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Review of Federal and Non-Governmental Methane Measurement and Monitoring

Christopher T. Clavin
Anne E. Ressler

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IDA SCIENCE & TECHNOLOGY POLICY INSTITUTE
1899 Pennsylvania Ave., Suite 520
Washington, DC 20006-3602

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Executive Summary

The President's *Climate Action Plan: Strategy to Reduce Methane Emissions* (subsequently referred to as the "strategy"), dated March 2014, outlines two broad U.S. goals related to measuring methane emissions: (1) improving bottom-up emission data relevant for mitigation and (2) advancing the science and technology for monitoring and validating atmospheric concentrations. Inventories of bottom-up measurements of greenhouse gas emissions are based on data about the source or the activity causing emissions. These estimates are often used to inform policy and program decisions. Top-down measurements infer emissions from atmospheric methane concentrations and are useful for identifying methane hot spots (regions of unusually high methane emissions relative to their surroundings) and validating bottom-up estimates. Recent scientific research has focused on measurement methods that pair these two different approaches to yield more accurate estimates of methane emissions.

To determine progress in meeting U.S. methane-measurement goals as called for in the strategy, the Office of Science and Technology Policy (OSTP) in the Executive Office of the President asked the IDA Science and Technology Policy Institute (STPI) to review recent literature on methane measurement and monitoring, describe current research activities that support the measurement and monitoring objectives of the strategy, and provide highlights of scientific findings from the Environmental Defense Fund's methane measurement research campaign and other relevant research findings.

A team of STPI researchers reviewed current Federal and non-governmental programs and projects that support research and development activities related to methane measurement and monitoring and collected information on current methane measurement research from Federal officials and researchers at the following organizations involved in the programs and projects reviewed:

- Department of Energy
- Environmental Protection Agency
- National Aeronautics and Space Administration (NASA) and NASA's Jet Propulsion Laboratory
- National Energy Technology Laboratory
- National Institute of Standards and Technology
- National Oceanic and Atmospheric Administration

- National Science Foundation
- Pipeline and Hazardous Materials Safety Administration
- United States Department of Agriculture
- United States Geological Survey

Based on input from these discussions and additional research, the STPI team found that the current portfolio of research indicates that integration of bottom-up inventory measurements and top-down atmospheric measurement approaches remains an important scientific topic that is actively being explored. Much of the scientific discussion revolves around integrating multiple fields of atmospheric measurement and modeling, life-cycle assessment, and greenhouse gas inventory composition with a focus on natural gas and petroleum systems emissions.

Recent Methane Emissions Measurement and Monitoring Research

Since the release of *Climate Action Plan: Strategy to Reduce Methane Emissions*, Federal and non-governmental research activities in this realm have focused on (1) improving emission factors for individual components and activities, (2) improving component- and site-scale leak detection equipment and flux estimation methodology, and (3) conducting region-specific scientific campaigns to improve emission estimation and validation. Parts of the scientific community have recently focused on understanding and accurately quantifying methane emissions from natural gas systems. Based upon the findings of the Environmental Protection Agency's Greenhouse Gas Inventory report published in April 2016, over 30% of anthropogenic methane emissions (human-caused emissions) can be attributed to the petroleum and natural gas sectors.

Research Campaigns to Improve Methane Measurements

In 2015 OSTP convened an ad hoc interagency working group to examine investments that Federal agencies are making to improve measurement methods, inventories, and detection technology. This working group compiled a portfolio of Federal activities supporting methane measurement research that spans natural gas and petroleum production, agriculture, solid waste, and other sectors. While these activities are diverse, their research outcomes are expected to support improvements in the representativeness of emission factors for sector-specific activity, the methods for and ability to collect activity data, the temporal and spatial coverage of atmospheric concentration data, and the state of emission validation science (through integration of bottom-up and top-down methodologies).

The current portfolio of Federal research activities generally supports the two strategic measurement and monitoring goals of *Climate Action Plan: Strategy to Reduce*

Methane Emissions. Federal activities that are either particularly relevant to the strategy's objectives or hold potential promise for integrating multiple measurement approaches to more accurately quantify emissions include:

- Improving sensor technology and measurement approaches
- Spatially-resolving U.S. Greenhouse Gas Inventory data
- Sustained atmospheric monitoring and sampling for estimating emissions
- Integrated measurement approaches for flux estimation
- International leadership and coordination on greenhouse gas measurement and monitoring

Opportunities for Research Coordination

Given these findings, Federal activities that are integrating multiple atmospheric measurement approaches with emission inventory approaches are likely to continue to improve emission verification methodologies for methane and other greenhouse gases. Still, opportunities exist to build on these successes and to promote better coordination between agencies involved in these activities.

Building on Research Successes

The following opportunities to build on research successes include activities related to improving bottom-up emission data and advancing science and technology for monitoring and validating atmospheric concentrations:

1. Continue investment in improving emission factors and activity data for the natural gas supply chain.
2. Drive down the cost of device- and site-scale leak detection and repair technology, and site-scale emission flux measurement technology.
3. Increase Earth observations density in strategic locations with multiple approaches (e.g. continuous in-situ measurements, flask samples, remote sensing, and satellite observations).
4. Expand research efforts to integrate measurement approaches, for multiple spatial and temporal scales.

Further Coordination of Interagency Methane Strategy Goals

Suggested activities to improve and formalize coordination so that Federal strategic methane measurement and monitoring goals can be met include:

1. Convene a Federal interagency scientific working group to make recommendations on Federal science and technology measurement goals and objectives that build on the current technology and research portfolio.
2. Incorporate perspectives of officials and researchers at academic; non-governmental; private sector; and state, tribal, and local government organizations in planning methane measurement and monitoring goals.

Contents

1. Background

The *President's 2013 Climate Action Plan* called for Federal agencies to develop an interagency methane strategy (Executive Office of the President (EOP) 2013). In March 2014, the EOP, with the support of Federal agencies, published *Climate Change Action Plan: Strategy to Reduce Methane Emissions* (EOP 2014). The strategy outlines Federal objectives for improving measurement of methane sources and emissions. It highlights efforts to support two broad methane emission measurement and monitoring goals: (1) improving bottom-up emission data relevant for mitigation, and (2) advancing the science and technology for monitoring and validating atmospheric concentrations.

The measurement section of the strategy describes the relative advantages and roles of "top-down" and "bottom-up" measurement methods. "Bottom-up" greenhouse gas inventories, which focus on the specific source or the activity causing emissions, are often used to inform policy and program decisions. "Top-down" measurements, which infer to emission quantities from atmospheric methane concentrations, are useful for identifying hot spot regions (where emissions are relatively higher than in surrounding areas) and validating bottom-up estimates. Recent scientific work has focused on developing and demonstrating methodologies for pairing these different approaches to more accurately estimate methane emissions.

A. Tasking

Interested in examining progress toward meeting U.S. methane measurement goals, the Office of Science and Technology Policy (OSTP) in the Executive Office of the President asked the IDA Science and Technology Policy Institute (STPI) to review recent literature on methane measurement and monitoring, describe current research activities that support the measurement and monitoring objectives of the strategy, and provide highlights of scientific findings from relevant non-governmental research efforts.

B. Method

A team of STPI researchers reviewed current Federal and non-governmental programs and projects that support research and development activities related to methane measurement and monitoring and collected information on similar activities from Federal officials and researchers at the Department of Energy (DOE), Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), NASA's Jet Propulsion Laboratory (JPL), National Energy Technology Laboratory (NETL), National

Institute of Standards and Technology (NIST), National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), Pipeline and Hazardous Materials Safety Administration (PHMSA), United States Department of Agriculture (USDA), and United States Geological Survey (USGS).

C. Scope

Federal agencies invest in research into other emission sources, including both biogenic and anthropogenic sources, such as agriculture operations, landfills, mining, and wetlands. This broader Federal research portfolio supports basic research questions that aim to better understand and characterize the trends associated with changes in global methane cycle.

Parts of the scientific community have recently focused on understanding and accurately quantifying methane emissions from natural gas and petroleum systems. As a result, this report provides an overview of recent methane measurement and monitoring research based upon recent scientific literature, with an emphasis on natural gas and petroleum system studies. It describes current Federal activities supporting the measurement and monitoring objectives of the strategy and highlights important scientific findings, such as those from the Environmental Defense Fund's methane measurement research campaign.

2. Review of Recent Methane Emissions Measurement and Monitoring Research

This chapter summarizes recent methane measurement and monitoring research findings for natural gas and petroleum systems and highlights opportunities to augment existing technology, methodology, or measurement networks to advance the goals of the strategy.

Since 2011, the scientific community has been increasingly interested in understanding and accurately quantifying methane emissions from natural gas systems. Based on the latest findings of the Energy Information Administration (EIA) and the Environmental Protection Agency (EPA), over 30% of anthropogenic methane emissions can be attributed to the oil and natural gas sectors, and domestic natural gas production is projected to increase in future decades (EIA 2015; EPA 2015). Recent scientific studies that use bottom-up inventory-based measurements and top-down atmospheric measurements provide differing estimates of methane emissions from natural gas systems across different spatial scales (e.g., component, site, region, national, and global scales) and time periods of study. Several other recent studies within the Barnett Shale region in Texas have provided indications that reconciling these estimates is possible. Researchers of multiple disciplines are attempting to address how to integrate these scientific measurement approaches. Thus, much of the discussion of recent scientific work revolves around integration of multiple fields of atmospheric measurement and modeling, life-cycle assessment, and composition of greenhouse gas inventories. Because these discussions emphasize emissions from natural gas and petroleum systems, examples cited in this chapter relate to natural gas and petroleum sources (Harriss et al. 2015; Brandt et al. 2014; Kirschke et al. 2013).

A. Bottom-Up Inventories and Reporting

Country-level anthropogenic greenhouse gas emission estimates are reported as a requirement for parties to the United Nations Framework Convention on Climate Change (UNFCCC). The EPA's GHG inventory report, published annually in April, reports all U.S. anthropogenic greenhouse gas emissions from 1990 through the most recent year for which data are available. Table 1 displays relevant data for 2014.

Table 1. Total Anthropogenic Methane Emissions for 2014

	Source Category*	2014 Emissions, Tg CH_4	Percentage of Emissions	Uncertainty Range, Tg CH_4
Petroleum and Natural Gas Systems	1B2a, 1B2b	9.7	33%	(7.8–15.9)
Enteric Fermentation	4A	6.6	22%	(5.8–7.8)
Landfills	6A1	5.9	20%	(4.1–9.5)
Coal Mining†	1B1A	2.7	9%	(2.4–3.1)
Manure Management	4B	2.4	8%	(2.0–2.9)
Wastewater Treatment	6B	0.6	2%	(0.4–0.6)
Other		1.2	4%	(0.9–1.9)
Total		**29.1**		**(23.4–41.7)**

Source: EPA (2016a).

* As defined in the United Nations Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC 1996, 2006).

† Coal mining data represent only active coal mines for consistent comparison with the GHGRP data. A separate category in the EPA inventory represents abandoned underground coal mines, around 0.2 Tg CH_4.

For its annual inventory report, EPA evaluates source data used to calculate emission estimates from a combination of activity data (e.g., cubic feet of gas produced and barrels of oil) and emission factors (i.e., emissions per unit of activity), and updates these estimates, as appropriate. Estimates in the inventory are intended to reflect all anthropogenic emissions in the United States, although there may be regional variation present in the underlying emission factors. Estimation of activity factors relies upon information collected by statistical agencies such as the EIA, individual state-level data and reports, industry surveys and reports, and data reported to the EPA's Greenhouse Gas Reporting Program (GHGRP).[1] The GHGRP requires annual reporting of GHG data and other relevant activity and operational information from large sources and suppliers in the U.S. For petroleum and natural gas systems (GHGRP Subpart W), annual emissions of carbon dioxide, methane and nitrous oxide are generally reported for facilities that emit over 25,000 metric tons per year.

The GHGRP collects emissions reports from 41 source categories, including non-agricultural sectors responsible for the majority of methane emissions (i.e., petroleum and natural gas systems, municipal solid waste and industrial landfills, and coal mines).[2] The program provides data that can be used to analyze and characterize emission trends for reporting facilities, including variation across facilities within an industry or across

1 EPA, "Greenhouse Gas Reporting Program (GHGRP)," https://www.epa.gov/ghgreporting.

2 Agricultural and land-use sectors are not required to report emissions to the GHGRP.

geographic regions. GHGRP data have supported annual improvements in activity data, emission factors, and other input to the EPA annual inventory.

In order to ensure data submitted to the GHGRP is accurate and complete, the EPA employs a multi-step data verification process.[3] This includes automated checks on data and certification of data at the time of submission, as well as an evaluation of data against a variety of electronic checks after submission. EPA can then follow-up with reporters on potential errors in the submitted data to resolve the discrepancy.

Emission factor estimation for the EPA's inventory report is also based upon data from research studies, the GHGRP, and industry, technical, and research organizations (EPA 2015). EPA estimates are revised as improved data on emission factors and activity data are available. At sub-national scales, state- and region-specific inventories follow guidelines similar to those at the national level.

B. Top-Down Monitoring and Modeling

Emissions fluxes can be inferred indirectly using atmospheric models based upon measured and remotely sensed concentrations of methane in the atmosphere. These "top-down" measurement, remote sensing, and modeling methods require the use of bottom-up inventory data to attribute modeled emissions to ground sources. Scientific studies published between 2012 and 2016 that used top-down methods to study natural gas and petroleum system emissions primarily attempted to "validate" or "verify" emission estimates from bottom-up inventories and studies. Some of these studies have explored the use of various methods to attribute observed changes in atmospheric concentrations of methane to their sources. These methods include release of tracer gases, examination of hydrocarbon enhancement ratios, and isotopic analysis.

Notable recent studies are those that emphasized (1) modeling approaches for region-specific quantification of emission flux based upon a combination of atmospheric measurements from stationary towers and aircraft campaigns (Peischl et al. 2015; Caulton et al. 2014; Bruhwiler 2014; Karion et al. 2015; Karion et al. 2013; Petron et al. 2014; Petron et al. 2012; Miller et al. 2013), (2) remote sensing technology, including satellite-based Earth observations, to constrain emission sources (Frankenberg et al. 2016; Thompson et al. 2016; Kort et al. 2014; Schneising et al. 2014; Deng et al. 2014; Turner et al. 2016), and (3) a combination of atmospheric measurement approaches in site- and regional-scale remote sensing campaigns coupled with location-specific, bottom-up inventories to attribute modeled emissions to specific sources (Lyon et al. 2015; Harriss et al. 2015).

[3] For more information on EPA's verification process, see "Greenhouse Gas Reporting Program: Report Verification," https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

C. Scientific Questions Relating to Disagreement between National Greenhouse Gas Inventory and Site and Regional Top-Down Atmospheric Measurements

Brandt et al. (2014) succinctly described the scientific challenge associated with attempting to reconcile bottom-up approaches at different spatial scales to top-down measurement approaches. The authors compared 15 years' worth of studies that estimated methane emissions across multiple spatial scales and found emissions at the component scale ranged between less than estimates in the EPA inventory to more than 100 times those estimates. Similar comparisons at regional and continental scales ranged from 100–300% higher and 50% higher, respectively, than the comparable EPA inventory estimates. This level of disagreement has been well-documented in the scientific literature over the past several years.

The most common sources for disagreement among emission estimates are non-representative sampling of industry practices, examination of different components, and use of dissimilar system boundaries (e.g., spatial, temporal, and sectoral) (Heath et al. 2015b). Research efforts in the past couple years, primarily funded by the Environmental Defense Fund, have focused on addressing this scientific question in specific U.S. regions. This work and other Federal investments are reviewed in the Chapter 3.

The 2014 EPA inventory report, published in April 2016, includes recalculations throughout the time series of emission estimates due to the revised activity data in the GHGRP data and research findings that provide emission factors for certain segments. The result of these recalculations is an increase from 1.0 Tg CH_4 to 2.6 Tg CH_4 (+157%) for petroleum systems and from 6.3 Tg CH_4 to 7.0 Tg CH_4 (+12%) for natural gas systems for 2013 emission estimates (EPA 2016b, 2016a).[4] Due to these recalculations, natural gas systems are the largest source of anthropogenic methane emissions in the 2014 report, whereas enteric fermentation was the largest source in the 2013 report. These recent revisions and incorporation of research findings may address some of the differences in bottom-up annual EPA inventory emission estimates and top-down regional emission estimates extrapolated to a national scale.

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4 Emissions estimates for natural gas systems, as a whole, increased by only 0.7 Tg CH_4, but individual segments experienced a much greater relative change. For example, compared to the 2013 inventory report, the 2014 production segment emissions estimates increased from 1.9 Tg CH_4 to 4.4 Tg CH_4 (+136%), transmission and storage emissions estimates decreased by 2.2 Tg CH_4 to 1.2 Tg CH_4 (–25%), and distribution emissions estimates decreased from 1.3 Tg CH_4 to 0.5 Tg CH_4 (–27%).

Petroleum system emission estimates increased primarily due to production segment emissions increasing from 1.0 Tg CH_4 to 2.6 Tg CH_4 (+164%), which is due to updating assumptions based on available GHGRP data and data and analysis in the EPA proposed New Source Performance Standards (NSPS) rule, 40 CFR Part 60, Subpart OOOOa.

D. Example of Recent Methane Measurement Technology Application: Characterizing Methane Emissions from the 2015–2016 Aliso Canyon Well Failure and Natural Gas Leak

The recent failure of a natural gas storage well at Southern California Gas Company's Aliso Canyon storage facility resulted in a significant natural gas leak and atmospheric methane emissions from October 23, 2015, through February 18, 2016. The occurrence of non-routine, major emission events similar to this failure highlight the deployable measurement assets that may aid emergency response officials, infrastructure owners and operators, and public health and regulatory officials in a rapidly changing event. Throughout this event, measurement and monitoring capabilities were deployed to rapidly detect and characterize environmental, climate, and public health impacts of this highly emitting, short-term event.

Recently published data on state-coordinated flights flown during the event to calculate atmospheric methane mass flux suggest an average leak rate of 53 ± 3 metric tons CH_4/hour for the first 6 weeks of the event and decreasing rates in the remaining nearly 11 weeks of the leak (Conley et al. 2016). California's Air Resources Board (ARB) preliminary estimates, which are based upon the same flight data described in Conley 2016, indicate a maximum hourly leak rate measured on November 28, 2015, of 58 ± 12 metric tons CH_4/hour and a decreasing leak rate trend in subsequent weeks (ARB 2016). The ARB estimates that 94,500 metric tons of CH_4 (equivalent to 2.6 million metric tons of CO_2[5]) were released from the leaking well.[6] Subsequent research conducted by Thompson et al., found that the Hyperion imaging spectrometer aboard the EO-1 satellite detected the methane plume from the Aliso Canyon leak on three overpasses in December 2015 and January 2016. Flux quantification was not reported in this research. The detection of the extreme Aliso Canyon leak from Hyperion was the first demonstrated attribution of orbital remote sensing detection of methane emissions to a single emission source (Thompson et al. 2016) Future publications on this topic are expected given additional research now being conducted.

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5 CO_2-eq was calculated using the 100-year global warming potential for methane without climate-carbon feedback from the Fifth Assessment Report (AR5) of the IPCC.

6 California Air Resources Board, "Aliso Canyon Natural Gas Leak," http://www.arb.ca.gov/research/aliso_canyon_natural_gas_leak.htm.

3. Current Research to Improve Methane Measurement and Monitoring

Since the publication of the strategy, Federal and non-governmental research activities that aim to improve measurement of methane emissions from natural gas and petroleum systems have emphasized: (1) improving emission factors and activity data for individual components and activities, (2) improving component- and site-scale leak detection equipment and flux estimation methodology, and (3) conducting region-specific scientific campaigns to improve methods for validating emission estimation.

In summer 2015, the Office of Science and Technology Policy (OSTP) convened an ad hoc interagency working group tasked with developing a better understanding of the investments Federal agencies are making to improve measurement detection methods, inventories, and detection technology. About the same time, the Environmental Defense Fund (EDF) and its collaborating research partners published the results of a campaign of studies focusing on improving the quantification of methane emission measurement from natural gas industry segments (EDF 2015). This chapter describes recent methane measurement and monitoring research activities by Federal agencies, EDF, and others.[7]

The research activities highlighted in this chapter were selected because of their relevance to either meeting U.S. methane measurement and monitoring objectives or integrating multiple measurement approaches to more accurately quantify emissions. Appendix A contains a comprehensive list of recent Federal, non-governmental, and academic activities identified by the working group.

A. Federal Activities Supporting Methane Measurement Research

The portfolio of Federal activities supporting methane measurement research spans a large space across natural gas and petroleum production, agriculture, solid waste, and other sectors. Despite the diverse spatial scales within these sectors, research outcomes are expected to support improvements in (1) representativeness of emission factors for sector-specific activity, (2) methodology and ability collect activity data, (3) temporal and spatial coverage

[7] Federal activities were identified by the OSTP-convened ad hoc interagency methane measurement and monitoring working group and a review of published literature. STPI researchers identified EDF’s activities through discussions with EDF’s Chief Scientist Steven Hamburg in May 2015 and review of EDF’s published materials.

of atmospheric concentration data (including remote sensing for emission detection), and (4) emission validation science (integration of bottom-up and top-down methodologies).

Table 2 summarizes the characteristics of methane measurement activities funded by Federal agencies and the science and technology improvements that are expected to be delivered from these investments.

Table 2. Types of Current Federal Activities in Methane Measurement and Monitoring and Expected Science and Technology Improvements

Spatial Scales	Research Activities (Funding Agencies)	Science and Technology Improvements Expected
Point source (e.g. device, unit, or component)	• Source-specific measurement campaigns across multiple sectors (NSF, USDA NIFA, DOE, RPSEA, and EPA) – Natural gas and petroleum system – Municipal solid waste and Industrial landfills – Agriculture – Coal Mining • Sensor technology development (ARPA-E)	• Emission factor improvement – Characterizing distribution of industrial sources of emissions' (i.e., natural gas and petroleum sector, agriculture) – Data supporting improving emission factors • Emission factor improvement, activity data, leak detection – Detection technology improvement for emission quantification, device emission monitoring, leak detection
Site or local	• Sensor technology development and integrated emission monitoring system (ARPA-E) • Remote sensing approaches (NOAA, NIST, NASA, and EPA)	• Emission validation science – Quantification of spatially isolated sources (multiple sectors) – Rapid detection of temporally infrequent, spatially dispersed "hot spots"
Area or regional	• Source attribution studies with simultaneous in-situ and remote sensing approaches (NOAA, NIST, NASA, and NSF) • Paired inventory and atmospheric measurement region-specific natural gas and petroleum measurement campaigns (NOAA, NIST, and RPSEA) • Regional-scale atmospheric inverse modeling for source attribution (DOE, NOAA, NIST, and NASA)	• Atmospheric concentration data – Regional identification of sources contributing to natural gas and petroleum sector emission source skewed distribution • Emission validation science – Reconciliation of bottom-up inventories and top-down emission quantification approaches
National, continental, or global	• Spatially resolved, gridded greenhouse gas inventory (NASA, with in-kind resources from EPA) • Ongoing, widespread surface and airborne measurements of atmospheric CH4 abundance and related tracers for top-down flux estimation at continental to global scale (NOAA and DOE) • Limited use of satellite measurements to identify regional "hot spots" (NASA and Los Alamos National Laboratory)	• Atmospheric concentration data, emission factor and activity factor improvement – Improvements in reconciliation between atmospheric modeling studies and national inventory estimates – Improvements in spatial uncertainty description in greenhouse gas inventory • Emission validation science – Identification of potential satellite observations applications for future emission measurement, reporting and verification

1. Improving Sensor Technology and Measurement Approaches

Research activities from Table 2: sensor technology development (device, unit or component scale; site or local scale), integrated emission monitoring system (site or local scale), and remote sensing approaches (site or local and area or regional scale).

The Advanced Research Projects Agency–Energy (ARPA-E) Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR) program provides up to $30 million to research teams developing highly sensitive and cost-effective sensor technology and innovative approaches to complete measurement systems that sense methane emissions, characterize leakage, identify locations of leaks, and provide data and communication functionality to operators. In December 2014, 11 MONITOR projects were announced that span a range of objectives, including detection systems (e.g., laser-based systems, mobile, unmanned aerial vehicle-mounted sensor systems, and man-portable systems) and new sensor technology (e.g., printable sensors, optical sensors, advanced spectrometers, and distributed sensor networks)[8] The Pipeline and Hazardous Materials Safety Administration (PHMSA) also has an interest in supporting research leading to development of technology for pipeline monitoring of leak detection. PHMSA currently maintains several research projects to integrate laser-based measurement approaches for optimal leak rate detection, to examine airborne differential-absorption light detection and ranging (LIDAR) technology for rapid aerial leak surveys, and to develop data processing applications.

Advances in low-cost sensors and turnkey detection systems could advance leak detection and repair approaches and reduce the costs associated with regulatory enforcement.

2. Gridding of U.S. Greenhouse Gas Inventory Data

Research activity from Table 2: spatially resolved, gridded greenhouse gas inventory (national, continental, or global scale).

The EPA is collaborating with researchers at Harvard University to develop a spatially resolved version of the EPA inventory's CH_4 emission estimates (Maasakkers et al. 2015; Maasakkers 2015). Top-down methodologies, specifically atmospheric inverse modeling studies, require the use of spatially resolved bottom-up inventory data. The best available spatially resolved national greenhouse gas emission data is from the Emissions Database for Global Atmospheric Research (EDGAR) maintained by the European Commission Joint Research Centre's Institute for Environment and Sustainability. Previous research suggests that the EDGAR database is not representative of U.S. emissions, as characterized by the EPA inventory (Lyon et al. 2015). The Harvard University/EPA effort to spatially resolve the inventory's methane data will provide the basis for future analyses to identify mismatches

[8] ARPA-E website, "MONITOR: Methane Observation Networks with Innovative Technology to Obtain Reductions," http://arpa-e.energy.gov/?q=arpa-e-programs/monitor.

between atmospheric measurements and specific locations and sources that contribute to deviations from the EPA's estimated emissions. Harvard and EPA are gridding the 2012 methane emission estimates from the 1990–2014 EPA inventory report (EPA 2016b) for multiple source categories. EPA is currently exploring ways to incorporate the gridding analysis as a regular component of the annual inventory report.

3. Sustained Atmospheric Monitoring and Sampling for Estimating Emissions

Research activities from Table 2: source attribution studies with simultaneous in-situ and remote sensing approaches (site or local scale) and ongoing, widespread surface and airborne measurements of atmospheric CH_4 abundance and related tracers for top-down flux estimation at continental to global scale (national, continental, or global scale).

NOAA maintains the Global Greenhouse Gas Reference Network (GGGRN), which provides over 70 atmospheric sampling sites and represents a set of long-term, calibrated measurements of greenhouse gas concentrations. These data provide the foundational set of reference measurements necessary to constrain emission flux estimates. Combined with other observation systems, such as satellites, the GGGRN data are used to identify and account for biases in satellite retrieval algorithms, as Turner et al. (2015) demonstrated. NOAA, DOE, and NASA investments have increased availability of tall tower and mountaintop atmospheric sampling sites and increased missions for aircraft-based sampling. Recent examples of the use of the GGGRN for measurement and monitoring of major emission events include the Deepwater Horizon oil rig spill in 2010 (Ryerson et al. 2011; Ryerson et al. 2012), the Elgin rig blowout in 2012, and the Aliso Canyon natural gas leak in 2015–16 (Conley et al. 2016).

4. Integrated Measurement Approaches for Flux Estimation

Research activities from Table 2: source attribution studies with simultaneous in-situ and remote sensing approaches (site or local scale) and regional-scale atmospheric inverse modeling for source attribution (area or regional scale).

The Megacities Carbon Project, run by NASA's Jet Propulsion Laboratory (JPL) and jointly funded by NIST, NASA, NOAA, and the Keck Institute for Space Studies, will deploy a series of measurement technologies in a large urban setting to test and design an operational system that could provide actionable information to attribute and evaluate the effects of climate policies in cities.[9] The project integrates major observational elements such as fixed tower in-situ sensors and flask samples, airborne observations, ground-based remote sensing, and satellite-based column measurements. The project ultimately could demonstrate an operational system that reliably integrates multiple measurement approaches, and demonstrates their application to support bottom-up inventory

[9] Megacities Project website, "Project Overview," https://megacities.jpl.nasa.gov/portal/about/.

improvements and analytical approaches to integrate top-down and bottom-up data to validate the performance of mitigation actions. Los Angeles was selected as one of the project pilot cities, with Federal investments supporting local observation network improvements in 2014.

The Indianapolis Flux Experiment (INFLUX), a partnership funded by NIST, is attempting to develop and evaluate methods for measuring and modeling greenhouse gas emission fluxes from urban environments.[10] NIST is funding INFLUX and Pennsylvania State University, Purdue University, University of Colorado/NOAA, and Arizona State are active contributors. The project deployed a series of observational capabilities to form a comprehensive observation network composed of in-situ tower-based measurement capabilities, flask sampling, periodic aircraft sampling, remote sensing approaches, and scanning Doppler LIDAR. When paired with the Hestia project, a region-specific bottom-up inventory effort, INFLUX will demonstrate approaches for measurement of area-wide greenhouse gas fluxes.[11]

5. International Leadership and Coordination

Activity from Table 2: ongoing, widespread surface and airborne measurements of atmospheric CH_4 *abundance and related tracers top-down flux estimation at continental to global scale (national, continental, or global scales).*

Federal agencies and partners support international efforts to monitor atmospheric methane, understand its trends and distribution, and characterize methane emissions to the atmosphere. International programs include the Committee on Earth Observation Satellites (CEOS) with participation from U.S. agencies such as NASA, NIST, and NOAA. CEOS coordinates Earth observations for ease of user community use and data access. In 2014, CEOS issued and began executing *CEOS Strategy for Carbon Observations in Space*, which included findings and recommendations for the development of an internationally coordinated and comprehensive global observing system for monitoring and verification of methane emissions (CEOS 2014).

Also in 2014, the World Meteorological Organization (WMO) agreed to pursue the implementation of an Integrated Global Greenhouse Gas Information System (IG3IS) for filling observation and modeling gaps, enhancing coordination of observing systems, and delivering products on policy-relevant scales (WMO 2015). IG3IS builds upon existing observations systems, including U.S.-supported systems such as NOAA's GGGRN, to identify observation gaps as well as data management and operational needs (WMO 2015).

[10] Pennsylvania State University website, "Indianapolis Flux Experiment (INFLUX)," http://sites.psu.edu/influx/.

[11] The Hestia Project website, "Welcome to The Hestia Project," http://hestia.project.asu.edu/.

B. Example of Non-Federal Activity Supporting Methane Measurement Research: Environmental Defense Fund's Campaign

Research performed by academic institutions, non-governmental organizations, and industry represents a spectrum of commercial technology development and demonstration research activities. The goals of these activities are as diverse as the Federal research activities, spanning bottom-up methods to support improvements in emission inventories to top-down approaches supported through research to reconcile differences in the broader bottom-up and top-down measurement approaches. Detailed information on non-Federal activities identified during this study are included in Appendix A, Tables A-2 and A-3. The remainder of this section focuses on the work of the Environmental Defense Fund (EDF), which has recently examined methane emissions from natural gas systems in a series of coordinated studies using a variety of measurement approaches.

Since 2012, EDF has funded 16 research projects in a campaign to improve the characterization of methane emissions from all segments of the natural gas supply chain (EDF 2015). Federal agencies provided partial study-specific support to researchers and for instrumentation used in a subset of the 16 studies. The full set of studies covered activities related to production through distribution of natural gas systems. Production segment studies examined multiple oil and natural gas production basins, including Barnett Shale, Eagle Ford, Denver-Julesberg, and Upper Green River. Distribution segment studies examined samples from the service territory of 13 local distribution companies (Lamb et al. 2015). Studies covering other segments were consistent with the production and distribution segment approach, deploying emission measurement technology in multiple locations from multiple companies.

In a focused study effort, EDF coordinated multiple research efforts in the Barnett Shale region in 2013 to understand and address critiques of previous studies where dissimilar system boundaries may have contributed to disagreement between top-down and bottom-up results. An overview of findings from that effort follows.

The campaign consisted of 11 different measurement approaches with spatial coverage at the component, site, and area levels. These approaches aimed to collect data to estimate the regional emission flux (from mass balance flight studies), source fingerprints (from isotopic and hydrocarbon enhancement ratio methods), and component- or site-level emission distribution characterization (from on-site and downwind plume capture methods) (Harriss et al. 2015). Using these methods, researchers attempted to characterize area-wide emission using top-down methods and aggregate site- and component-level emission estimates into a spatially and temporally representative bottom-up inventory that has system boundaries similar to the top-down studies.

Researchers funded by EDF, as described in Harriss et al. (2015), found that through top-down and bottom-up methods, methane flux from the region was estimated to be 76 ± 13

Mg CH_4/hour and 72 Mg CH_4/hour (range 63–83 Mg CH_4/hour, respectively(Harriss et al. 2015; Zavala-Araiza et al. 2015; Smith et al. 2015; Karion et al. 2015).[12] These results are approximately 150% greater than what would be expected from the application of nationally relevant EPA inventory assumptions prior to the most recent updates in April 2016 (discussed in Chapter 2),[13] which is consistent with the findings of Heath et al. (2015a). The bottom-up inventory developed for this study indicates that gathering compressor stations in the region represent the majority of the difference in emission estimates between the study's findings and results from assumptions derived from the 2013 EPA inventory report (Lyon et al. 2015). The results presented by (Lyon et al. (2015)) represent a significant improvement in region-specific, temporally-relevant emission inventory development due to the incorporation of the "fat tail" or super-emitters within the activity represented in their inventory.

The Barnett coordinated research campaign yielded the first integrated results of U.S. natural gas and oil production emissions where a custom bottom-up inventory was reconciled with top-down measurements with similar system boundaries. These results indicate that existing integrated bottom-up and top-down measurement approaches are compatible when appropriate and representative system boundaries (spatial, temporal, and sectoral) are maintained across methodologies.

[12] Both ranges report 95% confidence intervals.

[13] Lyon et al. (2015) derived the 2013 EPA inventory comparison figures from national emission and activity factors that were prorated by throughput data from the Barnett Shale region (e.g., gas produced or processed).

4. Opportunities for Coordination of Methane Measurement and Monitoring Research

Given the foregoing review of Federal activities provided by the ad hoc interagency working group, the STPI research team concluded that the current portfolio of Federal research activities support the two strategic measurement and monitoring goals of *Climate Change Action Plan: Strategy to Reduce Methane Emissions*. Outcomes from projects that are integrating multiple atmospheric measurement approaches with emission inventory approaches are likely to continue to improve emission verification methodologies for methane and other greenhouse gases. Some opportunities may exist to build on these successes and improve coordination between agencies.

A. Building on Current Research Portfolio Successes

Opportunities to build upon areas of successful investment include activities in the strategy's measurement and monitoring goals:

Improving bottom-up emission data relevant for mitigation

1. <u>Continued investment in improving emission factor and activity data for the natural gas supply chain</u>: Multiple Federal agencies' research programs continue to advance regional and national assumptions of emission factors and activity data.

   Future Coordination Opportunity: Improving understanding of undersampled and highly variable sources would improve assumptions critical to key Federal products, such as the EPA's greenhouse gas inventory report.

2. <u>Drive down the cost of device- and site-scale leak detection and repair technology, and site-scale emission flux measurement technology</u>: ARPA-E's MONITOR program is an example of ongoing support for the development of low-cost sensor technology and site-scale monitoring approaches.

   Future Coordination Opportunity: Future demand for cost-effective leak detection, repair, and monitoring technology may be driven, in part, by the EPA's final New Source Performance Standards (NSPS) for methane and volatile organic compound emissions from oil and natural gas sources (currently proposed) and other future Federal regulations that require leak detection or measurement technology. Opportunities exist to expand coordination activities across other agencies interested in researching and applying new sensor technology and to engage with third-party stakeholders interested in sensor technology development.

Advancing the science and technology for monitoring and validating atmospheric concentrations

1. Increase Earth observations density in strategic locations with multiple approaches (e.g. continuous in-situ measurements, flask samples, remote sensing, and satellite observations): The NOAA-supported Global Greenhouse Gas Reference Network (GGGRN), which is global in its reach but maintains higher resolution sampling across the United States, is the backbone for atmospheric observations for methane monitoring.

   Future Coordination Opportunity: Expand ground-based and airborne measurement networks, incorporating new technology using mobile platforms, including volunteer commercial ships and aircraft, or consider the benefits and feasibility of alternative satellite platforms, such as miniature satellites (CubeSats) for space research or commercial missions, to advance space-based methane measurement and monitoring capabilities.

2. Expand research efforts to integrate measurement approaches for multiple spatial and temporal scales: Notable Federal integrated monitoring efforts, such as NIST's INFLUX project and the multi-agency Megacities Carbon project, are key research activities that integrate across multiple fields to demonstrate the feasibility of multiple measurement methods for policy-specific goals.

   Future Coordination Opportunity: Development, deployment, and integration of site-scale sensors, area- or regional-scale platforms, and existing or expanded regional observation networks remains an area of opportunity for Federal coordination. These efforts identify how agency-specific coordination of capabilities, such as GGGRN, aircraft, or in-situ monitoring network capabilities, could enhance capabilities to characterize, attribute, and mitigate large, infrequent sources of emissions.

B. Further Coordination of Interagency Methane Strategy Goals

To help meet U.S. methane-reduction goals, researchers should integrate scientific findings across disciplines and agencies and enable the development of low-cost technology to identify, detect, and mitigate emission sources. Based upon the review of existing research activities and coordination efforts, STPI researchers observed that opportunities exist to improve and formalize Federal strategic methane and measurement research goals. Two suggested activities that could improve and formalize Federal strategic methane measurement and monitoring goals follow:

1. Convene a Federal interagency scientific working group to make recommendations on Federal science and technology measurement goals and objectives that build on the current technology and research portfolio. The significant research investments

of the Federal Government support the full breadth of methane measurement and monitoring efforts identified in this report. A Federal interagency scientific working group may find opportunities to augment efforts to support strategic priorities by examining the research objectives of existing programs, identifying gaps within the overall portfolio of measurement and monitoring research (such as further investigation of super-emitters or previously unaccounted emission sources), and comparing those activities to strategic policy goals and objectives.

2. Incorporate the perspectives non-Federal entities through input from academic, non-governmental, and private sectors, and state, local, and tribal government organizations. Input from these communities, which should include potential users of the scientific results in the private sector or state, local, and tribal governments, is critical information necessary to establish scientific objectives that result in the deployment of those findings, methods, or technologies to meet their respective strategic and policy objectives. The Federal Government could then assess how agencies could address those objectives to mutual benefit of all parties.

Appendix A.
Activities in Methane Measurement and Monitoring as of March 2016

Methodology for Data Collection and Program Cataloging

In summer 2015, the Office of Science and Technology Policy (OSTP) issued a data call to the ad hoc Federal interagency working group to compile an updated list of Federal interagency methane measurement and monitoring programs. STPI researchers conducted additional research on these programs and interviewed with Environmental Defense Fund staff to characterize non-governmental organization and private sector activity.

For each program the working group identified, STPI researchers classified whether it most closely aligned with top-down or bottom-up measurement methods, identified if the activity was applied to a specific spatial scale of emission measurement, and whether the research is examining emissions at point source, local, regional, national, or global scale. Project descriptions in Table A-2, Table A-3, and Table A-4 are excerpts from project descriptions, proposal documents, or text provided by members of the Federal interagency working group.

Table A-1 provides descriptions of the keywords used to characterize the studies.

Table A-1. Methane Measurement and Monitoring Program Cataloging Tags (Keywords)

Keywords	Descriptions
Emissions Inventory Greenhouse Gas Inventory	Data collection, including development of emission factor (bottom-up)
Flux Measurement	Measurement of emission flux (top-down)
Remote Sensing	Demonstration or use of remote sensing capabilities
Modeling	Development of new models or algorithms, use of existing models studies
Technology Development	New technology development for sensing, measurement, or monitoring
Reconciling TD/BU	Reconciling top-down and bottom-up data

STPI researchers also searched the EBSCO, Web of Science, and Google Scholar databases to identify recent (published after 2012) academic publications related to methane emission monitoring and measurement. Search terms included methane keywords ("methane emissions," "methane monitoring," "methane research," "methane technology," etc.) combined with "top-down" and "bottom-up."

Federal Government Activities

Together, STPI researchers and the interagency working group identified 67 programs and projects sponsored or conducted by Federal agencies. That number does not necessarily represent levels of funding provided by each agency. Information presented in Table A-2 represents the results of the input from the working group and review of publicly available information.

Table A-2. Federal Programs and Major Projects Related to Methane Emissions Measurement

Project Title or Topic	Years Active	Lead Research Organization(s)	Funding Agency, Program	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Mobile LiDAR Sensors for Methane Leak Detection	2014–	Bridger Photonics, Inc.	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
Bridger Photonics will develop a light-detection and ranging (LiDAR) system capable of rapid and precise methane measurements resulting in 3D topographic information about potential leak locations. A novel near infrared fiber laser will enable long range detection with high sensitivity and can be deployed on a range of mobile platforms to survey multiple sites per day. This mobile LiDAR system will dramatically reduce the cost to identify, quantify, and locate methane leaks compared to currently available technologies.						
An Intelligent Multi-modal CH_4 Measurement System (AIMS)	2014–	IBM	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
IBM's T.J. Watson Research Center is working in conjunction with Harvard University and Princeton University to develop an energy-efficient, self-organizing mesh network to gather data over a distributed methane measurement system. Data will be passed to a cloud-based analytics system using custom models to quantify the amount and rate of methane leakage						
goGCI—Portable Methane detection Solution	2014–	Rebellion Photonics	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
Rebellion Photonics plans to develop portable methane gas cloud imagers that can wirelessly transmit real-time data to a cloud-based computing service. This would allow data on the concentration, leak rate, location, and total emissions of methane to be streamed to a mobile device. The imager's low cost and high portability will allow for widespread deployment while mobile integration will provide increased awareness of leaks for faster leak repair						
RMLD-Sentry for Upstream Natural Gas Leak Monitoring	2014–	Physical Sciences, Inc.	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
Physical Sciences in conjunction with Heath Consultants Inc., Princeton University, the University of Houston, and Thorlabs Quantum Electronics Inc. will miniaturize their laser-based Remote Methane Leak Detector (RMLD) and integrate it with PSI's miniature unmanned aerial vehicle (UAV), known as the Instant Eye, to create the RMLD-Sentry. The measurement system is planned to be fully autonomous, providing technical and cost advantages compared to manual leak detection methods						
System of Printed Hybrid Intelligent Nano-Chemical Sensors (SPHINCS)	2014–	Palo Alto Research Center	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
Xerox Corporation's Palo Alto Research Center (PARC) will work with BP and NASA's Ames Research center to combine Xerox's low-cost print manufacturing and NASA's gas-sensing technologies to develop printable sensing arrays that will be integrated into a cost-effective, highly sensitive methane detection system. The system will be based on sensor array foils containing multiple printed carbon nanotube (CNT) sensors and supporting electronics. The novel CNT sensor arrays offer a low-cost solution to identify, quantify, and locate methane leaks compared to currently available technologies.						
Autonomous, High Accuracy Natural Gas Leak Detection System	2014–	Aeris Technologies	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
Aeris Technologies will partner with Rice University and Los Alamos National Laboratory to develop a complete methane leak detection system that allows for highly sensitive, accurate methane detection at natural gas systems. The team will combine its novel compact spectrometer based on a mid-infrared laser, its patent-pending multi-port sampling system, and an advanced computational approach to leak quantification and localization.						

Project Title or Topic	Years Active	Lead Research Organization(s)	Funding Agency, Program	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Ultra-Sensitive Methane Leak Detection System for the Oil and Gas Industry Exploiting a Novel Laser Spectroscopic Sensor with Revolutionary High Performance/ Low Cost	2014–	LI-COR	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
LI-COR is working with Colorado State University and Gener8 to develop cost-effective, highly sensitive optical methane sensors that can be integrated into mobile or stationary methane monitoring systems. Their laser-based sensor utilized optical cavity techniques, which provide long path lengths and high methane sensitivity, but previously have been costly. This project will produce a robust, highly sensitive, low-cost sensor to identify, quantify, and locate methane leaks from natural gas systems.						
Tunable Laser for Methane Sensing	2014–	Maxion Technologies, Inc.	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
Maxion Technologies is partnering with Thorlabs Quantum Electronics, Praevium Research Inc., and Rice University to develop a low cost, widely tunable, mid- infrared laser source to be used in systems to detect and measure methane emissions. The design targets a strong methane absorption region currently accessible only by expensive lasers, and will improve the sensitivity and selectivity of optical methane sensors. The new architecture is planned to reduce the cost of lasers capable of targeting methane optical absorption lines near 2.2 microns, enabling the development of affordable, high sensitivity sensors When incorporated into a methane detection system, this technology will enable significant reductions in the cost associated with identifying, quantifying, and locating methane leaks compared to currently available technologies.						
Microstructured Fiber for Infrared Absorption Measurements of Methane Concentration	2014–	GE	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
GE will partner with Virginia Tech to design, fabricate, and test a novel, hollow core, microstructured optical fiber for long path-length transmission of infrared radiation at methane absorption wavelengths. The hollow optical fiber will utilize a microstructured design that allows permeability to methane but maintains low-loss propagation of light over long distances. The design allows identification of the location of methane leaks along the length of the fiber, which provides significant flexibility in deployment. When fielded as a full methane detection system, this technology will enable significant reductions in the cost associated with identifying, quantifying, and locating methane leaks compared to currently available technologies.						
Frequency Comb-Based Remote Methane Observation Network	2014–	University of Colorado at Boulder	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
The University of Colorado at Boulder will team with the National Institute of Standards and Technology (NIST) and the Cooperative Institute for Research in Environmental Sciences (a partnership between CU Boulder and the National Oceanic and Atmospheric Administration) to develop a reduced-cost, dual frequency comb spectrometer. The frequency comb would consist of 105 evenly spaced, sharp, single frequency laser lines covering a broad wavelength range that included the unique absorption signatures of natural gas constituents like methane. When integrated into a complete methane detection system, the combs could lower the costs of methane sensing due to their ability to survey large areas or multiple gas fields simultaneously and will enable significant reductions in the cost associated with identifying, quantifying, and locating methane leaks compared to currently available technologies.						
An Autonomous Coded Aperture Mini Mass Spectrometer (autoCAMMS) Based Methane Sensing System	2014–	Duke University	DOE ARPA-E MONITOR	Local	Bottom-Up	Technology Development
Duke University will build a miniaturized, coded aperture mass spectrometer environmental sensor (CAMMS-ES) for use in a methane monitoring system. The coded aperture enables high resolution and high throughput in a compact device. The mass spectrometer design will be optimized for methane, and will provide the ability to distinguish between methane with different isotopic signatures for differentiating biogenic and geologic methane sources. Additionally, the sensor will identify other volatile organic compounds (VOCs) associated with natural gas production. The miniature mass spectrometer can be readily deployed and will dramatically reduce the cost to identify, quantify, and locate methane leaks compared to currently available technologies.						

Project Title or Topic	Years Active	Lead Research Organization(s)	Funding Agency, Program	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Methane Technology Test Facility	2016–	DOE	DOE ARPA-E MONITOR	Point Source, Local	Both	Testing
In order to evaluate the performance of each MONITOR technology with respect to quantifying and locating fugitive methane emissions, the MONITOR program seeks to develop a robust test site that simulates real-world natural gas wellpad conditions. Specifically, the MONITOR program will provide $3–$5 million to support the operation of a multi-user field test site-including, if necessary, design and construction, of a new test site, or alteration of an existing test site-for use by MONITOR program Awardees. The test facility will be competitively selected in mid-May.						
Extreme Value Statistical Analysis	2015–2016	NREL	DOE EPSA	N/A	Bottom-Up	Emissions Inventory
NREL is conducting extreme value statistical analysis of published methane emission data for natural gas systems to re-examine datasets to better characterize their sample distribution. This research also aims to better quantify the uncertainty associated with current inventory estimation methods, investigate alternatives to employing the arithmetic mean to estimate the emission factor, and understand if datasets can be combined via meta-analysis to improve sample size and therefore robustness of results. Research findings are under consideration for publication in a peer-reviewed Journal.						
Developing New Measurements to Characterize Methane Leak Rates and Methane Leak Frequency from Natural Gas Infrastructures	2016–		DOE FE	Point Source, Local	Bottom-Up	Emissions Inventory
The FY 2016 budget includes $5 million to improve the quantification of methane emissions from natural gas infrastructure to help update the U.S. Greenhouse Gas Inventory. Efforts will focus on understanding regional variation and reporting uncertainty in emissions estimates.						
Improving Measurement and Modeling of Methane Emissions from Natural Gas Infrastructure	2015	NETL	DOE FE	Local, Regional	Bottom-Up	Emissions Inventory, Modeling
NETL is funding measurements and modelling of methane emissions from natural gas infrastructure in the Marcellus region in Pennsylvania. Results are expected in the middle of 2016.						
Measurements and Modeling to Quantify Emissions of Methane and VOCs from Shale Gas Operations	2013–2016	Carnegie Mellon University	DOE FE	Local, Regional	Bottom-Up	Emissions Inventory
The goals of this project are to determine the leakage rates of methane and ozone-forming volatile organic carbons (VOCs) and the emission rates of air toxics from Marcellus shale gas activities at a process level. Methane emissions in the Marcellus Shale region shall be differentiated between “newer” sources associated with shale gas development and “older” sources associated with coal or conventional natural gas exploration						
Continuous, Regional Methane Emissions Estimates in Northern Pennsylvania Gas Fields Using Atmospheric Inversions	2013–2016	Penn State	DOE FE	Regional	Both	Emissions Inventory
Project The goal of this project is to quantify fugitive and total emissions of methane from the Marcellus gas production region of north-central Pennsylvania with an emphasis on detecting changes in emissions over time caused by changing gas production activity.						

<table>
<tr><th>Project Title or Topic</th><th>Years Active</th><th>Lead Research Organization(s)</th><th>Funding Agency, Program</th><th>Spatial Scale (Point Source, Local, Regional, National, Global)</th><th>Primary Methods (Bottom-Up, Top-Down, Both)</th><th>Key Science Topics Related to CH_4 Measurement and Monitoring</th></tr>
<tr><td>Assessing Fugitive Methane Emissions Using Natural Gas Engines in Unconventional Resource Development</td><td>2013–2016</td><td>West Virginia University</td><td>DOE FE</td><td>Local</td><td>Bottom-Up</td><td>Emissions Inventory, Technology Development</td></tr>
<tr><td colspan="7">The goal of this project is to create an inventory of diesel engines, their use, and their emissions incurred during unconventional well development. The first objective is to analyze the benefits of operating these or similar engines on dual fuel or dedicated natural gas to determine regulated and non-regulated emissions and fuel cost reductions. The next objective is to determine the effects of operating these or similar engines and fugitive methane emissions based on the operation of current technologies using a variety of natural gas compositions. The final objective will be to examine new catalyst formulations that can be used in conjunction with these developing technologies to minimize these new sources of fugitive methane emissions associated with unconventional well development.</td></tr>
<tr><td>Reconciling Top-Down and Bottom-Up Greenhouse Gas and Air Pollutant Emission Estimates from Unconventional Gas Development in the Denver-Julesburg Basin and in a Mid-Continent Basin</td><td>2014–2016</td><td>Colorado School of Mines</td><td>DOE FE</td><td>Regional</td><td>Both</td><td>Reconciling TD/BU</td></tr>
<tr><td colspan="7">The objective of the project is to provide the scientific and industrial communities with the first set of contemporaneous bottom-up and top-down measurements in a U.S. shale gas production basin. This project shall include advancements in comparing bottom-up and top-down components, aiming to reconcile potential differences between results from different approaches at the facility and basin scales, considering relevant uncertainty analysis for each approach.</td></tr>
<tr><td>Measurement of Hydrocarbon and Greenhouse Gas Emissions from Uncharacterized Area Sources</td><td>2014–2016</td><td>Utah State University</td><td>DOE FE</td><td>Local</td><td>Bottom-Up</td><td>Emissions Inventory</td></tr>
<tr><td colspan="7">This project will quantify emissions from uncharacterized area sources, including produced water evaporation ponds, land farms, areas with natural (and human-enhanced) geological seepage, and soils near wells in Utah's Uintah Basin. These sources have never been quantified but likely contribute significantly to overall ozone-forming hydrocarbon and greenhouse gas emissions. Quantification will improve the accuracy and efficacy of air quality decisions made by operators while expanding the pool of characterized emission sources that can be used in emission reductions schemes required by air quality regulators in the Uintah Basin and other areas. Emissions from facilities that employ different solid and liquid waste management strategies will be tested to determine the impact of each strategy on air emissions.</td></tr>
<tr><td>The Technology Integration Program: An Extension of the Environmentally Friendly Drilling Systems Program</td><td>2012–2016</td><td>Houston Advanced Research Center</td><td>DOE FE</td><td>Regional</td><td>Bottom-Up</td><td>Emissions Inventory</td></tr>
<tr><td colspan="7">The project has several tasks related to reducing methane emissions at oil and gas operations. One goal is to perform accurate emission measurements in order to determine the reduction in emissions when switching to dual fuel or natural gas powered engines. New protocols are also being developed to utilize portable sensors for fugitive sampling on-site. In order to reduce emissions from flaring, technologies are being field tested to utilize the flare gas for on-site power.</td></tr>
<tr><td>Life Cycle Analysis of Natural Gas Supply Chain</td><td>2009–2016</td><td>NETL</td><td>DOE FE</td><td>Regional, National</td><td>Bottom-Up</td><td>Modeling</td></tr>
<tr><td colspan="7">NETL's natural gas life cycle model was used to calculate the emissions from the natural gas sector, identify key supply chain dependencies, and prioritize CH_4 emission reduction opportunities. Key products included LCA reports (published in 2014 and 2016), and a paper on using common boundaries for assessing CH_4 emissions (published in Journal of Industrial Ecology in 2016).</td></tr>
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Project Title or Topic	Years Active	Lead Research Organization(s)	Funding Agency, Program	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Synthesis of Ground-Level Methane Measurements from the Natural Gas Supply Chain Using Life-Cycle Analysis	2014–2016	NETL	DOE FE	Regional, National	Bottom-Up	Modeling, Emissions Inventory
In collaboration with the Environmental Defense Fund (EDF), NETL used its natural gas life cycle model as a framework for integrating new CH_4 measurements. Emissions sources that were overlooked in past studies were identified. Emission sources with skewed emission distributions were analyzed. CH_4 emission reduction opportunities were prioritized. A paper has been submitted to Environmental Science and Technology.						
Natural Gas Pipeline Leak Rate Measurement System	2015–2017	Physical Sciences Inc.	DOT-PHMSA	Point Source, Local	Bottom-Up	Flux Measurement, Technology Development
This research will enhance capabilities to detect, locate, and quantify small natural gas pipeline leaks to prioritize remedial actions. The project will assemble and evaluate via field tests a system comprising a cost-effective synthesis of side-scan lasers, sensitive laser-based point sampling, and advanced data processing algorithms installed on a mobile leak survey platform. The research results will lead to advanced products and methodologies to be deployed by the leak survey industry for reducing the environmental impact of natural gas.						
Rapid Aerial Small Methane Leak Survey	2015–2017	Ball Aerospace & Technologies Corp.	DOT-PHMSA	Local, Regional	Top-Down	Remote Sensing, Technology Development
This R&D project develops new airborne differential absorption LIDAR (DIAL) technology that substantially reduces the cost of methane leak surveys as compared to the ground based, vehicle-mounted, in-situ sensors used today. It does this by swath-mapping broad areas of gas distribution networks 12X faster per unit area than vehicle mounted systems. The new instrument surveys broad areas >5X faster than existing DIAL which is designed to survey narrow transmission pipeline corridors and not gas distribution networks. Academic collaboration with a University of Colorado research laboratory provides Grade 3 leak rate quantification, allowing prioritization of leak repair.						
Framework for Verifying and Validating the Performance and Viability of Leak Detection Systems for Liquid and Natural Gas Pipelines	2015–2017	C-FER Technologies	DOT-PHMSA			
The primary objective of the project is to develop a Leak Detection Evaluation Framework for verifying and validating leak detection technologies. The framework will include standardized methods to assess the performance of technologies intended to detect small release events (i.e. leaks) and quantitative criteria to rank the performance of these systems over a range of release scenarios. The intent is to identify technologies that would be appropriate for field pilots but will not cover the processes required for the field pilot or operational implementation as these processes are well established in each operating company.						
PHMSA Research Roadmapping	2014–2015	DOT-PHMSA (with DOE, EPA, EDF)	DOT-PHMSA	National	Bottom-Up	Technology Development, Leak Rate Remote Sensing
Refine/Enhance/Develop methane leak survey technologies and methodologies to quantify detected emissions from relatively small volume rate leaks to prioritize a remedial action plan						
Evaluation of Remote Sensing Methods for Fence-Line Measurements		EPA ORD	EPA	Local	Bottom-Up	Remote Sensing
. EPA's Office of Research and Development is conducting evaluations of remote measurement methods for methane for use in fence-line monitoring of emissions						

Project Title or Topic	Years Active	Lead Research Organization(s)	Funding Agency, Program	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Natural Gas STAR Methane Challenge Program	2015–	Oil & Gas Companies	EPA	Local	Bottom-Up	Technology Development
Through the Methane Challenge Program, EPA is proposing to recognize leading companies that make voluntary, transparent commitments to increased action to reduce methane emissions from their operations. The Program is based on extensive stakeholder outreach and reflects a revision of EPA's previously proposed framework for an enhanced voluntary partnership in the oil and gas sector.						
Greenhouse Gas Reporting Program	2010–	EPA CCD	EPA	National	Bottom-Up	Emissions Inventory
In response to the FY2008 Consolidated Appropriations Act (H.R. 2764; Public Law 110-161), EPA issued the Mandatory Reporting of Greenhouse Gases Rule (74 FR 56260) which requires reporting of greenhouse gas data and other relevant information from large sources and suppliers in the United States. The purpose of the rule is to collect accurate and timely greenhouse gas data to inform future policy decisions. In general, the Rule is referred to as 40 CFR Part 98 (Part 98). Implementation of Part 98 is referred to as the Greenhouse Gas Reporting Program (GHGRP).						
Inventory of U.S. Greenhouse Gas Emissions and Sinks	1990–	EPA CCD	EPA	National	Bottom-Up	Emissions Inventory
In 1992, the United States signed and ratified the United Nations Framework Convention on Climate Change (UNFCCC). Parties to the Convention, by ratifying, "shall develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…"						
H_2O, CH_4, and HSRL Airborne Lidar Observations (H3ALO)	2015–2018	NASA LaRD	NASA LaRC	Regional	Top-Down	Technology Development, Remote Sensing
Objectives: Develop a combined Differential Absorption Lidar (DIAL) and High Spectral Resolution Lidar (HSRL) to enable new observations of atmospheric H_2O, CH_4 and aerosols from an aircraft platform. Develop a multi-wavelength receiver to enable lidar measurements of H_2O, CH_4, and aerosols. Demonstrate capability to interchange two common architecture lasers with a single receiver to enable H_2O DIAL + HSRL or CH_4 DIAL + HSRL measurements.						
A Compact Trace Gas Lidar for Simultaneous Measurements of Methane and Water Vapor Column Abundance	2015–2018	NASA GSFC, University of Maryland	NASA GSFC	Regional	Top-Down	Technology Development, Remote Sensing
Objectives: Develop component technology to enable methane and water vapor measurements at 1651 nm and 1652 nm respectively from airborne and spaceborne platforms. Demonstrate and validate simultaneous, high precision methane and water vapor measurements. Demonstrate methane column abundance with 1% precision. Advance the existing pump laser TRL by scaling its power and reducing Stimulated Brillouin Scattering (SBS).						
A Compact Remote Sensing Lidar for High Resolution Measurements of Methane	Complete 2016	NASA GSFC, University of Maryland	NASA GSFC	Regional	Top-Down	Technology Development, Remote Sensing
Objectives: Develop a compact, space-qualifiable laser transmitter for a LIDAR operating at 1.65 µm to enable CH_4 measurements with performance goals of:(1) output energy greater than 300 µJ and (2) linewidth less than 500 MHz. Reduce the risk, cost, size, mass and volume of the CH_4 lidar instrument by scaling the laser power of the existing laboratory breadboard, and demonstrate and validate high sensitivity CH_4 open path measurements.						

Project Title or Topic	Years Active	Lead Research Organization(s)	Funding Agency, Program	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Flight Hardened Methane DIAL Transmitter		NASA LaRC	NASA LaRC	Regional	Top-Down	Technology Development, Remote Sensing
Objectives: Complete development of an aircraft flight-hardened, pulsed 1.645 µm optical parametric oscillator (OPO) laser transmitter for methane DIAL in a flight-like package; Demonstrate 1 kHz pulse repetition rate wavelength switching between DIAL wavelengths Demonstrate high spectral purity laser output (>99.9%) at 1 kHz wavelength switching rate; and Deliver a fully packaged laser electronics module.						
CARVE Earth Venture Suborbital-1 Investigation (AK)	2012–	NASA JPL	NASA	Regional	Top-Down	Flux Measurement, Remote Sensing
The carbon budget of Arctic ecosystems is not known with confidence since fundamental elements of the complex Arctic biological-climatologic-hydrologic system are poorly quantified. Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) is collecting detailed measurements of important greenhouse gases on local to regional scales in the Alaskan Arctic and demonstrating new remote sensing and improved modeling capabilities to quantify Arctic carbon fluxes and carbon cycle-climate processes. Ultimately, CARVE will provide an integrated set of data that will provide unprecedented experimental insights into Arctic carbon cycling.						
Carbon Monitoring System Flux Project	2009–2011	NASA JPL	NASA	Multiple	Top-Down	Flux Measurement
The objective of the NASA CMS Flux Pilot Project is to incorporate the full suite of NASA observational, modeling, and assimilation capabilities to attribute CO_2 climate forcing to spatially resolved emissions. Achievement of this goal requires identifying atmospheric CO_2 signals of anthropogenic emission change against the backdrop of natural carbon cycle variability across a range of time scales. Critical to this project is the development of a framework that can estimate these emissions and their relationship to climate forcing with sufficient spatio-temporal resolution, accuracy, and precision for policy and scientific applications.						
GEO-CAPE Mission	2009–	Atmospheric Team-Harvard, NCAR	NASA	Multiple	Top-Down	Remote Sensing
Atmospheric observations will be made from a geostationary orbit positioned near 100 W to regularly view the domain extending from 10 N to 60 N and from the Pacific to the Atlantic Oceans. The GEO-CAPE mission is still in the pre-formulation study phase.						
Discover-AQ	2011–2014	NASA Langley	NASA	Regional	Top-Down	Remote Sensing, Modeling
DISCOVER-AQ is a 4-year campaign to improve the use of satellites to monitor air quality for public health and environmental benefit. Through targeted airborne and ground-based observations, DISCOVER-AQ will enable more effective use of current and future satellites to diagnose ground level conditions influencing air quality.						
Atmospheric Carbon and Transport–America	2015–2016	Penn State	NASA	Regional	Top-Down	Remote Sensing, Modeling
ACT–America will enable and demonstrate a new generation of atmospheric inversion systems for quantifying CO_2 and CH_4 sources and sinks. ACT–America will achieve these goals by deploying airborne and ground-based platforms to obtain data that will be combined with data from existing measurement networks and integrated with an ensemble of atmospheric inversion systems. Aircraft instrumented with remote and in situ sensors will observe how mid-latitude weather systems interact with CO_2 and CH_4 sources and sinks to create atmospheric CO_2/CH_4 distributions. A model ensemble consisting of a mesoscale atmospheric transport model with multiple physics and resolutions options nested within global inversion models and surface CO_2/CH_4 flux ensembles will be used to predict atmospheric CO_2 and CH_4 distributions.						

Project Title or Topic	Years Active	Lead Research Organization(s)	Funding Agency, Program	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
A Gridded (0.1 × 0.1), Monthly Resolved Version of the U.S. EPA's National Methane Emissions Inventory for Use as a Priori and Reference in Methane Source Inversions	2015	Harvard University	NASA Carbon Monitoring System	National	Bottom-Up	Emissions Inventory
Through the NASA CMS program, Harvard researchers are creating a directly evaluable gridded version of the U.S. EPA national bottom-up inventory for methane. They are converting the EPA methane emission inventory into a 0.1° × 0.1° gridded monthly emission inventory for the U.S. domain and individual years, suitable for direct evaluation with top-down constraints, with some caveats. Monthly gridding exploits the detailed algorithms and local activity data available to the EPA, as well as other fine-resolution data sets. For example, the project uses emission estimates from livestock based on EPA emission data per state, USDA livestock inventories per county, and USDA weighted land cover maps for sub-county localization. Furthermore, the project incorporates large individual point sources reported through the EPA Greenhouse Gas Reporting Program. Researchers are finding significant differences in the spatial patterns of emission sources compared with EDGAR v4.2. The resulting inventory improves comparability between top-down methods and bottom-up inventories, and from there achieve a better understanding of the factors controlling methane concentrations and their trends.						
NASA–USGS National Blue Carbon Monitoring System	2014-	USGS	NASA Carbon Monitoring System and USGS Land Carbon Program	National	Both	Flux Measurement; Emissions Inventory
The program seeks to use methane flux data collected in 6 sentinel sites (Puget Sound, San Francisco Bay, Louisiana, Everglades, Chesapeake Bay, Cape Cod) to quantify uncertainty with current IPCC methane emission default values, and calibrate emerging models (MEM-CH_4, IBIS) for better estimation of methane fluxes in coastal wetlands. The NASA CMS project, as a collator of extant validation data for C stocks and methane fluxes, also links with inverse-modeling approaches at continental and regional scales to assess attribution for coastal anomalies.						
Arctic Boreal Vulnerability Experiment (ABoVE)		NASA Terrestrial Ecology Program	NASA Terrestrial Ecology Program			Modeling, Remote Sensing
The Arctic-Boreal Vulnerability Experiment (ABoVE) is a NASA Terrestrial Ecology Program field campaign that will be conducted in Alaska and Western Canada (see Study Domain). ABoVE is a large–scale study of environmental change and its implications for social–ecological systems. ABoVE's science objectives are broadly focused on (1) gaining a better understanding of the vulnerability and resilience of Arctic and boreal ecosystems to environmental change in western North America, and (2) providing the scientific basis for informed decision–making to guide societal responses at local to international levels. Research for ABoVE will link field–based, process–level studies with geospatial data products derived from airborne and satellite sensors, providing a foundation for improving the analysis, and modeling capabilities needed to understand and predict ecosystem responses and societal implications. Several projects within the initiative focus on quantifying CO_2 and CH_4 fluxes in Arctic-Boreal ecosystems.USGS, for example, is leading the ABoVE Boreal Inland Waters Study in interior Alaska (beginning FY16) to address the goals of refining estimates and understanding the drivers and spatial/seasonal variability of CH_4 emissions from inland waterways, particularly from streams and rivers.						
Hestia Project Collaboration with INFLUX	2012–	Arizona State University	NASA, DOE, NSF (NIST with INFLUX experiments)	Local	Both	Flux Measurement; greenhouse Gas Inventory; Remote Sensing, Reconciling TD/BU
Arizona State University began a 3 year funded effort (NIST) to utilize atmospheric measurement of CO_2 and CH_4 (along with other related species) as a way to evaluate the Hestia effort in Indianapolis and take a crucial first step towards a monitoring, reporting and verification (MRV) system that could be deployed across the planet						

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Indianapolis Flux Experiment (INFLUX)	2010–	Penn State, NIST, Purdue University, the University of Colorado, NOAA and private sector partners	NIST	Local	Both	Flux Measurement; Emissions Inventory; Reconciling TD/BU
The Indianapolis Flux Experiment (INFLUX) was designed to develop and evaluate methods for the measurement and modeling of greenhouse gas fluxes from urban environments. Determination of greenhouse gas fluxes and uncertainty bounds is essential for the evaluation of the effectiveness of mitigation strategies.						
Northeast Corridor Urban Test Bed	2014–	NIST	NIST	Regional	Both	Flux Measurement, Greenhouse Gas Inventory, Remote Sensing, Reconciling TD/BU
The Northeast Corridor Urban Test Bed is part of NIST's effort to develop and assess performance of greenhouse gas measurement tools at urban sites. The Northeast Corridor is particularly important because it is the largest U.S. megacity, and it has a test bed with moderately complex topography and meteorology.						
Greenhouse Gas Emissions and Transport Project	2011–	NIST	NIST	Point Source	Both	Flux Measurement, Reconciling TD/BU
The capabilities of the NIST National Fire Research Laboratory (NFRL) will be extended to provide a test bed for performance evaluation of instruments and test methods used for the monitoring of greenhouse gas emissions from point sources at close to industrial scale. In addition, atmospheric dispersion models will be assessed and developed to design optimal placement of sensor systems and to provide realistic and substantial uncertainty estimates of greenhouse gas emissions from area sources based on sensor field measurements.						
Megacities Carbon Project	2015–	NASA JPL	NIST, NASA, NOAA, Keck Institute for Space Studies	Regional	Both	Flux Measurement, Greenhouse Gas Inventory, Remote Sensing, Reconciling TD/BU
The Megacities Carbon Project will develop and test methods for monitoring the greenhouse gas emissions of the largest human contributors to climate change: cities and their power plants. Pilot activities have already begun in the megacities of Los Angeles and Paris that build on existing research infrastructure there and collaborations between the teams involved. Discussions are also underway regarding inclusion of a third sister city in South America or Asia. Its goal is to 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. After the three-city pilot is established the project may be expanded to include additional cities. A key element of the project will be open and transparent data sharing between the international partners.						
SONGNEX 2015, Shale Oil and Nature Gas Nexus, Studying the Atmospheric Effects of Changing Energy Use in the U.S. at the Nexus of Air Quality and Climate Change	2015	NOAA ESRL, CIRES University of Colorado	NOAA	Regional	Top-Down	Flux Measurement, Remote Sensing, Modeling
The primary goal of NOAA's field study is to quantify the emissions of trace gases and fine particles from several different tight oil and shale gas basins in the western U.S., and to study the chemical transformation of these emissions. The study will be focused on basins which represent a mixture of oil and gas production regions at various stages of development.						

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TOPDOWN 2014	2014	NOAA ESRL, University of Colorado, University of Michigan	NOAA	Regional	Top-Down	Flux Measurement, Remote Sensing, Modeling
TOPDOWN2014 will quantify emissions from tight oil and shale gas basins via aircraft based measurements in: Bakken, Upper Green River Valley, Uintah, Denver-Julesberg, Haynesville, Eagle Ford, Marcellus.						
CarbonTracker-LaGrange and WRF-Flexpart	2014–	NOAA ESRL	NOAA	Regional	Top-Down	Modeling
NOAA ESRL has parallel efforts to use the WRF regional atmospheric model and Lagrangian particle dispersion models to estimate and attribute emissions for North America. WRF-Flexpart is being used to estimate emissions from urban processes and fossil fuel production along the Colorado Front Range, for the Four Corners region, for the Uintah Basin and other basins studies by NOAA and its partners in recent years. CarbonTracker-Lagrange will be used to estimate emissions at higher resolution for the continental U.S.						
NOAA ESRL CarbonTracker–CH_4 project	2012–	NOAA ESRL	NOAA and international partners for measurements	Global	Top-Down	Modeling
Global inverse modeling system for estimating methane emissions from continent-scale regions using the cooperative global network of in-situ observations. Major results include attribution of the recent global increase to a combination of increased emissions from tropical microbial sources with a contribution from anthropogenic sources, lower emissions from Asia and the Arctic than estimated by bottom-up techniques, and higher than expected North American emissions. Future development involves high resolution at global scales to improve simulation of continental sites, and use of multiple trace species observations to better constrain and attribute emissions.						
TOPDOWN 2015	2015	NOAA ESRL, NASA JPL, University of Colorado, University of Michigan, BLM, State of NM	NOAA, NSF, NASA, BLM	Regional	Top-Down	Flux Measurement, Remote Sensing, Modeling
TOPDOWN 2015 will investigate the sources of methane emissions causing the Four Corners hotspot in the U.S. Southwest. The team will use both airborne and ground-based instruments.						
AirWaterGas Sustainability Research Network	2012–2017	University of Colorado, California State Polytechnic University Pomona, Colorado School of Mines, Colorado School of Public Health (University of Colorado Denver), Colorado State University, NOAA, NREL, UCAR, University of Michigan	NSF	Regional	Bottom-Up	Emissions Inventory, Modeling
To better understand natural gas extraction's air quality impacts, the Air Quality team uses atmospheric measurements to estimate air emissions in two different natural gas basins in Colorado and Utah. Measuring methane, ozone precursors, and ozone in these places will allow them to compare emissions between basins and against available inventories. By gathering operational emissions data at a wide scale (the basin), the Air Quality team results can be used to evaluate mitigation measures implemented in those basins. This information will also feed a forecasting model that will simulate the air quality impacts of different energy (production and usage) scenarios over the next few decades. The basin-scale air quality information will be supplemented by finer-scale air quality data collected by citizen scientists in Boulder and at the Navajo Nation's Dine College.						

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Effects of Increased Freshwater Inputs and Saltwater Intrusion on the Current and Future Greenhouse Carbon Balance of Everglade Wetlands		University of Alabama, Florida International University	NSF	Local, Regional	Bottom-Up	Flux Measurement, Modeling
This project supports ongoing measurements of CO_2, CH_4, H_2O, and energy fluxes in Everglades National Park to help develop a carbon balance for the Florida everglades that includes the interactive effects of climate change, hydrology, and saltwater intrusion.						
UNS: Collaborative Research: Measurement and Modeling of the Pathways of Potential Fugitive Methane Emissions During Hydrofracking	2015–2018	Dartmouth College, Ohio State University	NSF	Regional	Top-Down	Flux Measurement, Emissions Inventory
This project will provide a much needed and timely set of baseline and fugitive methane emission measurements before and during hydrofracking operations that will quantify and identify the sources of methane emissions released during different components of the drilling and gas extraction operations process. This will fill a critical knowledge gap that will inform the development of effective management strategies and operations practices to minimize methane emissions and improve the overall greenhouse gas benefits of natural gas. This project will: (1) Quantify baseline and fugitive methane emissions during hydrofracking by collecting continuous landscape-scale methane flux measurements; (2) Identify biological and geological sources of methane emissions by measuring continuous atmospheric fluxes of 13C isotopes in methane; (3) Attribute measured methane fluxes to different components of the hydrofracking process by using a footprint model and advanced large eddy simulations to isolate flux sources in space and time.						
Dissertation Research: Quantification and Characterization of the Production of Methane in Living Trees	2014–2016	Yale University	NSF	Local, Regional	Bottom-Up	Flux Measurement
Previous studies into the production of methane in living trees suggest that trees have the potential to be a globally significant source of methane, which is an important greenhouse gas. Wood-rot inside living trees is known to be common, but the production of methane from this rotting material has not been considered in global methane budgets. Using a collaborative kit-based sampling effort, gas will be collected from living trees, dead wood, and debris, in western conifer forests and results evaluated in the context of forest management approaches that maximize carbon storage and hence limit methane production.						
Dissertation Research: Controls on Methane Flux from Arctic Tundra	2013–2015	San Diego State University Foundation	NSF	Regional, Global	Bottom-Up	Flux Measurement, Modeling
The two major environmental factors that affect the amount of methane being made and released from natural wetland ecosystems are (1) how wet the soil is, and (2) how warm the soil is, but little is known about how these factors interact during seasonal transition periods like late spring, when soils thaw and lose snow cover. This project uses a portable greenhouse gas analyzer to measure methane gas emissions from a northern Finnish mire during the 2013 spring transition period and summer growing season, using snow-melting and soil manipulation experiments to determine the influence of these variables on methane emission rates.						
Mapping and Quantifying Methane Seeps on the Eastern Siberian Shelf and Slope—A Component of the Swedish Russian U.S. Climate-Cryosphere-Carbon Interactions (SWERUS-C3) Program	2014–2016	University of New Hampshire	NSF	Regional	Bottom-Up	Flux Measurement
The project proposes to use the multibeam sonar on board the ODEN to locate and characterize gas seeps in the water column and then apply a newly developed wideband transceiver to the split-beam echosounder on board the ODEN to constrain the size and fate of gas bubbles rising to the surface. Together, these acoustic observations will help the SWERUS-C3 team understand the flux of methane from the seafloor into the water column and potentially into the atmosphere. If successful, these techniques will allow the mapping of the gas flux in the Arctic over scales never before possible.						

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A Robust and Sensitive In Situ Analyzer for Simultaneous Methane Carbon and Hydrogen Isotopic Measurements in the Deep Sea	2014–2017	Woods Hole Oceanographic Institution	NSF	Regional	Bottom-up	Technology development
In an effort to design advanced instrumentation for studying sources and biogeochemical cycling of methane (CH_4) in the deep ocean, the investigators will develop a Quantum cascade laser-based in situ methane isotope sensor. By combining an off-axis integrated cavity output spectroscopy-based approach with Quantum cascade lasers, this sensor will be capable of measuring in situ methane isotopes. A primary goal of this project is to demonstrate the use of Quantum cascade laser-based instrumentation for deep sea chemical sensing. A newly designed gas inlet system will be implemented to reduce interference by water and to enhance the sensitivity of in situ stable isotopic analyses. The sensor system will be field tested at a deep-sea methane-rich environment using the E/V Nautilus and the ROV Hercules.						
Collaborative Research: Year-Round Autonomous Sampling of Methane in Arctic Lakes	2014–2016	University of Maryland Center for Environmental Sciences, University of Alaska Fairbanks Campus, Bigelow Laboratory for Ocean Sciences	NSF	Regional	Bottom-Up	Emissions Inventory
The majority of methane flux to the Arctic atmosphere is estimated to come from soils and small lakes, although these estimates are based on few direct observations with large uncertainties. This proposed study, using in situ samplers and sensors, will allow an extensive microbial, gas and ion analytical program coupled with a network of physical and chemical sensor data to assess temporal conditions during winter months; to confirm fundamental processes and rates; to determine the interplay among microbial, geochemical and physical processes; and to develop a plan for a more inclusive study that takes advantage of low cost proxies for significant processes that best characterize temporal aspects of lake conditions. The project will enhance infrastructure for future research in the Arctic through the development of novel in situ sampling						
CAREER: Development of a Broadband Acoustic System for Quantifying the Flux of Free Gas in Methane Seeps	2014–2019	University of New Hampshire	NSF	Regional, Global	Bottom-Up	Technology Development
The project will develop a broadband acoustic system to quantify the depth dependent bubble size distribution and gas void fraction in methane seeps, and to measure the flux of methane gas escaping the seabed and rising through the water column. Inversion of acoustic measurements for these quantities will exploit the mechanical resonance of bubbles by observing the bubbles response at a wide range of frequencies (1–100 kHz).						
Methane Release from Thermokarst Lakes: Thresholds and Feedbacks in the Lake to Watershed Hydrology-Permafrost System	2015–2018	University of Alaska Fairbanks Campus	NSF	Regional	Na	Emissions Inventory
Uncertainties in the budget of atmospheric methane (CH_4), an important greenhouse gas released by thermokarst lakes, limit the accuracy of climate change projections. The objective of this grant is to refine climate feedback representations by integrating permafrost-hydrology-methane processes across scales (thermokarst-lake to watershed). Methane release from thermokarst lakes is typically considered to be solely derived from the lake and its talik (thaw bulb beneath the lake), while not accounting for the production, storage, and potential escape of CH_4 beneath the permafrost.						

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Collaborative Research: Investigating Northern Peatland Methane Dynamics by Synthesizing Measurements, Remote Sensing and Modeling from Local to Regional to Continental Scales	2013–2017	University of Arizona, University of Massachusetts Lowell, University of New Hampshire	NSF	Regional, Global	Both	Flux Measurement, Emissions Inventory
This project will collect new measurements and leverage long-term existing data on methane emissions from five well-studied research sites that span four northern climate zones. In addition, the project will use environmental and climate variables developed from remote sensing data collected by several satellites over vast areas of the far north. Using a unique scaling approach, the emissions from northern wetlands will be determined so that a global analysis can be performed. This project will implement new measurement technologies and enable more accurate representation of methane emissions on a global scale.						
EAPSI: Estimating Methane and Carbon Dioxide Emissions from the Three Gorges Reservoir in China	2014–2015	Witthaus-Yasarer Lindsey M	NSF	Regional	Top-Down	Emissions Inventory
Three Gorges Reservoir (TGR) in China is one of the largest reservoir systems in the world. Environmental concerns about TGR's construction and operation, such as nutrient enrichment of reservoir waters, algal blooms, fragmentation of critical habitats, and greenhouse gas emissions (methane and carbon dioxide) from the reservoir area, have drawn global concern. This project will use statistical and geospatial tools to create a spatially heterogeneous estimate of CH_4 and CO_2 emissions from Three Gorges Reservoir. The proposed work will integrate geospatial analysis into a long-term study of reservoir carbon fluxes.						
SBIR Phase I: Predictive Modeling and Automatic Control of Landfill Gas Collection	2015–2016	Loci Controls, Inc	NSF	Local, Regional	Bottom-Up	Technology Development
Landfill gas collection systems are currently operated manually and lack the embedded feedback capabilities to properly match the rate of gas extraction to the rate of generation in response to changing environmental conditions. The proposed control hardware is a wireless, fully automatic sensor and actuator device able to measure key characteristics of landfill gas and adjust gas extraction rates on individual wells in real time. The research objective is to utilize these capabilities to collect data and develop a deeper understanding of landfill gas generation and the complex interactions within the extraction system						
Regional Air Quality Impact of Natural Gas Production Operations	2014–2017	University of Maryland College Park	NSF	Regional	Both	Modeling
This proposal will investigate the regional nature of emissions from NG production operations including modern horizontal drilling and hydraulic fracturing. The primary testable hypothesis is that ground level air emissions of even short-lived species can be significant regional sources of pollution through vertical transport and advection. Rigorous analysis of ground level and aloft aircraft measurements of methane, VOCs, NOx, and PM2.5, including those made during the NASA DISCOVER-AQ campaign will be performed. Receptor based source apportionment will be conducted for multiple sites in the mid-Atlantic region. To improve our ability to simulate regional transport, existing vertical transport parameterization schemes available within the Community-scale Modeling and Air Quality (CMAQ) platform will be evaluated for several episodes in the mid-Atlantic region of the U.S. for 2007 and 2011.						

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<tr><td>MRI: Development of an Integrated Gas Monitoring and Source Identification Unmanned Aircraft System for Exploration, Compliance and Assessment</td><td>2016–2019</td><td>Texas A&M University Corpus Christi</td><td>NSF</td><td>Local, Regional</td><td>Top-Down</td><td>Remote Sensing, Technology Development</td></tr>
<tr><td colspan="7">This project, developing an integrated gas monitoring and source identification unmanned aircraft system (UAS), aims to explore, check environmental compliance, and assess critical activities to enable a wide range of appropriate multi- and inter-disciplinary activities with emerging developments in UAS and sensor technologies. These activities address regional and national oil and gas industry needs. Gas exploration and environmental compliance and assessment are critical activities for the energy industry. New sensor technologies for detecting emissions from land and water have improved the ability to detect gases and flux (such as helium, methane, carbon dioxide, and oil). Unfortunately, use of these technologies in gas exploration and source identification by the energy industry and regulatory agencies is limited (due to operation, deployment and effectiveness issues). The proposed instrument addresses these issues by integrating advanced gas sensing and imagery (SAR and EO–IR) technologies on a UAS.</td></tr>
<tr><td>Methane from Agriculture (International Project)</td><td>2014–2017</td><td>Penn State</td><td>USDA</td><td>Point Source</td><td>Bottom-up</td><td>Emissions Inventory</td></tr>
<tr><td colspan="7">Mainly to work on adapting beef cattle grazing system to a changing climate but also to mitigate greenhouse gases from beef productions systems in the Southern Great Plains. Includes as functional network of monitoring sites to measure and monitor storage and flux of water, carbon (CO_2, CH_4), and nitrogen (N_2O) in cow-calf and stocker production systems utilizing combinations of winter wheat, pasture, and rangeland forages. Establish baselines and develop a suite of existing or novel approaches and management practices that leads to a net decrease in the footprints or increased C sequestration in mixed beef-forage farms. Monitoring whole production systems as well as enteric methane emissions.</td></tr>
<tr><td>Greenhouse Gas Reduction through Agricultural Carbon Enhancement Network (GRACEnet)</td><td>2002–</td><td>USDA ARS</td><td>USDA ARS</td><td>Field Scale</td><td>Bottom-up</td><td>Emissions Inventory; Agricultural Emissions Reduction; Modeling Support</td></tr>
<tr><td colspan="7">The primary goals of GRACEnet are to quantify greenhouse gas emissions and other environmental impacts of cropped and grazed systems under “business as usual” management and to assess how those impacts change with management scenarios intended to increase soil carbon stocks and reduce greenhouse gas emissions. GRACEnet is a network of scientists across over 30 USDA ARS locations. Standard sampling protocols are used at each location and a common database has been created, facilitating the usefulness, consistency and ease of use of the data. Data are both lab and field generated, using soil sampling, chambers, and flux towers. Through the GRA and other efforts, GRACEnet data and sampling protocols have been used around the world. GRACEnet efforts have been widely documented through published data and peer–reviewed literature. In 2012, the GRACEnet book was published (Managing Agricultural Greenhouse Gases, Elsevier, Inc.).</td></tr>
<tr><td>Livestock GRACEnet</td><td>2012–</td><td>USDA ARS</td><td>USDA ARS</td><td>Local Facility And Field Scale</td><td>Bottom-Up</td><td>Emissions Inventory; Agricultural Emissions Reduction; Modeling Support</td></tr>
<tr><td colspan="7">The mission of Livestock GRACEnet is to lead the development of livestock management practices to reduce greenhouse gas, ammonia, and other emissions and provide a sound scientific basis for accurate measurement and modeling of emissions. Livestock GRACEnet is a network of scientists across over 13 USDA ARS locations and involves the measurement and/or modeling of livestock emissions from animal housing, manure management and enteric fermentation. Research includes animal diet impacts on methane emissions, manure storage, treatment and land application, anaerobic digestion, and others. Measurements are taken via soil sampling, chambers and flux towers.</td></tr>
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Improved Technologies for Anaerobic Digestion	2008–	USDA ARS	USDA ARS	Local Facility	Bottom Up	Emissions Inventory; Agricultural Emissions Reduction; Modeling Support
USDA ARS research at several locations is investigating how to minimize losses of methane to the atmosphere. Scientists are working on improved efficiencies for anaerobic digesters that utilize the methane produced to generate electricity, thereby reducing the methane released to the atmosphere. By making this technology applicable and relevant to smaller livestock producers and by making the process more efficient, this technology will become a practical solution for more producers.						
Model Development and Validation	2008–	USDA ARS	USDA ARS	Local Facility; Field Scale	Bottom Up	Emissions Inventory; Agricultural Emissions Reduction; Modeling Support
USDA ARS research at several locations is working on the development, calibration, validation and improvement of simulation models of methane and other greenhouse gas emissions. ARS field data efforts are specifically targeted to helping improve models such as DayCent and tools such as COMET-Farm. ARS scientists are working directly on the development of relevant models such as the Integrated Farm System Model (IFSM) and others. All of these modeling efforts rely on accurate and consistent field data to expand their usefulness to diverse soils, climates and cropping systems. USDA ARS collaborates with other federal agencies and universities across the U.S. on these modeling efforts.						
Enteric Fermentation Production, Genetics, Livestock Feed and Management Research	2011–2016	Purdue University	USDA NIFA	Point Source	Bottom Up	Emissions Inventory
Developing best methodologies to measure greenhouse gas from open-air agricultural operations. The results will enhance the farm operation specific database of greenhouse gas emissions, add to understanding of how emissions are influenced by region, climate, and management.						
Assessment of Methane Fluxes from Manure Management	2012–2017	University of Wisconsin	USDA NIFA	Point Source	Bottom-Up	Emissions Inventory
This is a large multifunctional project including research education and extension. The relevant objectives are: Develop a network of monitoring sites that measure carbon (C), nitrogen (N), water, and energy fluxes across each phase of the dairy production system: (a) enteric and barn fluxes, (b) manure handling and processing fluxes, and (c) soil level fluxes and which (d) create a publically available data library for all collected data; (2) Analyze and Integrate Process Models Across Scales: (a) to evaluate the effectiveness of animal, manure, and field-scale models to support decisions in a farm-level model, (b) to identify climate change scenarios and impacts for analysis with these models, and (c) to evaluate and improve regional benchmarks integrated into life cycle impact assessment;						
Assessment of Emissions from Grazing Systems and Rangeland and Pasture Management	2013–2018	Kansas State University	USDA NIFA	Point Source	Bottom Up	Emissions Inventory
Mainly to work on adapting beef cattle grazing system to a changing climate but also to mitigate greenhouse gases from beef productions systems in the Southern Great Plains. Includes as functional network of monitoring sites to measure and monitor storage and flux of water, carbon (CO_2, CH_4), and nitrogen (N_2O) in cow-calf and stocker production systems utilizing combinations of winter wheat, pasture, and rangeland forages. Establish baselines and develop a suite of existing or novel approaches and management practices that leads to a net decrease in the footprints or increased C sequestration in mixed beef-forage farms. Monitoring whole production systems as well as enteric methane emissions.						

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USGS Energy Resources Program (ERP)			USGS			
The ERP conducts research and assessments on the location, quantity, and quality of energy and carbon dioxide storage resources. Included in this research are the economic and environmental effects of resource extraction and use. Research within the ERP is primarily focused on the characterization of potential subsurface resources and not surface release of oil or natural gas. However, some current and past studies include the geologic and geochemical characterization of naturally occurring surface seeps of natural gas and oil.						
USGS Gas Hydrates Project			USGS	Local	Top Down	Flux Measurement
The USGS Gas Hydrates Project uses CRDS to measure methane and CO_2 concentrations in real-time while underway during shipboard surveys. The first spectrometer extracts gas samples from a standard seawater feed, producing concentration and carbon isotopic measurements every few seconds. When these data are combined with environmental parameters (e.g., wind speed, seawater temperature and salinity) through a Wanninkhof approach, they yield the methane flux across the sea-air interface. The second spectrometer collects air samples at different elevations above the sea surface on the ship. This produces an independent estimate of methane and CO_2 flux within the atmospheric marine boundary layer. In some cases, these surveys have been conducted during coincident airborne methane sensing, allowing complete characterization of methane dynamics from the sea-air interface to a height of hundreds of meters above the surface. The USGS Gas Hydrates Project has collected over 7000 kilometers of sea-air methane flux data in the Western Arctic Ocean from Amundsen Gulf to Bering Strait and from the coastline to the deepwater Canada Basin. In addition, we have acquired more than 700 kilometers of methane flux data on the northern U.S. Atlantic margin over hundreds of seafloor methane seeps that were newly discovered since 2012. We have also measured methane flux over tidal cycles in saltwater marshes. The marine data generally indicate low methane emissions across the sea-air interface in the deep ocean, even over active seafloor methane plumes and in areas where gas hydrates are inferred to be actively breaking down due to the impingement of warming ocean waters. The highest methane emissions occur in the Arctic Ocean coastal zone, where we have imaged widespread sediment methane accumulations that are inferred to be produced by microbial processes breaking down organic matter shed from the land and released from thawing subsea permafrost.						

Non-Governmental Organization Programs (NGOs)

The Environmental Defense Fund (EDF) is the primary NGO involved in methane emission research since the publication of the President's *Climate Action Plan: Strategy to Reduce Methane Emissions*. In addition to the Barnett Shale region coordinated campaign (highlighted in Section 3.B of this report), EDF has coordinated and funded other efforts to study natural gas supply chain methane emissions. EDF's bottom-up projects address all segments of the natural gas supply chain. EDF researchers deploy top-down measurement techniques to study local distribution of natural gas in several cities and conduct flyover studies over several oil and gas basins. EDF's work is notable for both its scope—providing a comprehensive view of all natural gas emission sources, plus top-down case studies of key basins—and its range of collaborators. Partners include Federal agencies (NOAA), universities (University of Texas and Colorado State, among others), and private industry (Aerodyne Research, Inc. and Atmospheric and Environmental Research, Inc.). Table A-3 provides summaries of current and previous EDF methane measurement studies. EDF (2015) provides additional details.

Table A-3. Major Environmental Defense Fund (EDF) Projects

Title	Study Years	Lead Research Organization(S)	Funding Agency, Program	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods (Bottom-up, Top-down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
EDF's 2012 Production Studies: Phase 1	2012	University of Texas at Austin	EDF	Point Source	Bottom-Up	Emissions Inventory
This study measured methane emissions at natural gas production sites—including some of the first measurements ever collected from hydraulically fractured wells. Diverse methods were used to directly measure methane emissions at well pads operated by nine cooperating U.S. natural gas companies. The study found that methane emissions from equipment leaks and pneumatic devices were larger than previously thought. The study also found that techniques to reduce emissions from well completions are effective at capturing 99% of the methane that was previously vented to the atmosphere, providing a data-based example of EPA regulations working.						
EDF's 2012 Production Studies: Phase 2	2012	University of Texas at Austin	EDF	Point Source	Bottom-Up	Emissions Inventory
This study expands on results from the first UT study by collecting additional data from two important emission sources associated with natural gas production: 1) liquid unloadings, when producing wells are cleared of water and other liquids inhibiting the flow of gas, and 2) pneumatic controllers used to regulate routine functions at well sites. UT coordinated with 10 natural gas companies on this effort. The study found that emissions from two sources—pneumatics and liquids unloading—were responsible for a significant portion of methane emissions from the production sector.						
EDF's 2012 Production Studies: Production Data Analysis	2012	Houston Advanced Research Center (HARC), EPA, EDF	EDF	Local, Regional	Bottom-Up	Emissions Inventory
Environmental Protection Agency (EPA) EPA's Office of Research and Development has collected fence line data on methane emissions at well production sites over several years EPA, HARC, and EDF, worked together to analyze the data further to investigate trends in production emissions. The report includes measurements from 210 production sites in the Barnett Shale and Eagle Ford regions of Texas, Colorado's Denver-Julesburg Basin, and the Upper Green River Basin gas fields surrounding Pinedale, Wyoming from 2010 to 2013. A statistical analysis of this data suggests unpredictable events, such as malfunctions and maintenance, have a strong influence on emission rates.						
EDF's 2012 Midstream Studies: Gathering and Processing Study	2012	Colorado State	EDF	Local, Regional	Bottom-Up	Emissions Inventory
CSU's Engines and Energy Conversion Laboratory led an effort to quantify national methane emissions associated with the natural gas industry's gathering infrastructure and gas processing facilities. Researchers worked with six industry companies and used tracer gas releases to quantify methane emissions from this sector. Initial findings from the measurement report show wide variations in the amount of methane leaking at U.S. gathering and processing facilities. Researchers with the study suggest leak detection and repair policies can be effective at minimizing emissions from these sources. A forthcoming paper will estimate nationwide leaks from this sector.						
EDF's 2012 Midstream Studies: Transmission and Storage Study	2012	Colorado State University. Carnegie Mellon University, Aerodyne Research	EDF	Local, Regional, National	Bottom-Up	Emissions Inventory
This study estimates the amount of methane lost during long-distance transportation and storage of natural gas as it moves across the country in cooperation with seven industry partners. The initial measurements paper used downwind tracer gas methods paired with direct on site measurements to report variable emissions data from site to site. The paper confirms compressors and equipment leaks are two primary sources for the sector's methane emissions. Researchers also developed a model to combine their measurements with data from EPA's Greenhouse Gas Reporting Program to derive a national emissions estimate for this industry segment.						

Title	Study Years	Lead Research Organization(S)	Funding Agency, Program	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods (Bottom-up, Top-down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
EDF's 2012 Local Distribution Studies: Multi-city Local Distribution Study	2012	Washington State University	EDF	Regional	Bottom-Up	Emissions Inventory
WSU's Laboratory for Atmospheric Research led a nationwide field study to better characterize and understand methane emissions associated with the delivery of natural gas. Researchers quantified methane emissions from facilities and pipes operated by 13 utilities in various regions. The data will be used to estimate emissions from distribution systems nationally. The study shows that methane emissions from local natural gas distribution systems are significant, especially in regions such as the Northeast where distribution infrastructure is older, but that progress is being made in reducing emissions from these systems, mainly through regulation and investment by utilities.						
EDF's 2012 Local Distribution Studies: Boston Study	2012	Harvard University, Duke University, Boston University, Aerodyne Research, and Atmospheric and Environmental Research	EDF	Local, Regional	Top-Down	Flux Measurement, Modeling
University scientists developed an innovative tower-based quantitative technique for use in the urban environment. The study found Boston's methane emissions are more than two times higher than inventory data suggests, with a yearly average loss rate between 2.1% and 3.3%.						
EDF's 2012 Local Distribution Studies: Indianapolis Study (related to NIST INFLUX)	2012	Washington State University	EDF	Local, Regional	Top-Down	Flux Measurement
To gain further regional insights of urban methane emissions, WSU coordinated with the National Institute of Standards and Technology to measure methane emissions in Indianapolis, which is part of a broader NIST project.						
Methane Mapping	2014–	Colorado State University	EDF	Point source, Local	Bottom Up	Emissions Inventory
Using mobile methane sensors, EDF partnered with Google to map methane emissions from pipelines under city streets. Led by researchers at Colorado State University, this method quantifies methane leaks from local distribution systems that utilities could use to identify and prioritize repair or replacement of leaky pipelines, not otherwise addressed as an immediate public safety risk.						
EDF's 2012 Basin Specific Studies: Flyover study: Denver-Julesburg Basin	2012	NOAA, University of Colorado at Boulder	EDF	Local	Top Down	Flux Measurement, Modeling
Researchers measured methane emissions from Colorado's most active oil and gas field using data gathered by aircrafts and compared the differences in atmospheric concentrations of hydrocarbons upwind and downwind of production areas. The study estimated methane emissions that were three times higher than estimates derived from EPA data. The study also found that levels of smog forming VOCs were twice as high as EPA estimates, and Benzene levels were 7 times higher than previously estimated.						

Title	Study Years	Lead Research Organization(S)	Funding Agency, Program	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods (Bottom-up, Top-down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
EDF's 2012 Basin Specific Studies: Barnett Study	2012	NA (Coordinated campaign)	EDF	Regional	Both	Flux Measurement, Remote Sensing, Modeling, Reconciling TD/BU
EDF convened 12 diverse research teams in October 2013 to measure methane emissions in the Barnett Shale in Texas. This campaign used a variety of aircraft, vehicle and ground-based measurements to quantify methane emitted across the natural gas supply chain. The study estimates regional methane emissions are 50% higher than estimates based on the Environmental Protection Agency's greenhouse gas inventory, and finds the majority of emissions come from a small number of sources.						
EDF's 2012 Basin Specific Studies: Flyover study: Barnett Shale	2012	NOAA, University of Colorado at Boulder, University of Michigan	EDF	Regional	Top Down	Flux Measurement, Modeling
As part of a broader project, scientists with NOAA and UC-Boulder's Cooperative Institute for Research in Environmental Sciences are measuring atmospheric concentrations of hydrocarbons in order to quantify and allocate regional methane emissions in an active oil-and gas basin that includes infrastructure						
EDF's 2012 Other Studies: Pump-to-wheels study	2012	West Virginia University	EDF	Regional	Bottom-Up	Emissions Inventory
WVU's Center for Alternative Fuels, Engines and Emissions, in cooperation with 10 companies and research organizations, led a study to directly measure methane emissions from the operation of natural gas fueled medium- and heavy duty vehicles, as well as CNG and LNG refueling and maintenance facilities. The study includes modeling emissions from this sector under differing growth scenarios.						
EDF's 2012 Other Studies: Pilot projects		University of Texas–Arlington, Harvard, Duke, Boston University, University of Colorado–Boulder	EDF	Regional	Both	Remote Sensing, Emissions Inventory
Three initial projects helped build the foundation for some of this research. University of Texas–Arlington collected methane data using mobile methane-sensing technology that helped inform the first UT study, as well as the Coordinated Campaign, and the methane mapping. Harvard, Duke, and Boston University researchers experimented with tower-based sensing systems for making methane emissions estimates in an urban environment. This work led to the larger Boston study. University of Colorado–Boulder scientists conducted research to identify elevated levels of methane and hydrogen sulfide that provided insights for subsequent overflight work.						
EDF's 2012 Other Studies: Filling gaps, including super emitters	2014	EDF	EDF	Regional	Top-Down	Emissions Inventory
The main objective of this effort is to address knowledge gaps not addressed by the other studies, including whether "superemitting" sites or sources produce a large share of emissions. Field work for this study was undertaken in late 2013.						
EDF's 2012 Other Studies: Project synthesis			EDF			
After the series of EDF-initiated studies are completed, EDF will engage stakeholders from across the projects to develop an integrated understanding of what was learned, including the development of an overall methane emission rate across the natural gas supply chain.						

Private Sector and Independent Academic Research

In addition to private sector contributions to EDF studies, private companies also serve as the lead research organizations for federally funded programs. For example, DOE's ARPA-E MONITOR program funds private research teams to develop sensor technology and methane measurement systems. (See Table A-2 for the full list of private sector research teams funded through ARPA-E MONITOR.) Additionally, EPA's Natural Gas STAR Methane Challenge Program recognizes and supports oil and gas companies committed to reducing methane emissions. (See Table A-2.)

In the course of the academic literature review, STPI researchers also identified several private sector entities that either funded studies or performed research in collaboration with academic researchers. Private sector actors included measurement and technology companies, oil and gas companies, and trade associations.

Table A-4 is a list of private sector collaboration and notable academic research. Due to significant private sector involvement in the large multi-investigator EDF studies, some EDF studies listed in Table A-3 are included in Table A-4 to recognize private sector research contributions.

Table A-4. Individual Research Projects and Private Sector Research

Title	Study Years	Lead Research Organization(s)	Funding Agency, Program	Funding Agency Category	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods Employed (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Use of GOSAT, TES, and Suborbital Observations to Constrain North American Methane Emissions in the Carbon Monitoring System	2012–2014	Harvard University	NASA Carbon Monitoring System	Federal	National	Top-Down	Flux Measurement, Modeling, Remote Sensing

Research Proposal Abstract: We propose to contribute to the NASA Carbon Monitoring System (CMS) with a four-dimensional variational (4D-var) inverse modeling capability for methane emissions in North America integrating satellite (GOSAT, TES), aircraft (CalNex, HIPPO, NOAA/CCGG), and surface-based (TCCON, NOAA/CCGG) observations. Our work will build on the existing CMS capability at JPL for carbon flux inversions using the adjoint of the global GEOS-Chem chemical transport model (CTM). Here we will apply the adjoint of the nested version of GEOS-Chem with $1/2^{\circ} \times 2/3^{\circ}$ (~50×50 km^2) horizontal resolution over North America and adjacent oceans. The nested model will enable fine-scale constraints on methane sources through the 4D-var inversion. We will focus on 2009 2011 when data from both GOSAT and TES are available together with aircraft campaign data over the U.S. from CalNex (May July 2010) and HIPPO (June September 2011). Combined use of GOSAT and TES data will enable us to separate boundary layer and free tropospheric contributions to the methane column through the inversion. The satellite data will be ingested in the 4D–var inverse model while the suborbital data will be used for independent analysis of the optimized methane fluxes. We will conduct a targeted analysis of the CalNex period to constrain methane sources in California by applying both Lagrangian (STILT) and Eulerian (GEOS–Chem) inverse modeling approaches to the aircraft and satellite data, testing the effect of different meteorological data sets and of different a priori constraints. This analysis will provide a unique opportunity to assess inverse modeling uncertainties related to resolution, data type (satellite or aircraft), meteorological model, and inversion procedure. We will use results from our continental–scale inversion of methane fluxes to better understand and quantify the major sources contributing to methane emissions in North America, and to provide guidance to the U.S. EPA for improving its national emission inventories. The inverse modeling capability for methane will be implemented into the existing CMS Flux Pilot Project at JPL for consistent inversion of CO_2 and methane fluxes over North America using the same 4D–var system. This will provide a powerful facility to monitor the fluxes of the two most important anthropogenic greenhouse gases. Our work will be directly responsive to major climate policy initiatives in the U.S. targeting methane emissions including the Global Climate Change and Clean Air Initiative of the U.S. State Department and the Global Methane Initiative of the U.S. EPA. P.I. Daniel Jacob and CoI Steve Wofsy will join the CMS Science Team as part of this project.

Title	Study Years	Lead Research Organization(s)	Funding Agency, Program	Funding Agency Category	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods Employed (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
High-Resolution Constraints on North American and Global Methane Sources Using Satellites	2014–2017	Harvard University	NASA Carbon Monitoring System	Federal	National	Top-Down	Modeling

Research Proposal Abstract: Our proposal will focus on the exploitation of GOSAT and TROPOMI data to better constrain anthropogenic and natural methane emissions at high resolution (0.25x0.33 deg) in North America and globally at (2x2.5 deg). Our work takes advantage of previous integration with CMS-Flux that uses a consistent 4DVAR capability and wetland emissions driven by common biogeochemical models and data. Products generated from this proposal will be used in collaboration with EPA scientists in integrating the information from bottom-up and top-down constraints on emissions. We anticipate a budget request of $300 K per year for three years.

<table>
<tr><th>Title</th><th>Study Years</th><th>Lead Research Organization(s)</th><th>Funding Agency, Program</th><th>Funding Agency Category</th><th>Spatial Scale (Point Source, Local, Regional, National, Global)</th><th>Primary Methods Employed (Bottom-Up, Top-Down, Both)</th><th>Key Science Topics Related to CH_4 Measurement and Monitoring</th></tr>
<tr><td>Top-down Estimate of Methane Emissions in California Using a Mesoscale Inverse Modeling Technique: The South Coast Air Basin</td><td>2015</td><td>NOAA</td><td>National Research Council, NOAA, California Energy Commission, Sandia National Laboratory</td><td>Federal</td><td>Regional</td><td>Top-Down</td><td>Modeling</td></tr>
<tr><td colspan="8">Research Proposal Abstract: In this study, we quantify CH_4 emissions with an advanced mesoscale inverse modeling system at a resolution of 8 km × 8 km, using aircraft measurements in the SoCAB during the 2010 Nexus of Air Quality and Climate Change campaign to constrain the inversion. To simulate atmospheric transport, we use the FLEXible PARTicle-Weather Research and Forecasting (FLEXPART-WRF) Lagrangian particle dispersion model driven by three configurations of the Weather Research and Forecasting (WRF) mesoscale model. We determine surface fluxes of CH_4 using a Bayesian least squares method in a four-dimensional inversion. Simulated CH_4 concentrations with the posterior emission inventory achieve much better correlations with the measurements ($R^2 = 0.7$) than using the prior inventory (U.S. Environmental Protection Agency's National Emission Inventory 2005, R2 = 0.5). The emission estimates for CH_4 in the posterior, 46.3 ± 9.2 Mg CH_4/h, are consistent with published observation-based estimates. Changes in the spatial distribution of CH_4 emissions in the SoCAB between the prior and posterior inventories are discussed. Missing or underestimated emissions from dairies, the oil/gas system, and landfills in the SoCAB seem to explain the differences between the prior and posterior inventories. We estimate that dairies contributed 5.9 ± 1.7 Mg CH_4/h and the two sectors of oil and gas industries (production and downstream) and landfills together contributed 39.6 ± 8.1 Mg CH_4/h in the SoCAB.</td></tr>
<tr><td>Comparison of Methods to Determine Methane Emissions from Dairy Cows in Farm Conditions</td><td>2015</td><td>Michigan State University, Swedish University of Agricultural Sciences</td><td>W. K. Kellogg Foundation, USDA
NIFA</td><td>Federal, NGO</td><td>Local</td><td>Bottom-Up</td><td>Emissions Inventory</td></tr>
<tr><td colspan="8">Nutritional and animal-selection strategies to mitigate enteric methane (CH_4) depend on accurate, cost-effective methods to determine emissions from a large number of animals. The objective of the present study was to compare 2 spot-sampling methods to determine CH_4 emissions from dairy cows, using gas quantification equipment installed in concentrate feeders or automatic milking stalls.</td></tr>
<tr><td>Lab-Assay for Estimating Methane Emissions from Deep-Pit Swine Manure Storages</td><td>2015</td><td>University of Illinois</td><td>Iowa Pork Producers Association, Iowa Experiment Station</td><td>Private sector</td><td>Local</td><td>Bottom-Up</td><td>Emissions Inventory</td></tr>
<tr><td colspan="8">Methane emission is an important tool in the evaluation of manure management systems due to the potential impact it has on global climate change. Field procedures used for estimating methane emission rates require expensive equipment, are time consuming, and highly variable between farms. The purpose of this paper is to report a simple laboratory procedure for estimating methane emission from stored manure. The test developed was termed a methane production rate (MPR) assay as it provides a short-term biogas production measurement. The MPR assay incubation time is short (3d), requires no sample preparation in terms of inoculation or dilution of manure, is incubated at room temperature, and the manure is kept stationary. These conditions allow for high throughput of samples and were chosen to replicate the conditions within deep-pit manure storages. In brief, an unaltered aliquot of manure was incubated at room temperature for a three-days to assay the current rate of methane being generated by the manure. The results from this assay predict an average methane emission factor of 12.2 ± 8.1 kg CH_4 head−1 yr−1 per year, or about 5.5 ± 3.7 kg CH_4 per finished animal, both of which compare well to literature values of 5.5 ± 1.1 kg CH_4 per finished pig for deep-pit systems (Liu et al., 2013). The average methane flux across all sites and months was estimated to be 22 ± 17 mg CH_4 m^{-2}-min^{-1}, which is within literature values for deep-pit systems ranging from 0.24 to 63 mg CH_4 $m^{-2}min^{-1}$ (Park et al., 2006) and similar to the 15 mg CH_4 m^{-2} min^{-1} estimated by (Zahn et al., 2001).</td></tr>
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Title	Study Years	Lead Research Organization(s)	Funding Agency, Program	Funding Agency Category	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods Employed (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Top–Down Methane Emission Estimates for the San Francisco Bay Area from 1990 to 2012	2015	Bay Area Air Quality Management District, Lawrence Berkeley National Laboratory	California Energy Commission's Natural Gas Research Program	State	Regional	Top-down	Emissions inventory, Modeling
Project Abstract: Methane is a potent greenhouse gas (GHG) that is now included in both California State and San Francisco Bay Area (SFBA) bottom-up emission inventories as part of California's effort to reduce anthropogenic GHG emissions. Here we provide a top-down estimate of methane (CH_4) emissions from the SFBA by combining atmospheric measurements with the comparatively better estimated emission inventory for carbon monoxide (CO). Local enhancements of CH_4 and CO are estimated using measurements from 14 air quality sites in the SFBA combined together with global background measurements. Mean annual CH_4 emissions are estimated from the product of Bay Area Air Quality Management District (BAAQMD) emission inventory CO and the slope of ambient local CH_4 to CO. The resulting top-down estimates of CH_4 emissions are found to decrease slightly from 1990 to 2012, with a mean value of 240 ± 60 $GgCH_4\ yr^{-1}$ (at 95% confidence) in the most recent (2009–2012) period, and correspond to reasonably a constant factor of 1.5–2.0 (at 95% confidence) times larger than the BAAQMD CH_4 emission inventory. However, we note that uncertainty in these emission estimates is dominated by the variation in CH_4:CO enhancement ratios across the observing sites and we expect the estimates could represent a lower-limit on CH_4 emissions because BAAQMD monitoring sites focus on urban air quality and may be biased toward CO rather than CH_4 sources.							
Prediction of Enteric Methane Emissions from Cattle	2014	University of California, Davis, South Dakota State University, University of Copenhagen	USDA NIFA Multistate Research Project, UC Davis	Federal	Regional, National	Bottom-Up	Modeling
Project Abstract: Agriculture has a key role in food production worldwide and it is a major component of the gross domestic product of several countries. Livestock production is essential for the generation of high quality protein foods and the delivery of foods in regions where animal products are the main food source. Environmental impacts of livestock production have been examined for decades, but recently emission of methane from enteric fermentation has been targeted as a substantial greenhouse gas source. The quantification of methane emissions from livestock on a global scale relies on prediction models because measurements require specialized equipment and may be expensive. The predictive ability of current methane emission models remains poor. Moreover, the availability of information on livestock production systems has increased substantially over the years enabling the development of more detailed methane prediction models. In this study, we have developed and evaluated prediction models based on a large database of enteric methane emissions from North American dairy and beef cattle. Most probable models of various complexity levels were identified using a Bayesian model selection procedure and were fitted under a hierarchical setting. Energy intake, dietary fiber and lipid proportions, animal body weight and milk fat proportion were identified as key explanatory variables for predicting emissions. Models here developed substantially outperformed models currently used in national greenhouse gas inventories. Additionally, estimates of repeatability of methane emissions were lower than the ones from the literature and multicollinearity diagnostics suggested that prediction models are stable. In this context, we propose various enteric methane prediction models which require different levels of information availability and can be readily implemented in national greenhouse gas inventories of different complexity levels. The utilization of such models may reduce errors associated with prediction of methane and allow a better examination and representation of policies regulating emissions from cattle.							

Title	Study Years	Lead Research Organization(s)	Funding Agency, Program	Funding Agency Category	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods Employed (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Estimating Methane Emissions from Landfills Based on Rainfall, Ambient Temperature, and Waste Composition: The CLEEN Model	2015	University of Texas at Arlington	Waste Management, Inc., Environmental Research and Education Foundation (EREF), Solid Waste Association of North America (SWANA) and Air and Waste Management Association (A&WMA)	Private Sector	Local, Regional	Bottom-Up	Modeling

Accurately estimating landfill methane emissions is important for quantifying a landfill's greenhouse gas emissions and power generation potential. Current models, including LandGEM and IPCC, often greatly simplify treatment of factors like rainfall and ambient temperature, which can substantially impact gas production. The newly developed Capturing Landfill Emissions for Energy Needs (CLEEN) model aims to improve landfill methane generation estimates, but still require inputs that are fairly easy to obtain: waste composition, annual rainfall, and ambient temperature. To develop the model, methane generation was measured from 27 laboratory scale landfill reactors, with varying waste compositions (ranging from 0% to 100%); average rainfall rates of 2, 6, and 12mm/day; and temperatures of 20, 30, and 37°C, according to a statistical experimental design. Refuse components considered were the major biodegradable wastes, food, paper, yard/wood, and textile, as well as inert inorganic waste. Based on the data collected, a multiple linear regression equation (R^2=0.75) was developed to predict first-order methane generation rate constant values k as functions of waste composition, annual rainfall, and temperature. Because, laboratory methane generation rates exceed field rates, a second scale-up regression equation for k was developed using actual gas-recovery data from 11 landfills in high-income countries with conventional operation. The Capturing Landfill Emissions for Energy Needs (CLEEN) model was developed by incorporating both regression equations into the first-order decay based model for estimating methane generation rates from landfills. CLEEN model values were compared to actual field data from 6 U.S. landfills, and to estimates from LandGEM and IPCC. For 4 of the 6 cases, CLEEN model estimates were the closest to actual.

Measurements of Methane Emissions from Natural Gas Gathering Facilities and Processing Plants: Measurement Methods	2014	Carnegie Mellon University, Aerodyne Research Inc., Colorado State University, Fort Lewis College,	Environmental Defense Fund (EDF), Access Midstream, Anadarko Petroleum Corporation, Hess Corporation, Southwestern Energy and Williams	NGO, Private Sector	Local	Top-Down	Emissions inUentory, Reconciling TD/BU

Project Abstract: Increased natural gas production in recent years has spurred intense interest in methane (CH_4) emissions associated with its production, gathering, processing, transmission and distribution. Gathering and processing facilities (G&P facilities) are unique in that the wide range of gas sources (shale, coal-bed, tight gas, conventional, etc.) results in a wide range of gas compositions, which in turn requires an array of technologies to prepare the gas for pipeline transmission and distribution. We present an overview and detailed description of the measurement method and analysis approach used during a 20-week field campaign studying CH_4 emissions from the natural gas G&P facilities between October 2013 and April 2014. Dual tracer flux measurements and onsite observations were used to address the magnitude and origins of CH_4 emissions from these facilities. The use of a second tracer as an internal standard revealed plume-specific uncertainties in the measured emission rates of 20-47 %, depending upon plume classification. Combining downwind methane, ethane (C_2H_6), carbon monoxide (CO), carbon dioxide (CO_2), and tracer gas measurements with onsite tracer gas release allows for quantification of facility emissions, and in some cases a more detailed picture of source locations.

Title	Study Years	Lead Research Organization(s)	Funding Agency, Program	Funding Agency Category	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods Employed (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Measurements of Methane Emissions at Natural Gas Production Sites in the United States	2015	University of Texas, Austin, Aerodyne Research, Inc., Arizona State University, Texas A&M University, College Station, Washington State University, Colorado School of Mines, University of California, Berkeley, California Institute of Technology, Pasadena	Environmental Defense Fund (EDF), Anadarko Petroleum Corporation, BG Group plc, Chevron, Encana Oil & Gas (USA) Inc., Pioneer Natural Resources Company, SWEPI LP (Shell), Southwestern Energy, Talisman Energy USA, and XTO Energy, an ExxonMobil subsidiary	NGO, Private sector	Local, Regional	Bottom-Up	NG Production, Emissions Inventory
This work reports direct measurements of methane emissions at 190 onshore natural gas sites in the United States. The measurements indicate that well completion emissions are lower than previously estimated; the data also show emissions from pneumatic controllers and equipment leaks are higher than Environmental Protection Agency (EPA) national emission projections. Estimates of total emissions are similar to the most recent EPA national inventory of methane emissions from natural gas production. These measurements will help inform policymakers, researchers, and industry, providing information about some of the sources of methane emissions from the production of natural gas, and will better inform and advance national and international scientific and policy discussions with respect to natural gas development and use.							
Direct Measurements of Methane Emissions from Abandoned Oil and Gas Wells in Pennsylvania	2014	Princeton University	National Oceanic and Atmospheric Administration Grant , support from Princeton and Yale, National Sciences and Engineering Research Council of Canada for the Postgraduate Scholarship-Doctoral Program	Federal	Local, Regional	Bottom-up	Emissions inventory
Project Abstract: Abandoned oil and gas wells provide a potential pathway for subsurface migration and emissions of methane and other fluids to the atmosphere. Little is known about methane fluxes from the millions of abandoned wells that exist in the United States. Here, we report direct measurements of methane fluxes from abandoned oil and gas wells in Pennsylvania, using static flux chambers. A total of 42 and 52 direct measurements were made at wells and at locations near the wells ("controls") in forested, wetland, grassland, and river areas in July, August, October 2013 and January 2014, respectively. The mean methane flow rates at these well locations were 0.27 kg/d/well, and the mean methane flow rate at the control locations was 4.5 × 10(–6) kg/d/location. Three out of the 19 measured wells were high emitters that had methane flow rates that were three orders of magnitude larger than the median flow rate of 1.3×10^{-3} kg/d/well. Assuming the mean flow rate found here is representative of all abandoned wells in Pennsylvania, we scaled the methane emissions to be 4–7% of estimated total anthropogenic methane emissions in Pennsylvania. The presence of ethane, propane, and n-butane, along with the methane isotopic composition, indicate that the emitted methane is predominantly of thermogenic origin. These measurements show that methane emissions from abandoned oil and gas wells can be significant. The research required to quantify these emissions nationally should be undertaken so they can be accurately described and included in greenhouse gas emission inventories.							

Title	Study Years	Lead Research Organization(s)	Funding Agency, Program	Funding Agency Category	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods Employed (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Methane Emissions from Leak and Loss Audits of Natural Gas Compressor Stations and Storage Facilities	2015	West Virginia University	Virginia University Research Corporation, George Berry Chair Endowment, EDF	NGO	Local	Bottom-Up	Emissions Inventory
As part of the Environmental Defense Fund's Barnett Coordinated Campaign, researchers completed leak and loss audits for methane emissions at three natural gas compressor stations and two natural gas storage facilities. Researchers employed microdilution high-volume sampling systems in conjunction with in situ methane analyzers, bag samples, and Fourier transform infrared analyzers for emission rate quantification. All sites had a combined total methane emission rate of 94.2 kg/h, yet only 12% of total emissions resulted from leaks. Methane slip from exhausts represented 44% of the total emissions. Remaining methane emissions were attributed to losses from pneumatic actuators and controls, engine crankcases, compressor packing vents, wet seal vents, and slop tanks. Measured values were compared with those reported in literature. Exhaust methane emissions were lower than emission factor estimates for engine exhausts, but when combined with crankcase emissions, measured values were 11.4% lower than predicted by AP–42 as applicable to emission factors for four-stroke, lean-burn engines. Average measured wet seal emissions were 3.5 times higher than GRI values but 14 times lower than those reported by Allen et at Reciprocating compressor packing vent emissions were 39 times higher than values reported by GRI, but about half of values reported by Allen et al. Though the data set was small, researchers have suggested a method to estimate site-wide emission factors for those powered by four-stroke, lean-burn engines based on fuel consumption and site throughput.							
Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol	2015	Carnegie Mellon University, Ft Lewis College, Colorado State University, Aerodyne Res Inc.	Dominion, Dow Chemical, Enable Gas Transmission LLC, EDF, Interstate Natural gas Association of America, Kinder Morgan Columbia Pipeline Group, TransCanada, Williams Companies Inc., Heising-Simons Foundation, etc.	Private sector	Local	Bottom-Up	Emissions Inventory
Equipment- and site-level methane emissions from 45 compressor stations in the transmission and storage (T&S) sector of the U.S. natural gas system were measured, including 25 sites required to report under the EPA Greenhouse Gas Reporting Program (GHGRP). Direct measurements of fugitive and vented sources were combined with AP-42-based exhaust emission factors (for operating reciprocating engines and turbines) to produce a study onsite estimate. Site-level methane emissions were also concurrently measured with downwind-tracer-flux techniques. At most sites, these two independent estimates agreed within experimental uncertainty. Site-level methane emissions varied from 2880 SCFM. Compressor vents, leaky isolation valves, reciprocating engine exhaust, and equipment leaks were major sources, and substantial emissions were observed at both operating and standby compressor stations. The site-level methane emission rates were highly skewed; the highest emitting 10% of sites (including two superemitters) contributed 50% of the aggregate methane emissions, while the lowest emitting 50% of sites contributed less than 10% of the aggregate emissions. Excluding the two superemitters, study-average methane emissions from compressor housings and noncompressor sources are comparable to or lower than the corresponding effective emission factors used in the EPA greenhouse gas inventory. If the two superemitters are included in the analysis, then the average emission factors based on this study could exceed the EPA greenhouse gas inventory emission factors, which highlights the potentially important contribution of superemitters to national emissions. However, quantification of their influence requires knowledge of the magnitude and frequency of superemitters across the entire T&S sector. Only 38% of the methane emissions measured by the comprehensive onsite measurements were reportable under the new EPA GHGRP because of a combination of inaccurate emission factors for leakers and exhaust methane, and various exclusions. The bias is even larger if one accounts for the superemitters, which were not captured by the onsite measurements. The magnitude of the bias varied from site to site by site type and operating state. Therefore, while the GHGRP is a valuable new source of emission information, care must be taken when incorporating these data into emission inventories. The value of the GHGRP can be increased by requiring more direct measurements of emissions (as opposed to using counts and emission factors), eliminating exclusions such as rod-packing vents on pressurized reciprocating compressors in standby mode under Subpart-W, and using more appropriate emission factors for exhaust methane from reciprocating engines under Subpart-C.							

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Anthropogenic Emissions of Methane in the United States	2013	Harvard University, Stanford, University of Michigan, NOAA, University of California at Berkeley, University of Colorado at Boulder, AER Inc, Institute for Environment and Sustainability (JRC-IES)	DOE Graduate Fellowships, NSF graduate fellowships, NOAA Climate Program (Carbon Cycle Program and Atmospheric Composition and Climate), NASA, NOAA, NSF, EDF, several programs through DOE, "U.S. intelligence community"	Federal	Regional, National	Top-Down	Emissions Inventory, Reconciling TD/BU

Project Abstract: This study quantitatively estimates the spatial distribution of anthropogenic methane sources in the United States by combining comprehensive atmospheric methane observations, extensive spatial datasets, and a high-resolution atmospheric transport model. Results show that current inventories from the U.S. Environmental Protection Agency (EPA) and the Emissions Database for Global Atmospheric Research underestimate methane emissions nationally by a factor of similar to 1.5 and similar to 1.7, respectively. Our study indicates that emissions due to ruminants and manure are up to twice the magnitude of existing inventories. In addition, the discrepancy in methane source estimates is particularly pronounced in the south-central United States, where we find total emissions are similar to 2.7 times greater than in most inventories and account for 24 ± 3% of national emissions. The spatial patterns of our emission fluxes and observed methane-propane correlations indicate that fossil fuel extraction and refining are major contributors (45 ± 13%) in the south-central United States. This result suggests that regional methane emissions due to fossil fuel extraction and processing could be 4.9 ± 2.6 times larger than in EDGAR, the most comprehensive global methane inventory. These results cast doubt on the U.S. EPA's recent decision to downscale its estimate of national natural gas emissions by 25–30%. Overall, we conclude that methane emissions associated with both the animal husbandry and fossil fuel industries have larger greenhouse gas impacts than indicated by existing inventories.

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Landscape-Level Terrestrial Methane Flux Observed from a Very Tall Tower	2015	University of Wisconsin, Auburn University, National Ecological Observation Network Inc, USGS, NOAA, NASA, University of California at Santa Barbara, U.S. Forest Service/USDA	NSF, NASA NACP, USDA Forest Service, NOAA	Federal	Regional	Top-Down	Flux Measurements, Modeling

Simulating the magnitude and variability of terrestrial methane sources and sinks poses a challenge to ecosystem models because the biophysical and biogeochemical processes that lead to methane emissions from terrestrial and freshwater ecosystems are, by their nature, episodic and spatially disjunct. As a consequence, model predictions of regional methane emissions based on field campaigns from short eddy covariance towers or static chambers have large uncertainties, because measurements focused on a particular known source of methane emission will be biased compared to regional estimates with regards to magnitude, spatial scale, or frequency of these emissions. Given the relatively large importance of predicting future terrestrial methane fluxes for constraining future atmospheric methane growth rates, a clear need exists to reduce spatiotemporal uncertainties. In 2010, an Ameriflux tower (US-PFa) near Park Falls, WI, USA, was instrumented with closed-path methane flux measurements at 122 m above ground in a mixed wetland-upland landscape representative of the Great Lakes region. Two years of flux observations revealed an average annual methane (CH_4) efflux of 785 ± 75 mg C – CH_4 m^{-2} yr^{-1}, compared to a mean CO_2 sink of –80g C – CO_2 m m^{-2} yr^{-1}, a ratio of 1% in magnitude on a mole basis. Interannual variability in methane flux was 30% of the mean flux and driven by suppression of methane emissions during dry conditions in late summer 2012. Though relatively small, the magnitude of the methane source from the very tall tower measurements was mostly within the range previously measured using static chambers at nearby wetlands, but larger than a simple scaling of those fluxes to the tower footprint. Seasonal patterns in methane fluxes were similar to those simulated in the Dynamic Land Ecosystem Model (DLEM), but magnitude depends on model parameterization and input data, especially regarding wetland extent. The model was unable to simulate short-term (sub-weekly) variability. Temperature was found to be a stronger driver of regional CH_4 flux than moisture availability or net ecosystem production at the daily to monthly scale. Taken together, these results emphasize the multi-timescale dependence of drivers of regional methane flux and the importance of long, continuous time series for their characterization.

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Allocating Methane Emissions to Natural Gas and Oil Production from Shale Formations	2015	University of Texas at Austin, URS Corp, Southwestern Energy Co	NSF, EPA, Texas Commission on Environmental Quality, American Petroleum Institute, EDF, Air monitoring and surveillance project	Federal, State, NGO	Local, Regional	Bottom-Up	Emissions Inventory

The natural gas supply chain includes production, processing, and transmission of natural gas, which originates from conventional, shale, coal bed, and other reservoirs. Because the hydrocarbon products and the emissions associated with extraction from different reservoir types can differ, when expressing methane emissions from the natural gas supply chain, it is important to allocate emissions to particular hydrocarbon products and reservoir types. In this work, life cycle allocation methods have been used to assign methane emissions from production wells operating in shale formations to oil, condensate, and gas products from the wells. The emission allocations are based on a data set of 489 gas wells in routine operation and 19 well completion events. The methane emissions allocated to natural gas production are approximately 85% of total emissions (mass based allocation), but there is regional variability in the data and therefore this work demonstrates the need to track natural gas sources by both formation type and production region. Methane emissions allocated to salable natural gas production from shale formations, based on this work, are a factor of 2 to 7 lower than those reported in commonly used life cycle data sets.

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A Multitower Measurement Network Estimate of California's Methane Emissions	2013	Lawrence Berkeley National Lab, California Air Resources Board, NOAA		State	Regional	Top-Down	Modeling

Project Abstract: We present an analysis of methane (CH_4) emissions using atmospheric observations from five sites in California's Central Valley across different seasons (September 2010 to June 2011). CH_4 emissions for spatial regions and source sectors are estimated by comparing measured CH_4 mixing ratios with transport model (Weather Research and Forecasting and Stochastic Time-Inverted Lagrangian Transport) predictions based on two 0.1deg CH_4 (seasonally varying California-specific (California Greenhouse Gas Emission Measurements, CALGEM) and a static global (Emission Database for Global Atmospheric Research, release version 42, EDGAR42)) prior emission models. Region-specific Bayesian analyses indicate that for California's Central Valley, the CALGEM- and EDGAR42-based inversions provide consistent annual total CH_4 emissions (32.87 ± 2.09 versus 31.60 ± 2.17 Tg CO_2eq yr^{-1}; 68% confidence interval (CI), assuming uncorrelated errors between regions). Summing across all regions of California, optimized CH_4 emissions are only marginally consistent between CALGEM- and EDGAR42-based inversions (48.35 ± 6.47 versus 64.97 ±– 11.85 Tg CO_2eq), because emissions from coastal urban regions (where landfill and natural gas emissions are much higher in EDGAR than CALGEM) are not strongly constrained by the measurements. Combining our results with those from a recent study of the South Coast Air Basin narrows the range of estimates to 43–57 Tg CO_2eq yr^{-1} (1.3–1.8 times higher than the current state inventory). These results suggest that the combination of rural and urban measurements will be necessary to verify future changes in California's total CH_4 emissions.

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Spatially Resolving Methane Emissions in California: Constraints from the CalNex Aircraft Campaign and from Present (GOSAT, TES) and Future (TROPOMI, geostationary) Satellite Observations	2014	Harvard University, University of Leicester, Cal Tech	NASA ACMAP, NASA-CMS, NASA, UK National Centre for Earth Observation, European Space Agency Climate Change Initiative	Federal, International	National	Top-Down	Modeling, Emissions Inventory, Remote Sensing
Project Abstract: We apply a continental-scale inverse modeling system for North America based on the GEOS-Chem model to optimize California methane emissions at 1/2 degrees × 2/3 degrees horizontal resolution using atmospheric observations from the CalNex aircraft campaign (May–June 2010) and from satellites. Inversion of the CalNex data yields a best estimate for total California methane emissions of 2.86 ± 0.21 Tg a^{-1}, compared with 1.92 Tg a^{-1} in the EDGAR v4.2 emission inventory used as a priori and 1.51 Tg a^{-1} in the California Air Resources Board (CARB) inventory used for state regulations of greenhouse gas emissions. These results are consistent with a previous Lagrangian inversion of the CalNex data. Our inversion provides 12 independent pieces of information to constrain the geographical distribution of emissions within California. Attribution to individual source types indicates dominant contributions to emissions from landfills/wastewater (1.1 Tg a^{-1}), livestock (0.87 Tg a^{-1}), and gas/oil (0.64 Tg a^{-1}). EDGAR v4.2 underestimates emissions from livestock, while CARB underestimates emissions from landfills/wastewater and gas/oil. Current satellite observations from GOSAT can constrain methane emissions in the Los Angeles Basin but are too sparse to constrain emissions quantitatively elsewhere in California (they can still be qualitatively useful to diagnose inventory biases). Los Angeles Basin emissions derived from CalNex and GOSAT inversions are 0.42 ± 0.08 and 0.31 ± 0.08 Tg a^{-1} that the future TROPOMI satellite instrument (2015 launch) will be able to constrain California methane emissions at a detail comparable to the CalNex aircraft campaign. Geostationary satellite observations offer even greater potential for constraining methane emissions in the future.							
Analyzing Source Apportioned Methane in Northern California during Discover-AQ-CA Using Airborne Measurements and Model Simulations	2014	NASA, Harvard University, University of California at Berkeley, Carnegie Inst. Science	NASA, University of California, California Energy Commission, California Air Resources Board	Federal, State	Regional	Top-down	Remote sensing, Modeling, Flux measurement
This study analyzes source apportioned methane (CH_4) emissions and atmospheric mixing ratios in northern California during the Discover-AQ-CA field campaign using airborne measurement data and model simulations. Source apportioned CH_4 emissions from the Emissions Database for Global Atmospheric Research (EDGAR) version 4.2 were applied in the 3D chemical transport model GEOS-Chem and analyzed using airborne measurements taken as part of the Alpha Jet Atmospheric eXperiment over the San Francisco Bay Area (SFBA) and northern San Joaquin Valley (SJV). During the time period of the Discover-AQ-CA field campaign EDGAR inventory CH_4 emissions were similar to 5.30 Gg day^{-1} (Gg = 1.0×10^9 g) (equating to similar to 1.90×10^3 Gg yr^{-1}) for all of California. According to EDGAR, the SFBA and northern SJV region contributes similar to 30% of total CH_4 emissions from California. Source apportionment analysis during this study shows that CH_4 mixing ratios over this area of northern California are largely influenced by global emissions from wetlands and local/global emissions from gas and oil production and distribution, waste treatment processes, and livestock management. Model simulations, using EDGAR emissions, suggest that the model under-estimates CH_4 mixing ratios in northern California (average normalized mean bias (NMB) = –5.2% and linear regression slope = 0.20). The largest negative biases in the model were calculated on days when large amounts of CH_4 were measured over local emission sources and atmospheric CH_4 mixing ratios reached values >2.5 parts per million. Sensitivity emission studies conducted during this research suggest that local emissions of CH_4 from livestock management processes are likely the primary source of the negative model bias. These results indicate that a variety, and larger quantity, of measurement data needs to be obtained and additional research is necessary to better quantify source apportioned CH_4 emissions in California.							

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Measurements of Methane Emissions at Natural Gas Production Sites in the United States	2013	University of Texas at Austin, URS Corp, Aerodyne Res Inc, Arizona State University, Texas A&M, Washington State University, Colorado School of Mines, University of California Berkeley, Cal Tech	EDF, Anadarko Petroleum Corp, BG Group plc, Chevron, Encana Oil Gas, Pioneer Natural Resources Company, SWEPI LP, Southwestern Energy, Talisman Energy USA, XTO Energy, etc.	NGO, Private Sector	National	Bottom-Up	Emissions Inventory
Engineering estimates of methane emissions from natural gas production have led to varied projections of national emissions. This work reports direct measurements of methane emissions at 190 onshore natural gas sites in the United States (150 production sites, 27 well completion flowbacks, 9 well unloadings, and 4 workovers). For well completion flowbacks, which clear fractured wells of liquid to allow gas production, methane emissions ranged from 0.01 Mg to 17 Mg (mean = 1.7 Mg; 95% confidence bounds of 0.67–3.3 Mg), compared with an average of 81 Mg per event in the 2011 EPA national emission inventory from April 2013. Emission factors for pneumatic pumps and controllers as well as equipment leaks were both comparable to and higher than estimates in the national inventory. Overall, if emission factors from this work for completion flowbacks, equipment leaks, and pneumatic pumps and controllers are assumed to be representative of national populations and are used to estimate national emissions, total annual emissions from these source categories are calculated to be 957 Gg of methane (with sampling and measurement uncertainties estimated at ± 200 Gg). The estimate for comparable source categories in the EPA national inventory is similar to 1,200 Gg. Additional measurements of unloadings and workovers are needed to produce national emission estimates for these source categories. The 957 Gg in emissions for completion flowbacks, pneumatics, and equipment leaks, coupled with EPA national inventory estimates for other categories, leads to an estimated 2,300 Gg of methane emissions from natural gas production (0.42% of gross gas production).							
Quantifying Sources of Methane Using Light Alkanes in the Los Angeles Basin, California	2013	University of Colorado at Boulder, NOAA	NOAA	Federal	Regional	Top-Down (tracer gas, measurements from aircraft)	Flux Measurements, Modeling, Reconciling TD/BU
Project Abstract: Methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), and C2–C5 alkanes were measured throughout the Los Angeles (L.A.) basin in May and June 2010. We use these data to show that the emission ratios of CH_4/CO and CH_4/CO_2 in the L.A. basin are larger than expected from population-apportioned bottom-up state inventories, consistent with previously published work. We use experimentally determined CH_4/CO and CH_4/CO_2 emission ratios in combination with annual State of California CO and CO_2 inventories to derive a yearly emission rate of CH_4 to the L.A. basin. We further use the airborne measurements to directly derive CH_4 emission rates from dairy operations in Chino, and from the two largest landfills in the L.A. basin, and show these sources are accurately represented in the California Air Resources Board greenhouse gas inventory for CH_4. We then use measurements of C2–C5 alkanes to quantify the relative contribution of other CH_4 sources in the L.A. basin, with results differing from those of previous studies. The atmospheric data are consistent with the majority of CH_4 emissions in the region coming from fugitive losses from natural gas in pipelines and urban distribution systems and/or geologic seeps, as well as landfills and dairies. The local oil and gas industry also provides a significant source of CH_4 in the area. The addition of CH_4 emissions from natural gas pipelines and urban distribution systems and/or geologic seeps and from the local oil and gas industry is sufficient to account for the differences between the top-down and bottom-up CH_4 inventories identified in previously published work.							

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Methane Emissions Estimate from Airborne Measurements over a Western United States Natural Gas Field	2013	University of Colorado at Boulder, NOAA, University of California Davis	Received support from participants of the 2012 Uintah Basin Winter Ozone and Air Quality Study, which was funded by Uintah Impact Mitigation Special Service District (UIMSSD), Western Energy Alliance, Bureau of Land Management (BLM), National Oceanic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA), National Science Foundation (NSF), and the State of Utah	Federal, State, Local	Regional	Top-Down	Flux Measurement

Project Abstract: Methane (CH_4) emissions from natural gas production are not well quantified and have the potential to offset the climate benefits of natural gas over other fossil fuels. We use atmospheric measurements in a mass balance approach to estimate CH_4 emissions of $55 \pm 15 \times 103$ kg $h^{-1}$from a natural gas and oil production field in Uintah County, Utah, on 1 day: 3 February 2012. This emission rate corresponds to 6.2%–11.7% (1σ) of average hourly natural gas production in Uintah County in the month of February. This study demonstrates the mass balance technique as a valuable tool for estimating emissions from oil and gas production regions and illustrates the need for further atmospheric measurements to determine the representativeness of our single-day estimate and to better assess inventories of CH_4 emissions.

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Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol	2013	Carnegie Mellon University, Fort Lewis College, Colorado State University, Aerodyne Research Inc.	Dominion, Dow Chemical, Enable Gas Transmission, LLC (formerly CenterPoint Energy Gas Transmission Company, LLC), Environmental Defense Fund (EDF), Interstate Natural Gas Association of America (INGAA), Kinder Morgan, Columbia Pipeline Group (formerly NiSource), TransCanada, and The Williams Companies, Inc.	NGO, Private Sector	Point Source	Both	NG Transmission and Storage, Emissions Inventory

Equipment- and site-level methane emissions from 45 compressor stations in the transmission and storage (T&S) sector of the U.S. natural gas system were measured, including 25 sites required to report under the EPA Greenhouse Gas Reporting Program (GHGRP). Direct measurements of fugitive and vented sources were combined with AP-42-based exhaust emission factors (for operating reciprocating engines and turbines) to produce a study onsite estimate. Site-level methane emissions were also concurrently measured with downwind-tracer-flux techniques. At most sites, these two independent estimates agreed within experimental uncertainty. Site-level methane emissions varied from 2−880 SCFM. Compressor vents, leaky isolation valves, reciprocating engine exhaust, and equipment leaks were major sources, and substantial emissions were observed at both operating and standby compressor stations. The site-level methane emission rates were highly skewed; the highest emitting 10% of sites (including two superemitters) contributed 50% of the aggregate methane emissions, while the lowest emitting 50% of sites contributed less than 10% of the aggregate emissions. Excluding the two superemitters, study-average methane emissions from compressor housings and noncompressor sources are comparable to or lower than the corresponding effective emission factors used in the EPA greenhouse gas inventory. If the two superemitters are included in the analysis, then the average emission factors based on this study could exceed the EPA greenhouse gas inventory emission factors, which highlights the potentially important contribution of superemitters to national emissions. However, quantification of their influence requires knowledge of the magnitude and frequency of superemitters across the entire T&S sector. Only 38% of the methane emissions measured by the comprehensive onsite measurements were reportable under the new EPA GHGRP because of a combination of inaccurate emission factors for leakers and exhaust methane, and various exclusions. The bias is even larger if one accounts for the superemitters, which were not captured by the onsite measurements. The magnitude of the bias varied from site to site by site type and operating state. Therefore, while the GHGRP is a valuable new source of emissions information, care must be taken when incorporating these data into emission inventories. The value of the GHGRP can be increased by requiring more direct measurements of emissions (as opposed to using counts and emission factors), eliminating exclusions such as rod-packing vents on pressurized reciprocating compressors in standby mode under Subpart-W, and using more appropriate emission factors for exhaust methane from reciprocating engines under Subpart-C.

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<tr><td>Measurements of Methane Emissions from Natural Gas Gathering Facilities and Processing Plants: Measurement Results</td><td>2013–2014</td><td>Carnegie Mellon University, Colorado State University, Aerodyne Research Inc., Fort Lewis College</td><td>Access Midstream, Anadarko Petroleum Corporation, Environmental Defense Fund (EDF), Hess Corporation, Southwestern Energy, and Williams Corporation.</td><td>NGO, Private Sector</td><td>Point Source</td><td>Top-Down</td><td>NG Gathering and Processing, Flux Measurement</td></tr>
<tr><td colspan="8">Facility-level methane emissions were measured at 114 gathering facilities and 16 processing plants in the United States natural gas system. At gathering facilities, the measured methane emission rates ranged from 0.7 to 700 kg per hour (kg/h) (0.6 to 600 standard cubic feet per minute (scfm)). Normalized emissions (as a % of total methane throughput) were less than 1% for 85 gathering facilities and 19 had normalized emissions less than 0.1%. The range of methane emissions rates for processing plants was 3 to 600 kg/ h (3 to 524 scfm), corresponding to normalized methane emissions rates <1% in all cases. The distributions of methane emissions, particularly for gathering facilities, are skewed. For example, 30% of gathering facilities contribute 80% of the total emissions. Normalized emissions rates are negatively correlated with facility throughput. The variation in methane emissions also appears driven by differences between inlet and outlet pressure, as well as venting and leaking equipment. Substantial venting from liquids storage tanks was observed at 20% of gathering facilities. Emissions rates at these facilities were, on average, around four times the rates observed at similar facilities without substantial venting.</td></tr>
<tr><td>Methane Emissions from Natural Gas Infrastructure and Use in the Urban Region of Boston, Massachusetts</td><td>2012–2013</td><td>Harvard University, Duke University, Boston University, Hofstra University, Aerodyne Research Inc., Atmospheric and Environmental Research Inc., Stanford University</td><td>NSF, NASA, EDF, Philanthropic Foundations</td><td>Regional</td><td>Top-Down</td><td>Emissions Inventory, Modeling, Remote Sensing</td><td></td></tr>
<tr><td colspan="8">Project Abstract: Methane emissions from natural gas delivery and end use must be quantified to evaluate the environmental impacts of natural gas and to develop and assess the efficacy of emission reduction strategies. We report natural gas emission rates for 1 y in the urban region of Boston, using a comprehensive atmospheric measurement and modeling framework. Continuous methane observations from four stations are combined with a high-resolution transport model to quantify the regional average emission flux, 18.5± 3.7 (95% confidence interval) g $CH_4 \cdot m^{-2} \cdot y^{-1}$. Simultaneous observations of atmospheric ethane, compared with the ethane-to-methane ratio in the pipeline gas delivered to the region, demonstrate that natural gas accounted for~60–100% of methane emissions, depending on season. Using government statistics and geospatial data on natural gas use, we find the average fractional loss rate to the atmosphere from all downstream components of the natural gas system, including transmission, distribution, and end use, was 2.7± 0.6% in the Boston urban region, with little seasonal variability. This fraction is notably higher than the 1.1% implied by the most closely comparable emission inventory.</td></tr>
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Demonstration of an Ethane Spectrometer for Methane Source Identification	2014	Aerodyne Research Inc., University of Colorado Boulder, NOAA, University of California Davis, University of Michigan Ann Arbor, Nanoplus Nanosystems and Technologies GMbH (Germany)			Point Source	Top-Down	Technology Development, Remote Sensing
Methane is an important greenhouse gas and tropospheric ozone precursor. Simultaneous observation of ethane with methane can help identify specific methane source types. Aerodyne Ethane-Mini spectrometers, employing recently available mid-infrared distributed feedback tunable diode lasers (DFB-TDL), provide 1 s ethane measurements with sub-ppb precision. In this work, an Ethane-Mini spectrometer has been integrated into two mobile sampling platforms, a ground vehicle and a small airplane, and used to measure ethane/methane enhancement ratios downwind of methane sources. Methane emissions with precisely known sources are shown to have ethane/methane enhancement ratios that differ greatly depending on the source type. Large differences between biogenic and thermogenic sources are observed. Variation within thermogenic sources are detected and tabulated. Methane emitters are classified by their expected ethane content. Categories include the following: biogenic (6%), pipeline grade natural gas (30%). Regional scale observations in the Dallas/Fort Worth area of Texas show two distinct ethane/methane enhancement ratios bridged by a transitional region. These results demonstrate the usefulness of continuous and fast ethane measurements in experimental studies of methane emissions, particularly in the oil and natural gas sector.							
Atmospheric Emission Characterization of Marcellus Shale Natural Gas Development Sites	2014	Drexel University, Aerodyne Research Inc., Montana State University, Electric Power Research Institute	The Electric Power Research Institute	NGO	Point Source	Both	Emissions Inventory
Limited direct measurements of criteria pollutants emissions and precursors, as well as natural gas constituents, from Marcellus shale gas development activities contribute to uncertainty about their atmospheric impact. Real-time measurements were made with the Aerodyne Research Inc. Mobile Laboratory to characterize emission rates of atmospheric pollutants. Sites investigated include production well pads, a well pad with a drill rig, a well completion, and compressor stations. Tracer release ratio methods were used to estimate emission rates. A first-order correction factor was developed to account for errors introduced by fenceline tracer release. In contrast to observations from other shale plays, elevated volatile organic compounds, other than CH_4 and C2H6, were generally not observed at the investigated sites. Elevated submicrometer particle mass concentrations were also generally not observed. Emission rates from compressor stations ranged from 0.006 to 0.162 tons per day (tpd) for NOx, 0.029 to 0.426 tpd for CO, and 67.9 to 371 tpd for CO_2. CH_4 and C2H6 emission rates from compressor stations ranged from 0.411 to 4.936 tpd and 0.023 to 0.062 tpd, respectively. Although limited in sample size, this study provides emission rate estimates for some processes in a newly developed natural gas resource and contributes valuable comparisons to other shale gas studies.							

Title	Study Years	Lead Research Organization(s)	Funding Agency, Program	Funding Agency Category	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods Employed (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Real-Time Remote Detection and Measurement for Airborne Imaging Spectroscopy: A Case Study with Methane	2014	Jet Propulsion Laboratory, Bubbleology Research International, University of Bremen (Germany), NASA	NASA	Federal	Local	Top-Down	Technology Development, Remote Sensing
Project Abstract: Localized anthropogenic sources of atmospheric CH_4 are highly uncertain and temporally variable. Airborne remote measurement is an effective method to detect and quantify these emissions. In a campaign context, the science yield can be dramatically increased by real-time retrievals that allow operators to coordinate multiple measurements of the most active areas. This can improve science outcomes for both single- and multiple-platform missions. We describe a case study of the NASA/ESA CO_2 and Methane Experiment (COMEX) campaign in California during June and August/September 2014. COMEX was a multi-platform campaign to measure CH_4 plumes released from anthropogenic sources including oil and gas infrastructure. We discuss principles for real-time spectral signature detection and measurement, and report performance on the NASA Next Generation Airborne Visible Infrared Spectrometer (AVIRIS-NG). AVIRIS-NG successfully detected CH_4 plumes in real-time at Gb s^{-1} data rates, characterizing fugitive releases in concert with other in situ and remote instruments. The teams used these real-time CH_4 detections to coordinate measurements across multiple platforms, including airborne in situ, airborne non-imaging remote sensing, and ground-based in situ instruments. To our knowledge this is the first reported use of real-time trace gas signature detection in an airborne science campaign, and presages many future applications.							
Retrieval Techniques for Airborne Imaging of Methane Concentrations Using High Spatial and Moderate Spectral Resolution: Application to AVIRIS	Data from 2008, Published in 2014	University of California Santa Barbara, Jet Propulsion Laboratory	NASA Earth and Space Science Fellowship Program	Federal	Local	Top-down	Remote Sensing, Modeling
Two quantitative retrieval techniques were evaluated to estimate methane (CH_4) enhancement in concentrated plumes using high spatial and moderate spectral resolution data from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). An iterative maximum a posteriori differential optical absorption spectroscopy (IMAP-DOAS) algorithm performed well for an ocean scene containing natural CH_4 emissions from the Coal Oil Point (COP) seep field near Santa Barbara, California. IMAP-DOAS retrieval precision errors are expected to equal between 0.31 to 0.61 ppm CH_4 over the lowest atmospheric layer (height up to 1.04 km), corresponding to about a 30 to 60 ppm error for a 10 m thick plume. However, IMAP-DOAS results for a terrestrial scene were adversely influenced by the underlying land cover. A hybrid approach using singular value decomposition (SVD) was particularly effective for terrestrial surfaces because it could better account for spectral variability in surface reflectance. Using this approach, a CH_4 plume was observed extending 0.1 km downwind of two hydrocarbon storage tanks at the Inglewood Oil Field in Los Angeles, California (USA) with a maximum near surface enhancement of 8.45 ppm above background. At COP, the distinct plume had a maximum enhancement of 2.85 ppm CH_4 above background, and extended more than 1 km downwind of known seep locations. A sensitivity analysis also indicates CH_4 sensitivity should be more than doubled for the next generation AVIRIS sensor (AVIRISng) due to improved spectral resolution and sampling. AVIRIS-like sensors offer the potential to better constrain emissions on local and regional scales, including sources of increasing concern like industrial point source emissions and fugitive CH_4 from the oil and gas industry.							

<table>
<tr><th>Title</th><th>Study Years</th><th>Lead Research Organization(s)</th><th>Funding Agency, Program</th><th>Funding Agency Category</th><th>Spatial Scale (Point Source, Local, Regional, National, Global)</th><th>Primary Methods Employed (Bottom-Up, Top-Down, Both)</th><th>Key Science Topics Related to CH_4 Measurement and Monitoring</th></tr>
<tr><td>High Resolution Mapping of Methane Emissions from Marine and Terrestrial Sources Using a Cluster-Tuned Matched Filter Technique and Imaging Spectrometry</td><td>Data from 2008, published in 2014</td><td>University of California Santa Barbara, University of Utah Salt Lake City</td><td>NASA North American Carbon Program (NACP) research grant (NNX07AC89G), a NASA California Space Grant, and the National Science Foundation, ATM Rapid Response program.</td><td>Federal</td><td>Local</td><td>Top-Down</td><td>Remote Sensing</td></tr>
<tr><td colspan="8">In this study, a Cluster-Tuned Matched Filter (CTMF) technique was applied to data acquired by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) over marine and terrestrial locations known to emit methane (CH_4). At the Coal Oil Point marine seepfield, prominent CH_4anomalies were consistent with advection from known areas of active seepage. For a region with natural CH_4 and oil seepage located west of downtown Los Angeles, significant CH_4anomalies were identified for known sources at the La Brea Tar Pits and in close proximity to probable sources, including an office complex documented as venting CH_4 continuously and hydrocarbon storage tanks on the Inglewood Oil Field. However, interpretation of anomalies was complicated by noise and false positives for surfaces with strong absorptions at the same wavelengths as CH_4 absorption features. Segmentation of results identified 16 distinct locations of contiguous pixels with high CTMF scores and segments were classified into probable CH_4 anomalies and confusers based on the spectral properties of the underlying surface over the full spectral range measured by AVIRIS. This technique is particularly well suited for application over large areas to detect CH_4 emissions from concentrated point sources and should permit detection of additional trace gasses with distinct absorption features, including carbon dioxide (CO_2) and nitrous oxide (N_2O). Thus, imaging spectrometry by an AVIRIS-like sensor has the potential to improve high resolution greenhouse gas mapping, better constraining local sources.</td></tr>
<tr><td>Point Source Emissions Mapping Using the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)</td><td>2012</td><td>University of California Santa Barbara, University of Utah</td><td></td><td></td><td>Local, Regional</td><td>Top-Down</td><td>Modeling, Remote Sensing</td></tr>
<tr><td colspan="8">The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) measures reflected solar radiation in the shortwave infrared and has been used to map methane (CH_4) using both a radiative transfer technique and a band ratio method. However, these methods are best suited to water bodies with high sunglint and are not well suited for terrestrial scenes. In this study, a cluster-tuned matched filter algorithm originally developed by Funk et al. [3] for synthetic thermal infrared data was used for gas plume detection over more heterogeneous backgrounds. This approach permits mapping of CH_4, CO_2 (carbon dioxide), and N_2O (nitrous oxide) trace gas emissions in multiple AVIRIS scenes for terrestrial and marine targets. At the Coal Oil Point marine seeps offshore of Santa Barbara, CA, strong CH_4 anomalies were detected that closely resemble results obtained using the band ratio index. CO_2 anomalies were mapped for a fossil-fuel power plant, while multiple N_2O and CH_4 anomalies were present at the Hyperion wastewater treatment facility in Los Angeles, CA. Nearby, smaller CH_4 anomalies were also detected immediately downwind of hydrocarbon storage tanks and centered on a flaring stack at the Inglewood Gas Plant. Improving these detection methods might permit gas detection over large search areas, e.g., identifying fugitive CH_4 emissions from damaged natural gas pipelines or hydraulic fracturing. Further, this technique could be applied to other trace gasses with distinct absorption features and to data from planned instruments such as AVIRISng, the NEON Airborne Observation Platform (AOP), and the visible-shortwave infrared (VSWIR) sensor on the proposed HyspIRI satellite</td></tr>
</table>

Title	Study Years	Lead Research Organization(s)	Funding Agency, Program	Funding Agency Category	Spatial Scale (Point Source, Local, Regional, National, Global)	Primary Methods Employed (Bottom-Up, Top-Down, Both)	Key Science Topics Related to CH_4 Measurement and Monitoring
Quantifying Lower Tropospheric Methane Concentrations Using GOSAT Near-IR and TES Thermal IR Measurements	2015	Jet Propulsion Laboratory, Harvard University, Bay Area Environmental Research Institute, University of Leicester	NASA ROSES CSS and the NASA Carbon Monitoring System	Federal	NA	Top-Down	Modeling, Remote Sensing
Project Abstract: Evaluating surface fluxes of CH_4 using total column data requires models to accurately account for the transport and chemistry of methane in the free troposphere and stratosphere, thus reducing sensitivity to the underlying fluxes. Vertical profiles of methane have increased sensitivity to surface fluxes because lower tropospheric methane is more sensitive to surface fluxes than a total column, and quantifying free-tropospheric CH_4 concentrations helps to evaluate the impact of transport and chemistry uncertainties on estimated surface fluxes. Here we demonstrate the potential for estimating lower tropospheric CH_4 concentrations through the combination of free-tropospheric methane measurements from the Aura Tropospheric Emission Spectrometer (TES) and X CH_4 (dry-mole air fraction of methane) from the Greenhouse gases Observing SATellite—Thermal And Near-infrared for carbon Observation (GOSAT TANSO, herein GOSAT for brevity). The calculated precision of these estimates ranges from 10 to 30 ppb for a monthly average on a 4° × 5° latitude/longitude grid making these data suitable for evaluating lower-tropospheric methane concentrations. Smoothing error is approximately 10 ppb or less. Comparisons between these data and the GEOS-Chem model demonstrate that these lower-tropospheric CH_4 estimates can resolve enhanced concentrations over flux regions that are challenging to resolve with total column measurements. We also use the GEOS-Chem model and surface measurements in background regions across a range of latitudes to determine that these lower-tropospheric estimates are biased low by approximately 65 ppb, with an accuracy of approximately 6 ppb (after removal of the bias) and an actual precision of approximately 30 ppb. This 6 ppb accuracy is consistent with the accuracy of TES and GOSAT methane retrievals.							
Estimating Global and North American Methane Emissions with High Spatial Resolution Using GOSAT Satellite Data	Data from 2009–2011, published 2015	Harvard University, NOAA, Lawrence Berkeley National Lab, University of Leicester, Jet Propulsion Laboratory, University of Wollongong, University of Bremen, Los Alamos National Laboratory, Karlsruhe Institute of Technology, University of Colorado Boulder, California Institute of Technology	NASA Carbon Monitoring System and a Department of Energy (DOE) Computational Science Graduate Fellowship (CSGF), among many other indirect sources of funding	Federal	National, Global	Top-Down	Emissions Inventory
Project Abstract: We use 2009–2011 space-borne methane observations from the Greenhouse Gases Observing SATellite (GOSAT) to estimate global and North American methane emissions with 4° × 5° and up to 50 km × 50 km spatial resolution, respectively. GEOS-Chem and GOSAT data are first evaluated with atmospheric methane observations from surface and tower networks (NOAA/ESRL, TCCON) and aircraft (NOAA/ESRL, HIPPO), using the GEOS-Chem chemical transport model as a platform to facilitate comparison of GOSAT with in situ data. This identifies a high-latitude bias between the GOSAT data and GEOS-Chem that we correct via quadratic regression. Our global adjoint-based inversion yields a total methane source of 539 Tg a^{-1} with some important regional corrections to the EDGARv4.2 inventory used as a prior. Results serve as dynamic boundary conditions for an analytical inversion of North American methane emissions using radial basis functions to achieve high resolution of large sources and provide error characterization. We infer a U.S. anthropogenic methane source of 40.2–42.7 Tg a^{-1} as compared to 24.9–27.0 Tg a^{-1} in the EDGAR and EPA bottom-up inventories, and 30.0–44.5 Tg a^{-1} in recent inverse studies. Our estimate is supported by independent surface and aircraft data and by previous inverse studies for California. We find that the emissions are highest in the southern-central U.S., the Central Valley of California, and Florida wetlands; large isolated point sources such as the U.S. Four Corners also contribute. Using prior information on source locations, we attribute 29–44 % of U.S. anthropogenic methane emissions to livestock, 22–31 % to oil/gas, published by Copernicus Publications on behalf of the European Geosciences Union. 7050 A. J. Turner et al.: Estimating methane emissions with GOSAT 20 % to landfills/wastewater, and 11–15 % to coal. Wetlands contribute an additional 9.0–10.1 Tg a^{-1}.							

References

Air Resources Board (ARB). 2016. Aliso Canyon Natural Gas Leak: Preliminary Estimate of Greenhouse Gas Emissions. http://www.arb.ca.gov/research/aliso_canyon/aliso_canyon_natural_gas_leak_updates-sa_flights_thru_March_24_2016.pdf.

Brandt, A. R., G. Heath, E. A. Kort, F. O'Sullivan, G. Petron, S. Jordaan, P. Tans, J. Wilcox, A. Gopstein, D. Arent, S. C. Wofsy, N. Brown, R. Bradley, G. D. Stucky, D. Eardley, A. Patrinos, and R. Harriss. 2014. "Methane Leakage from North American Natural Gas Systems: Sources, Uncertainties, and Policy Implications " *Science* 343 (6172):733-735. doi: 10.1126/science.1247045.

Bruhwiler, L., Dlugokencky, E., Masarie, K., Ishizawa, M., Andrews, A., Miller, J., Sweeney, C., Tans, P., and Worthy, D. . 2014. "Carbontracker-Ch_4: An Assimilation System for Estimating Emissions of Atmospheric Methane." *Atmospheric Chemistry and Physics* 14:8269–93. doi: doi:10.5194/acp-14-8269-2014.

Caulton, D. R., P. B. Shepson, R. L. Santoro, J. P. Sparks, R. W. Howarth, A. R. Ingraffea, M. O. L. Cambaliza, C. Sweeney, A. Karion, K. J. Davis, B. H. Stirm, S. A. Montzka, and B. R. Miller. 2014. "Toward a Better Understanding and Quantification of Methane Emissions from Shale Gas Development." *Proceedings of the National Academy of Sciences* 111 (17):6237-6242. doi: 10.1073/pnas.1316546111.

Committee on Earth Observation Satellites (CEOS). 2014. *Ceos Strategy for Carbon Observations from Space. The Committee on Earth Observations Satellites (Ceos) Response to the Group on Earth Observations (Geo) Carbon Strategy*. Japan: JAXA and I&A Corporation.

Conley, S., G. Franco, I. Faloona, D. R. Blake, J. Peischl, and T. B. Ryerson. 2016. "Methane Emissions from the 2015 Aliso Canyon Blowout in Los Angeles, Ca." *Science*. doi: 10.1126/science.aaf2348.

Deng, F., D. B. A. Jones, D. K. Henze, N. Bousserez, K. W. Bowman, J. B. Fisher, R. Nassar, C. O'Dell, D. Wunch, P. O. Wennberg, E. A. Kort, S. C. Wofsy, T. Blumenstock, N. M. Deutscher, D. W. T. Griffith, F. Hase, P. Heikkinen, V. Sherlock, K. Strong, R. Sussmann, and T. Warneke. 2014. "Inferring Regional Sources and Sinks of Atmospheric Co2 from Gosat Xco2 Data." *Atmospheric Chemistry and Physics* 14 (7):3703–3727. doi: 10.5194/acp-14-3703-2014.

Energy Information Administration (EIA). 2015. *Annual Energy Outlook 2015*: Department of Energy. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf.

Environmental Defense Fund (EDF). 2015. Methane Research: The 16 Study Series.

Environmental Protection Agency (EPA). 2015. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013*: EPA 430-R-15-004. http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Chapter-Upfront.pdf.

———. 2016a. Inventory of U.S. Ghg Emissions and Sinks: Revision under Consideration for Gathering and Boosting Emissions.

———. 2016b. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014*: EPA 430-R-16-002. https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2016-Chapter-Upfront.pdf.

EPA. 2015. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013. edited by Environmental Protection Agency (EPA).

Executive Office of the President (EOP). 2013. *The President's Climate Action Plan*. Washington, D.C.: EOP. https://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf.

———. 2014. *Climate Action Plan: Strategy to Reduce Methane Emissions*. Washington, D.C.: EOP, https://www.whitehouse.gov/sites/default/files/strategy_to_reduce_methane_emissions_2014-03-28_final.pdf.

Frankenberg, C., A. K. Thorpe, D. R. Thompson, G. Hulley, E. A. Kort, N. Vance, J. Borchardt, T. Krings, K. Gerilowski, C. Sweeney, S. Conley, B. D. Bue, A. D. Aubrey, S. Hook, and R. O. Green. 2016. "Airborne Methane Remote Measurements Reveal Heavy-Tail Flux Distribution in Four Corners Region." *Proceedings of the National Academy of Sciences*. doi: 10.1073/pnas.1605617113.

Harriss, R., R. A. Alvarez, D. Lyon, D. Zavala-Araiza, D. Nelson, and S. P. Hamburg. 2015. "Using Multi-Scale Measurements to Improve Methane Emission Estimates from Oil and Gas Operations in the Barnett Shale Region, Texas." *Environmental Science & Technology* 49 (13):7524-7526. doi: 10.1021/acs.est.5b02305.

Heath, G., E. Warner, D. Steinberg, and A. R. Brandt. 2015a. *Estimating U.S. Methane Emissions from the Natural Gas Supply Chain: Approaches, Uncertainties, Current Estimates, and Future Studies*. Golden, CO: Joint Institute for Strategic Energy Analysis. http://www.nrel.gov/docs/fy16osti/62820.pdf.

———. 2015b. Estimating U.S. Methane Emissions from the Natural Gas Supply Chain: Approaches, Uncertainties, Current Estimates, and Future Studies. edited by National Renewable Energy Laboratory.

Intergovernmental Panel on Climate Change (IPCC). 1996. *Revised 1996 Ipcc Guidelines for National Greenhouse Gas Inventories*. IPCC. http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html.

———. 2006. *2006 Ipcc Guidelines for National Greenhouse Gas Inventories*. IPCC. http://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Karion, A., C. Sweeney, E. A. Kort, P. B. Shepson, A. Brewer, M. Cambaliza, S. A. Conley, K. Davis, A. Deng, M. Hardesty, S. C. Herndon, T. Lauvaux, T. Lavoie, D. Lyon, T. Newberger, G. Pétron, C. Rella, M. Smith, S. Wolter, T. I. Yacovitch, and P. Tans. 2015. "Aircraft-Based Estimate of Total Methane Emissions from the Barnett Shale Region." *Environmental Science & Technology* 49 (13):8124-8131. doi: 10.1021/acs.est.5b00217.

Karion, A., C. Sweeney, G. Petron, G. J. Frost, M. Hardesty, J. Kofler, B. R. Miller, T. Newberger, S. Wolter, R. Banta, A. Brewer, E. Dlugokencky, P. M. Lang, S. A. Montzka, R. Schnell, P. P. Tans, M. Trainer, R. Zamora, and S. Conley. 2013. "Methane Emissions Estimate from Airborne Measurements over a Western United States Natural Gas Field." *Geophysical Research Letters*. doi: 10.1002/grl.50811.

Kirschke, S., P. Bousquet, P. Ciais, M. Saunois, J. G. Canadell, E. J. Dlugokencky, P. Bergamaschi, D. Bergmann, D. R. Blake, L. Bruhwiler, P. Cameron-Smith, S. Castaldi, F. Chevallier, L. Feng, A. Fraser, M. Heimann, E. L. Hodson, S. Houweling, B. Josse, P. J. Fraser, P. B. Krummel, J.-F. Lamarque, R. L. Langenfelds, C. Le Quere, V. Naik, S. O'Doherty, P. I. Palmer, I. Pison, D. Plummer, B. Poulter, R. G. Prinn, M. Rigby, B. Ringeval, M. Santini, M. Schmidt, D. T. Shindell, I. J. Simpson, R. Spahni, L. P. Steele, S. A. Strode, K. Sudo, S. Szopa, G. R. van der Werf, A. Voulgarakis, M. van Weele, R. F. Weiss, J. E. Williams, and G. Zeng. 2013. "Three Decades of Global Methane Sources and Sinks." *Nature Geosci* 6 (10):813–823. doi: 10.1038/ngeo1955. http://www.nature.com/ngeo/journal/v6/n10/abs/ngeo1955.html#supplementary-information.

Kort, E. A., C. Frankenberg, K. R. Costigan, R. Lindenmaier, M. K. Dubey, and D. Wunch. 2014. "Four Corners: The Largest Us Methane Anomaly Viewed from Space." *Geophysical Research Letters*:6898–6903. doi: 10.1002/2014GL061503.

Lamb, B. K., S. L. Edburg, T. W. Ferrara, T. Howard, M. R. Harrison, C. E. Kolb, A. Townsend-Small, W. Dyck, A. Possolo, and J. R. Whetstone. 2015. "Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States." *Environmental Science & Technology* 49:5161–5169. doi: 10.1021/es505116p.

Lyon, D. R., D. Zavala-Araiza, R. A. Alvarez, R. Harriss, V. Palacios, X. Lan, R. Talbot, T. Lavoie, P. Shepson, T. I. Yacovitch, S. C. Herndon, A. J. Marchese, D. Zimmerle, A. L. Robinson, and S. P. Hamburg. 2015. "Constructing a Spatially Resolved Methane Emission Inventory for the Barnett Shale Region." *Environmental Science & Technology* 49 (13):8147-8157. doi: 10.1021/es506359c.

Maasakkers, J. 2015. *A Gridded Version of the Epa National Methane Inventory*. http://www3.epa.gov/ttn/chief/conference/ei21/session4/maasakkers_pres.pdf.

Maasakkers, J., D. J. Jacob, M. Sulprizio, A. Turner, M. Weitz, T. Wirth, C. Hight, M. DeFigueiredo, and A. Bloom. 2015. A Gridded (0.1°×0.1°), Monthly Resolved Version of the Epa Us Ghg Inventory Methane Emissions for Use as a Priori and Reference in Methane Source Inversions. Harvard University.

Miller, S. M., S. C. Wofsy, A. M. Michalak, E. A. Kort, A. E. Andrews, S. C. Biraud, E. J. Dlugokencky, M. L. Fischer, G. Janssens-Maenhout, B. R. Miller, S. A. Montzka, and C. Sweeney. 2013. “Evidence for a Large Fossil Fuel Methane Source over the South-Central Us.” *Proceedings of the National Academy of Sciences of the United States of America*.

Peischl, J., T. B. Ryerson, K. C. Aikin, J. A. de Gouw, J. B. Gilman, J. S. Holloway, B. M. Lerner, R. Nadkarni, J. A. Neuman, J. B. Nowak, M. Trainer, C. Warneke, and D. D. Parrish. 2015. “Quantifying Atmospheric Methane Emissions from the Haynesville, Fayetteville, and Northeastern Marcellus Shale Gas Production Regions.” *Journal of Geophysical Research: Atmospheres* 120 (5):2119-2139. doi: 10.1002/2014JD022697.

Petron, G., G. Frost, B. R. Miller, A. I. Hirsch, S. A. Montzka, A. Karion, M. Trainer, C. Sweeney, A. E. Andrews, L. Miller, J. Kofler, A. Bar-Ilan, E. J. Dlugokencky, L. Patrick, C. T. Moore, T. B. Ryerson, C. Siso, W. Kolodzey, P. M. Lang, T. Conway, P. Novelli, K. Masarie, B. Hall, D. Guenther, D. Kitzis, J. Miller, D. Welsh, D. Wolfe, W. Neff, and P. Tans. 2012. “Hydrocarbon Emissions Characterization in the Colorado Front Range: A Pilot Study.” *Journal of Geophysical Research-Atmospheres* 117. doi: 10.1029/2011jd016360.

Petron, G., A. Karion, C. Sweeney, B. R. Miller, S. A. Montzka, G. Frost, M. Trainer, P. Tans, A. Andrews, J. Kofler, D. Helmig, D. Guenther, E. Dlugokencky, P. Lang, T. Newberger, S. Wolter, B. Hall, P. Novelli, A. Brewer, S. Conley, M. Hardesty, R. Banta, A. White, D. Noone, D. Wolfe, and R. Schnell. 2014. “A New Look at Methane and Non-Methane Hydrocarbon Emissions from Oil and Natural Gas Operations in the Colorado Denver-Julesburg Basin.” *Journal of Geophysical Research: Atmospheres*:2013JD021272. doi: 10.1002/2013JD021272.

Ryerson, T. B., K. C. Aikin, W. M. Angevine, E. L. Atlas, D. R. Blake, C. A. Brock, F. C. Fehsenfeld, R.-S. Gao, J. A. deGouw, D. W. Fahey, J. S. Holloway, D. A. Lack, R. A. Lueb, S. Meinardi, A. M. Middlebrook, D. M. Murphy, J. A. Neuman, J. B. Nowak, D. D. Parrish, J. Peishl, A. E. APerring, I. B. Pollack, A. R. Ravishankara, J. M. Roberts, J. P. Schwarz, J. R. Spackman, H. Stark, C. Warneke, and L. A. Watts. 2011. “Atmospheric Emissions from the Deepwater Horizon Spill Constrain Air-Water Partitioning, Hydrocarbon Fate, and Leak Rate.” *Geophysical research Letters* 38 (7). doi: 10.1029/2011GL046726.

Ryerson, T. B., R. Camilli, J. D. Kessler, E. B. Kujawinski, C. M. Reddy, D. L. Valentine, E. Atlas, D. R. Blake, J. A. De Gouw, S. Meinardi, D. D. Parrish, J. Peischl, J. S. Seewald, and C. Warneke. 2012. “Chemical Data Quantify Deepwater Horizon Hydrocarbon Flow Rate and Environmental Distribution.” *Proceedings of the National Academy of Sciences* 109 (50). doi: http://doi.org/10.1073/pnas.1110564109.

Schneising, O., J. P. Burrows, R. R. Dickerson, M. Buchwitz, M. Reuter, and H. Bovensmann. 2014. “Remote Sensing of Fugitive Methane Emissions from Oil and Gas Production in North American Tight Geologic Formations.” *Earth's Future* 2 (10):548-558. doi: 10.1002/2014EF000265.

Smith, M. L., E. A. Kort, A. Karion, C. Sweeney, S. C. Herndon, and T. I. Yacovitch. 2015. “Airborne Ethane Observations in the Barnett Shale: Quantification of Ethane Flux and Attribution of Methane Emissions.” *Environmental Science & Technology* 49 (13):8158-8166. doi: 10.1021/acs.est.5b00219.

Thompson, D. R., A. K. Thorpe, C. Frankenberg, R. O. Green, R. Duren, L. Guanter, A. Hollstein, E. Middleton, L. Ong, and S. Ungar. 2016. “Space-Based Remote Imaging Spectroscopy of the Aliso Canyon Ch4 Superemitter.” *Geophysical Research Letters* 43 (12):2016GL069079. doi: 10.1002/2016GL069079.

Turner, A. J., D. J. Jacob, J. Benmergui, S. C. Wofsy, J. D. Maasakkers, A. Butz, O. Hasekamp, and S. C. Biraud. 2016. “A Large Increase in U.S. Methane Emissions over the Past Decade Inferred from Satellite Data and Surface Observations.” *Geophysical Research Letters* 43 (5):2218-2224. doi: 10.1002/2016GL067987.

Turner, A. J., D. J. Jacob, K. J. Wecht, J. D. Maasakkers, A. E. A. E. Lundgren, H. B. S. C. Biraud, K. W. Bowman, N. M. Deutscher, M. K. Dubey, D. W. T. Griffith, A. K. F. Hase, J. Notholt, H. Ohyama, R. Parker, V. H. Payne, R. Sussmann, C. Sweeney, V. A. Velazco, T. Warneke, P. O. Wennberg, and D. Wunch. 2015. “Estimating Global and North American Methane Emissions with High Spatial Resolution Using Gosat Satellite Data.” *Atmospheric Chemistry and Physics* 15:7049–7069. doi: 10.5194/acp-15-7049-2015.

World Meteorological Organization (WMO). 2015. *Implementing and Integrated, Global Greenhouse Gas Information System (Ig3is)*. https://www.wmo.int/pages/prog/arep/gaw/ghg/documents/GHGIGIS2015.pdf.

Zavala-Araiza, D., D. Lyon, R. A. Alvarez, V. Palacios, R. Harriss, X. Lan, R. Talbot, and S. P. Hamburg. 2015. “Toward a Functional Definition of Methane Super-Emitters: Application to Natural Gas Production Sites.” *Environmental Science & Technology* 49 (13):8167-8174. doi: 10.1021/acs.est.5b00133.

Abbreviations

ARB	California Air Resources Board
ARPA-E	Advanced Research Projects Agency-Energy
CH_4	methane
CO_2	carbon dioxide
DOE	Department of Energy
EDF	Environmental Defense Fund
EDGAR	Emissions Database for Global Atmospheric Research
EIA	Energy Information Administration
EOP	Executive Office of the President
EPA	Environmental Protection Agency
GGGRN	Global Greenhouse Gas Reference Network
GHGRP	Greenhouse Gas Reporting Program
IDA	Institute for Defense Analyses
IG3IS	Integrated Global Greenhouse Gas Information System
IPCC	Intergovernmental Panel on Climate Change
JPL	Jet Propulsion Laboratory
LIDAR	light detection and ranging
NASA	National Aeronautics and Space Administration
NIFA	National Institute of Food and Agriculture
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
NSPS	New Source Performance Standards
OSTP	Office of Science and Technology Policy
PHMSA	Pipeline and Hazardous Materials Safety Administration
RPSEA	Research Partnership to Secure Energy for America
STPI	Science and Technology Policy Institute
TD/BU	top-down/bottom-up
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WMO	World Meteorological Organization

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Clavin, Christopher T.
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14. ABSTRACT
STPI researchers reviewed current Federal and non-governmental programs and projects that support research and development activities related to methane measurement and monitoring. Information was also collected information on current methane measurement research from Federal officials and researchers at organizations involved in the programs and projects reviewed. Based on input from these discussions and additional research, STPI found that the current portfolio of research indicates that integration of bottom-up inventory measurements and top-down atmospheric measurement approaches remains an important scientific topic that is actively being explored. Current scientific questions revolve around integrating multiple fields of atmospheric measurement and modeling, life-cycle assessment methodology, and integrating atmospheric measurement and life-cycle assessment processed based measurement approaches. Opportunities exist within the Federal government to build on existing research activities and to promote better coordination between agencies to support methane measurement research to aid mitigation approaches.

15. SUBJECT TERMS
atmospheric science, climate change, greenhouse gas, methane

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