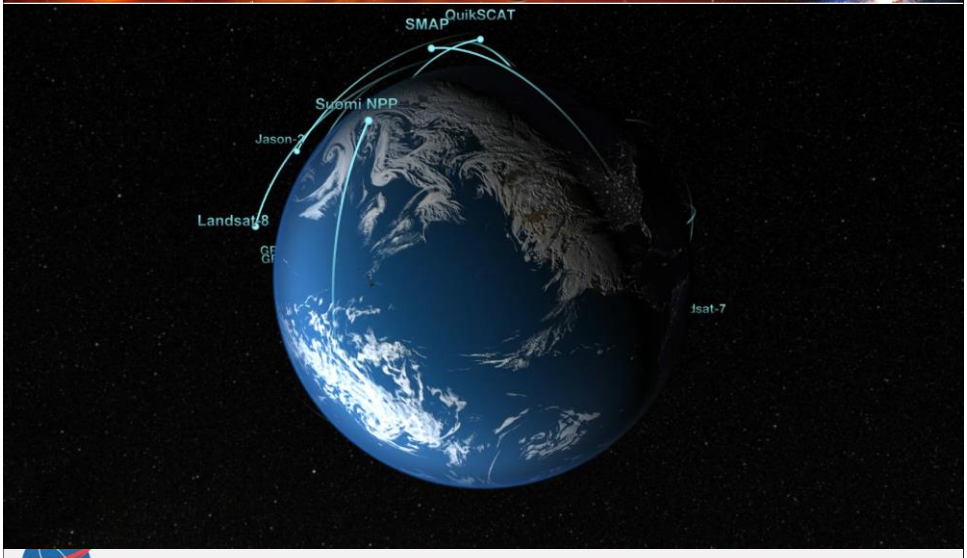
NASA's Carbon Cycle, missions and research

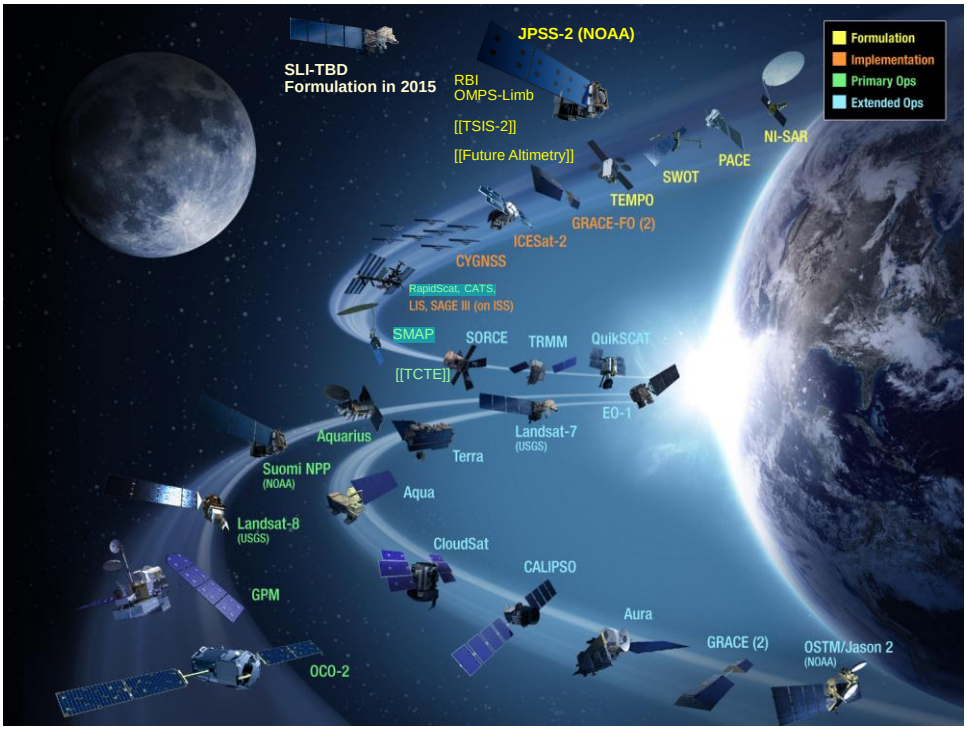
MOST of NASA's space missions obtain SOME information useful for the Carbon Cycle!

Research is funded through:

- Terrestrial Ecology (Hank Margolis)
- Ocean Biology/biogeochemistry (Paula Bontempi)
- Land Cover/Land Use Change (Garik Gutman)
- Biodiversity (Woody Turner)
- Carbon Cycle Science (these and others)
- Science of Terra/Aqua/Aura/NPP (many)
- OCO-2 Science Team (Ken Jucks)
- Carbon Monitoring System (Jucks, Margolis, Hibbard)

Current NASA missions





Overall FY2016 Budget Summary

- ESD budget increases significantly

	FY15	FY16	FY17	FY18	FY19	FY20
FY16	**1.730**	**1.894**	**1.913**	**1.932**	**1.952**	**1.971**
FY15		1.762	1.784	1.805	1.829	---

- NASA now has mandate for additional long-term measurements for the nation:
  - Altimetry after Jason-3
  - Solar Irradiance, Ozone Profile, Earth Radiation Budget all starting in FY16
- Sustainable Land Imaging Program (w/USGS; NASA funds flight hardware):
  - TIR-FFD (2019)
  - Upgraded Landsat-9 (2023)
  - Focused technology development to inform designs of Landsat-10+
- Continued development and launch of: SAGE-III/ISS, ECOSTRESS/ISS, GEDI/ISS, CYGNSS, TEMPO, GRACE-FO, ICESat-2, SWOT, NISAR, PACE
- Continue Venture Class on schedule with full funding
- OCO-3 completion and flight to ISS in late 2017
- CLARREO Technology Demonstration instruments on ISS - development and flight in late 2019 (2 instruments, Reflected Solar/HySICS and IR Pathfinder)

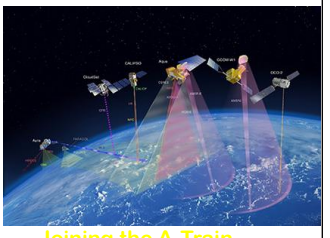
"Carbon Cycle" missions: A NASA Emphasis!

- OCO-2 has completed one year of observations!
- OCO-3 is back in the budget and should enter Phase C in a few months.
- ASCENDS remains in pre Phase A, technologies are developing nicely.
- GEDI (in Phase B, PDR next month),
- ECOSTRESS (in Phase C),
- LandSat continuity (for USGS, in "planning")
- PACE (still in pre-Phase A)

OCO-2 update: A Perfect Launch: July 2, 2014

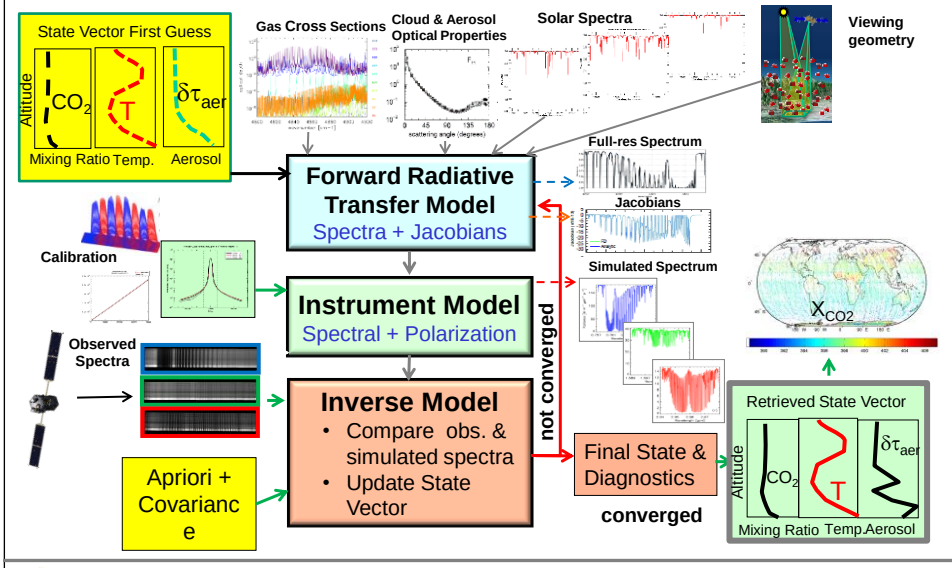
Lift-off:2:56 am PDT

Separation!

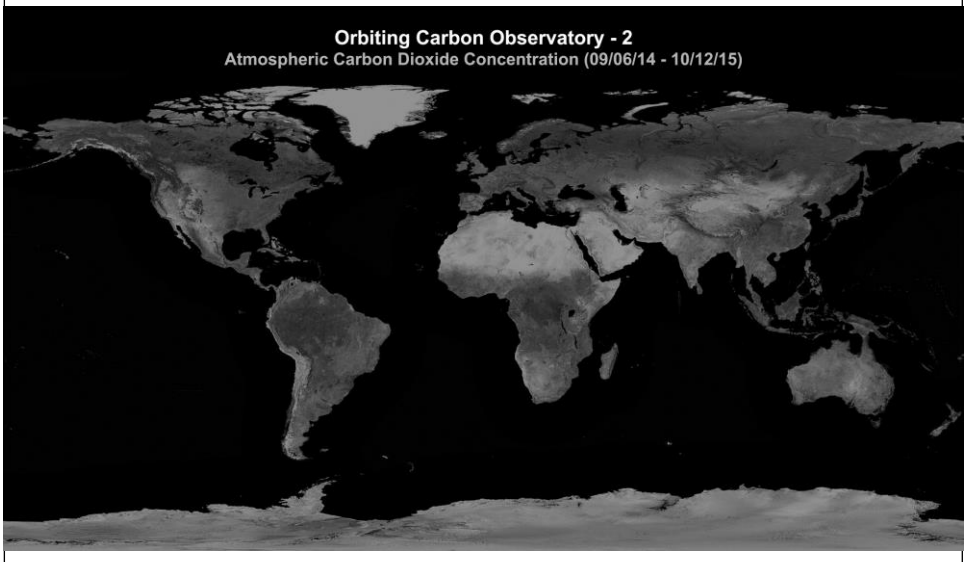


Joining the A-Train
3 August 2014

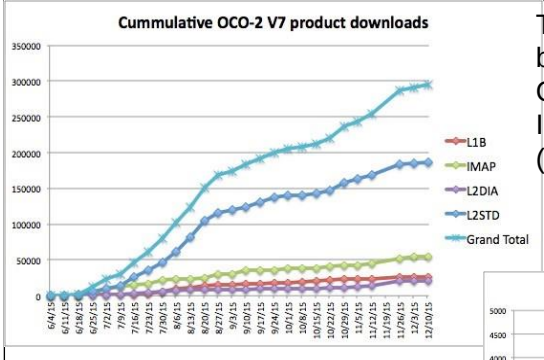
The OCO-2 XCO2 Retrieval Algorithm



A Quick Look at the First 13 Months of Operations

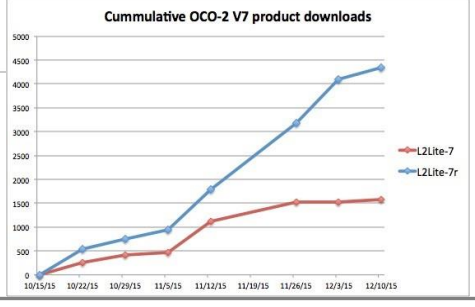


OCO-2 Version 7 Data Products



The OCO-2 Data Products can be obtained from the NASA Goddard Earth Science Data and Information Services Center (GES-DISC) at:

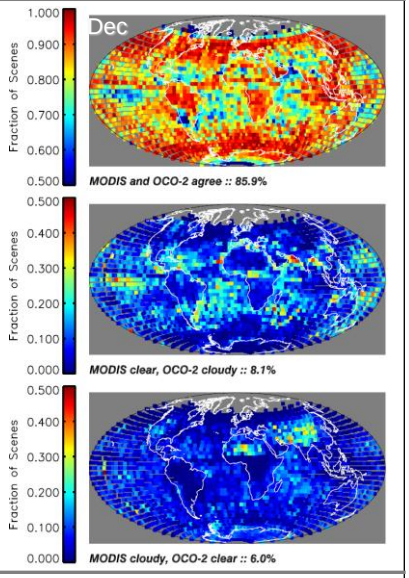
disc.sci.gsfc.nasa.gov/OCO-2



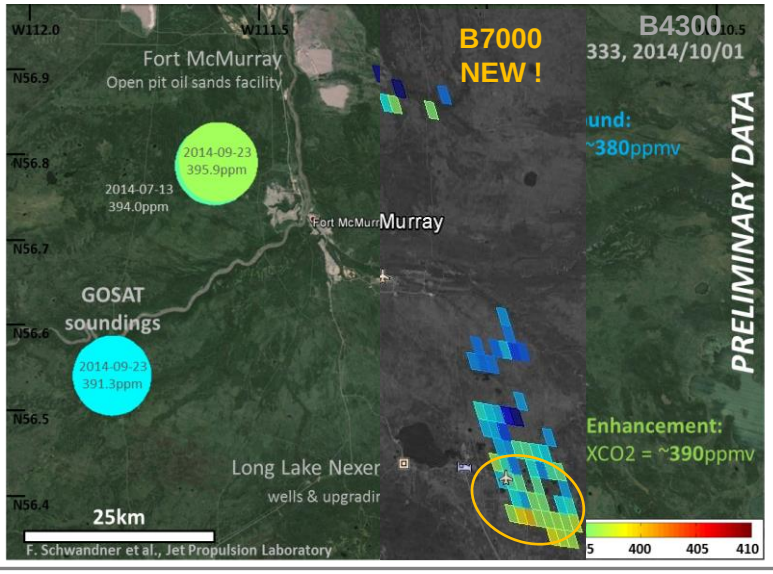
Products are available in 2 formats:
- Complete “Standard” L1B and L2 Product files (HDF5)
- Compact “Lite” files that include bias-corrected X_{CO2} with “warn levels” indicating reliability

Prescreening: Cloud Screening
(Taylor et al.)

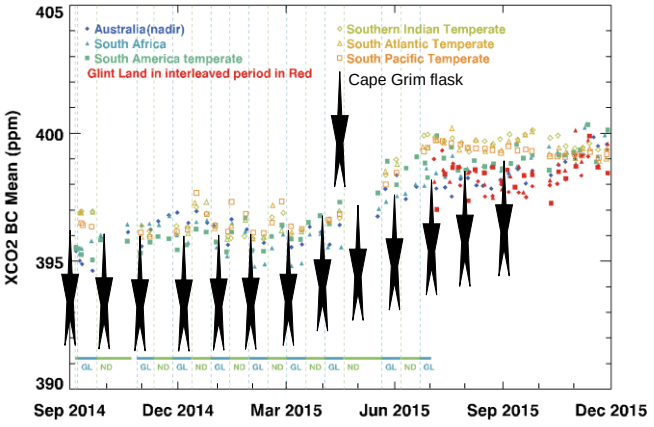
- The OCO-2 cloud screening approach includes 2 fast algorithms:
  - O_2 A-band Preprocessor (ABP)
    - Rayleigh scattering + O_2 absorption
    - Most sensitive to high clouds
  - IMAP DOAS Preprocessor (IDP)
    - Gas absorption, no scattering
    - Applied to CO_2 channels
    - Most sensitive to low clouds
- OCO-2 cloud screening results have been validated against MODIS-Aqua cloud mask product
  - ~85% agreement in global average
  - Disagreements due to co-location errors, thin aerosols and other factors



Small-Scale Emission Structures - Alberta Tar Sands, Canada [Schwandner et al.]

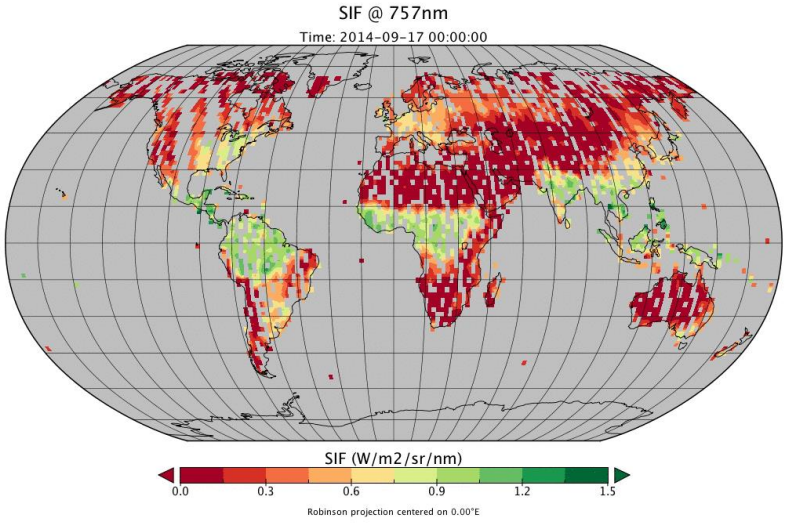


Temporal Changes in X_{CO2} Impact of Bias Corrections [Fisher et al.]



Validation Against Other Standards

Solar Induced Fluorescence



OCO-2 Summary

- OCO-2 was successfully launched on 2 July 2014, and began routine operations on 6 September 2014
  - Now returning about 1 million measurements each day over the sunlit hemisphere
  - Over 10% of these measurements are sufficiently cloud free to yield full-column estimates of X_{CO2}
- Over one year of data has been delivered to the Goddard Earth Sciences Data and Information Services Center (GES-DISC) for distribution to the science community
  - All data back to September 6 2014 have been reprocessed

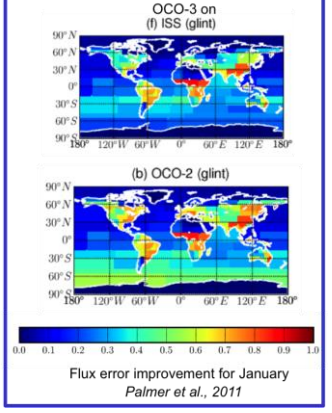
http://disc.sci.gsfc.nasa.gov/OCO-2

- This product is now being used by the world's carbon cycle science community to identify and quantify the CO_2 sources and sinks on regional scales over the globe

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

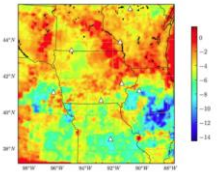
OCO-3 Science Overview

Continued Global CO_2 Flux Estimates



Unique Science Opportunities with OCO-3

Anthropogenic Emissions
Enabled by enhanced target mode using pointing mirror assembly



Terrestrial Carbon Cycle
Process studies enabled by measurements at all sunlit hours

Model Flux for MCI expt

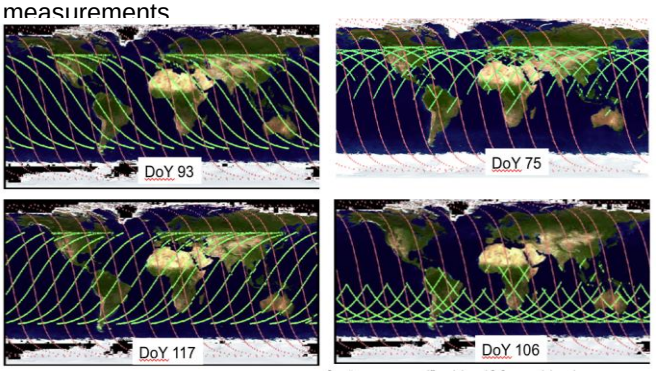
From Wu et al., 201

- OCO-3 is being designed for the International Space Station
- Continues global sampling (with time of day information), adds complimentary mapping capability

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Seasonal and Latitudinal Variations of OCO-3 Global Sampling from ISS

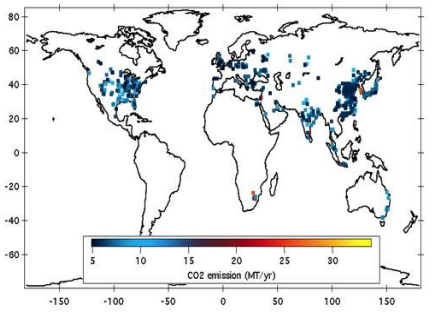
- Sampling would be dense at mid-latitudes, while providing good coverage of tropics and sub-tropics
- 2-axis pointing systems would enable new operations concept with nadir *and* glint observations taken every day, effectively doubling the number of samples over oceans as compared to OCO-2
- Data collected over all sunlit hours, especially valuable for SIF measurements



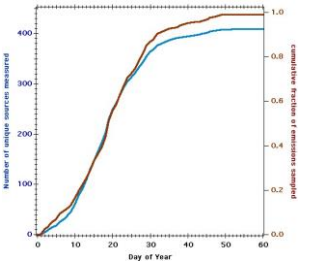
Proposed OCO-3/ISS orbits (green) and OCO-2 (pink). On “turn-around” orbits, ISS would provide better coverage of mid latitudes of one hemisphere.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Point Sources Readily Sampled With OCO-3



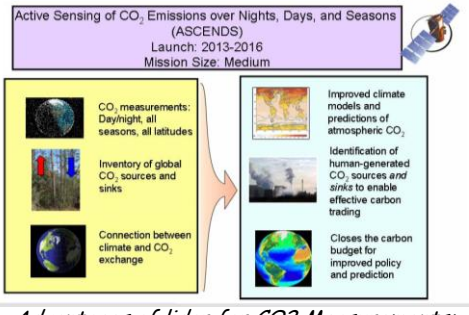
- There are 560 point sources that emit more than 5 MT of CO_2 per year, which we can see from space
- OCO-3 mapping mode can capture all with 430 different mapping mode measurements
- With just 100 maps, more than 90% of emissions can be sampled.



- With OCO-3 flexibility,
  - can sample 5 to 40% of emissions in a single day.
  - In just 30 days, more than 90% of the emissions sources are uniquely sampled
  - (OCO-2 typically samples 2% of emissions or less per day)

NASA's ASCENDS Mission

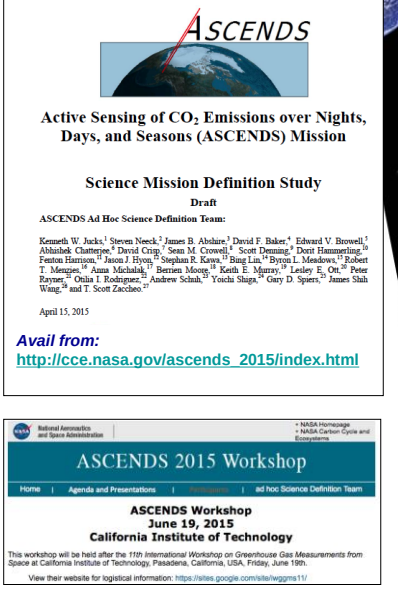
Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS)



Advantages of lidar for CO2 Measurements:

- Measures at night & all times of day
- Measures at high latitudes & continuously over oceans
- Measures through broken clouds & through thin cirrus
- Measures to cloud tops
- Constant nadir/zenith path

=> Improved spatial coverage with high accuracy



ASCENDS

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission

Science Mission Definition Study

Draft

ASCENDS Ad Hoc Science Definition Team:

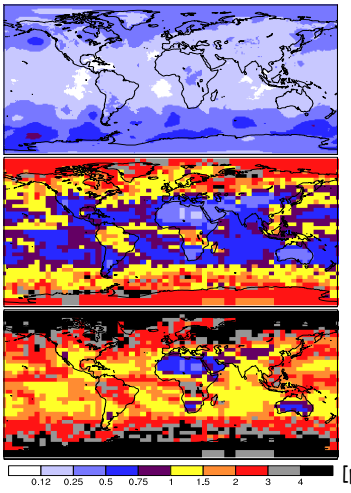
Kenneth W. Jucks,[1] Steven Neeck,[2] James B. Abshire,[3] David F. Baker,[4] Edward V. Browell,[5] Abhishek Chatterjee,[6] David Crisp,[7] Sean M. Crowell,[8] Scott Denning,[9] Dorit Hammerling,[10] Fenton Harrison,[11] Jason J. Hyon,[12] Stephan R. Kawa,[13] Bing Lin,[14] Byron L. Meadows,[15] Robert T. Menzies,[16] Anna Michalak,[17] Berrien Moore,[18] Keith E. Murray,[19] Lesley E. Ott,[20] Peter Rayner,[21] Otilia I. Rodriguez,[22] Andrew Schnik,[23] Yoichi Shiga,[24] Gary D. Spiers,[25] James Shih Wang,[26] and T. Scott Zaccheo.[27]

April 15, 2015

Avail from:
http://cce.nasa.gov/ascends_2015/index.html

Key Science Accomplishments for 2015

• Errors in CO_2 retrievals due to using surface pressure from meteorological reanalyses (instead of a dedicated O_2 instrument) appear to be small vs. other retrieval errors



X_{CO2} retrieval errors due to using surface pressure from a meteorological reanalysis to set the total column airmass, as:

$\sigma_{XCO2} = \sigma_{Psurf} \times 400 \text{ ppm} / 1000 \text{ hPa}$

(σ_{Psurf} taken from the st. dev. of three reanalyses investigated by Ott & Zaccheo)

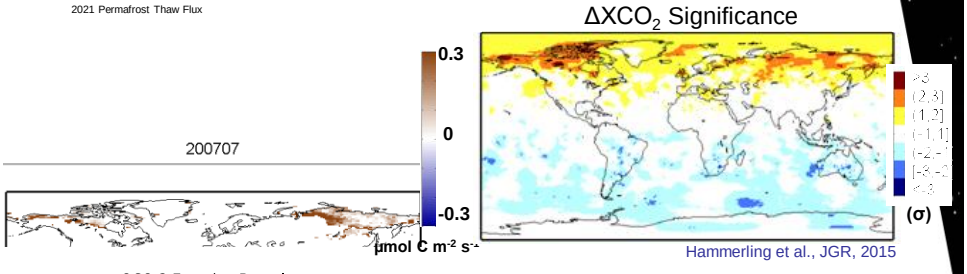
Other retrieval errors, assuming a 0.25 ppm uncertainty at Railroad Valley

Other retrieval errors, assuming a 0.50 ppm uncertainty at Railroad Valley

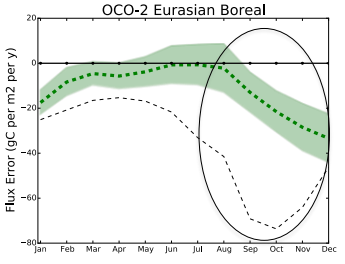
Caveat: this comparison assumes that the surface pressure errors are random: if they are correlated significantly across time and space, they may cause systematic errors in the X_{CO2} retrievals of more importance. These correlations are currently being assessed.

Key Science Accomplishments for 2015

• Permafrost thawing CO_2 perturbation readily detectable with ASCENDS observations



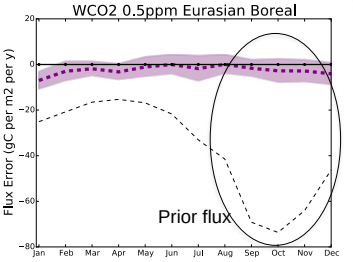
Hammerling et al., JGR, 2015



Shaded = Posterior from Atmospheric Inversion

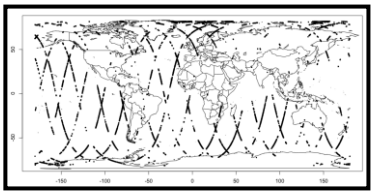
Late season thaw not observed by passive platform

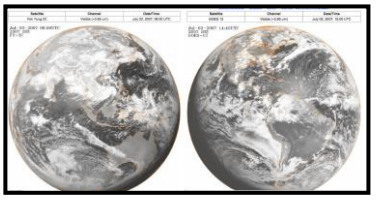
Crowell et al., 2015, in prep



Key Science Accomplishments for 2015

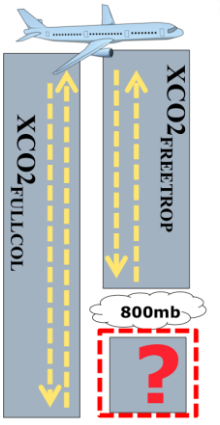
- Cloud slicing and contribution of constraints from vertically resolved column mean CO_2
  - Low level thick PBL-top clouds allow the ability for the instrument to recover "within PBL" XCO_2 concentrations by estimating the difference between cloudy and clear scenes
  - Most of these clouds appear to exist over oceans but there are also sporadic opportunities over land.





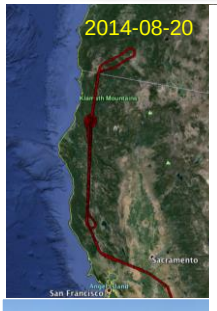
We calculate the occurrence of very ***bright single layer clouds between 0.5km and 4km*** with OD>1 for 7/2/2007.

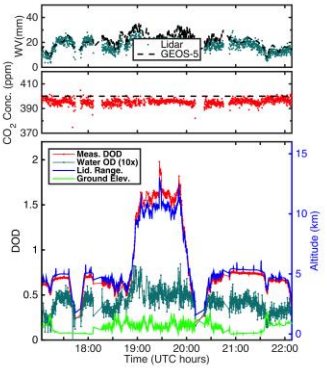
Corresponding GOES imagery for 7/2/2007

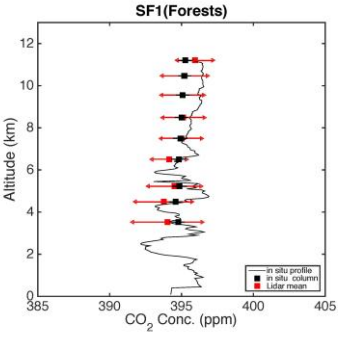


CO2 Sounder: Tall forests in Coastal California

(Redwood forests on several km high mountains)







Why ?: Accurate CO_2 measurements over Amazon, Congo & Boreal forests are important for ASCENDS

- Varying tree canopy & terrain -> rapid change in column length
- **Results show accurate (very low bias) measurements in challenging conditions**

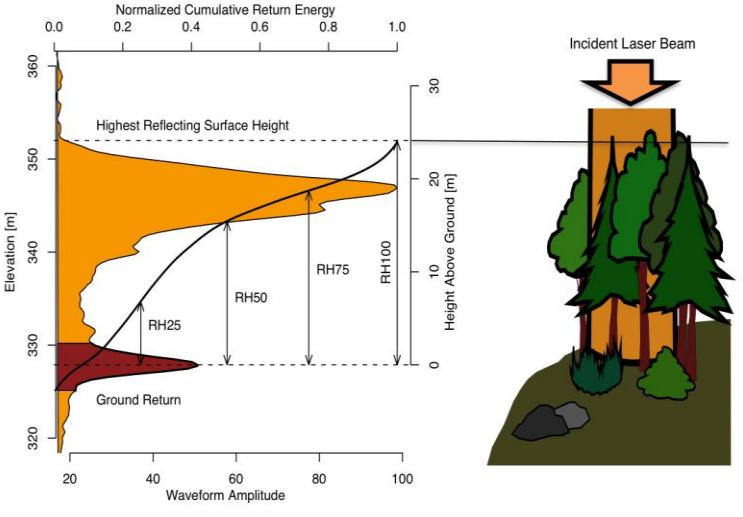
Pre-Aerosol, Cloud, and ocean Ecosystem (PACE) Mission

Pre-Aerosol, Cloud, and ocean Ecosystem (PACE) is an ocean color, aerosol, and cloud mission identified in the 2010 report "Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space Science".

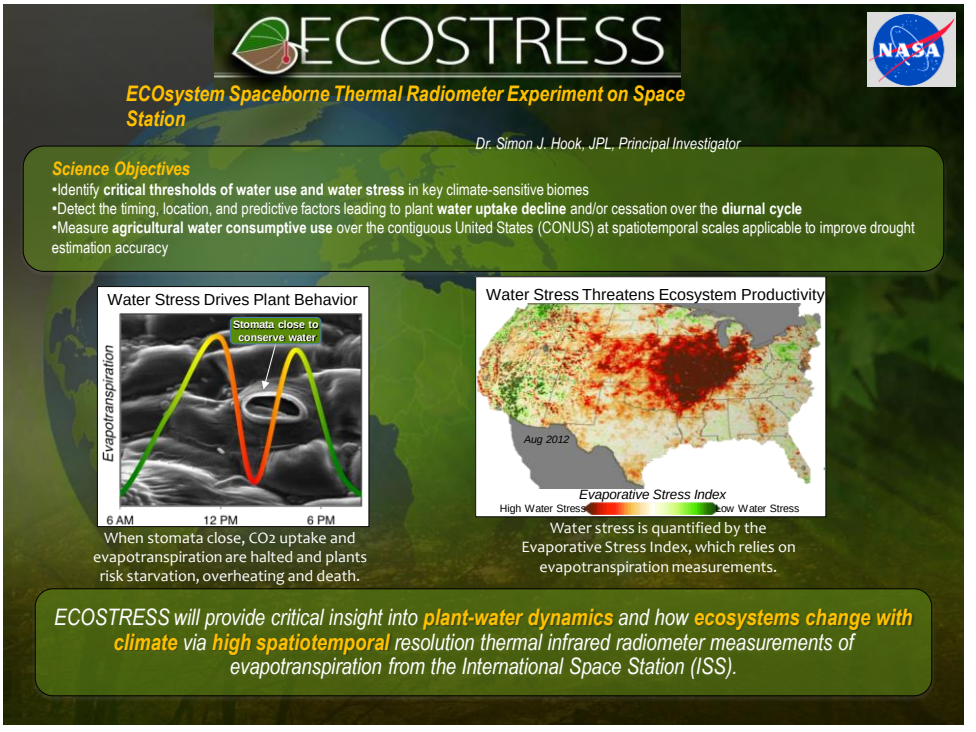
Science Objectives

- **Primary:** Understand and quantify global ocean biogeochemical cycling and ecosystem function in response to anthropogenic and natural environmental variability and change: **ocean color sensor**
- Extend key Earth system data records on global ocean ecology, biogeochemistry, clouds, and aerosols (expanded ocean color sensor similar to MODIS)
- **Secondary:** Understand and resolve/quantify the role of aerosols and clouds in physical climate (the largest uncertainty): **polarimeter**

Risk	• 8705.4 Payload Risk Class C
Launch	• 2022/2023, budget and profile driven
Orbit	• 97° inclination; ~650 km altitude; sun synchronous
Duration	• 3 years
Payload	• Ocean color instrument; potential for a polarimeter
LCC	• **$805M Cost Cap**



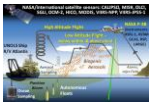
GEDI



Earth Venture Suborbital -2

Atmospheric Tomography Experiment (ATom) – Harvard University (Steve Wofsy)

This investigation will study the impact of human-produced air pollution on certain greenhouse gases and aerosols. Airborne instruments will look at how atmospheric chemistry is transformed by various air pollutants and at the impact on methane and ozone which affect climate. Flights aboard NASA's DC-8 will originate from the Armstrong Flight Research Center in Palmdale, California, fly north to the western Arctic, south to the South Pacific, east to the Atlantic, north to Greenland, and return to California across central North America.

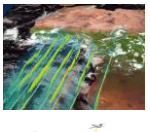


North Atlantic Aerosols and Marine Ecosystems Study (NAAMES) – Oregon State U. (Mike Behrenfeld)

This investigation will improve predictions of how ocean ecosystems would change with ocean warming. The mission will study the annual life cycle of phytoplankton and the impact small airborne particles derived from marine organisms have on climate in the North Atlantic. The large annual phytoplankton bloom in this region may influence the Earth's energy budget. Research flights by NASA's C-130 aircraft from Wallops Flight Facility, Virginia, will be coordinated with a University-National Oceanographic Laboratory System (UNOLS) research vessel.

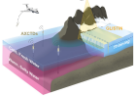
Atmospheric Carbon and Transport – America – Penn State University (Kenneth Davis)

This investigation will quantify the sources of regional carbon dioxide, methane and other gases, and document how weather systems transport these gases in the atmosphere. The research goal is to improve identification and predictions of carbon dioxide and methane sources and sinks using spaceborne, airborne and ground-based data over the eastern United States. Research flights will use NASA's C-130 from Wallops and the UC-12 from Langley Research Center in Hampton, Virginia.



ObseRvations of Aerosols Above Clouds and Their IntEractionS (ORACLES) – ARC (Jens Redemann)

ORACLES will probe how smoke particles from massive biomass burning in Africa influences cloud cover over the Atlantic. Particles from this seasonal burning that are lofted into the mid-troposphere and transported westward over the southeast Atlantic interact with permanent stratocumulus "climate radiators," which are critical to the regional and global climate system. NASA aircraft, including a Wallops P-3 and an Armstrong ER-2, will be used to conduct the investigation flying out of Walvis Bay, Namibia.



Oceans Melting Greenland (OMG) – JPL (Josh Willis)

The objective of OMG is to investigate the role of warmer saltier Atlantic subsurface waters in Greenland glacier melting. The study will help pave the way for improved estimates of future sea level rise by observing changes in glacier melting where ice contacts seawater. Measurements of the ocean bottom as well as seawater properties around Greenland will be taken from ships and the air using several aircraft including a NASA S-3 from Glenn Research Center in Cleveland, Ohio, and Gulfstream III from Armstrong.

CARVE, EVS-1, has just completed observations, is in a no-cost extension.

CMS At-a-Glance

- Started in response to a 2010 congressional appropriation
- Designed to characterize, quantify, understand, and predict the evolution of global carbon that can be affected by human activity through improved monitoring of carbon stocks and fluxes.
- Takes full advantage of and prioritizes NASA's ongoing (current and future) space-based observations and associated research and applied activities.
- Now budgeted for approximately $10M annually.
- NASA incorporates several other agencies into CMS through their participation in competitively-selected investigations (e.g., USDA, USGS, NOAA, EPA, and DOE)
- Includes three primary facets: biomass, flux, and scoping/outreach.
- 3 solicitations to date with 32 ongoing investigations.

NASA's high-level CMS Objectives

- Make significant contributions in characterizing, quantifying, understanding, and predicting the evolution of global carbon sources and sinks as well as biomass
- Use the full range of NASA satellite observations and modeling/analysis capabilities to support national and international policy and policymakers
  - Use space-based and in-situ data to maintain global emphasis while also providing finer scale regional information
  - Develop an evolutionary approach which accommodates planned increasing capabilities in space-based measurements, modeling, and data assimilation
  - Leverage capabilities of NASA centers and incorporate NASA-funded researchers through the competitive process
  - Continue to engage with and contribute to related U.S. and international systems
  - Create products to evaluate and inform near-term policy development and planning
- Ensure high quality community involvement through open solicitations and peer review.

National Aeronautics and Space Administration | Carbon Monitoring System (CMS)

CMS Core Elements

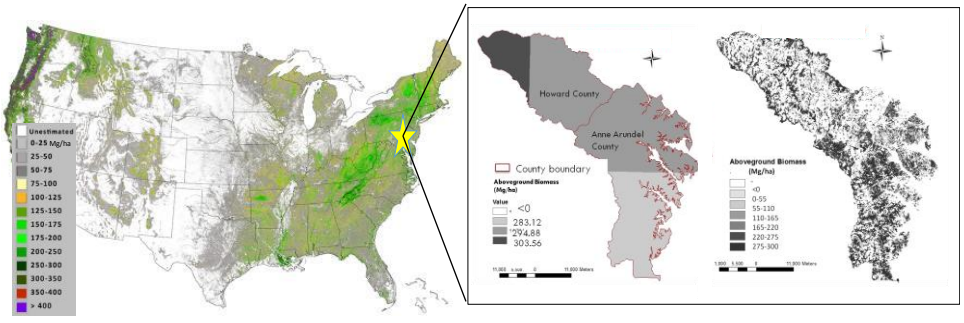
Biomass Pilot: Use satellite and in-situ data to produce quantitative estimates of aboveground terrestrial vegetation biomass on a national and local scale; and assess whether these results meet our monitoring needs (24 investigations, 15 ongoing)

***Flux Pilot*:** Combine satellite and model (terrestrial and oceanic) data to tie the atmospheric observations to surface exchange processes; and estimate the atmosphere-biosphere CO_2 exchange. (28 investigations, 18 ongoing)

Scoping/End User Engagement Efforts: Identify research, products, and analysis system evolutions required to support carbon policy and management as global observing capability increases. (3 investigations, 2 ongoing)

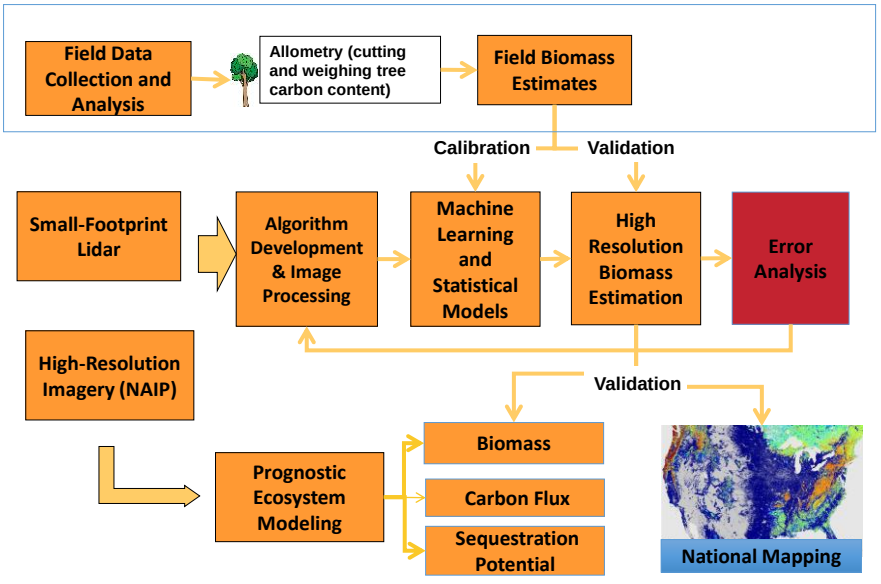
CMS Pilots: Biomass

The Biomass pilots combines Continental US estimates from imaging satellites with local airborne lidar observations of vegetation canopy biomass qualities. This allows one to scale up the local, more precise, observations more globally.

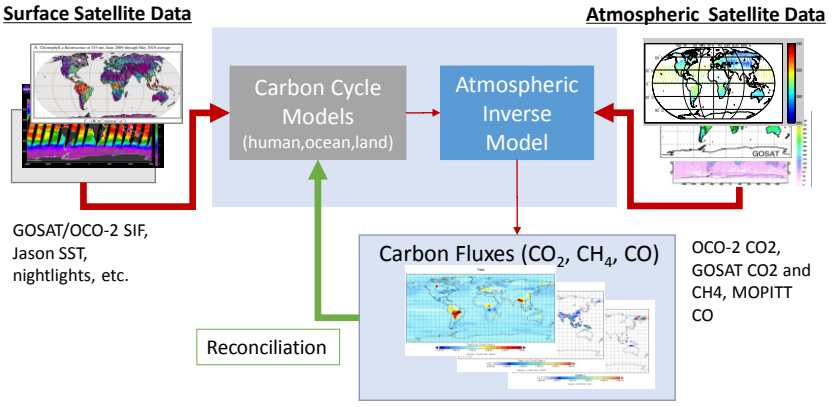


National Aeronautics and Space Administration | Carbon Monitoring System (CMS)

CMS-Biomass Framework



CMS-Flux Framework



CMS-Flux attributes atmospheric carbon (CO_2, CO, CH_4) to surface-atmosphere carbon fluxes using NASA satellites, modeling, and assimilation.

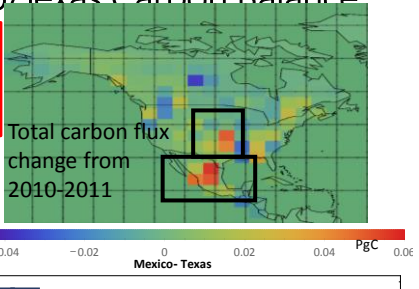
CMS-Flux products help reconcile carbon cycle processes, e.g., fires, drought, with atmospheric carbon observations

National Aeronautics and Space Administration | Carbon Monitoring System (CMS)

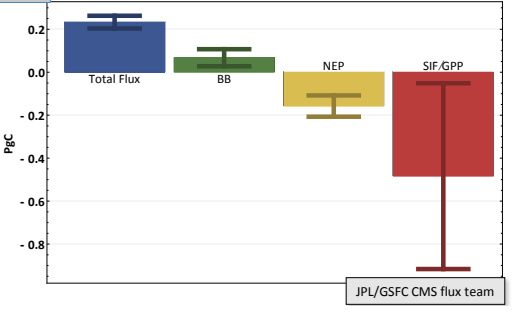
Impact of 2011 drought on Mexico/Texas Carbon Balance

In 2011, Texas and Mexico experienced recording breaking droughts leading to fires, livestock loss, and food shortages costing over 10 billion dollars. What was the impact on the regional carbon balance?

The CMS-Flux integrated satellite observations of xCO2 and solar-induced fluorescence(SIF) from GOSAT as well as CO from MOPITT to infer the constituent fluxes driving the Mexico-Texas carbon balance between 2011-2010.



- Mexico/Texas lost 0.23 PgC of carbon between 2011 and 2010.
- Approximately equal to fossil fuel production in Mexico/Texas.
- Caused by increases in biomass burning (BB) (~35%) and decreases in net ecosystem production (NEP) (~65%).
- Gross primary productivity (GPP) loss inferred from GOSAT SIF (Parazoo et al, 2013) was an important contributor to the NEP loss

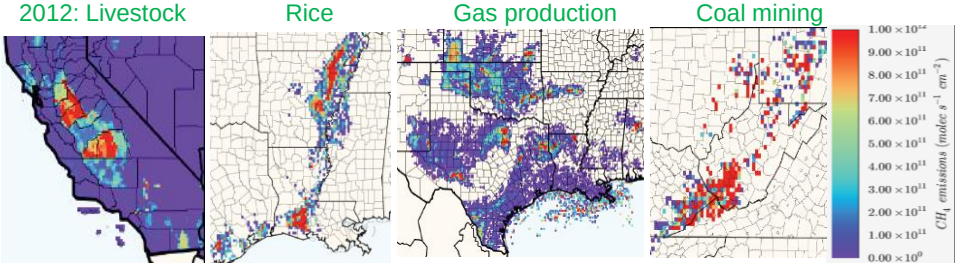


Gridded EPA national methane inventory for inverse analyses

A collaborative NASA CMS project

- **Motivation**: inverse analyses of satellite and suborbital methane data find the EPA national methane inventory to be too low by ~30%, but interpretation is difficult because the inventory is only available as national totals
- **This project** builds a layered 0.1ºx0.1º monthly version of the EPA inventory to guide inverse analyses and yield improved understanding of US methane sources
- Gridded inventory will be completed and publicly released in September 2015; EPA plans to host and distribute it.

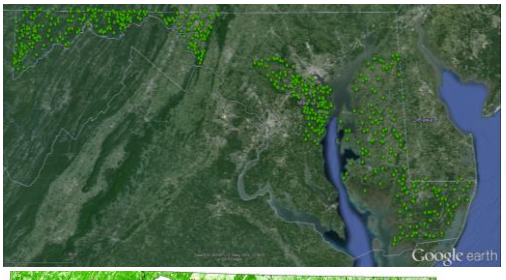
2012: Livestock | Rice | Gas production | Coal mining

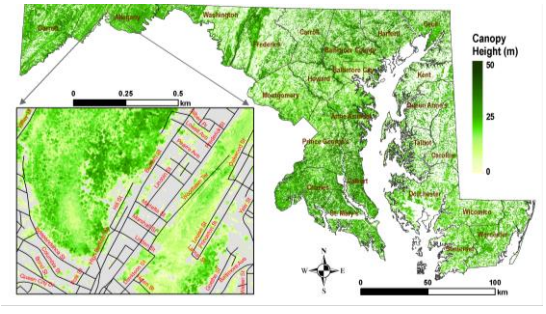


Harvard: Bram Maasakkers, Melissa Sulprizio, Daniel Jacob (PI)
EPA: Melissa Weitz, Tom Wirth, Cate Hight, Bill Irving

National Aeronautics and Space Administration | Carbon Monitoring System (CMS)

Calibrating Forest Structure: Field and Lidar Data





Plot Data in the Field

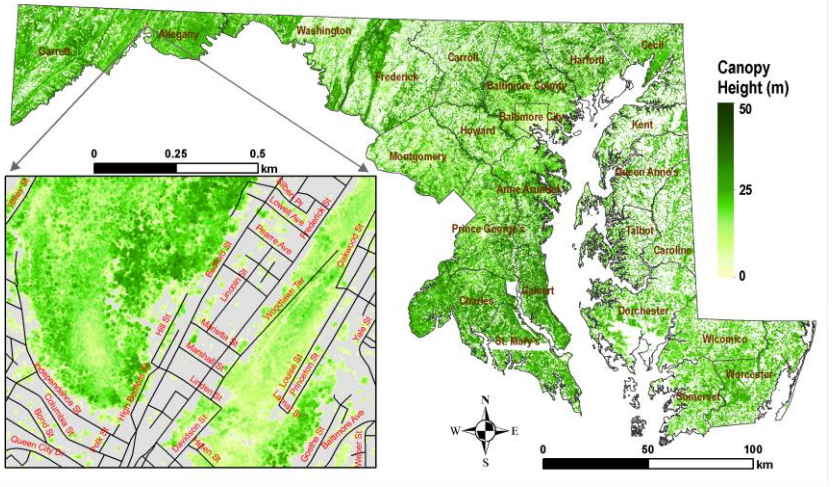
- Stratified sample
- NLCD strata
- Height classes
- ~ 800 variable radius plots
- Forest Inventory and Analysis (FIA) plots

Airborne Lidar Data

- Leaf-off/Leaf-on
- ~ 1 pt/m^2
- Canopy structure
- Multiple coverages

UMD/GSFC CMS biomass team

Lidar Canopy Height [1 m]



National Aeronautics and Space Administration | Carbon Monitoring System (CMS)

Carbon Monitoring System: An operational multi-sensor design for forest carbon monitoring to support REDD+ in Kalimantan, Indonesia.

- Background: Scientists at Applied GeoSolutions, Jet Propulsion Laboratory, Winrock International, and the University of New Hampshire are working with the government of Indonesia to enhance the National Forest Monitoring System in Kalimantan, Indonesia. The establishment of a reliable, transparent, and comprehensive NFMS has been limited by a dearth of relevant data that are accurate, low-cost, and spatially resolved at subnational scales. In this NASA project, we are developing, evaluating, and validating several critical components of a NFMS in Kalimantan, Indonesia, focusing on the use of LiDAR and radar imagery for improved carbon stock and forest degradation information.
- Highlight: As part of this project, Applied GeoSolutions and the University of New Hampshire have developed an Open Source Software package to process large amounts LiDAR data quickly, easily, and accurately. The Open Source project is called lidar2dems and includes the classification of raw LAS point clouds and the creation of Digital Terrain Models (DTMs), Digital Surface Models (DSMs), and Canopy Height Models (CHMs).
- Relevance: Comprehensive, well documented, freely available software for processing LiDAR data can enable countries such as Indonesia to cost effectively monitor their forests with high precision.

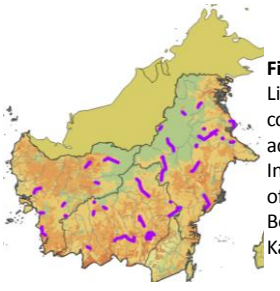


Figure 1: Our 2014 LiDAR data buy covers 104,000 ha across the Indonesian portion of the island of Borneo (i.e. Kalimantan)

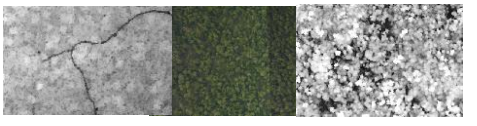


Figure 2. The freely available, open source software lidar2dems can be found at: http://applied-geosolutions.github.io/lidar2dems/

Applied · Geosolutions

University of New Hampshire

Contact: Stephen Hagen
shagen@appliedgeosolutions.com
Work funded by NASA Grant NNX13AP88G

Sonoma County End User Engagement Example

- Summer 2015 – Evaluate and incorporate CMS biomass estimates
- Fall 2015 – Publish vegetation map for 27 plant cover types using CMS LiDAR
- Fall 2016 – Publish vegetation and habitat map for 45 plant cover types using CMS canopy and vegetation height to crosswalk with California Wildlife Habitat Relationships classification
- Fall 2016 – Incorporate data findings into 10-year countywide conservation plan

SONOMA COUNTY AGRICULTURAL PRESERVATION AND OPEN SPACE DISTRICT

NASA Carbon Cycle!

- NASA's work in Carbon Cycle research and observations is extensive.
- CO2 observing missions are planned out into the future.
- GEDI, ECOSTRESS, PACE will take the next steps.
- The research programs are strong and take full advantage of these observations.
- The Carbon Monitoring System is being used as an integrating program to make this research more accessible to end users.