Long-term observations of atmospheric trace gases: challenges, implementation and operation

Martin Steinbacher

Empa, Laboratory for Air Pollution / Environmental Technology &
WMO/GAW Quality Assurance / Science Activity Centre Switzerland

BMKG webinar, 12 November 2020

Empa
Materials Science and Technology

Long-term observations of atmospheric trace gases: challenges, implementation and operation

Martin Steinbacher

Empa, Laboratory for Air Pollution / Environmental Technology &
WMO/GAW Quality Assurance / Science Activity Centre Switzerland

BMKG webinar, 12 November 2020

Empa
Materials Science and Technology

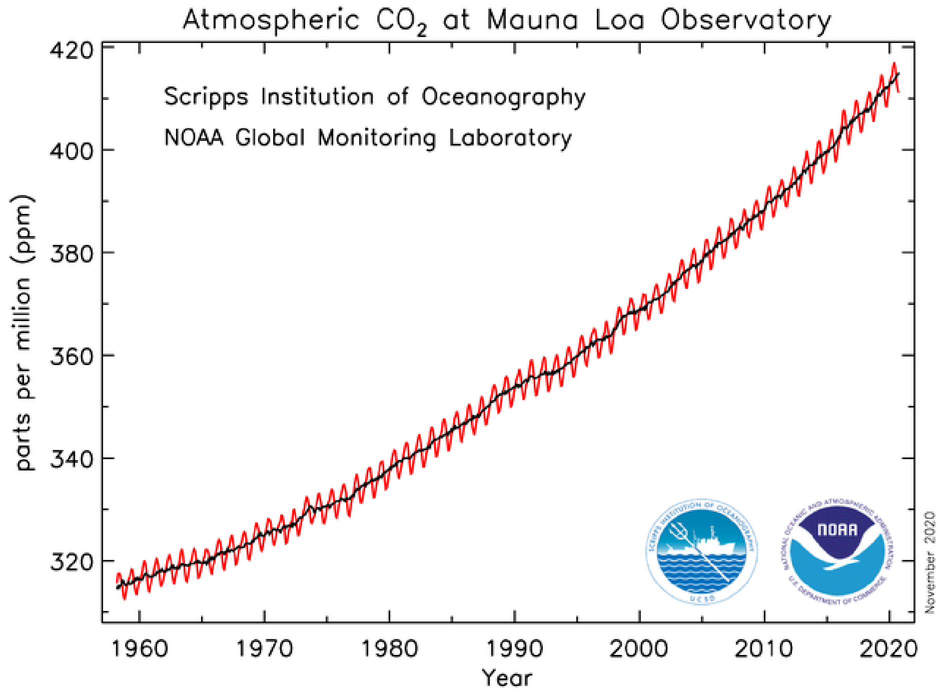
Key considerations – why ?

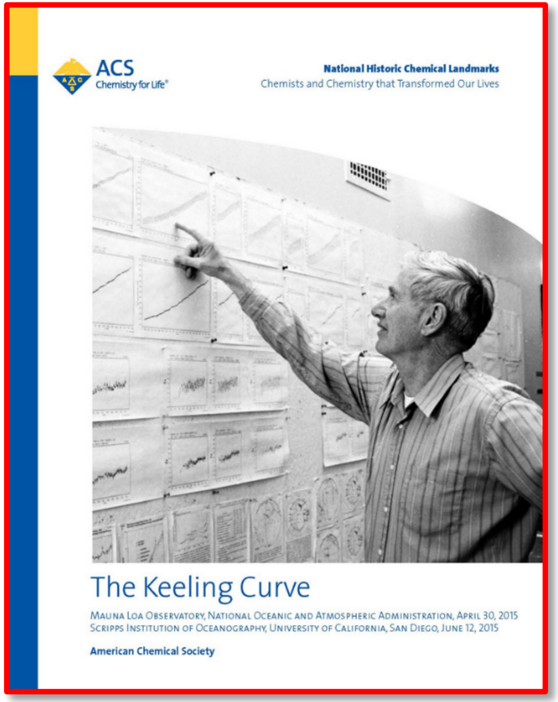
- Why are ambient air measurements needed?
- Which compounds are of interest?
  (gaseous compounds, particulates, deposition, meteorological parameters)
- What kind of data series are needed?
  (continuous, discrete, time resolution, concentration range)
- Where are measurements reasonable?
  (e.g., representativeness of the sample, avoid influence of undesirable sources)
- When is the right time to measure?
  (e.g., annual or diurnal cycles of compounds, during special weather conditions)

martin.steinbacher@empa.ch

An iconic example – carbon dioxide (CO2) at Mauna Loa

Most likely the best known atmospheric record




ACS
Chemistry for Life®

National Historic Chemical Landmarks
Chemists and Chemistry that Transformed Our Lives

The Keeling Curve

MAUNA LOA OBSERVATORY, NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, APRIL 30, 2015
SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA, SAN DIEGO, JUNE 12, 2015

American Chemical Society

Example – targeted compatibility for CO2

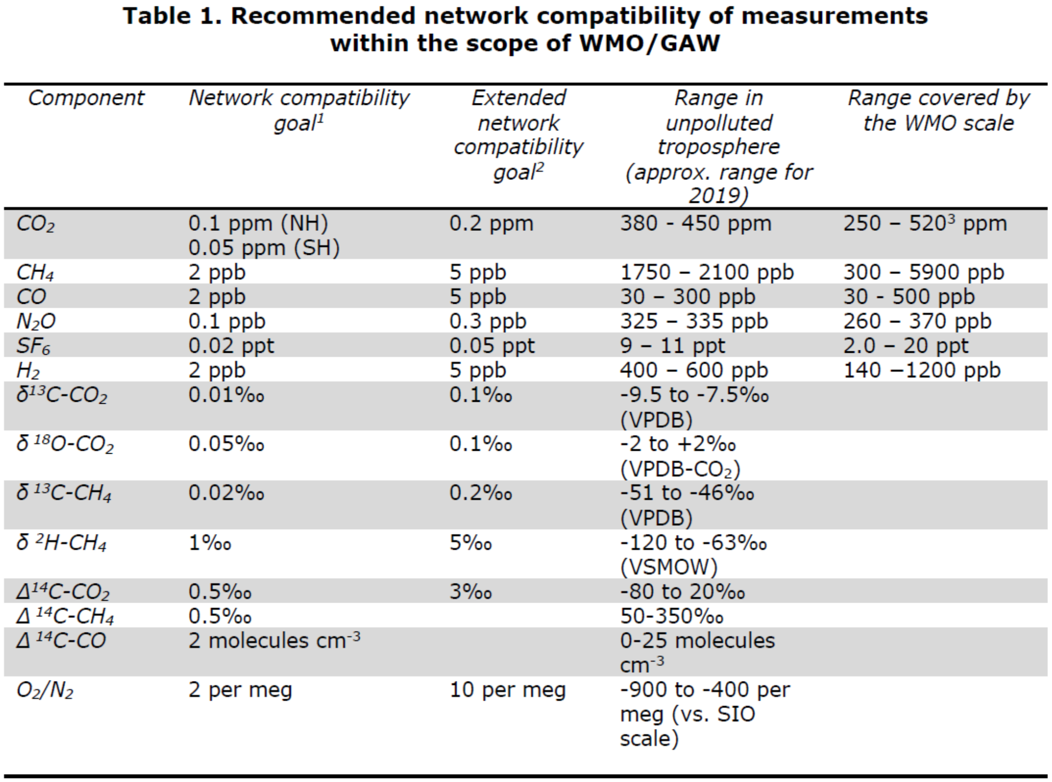
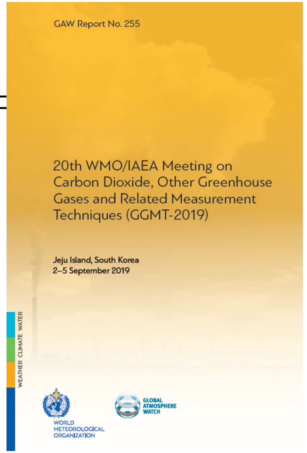


Table 1. Recommended network compatibility of measurements within the scope of WMO/GAW

Component	*Network compatibility goal*[1]	*Extended network compatibility goal*[2]	*Range in unpolluted troposphere (approx. range for 2019)*	*Range covered by the WMO scale*
CO_2	0.1 ppm (NH) 0.05 ppm (SH)	0.2 ppm	380 - 450 ppm	250 – 520[3] ppm
CH_4	2 ppb	5 ppb	1750 – 2100 ppb	300 – 5900 ppb
CO	2 ppb	5 ppb	30 – 300 ppb	30 - 500 ppb
N_2O	0.1 ppb	0.3 ppb	325 – 335 ppb	260 – 370 ppb
SF_6	0.02 ppt	0.05 ppt	9 – 11 ppt	2.0 – 20 ppt
H_2	2 ppb	5 ppb	400 – 600 ppb	140 –1200 ppb
$\delta^{13}C\text{-}CO_2$	0.01‰	0.1‰	-9.5 to -7.5‰ (VPDB)	
$\delta\, ^{18}O\text{-}CO_2$	0.05‰	0.1‰	-2 to +2‰ (VPDB-CO_2)	
$\delta\, ^{13}C\text{-}CH_4$	0.02‰	0.2‰	-51 to -46‰ (VPDB)	
$\delta\, ^{2}H\text{-}CH_4$	1‰	5‰	-120 to -63‰ (VSMOW)	
$\Delta^{14}C\text{-}CO_2$	0.5‰	3‰	-80 to 20‰	
$\Delta\, ^{14}C\text{-}CH_4$	0.5‰		50-350‰	
$\Delta\, ^{14}C\text{-}CO$	2 molecules cm^{-3}		0-25 molecules cm^{-3}	
O_2/N_2	2 per meg	10 per meg	-900 to -400 per meg (vs. SIO scale)	



GAW Report No. 255

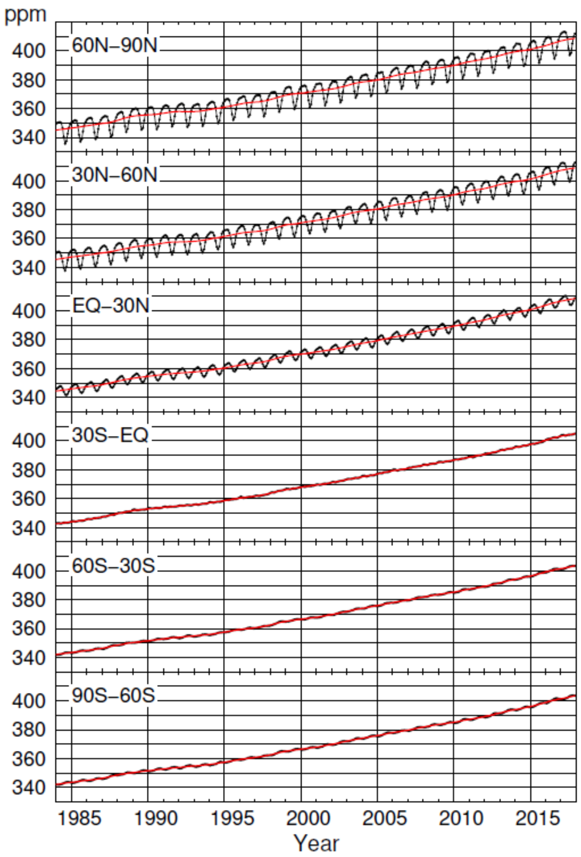
20th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases and Related Measurement Techniques (GGMT-2019)

Jeju Island, South Korea
2–5 September 2019

GGMT-2019 Report,
GAW Report Nr. 255, 2020

"… The WMO/GAW network compatibility are the scientifically-determined maximum bias among monitoring programmes that can be included without significantly influencing fluxes inferred from observations with models. …"

Example – targeted compatibility for CO2



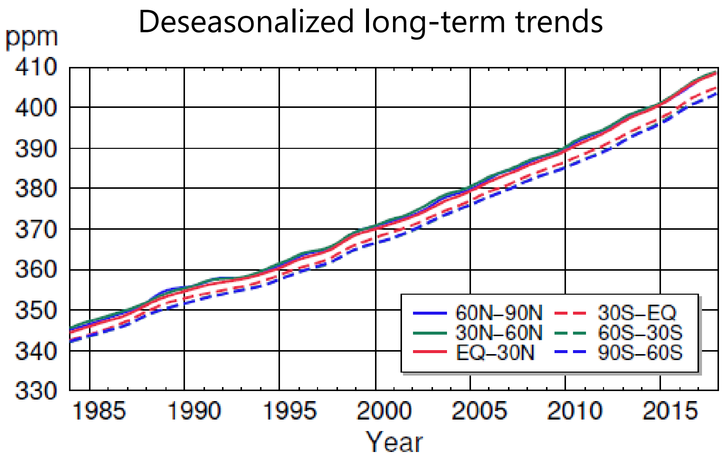
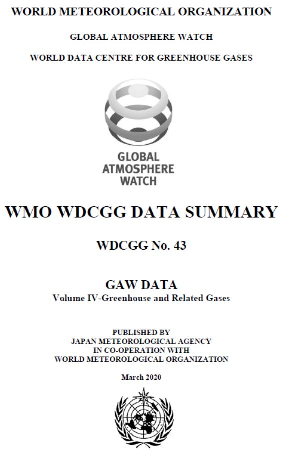


Fig. 1.3 Monthly mean mole fractions of CO_2 from 1984 to 2017 averaged over each 30° latitudinal zone (black) and their deseasonalized long-term trends (red).


WORLD METEOROLOGICAL ORGANIZATION

GLOBAL ATMOSPHERE WATCH

WORLD DATA CENTRE FOR GREENHOUSE GASES

GLOBAL
ATMOSPHERE
WATCH

WMO WDCGG DATA SUMMARY

WDCGG No. 43

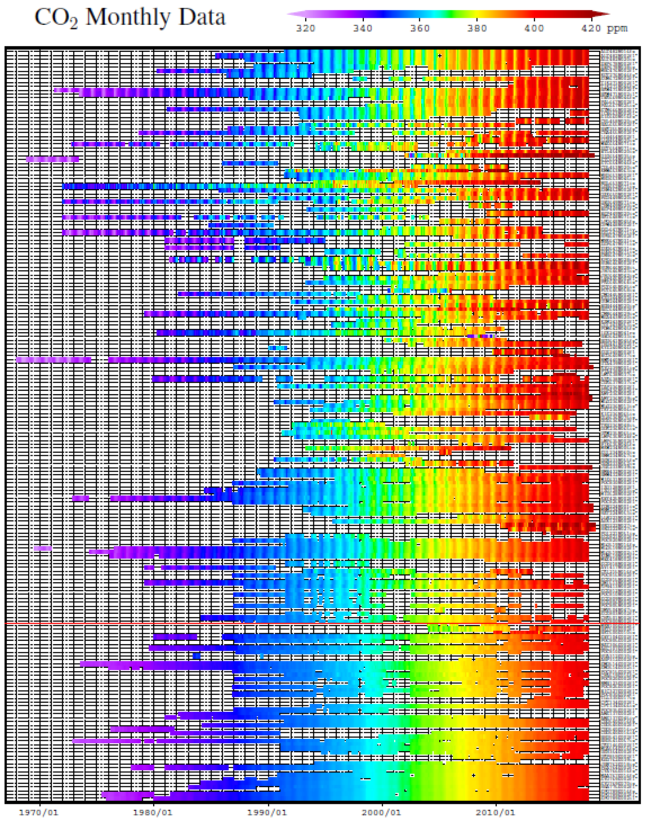
GAW DATA
Volume IV-Greenhouse and Related Gases

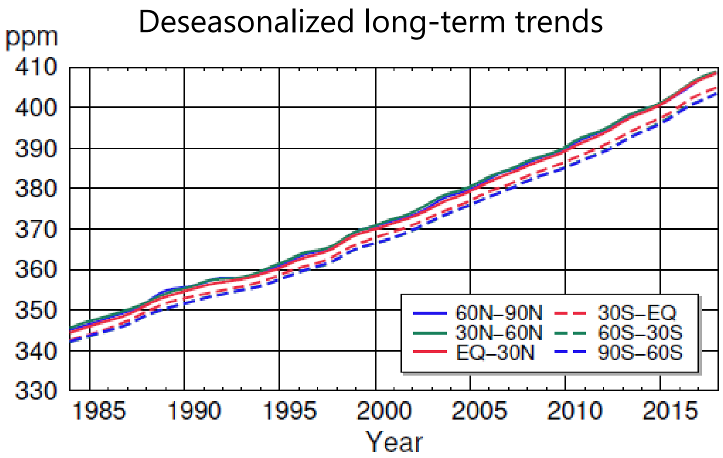
PUBLISHED BY
JAPAN METEOROLOGICAL AGENCY
IN CO-OPERATION WITH
WORLD METEOROLOGICAL ORGANIZATION

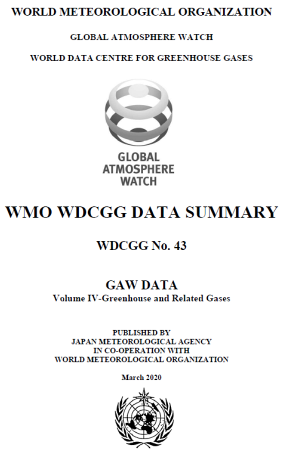
March 2020

WDCGG Data Summary
Report #43, 2020

Example – targeted compatibility for CO2






WORLD METEOROLOGICAL ORGANIZATION

GLOBAL ATMOSPHERE WATCH

WORLD DATA CENTRE FOR GREENHOUSE GASES

GLOBAL
ATMOSPHERE
WATCH

WMO WDCGG DATA SUMMARY

WDCGG No. 43

GAW DATA
Volume IV-Greenhouse and Related Gases

PUBLISHED BY
JAPAN METEOROLOGICAL AGENCY
IN CO-OPERATION WITH
WORLD METEOROLOGICAL ORGANIZATION

March 2020

WDCGG Data Summary
Report #43, 2020

- compatibility goals mainly motivated by small spatial gradients

Plate 1.1 Monthly mean CO$_2$ mole fractions that have been reported to the WDCGG.

Example – ozone: different goals for different tasks

Table 12: Scientific tasks, goals, and requirements for future tropospheric ozone monitoring. DOI: https://doi.org/10.1525/elementa.376.t12

Scientific task or question	Goals and Requirements	Station location	Comment
Long-term tropospheric ozone monitoring	Detection of long-term ozone distribution changes, ozone transport changes. Need decadal stability of ~1 nmol mol^{-1}. Vertical profiling important.	Multiple sites in different regions and land use classifications. Choice of sites should be guided by objectively quantified station spatial representativeness.	Current global network is unevenly distributed and covers only ~25% of the globe (*TOAR-Surface ozone database*). Sites with long-term records are very important.
Air quality model validation	Moderate accuracy and precision, preferably 3–5% level. Need vertical resolution of ~0.2 km or better. Need hourly time resolution, at least for short (campaign) periods. Flux measurements.	Multiple sites in different regions. Choice of sites should be guided by objectively quantified station spatial representativeness. Collocated profile measurements of other species desirable. Sites with multi-year data records are of value for background climatology.	Measurement campaigns at multiple sites are desirable. Measurements of surface deposition fluxes for different environments are needed (Hardacre et al., 2015; Bariteau et al., 2010; Luhar et al. 2017, 2018).
Chemical data assimilation	Moderate accuracy and precision, preferable 3–5% level. Vertically-resolved measurements desirable. Daily or better time resolution.	Many sites in different regions. Choice of sites should be guided by objectively quantified site spatial representativeness. Satellite, surface monitor, aircraft data.	Can we increase the impact of sparse measurements? Aircraft, lidar, ozonesondes have small measurement errors, relative to model error. Data impact should therefore be significant.
Satellite ozone data validation	High accuracy and high precision, preferably 2–3% level. Profile (free tropospheric) information required.	Location should represent different observational conditions (latitude, ozone profiles, etc.) and preferably have related measurements (surface O_3, total O_3, aerosol)	Data quality of prime importance; periodic re-evaluation needed.
How do ozone levels in the free troposphere affect levels in the planetary boundary layer (PBL)?	Measurement campaigns with vertical sounding at a resolution down to a few hours – lidar, satellite, sonde and other met measurements, possibly at multiple sites.	Sites in different latitude bands. Sites with multi-year measurement records are of value for background climatology. More sites at lower latitudes.	Important to interpreting satellite measurements, which are primarily sensitive to ozone above the PBL (Crawford and Pickering, 2014; Martins et al. 2015).

Tarasick et al., 2019

Key consideration – which technique to be used ?

Useful resources:

- WMO/GAW reports
- measurement guidelines

GAW Report No. 228

WMO Global Atmosphere Watch (GAW)
Implementation Plan: 2016-2023

GAW Report No. 195

WMO/GAW Expert Workshop on Global
Long-term Measurements of Nitrogen Oxides and
Recommendations for GAW Nitrogen Oxides Network

(Hohenpeissenberg, Germany, 8-9 October 2009)

GAW Report No. 209

Guidelines for Continuous Measurements of
Ozone in the Troposphere

GAW Report No. 255

20th WMO/IAEA Meeting on
Carbon Dioxide, Other Greenhouse
Gases and Related Measurement
Techniques (GGMT-2019)

Jeju Island, South Korea
2–5 September 2019

GAW Report No. 227

WMO/GAW Aerosol Measurement Procedures,
Guidelines and Recommendations

2nd Edition
2016

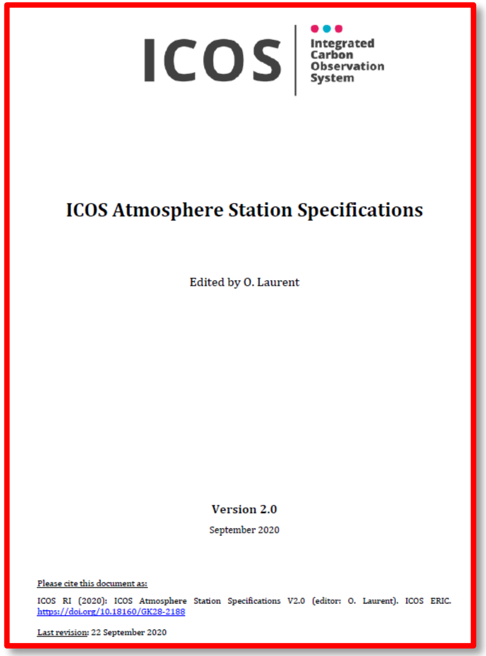
WMO-No. 1177

martin.steinbacher@empa.ch

Key consideration – which technique to be used ?

Useful resources:

- WMO/GAW reports
- measurement guidelines
- project reports, webpages



ICOS
Integrated
Carbon
Observation
System

ICOS Atmosphere Station Specifications

Edited by O. Laurent

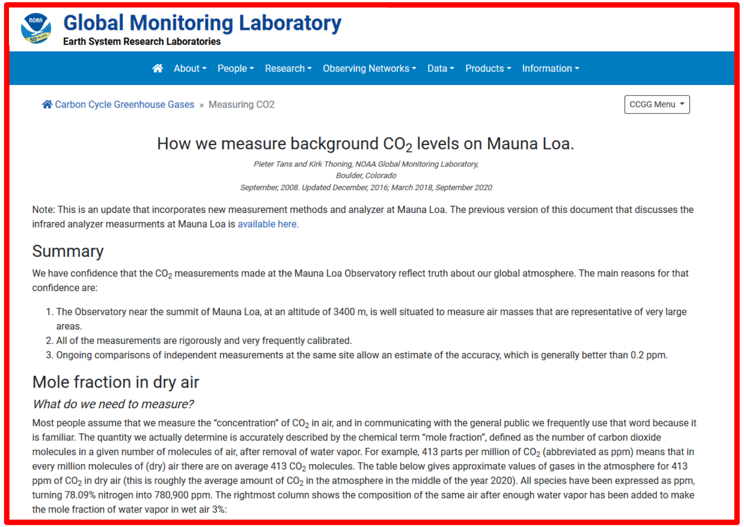
Version 2.0

September 2020

Please cite this document as:

ICOS RI (2020): ICOS Atmosphere Station Specifications V2.0 (editor: O. Laurent). ICOS ERIC. https://doi.org/10.18160/GK28-2188

Last revision: 22 September 2020



How we measure background CO_2 levels on Mauna Loa.

Pieter Tans and Kirk Thoning, NOAA Global Monitoring Laboratory,
Boulder, Colorado
September, 2008. Updated December, 2016; March 2018, September 2020

Note: This is an update that incorporates new measurement methods and analyzer at Mauna Loa. The previous version of this document that discusses the infrared analyzer measurments at Mauna Loa is available here.

Summary

We have confidence that the CO_2 measurements made at the Mauna Loa Observatory reflect truth about our global atmosphere. The main reasons for that confidence are:

1. The Observatory near the summit of Mauna Loa, at an altitude of 3400 m, is well situated to measure air masses that are representative of very large areas.
2. All of the measurements are rigorously and very frequently calibrated.
3. Ongoing comparisons of independent measurements at the same site allow an estimate of the accuracy, which is generally better than 0.2 ppm.

Mole fraction in dry air

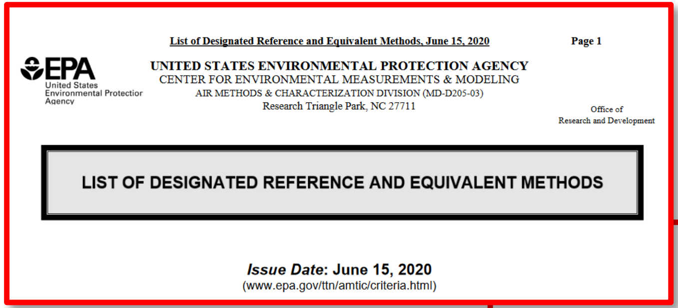
What do we need to measure?

Most people assume that we measure the “concentration” of CO_2 in air, and in communicating with the general public we frequently use that word because it is familiar. The quantity we actually determine is accurately described by the chemical term “mole fraction”, defined as the number of carbon dioxide molecules in a given number of molecules of air, after removal of water vapor. For example, 413 parts per million of CO_2 (abbreviated as ppm) means that in every million molecules of (dry) air there are on average 413 CO_2 molecules. The table below gives approximate values of gases in the atmosphere for 413 ppm of CO_2 in dry air (this is roughly the average amount of CO_2 in the atmosphere in the middle of the year 2020). All species have been expressed as ppm, turning 78.09% nitrogen into 780,900 ppm. The rightmost column shows the composition of the same air after enough water vapor has been added to make the mole fraction of water vapor in wet air 3%:

Key consideration – which technique to be used ?

Useful resources:

- WMO/GAW reports
- measurement guidelines
- project reports, webpages
- Environment Agencies, European Committee for Standardization (CEN)



List of Designated Reference and Equivalent Methods, June 15, 2020 Page 1

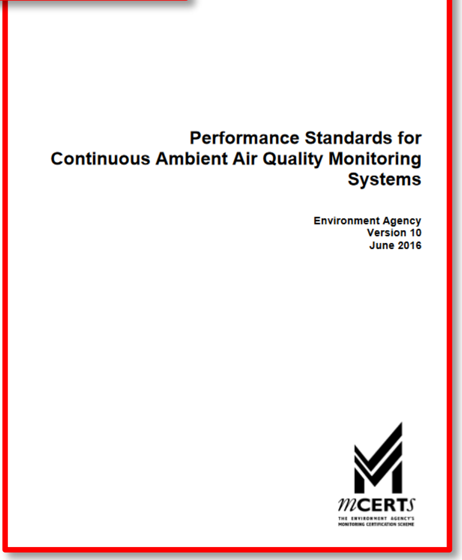
EPA United States Environmental Protection Agency

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
CENTER FOR ENVIRONMENTAL MEASUREMENTS & MODELING
AIR METHODS & CHARACTERIZATION DIVISION (MD-D205-03)
Research Triangle Park, NC 27711

Office of
Research and Development

LIST OF DESIGNATED REFERENCE AND EQUIVALENT METHODS

Issue Date: **June 15, 2020**
(www.epa.gov/ttn/amtic/criteria.html)

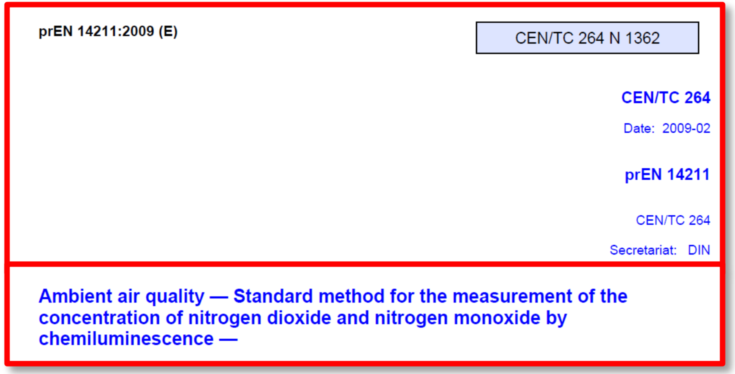


Environment Agency

Performance Standards for
Continuous Ambient Air Quality Monitoring
Systems

Environment Agency
Version 10
June 2016

mCERTS
THE ENVIRONMENT AGENCY'S
MONITORING CERTIFICATION SCHEME



prEN 14211:2009 (E)

CEN/TC 264 N 1362

CEN/TC 264

Date: 2009-02

prEN 14211

CEN/TC 264

Secretariat: DIN

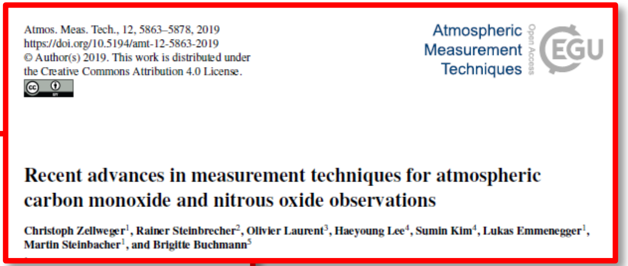
Ambient air quality — Standard method for the measurement of the concentration of nitrogen dioxide and nitrogen monoxide by chemiluminescence —

Key consideration – which technique to be used ?

Useful resources:

- WMO/GAW reports
- measurement guidelines
- project reports, webpages
- Environment Agencies, European Committee for Standardization (CEN)
- publications
- consultation of peers

- don't forget the periphery

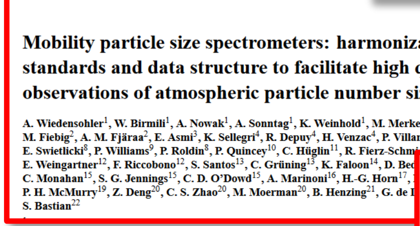


Atmos. Meas. Tech., 12, 5863–5878, 2019
https://doi.org/10.5194/amt-12-5863-2019

Atmospheric Measurement Techniques

Recent advances in measurement techniques for atmospheric carbon monoxide and nitrous oxide observations

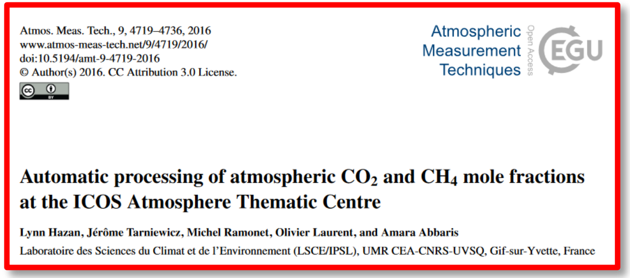
Christoph Zellweger[1], Rainer Steinbrecher[2], Olivier Laurent[3], Haeyoung Lee[4], Sumin Kim[4], Lukas Emmenegger[1], Martin Steinbacher[1], and Brigitte Buchmann[5]



Atmos. Meas. Tech., 5, 657–685, 2012
www.atmos-meas-tech.net/5/657/2012/
doi:10.5194/amt-5-657-2012

Mobility particle size spectrometers: harmonization of technical standards and data structure to facilitate high quality long-term observations of atmospheric particle number size distributions

A. Wiedensohler[1], W. Birmili[1], A. Nowak[1], A. Sonntag[1], K. Weinhold[1], M. Merkel[1], B. Wehner[1], T. Tuch[1], S. Pfeifer[1], M. Fiebig[2], A. M. Fjäraa[2], E. Asmi[3], K. Sellegri[4], R. Depuy[4], H. Venzac[4], P. Villani[4], P. Laj[5], P. Aalto[6], J. A. Ogren[7], E. Swietlicki[8], P. Williams[9], P. Roldin[8], P. Quincey[10], C. Hüglin[11], R. Fierz-Schm
E. Weingartner[12], F. Riccobono[12], S. Santos[13], C. Grüning[13], K. Faloon[14], D. Bec
C. Monahan[15], S. G. Jennings[15], C. D. O'Dowd[15], A. Marinoni[16], H.-G. Horn[17],
P. H. McMurry[19], Z. Deng[20], C. S. Zhao[20], M. Moerman[20], B. Henzing[21], G. de
S. Bastian[22]



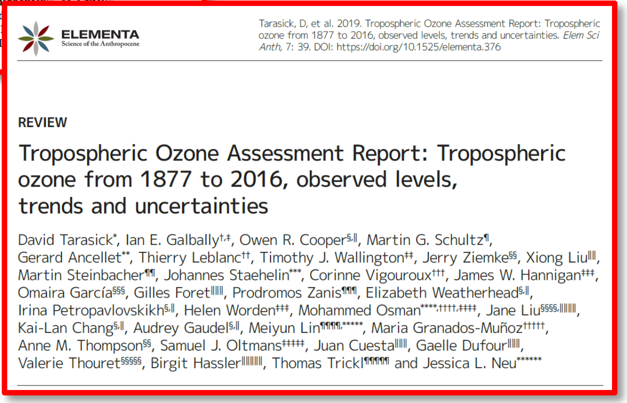
Atmos. Meas. Tech., 9, 4719–4736, 2016
www.atmos-meas-tech.net/9/4719/2016/
doi:10.5194/amt-9-4719-2016

Atmospheric Measurement Techniques

Automatic processing of atmospheric CO_2 and CH_4 mole fractions at the ICOS Atmosphere Thematic Centre

Lynn Hazan, Jérôme Tarniewicz, Michel Ramonet, Olivier Laurent, and Amara Abbaris

Laboratoire des Sciences du Climat et de l'Environnement (LSCE/IPSL), UMR CEA-CNRS-UVSQ, Gif-sur-Yvette, France



ELEMENTA
Science of the Anthropocene

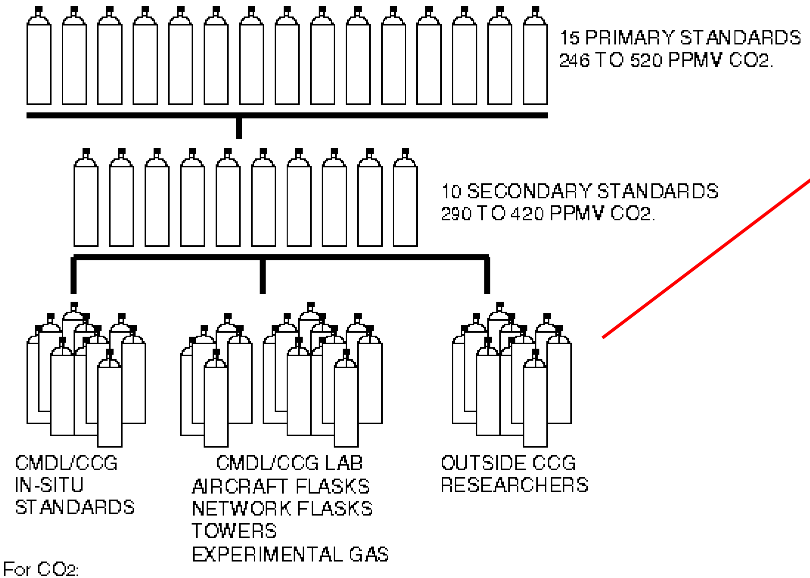
Tarasick, D, et al. 2019. Tropospheric Ozone Assessment Report: Tropospheric ozone from 1877 to 2016, observed levels, trends and uncertainties. *Elem Sci Anth*, 7: 39. DOI: https://doi.org/10.1525/elementa.376

REVIEW

Tropospheric Ozone Assessment Report: Tropospheric ozone from 1877 to 2016, observed levels, trends and uncertainties

David Tarasick[*], Ian E. Galbally[†,‡], Owen R. Cooper[§,‖], Martin G. Schultz[¶], Gerard Ancellet[**], Thierry Leblanc[††], Timothy J. Wallington[‡‡], Jerry Ziemke[§§], Xiong Liu[‖‖], Martin Steinbacher[¶¶], Johannes Staehelin[***], Corinne Vigouroux[†††], James W. Hannigan[‡‡‡], Omaira García[§§§], Gilles Foret[‖‖‖], Prodromos Zanis[¶¶¶], Elizabeth Weatherhead[§,‖], Irina Petropavlovskikh[§,‖], Helen Worden[‡‡‡], Mohammed Osman[****,††††,‡‡‡‡], Jane Liu[§§§§,‖‖‖‖], Kai-Lan Chang[§,‖], Audrey Gaudel[§,‖], Meiyun Lin[¶¶¶¶,*****], Maria Granados-Muñoz[†††††], Anne M. Thompson[§§], Samuel J. Oltmans[‡‡‡‡‡], Juan Cuesta[‖‖‖], Gaelle Dufour[‖‖‖], Valerie Thouret[§§§§§], Birgit Hassler[‖‖‖‖‖], Thomas Trickl[¶¶¶¶¶] and Jessica L. Neu[******]

Key consideration – traceability and calibration

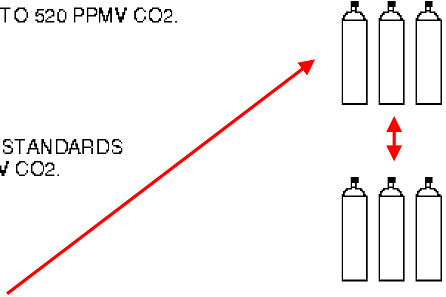


For CO2:
CALIBRATION PRECISION; 0.014 µmol/mol [1 sd of calibrations < 6 months apart].
precision for < 325 approx. 0.1
precision for > 425 approx. 0.25

Absolute Uncertainty; 0.1 µmol/mol
Internal consistency [325-425 µmol/mol]; 0.04 µmol/mol [2 sigma] [< 2 years]

https://www.esrl.noaa.gov/gmd/ccl/airstandard.html

station operators

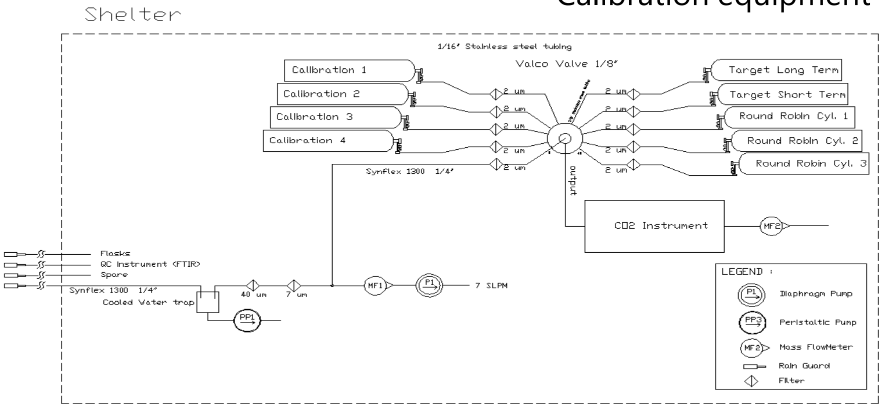


primary
laboratory
standards

working
standards
(in-situ)

Calibration equipment

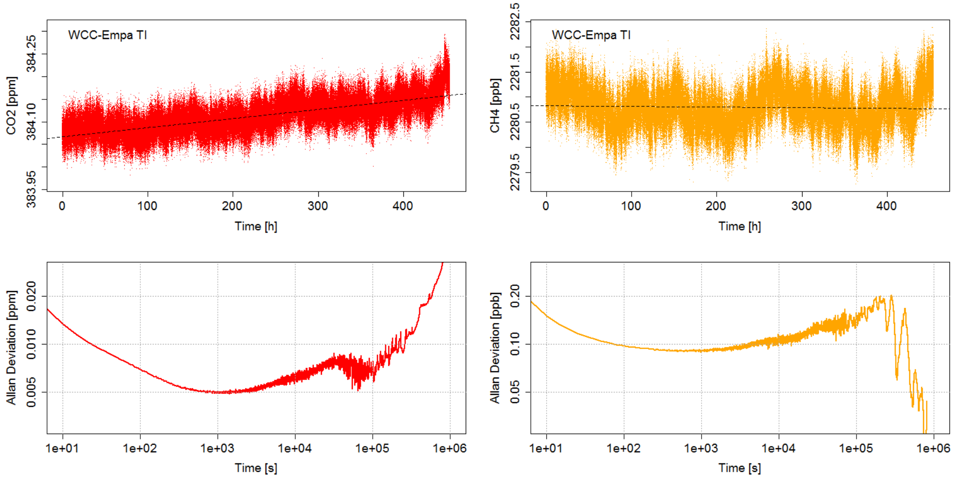
air
inlet(s)



ICOS RI, 2020

Key consideration – frequency of calibration and QA/QC

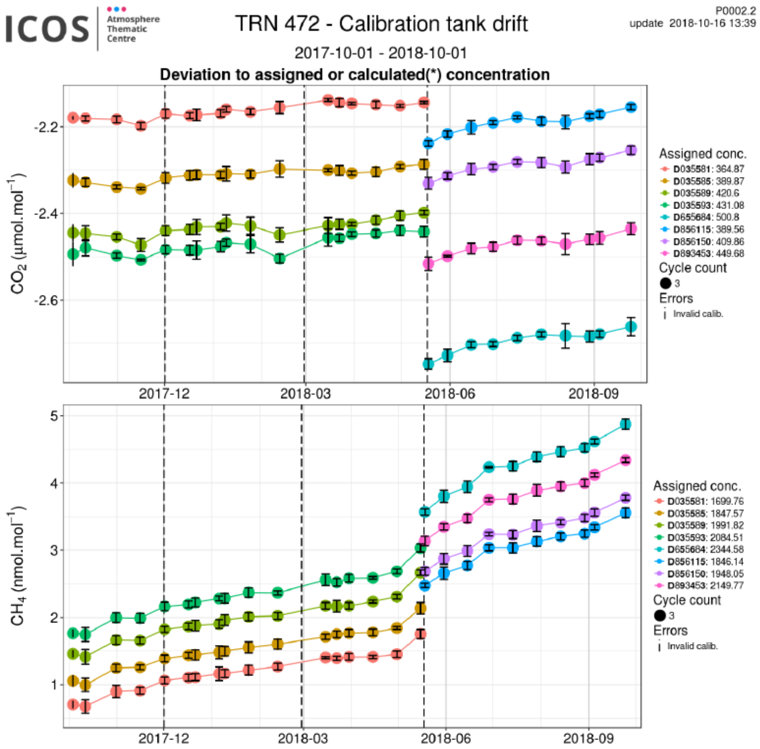
laboratory tests



Zellweger et al., 2016

"… A thorough analysis of the CO_2 and CH_4 stability of [this type of cavity enhanced laser spectrometer] indicates that the optimal calibration frequency is approximately 30 h. …"

(long-term) field tests

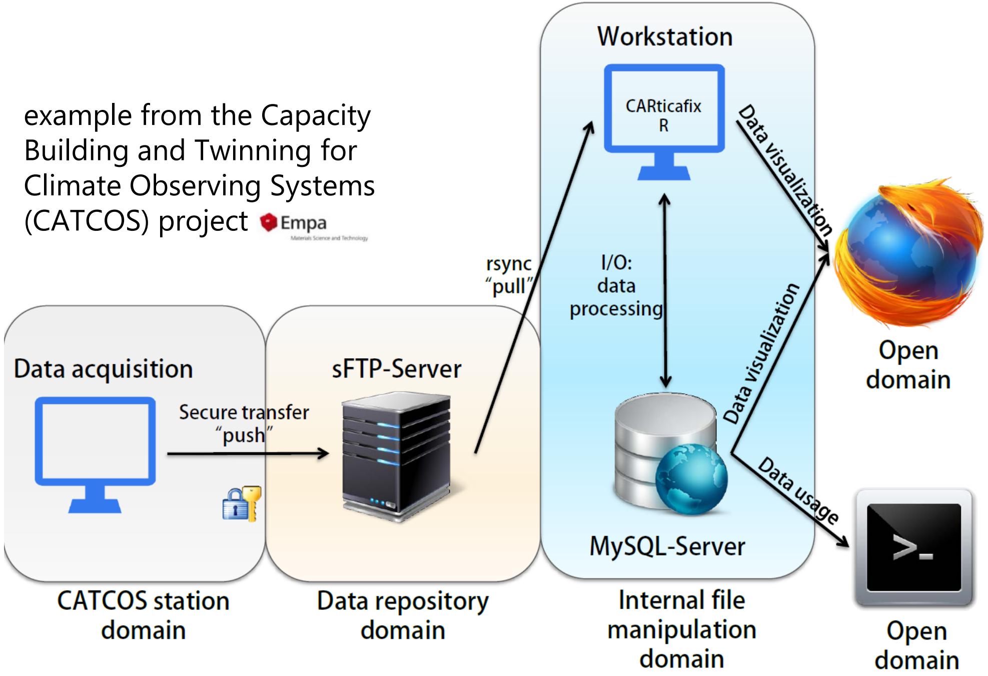


Yver-Kwok et al., 2020

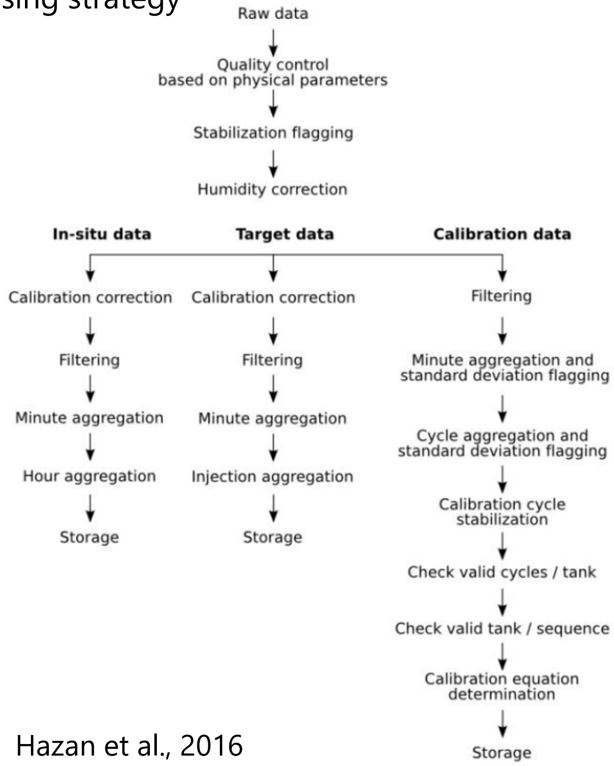
Key consideration – data Management

overall concept

example from the Capacity Building and Twinning for Climate Observing Systems (CATCOS) project



data processing strategy


Raw data
↓
Quality control based on physical parameters
↓
Stabilization flagging
↓
Humidity correction

In-situ data
↓
Calibration correction
↓
Filtering
↓
Minute aggregation
↓
Hour aggregation
↓
Storage

Target data
↓
Calibration correction
↓
Filtering
↓
Minute aggregation
↓
Injection aggregation
↓
Storage

Calibration data
↓
Filtering
↓
Minute aggregation and standard deviation flagging
↓
Cycle aggregation and standard deviation flagging
↓
Calibration cycle stabilization
↓
Check valid cycles / tank
↓
Check valid tank / sequence
↓
Calibration equation determination
↓
Storage

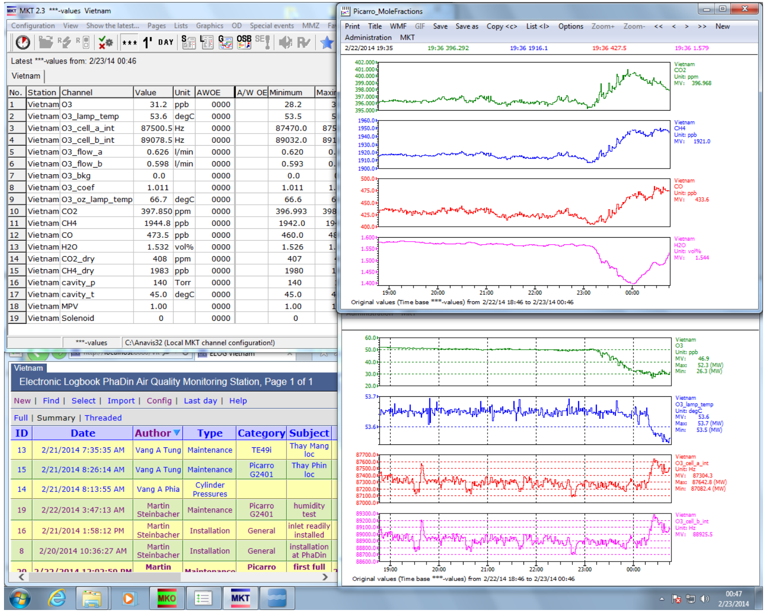
Hazan et al., 2016

Key consideration – data Management

IT (hardware and software) resources are needed

on-site

central data processing unit



Latest ***-values from: 2/23/14 00:46

Vietnam

No.	Station	Channel	Value	Unit	AWOE	A/W OE	Minimum	Maxi
1	Vietnam	O3	31.2	ppb	0000		28.2	3
2	Vietnam	O3_lamp_temp	53.6	degC	0000		53.5	5
3	Vietnam	O3_cell_a_int	87500.5	Hz	0000		87470.0	875
4	Vietnam	O3_cell_b_int	89078.5	Hz	0000		89032.0	891
5	Vietnam	O3_flow_a	0.626	l/min	0000		0.620	0.
6	Vietnam	O3_flow_b	0.598	l/min	0000		0.593	0.
7	Vietnam	O3_bkg	0.0		0000		0.0	
8	Vietnam	O3_coef	1.011		0000		1.011	1.
9	Vietnam	O3_oz_lamp_temp	66.7	degC	0000		66.6	6
10	Vietnam	CO2	397.850	ppm	0000		396.993	398
11	Vietnam	CH4	1944.8	ppb	0000		1942.0	19
12	Vietnam	CO	473.5	ppb	0000		460.0	48
13	Vietnam	H2O	1.532	vol%	0000		1.526	1.
14	Vietnam	CO2_dry	408	ppm	0000		407	
15	Vietnam	CH4_dry	1983	ppb	0000		1980	1
16	Vietnam	cavity_p	140	Torr	0000		140	
17	Vietnam	cavity_t	45.0	degC	0000		45.0	4
18	Vietnam	MPV	1.00		0000		1.00	1
19	Vietnam	Solenoid	0		0000		0	

***-values C:\Anavis32 (Local MKT channel configuration!)

Original values (Time base ***-values) from 2/22/14 18:46 to 2/23/14 00:46

Vietnam

Electronic Logbook PhaDin Air Quality Monitoring Station, Page 1 of 1

New | Find | Select | Import | Config | Last day | Help

Full | Summary | Threaded

ID	Date	Author	Type	Category	Subject
13	2/21/2014 7:35:35 AM	Vang A Tung	Maintenance	TE49i	Thay Mang loc
15	2/21/2014 8:26:14 AM	Vang A Tung	Maintenance	Picarro G2401	Thay Phin loc
14	2/21/2014 8:13:55 AM	Vang A Phia	Cylinder Pressures		
19	2/22/2014 3:47:13 AM	Martin Steinbacher	Maintenance	Picarro G2401	humidity test
16	2/21/2014 1:58:12 PM	Martin Steinbacher	Installation	General	inlet readily installed
8	2/20/2014 10:36:27 AM	Martin Steinbacher	Installation	General	installation at PhaDin
20	2/22/2014 12:02:50 PM	Martin	Maintenance	Picarro	first full

Station PDI

Species to visualize: ○ CH4 ● CO2 ○ CO ○ H20 ○ O3

Flag number: Logging actions...

Filters: ☑ Unfiltered ☑ NotAvailable ☑ Low ☑ High ☑ Extreme ☑ Delta ☑ Manual

Date: 2014-02-14 14:30:00 2014-03-14 15:00:00

Operations: Previous month | Next month | Refresh | Identify | Save sele

Flag period: 2014-05-14 14:30:00 2014-06-14 15:00:00

Comments: Manually flagged.

Confirmation/Cancel: Flag data/replot | Exit

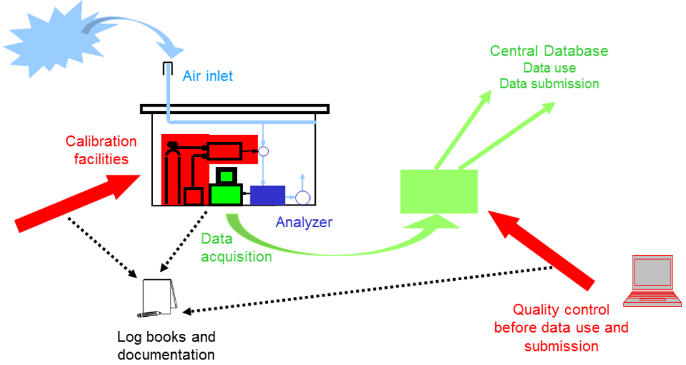
```
##########################################################################
##########################
# libraries used #
##########################
library(chron)
library(epicalc)

## load tools
source("C:\\Users\\mst\\Documents\\R_project\\functions\\mst.R")

##########################
# generate recent date, required for data export filename generation
sys.date <- as.character(Sys.Date())
today <- paste(substring(sys.date, 3, 4), substring(sys.date, 6, 7), substring(sys.date, 9, 10), sep="")
##########################################################################

#memory.limit(size = 4000)

##########################################################################
# 1 - INPUT SECTION
##########################################################################

################
# ENTER YEAR and MONTH; months < october  without leading '0'
################
yyyy <- 2019
#mm <- 1001
mm <- 7
################

YYYY <- as.character(yyyy)
MM <- ifelse(mm < 10, paste("0", as.character(mm), sep=""), as.character(mm))

################
# ENTER path where different folders for separate months are
################
path.base <- "C:\\Users\\mst\\Documents\\jungfraujoch\\Picarro\\"
################

################
# ENTER pattern for find files command
################
pattern = "DataLog_User_Sync"
################

################
# ENTER number of requested decimal places for trace gases averaging
################
d <- 3
################

#################
## ENTER path and filename for processing info, in particular for span coeeficicients for loess fits of ref gases
#################
# default values
span.co2 <- 0.75
```

log book (meta data management) !

Conclusions – infrastructure requirements

Measurement site infrastructure

- shelter
- mast for free exposure of the inlet
- reliable power supply
- air conditioning
- internet access
- access to the station (365 days a year)
- local support
- …



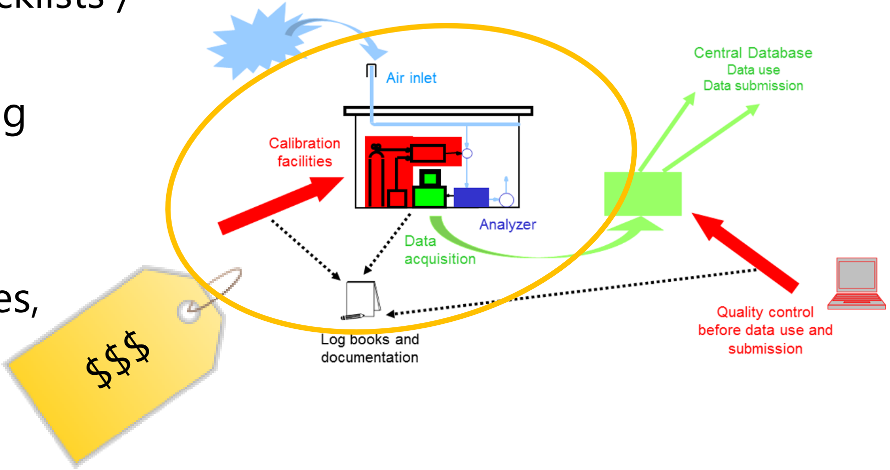
Instrument(s) and periphery

- adequate GHG analyzer
- periphery for automatic calibration
- reference gases (cals, targets)
- pressure reducers
- plumbing (additional pumps, tubing, connectors, inlet hat, drying unit, …)
- documentation tools
- data logger / data visualization

- consumables, spare parts, backup instruments, …

Conclusions – more general

- clearly define the motivation / goals of your monitoring
    - identify data quality objectives
- select suitable instrumentation (and periphery)
- design operation and calibration strategy (and revise if needed)
- prepare Standard Operation Procedures / checklists / troubleshooting strategies
- implement robust data management (including documentation and meta data)
- draw up a sustainable budget (for consumables, wear parts, instrument replacements, …)



Further reading

WMO/GAW reports can be found at https://community.wmo.int/gaw-reports

Hazan et al., Automatic processing of atmospheric CO2 and CH4 mole fractions at the ICOS Atmosphere Thematic Centre, Atmos. Meas. Tech., 9, 4719–4736, https://doi.org/10.5194/amt-9-4719-2016, 2016.

Tarasick et al., Tropospheric Ozone Assessment Report: Tropospheric ozone from 1877 to 2016, observed levels, trends and uncertainties, Elementa, 7 (39), https://doi.org/10.1525/elementa.376, 2019.

Yver-Kwok et al., Evaluation and optimization of ICOS atmospheric station data as part of the labeling process, Atmospheric Measurement Techniques Discussion, in review, https://doi.org/10.5194/amt-2020-213, 2020.

Zellweger et al., Recent advances in measurement techniques for atmospheric carbon monoxide and nitrous oxide observations, Atmospheric Measurement Techniques, 12, 5863–5878, https://doi.org/10.5194/amt-12-5863-2019, 2019.

Zellweger et al., Assessment of recent advances in measurement techniques for atmospheric carbon dioxide and methane observations, Atmospheric Measurement Techniques, 9, 4737-4757, doi:10.5194/amt-9-4737-2016, 2016.ICOS RI (2020): ICOS Atmosphere Station Specifications v2.0, ICOS ERIC, https://doi.org/10.18160/GK28-2188

https://www.esrl.noaa.gov/gmd/ccgg/about/co2_measurements.html

Thank you for your attention !

martin.steinbacher@empa.ch