

Impact case study (REF3)

Institution: Imperial College London		
Unit of Assessment: 9 – Physics		
Title of case study: B9-4 Validation of CO ₂ emissions informing climate change mitigation policies		
Period when the underpinning research was undertaken: 2013-2018		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Dr Heather Graven	Role(s) (e.g. job title): Senior Lecturer	Period(s) employed by submitting HEI: Oct 2013-present
Period when the claimed impact occurred: 2016-2020		
Is this case study continued from a case study submitted in 2014? N		
1. Summary of the impact (indicative maximum 100 words)		
<p>Reliable systems for validation of reported greenhouse gas emissions are needed to monitor and guide government and business actions to mitigate climate change. Heather Graven created the first atmospheric observation-based system to provide independent evaluation of fossil fuel CO₂ emissions on the scale of a political state, utilising measurements of the ratio of carbon isotopes (¹⁴C/C) in atmospheric CO₂. The system was used to validate reported greenhouse gas emissions in California, which formed the basis of California's climate policy. The direct beneficiaries are California's government and citizens, but the impact is much broader as the system is serving as a model for similar systems being developed elsewhere including the European Copernicus Atmosphere Monitoring Service and the US National Oceanic and Atmospheric Administration.</p>		
2. Underpinning research (indicative maximum 500 words)		
<p>As governments and businesses develop actions to reduce greenhouse gas emissions, reliable systems for validation of reported emissions are needed to verify that emissions are being accurately reported and to monitor the effectiveness of policies to reduce emissions. This validation has been critical for other types of emissions; for example, atmospheric measurements of chlorofluorocarbon-11 showed that there were unreported emissions from China occurring in 2014-16, in violation of the Montreal Protocol to protect the ozone layer. In addition, atmospheric measurements also helped uncover the deliberate underestimate of nitrogen oxide emissions by Volkswagen and other companies, which has serious impacts on air quality.</p> <p>By far the largest source of greenhouse gases is CO₂ from fossil fuel combustion. Countries and regions report their CO₂ emissions from fossil fuels by counting what they have used, such as the amount of oil, coal or gas they have burned. However, there may be uncertainty in these estimates, for example depending on the composition of the fuel.</p> <p>Dr Graven took up her position at Imperial College London in October 2013, bringing with her a recently awarded grant from NASA. The period of 2013-18 represents the development and demonstration of a technique to estimate CO₂ emissions from fossil fuels over the area of a political state using atmospheric measurements.</p> <p>The project which led to [1] addressed a key difficulty in the identification of manmade CO₂ emitted by fossil fuel burning, as opposed to natural CO₂ emitted from plants or bacteria. Because gas, coal and oil are millions of years old, their carbon lacks a type of radioactive carbon, an isotope called carbon-14 or ¹⁴C, which decays over time. Natural CO₂ from plants or bacteria contains ¹⁴C that is produced naturally in the atmosphere by cosmogenic radiation, and ¹⁴C that was produced</p>		

in the atmosphere by the nuclear weapons tests in the 1950s and 60s. The ratio $^{14}\text{C}/\text{C}$ in fossil fuels is zero whereas the ratio $^{14}\text{C}/\text{C}$ in live plants or bacteria is 10^{-12} . By measuring the ratio of carbon isotopes in CO_2 , the amount of carbon that has been added from fossil fuel combustion can be calculated.

Measurements at nine monitoring stations around California were conducted over three months in 2014-15. The measurements were combined with a California-specific atmospheric circulation model, which tracks how air moves around the state, to estimate emissions. These estimates were compared with emissions reported by the California Air Resources Board, which are based on accounting of fuel use. The reported and actual emissions matched within the uncertainties, providing an independent validation of California's reported emissions. The main findings are presented in an article in *Environmental Research Letters* [1]. A previous article set out the method and tested it with simulated data from one atmospheric model [2], and a subsequent article [3] specifically addressed the uncertainties arising from atmospheric modelling by comparing results from three state-of-the-art atmospheric models, finding that atmospheric model uncertainty did not significantly increase the uncertainty in the estimated state-wide emissions, as compared to the result in [1]. A follow-up study with many of the same authors used a smaller network of sites in California that were observed over a longer period, also finding that reported emissions were consistent with atmospheric observations [4]. Dr Graven's research [1] subsequently underpinned and was cited a paper by Basu et al [5] which applied similar methodology to an observation network spanning the continental US, finding that atmospheric observations again validate reported emissions. Since that study had a nation-wide scope, its validation of reported emissions directly supports the US submission to the United Nations Framework Convention on Climate Change and the Paris Agreement.

The atmospheric monitoring technique demonstrated in Dr Graven's study can help to better understand greenhouse gas emissions from specific regions and how they are changing over time, providing critical verification of reported emissions. The study is being used as a model for the development of the European Copernicus Atmosphere Monitoring Service, US National Oceanic and Atmospheric Administration [5] and other systems.

3. References to the research (indicative maximum of six references)

Peer-reviewed Articles:

- [1] Graven, H, ML Fischer, T Lueker, S Jeong, TP Guilderson, RF Keeling, R Bambha, K Brophy, W Callahan, X Cui, C Frankenberg, KR Gurney, BW LaFranchi, SJ Lehman, H Michelsen, JB Miller, S Newman, W Paplawsky, NC Parazoo, C Sloop, SJ Walker, 2018. Assessing Fossil Fuel CO_2 Emissions in California Using Atmospheric Observations and Models, *Environmental Research Letters*, 13, 065007, doi:10.1088/1748-9326/aabd43.
- [2] Fischer, ML, N Parazoo, K Brophy, X Cui, S Jeong, J Liu, R Keeling, TE Taylor, K Gurney, T Oda, H Graven, 2017. Simulating Estimation of California Fossil Fuel and Biosphere Carbon Dioxide Exchanges Combining In-situ Tower and Satellite Column Observations, *Journal of Geophysical Research – Atmospheres*, doi:10.1002/2016JD025617.
- [3] Brophy, K, H Graven, AJ Manning, E White, T Arnold, ML Fischer, S Jeong, X Cui, and M Rigby, 2019. Characterizing Uncertainties in Atmospheric Inversions of Fossil Fuel CO_2 Emissions in California, *Atmospheric Chemistry and Physics*, 19, 2991-3006, doi:10.5194/acp-2018-473.
- [4] Cui, X, S Newman, X Xu, AE Andrews, J Miller, S Lehman, Y-K Hsu, S Jeong, J Zhang, C Priest, M Campos-Pineda, KR Gurney, H Graven, J Southon, ML Fischer, 2019. Atmospheric Observation-based Estimation of Fossil Fuel CO_2 Emissions from Regions of Central and Southern California, *Science of the Total Environment*, 664, 381-391, doi:10.1016/j.scitotenv.2019.01.081.
- [5] Basu, S, SJ Lehman, JB Miller, AE Andrews, C Sweeney, KR Gurney, X Xu, J Southon, PP Tans, 2020, Estimating US fossil fuel CO_2 emissions from measurements of ^{14}C in atmospheric CO_2 , *Proceedings of the National Academy of Sciences*, 117 (24) 13300-13307, doi: 10.1073/pnas.1919032117.

Datasets:

Graven, H, ML Fischer, T Lueker, S Jeong, TP Guilderson, RF Keeling, R Bambha, K Brophy, W Callahan, X Cui, C Frankenberg, KR Gurney, BW Lafranchi, S Lehman, HA Michelsen, JB Miller, S Newman, W Paplawsky, NC Parazoo, C Sloop, and SJ Walker, 2018. CMS: Atmospheric CO₂ and C Isotopes, Fossil Fuel Contributions, California, 2014-2015. ORNL DAAC, Oak Ridge, Tennessee, USA, doi:10.3334/ORNLDAAC/1641.

Fischer, ML, NC Parazoo, K Brophy, X Cui, S Jeong, J Liu, R Keeling, TE Taylor, KR Gurney, T Oda and H Graven. 2017. CMS: CO₂ Signals Estimated for Fossil Fuel Emissions and Biosphere Flux, California. ORNL DAAC, Oak Ridge, Tennessee, USA. doi:10.3334/ORNLDAAC/1381

4. Details of the impact (indicative maximum 750 words)

The primary impact of the underpinning research is its validation of the reported emissions of CO₂ from fossil fuel burning in California, the accurate reporting of CO₂ emissions was critical to California's climate change mitigation policies including the "Global Warming Solutions Act (AB) 32". The significance of this impact is that by providing independent assessment of California's emissions, the research enables California's government and citizens to have confidence in its action to reduce climate change. Corroborating statements from beneficiaries at the California Air Resources Board, the United Nations Framework Convention on Climate Change (UNFCCC) and the European Centre for Medium-Range Weather forecasting provide evidence of the impact.

California is currently implementing ambitious reduction strategies to reduce Short Lived Climate Pollutants. Dr Graven's research directly supports California's program by addressing a key challenge; the evaluation of fossil fuel CO₂ emissions and the separation of fossil and natural CO₂ by using radiocarbon measurements. Dr Graven's study has had an impact in California by helping to provide confidence in the CO₂ emissions reported in the greenhouse gas emissions inventory. The Chief of Research Planning, Administration, & Emission Mitigation for the California Air Resources Board writes

"With Assembly Bill (AB) 32 requiring a sharp reduction of greenhouse gas (GHG) emissions, California set the stage for its transition to a sustainable, low-carbon future. [...] The study led by Dr Heather Graven of the CO₂ emissions from fossil fuels in California (Graven et al. Environ. Res. Lett., 2018) investigates regional CO₂ emissions trends throughout the state, and thus provides an important validation of the CO₂ emissions in the California greenhouse gas inventory" [A].

The impact has a broader reach because the research is being used as a model for other emissions assessment systems, such as the one being developed by the European Copernicus Service. The Deputy Director of the Copernicus Atmosphere Monitoring Service says

"The study led by Dr Heather Graven of the CO₂ emissions from fossil fuels in California (Graven et al. Environ. Res. Lett., 2018) provides an important model for the development of our EU system. It is the only study to date that validates fossil fuel CO₂ emissions on the scale of a political state using a network of atmospheric observation sites. [...] Dr Graven is a member of the CHE External Expert Group and her work and expertise has been a very important contribution to our discussions on how to provide policy relevant monitoring of fossil fuel CO₂ emissions in Europe." [B]

Our research has been featured in the United Nations Framework Convention on Climate Change conference and it is influencing plans for evaluation of the international efforts to address climate change under the Paris Agreement [C]. The Lead Officer for Research and Systematic Observation for the UNFCCC, writes

"Dr Graven was invited to present her work at the research dialogue in 2016 on the validation of CO₂ emissions from fossil fuels in California (Graven et al., Environ. Res. Lett., 2018). Her work demonstrated an important new method that can be used to support national efforts for greenhouse gas emissions mitigation contributing to the Paris Agreement. It supports enhanced transparency of action, which is a key focus for the implementation of the Paris Agreement. The development of methods for Parties to be able to independently validate reported greenhouse gas

emissions using atmospheric measurements has an impact on international policy by enhancing confidence and trust between Parties.” [C, D]

Dr Graven formulated the idea for the project, wrote the proposal, gathered collaborators and led the project. Collaborators provided support on field campaigns (UCSD, LBNL, Caltech, Sandia, NOAA, CARB), measurements of samples (UCSD, LLNL) and atmospheric modelling and analysis (LBNL). Two publications were led by Imperial ([1, 3]) and two by LBNL ([2, 4]).

Direct beneficiaries are the citizens of California (39.5M) and the government of California, specifically the Air Resources Board which is the government agency leading the implementation of California’s “Global Warming Solutions Act” to mitigate greenhouse gas emissions. The independent validation by H. Graven’s team provides confidence in the methods used by the Air Resources Board to calculate California’s emissions and how accurately they can monitor the success of California’s climate change mitigation policies. Other political entities such as the European Commission and the United Nations Framework Convention on Climate Change benefit by the demonstration of the method for validating emissions. The European Commission is developing such a system through its Copernicus Services programme.

To disseminate the research to beneficiaries, Dr Graven and her research team were in direct contact with staff at the California Air Resources Board through 2013-18 and communicated the research to them via email and presentations. Dr Graven gave an invited presentation to United Nations Framework Convention on Climate Change Research Dialogue in 2016. Dr Graven gave an invited presentation to the EU project “CO₂ Human Emissions”, a new initiative to develop a European system to monitor human activity-related CO₂ emissions across the world, in 2018. Conference presentations to scientists and governmental officials occurred in 2016 and 2017, at the Global Climate Observing System conference and the American Geophysical Union conferences. To communicate with citizens, a press release was put out in 2018 upon publication of [1] and the research was included in news stories from 11 different news outlets including BBC News. The article has an Altmetric score of 106, in the top 5% of all research outputs [E, F, G, H].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Letter from Chief of Research Planning, Administration, & Emission Mitigation, California Air Resources Board.

[B] Letter from Deputy Head of the Copernicus Atmosphere Monitoring Service, European Centre for Medium-Range Weather Forecasting

[C] Meeting Report for UNFCCC Research Dialogue in May 2016

https://unfccc.int/sites/default/files/researchdialogue_2016_2_summaryreport.pdf (Archived [here](#))

[D] Letter from Lead Officer for Research and Systematic Observation, United Nations Framework Convention on Climate Change Secretariat

[E] Press release for publication in *Environmental Research Letters*

https://www.eurekalert.org/pub_releases/2018-04/icl-aff041218.php (Archived [here](#))

[F] Study featured in news articles in BBC News and elsewhere

<http://www.bbc.com/future/story/20180808-the-scientists-who-track-down-ozone-pollutants-like-cfcs> (Archived [here](#))

[G] <https://eandt.theiet.org/content/articles/2018/04/fossil-fuel-emissions-measured-in-california-s-atmosphere/> (Archive [here](#))

[H] ERL article metric for news outlets <https://iop.altmetric.com/details/36787486/news> (Archived [here](#))