Climate Change Issues and Metrology Challenges
U.S. Projects – INFLUX, LA Basin

An Opportunity for the Global Metrology Community

Planning Workshop for an Initiative

on

Renewable Energy and Climate Science for the Americas:

Metrology and Technology Challenges

CENAM, October 8-9, 2013

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NIST

Agenda

Address 3 Questions:

- What is NIST's Greenhouse Gas and Climate Science Measurements Program and How Do INFLUX and the LA Megacity Carbon Project Fit Within It?
- What Could be the Impact on the NMI's of the Americas and other Regions?
- What Could Be a Path Forward

- A Little Background on Earth Systems
- The Current Landscape
- Greenhouse Gas Measurement Needs in the Future
- International Interests and Drivers
- Cities and Megacities
- An International Greenhouse Measurements Test Bed Framework Concept
- Summary
- NIST Greenhouse Gas and Climate Science Measurements Program

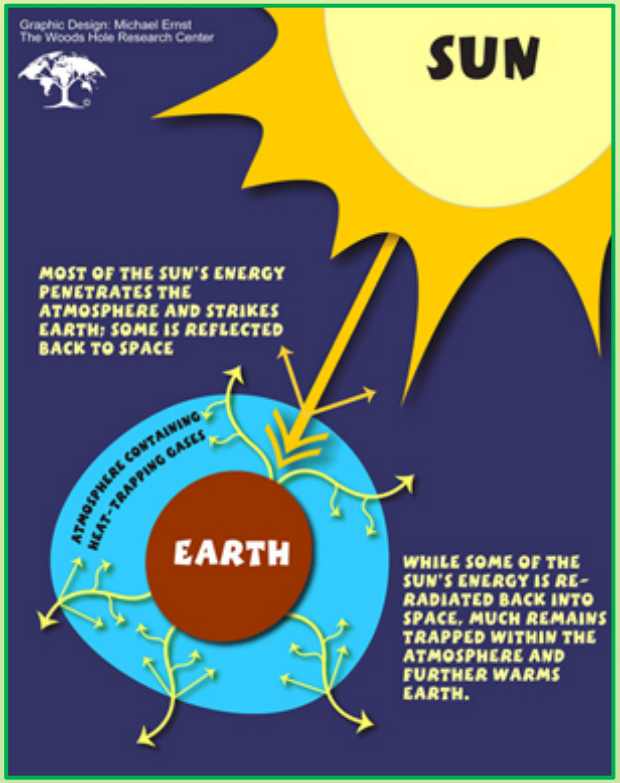
Earth's Systems are Powered by Solar Photons

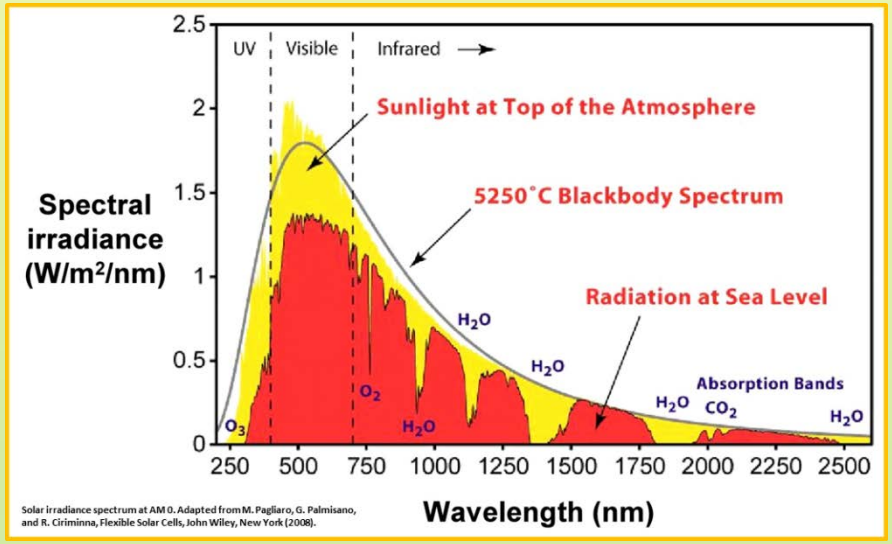
Fate & Effects of Incident Photons

Solar Energy falling on the Earth's surface undergoes numerous physical processes.

Effects on incoming solar photons:

- Reflection and scattering by clouds, particles, and molecules in the atmosphere
  - Scattered in the atmosphere & don't impact the Earth
  - Scattered & reflected by the Earth's surface through the atmosphere to space
- Energy conversion by various mechanisms at Earth's Surface
  - Photosynthesis converts photons to biochemical energy
  - Surface absorption & conversion
    - Man-Made Surfaces – roads, parking lot surfaces, buildings
    - Natural Surfaces – soils, rocks, rivers & streams, oceans





Radiative Processes & Effects

- The Sun is a high temperature radiation source emitting short wavelength radiation – visible & ultraviolet
- Components of Earth's atmosphere selectively absorb solar radiation on its way to the surface
  - Ozone (O_3) strongly absorbs UV radiation protecting plant and animal life on Earth's surface
  - The greenhouse effect:
    - maintains Earth's surface temperature near 23° C
    - driven by strong infrared absorption
    - water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halocarbons

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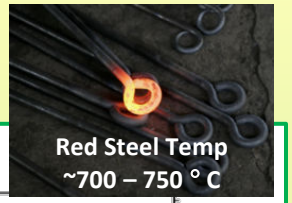
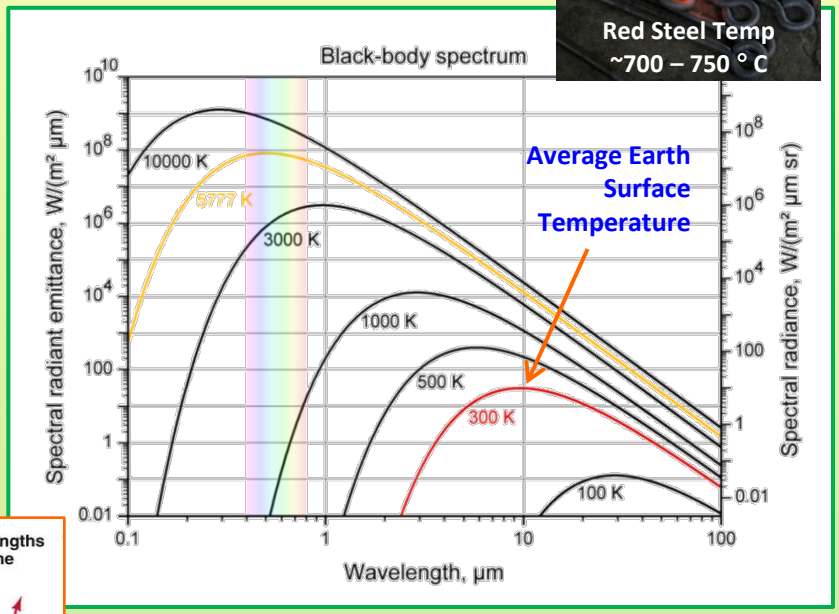
Earth's Greenhouse

Powered by Solar & Earth's Radiation



Earth's Surfaces Emit Radiation

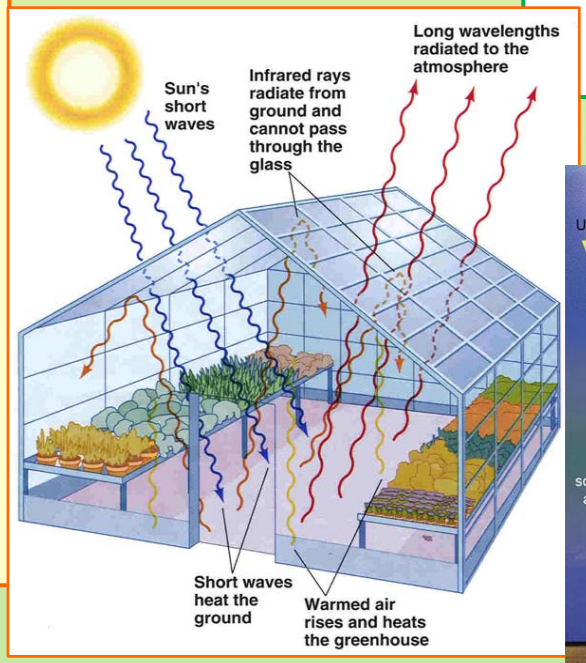
- Earth's surface absorbs & converts shortwave radiation, visible and near ultraviolet, to longer wave radiation in the infrared
- Thermal, or Blackbody, radiation intensity depends on surface temperatures
- ~9.7 μm radiation emitted by an ~295 K (~23 °C) surface temperature



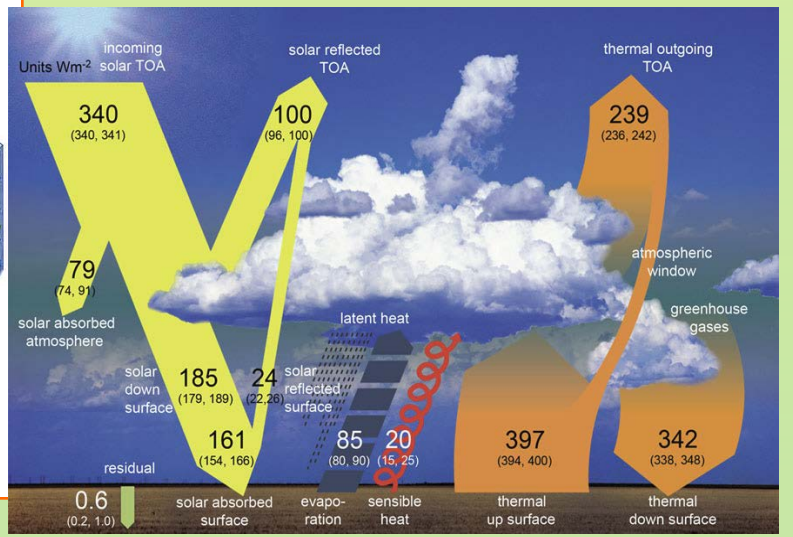
Selective Absorption Warms Atmospheric Gases

- Earth's surface acts as a radiation source, re-emitting thermal radiation in the infrared
- Molecular gases, CO_2, CH_4, N_2O, & H_2O strongly absorb thermal radiation over ~ 2 – 30 μm,
- Small concentration have large effects due to their absorption strength
- Molecular collisions quickly transfers absorbed thermal energy to the major atmospheric gases, N_2 & O_2
- Radiate back to the surface

Earth's Greenhouse



Earth's Energy Budget



Wild, Folini, Schar, Fold, Loeb, König-Langlom. Clim Dyn (2013) 40:3107–3134

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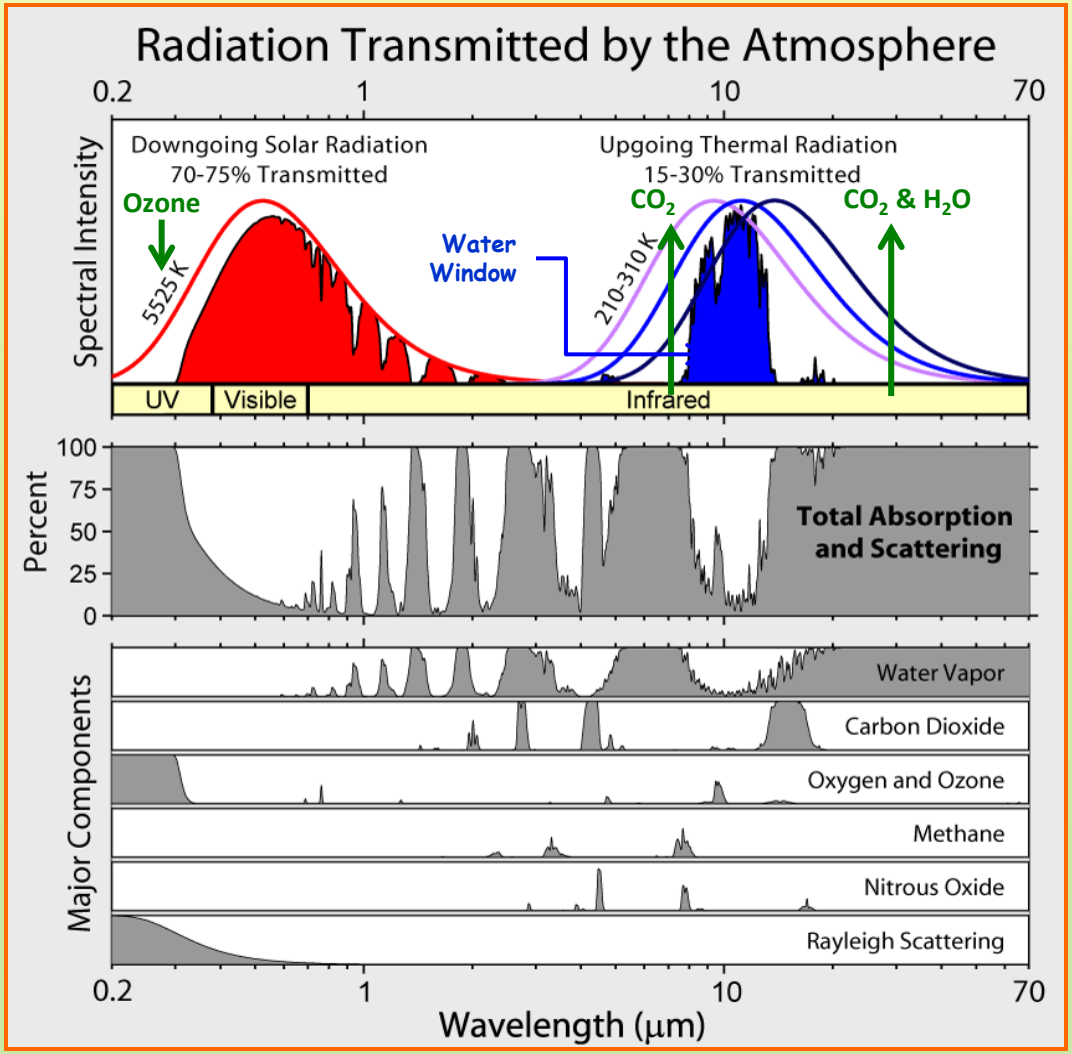
NIST Program Rationale

Greenhouse Gas and Climate Science Measurements Research Focus



- **Radiometric Measurements & Standards**
  - Solar Irradiance (received) & Radiance (source, reflected and emitted)
  - Improved Standards for Satellite and Remote Observations
    - Top of the Atmosphere – Solar Incoming
    - Standards and Methodologies Advancing Various Measurements
  - Advancing measurement capabilities for surface measurement
    - Surface – Energy at Earth's surface
- **Advanced Measurement Tools**
  - High Accuracy Optical Spectroscopy of Greenhouse Gases at Atm. Conc. Levels
  - Remote sensing – surface and satellite based
  - New generations of concentration measurement instruments – Cavity Ringdown Spectroscopy
  - Higher sampling rate approaches for stable and unstable isotope measurements used as ecological process tracers
- **Urban and Regional Measurements**
  - Inventory Data Diagnostic and Verification Methodologies

Current Climate Observation and Measurement Systems

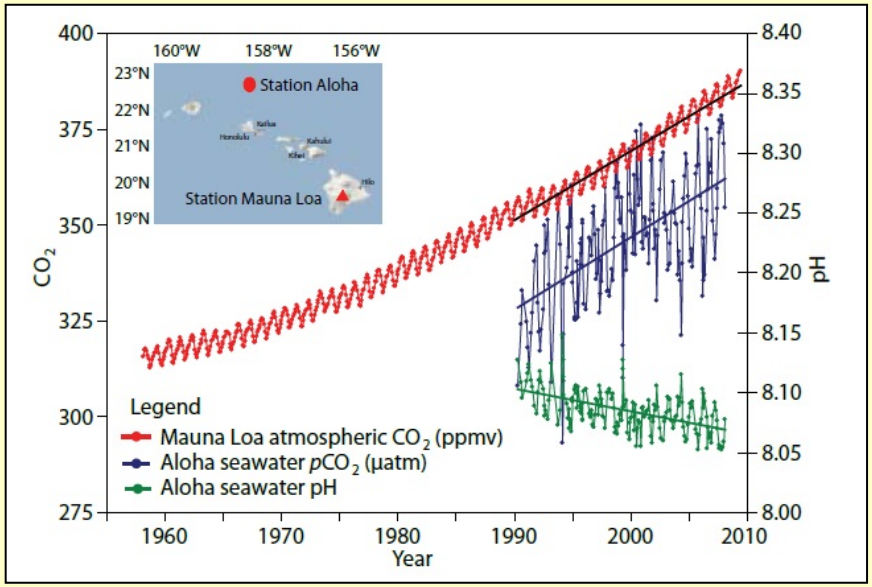
Global Focus – the Climate Science Community

Climate Science Community is Focused on the Global Climate System

- **Research Agency Focus – Global Behaviors (Atmosphere & Ocean)**
  - Much Smaller Focus on Data Underpinning GHG Inventories in the U.S.
  - Largely Outside the Climate Science Community
- **Observations are Central to Scientific Advances**
  - Satellite and Surface-Based Systems
- **Ecological Process-Driven Research**
  - Interactions between land, atmosphere , & ocean
  - Forests, agriculture, oceans (coastal and deep), etc.
- **Earth System Impacts**
  - Greenhouse Gas Mitigation is a rallying point
  - Ecological Tipping points are a major concern
  - GHG inventory information often used to compare and assess human-induced and natural impacts on atmosphere, land & oceans

13 U.S. Global Change Research Program Agencies
Natural Earth System or Agricultural Process Focus

CO_2, pCO_2, and pH Time Series



Time series of atmospheric CO_2 at Mauna Loa (in parts per million volume, ppmv; red), surface ocean pCO_2 (µatm; blue) and surface ocean pH (green) at Ocean Station ALOHA in the subtropical North Pacific Ocean. Note that the increase in oceanic CO_2 over the past 17 years is consistent with the atmospheric increase within the statistical limits of the measurements.

Mauna Loa data courtesy of Pieter Tans, National Oceanic and Atmospheric Administration/Earth System Research Laboratory ; Hawaii Ocean Time-Series (HOT)/ALOHA data courtesy of David Karl of University of Hawaii ; see also Dore et al., 2009

International Climate Policy Drivers

Focus on Greenhouse Gas Mitigation Issues

International Greenhouse Gas Mitigation Efforts are being founded on concepts and practices central to NMI missions and that of the International NMI Community.

- **Consistency, Transparency, Accuracy and Comparability of GHG inventories.**
- **The Capability to Measure, Report, and Verify GHG Inventories will be keystones for their recognition internationally.**
- **Concepts in UNFCCC's Bali Action Plan, and its likely antecedents, appear to be based on proven scientific principles used by NMIs throughout their operations.**

The Bali Action Plan, Section 1 – UNFCCC Convention of the Parties #13, 2007

- Recognizing that deep cuts in global emissions will be required …,
- Decides to launch a comprehensive process to enable the full, effective and sustained implementation of the Convention … to reach an agreed outcome and adopt a decision at its fifteenth session, by addressing, inter alia:
  - A shared vision for long-term cooperative action, including a long-term global goal for emission reductions, … ;
  - Enhanced national/international action on mitigation of climate change, including, … of:
    - a) *Measurable, Reportable and Verifiable (MRV) Nationally Appropriate Mitigation Commitments Or Actions (NAMAs),* including quantified emission limitation and reduction objectives, by all developed country Parties, while ensuring the comparability of efforts among them, taking into account differences in their national circumstances;
    - b) Nationally appropriate mitigation actions by developing country Parties in the context of sustainable development, supported and enabled by technology, financing and capacity-building, in a measurable, reportable and verifiable manner;
    - c) …

Issues & Opportunities

- GHG Mitigation Policies closely linked with national energy/energy security
- MRV Concepts of the Bali Action Plan have become widespread in climate mitigation discussions
- Opportunity may arise to more closely define MRV definitions, i.e., independent verification
- Desire to reduce environmental impacts, while promoting sustainability
- The international economic community relies on, and often takes for granted, services provided by the NMI.
- This affords the NMI community with an opportunity.

Supporting International Greenhouse Gas Mitigation

An Opportunity for NMI's

National & International Economic System Involvement

- **NMI Interaction, Participation, and Role**
  - Classic weights and measures activities ensuring equity in trade and in regulation
  - Advances in the science and technologies of standards and measurements
    - Establishing and consolidating the SI
    - Meeting the standards needs for advances in science and technology
      - Extending standards for advancing technologies
      - broader involvement in chemical and biochemical measurements and standards
    - Advanced measurement capabilities
      - Cavity Ring-Down Spectroscopy – gas concentration for field measurements
  - Confidence in the scientific validity of measurements and standards systems developed and disseminated by NMI's
- **Variable confidence in the climate science community on climate change**

- **Meet the Measurements and Standards Needs of Greenhouse Mitigation**
- **Provide the International Recognition for the Measurement Systems Required**

Greenhouse Gas Measurement Needs in the Future

Combined Satellite and Surface-Based Measurements: 2020 - 2050

GHG Observing Satellites On Orbit
- GOSAT - Japanese Aerospace Exploration Agency

Planned Systems - NASA
- Orbiting Carbon Observatory (OCO II) - 2014
- OCO III – Intnt'l. Space Station – 2017?
- ASCENDS (Active Sensing of CO_2 Emissions over Nights, Days, and Seasons) – Launch Date?

System Development - ESA
- CarbonSat –CO_2 and CH_4 observations

Satellites - Total-Column Integrated Greenhouse Gas Concentration Measurements

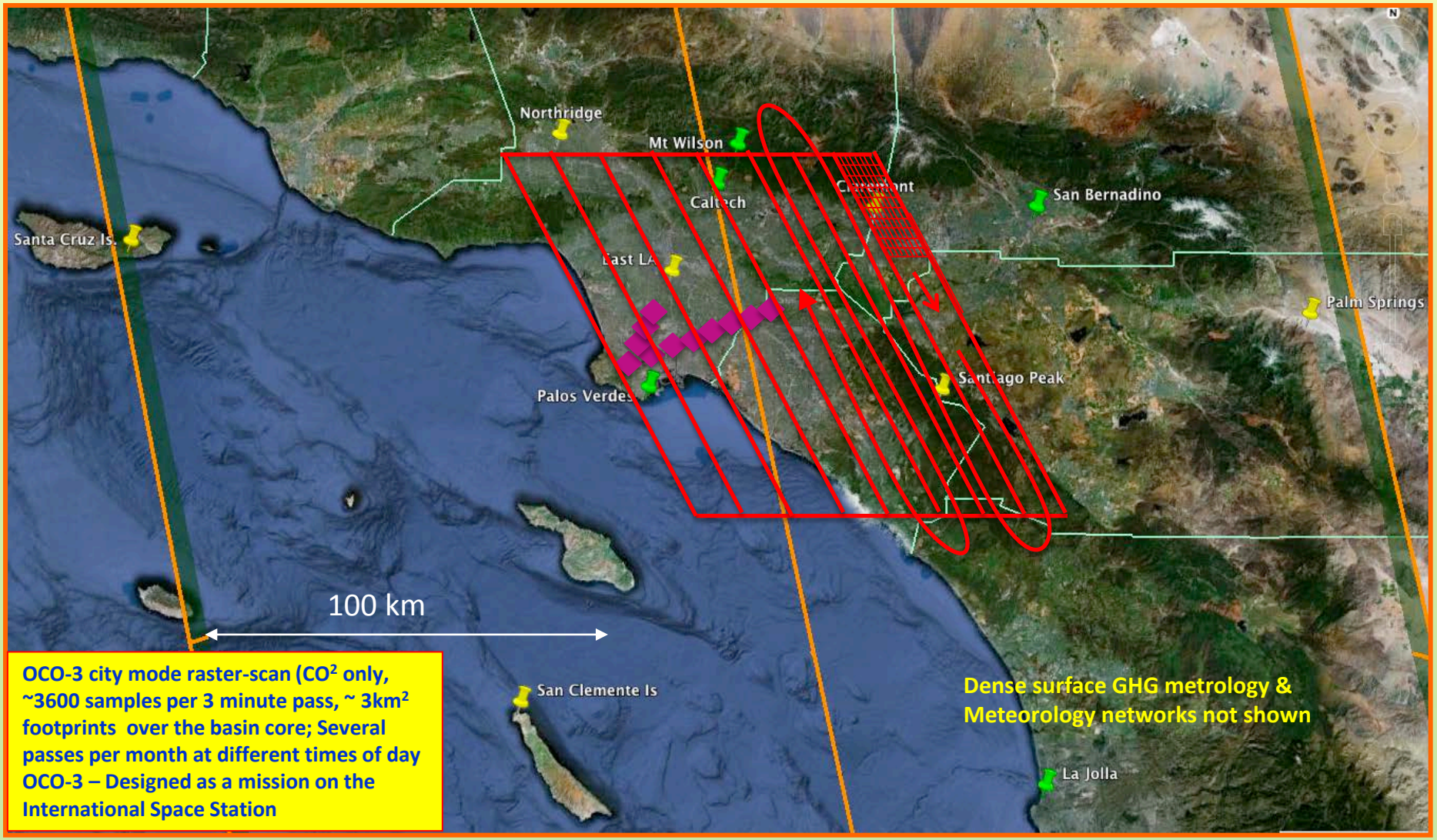
- Multiple satellite-based instruments on planned or on orbit
  - Low Earth (LEO) and Geosynchronous Orbits (GEO)
  - Most will use near-infrared spectroscopic instruments
- Effective and recognized traceability strategies will be needed
  - GHG concentration sensitivity at the 1 in 400 or better level and observing footprints of ~3 to 10 km^2
  - Vertical concentration profiles (atmospheric boundary layer and lower troposphere) are temporally variable and will be needed to reduce inaccuracies
- Do not make GHG flux measurements as currently conceived, GHG concentration only

Surface-Based Systems Greenhouse Gas Concentration and Transport (Flux) Measurements

- Flux measurement capability can support attribution and independent verification of inventory data
  - Atmospheric GHG transport relies upon atmospheric boundary layer measurement and modeling
- 1 - 5 km^2 or better geo-spatial resolution
- New measurement methodologies needed for independently diagnosing and ultimately verifying inventory data
- Calibration capability for satellite observation of

Satellite GHG Monitoring – A Future Example

OCO-3 City-Mode over a Megacity (LA Example, ~ 2018)



Existing/planned GHG station | Proposed GHG stations | GOSAT samples | OCO-2 samples (1 x 3 km spot | OCO-3 samples

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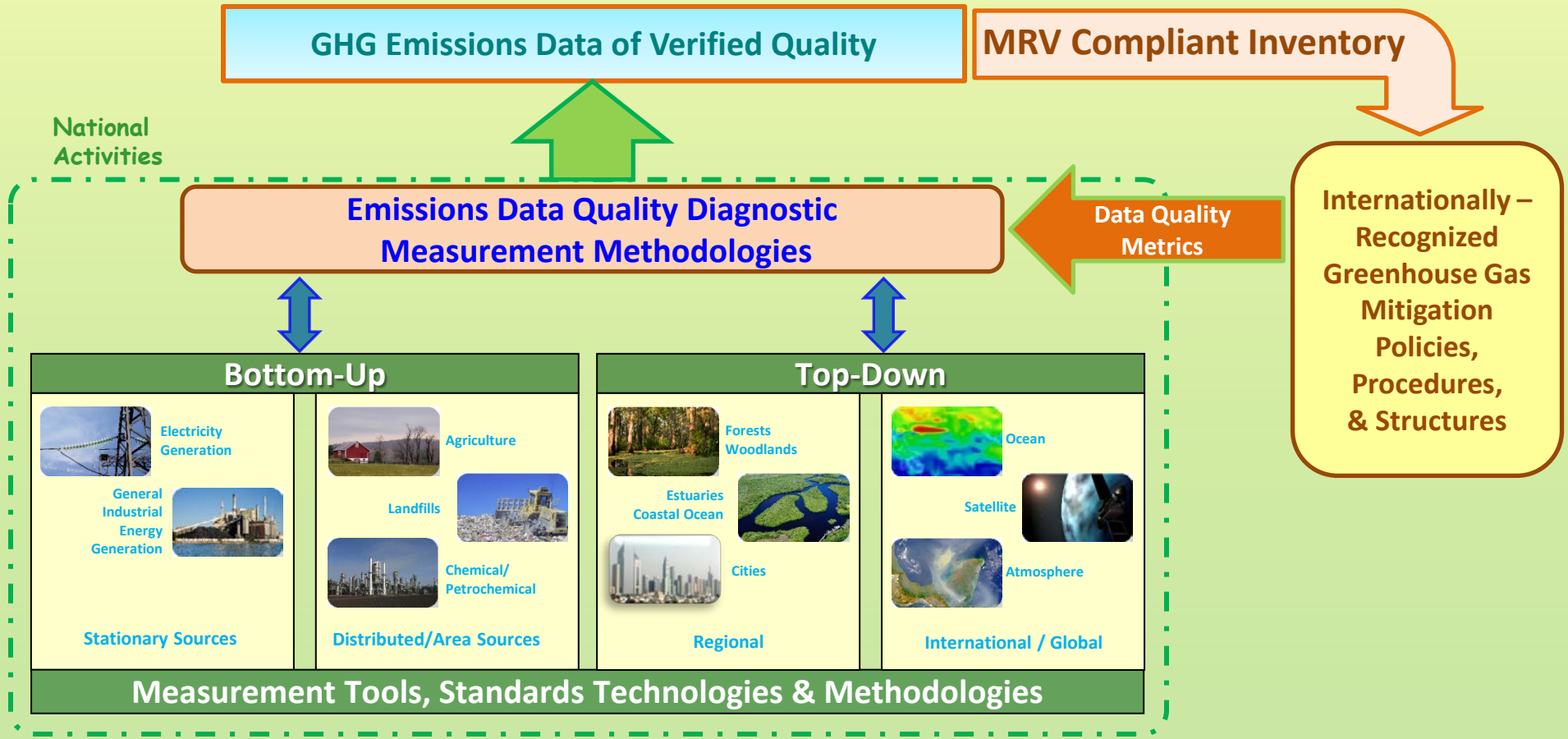
Measurement Systems Concept Supporting Mitigation

Enhancing Consistency, Transparency, Comparability, and Accuracy



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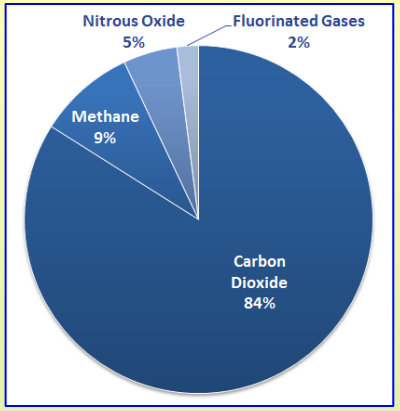
What is NIST Doing in Greenhouse Gas and Climate Science Measurements



2011 U.S. Emissions
6,702 M Metric Tons CO_{2e}

Program Objectives:

- **Develop advanced measurement tools and standards:**
  - Improve the accuracy capability for:
    - Greenhouse gas inventory data, and
    - Remote observations, both satellite and surface-based

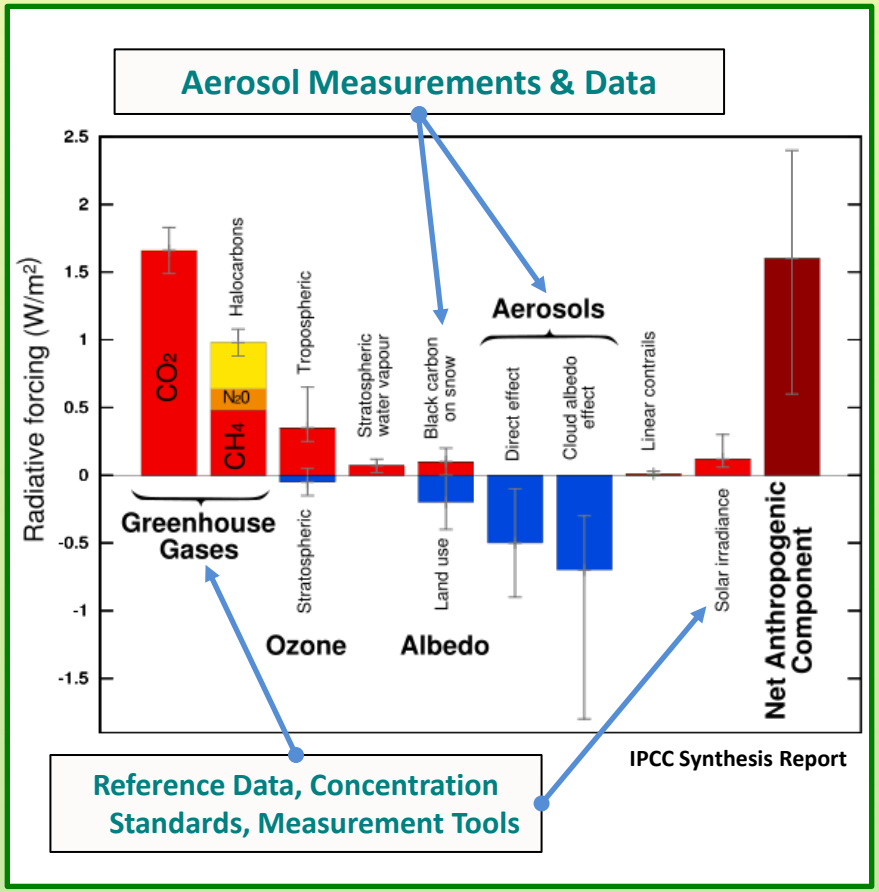
    with an emphasis on cities and metropolitan areas.
  - Independently verify greenhouse gas emissions inventories both nationally and internationally, and
  - Extend measurement science to better understand and describe the Earth's climate and its change drivers.
- **Enable international measurement standards and protocol developments that ensures accuracy, confidence, and reliability of local and global assessments of GHG emissions.**

GHG Emissions Data, the basis for:
- National GHG inventories
- Basic data/information utilized by future market-based and/or regulatory-based mitigation policy mechanisms
- Primary atmospheric radiative forcing agents

Remote Observations:
- A Mainstay for Climate Observations
- Accuracy and continuity of climate data records
- Potential applications in GHG mitigation policy verification

Program Components

Greenhouse Gas and Climate Science Measurements



- **GHG Measurements Tools, Standards, and Reference Data**
  - GHG Concentration Standards
  - Spectroscopic Reference Data
  - Surface Air Temperature Assessment
- **Climate Science Measurements - Advanced Satellite Calibration Standards**
  - Optical and Microwave
- **Aerosol Measurement Science**
  - Black Carbon Optical Properties
  - Black Carbon Reference Materials and Measurements
- **Stationary/Point Source Metrology**
  - Test Beds for Continuous Emission Monitoring Technologies
- **Distributed GHG Source Metrology**
  - GHG Flux Measurement Tools
    - Differential Absorption Lidar Developments
  - Measurement Approaches in Urban Settings
    - Dense GHG Observing Networks – Measurements to Independently Verify GHG Emission Inventories
    - Indianapolis Flux Experiment
    - Los Angeles Megacity Carbon Project: Extension to Megacities and Development of an International Metrology Framework for MRV

URBAN GREENHOUSE GAS MEASUREMENTS

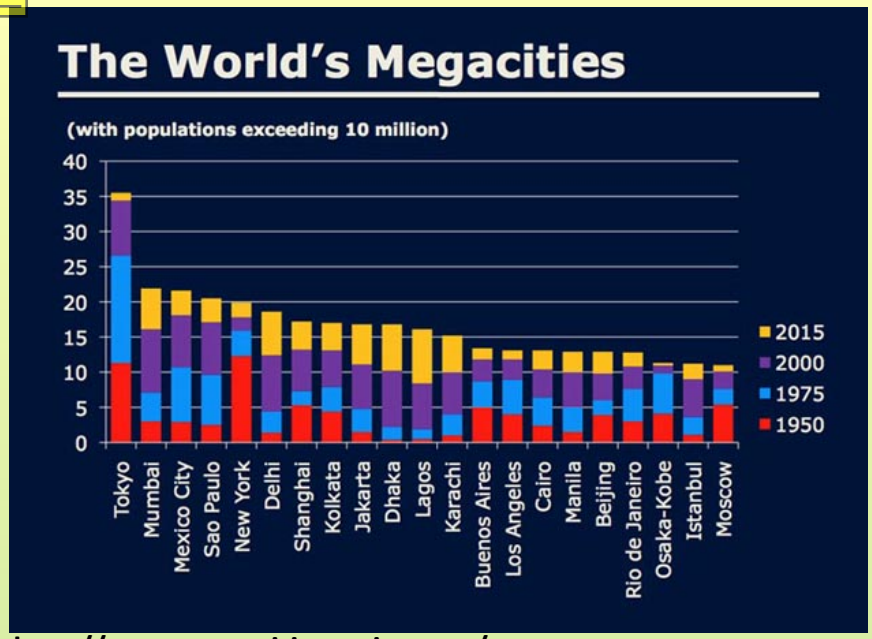
A PROPOSAL TO ESTABLISH AN INTERNATIONAL TEST BED FRAMEWORK

Questions:

- Why Cities ?
- U.S. Examples of Urban GHG Measurements and Test Beds
  - Cities and Megacities – The Indianapolis Flux Experiment and the LA Megacity Carbon Project
- An International Test Bed Framework Concept
- Can Convention of the Mètre Structures be used to Establish a Measurements and Standards System Supporting International GHG Mitigation Agreements ?
- What are Challenges for NMI's

  - Setting up a test bed –
  - Top Down and Bottom Up Emissions Determinations & Uncertainties

Megacities Pose a Significant Measurement Challenge



http://www.megacitiesproject.org/

Surface Observation Networks for Urban GHG Dome Characterization

- Metrolitan Areas are forecast to have ~80% of worlds population by 2050
  - U.S. forecast to be 90%
- Aggregated GHG emissions of Top 40 MegaCities rank 3rd behind the U.S. and China.
- Policy implementation done by cities
- Cities are pro-active & information users

- The C40 Organization
  - Formed by city Mayors
  - Current Chair – M. Bloomberg, NYC
  - Steering Committee:
    Berlin, Hong Kong, Jakarta, Johannesburg, Los Angeles, London, New York City, Sao Paulo, Seoul & Tokyo
  - Current Members
    - 58 cities world wide

C40 CITIES Climate Leadership Group
CLINTON CLIMATE INITIATIVE
Bloomberg Philanthropies
ICLEI Local Governments for Sustainability
The World Bank
ARUP
CARBON DISCLOSURE PROJECT

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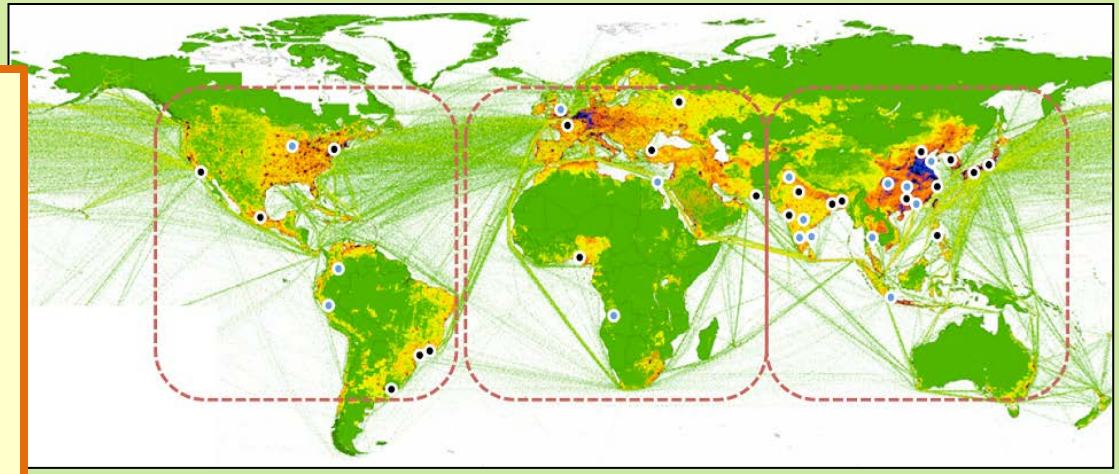
City Gov’ts Need Actionable Information

Decision Makers, Regulators, and/or Markets Need Reliable and Actionable Information – at geospatial scales that:

- **Identify the Location of Emission Sources**
  - Where To Go and Who Has Responsibility for the Emission or Removal
  - GHG Inventories are composed of many information sources found at local levels
  - Diagnose and Reconcile Emissions Data Discrepancies
  - Ultimately Validate Emissions Data with Independent Measurement Results
- **Provide reliable GHG flux Information with an unquestioned scientific basis**



Scientific / Technological Questions & Challenges

- High Fidelity at Smaller Spatial Scales
- Identifying Emission Sources
  - Geospatial resolution of a few km^2
  - Measuring emission flux
- Characterization & Modeling Atmospheric Boundary Layer Dynamics at ~1 km scales
- Bridging the Research to Operations Gap
- Connecting Measurement Results with Mitigation Policy

Developing &Demonstrating Greenhouse Gas Measurement Tools at Urban Scales in the U.S.

The Indianapolis Flux Experiment (INFLUX)

A Top-Down/Bottom-Up Greenhouse Gas Quantification Experiment in the City of Indianapolis, Indiana

The LA Megacity Carbon Project

The Indianapolis Flux Experiment (INFLUX)

A Top-Down/Bottom-Up Greenhouse Gas Quantification Experiment

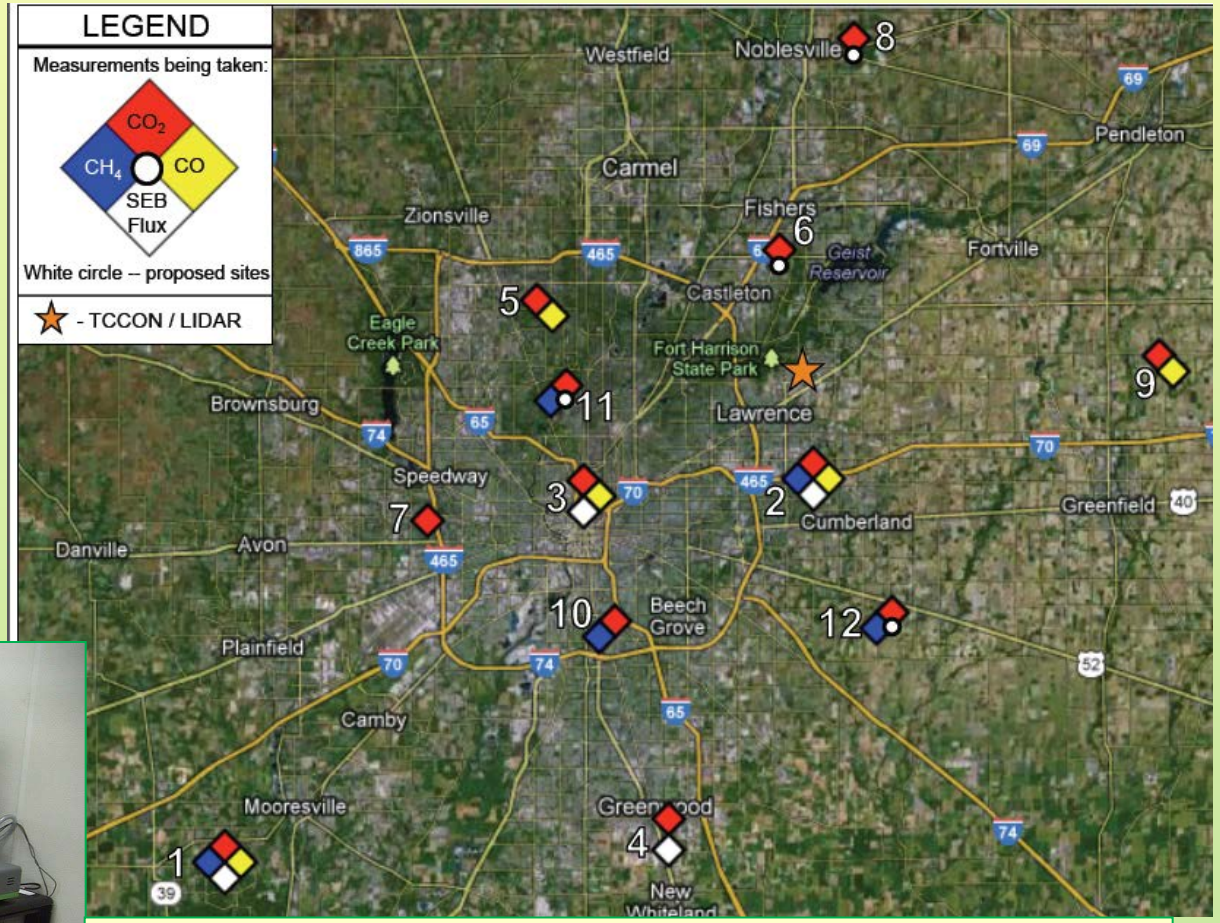
Objective:

Develop measurement tools to provide independent verification of greenhouse gas inventories at urban and regional scales

- **Phase I – NIST and university partners initiated the INFLUX (Indianapolis Flux) Experiment in 2010 as a Pilot project**
  - Can the mass of CO_2 emitted by a small city be measured with quantified uncertainty using top-down and bottom-up methods?
  - Combined Aircraft and surface-based measurement methodology
  - High temporal and spatial resolution CO_2 inventory – Augmentation of EPA information
- **Phase II – Demonstrate measurement, characterization, and quantification of GHG Urban Domes and their dynamics utilizing a *Dense Measurement Network* approach coupled with aircraft observations :**
  - A measurement method of demonstrated performance supporting the concepts of Measurable, Reportable and Verifiable (MRV) GHG Emissions and Removals
  - Demonstrate reconciliation methodologies for bottom-up (self-reported) inventory statements with top-down measurement results
- **An Interdisciplinary Research Effort Advanced by Recent Technological Advances in:**
  - Real time measurements of greenhouse gas mixing ratios in the atmosphere,
  - Atmospheric boundary layer measurements and models,
  - GHG inventory determination at urban spatial scales, and
  - GHG plume inversion methodologies.
- **Quantitative Goals**
  - Measure emission fluxes to within 10% or better
  - Identify major emitter locations within 1 km^2

INFLUX Dense Observing Network

Ground-Based Instrumentation and Observing Network



Tower 1, Mooresville

- On left is the CO_2-only Picarro.
- On right is the 4 species Picarro Analyzer (CO_2/CH_4/CO/H_2O) placed above the NOAA flask sampling system - pressurized Flask Package in foreground.
- Calibration tanks in the background.

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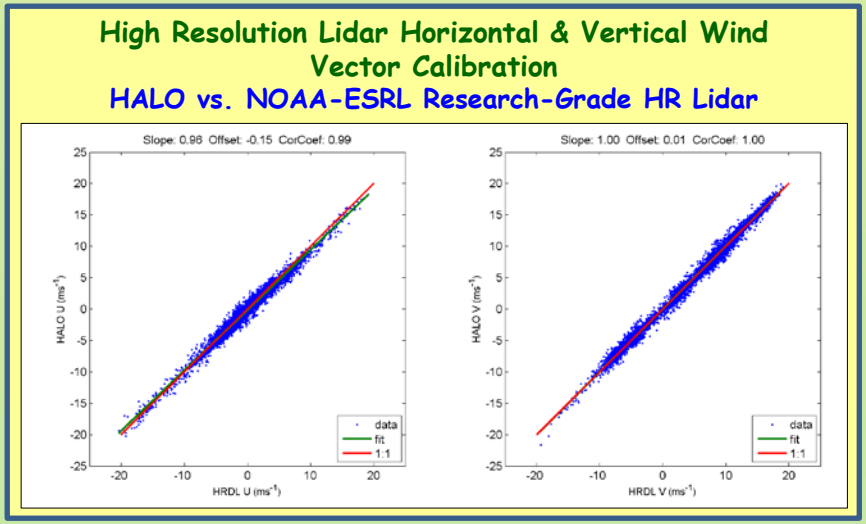
Current Status

- Aircraft experiments are to be published in the next few months – Purdue Univ.
- 12 Towers Became Operational - ~ May 1, 2013 – PSU, Earth Networks, NIST
- Flask samples analyzed for ~40 trace gases including $^{14}CO_2$ as a fossil fuel CO_2 tracer – Univ. of Colorado (NOAA)
- Modeling System is operational – PSU (Pennsylvania State Univ.) & NIST
  - Requires additional constraining parameter measurements to improve WRF accuracy – High Resolution Lidar for ABL height, 3D wind vector, and turbulence intensity measurements
  - Surface Energy Flux measurements are being installed to better characterization land-atmosphere interaction parameters
    - 2 operational, 3 additional to be installed in 2013
  - High resolution Lidar system being installed now for boundary layer characterization
  - Inversion models operational with encouraging initial Inversion results
- INFLUX to be operational at least until 2016 - 2018 to demonstrate performance capabilities over a range of weather and seasonal changes



The LA Megacity Carbon Project

Motivation:

Determine GHG emissions of a city in terms of measurement uncertainty.

Currently estimated differences between actual and reported emissions that by 50% or more when comparing inventory estimates with atmospheric measurements for a specific location, sector or gas.

Objective:

Demonstrate a scientifically-robust capability to measure multi-year emission trends of carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) attributed to individual megacities and selected major sectors.

Reduce uncertainty by jointly improving GHG emissions data and atmospheric observations.

Use independent and accurate measurements, identify error sources to improve emissions data quality and ultimately, validate basis for emission inventory.

Approach:

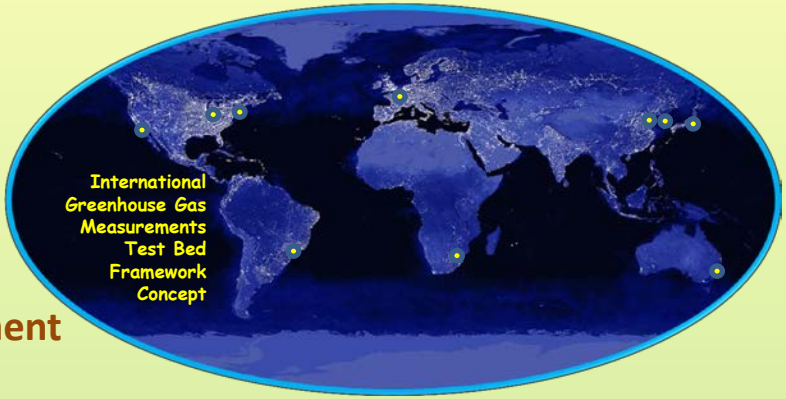
Use dense GHG observing networks and aircraft observations coupled with state-of-the-art boundary layer measurements and characterization methods to observe trends in the emissions in / to / from the South Coast Air Basin.

MegaParis CO_2 Project

http://co2-megaparis.lsce.ipsl.fr/#en

International Greenhouse Gas Measurement Test Bed Framework

International Metrology & Climate Communities Engagement

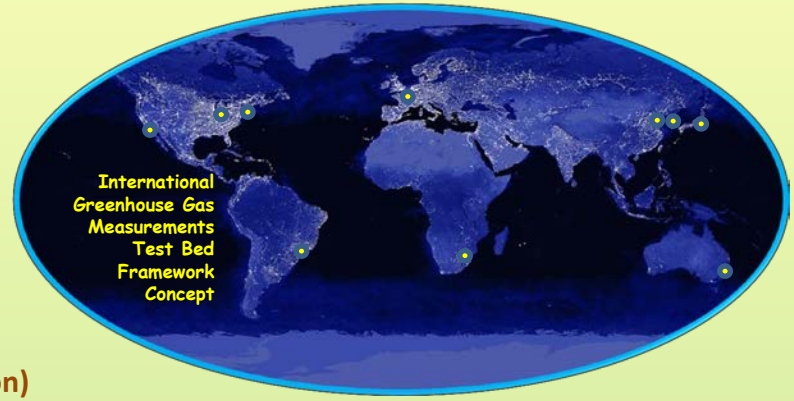


Concept:

- **Establish an International Greenhouse Gas Measurements Test Bed Framework that:**
  - Enables joint development of advanced measurement capabilities for urban and regional GHG domes and their dynamics,
  - Establishes scientific validity and performance capabilities of advanced measurement methodologies and instruments,
  - Provides a focus for multi-organization efforts with locations and organization on all continents but Antarctica,
  - Facilitates open, internationally-recognized measurement methodology development and evaluation with open data exchange and utilization across national borders, and
  - Strengthens methods to correlate and calibrate satellite measurements in-situ with those made on the surface as a means to establish SI traceability
- **As the Basis for Global Recognition of Measurement Capabilities for:**
  - Diagnosing the quality of GHG emissions data and
  - Verification support for global Measurement, Reporting and Verification (MRV) concepts likely to be required by future international mitigation agreements

International Metrology & Climate Community Engagement

International Greenhouse Gas Measurement Test Bed Framework



Approach:

- **Utilize population centers, megacities, as test bed sites of an international framework for joint development of urban GHG measurement methodologies.**
- **Engage with nations or regions that have:**
  - Suitably located megacities (one or two cities per continent / region)
  - The scientific and technological capabilities needed, and
  - The necessary national interest and will to commit the resources necessary
- **Joint GHG measurement science research to develop and demonstrate methodologies thoroughly vetted for their scientific foundation, accuracy, and recognition within the international community.**
- **Use structures of the Convention of the Mètre**
  - Existing, internationally-recognized treaty organization with well-demonstrated working relationships and the necessary organizational structures largely in-place
  - Facilitate communication, organization
  - Broaden international linkages – WMO, international climate change/science

Facilitating Organization Linkages

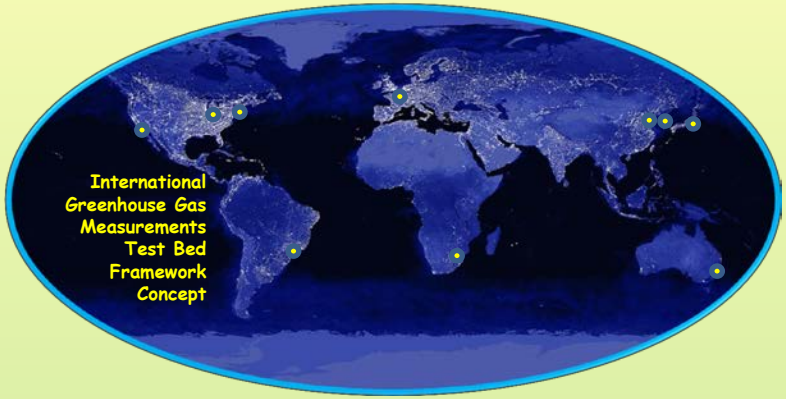
- Individual cities, Mayor Organizations
- International cities organizations – C40
- International Climate Organizations
  - WMO
  - GEO – Global Earth Observations

Some Challenges for NMIs

- **Most NMI's currently may not have the necessary skill sets and connections**
  - Partnering with national organization to aggregate the necessary technical resources / expertise necessary to address this class of measurement science research
  - Strengthen expertise in climate science and related disciplines to successfully interface with both the national climate science community and the international community

International Metrology & Climate Communities Engagement

International Greenhouse Gas Measurement Test Bed Framework



Recent Discussions

- **Asia: China**
  - Oct. 2011 – NIM Workshop on Climate Change Metrology and Initial Megacity Concept Discussions
  - Sept 2012 – Workshop on Measurements and Standards for Climate Change, ~17 agencies & Univ. attending
- **The Americas: Brazil (INMETRO) and SIM (Gen. Assembly Mtg. at CENAM, Oct. 2013)**
  - Brazil, Early 2011 – Initial Concept Discussion & Participation in the 1st LA Megacity workshop & Initial Planning of a Joint INMETRO-NIST Workshop in Brazil (2014).
  - SIM – OAS – NIST workshop following SIM General Assembly Meeting (Oct. 2013)
- **The European Union**
  - April 2012 NIST GHG Program Overview at LNE attendance by NPL & VSL
  - Feb. 2013 NPL, International NMI Conference on Low Carbon and Climate Science
  - April 2013 PTB, GHG Program Overview, 2nd ERMP Symposium
- **Australia: NMIA**
  - Oct. 2011 – NIST GHG Program Overview – Dept. of Climate Change and Energy Efficiency.
- **Africa: South Africa**
  - April 2013 – Informal discussions, email follow-up
- **BIPM**
  - Discussion of BIPM Facilitation and Liaison Role (April 2013)

Summary

- **Populations are concentrated in cities and urban regions localizing energy usage and GHG emissions.**
  - **Current trends forecast continued growth**
- **Suitably located megacities could be the focus of international engagement in joint GHG measurement system development and demonstration**
- **Concept realization could be accomplished by engaging nations and regions**
  - **Suitably located megacities,**
  - **The necessary scientific and technological capabilities, or significant beginnings**
  - **The fiscal resources and interest needed to pursue joint GHG measurement science research**
  - **Develop and demonstrate methodologies thoroughly vetted for their scientific foundation, accuracy, and recognition within the international community.**

Discussion Points

- **Structure of the Convention of the Mètre**
  - Facilitate communication and transparency in the sharing of data and the development of measurement methodologies,
  - Facilitate the international recognition of these, and
  - Link to the World Meteorological Organization and similar international climate change/science organizations focused on climate change-related issues.
- **Brazil, China & U.S. Collaboration**
  - Formation of China's National Low Carbon Technologies committee to support cap and trade activities
  - INMETRO, NIM, and NIST are working together on the International Test Bed Concept?
- **Questions:**
  - How to move toward developing measurement systems supporting verification of emissions in the MRV context?
  - Working together, can a group of NMI's convince their respective nations to make the necessary investment?
  - Can a group of NMIs work together to convince the policy community to be a focal point for measurements needs?