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Capstone Papers

Title
Evaluation of Methane Data Products: Using Visualizations of Satellite and Airborne Methane Observations to Detect the Aliso Canyon Natural Gas Leak

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This page outlines how the following capstone project meets the requirements of the Masters of Advanced Studies, Climate Science and Policy program at the Scripps Institution of Oceanography, and is intended for the academic and executive directors of the program—Dr. Lynn Russell and Dr. Ellie Farahani.

Necessity for the Project

Mitigation of anthropogenic methane emissions in tandem with those of carbon dioxide may be essential to limit the current warming of the Earth to two degrees Celsius as supported by the Intergovernmental Panel on Climate Change. Methane is the second most prevalent greenhouse gas in the atmosphere, after carbon dioxide. Methane is a potent greenhouse gas with high global warming potential (GWP[1]) of 72 over 20 years. Methane also has secondary climate and air quality impacts as a precursor to ozone. Despite awareness of the impacts of methane, global methane concentrations have increased by a factor of 2.5 compared to 1750 levels. This increase has accelerated global warming, pushing the global temperature increase closer to the two-degree threshold (IPCC, 2014).

In California, inventoried state-wide methane emissions have increased by 5.2 MTCO2eq[2] between 2000 and 2014 (ARB, 2016a). The California Air Resources Board (ARB) is the agency which has the authority to monitor, inventory and mitigate methane emissions. California has goals to reduce methane emissions by 40% compared to 2013 levels by 2030 (State Bill 1383) and the ARB has developed a strategic plan to achieve that target (Short-Lived Climate Pollutant Plan). However, recent studies conducted by third-party research agencies show 30~50% discrepancy between the atmospheric methane measurements and methane emissions inventoried by the ARB. Resolving this discrepancy is a known state priority. The ARB, as outlined in Assembly Bill 1496, has vested interest in identifying and monitoring methane hot spots in California, as they are known to be responsible for large fractions of the total state methane emissions (SLCP Reduction Strategy Plan).

This project seeks to provide the California Air Resources Board with up-to-date knowledge on the utility of several methane research data products for identifying methane hot spots with high temporal or spatial resolution, a crucial facet of the Board's strategic plan to reduce fugitive emissions of methane.

Project Goals

The goal of this project is to evaluate several existing methane data sets and their potential to detect methane emissions hot spots in California with high temporal or spatial resolution. Aliso Canyon Natural Gas Leak is used as a test case and an example hot spot to evaluate the data sources. Detailed descriptions of the selected data sources are given in *Data Sources* of the attached Evaluation. A secondary goal of the project is to use scientific visualizations of methane data products as a communication tool.

Deliverables

The main deliverable of this project is a written Evaluation of the selected methane data sources for their usefulness in detecting methane hot spots in California. To achieve the secondary goal mentioned above, visualizations based on scientific methane

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[1] Global Warming Potential (GWP) is a quantity that measures the heat-trapping capacity of a greenhouse gas compared to carbon dioxide, which has a relative GWP of 1.

[2] MTCO2eq: Millions of Tons equivalent of carbon dioxide

data products, one of satellite and another of aircraft origin, are created and applied to make the evaluations. For the chosen satellite data, time series and maps are generated. For the aircraft measurements of methane (HyTES), Google Earth overlays combining the plume images with a specific Vista layer are created. Additionally, a prototype website was developed as an exercise to host an interactive visualization based on the emissions data from the ARB, and to explore interactive visualization as a communication tool.

Target Audience

The Evaluation is intended for the California Air Resources Board (ARB), the state agency with the authority to monitor, inventory, and reduce the greenhouse gases in California. ARB has high priority in identifying hot spot emissions of methane in California, as outlined in Assembly Bill 1496.

Project Outcome

Based on my evaluation of methane data products, the airborne spectrometer methane plume images overlaid with Geospatial Information System (GIS) maps of gas and oil well locations in California were effective in visually illustrating that the Aliso Canyon gas leak originated from Well #25, which is in the Aliso Canyon Oil Field. Therefore, this test case illustrates that the combined usage of these data products (Hyperspectral Thermal Emissions Spectrometer and Vista) is a promising tool for locating hot spots of methane to the point source. Maps of methane concentrations based on GOSAT satellite data did not have sufficient spatial resolution to spotlight a methane hot spot to the point source level, but indicated increasing atmospheric methane concentrations in California. GOSAT time series of annual mean methane concentrations for one point closet to the Aliso Canyon Oil Field clearly indicated increasing methane observations during the plotted time period (2009-2016), and still holds promise for showing methane enhancements during the gas leak. A follow-up analysis idea is included in the *Continuation Plan* (below). More specific targeted recommendations for the California Air Resources Board are included in *Recommendations* of the Evaluation. This project was low budget at $255.44, which was used for transportation. These include transportation costs to visit my expert advisor, Dr. Francesca Hopkins at University of California, and transportation and lodging costs to visit the South Coast Air Quality Management District, my initial target audience.

Skills Acquired

This project provided the opportunity to work with different types of data sources, including geospatial data, regulatory data from the California Air Resources Board, and aircraft as well as satellite data on methane; and different types of data formats: shapefiles, kmz, csv, json, hdf5, and NetCDF. Software used/learnt for the project include: Python (Basemap, pandas, Matplotlib, numpy), d3.js. and Google Earth. This project significantly improved my analytical skills of scientific data.

As a part of the capstone experience, I attended two workshops organized by the National Academy of Sciences on anthropogenic emissions of methane, one remotely, and another in person at the University of California-Davis. These workshops provided a context for current knowledge regarding the monitoring and mitigation challenges of methane, as well as insider perspectives from scientists, regulators, and industry. The workshops showed that, for ARB to achieve its methane mitigation goals, a quantified understanding of methane emissions sources and a more comprehensive understanding of their

distribution across different economic sectors in California is needed, and that neither monitoring nor mitigation is possible without the collaboration of all three stakeholders: regulators, scientists and emitters.

Risk Assessment

Several risks were identified and addressed. The first risk was found and addressed after my visit to the South Coast Air Quality Management District, when it was found that the South Coast AQMD's interest in methane was much more scientific (to improve their modeling), and the ARB had both regulatory and enforcement interest in methane emissions. The target audience was re-scoped to be the ARB thereafter. Secondly, initial project goal was to present images from two research methane data products side by side. However, upon working hands-on with the data sources, I found that both products included *kmz* file formats, and could be overlaid onto each other via Google Earth. Placing the images of different resolutions side-by-side, when they can be integrated smoothly via Google Earth, was deemed unnecessary. My project was re-scoped to include snapshots of Google Earth overlaid images instead. Focusing on the aircraft measurements made during the duration of the Aliso Canyon Natural Gas Leak, final images that strongly identified point sources of methane were created. A second major risk came from the limitation of the data products. As an example, the methane plume images (Level 3 data product from HyTES) used mapped unitless values that were a priori versions of methane concentrations. The threshold value used to indicate methane presence in the plume images is not publically available. Therefore, threshold or a legend is missing from the final images based on plume images. This is a limitation because the data product is not mature enough yet.

Continuation Plan

Immediate continuation idea is highlighted here. Please see *Future Work* in the attached Evaluation for additional plans. First, analysis of GOSAT satellite data will be continued: a) monthly time series of methane concentrations that filters out seasonality will be plotted to see if removing methane seasonal trend will enable detection of methane hot spots, delineating the Aliso Canyon Gas Leak as an anomaly in the time series. If the new time series indicate an anomaly during the gas leak duration, a statistical significance of the anomaly will be quantified. Secondly, working on this project underlined my strong interest in remote sensing spectrometer data. I plan to spend the summer analyzing raw radiance data from HyTES to generate methane plume images.

Dissemination Plan

I have contacted these individuals from the California Air Resources Board (ARB), whose names are mentioned in the *Acknowledgements* (of the attached Evaluation): Jorn Herner (Research Division), Anny Huang (Air Quality Planning and Science Division / Inventory), Patrick Gaffney (Industrial Strategies Division / Greenhouse Gas Reporting Program) and Kathleen Kozawa (Industrial Strategies Division). Three of the identified personnel were present at the National Academy of Sciences meeting on methane hosted at the University of California – Davis. I will be emailing a one-summary version of the full evaluation with specific recommendations on how methane research data products from satellite (GOSAT) and airborne spectrometer (HyTES) can be useful for the ARB. The recommendations will be supplemented by visualizations created for this project.

Evaluation of Methane Data Products:

Using Visualizations of Satellite and Airborne Methane Observations to Detect the Aliso Canyon Natural Gas Leak

June 13, 2017

Moon J. Limb

CLIMATE SCIENCE AND POLICY

SCRIPPS INSTITUTION OF OCEANOGRAPHY

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Executive Summary

Mitigation of anthropogenic methane emissions in tandem with those of carbon dioxide may be essential to limit the current warming of the Earth to two degrees Celsius as supported by the Intergovernmental Panel on Climate Change. Methane is the second most prevalent greenhouse gas in the atmosphere, after carbon dioxide. Methane is a potent greenhouse gas. Methane also has secondary climate and air quality impacts as a precursor to ozone. Despite awareness of the environmental impacts of methane, global methane concentrations have increased by a factor of 2.5 compared to 1750 levels. This increase has accelerated global warming, pushing the global temperature increase closer to the two-degree threshold (IPCC, 2014).

In California, inventoried state-wide methane emissions have increased by 5.2 MTCO2eq[1] between 2000 and 2014, although statewide greenhouse gas emissions have decreased (ARB, 2016a). Furthermore, recent studies conducted by third-party research agencies show 30~50% discrepancy between the atmospheric methane measurements and methane emissions inventoried by the California Air Resources Board (ARB) (Jeong et al. 2016). Several studies indicate that a large fraction of this gap can be attributed to fugitive sources of emissions from the natural gas infrastructure (Hopkins et al. 2016). Therefore, as outlined in Assembly Bill 1496, using the best available methane research products to identify and monitor methane hot spots in California is an urgent state priority. As highlighted in the Revised Proposed Short-Lived Climate Pollutant Reduction Strategy, targeting these hot spots which contribute large fractions of emissions to the total state methane emissions is a potentially effective mitigation strategy.

The present *Evaluation* seeks to provide the California Air Resources Board (ARB) with up-to-date information on the utility of the selected methane data products in detecting methane hot spots with high temporal or spatial resolution. Aliso Canyon Natural Gas Leak was used as a test case. Based on the evaluations summarized below, a combined usage of two NASA-JPL products (HyTES and Vista) were effective in detecting the Aliso Canyon Gas Leak to the point source (Well 25), and it is a highly promising tool for future methane hot spot detection. Furthermore, visualizations based on GOSAT satellite data indicated that annual methane levels in the Aliso Canyon Oil Field were higher than the global average. GOSAT time series also confirmed atmospheric methane concentrations over the oil field have increased from 2009-2016. GOSAT satellite data is a potentially valuable tool for measuring the ARB's methane mitigation progress at the regional level. A follow-up analysis in in progress to more accurately determine GOSAT data's ability to detect methane leaks or hot spots as a temporal anomaly. In conclusion, it is recommended that both research data products, particularly when combined with spatial information, such as map of California, are promising tools that ARB may investigate in informing its policy.

Specific recommendations and how these research products can be useful for the ARB are compiled in *Recommendations for the California Air Resources Board* (Section 6 of the *Evaluation)*.

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[1] MTCO2eq: Millions of Tons equivalent of carbon dioxide

1 Introduction

1.1 Methane and Climate Change

Mitigation of anthropogenic methane emissions in tandem with those of carbon dioxide may be essential to limit the current warming of the Earth to two degrees Celsius, a warming threshold agreed on by scientists as the point after which human society may face more disastrous and unpredictable impacts of climate change (Intergovernmental Panel on Climate Change, 2014). This two-degree Celsius threshold is the target that guides the climate change mitigation goals and plans of policymakers. Methane is the second most prevalent greenhouse gas in the atmosphere, second to carbon dioxide. Because methane has a short-residence time of 12.4 years in the atmosphere, reducing current emissions has the potential to not only mitigate global warming, but also cause future methane concentrations to start decreasing (Victor et al. 2012). A decrease in total atmospheric concentrations of methane in the near-term can potentially curb the current rate of warming significantly. Methane also poses air quality concerns as a precursor to ozone, an air pollutant and another powerful greenhouse gas. Despite the climate and secondary air quality impacts of atmospheric methane, global methane concentrations have increased by a factor of 2.5 compared to 1750 levels and are projected to increase further (IPCC, 2014).

As a world leader on climate action, the state of California has ambitious goals for methane mitigation. In California, methane accounts for 9% of the total state greenhouse gases emissions (California Air Resources Board, 2016a). However, methane emissions have increased by 5.2 MTeqCO$_2$[2] between 2000 and 2014, while total state greenhouse gas emission have decreased. Methane is one of the seven greenhouse gases that California has designated for mitigation under the 2006 Assembly Bill 32, also known as the Global Warming Solutions Act (California Legislature Assembly, 2006). Under this statute, the California Air Resources Board (ARB) is given the responsibility to inventory methane emissions, along with those of other short-lived climate pollutants, and to establish a strategic plan to reach the proposed mitigation targets (California Legislature Assembly, 2014). Several bills specifically highlight the importance of methane in California's climate action efforts. State Bill 1383 sets the state-wide methane emissions reductions target to curtail California's methane emissions by 40% compared to 2013 levels by 2030. A recent bill prioritizes fugitive emissions in state policy, underscoring the need for enhanced understanding of methane hot spots and of methane leaks from the drilling, production, and transportation of natural gas, the components of a natural gas infrastructure (Assembly Bill 1496).

Central to any effective greenhouse gas mitigation plan is an accurate inventory of current and past emissions. First, an accurate accounting of present methane emissions will help set a baseline against which mitigation efforts can be measured. Second, a quantified understanding of current sources, emission levels, and spatial distribution of methane emissions will help the regulators make targeted and effective mitigation strategies. However, atmospheric measurements of methane made by the scientists indicate that California's inventoried methane emissions can be underestimated by up to 30 to 50% (Jeong et al., 2016; Hopkins et al., 2016). One study focusing on the South Coast Air Basin of California indicated that fugitive

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[2] MTeqCO^2: megatons equivalent of carbon dioxide

methane emissions from the natural gas infrastructure explain around 50% of the discrepancy (Hopkins et al., 2016). Fugitive emissions may be unintentional or intended, and mainly occur in the oil and gas sector. In California, 95% of fugitive methane emissions are estimated to be from the oil and gas sector (Carranza et al., draft manuscript, 2017). Recent observations suggest that fugitive emissions of methane follow a fat-tailed distribution-- that is, few sources contribute a large fraction of the total emissions (Brandt et al. 2014). It is thought that targeting these emissions hot spots will result in extensive mitigation benefits.

The Board has a priority concern in integrating the best available methane data sources, whether of research or regulatory origin, to develop an accurate inventory system. The Board also has a designated Research Division that collaborates with research agencies (such as NASA-JPL and Berkeley Laboratory) to inform its *planning* and policy making divisions. Understanding the methane data sources, both their utility and limitations, will help the ARB to focus its research efforts in the specific areas that need more data collection or improvement.

1.2   Case Study: Aliso Canyon Natural Gas Leak

The Aliso Canyon Natural Gas Leak provides a test case for evaluation of different methane data sources. Methane data products from both airborne and satellite remote sensing observations were chosen due to their availability during the leak time frame.

The Aliso Canyon Natural Gas Leak was a leak incident from a natural gas storage well operated by the Southern California Gas Company (SoCalGas). The gas leak was a public disaster that lasted for months, from first reporting on October 23, 2015, to confirmed plugging of the leak on February 11, 2016. It is the largest documented leak of methane in the United States and during the leak, it contributed 1/5 of the California's total greenhouse gas emissions (Conley et al., 2016). As reparations for the damage done by the leak, SoCalGas has been charged to mitigate 109,000 metric tons equivalent of CO_2 emissions. The Aliso Canyon Gas Leak demonstrated that a single gas leak can significantly hinder the state's progress on greenhouse gas emissions reductions, thereby, bringing methane leakage from natural gas infrastructure into policy concerns. The gas leak tested the degrees to which research methane data products could be used to monitor and measure a gas leak in real-time.

1.3   Goals of the Capstone Project

The goal of this project is to evaluate several methane research data products for their potential to detect methane hot spots in California. The intended audience of the evaluations is the California Air Resources Board (ARB or the Board). Methane data sources are critical to the ARB's decision making process, as the agency needs to make targeted and informed reduction plan of surface methane emissions. In the present study, several methane data products are visualized to evaluate their visual utility for informing the Board. The Aliso Canyon Gas Leak is used as a test case to determine whether the leak anomalies can be identified from the data studied. Understanding how the visualizations created in this project inform the analysis of the Aliso Canyon Gas leak can indicate the potential of the data products to study future leaks. A secondary goal of the project is to use visualizations of complex scientific data products as a communications tool.

2 Data and Methods

2.1 Data Sources

This project used four different methane data sources, including three research data products of methane from two research agencies – Japan Aerospace Exploration Agency (JAXA) and NASA-Jet Propulsion Laboratory (JPL) and one regulatory methane data from the California Air Resources Board. A detailed description of each source is given below.

> **Box 1: What is a research data product?**
>
> A research data product is an umbrella term that describes scientific data that has been developed for a specific scientific research purpose, and has been collected, processed one or more times, quality controlled, and is ready to be used for further analysis. The final data product may be derived from multiple input sources of data, and may incorporate different types of measurements. Detailed descriptions of the research data products used for this project are given below. Usually, research data products have data levels indicated by numbers ranging from L1 to L4 or more, indicating the levels of data processing, where increasing number indicates further processing to correct for biases or artifacts and screening to eliminate problematic points.

2.1.1 Satellite Data of Methane (A)

To evaluate whether satellite data of methane can identify methane enhancement in the California region, I analyzed Level 3 (L3) data product based on the Greenhouse Gas Observing SATellite (GOSAT) data from the Japan Aerospace Exploration Agency (JAXA). The L3 data product is a monthly average of methane column-average mixing ratio in units of parts per million by volume [ppmv], based on short-wave infrared radiation measurements. Two sensors, greenhouse gas observation sensor (TANSO-FTS) and a cloud/aerosol sensor (TANSO-CAI), are onboard GOSAT and work together to monitor carbon dioxide and methane. GOSAT is the world's first operating satellite that was specifically designed to measure greenhouse gas emissions**.** Launched in 2009, it is a low Earth orbiting (LEO) satellite. GOSAT provides spatially sparse dense data points, which are 2.5 degrees apart in latitude and longitude, but has a dense temporal resolution as it obtains global coverage every 3 days (Jacob et al. 2016). The 3-day revisit time of same ground location makes GOSAT data suitable for temporal trend analysis, however, most of the surveyed studies focused on the analysis of GOSAT data using inversion method to derive local methane emissions values, and focused solely on few months or few years (Turner et al. 2016*).*

GOSAT data was chosen to be evaluated because several papers on methane mentioned using GOSAT data, in combination with chemical transport model and other ground level measurements to infer methane trends in the United States (Jacob et al., 2016). Also, a 3-day revisit time of same ground location makes GOSAT data suitable for temporal trend analysis, yet, most of the surveyed studies focused on the analysis of GOSAT data using inversion method to derive local methane emissions values, and focused solely on few months or few years (Turner et al. 2016*).* This project is the first to calculate

and visualize GOSAT anomalies values for 2009-2016, for specific locations within California. Several other studies focusing on the United States methane emissions have analyzed data from Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), an imaging spectrometer onboard the European Space Agency's satellite Envisat (Wecht et al., 2014). However, SCIAMACHY was operational from 2003-2012 and did not have data available for the duration of the gas leak.

Furthermore, GOSAT was indicated in the California Air Resources Board's report (Determination of Total Methane Emissions from the Aliso Canyon Natural Gas Leak Incident, ARB, 2016b) as one of the two satellites that detected methane enhancements during the gas leak. However, based on the ARB report references, GOSAT data has not yet been used to detect methane enhancements in California.

2.1.2 Methane Plume Images from Airborne Spectrometer (B)

The plume images used for this project are a Level 3 Data Product based on raw data captured by the Hyperspectral Thermal Emission Spectrometer (HyTES) on board an aircraft. The data product based on HyTES used the data processing levels outlined in Earth Observing System Data and Information System (EOSDIS). According to EOSDIS data processing levels, level 3 data are variables that are mapped on uniform space and time grid scale (NASA-JPL, n.d.).

HyTES is an airborne infrared imaging spectrometer owned and operated by the NASA-Jet Propulsion Laboratory. HyTES can produce plume images of methane with high spatial resolution (2m at 1km flight altitude), resulting in images at 2 meters resolution, a scale fine enough for detection of a discrete point source. HyTES also has high spectral resolution (256 bands from 7.5 to12 micrometers) (Hook et al. 2013). A high number of bands, or wavelength intervals, are captured by spectrometer, which provides sufficient data points for detecting atmospheric methane enhancements in the presence of other trace gas and water vapor. HyTES is a promising tool for the attribution and quantification of methane and other trace gas sources (Hulley et al., 2016).

The focus here is on six aircraft flights over the Aliso Canyon Oil Field (*Table 1*) taken in January 2016, during the Aliso Canyon Gas Leak. Seven to thirteen plume images were available for each set of flights. Wind affects the spatial patterns of observed methane, and adds complexity to source attributions of methane from the aircraft data. Therefore, wind direction at the flight time affected the choice of flight direction (ex. Northeast to Southwest from January 26, 2016 flight) to optimize the capture of the plume within a single aircraft swath. A full catalogue of available aircraft measurements and plume images can be accessed at https://hytes.jpl.nasa.gov/order/. The data used is detailed in *Table 1*.

Acquisition Date	Location	L1 & L2	L3	Planned Start (Latitude/Longitude)	Planned Stop (Latitude/ Longitude)	Segments	AGL (m)	Pixel Size (~m)
1/26/16	Aliso Canyon Northeast to Southwest Low, CA	Version 2	Version 1.1	34.3669, -118.554	34.2716, -118.602	1	1805.54	3.29
1/25/16	Aliso Canyon North to South Low, CA	Version 2	Version 1.1	34.2844, -118.579	34.365, -118.583	1	1815.66	3.31
1/17/16	Aliso Canyon North to South Low, CA	Version 2	Version 1.1	34.3583, -118.566	34.2711, -118.562	1	1776.94	3.24
1/14/16	Aliso Canyon Northeast to Southwest High, CA	Version 2	Version 1.1	34.2643, -118.618	34.3552, -118.48	1	2179.82	3.97
1/14/16	Aliso Canyon North to South High, CA	Version 2	Version 1.1	34.2959, -118.556	34.4117, -118.563	1	2178.55	3.97
1/12/16	Aliso Canyon North to South High, CA	Version 2	Version 1.1	34.2942, -118.579	34.372, -118.583	1	2087.34	3.8

Table 1: List of HyTES Flights over the Aliso Canyon Oil Field.

2.1.1.1 An Example of a Methane Plume Image

A screenshot of plume images of methane is given in **Figure 1**. Green pixels in the image indicate the presence of atmospheric methane above a defined threshold at that location. The pixel intensity is based on Clutter Matched Filter output (Explained in detail in *Box 1*) values, which are unitless quantities that have strong correlation with retrieved methane concentrations. Higher pixel intensity corresponds to higher absorption of thermal infrared radiation by methane. Gray background corresponds to the surface temperature of the surrounding environment. The images provide valuable qualitative information on whether methane is present in the observed area.
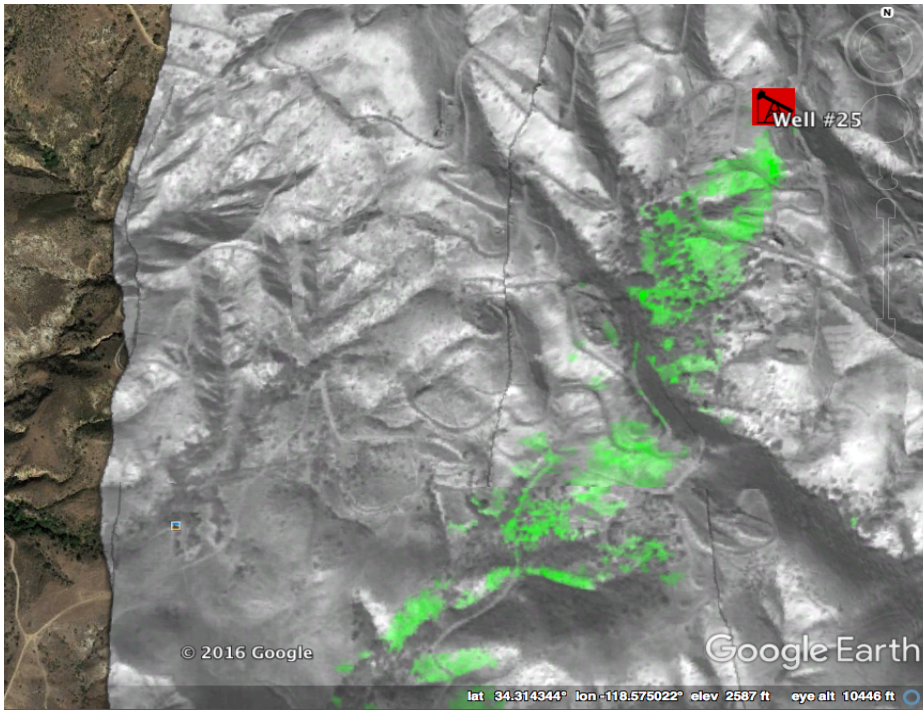

Figure 1: A screenshot of a several plume images as seen via Google Earth. Data from January 25, 2016 flight.

Box 2: What is a Clutter Matched Filter (CMF)

A Clutter Matched Filter (CMF) is a computational technique that takes in infrared radiation measurements from the spectrometer and, using the known spectral signature of a trace gas from HITRAN database, identifies whether there is significant enhancement of that trace gas for each pixel of the dataset to form an image. The final output image produced shows a methane plume with green pixels indicating the presence of enhanced methane levels relative to the local background.

CMF is optimized to detect only the strongest methane sources and minimize false positives. CMF allows for fast generation of plume images, within a few hours of aircraft flight measurements. The plume images can be then used to a) determine which parts of the data should re-analyzed with a more computationally intensive and slower retrieval algorithm to derive methane partial column mole fractions with quantified statistical uncertainty, and b) determine which locations show large and/or persistent methane point source emissions and require further follow-up measurements (ex. in situ/ground).

2.1.3 Maps of methane emitting infrastructure (C)

Vista, another NASA-Jet Propulsion Laboratory data product, is a database of Geospatial Information System (GIS) layers that map methane emitting infrastructure in California. In the present version, there are thirteen spatial layers, or maps that can be overlaid on each other. The layers correspond to different methane emitting sectors, which combined account for 99 % of known methane emissions in California (Carranza et al., draft manuscript, 2017). The layers were determined according to the Intergovernmental Panel on Climate Change (IPCC) categorization of methane source sectors, and range from locations of oil and gas wells to locations of dairy farms.

The current version, Vista-LA, focuses on the South Coast Air Basin (SoCAB), which is likely highest methane-emitting air basin in California (Jeong et al., 2016). South Coast Air Basin is one of the fifteen air basins that California is divided into for the purposes of air quality control regulation by the respective Air Quality Management Districts. South Coast Air Quality Management District (South Coast AQMD) is the agency that oversees the air quality of SoCAB.

In the current project, only one Vista-LA layer, a GIS map of all known locations of oil and gas wells in SoCAB, was used. This map was based on the 2016 data from the California Department of Conservation, Division of Oil, Gas and Geothermal Resources (DOGGR) and included 32,527 oil and gas wells (Carranza et al., 2017). I chose this layer because it is known that the Aliso Canyon Gas Leak originated from Well SS25, which is included in the Vista layer.

2.1.4 Reported Methane Emissions Data (D)

In addition to the scientific research data on methane (mentioned above in A, B and C), regulatory methane data from the California Air Resources Board (ARB or the Board) was analyzed. The goals for this analysis were two-fold: to become

more familiar with the regulatory methane data and to gain an understanding of the normal, estimated, pre-leak methane levels in California.

Scientific research products based on spectrometer measurements, onboard aircraft (A) or satellite (C) can provide high resolution estimates of atmospheric methane concentrations. However, policy decisions in California are primarily based on the regulatory methane data from the ARB. The Board has two sources of methane data: greenhouse gas inventory and the reported emissions data under the Greenhouse Gas Mandatory Reporting Regulation (MRR). ARB's inventory data has a single, state-wide value, and is not valuable for visualizing methane emissions at a local, air basin level. Therefore, I chose to analyze MRR data for methane, which had emissions value for each reporting source. Each source also had additional information such as, its air basin, and could be visualized per air basin.

MRR reports include emitting sources such as fuel suppliers and electricity importers. Sources that emit less than 10,000 MTeqCO$_2$ are generally too small to require reporting. However, determination of which emitters are required to report is sector dependent. A full list of emitters who are required to report under MRR is given in the ARB webpage (ARB, 2016e). The complete dataset also includes detailed information about other greenhouse gases such as carbon dioxide. Only methane emissions were used for my project.

MRR data for the years that overlap with the Aliso Canyon Gas Leak are presently not available. The most recent data, from 2014 reported emissions report, was used for my project to generate a map shown in Figure 5. Recently in 2016, ARB has released an Integrated Emissions Visualization Tool (version 1.0) that includes a Google map of California with location indicators of emitting facilities, and supports various filter and search functionalities (California Air Resources Board, 2017). However, a choropleth map of methane emissions is a new visualization that is not yet found on the ARB website. The choropleth map reveals information not apparent in either GOSAT or HyTES data products. It visually highlights methane emissions sources are densely located in the South Coast Air Basin and other urban regions of the state, suggesting urban areas as important methane mitigation targets.

2.2   Quality Assurance and Control

I ensured the quality of the project by using data sources from credible organizations, including NASA-Jet Propulsion Laboratory, JAXA, and the ARB. Each of the data sources had been quality controlled and/or validated internally by the distributing organizations. To get most up-to-date information on how HyTES and VISTA-LA products can be used together, I had several conversations with Talha Rafiq from the NASA-JPL, the expert on Vista, and my advisor, Dr. Francesca Hopkins, who collaborated on both of the JPL data products used in this project.

3.   Data Visualizations and Evaluation

3.1 GOSAT Satellite Visualizations

3.1.1 GOSAT Color Maps (A)

To evaluate whether GOSAT data indicated any abnormality in methane levels during the Aliso Canyon Gas Leak, I made color maps of methane column mixing ratio ([ppmv]) for these dates: a) all months from October 2015 to March 2016 (one month after the plugging of the leak), b) October data from 2009 to 2016, c) February from 2013 to 2016 (February was chosen instead of January because one year of January was missing data). The color maps are referred in the following report as Aliso maps (*Figure 2* below), October maps (Appendix B, *Figure B1*), February maps (Appendix B, *Figure B3*), respectively. The October and February maps were created to see if October 2015 and February 2016 color maps showed unusually high methane concentrations compared to other years.

Overall, there was a visible trend in emissions over the course of the natural gas leak (Aliso maps in *Figure 2*). All plotted maps –Aliso maps, October maps, and February maps– indicated an increasing trend. However, without the knowledge of atmospheric transport patterns of methane, it is difficult to make specific conclusions about what fraction of the increase in GOSAT-detected methane concentrations can be attributed to local versus global sources of emissions.
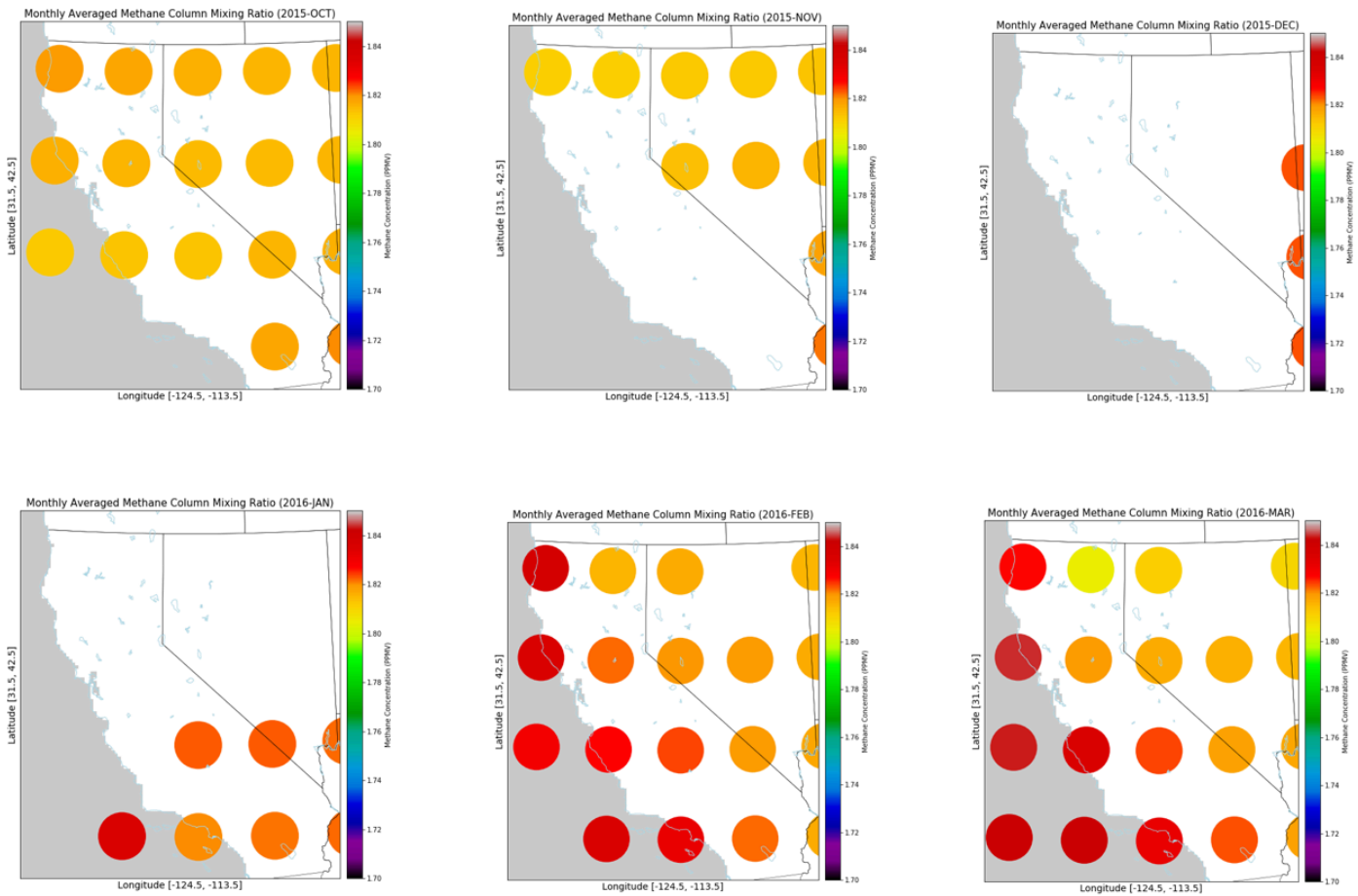

Figure 2: Maps based on GOSAT data from October 2015 to March 2016. The dots indicate monthly average methane concentrations based on GOSAT Level 3 data (column mixing ratios of methane). The plotted range are 1.70 to 1.84 parts per million (ppmv). The dots are 2.5 degree (latitude and longitude) apart and indicate observed methane

concentrations. In these maps, the redder color indicates higher observed methane concentrations. Methane observations are all above 1.80 ppmv which, relative to other plotted maps, are high. The dots are made bigger for readability. Missing dots are omitted invalid data.

Furthermore, plots of methane concentrations from different months indicated monthly variations. The time period plotted were too limited ((a) to (c) above), to make a conclusive deduction about methane seasonality, or monthly patterns. A more rigorous analysis idea to determine whether GOSAT data shows any methane increases during the Aliso Canyon Gas Leak is proposed in *Future Work*.

In conclusion, GOSAT data sets did not have high spatial resolution required for identifying methane hot spot to the emissions source; for California, data points were 2.5 by 2.5 degrees apart in latitude and longitude, which corresponds to approximately 111 km x 111 km, or one data point for every 12321 km^2 grid. Seven GOSAT data points covered the whole California region. However, GOSAT maps illustrated increasing methane trend levels from 2009 to 2016, indicating that they are useful for studying long-term regional trends.

3.1.2. GOSAT Time Series (A)

To assess if the Aliso Canyon Gas Leak can be spotted as a temporal anomaly in the GOSAT data, a time series of methane concentrations for the GOSAT data point nearest to the Aliso Canyon Oil Field was plotted. The data point used was close to the Aliso Canyon Oil Field, 34 North in latitude and -118.5 in longitude, based on USGS data on oil field locations was used. Time series were plotted for: a) Global annual mean methane concentrations (*Figure B4*, Appendix B) b) Global annual methane anomalies c) Aliso Canyon annual mean methane concentrations and d) Aliso Canyon annual mean methane anomalies (global trend removed). Time series for the Aliso Canyon locations are included below as *Figure 3*.
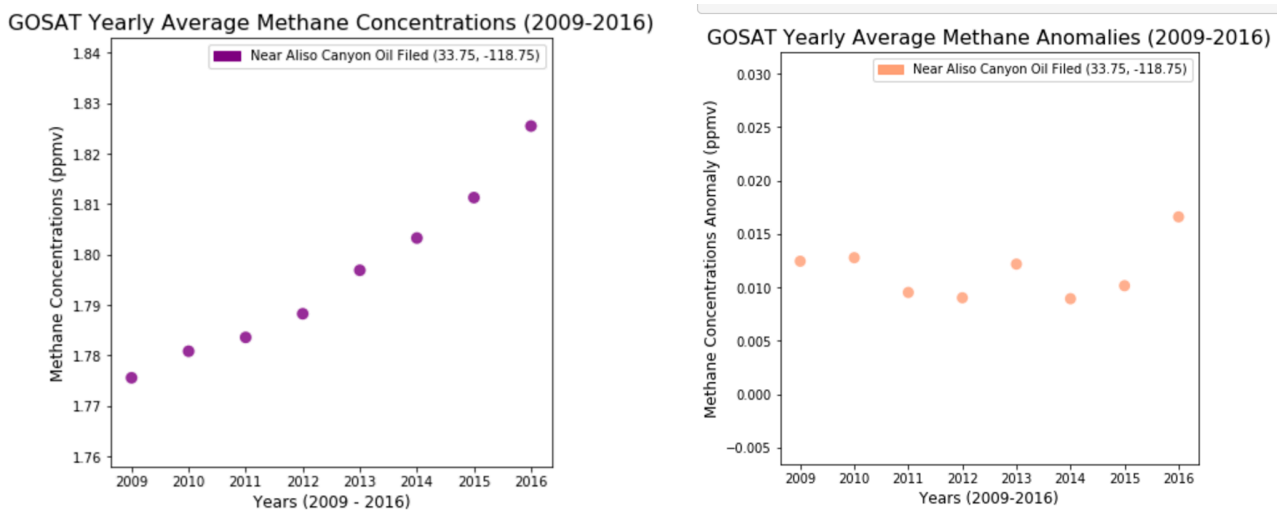
Figure 3: On the left is yearly avearged methane concentration values for the Aliso Canyon location from 2009 to 2016. The plot shows rising methane levels over the eight years from approximately 1.775 ppmv to 1.825 ppmv, an increase of nearly 0.05 ppmv. There is a particularly high leap between 2015 and 2016 values. On the right, is yearly averaged methane anomalies values with the global trend removed. This figure indicates that methane concentrations, on average is higher than the global average methane level by 0.010 ppmv or higher. Again, 2016

data point seems is a potential anomaly. Both plots are based on GOSAT data for the GOSAT data point closest to the Aliso Canyon Oil Field.

3.2   Snapshots of Google Earth Overlays (B+C)

Hyperspectral Thermal Emission Spectrometer (HyTES) and VISTA could be combined to understand emissions from different methane source sectors, including fugitive emissions, as mentioned in Carranza et al. (draft manuscript, 2017). In this project, Google Earth Overlays based on two data products were created to visually identify methane leakage from the Aliso Canyon Natural Gas Leak.
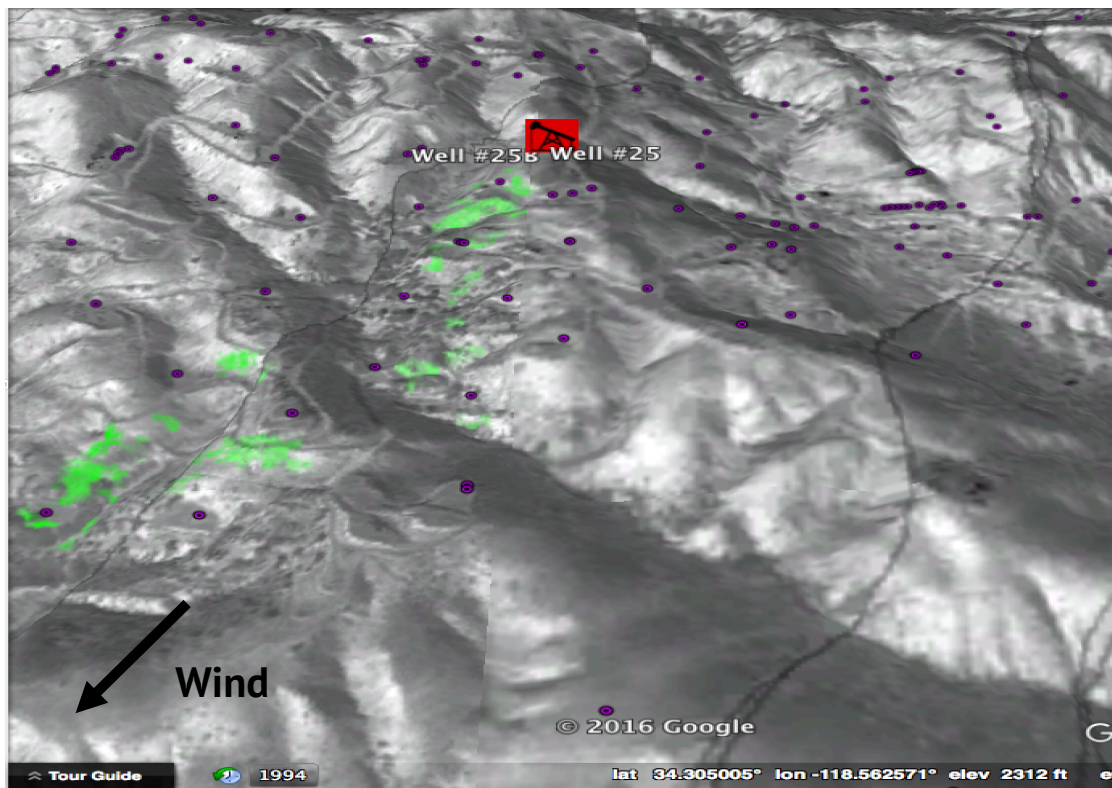

Figure 4: A methane plume image (from HyTES measurements) overlaid on top of a GIS map of oil and gas well locations over the Aliso Canyon Oil Field. The purple dots are locations of oil and gas wells. Well SS25, the source of leakage, is spotlighted with a red gas rig icon. The black arrow on the bottom left hand corner indicates the approximate wind direction on the day, towards the Southwest. Screenshot is from Google Earth and plume images are from January 26, 2016 HyTES measurements.

As mentioned earlier, it is known that the Aliso Canyon Gas Leak originated from Well SS25. Therefore, Google Earth Overlays (example image in *Figure 4*) were created to test if the overlaid images could verify that methane leakage originated from Well SS25. For each of the flights, one or multiple plume images were overlaid, both measurements from the same day and from multiple dates, to study whether overlaid images verified that Well SS25 was the emitting source.

Figure 4 is an example of an overlaid image that was created based on the January 26 flight. The location of the Well SS25 -– the source of the leak – is spotlighted by the red icon with a gas rig image. The green pixels indicate methane detected by HyTES, where higher intensity signifies higher concentrations of methane. On January 26, HyTES was flown from

Northeast to Southwest (*Table 1*) direction, based on the wind along the same direction. Knowing the wind path, green pixels appear as if they are spewing out from Well SS25 in the direction of the wind. The green plumes near the source show a narrower width, and seem to widen further away from the source, showing methane plumes dissipate away from the source by the wind.

It is concluded that combining the two methane data products--HyTES images of detected methane plumes and Vista maps of methane emitting structures--can be a powerful way to detect a source of emissions. In the *Figure 4*, there are many gas wells in close proximity, and therefore, it may be challenging to pinpoint the exact well that is causing the leak. However, it is evident that the overlaid HyTES + VISTA images, especially with data from multiple aircraft flights, can significantly limit the spatial scope of further investigation. In the given example, possible leak sources can possibly be constrained to ten or less wells. Using VISTA and HyTES on the Google Earth platform is a powerful and promising way to detect and attribute fugitive emissions of methane at a resolution level close to point sources.

3.3   An Interactive Choropleth Map (D)

To visualize reported methane emissions (MRR) data for a normal year, previous to the Aliso Canyon leakage event, an interact choropleth map of methane emissions based on the 2014 reported methane emissions data was created.

To code the map of California divided into air basins, I combined a spatial data set, a shapefile containing information of the boundaries of California state and its air basins, with a tabular data containing methane emissions reported by facilities. Two data sets could be combined because both included air basin names. For the MRR data, total summed methane emissions values were calculated using Pandas, Python scientific computing tool. The total methane concentrations and the air basin name are indicated upon hover over the air basin. The darker color represents higher total reported emissions of methane.

Tens of maps were generated using different color schemes and legend thresholds. The final version in *Figure 5* was chosen after incorporating feedback from my peers and advisors. This figure is another visual communication tool that shows the highest emitting air basins in California. Although reported emissions data cannot characterize the state methane emissions in a comprehensive and is information that the ARB is already aware of, combined usage of regulatory methane emission data with scientific research products is recommended. For example, regulatory data set provides context for state or air-basin level methane emissions that is not available in high resolution methane data products such as HyTES plume images. Regulatory information, used jointly with research-based information on methane, can be used to determine regions or sectors that should be prioritized for methane mitigation efforts. For example, it will be useful to know whether fugitive emissions tend to occur from largest emitting facilities (ex. SoCalGas), or whether small facilities or gas infrastructure can still contribute a large fraction of emissions.
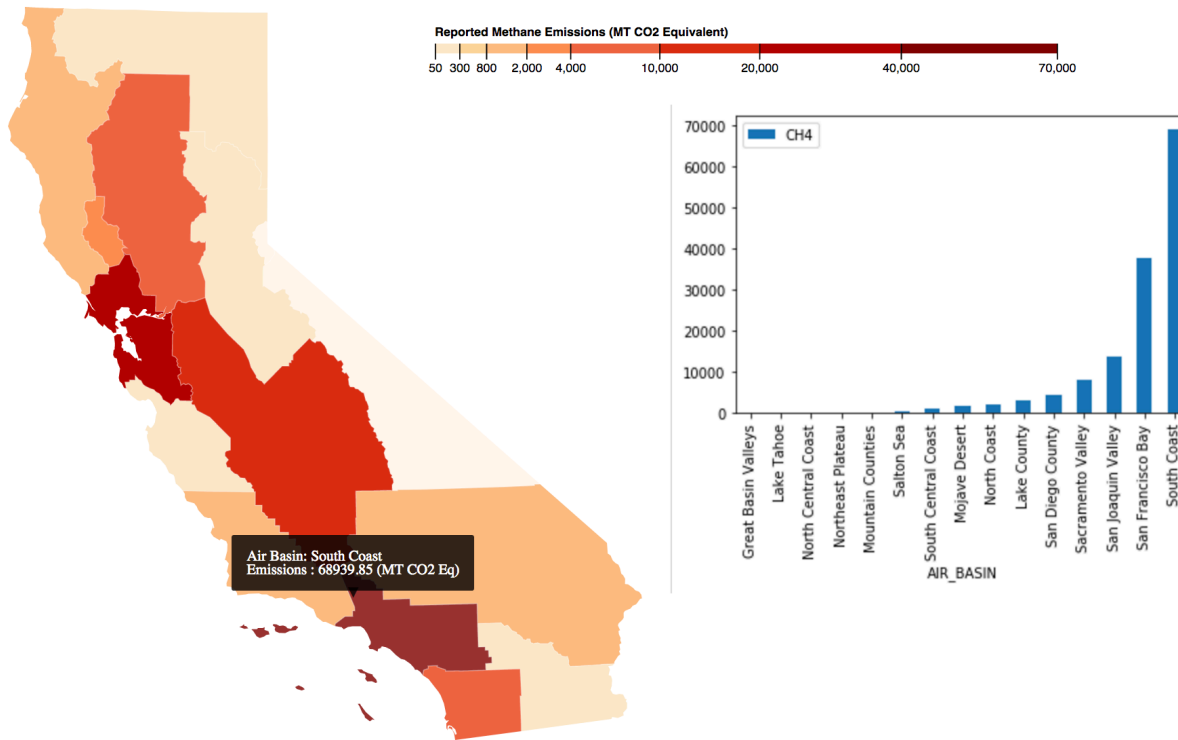
Figure 5: A web-based, interactive 'choropleth' map of California divided into air basins. Red color gradient corresponds to methane levels, where darker color indicates higher reported emission values. The map illustrates that high density of methane emission sources are in urban regions such as the South Coast Air Basin and the San Francisco Bay Air Basin, suggesting the two air basins should be prioritized as emissions reduction targets. Data is from the 2014 reported methane emissions data (methane in $MTeqCO^2$) from the California Air Resources Board.

3.4 Prototype Web page (upcoming)

Additionally, prototype webpage was developed as an exercise to develop interactive visualizations. This is a potentially promising platform for communicating the visualizations created in this project. A screenshot of the main page is included in the *Appendix A*.

3.5 Limitations

Several limitations of the visualization created in this project, and their data sources are outlined below.

The visualizations based on the GOSAT data have limitations in that, although looking at October maps from 2009 to 2016 show an overall increasing concentration of methane emissions (Appendix B-1), it is hard to make any scientific conclusion about whether any part of the increase was from the Aliso Canyon Natural Gas Leak. Furthermore, one cannot conclude that the increased overall methane concentrations are from local sources of emissions, or are a result of increased global methane concentrations. Therefore, the satellite maps are useful for showing global trends, but making any quantitative deductions will require incorporation of both knowledge of atmospheric methane's transport behavior in the form of chemical transport models, and incorporation of local measurements of methane that can help constrain the interpretation of satellite data. There are existing studies that conduct Bayesian Inversion methods using a combination of satellite data, Chemical Transport Models (CTM), and ground-level measurements to derive localized emissions estimate for whole or parts of

California, such as CALGEM. These are more promising analysis that can make satellite data more useful for California, and help identify hot spot observations over a longer timescale. But as it stands, the present temporal and spatial resolutions of satellite data are too sparse to make any conclusive or quantitative deductions about locations of high methane emitters to a specific location.

Snapshots of methane plume images overlaid on Vista layers created in this project (B+C) are static images that are limited in comparison to the original data files that can be opened in Google Earth, whose interactive and 3-dimensional functionalities provide more insight into the surroundings of where the plume image was captured. Also, the plots were analyzed with the knowledge that leak originated from Well 25, but did not derive the well location based on two data sources. Lastly, a current limitation of HyTES-based plume images is that algorithms to retrieve methane emissions fluxes from the HyTES is still in development. Although Kuai et al. (2016) describe the algorithm for the case study of the Kern River Oil Field region, the algorithm is in development (correspondence with Dr. Francesca Hopkins, 2017), and the output of the algorithm was not yet available publicly. Therefore, I was not able to add a legend nor indicate a meaningful threshold value (in units of methane concentrations or emissions) for the detected methane emissions. While the plume images have credibility because they are JPL products, I cannot indicate statistical significance or percent of uncertainty for the methane detection. Despite this limitation, the plume images are useful for providing qualitative information, including detecting methane hot spots, rapidly constraining areas for follow-up ground measurements, and potentially helping the ARB to prioritize certain emissions sources for mitigation.

The choropleth map of reported emissions is one data source that was not meant for point-source detection evaluation. It is an example of a visual communication of existing regulatory data on methane. A limitation of the choropleth map is its exclusion of certain methane source sectors such as agriculture.

4   Future Work

Remaining capstone tasks that will be carried out in June are outlined here.

Further analysis of GOSAT time series is needed to state with confidence if GOSAT time series can be used to detect methane hot spots or leakage as a temporal anomaly. First step is to plot monthly methane time series for the Aliso Canyon location to improve the temporal resolution. Next both global trend and seasonality will be removed to improve the identification of the potential leak anomaly. If this time series indicates an anomaly, statistical significance of the anomaly will be quantified.

Secondly, feasibility of overlaying methane plume images from HyTES (B) on Google Maps will be evaluated. Currently, NASA website includes Google Map images of flight trajectories, but only provide static images of plume images, without the surrounding context (ex. Locations of oil wells as provided by Vista). Although this visualization will not have full functionality of Google Earth, nor replace Google Earth overlays of HyTES and Vista, if feasible, this is a promising alternative, exploratory analysis tool for the ARB. Google Earth requires downloading individual data sets for HyTES and Vista, but web-based methane plume images will not have the same overhead.

Third, to extend the choropleth map of California to include locations of methane emitting facilities and represent their methane concentrations visually as a circle. In this visualization, circle size will correspond to methane concentrations. This may be a useful tool for visual comparison of relative contributions of each emitter, and pinpoint any super emitters clearly on the map.

5   Conclusion

In this project, several methane research data products were visualized and evaluated for their potential to spot the Aliso Canyon Natural Gas Leak as an anomaly with either high temporal or spatial accuracy. The visualizations were used as an exploratory data analysis tool to evaluate the data products. Two sets of visualizations were created: California maps with methane concentration plotted above and annual time series (global trend filtered) of methane concentrations for one location closest to the Aliso Canyon Oil Field. Both were useful for showing long term regional changes in methane levels. GOSAT time series may be useful for identifying methane hot spots as anomalies, but further analysis, as outlined in *Future Work*, is required to validate this hypothesis. In comparison, a combined usage of two NASA-JPL products is a promising tool for future detection of methane leaks and hot spots. Google Earth overlays based on HyTES and Vista data products validated that the Aliso Canyon natural gas leak originated form Well 25 in the Aliso Canyon Oil Field, a location with hundreds of oil and gas wells, and numerous other infrastructure associated with underground natural gas storage (e.g., compressors, pipelines). A combined usage of two products is a promising tool for both methane hot spot detection and for rapidly constraining areas for follow-up measurements that are more computationally intensive and/or costly.

It is concluded that both GOSAT satellite and HyTES airborne remote sensing measurements of methane can be useful for the California Air Resources Board. GOSAT observations of methane can be used to monitor the effectiveness of the ARB's methane reduction efforts in the upcoming years. Furthermore, GOSAT and other satellite data can be useful for a finer-scale regional analysis, when used together with airborne or ground-level measurements that provide higher spatial resolution. GOSAT visualizations also provide the ARB with scientific confirmation that methane levels in California have been increasing, raising the urgency for methane reduction efforts. Finally, Google Earth overlays based on the NASA-JPL products demonstrate that scientists at JPL have developed a highly promising tool that is an important step in resolving discrepancies between top-down atmospheric measurements and bottom-up inventories of methane. The present capstone project focused on the Aliso Canyon Gas Leak, but the findings can be generalized to make conclusions about the potential of the data sources and their utility for characterizing future gas leaks and hot spots.

6   Recommendations for the California Air Resources Board

This project provided the opportunity to do an extensive literature review of both scientific research and policy documents on methane emissions. Based on the literature review as part of this study and evaluations described in the *Data Visualizations & Evaluations* Section, the following recommendations are compiled for the Air Resources Board's consideration.

1. To consider using satellite measurements of methane to monitor long-term methane reductions progress in California. As demonstrated in this evaluation, current satellite data on methane can show long-term regional trend of methane. Therefore,

GOSAT satellite data can be a useful tool for monitoring methane concentrations over California and can be used as one of the yardsticks to measure California's methane reductions progress. Secondly, it is recommended that the Board continue the evaluation started on this project, to further evaluate whether GOSAT monthly time series can be used to detect methane anomaly in California. Finally, there are proposed satellites with finer temporal resolutions, such as TROPOMI with hourly resolutions of methane measurements (*Table E-1* in Appendix E). JAXA also has plans for GOSAT-2 which will provide methane observations with higher precision. Hence, future satellites are promising tools for detecting methane anomalies from space, and hold potential for raising a red flag if methane concentrations exceed a certain threshold.

2. To use visualizations of multiple data sources to derive insight about methane hot spots. As illustrated by combined visualizations of HyTES methane plumes and a Vista layer, integrating multiple data sources and types can be a valuable tool for discovering insights that is not visible in the sources when analyzed independently. Google Earth overlays based on HyTES and Vista particularly demonstrated that viewing methane observations in concert with spatial information shows high prospects for methane source detection. GOSAT maps and choropleth map are also exemplary visualizations that show effectiveness of integrated visualizations. Both visualizations combined a data source on methane levels – concentrations in the case of GOSAT maps and emissions for the choropleth map– with a spatial information, map of California. Therefore, it is recommended that the ARB use not only collect and study multiple observations of methane, as it is currently doing, but to combine methane observations with spatial information to identify methane hot spots. It is highly recommended that the ARB work with the experts who worked on HyTES and Vista data products at NASA-JPL to use current versions of two products. This can provide useful information and help identify methane hot spots and/or local areas in California to target methane reduction efforts.

3. To employ scientific visualizations as a communications tool. This project demonstrated that visualizations of methane data sources can be used as an exploratory data analysis tool to study a scientific inquiry. However, visualizations of complex scientific data, such as methane concentrations or emissions, can also be an impactful communications tool and reach a wider audience, such as the public, air quality management districts, methane emitters, or various divisions at the ARB, who are less familiar with the data sources. For example, GOSAT used color gradient to visually communicate increasing methane levels in California, showing the urgency of the methane emissions problem. Google Earth overlays of HyTES and Vista captured the invisible methane leakage. Green plume of methane flowing downwind from the leak source towards the residential Porter Ranch area visually highlights the dangers of methane leaks. It is therefore recommended that visualizations of methane data are used by the ARB to communicate information about methane data— from the location of hot spots to methane trends in California.

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Appendices

Appendix A: Screenshots of Prototype Website

Figure A1 is a screenshot of the main page of the prototype website. The main page has three icons--aircraft, satellite, California Air Resources Board logo--one for each data source. Each icon will link to a detailed page for the given data source, bringing up a short description of the data source used and a catalogue of visualizations made based on the data.
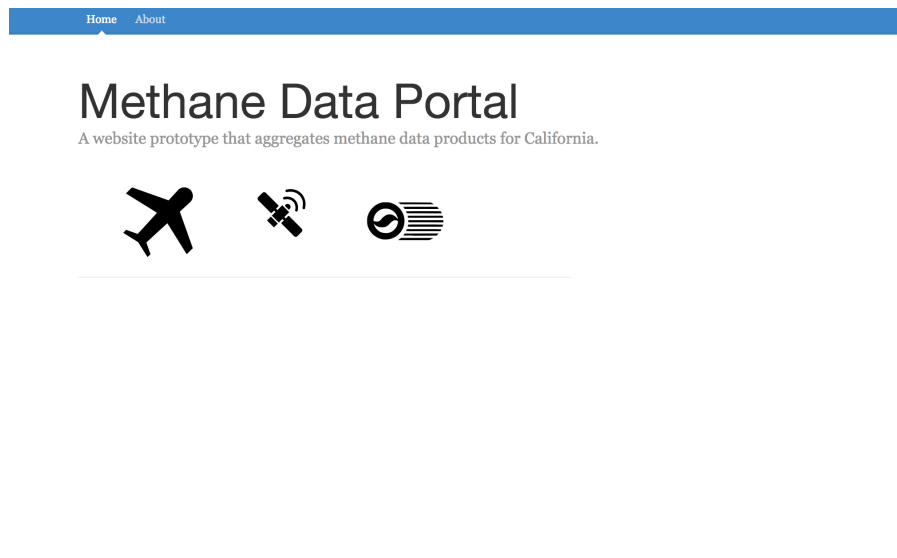

Figure A1: A screenshot of the main page (prototype website).

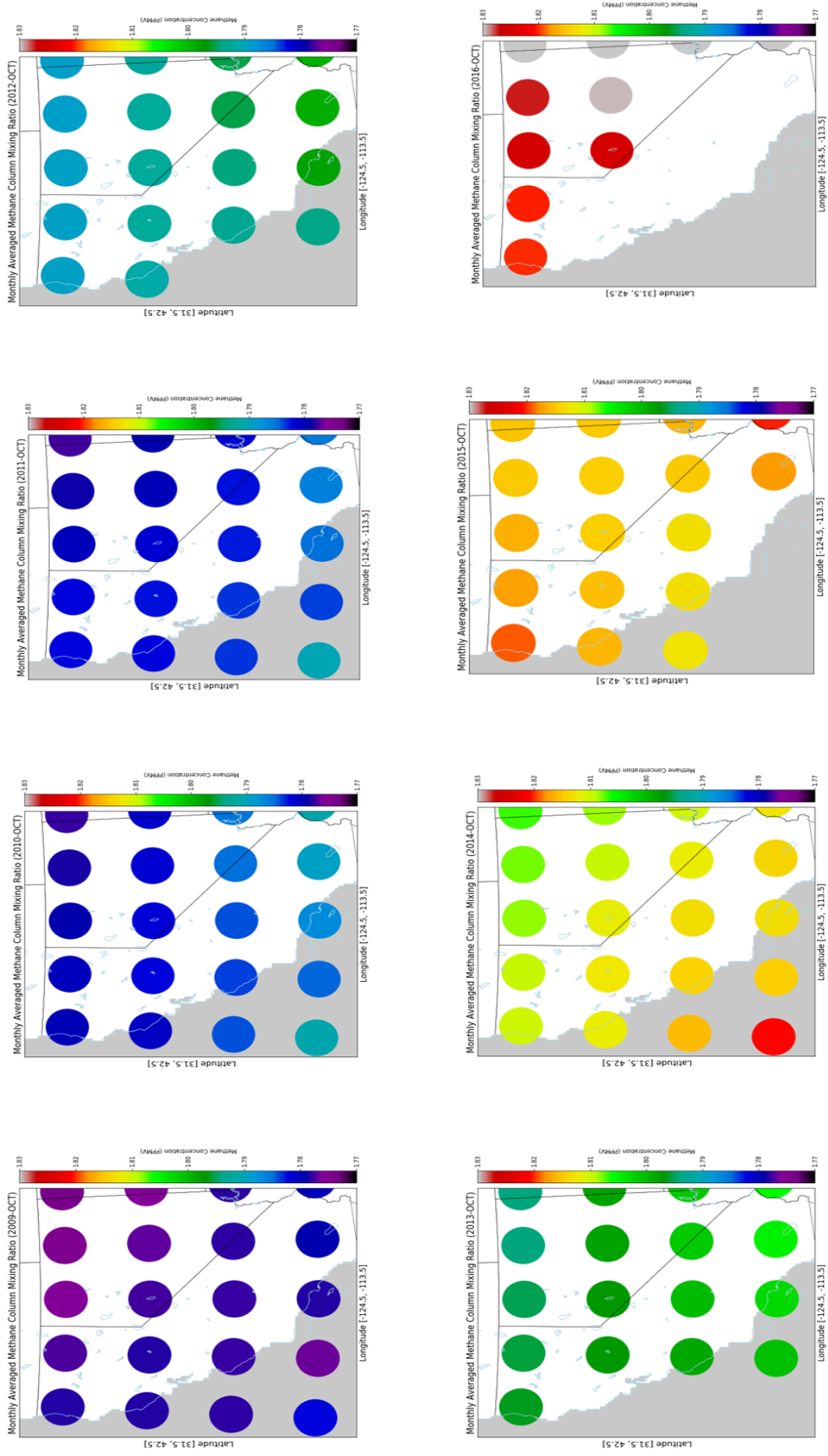## Appendix B: Additional GOSAT Maps and Time Series

Figure B1: Maps based on GOSAT data, for all available Octobers (2009-2016). The plotted range are 1.77 to 1.83 ppmv (unlike Figure 2, which has a range of 1.70 to 1.84 ppm). Gray dots in the last figure are methane concentration values that were out of bound (higher than 1.83 ppm). All details are
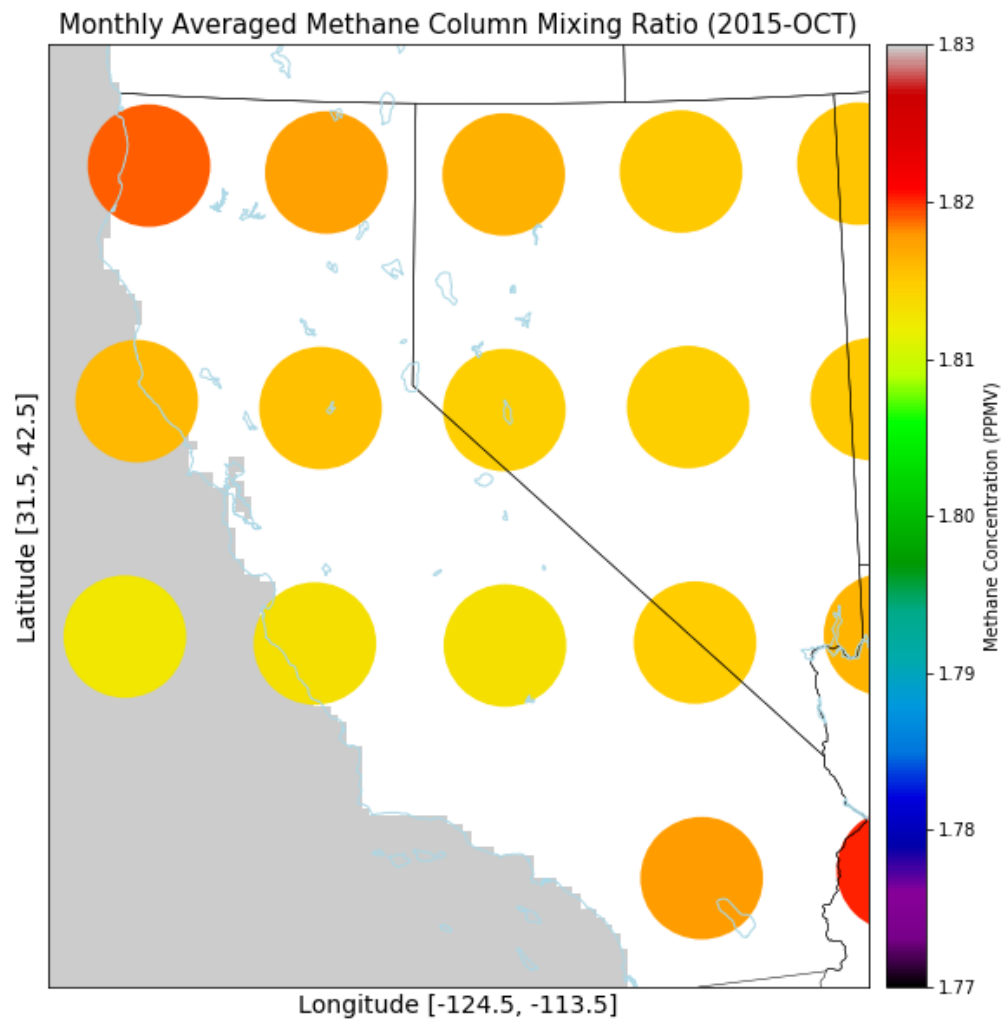
Figure B2: A zoomed-in version of one October map. Map from October 2014. Latitude and longitude bounds are indicated on the *y* and *x* axes, respectively. The plotted concentrations range from 1.81 ppm to 1.82 ppm, based on the color bar.
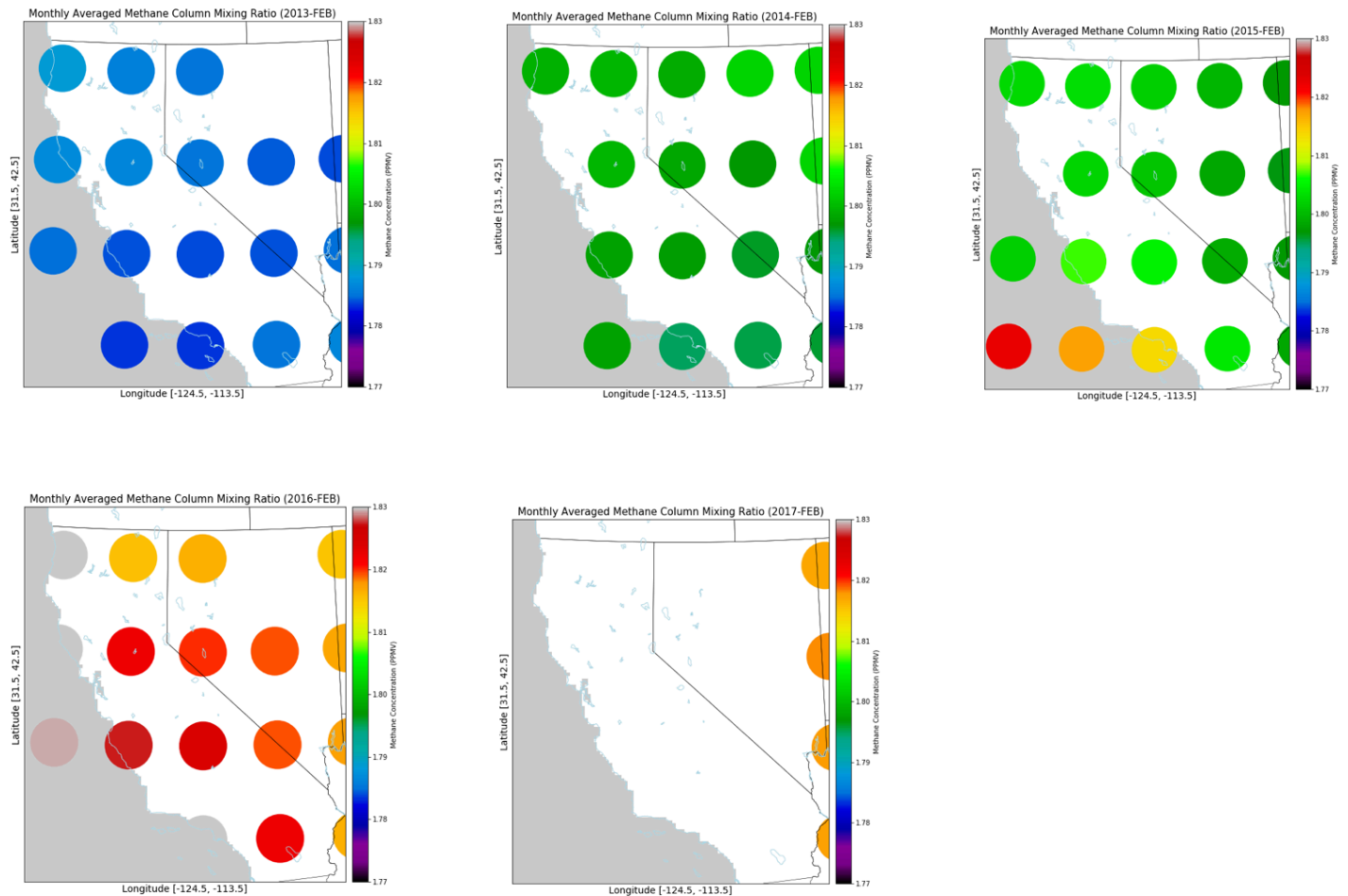
Figure B3: All GOSAT maps from February 2013 to 2016. The plotted range are 1.77 to 1.83 ppmv as in Figure B1.
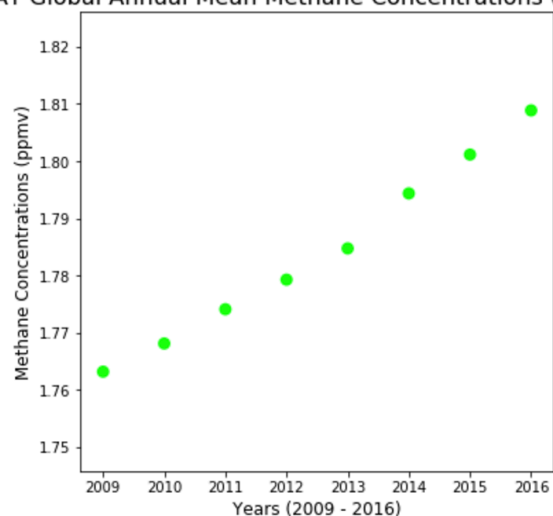

Figure B4: Global annual mean methane concentrations (2009-2016) based on GOSAT Level 3 data of monthly methane mixing ratios. For each year, a single methane average concentration was calculated based on monthly observations. There is an increasing trend from approximately 1.76 ppmv in 2009 to 1.81 ppmv in 2016. The annual increase seems consistent over the eight years. 2016 data point in this figure, compared to the 2016 point in the Aliso Canyon time series, does not indicate potential anomaly. The average annual methane concentrations for the Aliso Canyon point is higher than the global average.

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Appendix D: Table from ARB's report on Aliso Canyon Natural Gas Leak

Table D1: A table from California Air Resources Board's report on the Aliso Canyon Gas Leak. (ARB, 2016b). Data sources from Project Teams/instruments that were used in this project – HyTES (airborne remote sensing) and GOSAT (satellite remote sensing) – are highlighted in yellow.

Table 2: Overview of other methods

Method	Project Teams	Measurement Approach	Measurement Frequency
Airborne Measurements	Scientific Aviation	Small airplanes with instruments measuring methane and other pollutants flying downwind of the leak through the plume at various elevations.	11 measurements campaigns made during the leak
Ground-Based Remote Sensing	NASA JPL, Caltech 1. TCCON, 2. CLARS	Ground based spectrometers use sunlight and its attenuation to estimate GHG concentration in the atmosphere above LA.	Continuous, operating pre-leak and afterwards
Airborne Remote Sensing	NASA, JPL, NIST [AVIRIS, HyTES]	Imaging spectrometers deployed on aircraft image the methane plume at the leak site with high resolution (meters) and spatial accuracy.	Only a few hours on select days
Satellite Remote Sensing	Hyperion EO1, GOSAT	Satellite sensors measure enhancement of methane at different locations in and around the LA basin. No emission estimate expected at this point.	Continuous, intermittent, repeated every few days, large pixels
Tower-Based Measurements and Large Eddy Simulation Modeling	Megacities Carbon Project	GHG tower network, with atmospheric transfer models and high-resolution flow-resolving models to directly simulate the methane plume at the leak site and its propagation into the atmosphere. Fitting of results to observations can be used to estimate leakage flux.	Continuous measurements, operating pre-leak and afterwards; intermittent plume identification

Appendix E: Summary Table of Methane-Observing Satellites

Table E-1 (Table 1 from Jacob et al., 2016) lists past, present and upcoming satellites that have instruments for measuring atmospheric methane concentrations. A particularly promising satellite is TROPOMI, which will have a revisit time of 1 day.

Table 1. Satellite instruments for measuring tropospheric methane[a].

Instrument	Agency[b]	Data period	Overpass time [local]	Fitting window [nm] (spectral resolution)	Pixel size [km^2][c]	Coverage[d]	Precision[e]	Reference
Low Earth orbit[f]								
Solar backscatter								
SCIAMACHY	ESA	2003–2012	10:00	1630–1670 (1.4)[g]	30 × 60	6 days	1.5 %[h]	Frankenberg et al. (2006)
GOSAT[i]	JAXA	2009–	13:00	1630–1700 (0.06)	10 × 10	3 days[j]	0.7 %	Kuze et al. (2016)
TROPOMI	ESA, NSO	2017–	13:30	2310–2390 (0.25)	7 × 7	1 day	0.6 %	Butz et al. (2012)
GHGSat	GHGSat, Inc.	2016–	09:30	1600–1700 (0.1)	0.05 × 0.05[k]	12 × 12 km^2 grid[l]	1–5 %	Footnote[m]
GOSAT-2	JAXA	2018–	13:00	1630–1700, 2330–2380 (0.06)	10 × 10	3 days[j]	0.4 %	Glumb et al. (2014)
CarbonSat	ESA	proposed		1590–1680 (0.3)	2 × 2	5–10 days	0.4 %	Buchwitz et al. (2013)
Thermal emission								
IMG	MITI	1996–1997	10:30/22:30	7100–8300 (0.7)	8 × 8	along track	4 %	Clerbaux et al. (2003)
AIRS	NASA	2002–	13:30/01:30	6200–8200 (7)	45 × 45	0.5 days	1.5 %	Xiong et al. (2008)
TES	NASA	2004–2011	13:30/01:30	7580–8850 (0.8)	5 × 8	along track	1.0 %	Worden et al. (2012)
IASI	EUMETSAT	2007–	09:30/21:30	7100–8300 (1.5)	12 × 12	0.5 days	1.2 %	Xiong et al. (2013)
CrIS	NOAA	2011–	13:30/01:30	7300–8000 (1.6)	14 × 14	0.5 days	1.5 %	Gambacorta et al. (2016)
Active (lidar)								
MERLIN	DLR/CNES	2020–	13:30/01:30	1645.552/1645.846[n]	pencil	along track	1–2 %[o]	Kiemle et al. (2014)
Geostationary								
GEO-CAPE[p]	NASA	proposed	continuous	2300 nm band	4 × 4[q]	1 h[r]	1.0 %	Fishman et al. (2012)
GeoFTS	NASA	proposed	continuous	1650 and 2300 nm bands	3 × 3[q]	2 h[r]	< 0.2 %	Xi et al. (2015)
geoCARB	NASA	proposed	continuous	2300 nm band	4 × 5[q]	2–8 h[r]	1.0 %	Polonsky et al. (2014)
G3E	ESA	proposed	continuous	1650 and 2300 nm bands	2 × 3[s]	2 h[r]	0.5 %	Butz et al. (2015)

(Jacob et al. 2016)

Appendix F: Software Used to Create Visualizations

Software Used

NAME	GOSAT	HyTES NASA	VISTA NASA	AIR RESOURCES BOARD Reported Emissions / Website
Software	Python, Matplotlib, Numpy, Pandas	Google Earth	Google Earth	JavaScript, TopoJSON, d3.js, Python, Flask, Excel
Data Format	netcdf / h5	kmz	kmz	csv, json

Appendix G: Responses to Feedback from Capstone Advisor Committee

Detailed responses to feedback provided by the capstone advisor committee have been compiled. They are not included here due to length, but are available upon request.