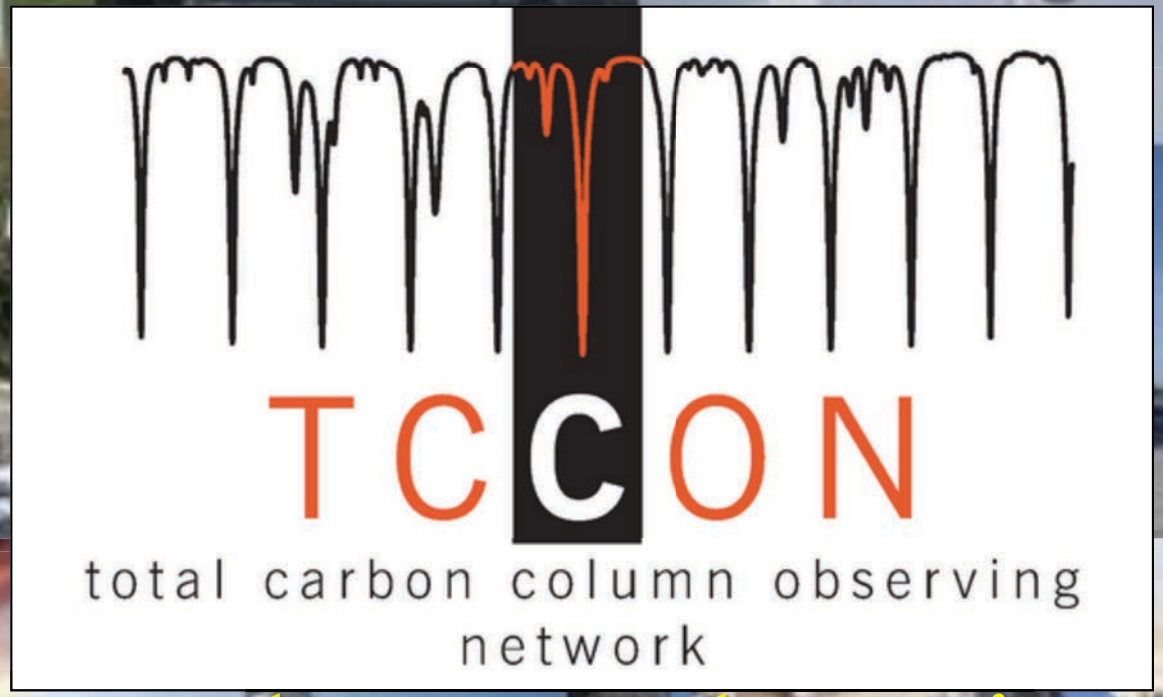
Validation of satellite-based GHG with TCCON (Total Carbon Column Observing Network)



Isamu Morino[1], Osamu Uchino[1], Hirofumi Ohyama[1], Kei shiomi[2], Paul Wennberg[3], Justus Notholt[4], Thorsten Warneke[4], Dietrich Feist[5, 6] , David Griffith[7], Nicholas Deutscher[7], Debra Wunch[8], and TCCON partners[9]

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[6] Max Planck Institute for Biogeochemistry, Jena, Germany;
[7] University of Wollongong, Wollongong, NSW Australia;
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[9] http://tccon-wiki.caltech.edu

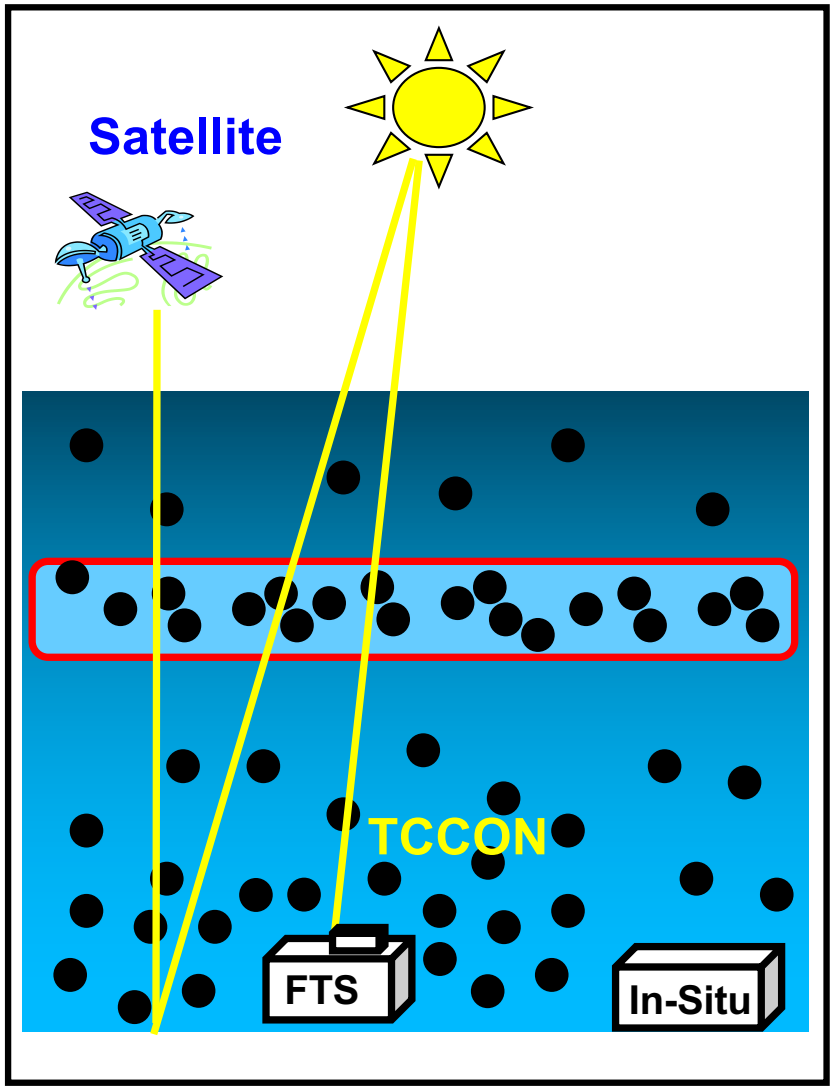
CEOS AC-VC
Tokyo 2019,
Jun 10, 2019

Outline

- TCCON (Total Carbon Column Observing Network)
  - Remote sensing of total column CO_2, CH_4, N_2O, CO …
  - TCCON data usages
  - TCCON spectra
  - Expansion of TCCON
  - TCCON data record
- TCCON sites operated by Japanese organizations
  - Rikubetsu, Tsukuba and Saga
  - Burgos
- Publications with TCCON
- Recent paper list related satellite validation with TCCON
- Summary
- TCCON challenges for satellite validation
- COCCON (COllaborative Carbon Column Observing Network)

TCCON (Total Carbon Column Observing Network): Remote sensing of total column CO_2, CH_4, N_2O, CO …

- Direct-sun solar absorption spectroscopy in the near IR using FTS
- Retrieve total column amounts
- Derive column average dry air mole fractions (e.g. X_{CO2})
  - Using column O_2 as internal standard
  - $X_{CO2} = CO_2/O_2 \times 0.2095$
- Precisions (2σ)
  - XCO_2: ~1 ppm (0.3%)
  - XCH_4: ~5 ppb (0.5%)
  - XCO: < 4 %
- Accuracies by comparison with integrated aircraft in situ profiles using WMO-calibrated instruments



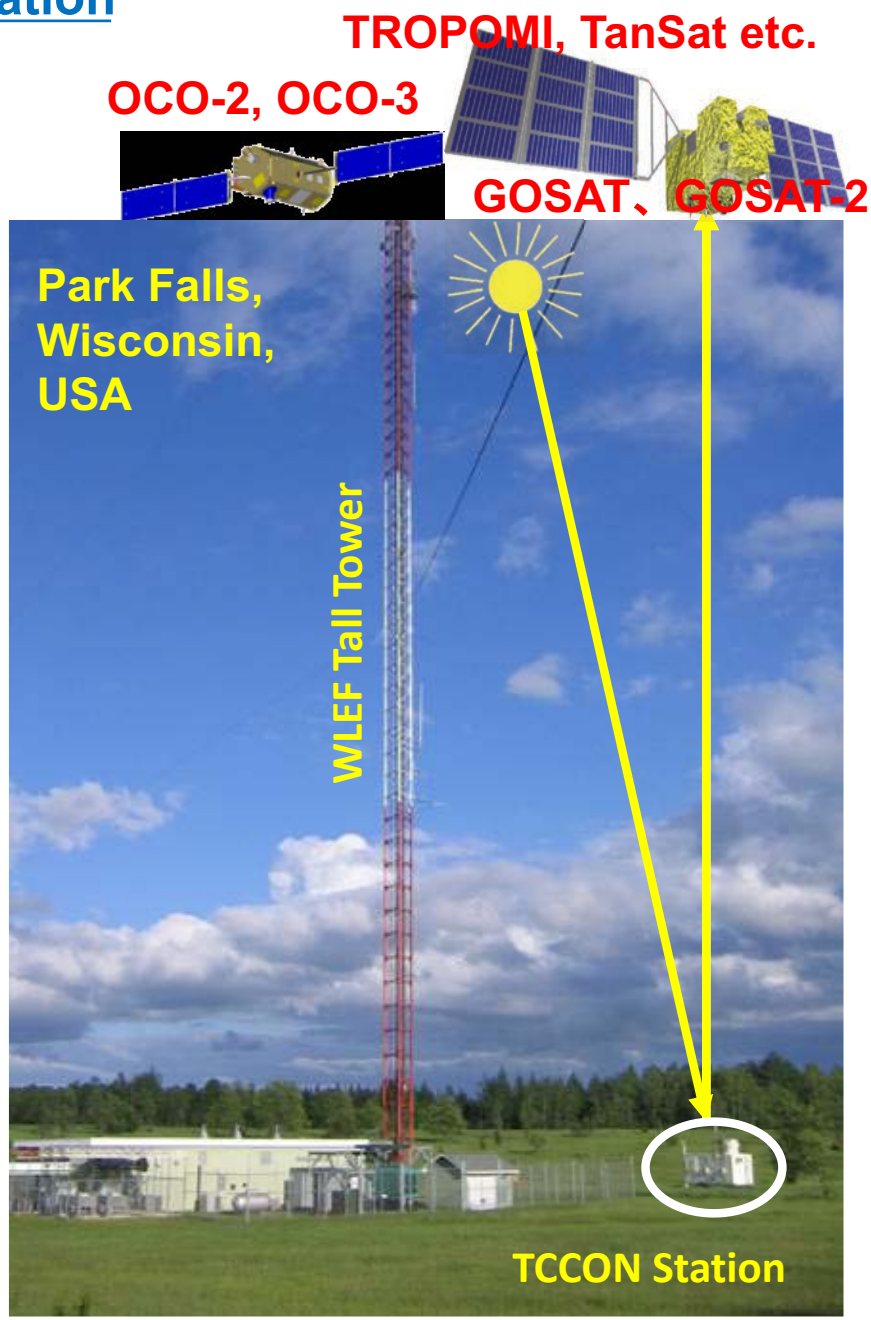
TCCON data usages

TCCON has formed a crucial part of the validation efforts of all past and current satellites!

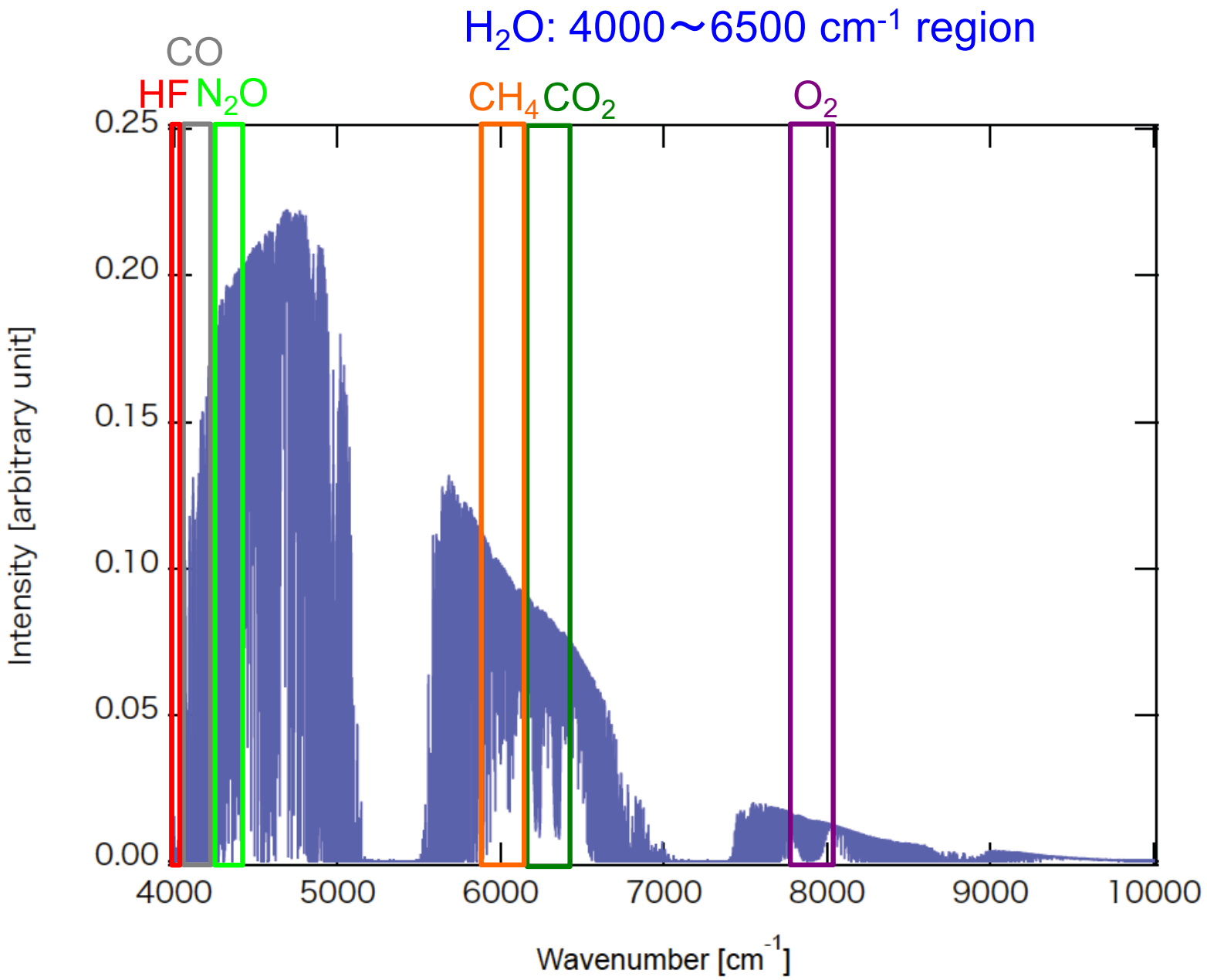
- Verification datasets and assimilation datasets in modelling study and improving our understanding of the carbon cycle

- **Providing the primary validation (ground-truth) dataset for satellite remote sensing instruments**
  - SCIAMACHY (ESA, stop operation in 2012)
  - GOSAT (JAXA-NIES-MOE, launched in 2009)
  - OCO-2 (NASA, launched in 2014)
  - GHGSat (Claire, launched in 2016)
  - TanSat (CAS-MOST-CMA, launched in 2016)
  - TROPOMI(ESA, 2017)
  - GOSAT-2 (JAXA-MOE-NIES, launched in Oct 2018)
  - OCO-3 (NASA, deployed in May 2019)
  - MicroCarb (CNES, to be launched in 2021)
  - GeoCARB(NASA, to be launched in 2022)
  - Merlin (DLR-CNES, to be launched in 2024)
  - GOSAT-3 (JAXA-MOE-NIES, considered, to be launched in 2023)

- Providing a transfer standard between the satellite measurements and the ground-based *in situ* network



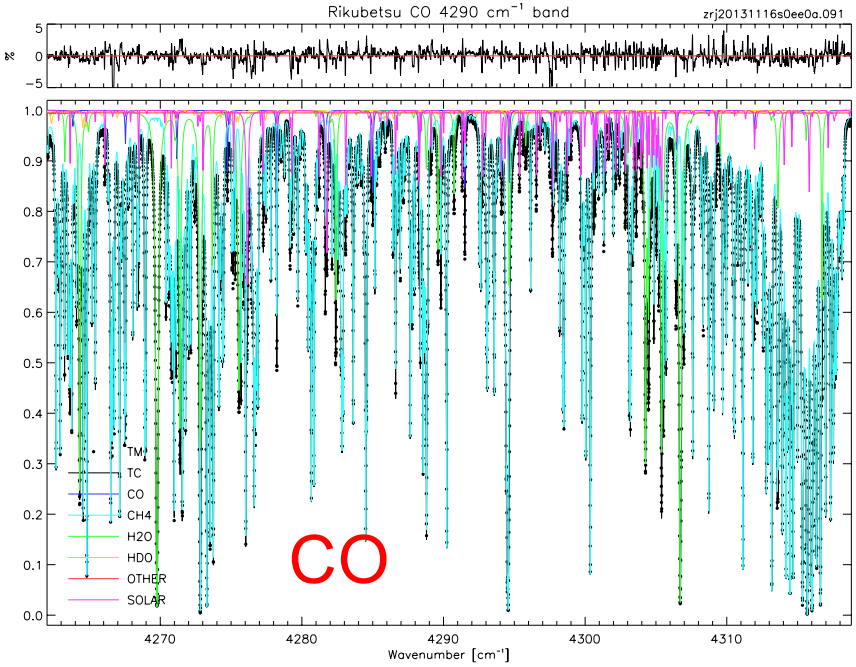
NIR absorption spectrum used in TCCON

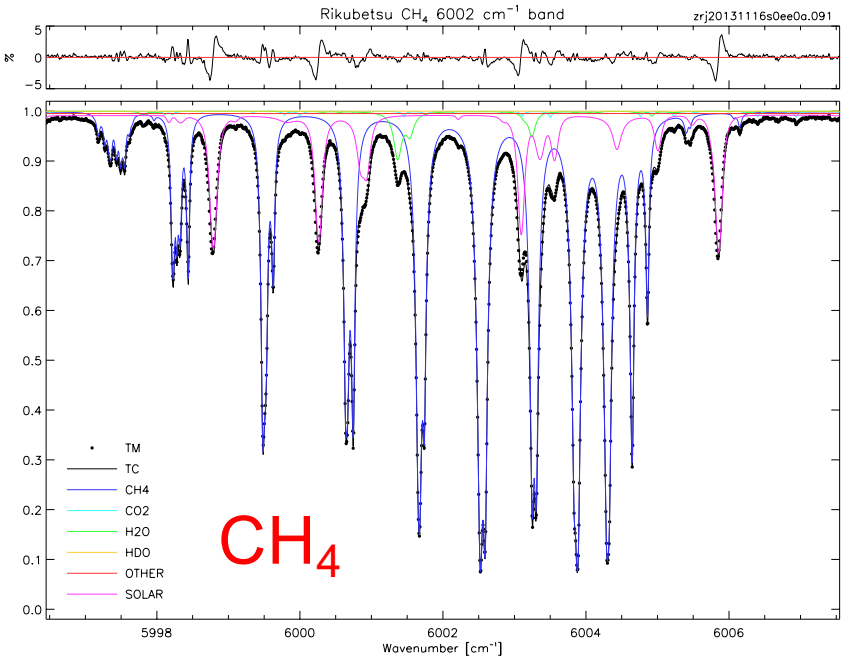


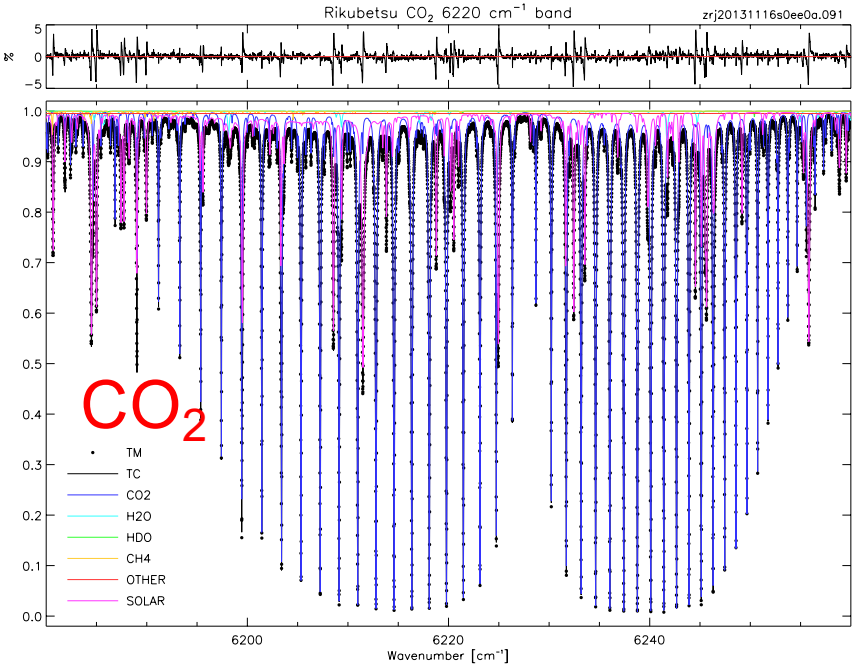
InGaAs det. Aug. 10, 2011, Tsukuba 125 HR

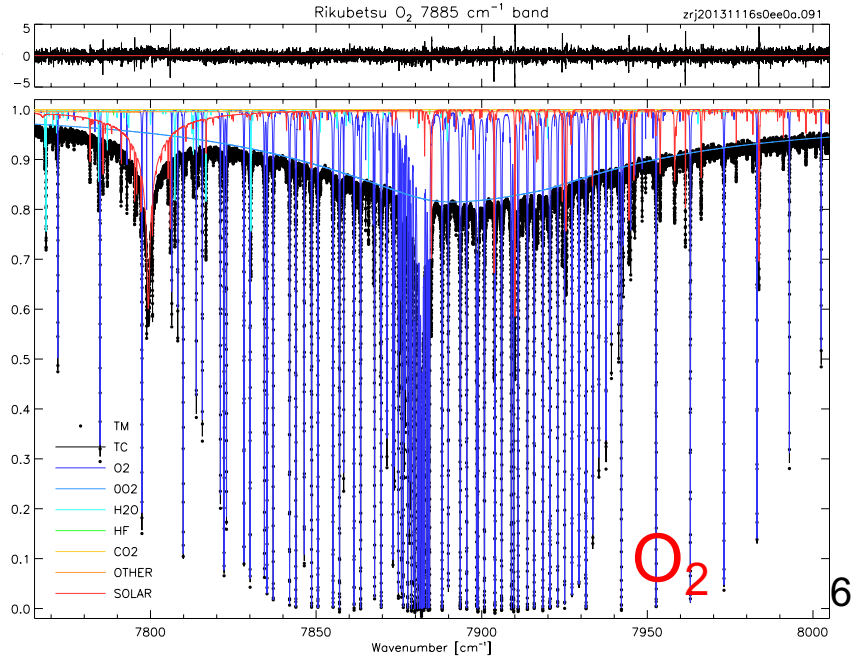
Spectra analyzed by GFIT profile scaling retrieval

Nov 16, 2013/11/16









Expansion of TCCON for validating space-based GHG data and reducing uncertainties in carbon cycle studies

- Established in 2004 and the measurements at Park Falls, Lauder, and Ny Alesund have started. More than 25 sites! Operating by individual sites.
- The lack (red ellipses) of reliable validation data for the satellite-based greenhouse gas observing missions is a common limitation in global carbon-cycle studies that.

Contribution by the GOSAT series project

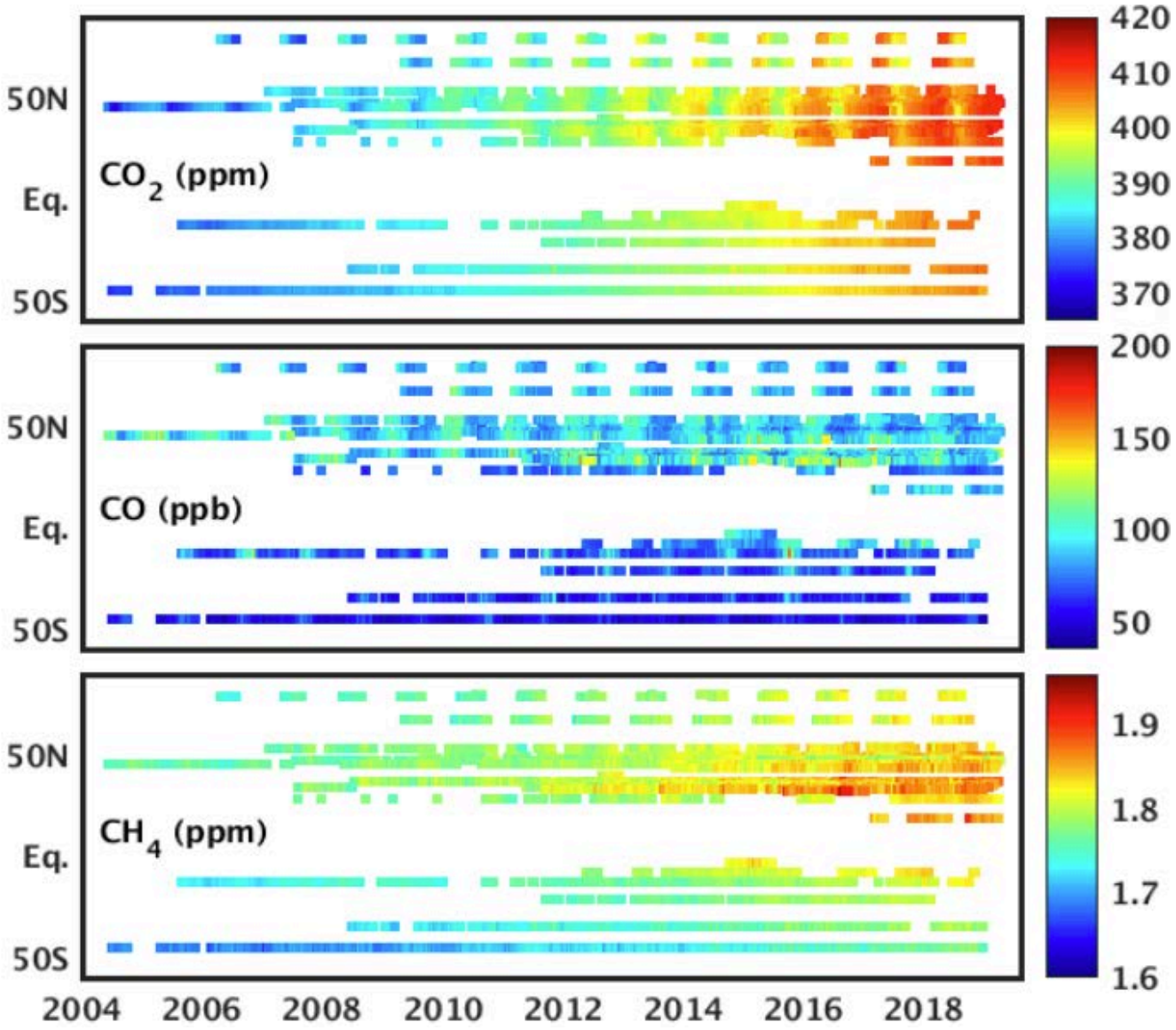
The TCCON data record

https://tccondata.org

Providing time-resolved, high quality, consistent retrievals around the globe.

A network of highly skilled FTS experts.

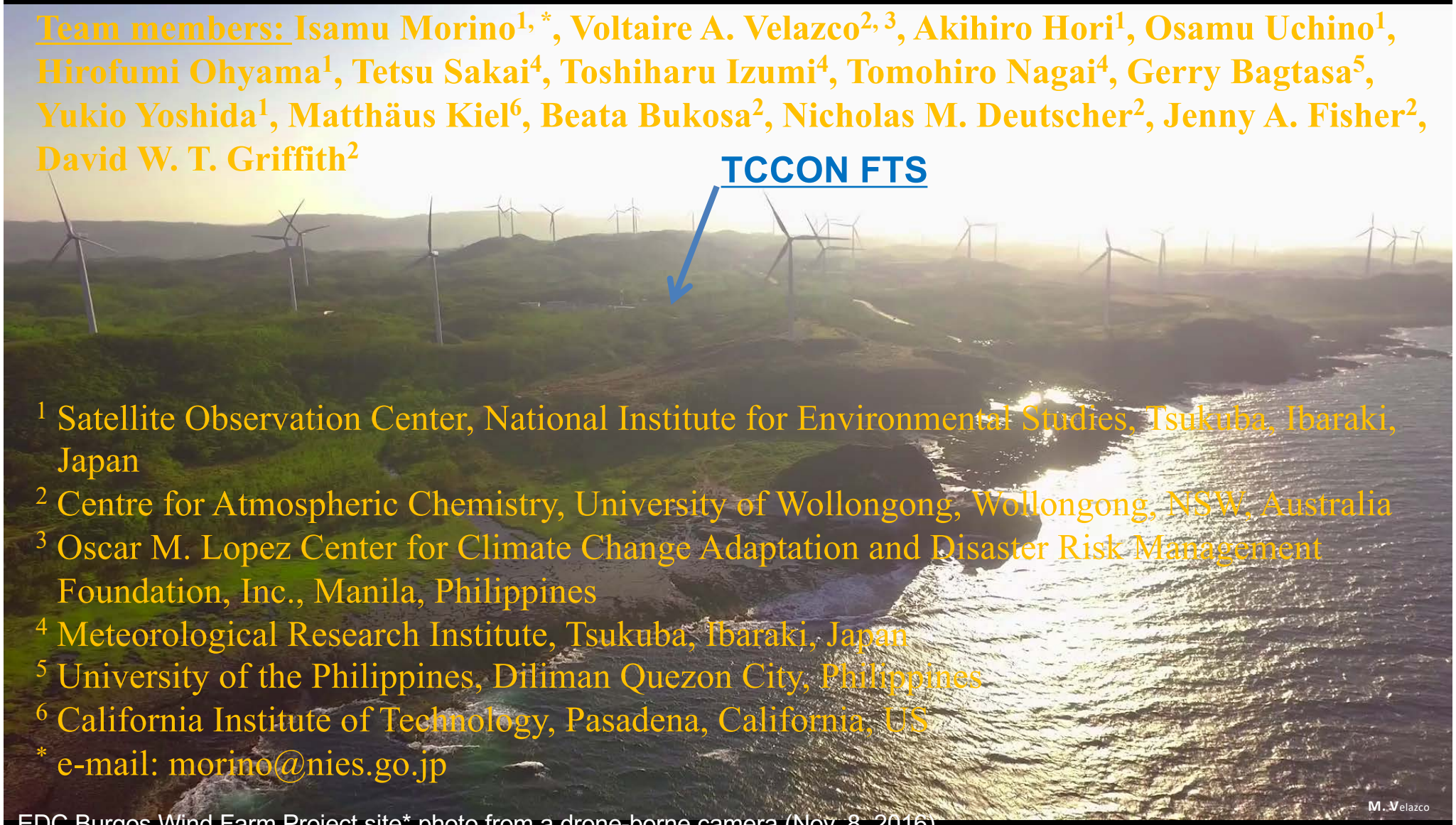
A network of scientists who are integrated into the communities we serve who can advise on the appropriate use and interpretation of our dataset.



TC[illegible] ed by Japanese organizations

Burgos Philippines as a new TCCON site in South-East Asia

Team members: Isamu Morino[1, *], Voltaire A. Velazco[2, 3], Akihiro Hori[1], Osamu Uchino[1], Hirofumi Ohyama[1], Tetsu Sakai[4], Toshiharu Izumi[4], Tomohiro Nagai[4], Gerry Bagtasa[5], Yukio Yoshida[1], Matthäus Kiel[6], Beata Bukosa[2], Nicholas M. Deutscher[2], Jenny A. Fisher[2], David W. T. Griffith[2]



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[5] University of the Philippines, Diliman Quezon City, Philippines
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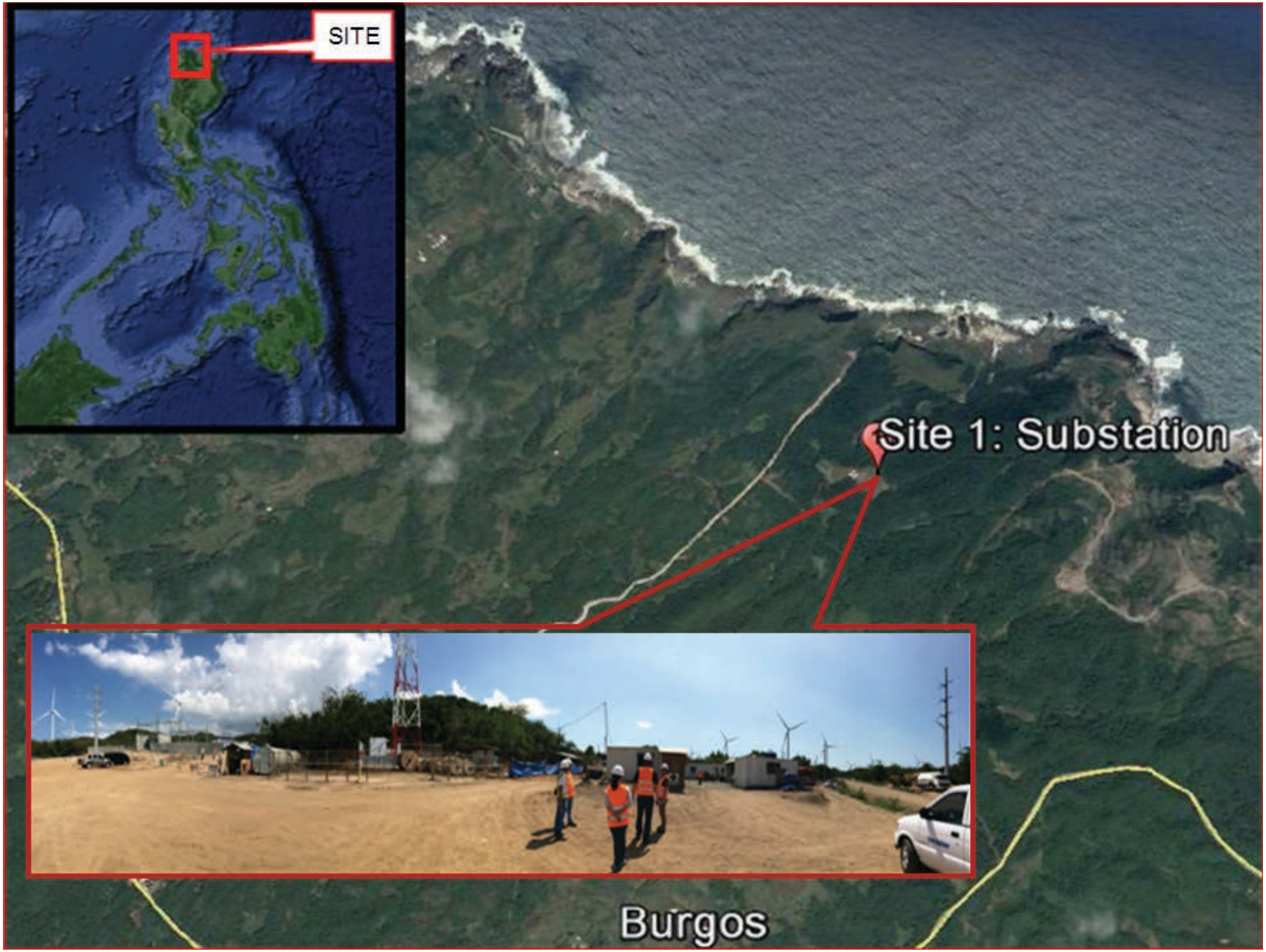
[*] e-mail: morino@nies.go.jp

EDC Burgos Wind Farm Project site* photo from a drone-borne camera (Nov. 8, 2016)
*Located in Ilocos Norte, Philippines, a "coal-free" province

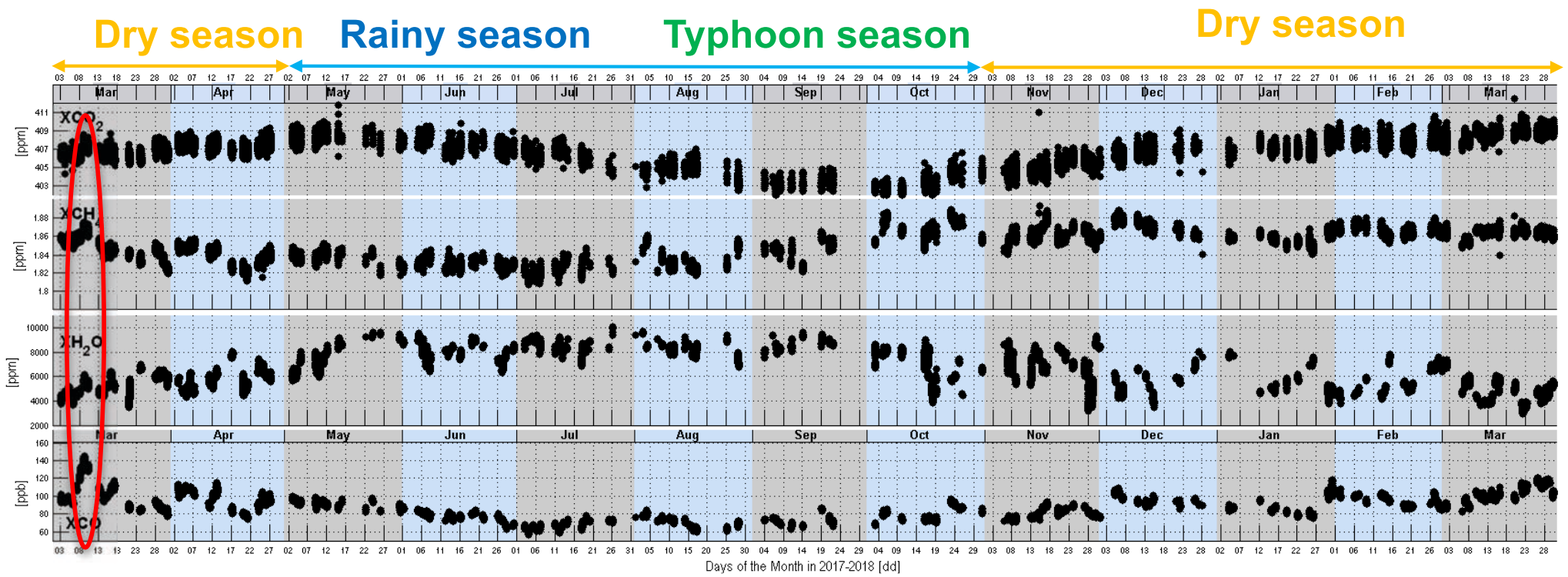
A new TCCON site within the EDC Burgos Wind Farm Project



The TCCON container was placed within the EDC (Energy Development Corporation) Burgos Wind Farm Project, specifically at the substation site where technical support is available in close proximity.


HALO into sunset over Burgos on March 12, 2018
TCCON container where Bruker FTS 125 HR FTS and Mie LiDAR are installed on right and left sides, respectively
Skyradiometer
LiDAR
FTS
An EM27/SUN portable FTS to compare the TCCON FTS and contribute the EMeRGe campaign in March 2018

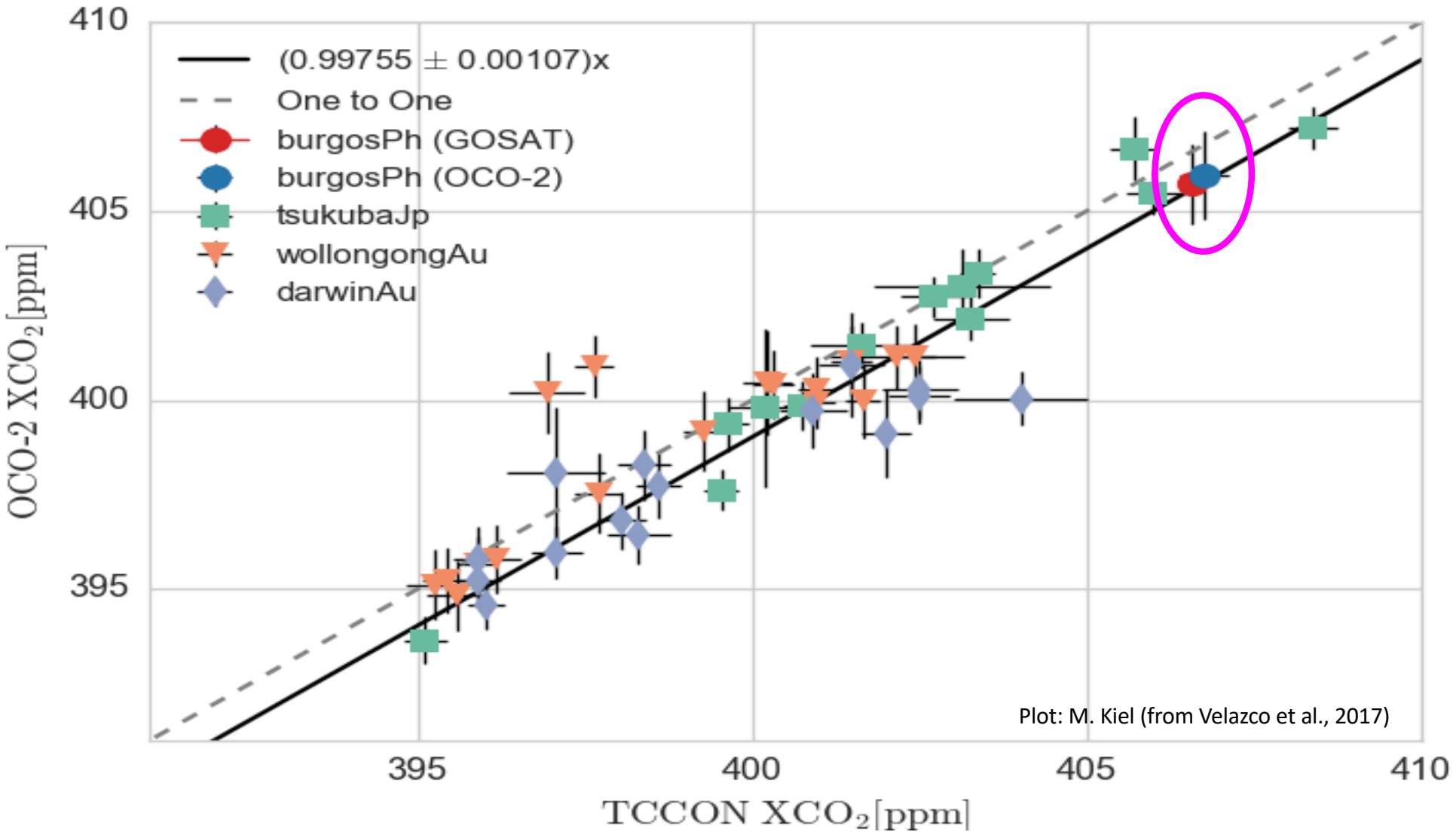
Retrieved column-averaged dry air mole fractions of CO_2, CH_4 , H_2O and CO.



Elevated XCO, XCH_4, and XCO_2, probably due to biomass burning were clearly detected!

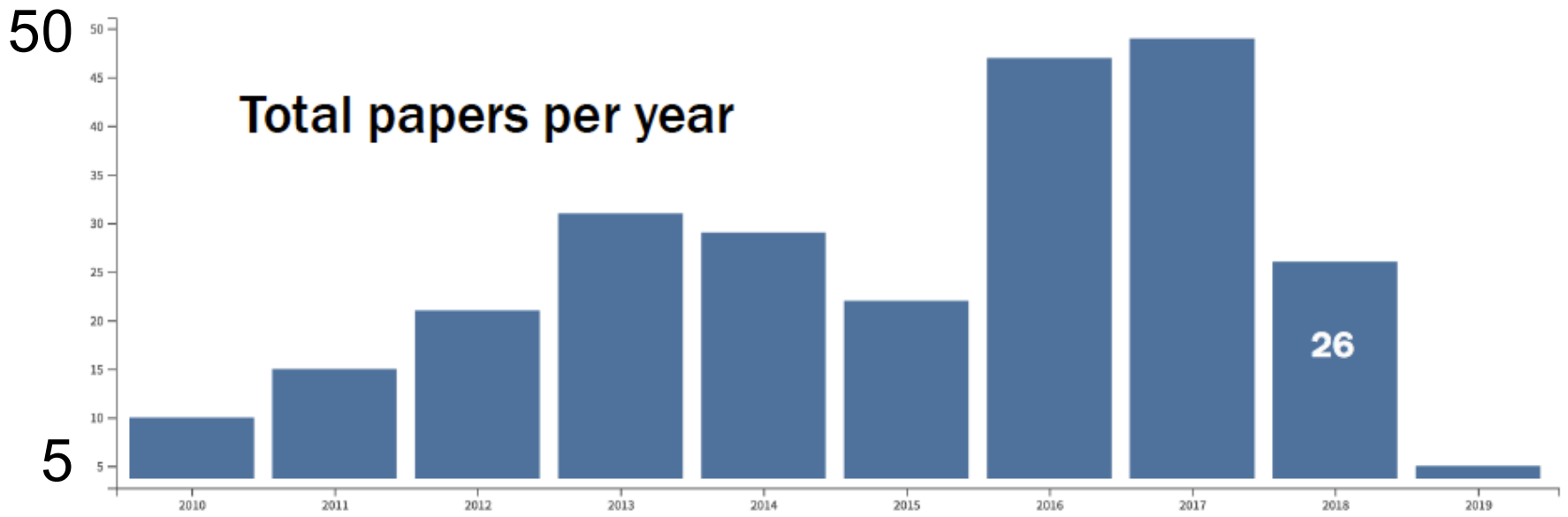
210 measurement days from Mar. 2017 to Mar 2018!!

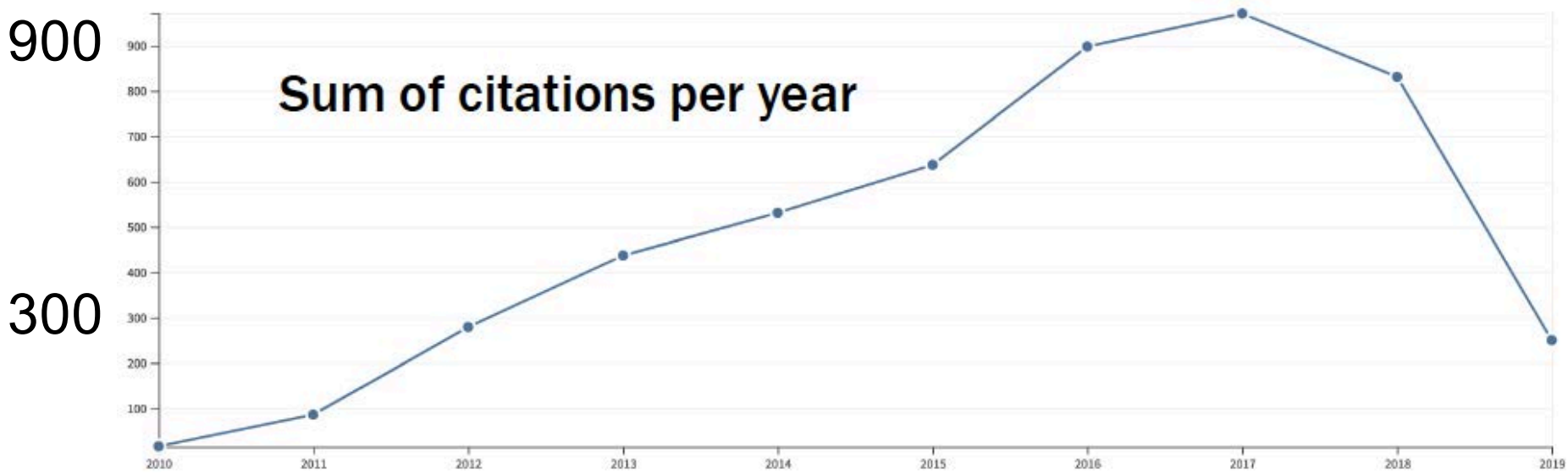
GOSAT & OCO-2 Satellite Data Comparisons



Target mode XCO_2 retrievals from the OCO-2 satellite vs. XCO_2 from TCCON stations. Only stations in Tsukuba, Wollongong, Darwin and Burgos are shown for clarity. The calibration line (solid black line) is derived from all TCCON sites. The most recent GOSAT sounding (red circle) is also added on this plot, but not included in the calculation of the calibration curve. It falls within 0.13 ppm of the OCO-2 calibration line. The two outliers in the OCO-2 measurements over Wollongong (downward triangles) are probably due to bias induced by stratospheric aerosols caused by the eruption of the Calbuco volcano on Apr. 22 2015. (http://www.mdpi.com/2072-4292/9/12/1228)

255 Publications with TCCON as of Apr 27, 2019





Recent paper list related satellite validation with TCCON

SCIAMACHY CO:

- P. Hochstaffl, F. Schreier, G. Lichtenberg and S. G. García, Validation of Carbon Monoxide Total Column Retrievals from SCIAMACHY Observations with NDACC/TCCON Ground-Based Measurements, Remote Sens. 2018, 10(2), 223; https://doi.org/10.3390/rs10020223
  - plus Addendum to add TCCON references!

OCO-2 CO_2:

- Wu, L., Hasekamp, O., Hu, H., Landgraf, J., Butz, A., aan de Brugh, J., Aben, I., Pollard, D. F., Griffith, D. W. T., Feist, D. G., Koshelev, D., Hase, F., Toon, G. C., Ohyama, H., Morino, I., Notholt, J., Shiomi, K., Iraci, L., Schneider, M., de Maziere, M., Sussmann, R., Kivi, R., Warneke, T., Goo, T. & Te, Y. (2018). Carbon dioxide retrieval from OCO-2 satellite observations using the RemoTeC algorithm and validation with TCCON measurements. Atmospheric Measurement Techniques, 11 (5), 3111-3130.
- Bi, Y., Wang, Q., Yang, Z. et al., Validation of Column-Averaged Dry-Air Mole Fraction of CO_2 Retrieved from OCO-2 Using Ground-Based FTS Measurements, J Meteorol Res (2018) 32: 433. https://doi.org/10.1007/s13351-018-7118-6
- 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.: Improved retrievals of carbon dioxide from Orbiting Carbon Observatory-2 with the version 8 ACOS algorithm, Atmos. Meas. Tech., 11, 6539-6576, https://doi.org/10.5194/amt-11-6539-2018, 2018.
- Kulawik et al., in prep

Recent paper list related satellite validation with TCCON

Copernicus CO_2 and CH_4:

- Buchwitz, M., Reuter, M., Schneising, O. et al., Copernicus Climate Change Service (C3S) Global Satellite Observations of Atmospheric Carbon Dioxide and Methane, Adv. Astronaut. Sci. Technol. (2018) 1: 57. https://doi.org/10.1007/s42423-018-0004-6

GOSAT CO_2, CH_4 and H_2O:

- A. Bril, S. Maksyutov, S. Oshchepkov, Y. Yoshida, R. Imasu, C. Iwasaki, A. Chaikovsky, A. Fedarenka, "Development of the empirical orthogonal functions-based algorithm for the retrievals of atmospheric CO_2 total column amount from space-borne observations of reflected sunlight," J. Appl. Rem. Sens. 12(4) 046012 (31 October 2018)
- Kenea, S.T., Oh, YS., Goo, TY. et al. Comparison of XCH_4 Derived from g-b FTS and GOSAT and Evaluation Using Aircraft In-Situ Observations over TCCON Site, Asia-Pacific J Atmos Sci (2019). https://doi.org/10.1007/s13143-019-00105-0
- Trieu, T.T.N.; Morino, I.; Ohyama, H.; Uchino, O.; Sussmann, R.; Warneke, T.; Petri, C.; Kivi, R.; Hase, F.; Pollard, D.F.; Deutscher, N.M.; Velazco, V.A.; Iraci, L.T.; Podolske, J.R.; Dubey, M.K. Evaluation of Bias Correction Methods for GOSAT SWIR XH_2O Using TCCON data. Remote Sens. 2019, 11, 290.
- K. Arai, T. Higuchi, H. Okumura, H. Ohyama, S. Kawakami and K. Shiomi, “Quality Flag of GOSAT/FTS Products Taking into Account Estimation Reliability” International Journal of Advanced Computer Science and Applications(ijacsa), 9(9), 2018. http://dx.doi.org/10.14569/IJACSA.2018.090909
- de Lange, A. and Landgraf, J.: Methane profiles from GOSAT thermal infrared spectra, Atmos. Meas. Tech., 11, 3815-3828, https://doi.org/10.5194/amt-11-3815-2018, 2018.

Recent paper list related satellite validation with TCCON

GOSAT CO_2, CH_4 and H_2O (continued):

- Kivimäki, E., H. Lindqvist, J. Hakkarainen, M. Laine, R. Sussmann, A. Tsuruta, R. Detmers, N. M. Deutscher, E. J. Dlugokencky, F. Hase, O. Hasekamp, R. Kivi, I. Morino, J. Notholt, D. F. Pollard, C. Roehl, M. Schneider, M. K. Sha, V. A. Velazco, T. Warneke, D. Wunch, Y. Yoshida, and J. Tamminen (2019), Evaluation and Analysis of the Seasonal Cycle and Variability of the Trend from GOSAT Methane Retrievals, Remote Sens., 11(882), 31, doi:10.3390/rs11070882.

TROPOMI CO and CH_4:

- Sha et al., in prep.
- Schneising et al., in prep.

MOPITT CO

- Hedelius, J. K., He, T.-L., Jones, D. B. A., Buchholz, R. R., De Mazière, M., Deutscher, N. M., Dubey, M. K., Feist, D. G., Griffith, D. W. T., Hase, F., Iraci, L. T., Jeseck, P., Kiel, M., Kivi, R., Liu, C., Morino, I., Notholt, J., Oh, Y.-S., Ohyama, H., Pollard, D. F., Rettinger, M., Roche, S., Roehl, C. M., Schneider, M., Shiomi, K., Strong, K., Sussmann, R., Sweeney, C., Té, Y., Uchino, O., Velazco, V. A., Wang, W., Warneke, T., Wennberg, P. O., Worden, H. M., and Wunch, D.: Evaluation of MOPITT version 7 joint TIR-NIR XCO retrievals with TCCON, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2019-201, in review, 2019.

Summary of TCCON

- TCCON data:

  compared to the WMO scale.

  Uncertainties: XCO_2<0.25 %, XCH_4<0.5%, XCO<4%, XN_2O <1%, and XH_2O<1.3%.

- Widely used in studies on atmospheric chemistry and carbon cycle

- Firmly established as an important validation resource for satellite-based products

- TCCON data is publicly available in the web **https://tccondata.org**

  We would like ask you to read the TCCON Data License when using!

https://tccondata.org

Total Carbon Column Observing Network (TCCON)

(https://tccon-wiki.caltech.edu)**TCCON** is a network of ground-based Fourier Transform Spectrometers recording direct solar spectra in the near infrared spectral region. From these spectra, accurate and precise column-averaged abundances of CO_2, CH_4, N_2O, HF, CO, H_2O, and HDO are retrieved and reported here. A technical report describing the retrievals is found here (https://doi.org/10.14291/tccon.ggg2014.documentation.R0/1221662); solar (https://doi.org/10.14291/tccon.ggg2014.solar.R0/1221658) and telluric (https://doi.org/10.14291/tccon.ggg2014.atm.R0/1221656) spectral linelists used in the retrievals are publically available.

Data in netCDF format are publicly available no later than one year after the spectra are recorded; many sites release their data earlier. Citation and data use requirements are included in the license associated with each record. Column averaging kernels and a priori profiles are included in the files. Information on how to use these can be found here (https://tccon-wiki.caltech.edu/Network_Policy/Data_Use_Policy/Auxiliary_Data). To produce TCCON a priori profiles for locations and times where there are no TCCON measurements, a stand-alone program can be downloaded (https://doi.org/10.14291/tccon.ggg2014.priors.R0/1221661).

✉ Sign up (http://lists.gps.caltech.edu/mailman/listinfo/tccon-users) to the TCCON Users email list to get email updates on TCCON data releases.

TCCON Column-Averaged Dry-Air Mole Fractions of CO_2, CO, N_2O, CH_4, H_2O, HDO, and HF

Download All GGG2014 Data (https://doi.org/10.14291/TCCON.GGG2014)

Site	Start Date	End Date
Ascension Island (SH) [ascension01]	2012-	2018-

TCCON challenges for satellite validation

- Satellites are now achieving sub-ppm precision in XCO_2
  - TCCON claims ~0.4 ppm precision (1σ): ILS, instrumentation, surface pressure, improved spectroscopy and a priori profiles etc.
- Site-to-site consistency is our biggest challenge
  - Airmass dependence is seen as a major problem in the satellite and modeling community
- Active missions (e.g. MERLIN) have vastly different averaging kernels to TCCON
- With TROPOMI, GOSAT-2, and near future missions, we will be relied upon for XCO and other products (XN_2O, XH_2O, XHDO) in addition to XCO_2 and XCH_4
  - These retrievals have not been under the same scrutiny as XCO_2
  - We have no tie to a trace-gas standard scale for HDO
  - Our 7% CO scaling remains an outstanding issue,
- Network continues to expand:
  - Missing areas: Africa, India, Siberia, South America
  - Expensive for setting up a new site (about 1 M US$) and operation (about 0.1 M US$)
  - Portable FTS network →**COCCON**

COCCON (COllaborative Carbon Column Observing Network)

EM27/SUN (pendulum FTS-Spectrometer, 0.2 M US$)

Resolution: 0.5 cm^{-1}, two InGaAs detectors

Dimension: 35 x 40 x 27 cm, weight: ~25 kg

data processing : PROFFAST* (PROFFIT, GFIT)

*designed for low resolution spectra

Checking of ILS and stability

Calibration

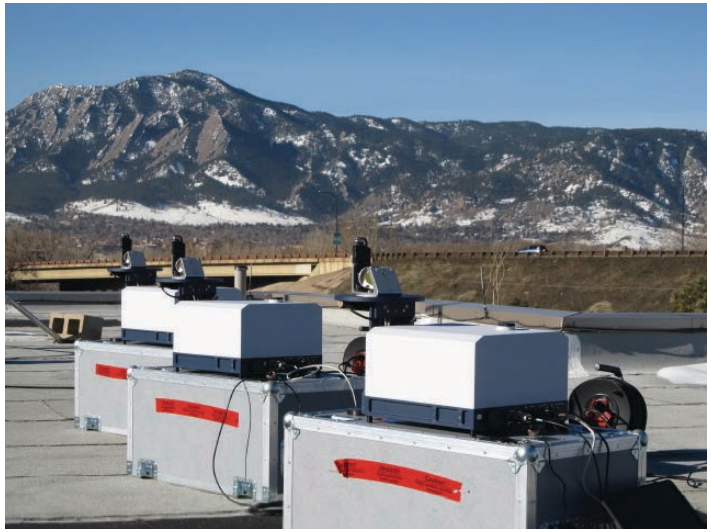
More than 30 devise operated worldwide

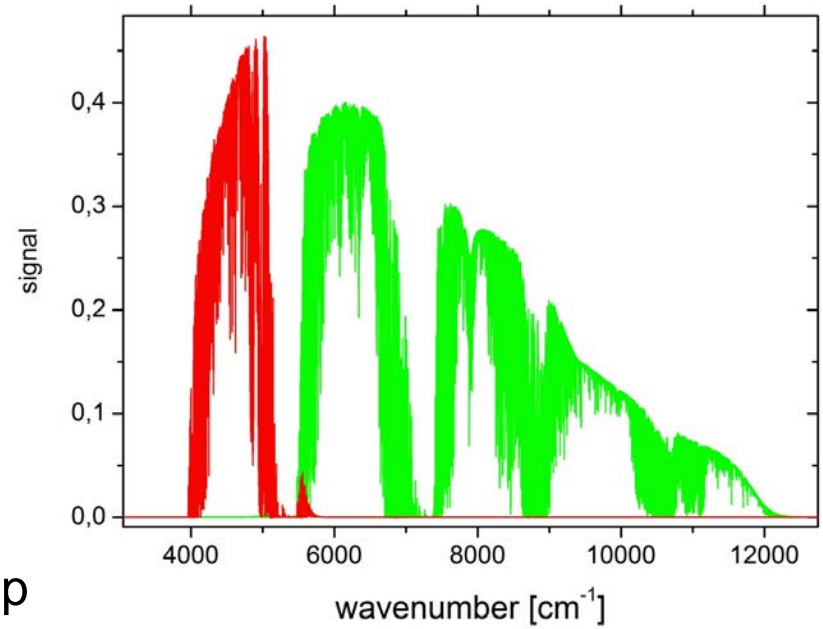
Measurement campaigns

Paris, Berlin, Boulder, Tokyo etc.

City emissions, dairy farm, coal mining etc.

Now networking started!





https://www.imk-asf.kit.edu/english/COCCON.php