CSQ-1 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What anthropogenic and natural processes are driving the global carbon cycle?	A) Quantify CO_2 and CH_4 emissions from both anthropogenic and natural sources and CO_2 removals from natural sinks on spatial scales from individual facilities or field plots to regional and global scales on seasonal time scales.	• Column-averaged atmospheric CO_2 and CH_4 dry air mole fractions (XCO_2, XCH_4) and their gradients.	• High-spectral-resolution imaging spectroscopy of CO_2, CH_4 and O_2 bands at 1-10 km spatial resolution with 0.1 to 0.5% accuracies.	• Atmospheric CO_2 and CH_4 retrieval algorithms • Atmospheric flux inverse models	Integrated constraint on net emissions and removals of CO_2 and CH_4 for climate change (CC) mitigation and adaptation policy Climate finance. Monitor the efficacy of decarbonization policies and CO_2 removal strategies
	B) Distinguish intense anthropogenic CO_2 and CH_4 point source emissions associated with fossil fuel extraction, transport and use and land use change from wildfires and weak, spatially-extensive sources (wetlands, permafrost melting, agriculture).	• High spatial and temporal resolution measurements to detect CO_2 and CH_4 emission plumes • Observations of co-emitted species (NO_2, CO) to discriminate combustion sources • Fire radiative power	• High-spectral-resolution imaging spectroscopy of NO_2 and CO at 1-10 km spatial resolution • High-spatial resolution (< 30m) multi-spectral and hyperspectral imaging	• Atmospheric GHG retrieval algorithms • Atmospheric assimilation systems • Discrete plume models	
	C) Quantify emissions and removals (fluxes) of CO_2 by the land biosphere on sub-seasonal time scales with the accuracy needed to quantify and distinguish long-term (decadal) changes from climate perturbations and disturbances (e.g., drought, floods, wildfire) and human activities (e.g., deforestation, intense agriculture).	• XCO_2 and XCH_4 and their gradients at 0.1 to 10 km resolution • Solar induced chlorophyll fluorescence (SIF) • Land use and land use change (LULUC)	• High-spectral-resolution imaging spectroscopy of CO_2 and Sif at 1-10 km spatial resolution • high spatial resolution NDVI, NIRv, Fire radiative power	• SIF retrievals • Empirical light Use Efficiency and Machine learning models	

CSQ-1 Narrative

Since the beginning of the industrial age, anthropogenic CO_2 emissions from fossil fuel combustion, land use change and other activities have increased and are now adding more than 40 billion tonnes of CO_2 to the atmosphere each year. These emissions have increased the atmospheric CO_2 concentration by about 50% from values near 277 parts per million by volume (ppm) prior to 1750 to values near 420 ppm in 2023 (see https://gml.noaa.gov/ccgg/trends/). Over this same period, methane (CH_4) emissions from fossil fuel extraction, transport and use, changes in agriculture and wetlands and waste management practices have increased the atmospheric CH_4 concentrations by more than 160%, from values near 0.72 ppm to more than 1.90 ppm. These large changes in the atmospheric carbon reservoir affect the Earth's energy balance because CO_2 and CH_4 are efficient atmosphere greenhouse gases (GHGs). Anthropogenic CO_2 and CH_4, alone, contribute more than 90% of the present-day 1.1 °C global warming (IPCC 2021).

Anthropogenic emissions of CO_2 and CH_4 would have produced much larger changes in the atmospheric composition and climate if these carbon-bearing gases were not regulated by natural processes. For example, on multi-year time scales, natural sinks in the land biosphere and ocean remove over half of the CO_2 emitted into the atmosphere by anthropogenic activities, consistently maintaining the airborne fraction near 0.45 over the past 60 years (e.g., Ballantyne et al., 2012; Bennedsen et al., 2019; Friedlingstein et al. 2021). For CH_4, the primary sink is oxidation by the hydroxyl radical (OH^-), which limits its atmospheric lifetime to about a decade (Saunois et al., 2020).

While anthropogenic CO_2 emissions from fossil fuel combustion are well constrained in well-designed bottom-up inventories, those from land-use change and management and natural sources and sinks of CO_2 and CH_4 are not well understood. In addition, there is growing evidence that natural carbon sources and sinks are beginning to evolve in response to continuing anthropogenic forcing and climate change. For example, while the efficiency of the ocean sink has increased in proportion to the atmospheric CO_2 abundance, the response of the land biospheric carbon sink has been more complicated, becoming less efficient in the tropics and somewhat more efficient across the northern extratropics (Crisp et al., 2021). Modelling studies suggest that the overall efficiency of the land sink will decrease with increasing emissions (IPCC 2021).

Recent changes in the atmospheric CH_4 reservoir are even less well understood. CH_4 has a diverse range of natural sources, led by emissions from wetlands (~33%), inland waters, termites and wildfire (~7%). Its primary anthropogenic sources are agriculture (~25%), fossil fuel extraction, transport and use (~18%), waste management (~12%) and biomass burning (Saunois et al., 2020; IEA, 2020). While atmospheric oxidation is the primary CH_4 sink, soils are responsible for removing ~6% of the atmospheric CH_4 each year. The global atmospheric CH_4 growth rate was 8-12 parts per billion per year (ppb/yr) between 1983 and 1991, but then fell to -5 to 5 ppb/yr from 1992 to 2014, and then began rising rapidly to > 15 ppb/yr by 2020 and continues to grow. The causes for these changes are not well understood, but there is growing isotopic evidence that the recent increased growth rate is driven primarily by increased emissions from biogenic sources (wetlands, agriculture and waste) rather than fossil fuel sources (e.g., Nisbet et al., 2019).

At global scales, the ocean, land, and atmospheric carbon reservoirs are expected to continue changing in response to continuing human activity (deforestation, forest degradation, intense agriculture), disturbance (drought, flooding, wildfire, infestation, tree mortality) and GHG-induced warming. Sustained and expanded global, space-based remote sensing observations are becoming more essential for monitoring these changes.

Observations needed to constrain anthropogenic emissions of CO_2 and CH_4

Our understanding of the carbon cycle and its response to natural and anthropogenic forcing has grown steadily over the past two decades as more advanced carbon cycle measurements have been made from land, ocean, airborne and satellite sensors. These data have been analyzed by carbon cycle models to constrain net CO_2 and CH_4 emissions and removals on global scales over decadal time scales. However, these measurements and models are not yet adequate to fully constrain the relative roles of land and ocean carbon sinks or to provide the time-critical, policy relevant information needed to implement and assess the effectiveness of emissions reduction policies at national scales.

To meet these emerging needs, both the observations and models of CO_2 and CH_4 require much greater precision, accuracy, and spatial and temporal resolution and coverage. High precision and accuracy are needed to detect and quantify CO_2 and CH_4 sources and sinks because the background concentrations of these gases are large enough that even the most intense anthropogenic and natural sources and sinks produce changes larger than a fraction of 1% on scales ranging from large urban areas to nations. Improved resolution and coverage are needed because both CO_2 and CH_4 have a diverse range of sources and CO_2 has a wide range of natural sinks that span a wide range of spatial and temporal scales.

While measurements of CO_2, CH_4, and other GHGs from ground-based, ship-borne and airborne in situ networks will continue to provide the most precise and accurate estimates of atmospheric concentrations and their growth rates on global scales, these networks are too sparse to identify and characterize CO_2 and CH_4 sources and sinks on scales ranging from large urban areas to nations. Recent advances in space-based remote sensing methods are providing new opportunities to augment the spatial and temporal resolution and coverage of the ground-based and airborne GHG networks. For example, Japan's Greenhouse Gases Observing Satellite (GOSAT) and GOSAT-2 and NASA's Orbiting Carbon Observatory-2 (OCO-2) and OCO3 are now returning over a hundred thousand estimates of the column average CO_2 dry air mole fraction (XCO_2) over the sunlit hemisphere of the globe each day with accuracies near 1 ppm (O'Dell et al., 2018; Kiel et_ al., 2019; Müller et al., 2021). Japan's GOSAT, GOSAT-2 and the Copernicus Sentinel 5 TROPOMI instrument are providing near global estimates of the column-averaged CH_4 dry air mole fractions (XCH_4) each day.

Ground-based, airborne, and space-based CO_2 and CH_4 estimates are being assimilated into models, along with estimates of atmospheric transport to derive estimates of CO_2 and CH_4 fluxes on spatial scales that range from individual facilities or field plots to large urban areas, to regional or national scales and to the globe. These modeling tools have evolved substantially over the past decade, and are now providing new insights into CO_2 and CH_4 emissions and CO_2 sinks on both local scales (e.g., individual power plants or pipeline leaks; e.g., Nasar et al., 2022; Cusworth et al., 2020) and regional-to-global scales (c.f., Chevallier, 2021; Peiro et al., 2021; Worden et al., 2022; Byrne et al. 2023). For example, Worden et al. (2022) find that their analysis of GOSAT data can quantify net CH_4 fluxes from up to 57 of largest countries. Similarly, Byrne et al. (2023) found that OCO-2 data could be analyzed to yield estimates of net carbon fluxes from the largest ~100 countries.

These top-down atmospheric CO_2 and CH_4 flux estimates complement the inventories of GHG emissions compiled by nations by providing an integrated constraint on the emissions and removals of CO_2 and CH_4 by all processes. They can also provide insights into processes omitted from national inventories, including transient fluxes of CO_2 and CH_4 associated with disturbances (e.g., severe weather, wildfire) and carbon flux changes on unmanaged lands that are associated with human activities or climate change. Because of this, these top-down atmospheric flux estimates are beginning to provide new insights into many aspects of the global carbon cycle.

While these space-based atmospheric CO_2 and CH_4 sensors provide much greater resolution and coverage than ground-based, ship-based and airborne sensors, they still do not yet have the spatial or temporal resolution needed to provide reliable estimates of net emissions from smaller countries or to discriminate anthropogenic from natural sources. They also do not yet have the precision or accuracy needed to quantify the weak, but spatially extensive CO_2 fluxes over the ocean. These shortcomings will be addressed to some extent over the next few years with the launch of new satellites, such as the Copernicus CO2M constellation. These sensors will extend the pioneering OCO, GOSAT and TROPOMI datasets with sub-monthly sampling of CO_2 and CH_4 over most of the globe at a spatial resolution of 2 km by 2 km. Simultaneous, co-bore-sighted observations of nitrogen dioxide (NO_2) will help to distinguish CO_2 plumes associated with high temperature combustion from land use sources or natural sources and sinks. These measurements will be augmented by data from public and private sector sensors such as GHGSat, PRISMA, Sentinel 2, EMIT, Carbon Mapper. These sensors provide much less coverage, but much higher spatial resolution to identify the locations of intense plumes of CO_2 and CH_4. These data should improve our ability to distinguish natural from anthropogenic emissions and to identify the specific sectors (i.e., energy, industry, agriculture, forestry) responsible for anthropogenic emissions. There are currently no plans for deploying space-based sensors with the precision and accuracy needed to measure ocean CO_2 fluxes.

These new sensors will offer new opportunities for monitoring natural and anthropogenic sources and sinks, but also pose several challenges. For example, they will gather orders of magnitude more measurements than existing space-based sensors and these data will have a wide range of precisions, accuracies, resolutions and coverage. Their measurements will have to be cross-calibrated against recognized standards before they can be combined to enhance coverage or provide data continuity. Remote sensing retrieval algorithms with much greater computational speed and accuracy are needed to analyze these large space-based datasets. Expanded ground-based and airborne validation systems, such as the Total Carbon Column Observing Network (TCCON; Wunch et al., 2017), COllaborative Carbon Column Observing Network (COCCON; Frey et al. 2019) and AirCore (Karion et al., 2010) will then be needed to identify and correct biases and relate these space-based data to the World Meteorological Organization (WMO) *in situ* atmospheric standards so that these data can be combined in flux inversion studies. Once these data are validated, atmospheric inverse models with much greater resolution and accuracy will be needed to retrieve reliable estimates of CO_2 and CH_4 fluxes on scales spanning large urban areas to nations or continents. Models that combine CO_2 and CH_4 flux estimates with other measurements or models of the land biosphere are needed to better diagnose or predict changes in land carbon stocks associated with human activities or climate change.

References

Ballantyne, A. P., Alden, C. B., Miller, J. B., Tans, P. P. and White, J. W. C. (2012). Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature*, **488**, 70–72. doi:10.1038/nature11299

Bennedsen, M., Hildebrand, E. and Koopman, S. (2019). Trend analysis of the airborne fraction and sink rate of anthropogenically released CO_2. *Biogeosciences*, **16**, 3651–3663. doi:10.5194/bg-16-3651-2019

Berninger, A., Lohberger, S., Stängel, and Siegert, F., (2018). SAR-Based Estimation of Above-Ground Biomass and Its Changes in Tropical Forests of Kalimantan Using L- and C-Band. *Remote Sensing*, **10**, 831. doi: 10.3390/rs10060831

Byrne, B., Baker, D. F., Basu, S., Bertolacci, M., Bowman, K. W., Carroll, D., Chatterjee, A., Chevallier, F., Ciais, P., Cressie, N., Crisp, D., Crowell, S., Deng, F., Deng, Z., Deutscher, N. M., Dubey, M. K., Feng, S., García, O. E., Griffith, D. W. T., Herkommer, B., Hu, L., Jacobson, A. R., Janardanan, R., Jeong, S., Johnson, M. S., Jones, D. B. A., Kivi, R., Liu, J., Liu, Z., Maksyutov, S., Miller, J. B., Miller, S. M., Morino, I., Notholt, J., Oda, T., O'Dell, C. W., Oh, Y.-S., Ohyama, H., Patra, P. K., Peiro, H., Petri, C., Philip, S., Pollard, D. F., Poulter, B., Remaud, M., Schuh, A., Sha, M. K., Shiomi, K., Strong, K., Sweeney, C., Té, Y., Tian, H., Velazco, V. A., Vrekoussis, M., Warneke, T., Worden, J. R., Wunch, D., Yao, Y., Yun, J., Zammit-Mangion, A., and Zeng, N. (2023). National CO2 budgets (2015–2020) inferred from atmospheric CO_2 observations in support of the global stocktake, *Earth Syst. Sci. Data*, **15**, 963–1004, doi: 10.5194/essd-15-963-2023

Chevallier, F. (2021). Fluxes of carbon dioxide from managed ecosystems estimated by national inventories compared to atmospheric inverse modeling. *Geophysical Research Letters*, e2021GL093565. doi: 10.1029/2021GL093565

Crisp, D., Dolman, H., Tanhua, T., McKinley, G. A., Hauck, J., Bastos, A., Sitch, S., Eggleston, S., and Aich, V. (2022). How well do we understand the land-ocean-atmosphere carbon cycle? *Reviews of Geophysics*, **60**, e2021RG000736. doi: 10.1029/2021RG000736

Duncanson, L., Kelllner, J. R., Armston, J., et al. (2022). Aboveground biomass density models for NASA's Global Ecosystem Dynamics Investigation (GEDI) lidar mission. *Remote Sensing of Environment*, **270**, 112845. doi: 10.1016/j.rse.2021.112845

Fawcett, D., Sitch, S., Ciais, P., Wigneron, J.-P., Silva-Junior, C. H. L., Heinrich, V., Vancutsem, C., Achard, F., Bastos, A., Yang, H., Li, X., Albergel, C., Friedlingstein, P., and Aragão, L. E. O. C. (2022). Declining Amazon biomass due to deforestation and subsequent degradation losses exceeding gains. Global Change Biology, 29, 1106-1118. doi: 10.1111/gcb.16513

Frey, M., Sha, M. K., Hase, F., Kiel, M., Blumenstock, T., Harig, R., Surawicz, G., Deutscher, N. M., Shiomi, K., Franklin, J. E., Bösch, H., Chen, J., Grutter, M., Ohyama, H., Sun, Y., Butz, A., Mengistu Tsidu, G., Ene, D., Wunch, D., Cao, Z., Garcia, O., Ramonet, M., Vogel, F. and Orphal, J. (2019). Building the COllaborative Carbon Column Observing Network (COCCON): long-term stability and ensemble performance of the EM27/SUN Fourier transform spectrometer. *Atmospheric Measurement Techniques*, **12**, 1513–1530. doi: 10.5194/amt-12-1513-2019

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M.,Bakker, D. C. E., Hauck, J., Le Quéré, C., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Canadell, J. G., Ciais, P., Jackson, 100 R. B., Alin, S. R., Anthoni, P., Bates, N. R., Becker, M., Bellouin, N., Bopp, L., Chau, T. T. T., Chevallier, F., Chini, L. P., Cronin, M., Currie, K. I., Decharme, B., Djeutchouang, L. M., Dou, X., Evans, W., Feely, R. A., Feng, L., Gasser, T., Gilfillan, D., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, 105 Ö., Harris, I., Houghton, R. A., Hurtt, G. C., Iida, Y., Ilyina, T., Luijkx, I. T., Jain, A., Jones, S. D., Kato, E., Kennedy, D., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Körtzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lienert, S., Liu, J., Marland, G., McGuire, P. C., Melton, J. R., Munro, D. 110 R., Nabel, J. E. M. S., Nakaoka, S.-I., Niwa, Y., Ono, T., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rödenbeck, C., Rosan, T. M., Schwinger, J., Schwingshackl, C., Séférian, R., Sutton, A. J., Sweeney, C., Tanhua, T., Tans, P. P., Tian, H., Tilbrook, B., Tubiello, F., van der Werf, G. R., 115 Vuichard, N., Wada, C., Wanninkhof, R., Watson, A. J., Willis, D., Wiltshire, A. J., Yuan, W., Yue, C., Yue, X., Zaehle, S., and Zeng, J.: Global Carbon Budget 2021, *Earth Syst. Sci. Data*, **14**, 1917–2005, https://doi.org/10.5194/essd-14-1917-2022, 2022

IEA (2020), *Methane Tracker 2020*, IEA, Paris https://www.iea.org/reports/methane-tracker-2020, License: CC BY 4.0

IPCC 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896

Karion, A., Sweeney, C., Tans, P. P. and Newberger, T. (2010). AirCore: An innovative atmospheric sampling system. *Journal of Atmospheric and Oceanic Technology*, **27**, 1839–1853. doi:10.1175/2010JTECHA1448.1

Kiel, M., O'Dell, C. W., Fisher, B., Eldering, A., Nassar, R., MacDonald, C. G. and Wennberg, P. O. (2019). How bias correction goes wrong: measurement of XCO_2 affected by erroneous surface pressure estimates. Atmospheric Measurement Techniques, 12, 2241-2259. doi: 10.5194/amt-12-2241-2019

Labrière, N., Davies, S. J., Disney, M. I., Duncnason, L. I., Herold, M., Lewis, S. L., Phillips, O. L., Quegan, S., Saatchi, S., S., Schepaschenko, D. G., Scipal, K., Sist, P., and Chave, J. (2022). Toward a forest biomass reference measurement system for remote sensing applications. *Global Change Biology*, **2**

Liu, Y. Y., Van Dijk, A. I., De Jeu, R. A., Canadell, J. G., McCabe, M. F., Evans, J. P., and Wang, G. (2015). Recent reversal in loss of global terrestrial biomass, *Nature Climate Change*, **5**, 470–474. doi: 10.1038/nclimate2581

Müller, A., Tanimoto, H., Sugita, T., Machida, T., Nakaoka, S., Patra, P. K., Laughner, J., and Crisp, D. (2021). New approach to evaluate satellite-derived XCO_2 over oceans by integrating ship and aircraft observations, *Atmospheric Chemistry and Physics*, **21**, 8255–8271. doi: 10.5194/acp-21-8255-2021.

O'Dell, C. W., Eldering, A., Wennberg, P. O., Crisp, D., Gunson, M. R., Fisher, B., Frankenberg, C., Kiel, M., Lindqvist, H., Mandrake, L., Merrelli, A., Natraj, V., Nelson, R. R., Osterman, G. B., Payne, V. H., Taylor, T. E., Wunch, D., Drouin, B. J., Oyafuso, F., Chang, A., McDuffie, J., Smyth, M., Baker, D. F., Basu, S., Chevallier, F., Crowell, S. M. R., Feng, L., Palmer, P. I., Dubey, M., García, O. E., Griffith, D. W. T., Hase, F., Iraci, L. T., Kivi, R., Morino, I., Notholt, J., Ohyama, H., Petri, C., Roehl, C. M., Sha, M. K., Strong, K., Sussmann, R., Te, Y., Uchino, O. and Velazco, V. A. (2018). Improved retrievals of carbon dioxide from Orbiting Carbon Observatory-2 with the version 8 ACOS algorithm, *Atmospheric Measurement Techniques,* **11**: 6539–6576. doi:10.5194/amt-11-6539-2018

Peiro, H., Crowell, S., Schuh, A., Baker, D. F., O'Dell, C., Jacobson, A. R., Chevallier, F., Liu, J., Eldering, A., Crisp, D., Deng, F., Weir, B., Basu, S., Johnson, M. S., Philip, S., and Baker, I. (2022). Four years of global carbon cycle observed from the Orbiting Carbon Observatory 2 (OCO-2) version 9 and in situ data and comparison to OCO-2 version 7, *Atmos. Chem. Phys.*, **22**, 1097–1130, doi: 10.5194/acp-22-1097-2022

Powell, S. L., Cohen, W. B., Healey, S. P., Kennedy, R. E., Moisen, G. G., Pierce, K. B., Ohmann, J. L. (2010): Quantification of live aboveground forest biomass dynamics with Landsat time-series and field inventory data: a comparison of empirical modeling approaches. *Remote Sens. Environ*. **114**, 1053–1068. doi: 10.1016/j.rse.2009.12.018

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T. A., Salas, W., Zutta, B. R., Buermann, W., Lewis, S. L., Hagen, S., Petrova, S., White, L., Silman, M. and Morel, A. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences*, **108**, 9899-9904. doi: 10.1073/pnas.1019576108

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, 1 R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P. M., Covey, K., Curry, C. L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M. I., Hoglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., Jensen, K. M., Joos, F., Kleinen, T., Krummel, P. B., Langenfelds, R. L., Laruelle, G. G., Liu, L., Machida, T., Maksyutov, S., McDonald, K. C., McNorton, J., Miller, P. A., Melton, J. R., Morino, I., Muller, J., Murguia-Flores, F., Naik, V., Niwa, Y., Noce, S., O'Doherty, S., Parker, R. J., Peng, C., Peng, S., Peters, G. P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W. J., Rosentreter, J. A., Segers, A., Simpson, I. J., Shi, H., Smith, S. J., Steele, L. P., Thornton, B. F., Tian, H., Tohjima, Y., Tubiello, F. N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T. S., van Weele, M., van der Werf, G. R., Weiss, R. F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q., and Zhuang, Q.: The Global Methane Budget 2000–2017, *Earth Syst. Sci. Data*, **12**, 1561–1623, https://doi.org/10.5194/essd-12-1561-2020, 2020.

Urbazaev, M., Thiel, C., Cremer, F., Dubayah, R., Migliavacca, M., Reichstein, M., and Schmullius, C. (2018). Estimation of forest aboveground biomass and uncertainties by integration of field measurements, airborne LiDAR, and SAR and optical satellite data in Mexico. *Carbon Balance and Management*, **13**, 5. doi: 10.1186/s13021-018-0093-5

Worden, J. R., Cusworth, D. H., Qu, Z., Yin, Y., Zhang, Y., Bloom, A. A., Ma, S., Byrne, B., Scarpelli, T., Maasakkers, J. D., Crisp, D., Duren, R., and Jacob, D. J. (2022). The 2019 methane budget and uncertainties at 1° resolution and each country through Bayesian integration of GOSAT total column methane data and a priori inventory estimates. *Atmos. Chem. Phys.*, **22**, 6811-6841. doi: 10.5194/acp-22-6811-2022

Wunch, D., Wennberg, P. O., Osterman, G., Fisher, B., Naylor, B., Roehl, C. M., O'Dell, C., Mandrake, L., Viatte, C., Griffith, D. W., Deutscher, N. M., Velazco, V. A., Notholt, J., Warneke, T., Petri, C., De Maziere, M., Sha, M. K., Sussmann, R., Rettinger, M., Pollard, D., Robinson, J., Morino, I., Uchino, O., Hase, F., Blumenstock, T., Kiel, M., Feist, D. G., Arnold, S. G., Strong, K., Mendonca, J., Kivi, R., Heikkinen, P., Iraci, L., Podolske, J., Hillyard, P. W., Kawakami, S., Dubey, M. K., Parker, H. A., Sepulveda, E., Rodriguez, O. E. G., Te, Y., Jeseck, P., Gunson, M. R., Crisp, D. and Eldering, A. (2017). Comparisons of the Orbiting Carbon Observatory-2 (OCO-2) XCO_2 measurements with TCCON, *Atmospheric Measurement Tech*niques, **10**, 2209–2238. doi: 10.5194/amt-10-2209-2017