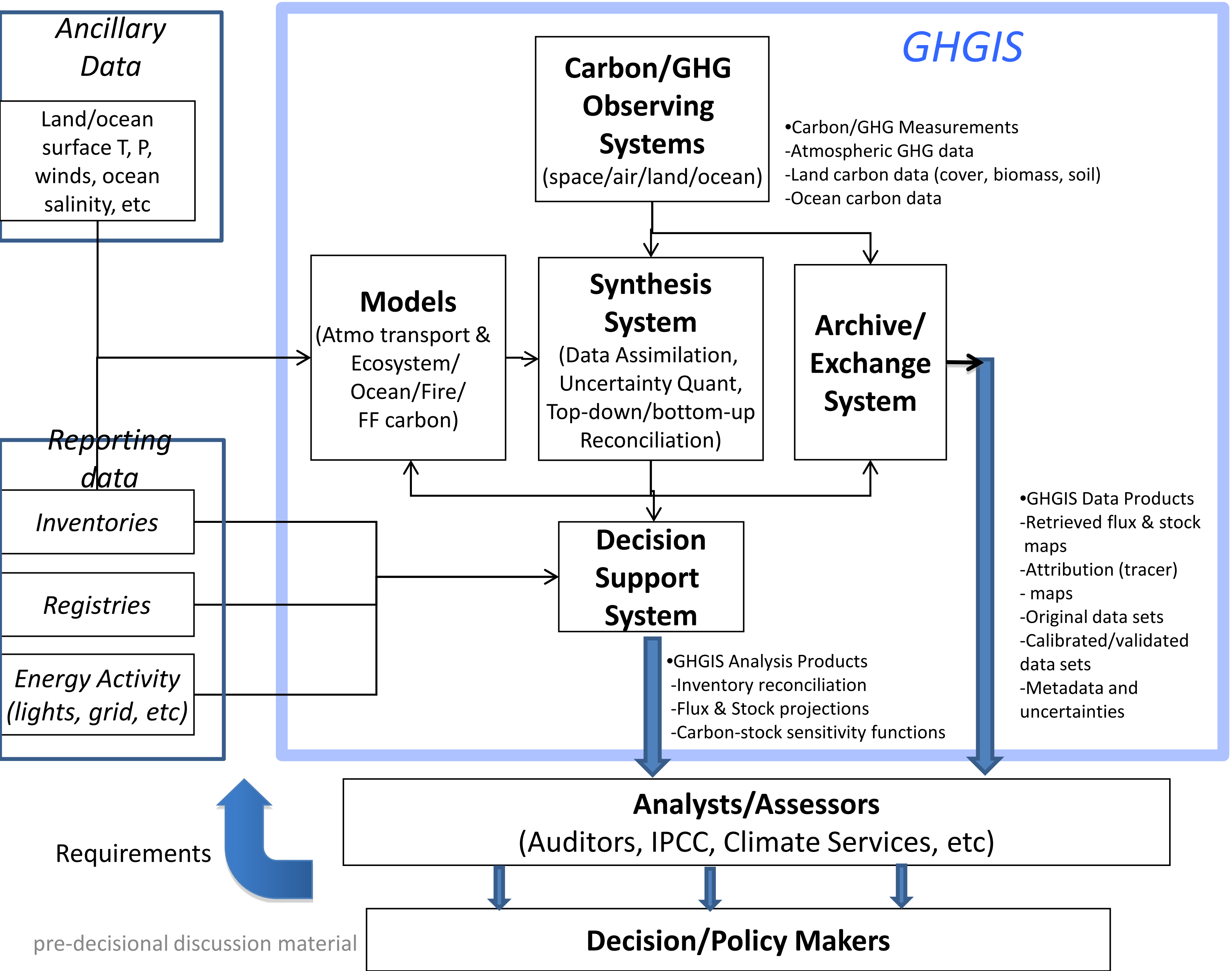
Priorities for improvement
(to enable top-down/bottom-up reconciliation)



$$S_{NEI} \leftarrow\rightarrow S_{NEI'} = S_{atmo} - S_{terr} - S_{nonNEI}$$

Duren, Miller, DeCola 2010, GRL, submitted

Towards a global Greenhouse Gas Information System (GHGIS)



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)

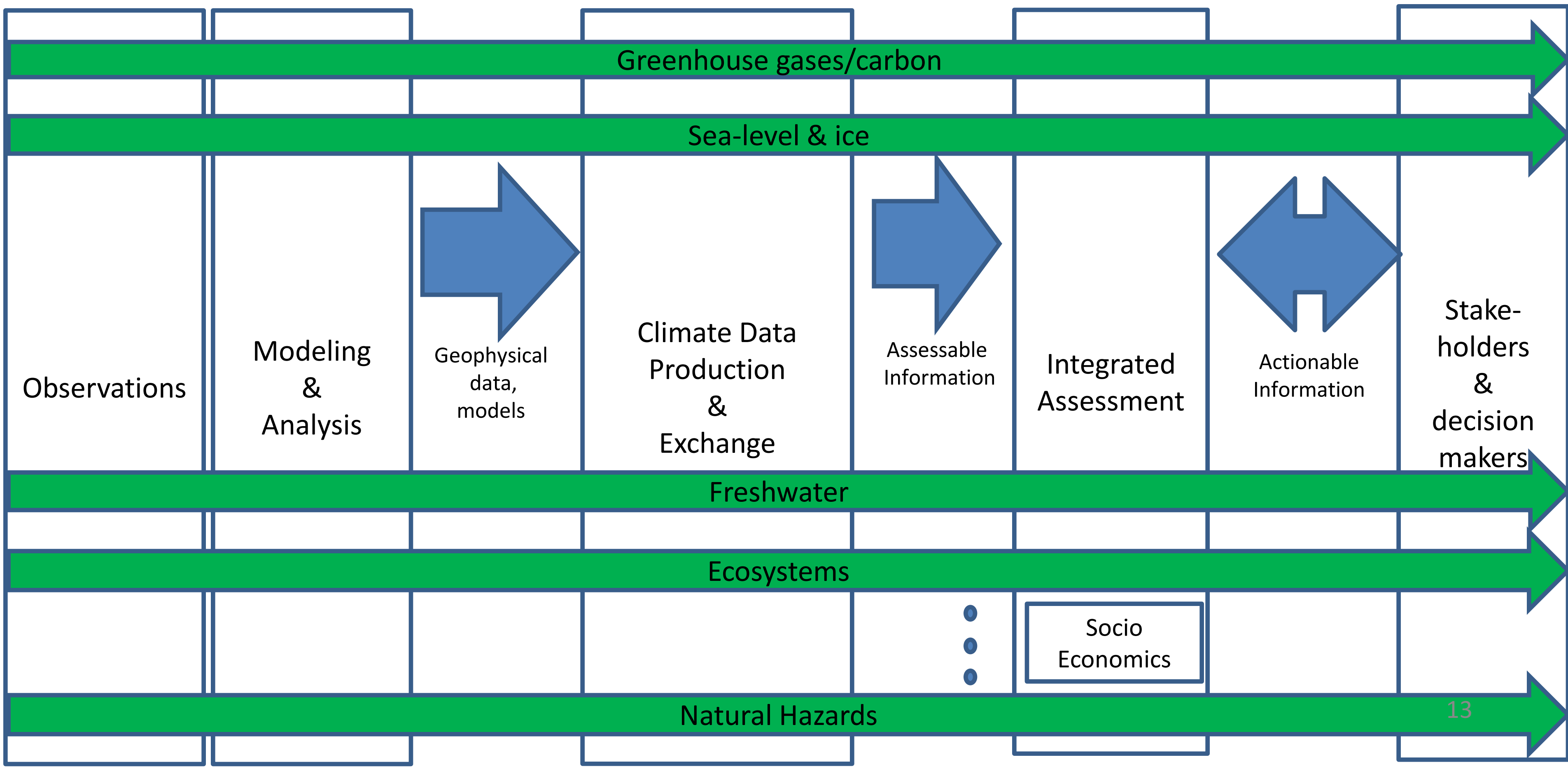
2. Current observational (& modeling) capabilities are significant & improving - but they were designed for scientific research, not **decision support** (not "operational").

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_2O, 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 – <u>*if*</u> 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



Backup material

Motivation & Scope

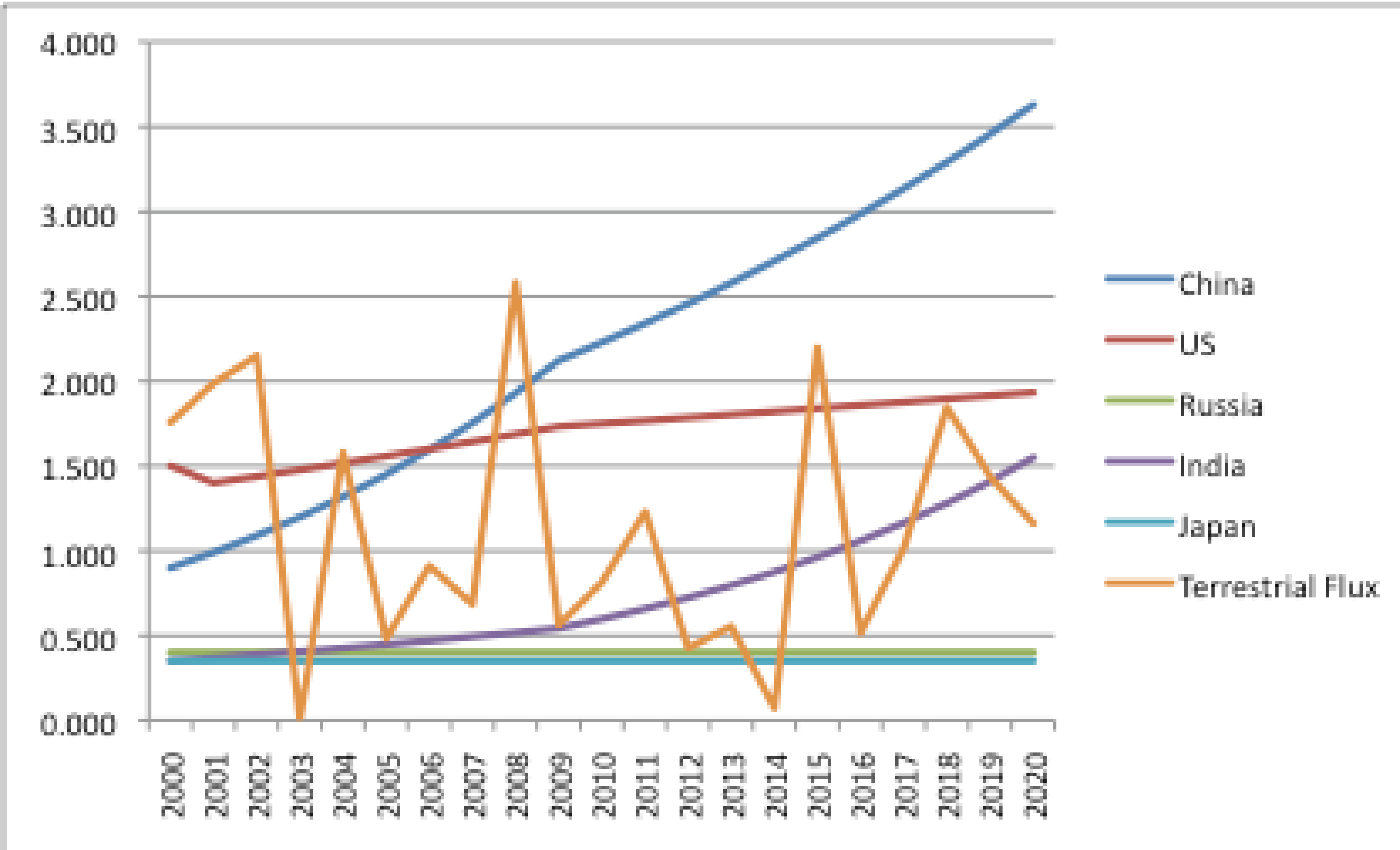
- Uncertainties in GHG & carbon data represent risks to the global economy and to policies intended to stabilize GHG emissions

- 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_2O 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?

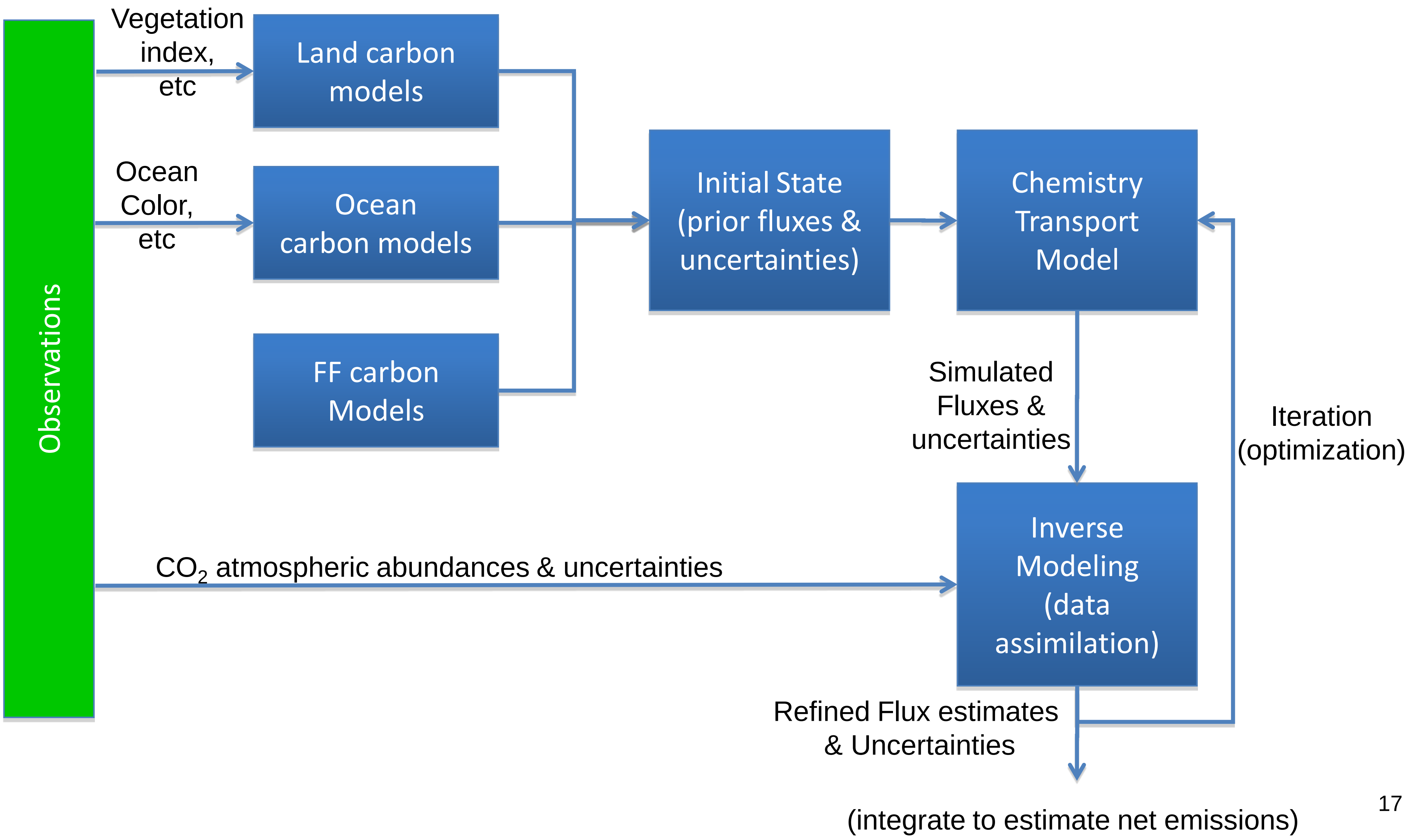


FF emission trajectories after Marland, 2010
Terrestrial flux after Canadell et al., 2007

By “observations”, we mean observations + models

(because we do not have perfect spatio-temporal sampling)

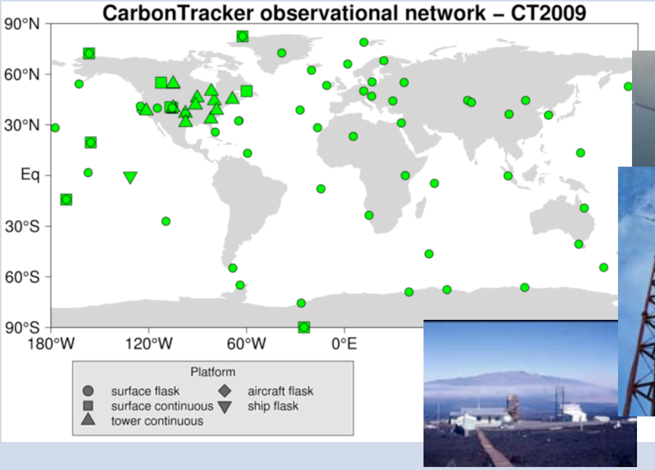
Generic inverse modeling approach for CO_2



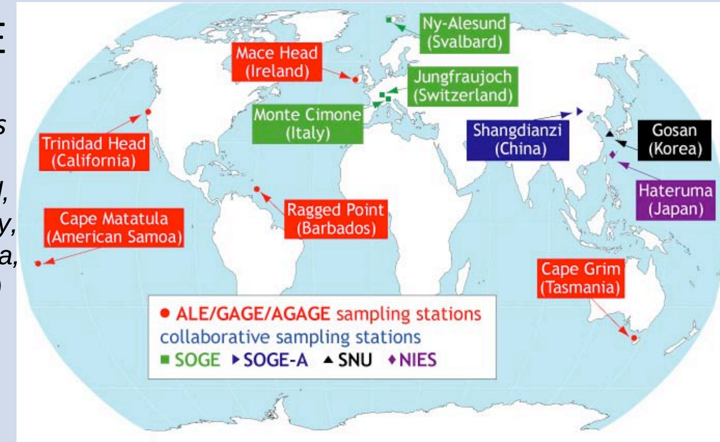
Current observations of GHGs from the surface/air

Concentrations → flux inversions

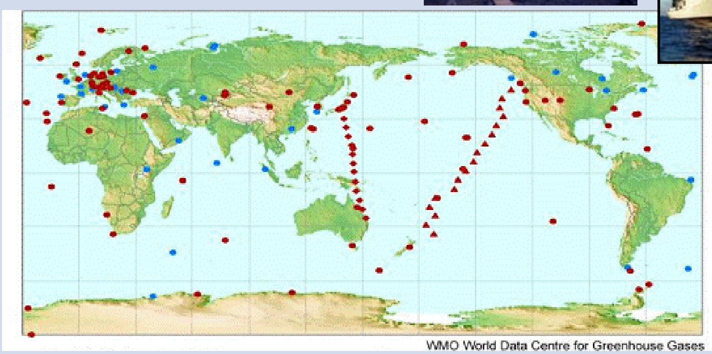
Carbon Tracker
NOAA



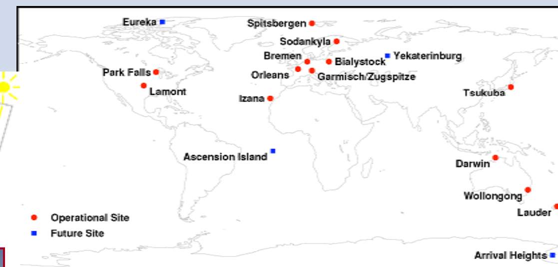
AGAGE
NASA & partners (from Switzerland, Italy, Norway, Japan, Korea, and China)

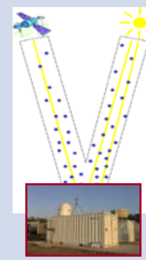


GAW
WMO

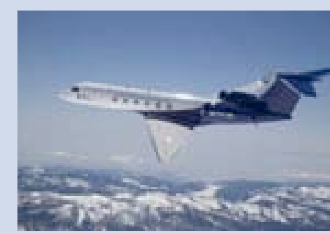


TCCON
NASA

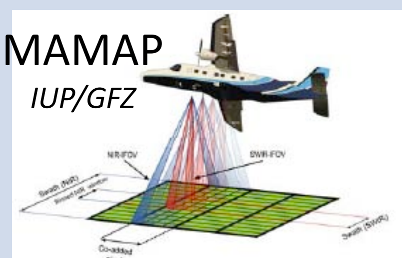




HIPPO
NSF/NOAA



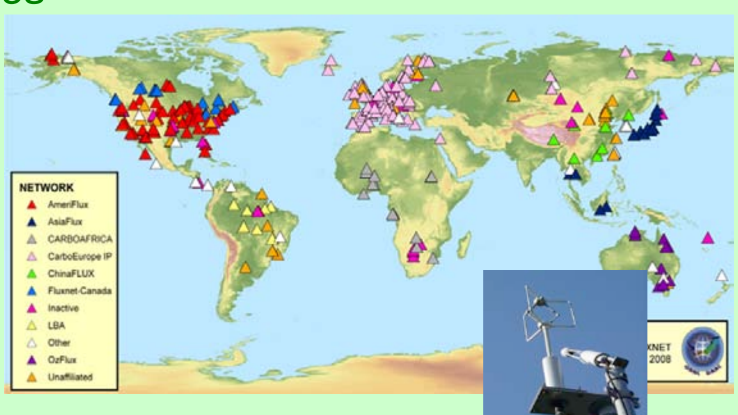
MAMAP
IUP/GFZ



CAMS
DOE

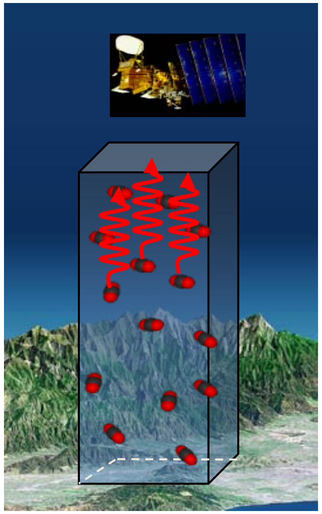
Direct fluxes

FluxNet
WMO, DOE, NSF, DOC, USDA, NASA



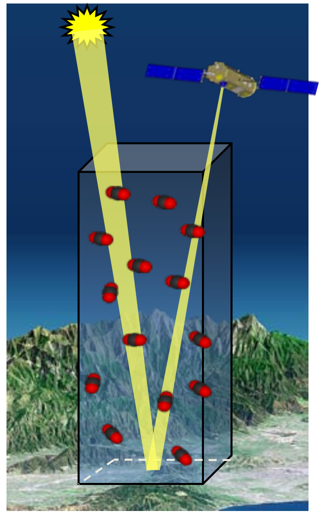
Current observations of GHGs from satellites

AIRS, TES, IASI

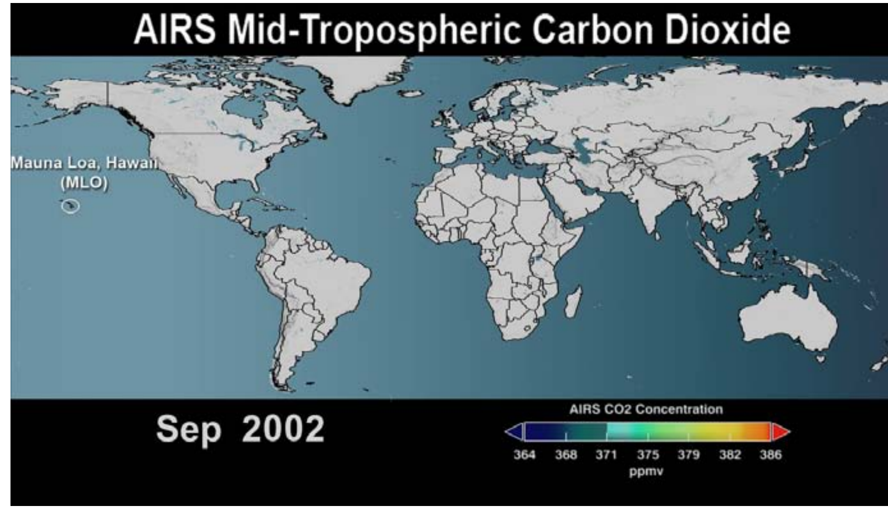


thermal-emission

SCIAMACHY, GOSAT



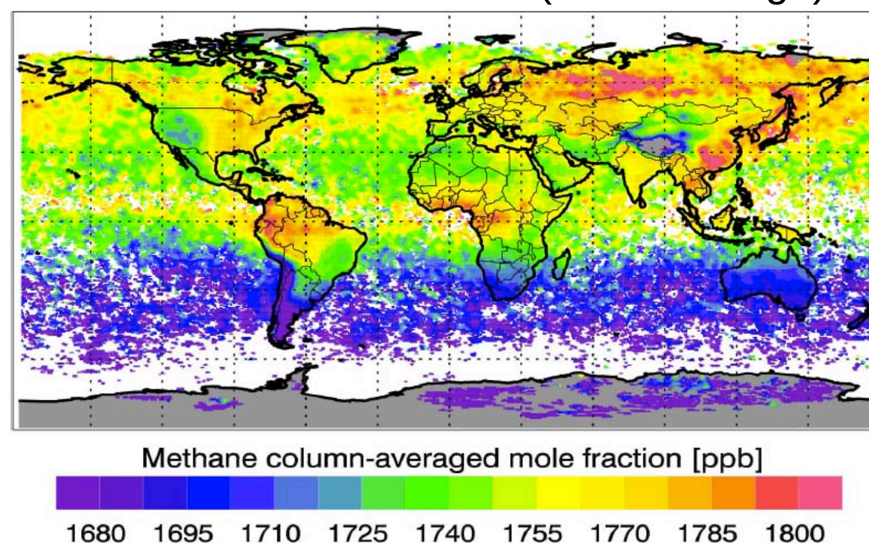
reflected sunlight



AIRS CO2 animation http://airs.jpl.nasa.gov/

Source: Chahine et al., 2008

SCIAMACHY Methane (2003 average)



Source: Buchwitz et al., 2007

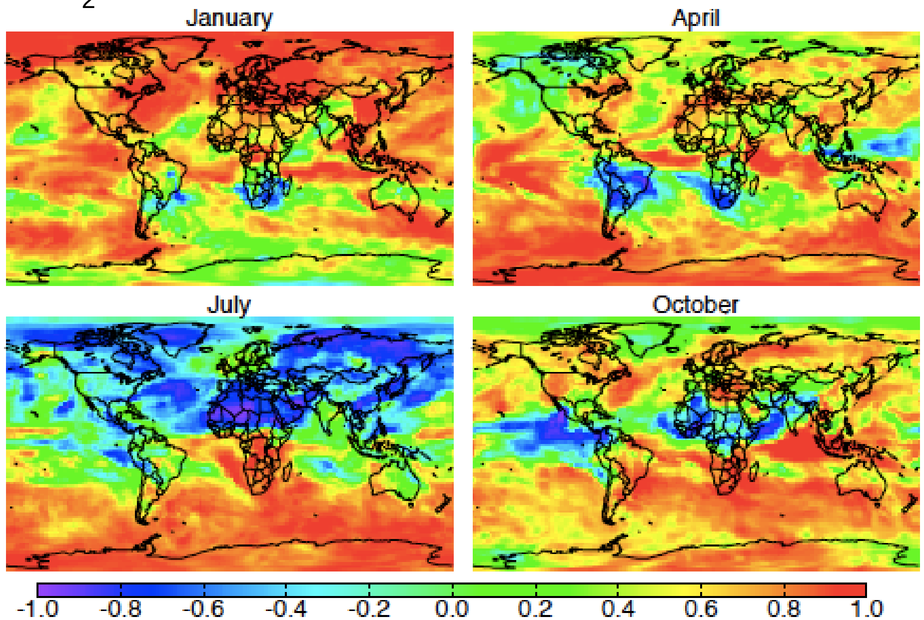
Currently Operational Missions

Measurement Method	Instrument	CO_2 Measurement	CO_2 Product Precision*	Down-track Sampling	Other gasses retrieved
Reflected Sunlight	SCIAMACHY	Total Column	3-10 ppm	60 km	CH_4, N_2O, CO, O_3, NO_2, H_2O, SO_2, others
	GOSAT/IBUKI	Total Column	4 ppm	10.5 km	CH_4, O_2, O_3, H_2O
Thermal Emission	AIRS	Mid-Trop	1 – 2 ppm	45 km	CH_4, CO, O_3, H_2O, SO_2
	IASI-A	Mid-Trop	2 ppm	100 km	CH_4, N_2O, CO, O_3, H_2O, others
	TES	Mid-Trop	~5 ppm	~50 km	CH_4, N_2O, CO, O_3, H_2O, HNO_3

*CO_2 products often have different precision and spatial scale than for individual samples

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

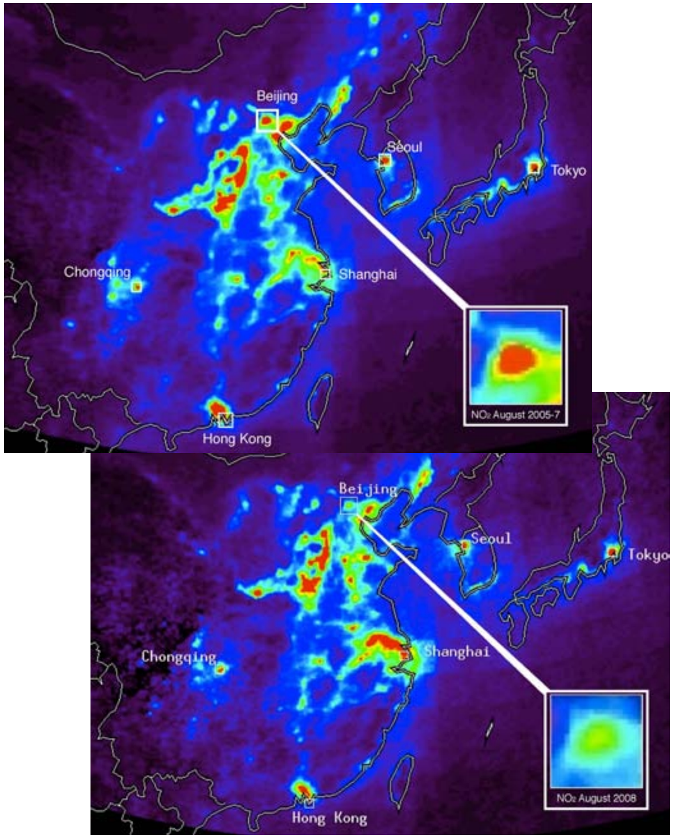
XCO_2/XCO Correlation Coefficients - GEOS-Chem model



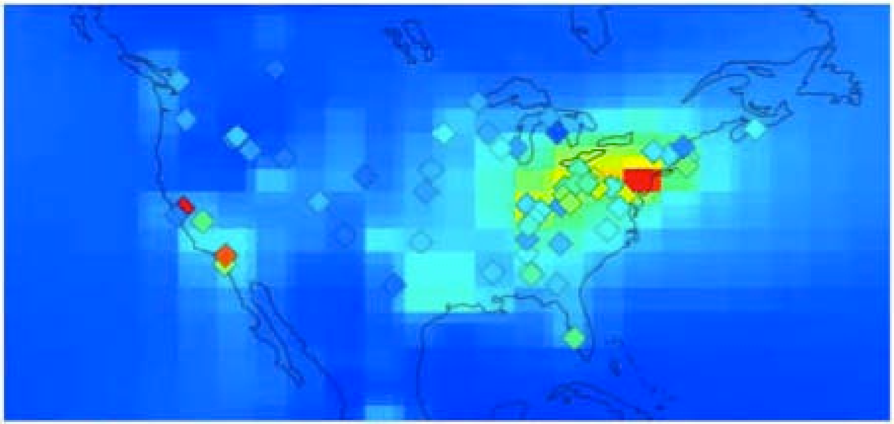
Wang et al., ACP (2009)

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

Observations from OMI satellite show 50% reduction in NO_2 in Beijing following strict traffic restrictions in preparation for the Olympic games.



http://www.nasa.gov/topics/earth/features/olympic_pollution.html



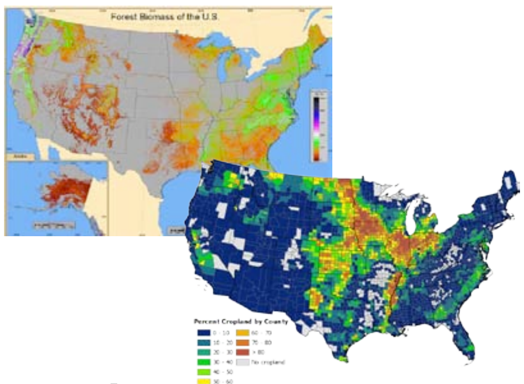
Turnbull et al, JGR, 2009

$\Delta^{14}CO_2$ surface observations & models as FF tracers (&/or to “calibrate” CO)

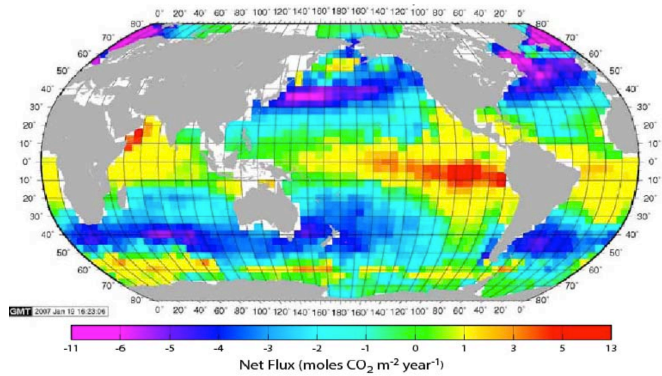
Examples of current observations of land/ocean carbon

Surface-based &/or fusion with satellite data

Forest & Soil Carbon inventories (FIA & NRI)
USDA

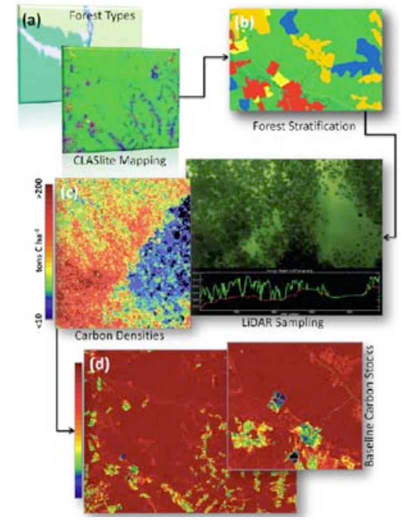


Annual mean air-sea CO_2 flux (2000)
Inferred from 30 ys of in-situ pCO_2 observations



Takahashi et al., Deep Sea Res II, 2009

Forest Biomass from satellite imaging & airborne lidar
Carnegie



Source: G. Asner, 2009

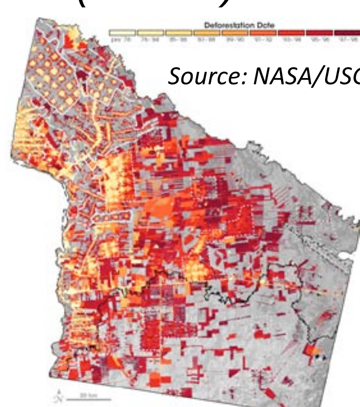
Satellites

Vegetation greenness, health and productivity: Landsat-7, MODIS, AVHRR, EO-1

Ocean color/photosynthetic activity: MODIS

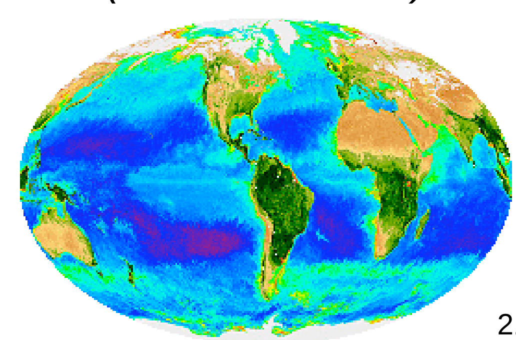
Ecosystem Structure/biomass: ALOS PALSAR

Deforestation (Landsat)



Source: NASA/USGS/UMD

Global Biosphere Productivity (MODIS/SeaWIFS)



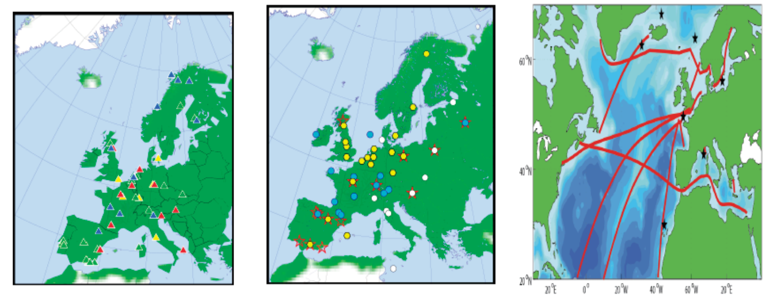
Source: NASA

The Future (planned): some highlights of GHG observations

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

Integrated Carbon Observation System (ICOS)

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

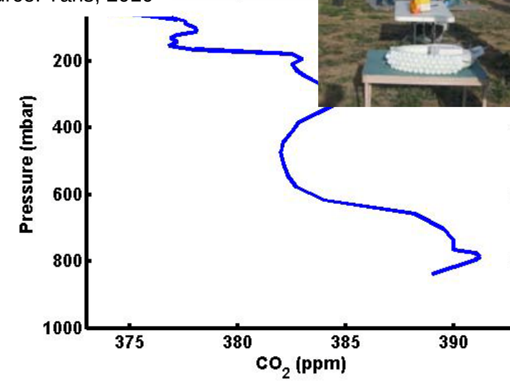


50 Ecosystem stations | 50 Atmospheric stations | Ocean ship and stations

Source: Ciais et al., 2009

NOAA Aircore (GHG vertical profiles)

Source: Tans, 2010



Planned Missions 2013-2010

Measurement Method	Instrument	CO_2 Measurement	CO_2 Product Precision*	Down-track Sampling	Other gasses retrieved
Reflected Sunlight	OCO-2	Total Column	1 ppm	2.3 km	O_2
	pre-Sentinel-5	Total Column	tbd	10km	CH_4, CO, O_3, NO_2, SO_2
	Sentinel-5	Total Column	tbd	tbd	tbd
Thermal Emission	IASI-B	Mid-Trop	2 ppm	100 km	CH_4, N_2O, CO, O_3, H_2O, others
	IASI-C	Mid-Trop	2 ppm	100 km	CH_4, N_2O, CO, O_3, H_2O, others
	JPSS CrIS	Mid-Trop	tbd	tbd	tbd
Active (LIDAR)	ASCOPE	Lower-trop	2 – 4 ppm	~100 km	CO
	ASCENDS	Lower-trop	2 – 4 ppm	~100 km	CO

*CO_2 products often have different precision and spatial scale than for individual samples

DOE CAMS

increase in 14C throughput

The Future (planned): highlights of Land/ocean carbon observations

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

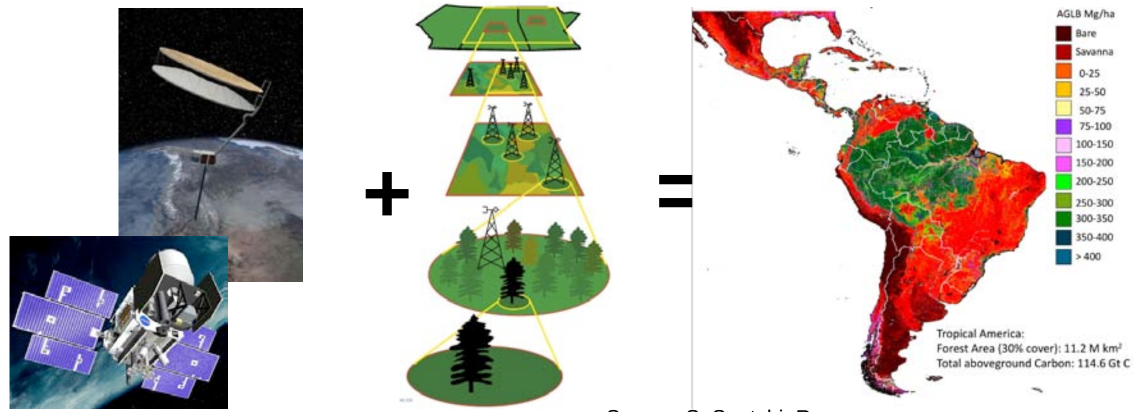
Ocean color/photosynthetic activity: GEOCAPE

Freeze-Thaw, Land Photosynthetic activity : SMAP

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

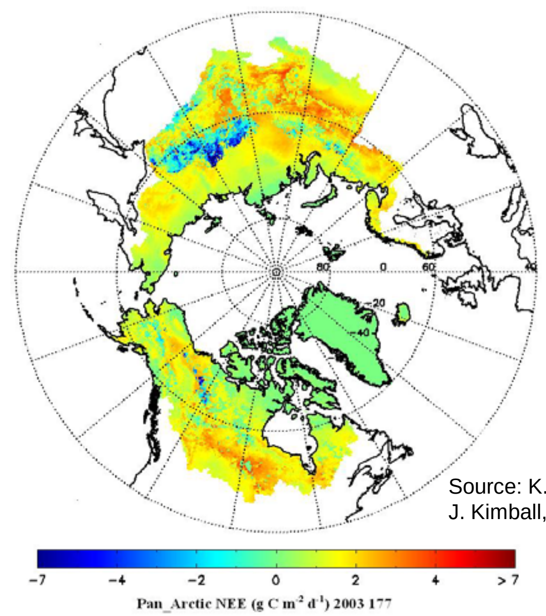
ACTIVE sensors

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



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

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



Source: K. MacDonald, J. Kimball, et al 2009

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 CO_2, followed by CH_4 & 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