

Metadata for Atmospheric Measurements at the Broomfield Soaring Eagle (BSE) Monitoring station

Boulder A.I.R.

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Site location

39.9844 N, 105.0364 W, 1607 m asl (5272 ft asl)

The station facility is a climate-controlled, insulated trailer approximately 16 ft long x 8 ft wide x 8 ft tall. Attached to the trailer is a 20 ft triangular meteorological aluminum tower which supports the meteorological equipment and air sampling inlet lines.

Wind Speed / Wind Direction

Wind conditions are recorded with an RM Young Wind Monitor AQ, 05305-PT, mounted on the meteorological tower at 5.6 m height. Every 6 months, wind speed and wind direction calibration checks are performed by an operator on the RM Young Wind Monitor, using a vane angle stand (RM Young, 18112) and an anemometer drive (RM Young, 200-15,000 RPM, 18802) standard. For the wind direction, South (180 degrees), West (270 degrees), East (90 degrees) and North (0 degrees) positions are checked, rotating the sensor clockwise and then counterclockwise, for a total of 8 points. For the wind speed, 4 speeds are used: 600 rpm (3.07 m/s), 1700 rpm (8.70 m/s), 3300 rpm (16.90 m/s) and 5400 rpm (27.65 m/s) in both directions (clockwise and counterclockwise) along with a zero check for a total of 9 points. An audit has been performed by the Colorado Department of Public Health and Environment (CDPHE) on the RM Young Wind Monitor on 15 October 2021. The wind speed sensor had <0.1% error for both clockwise and counterclockwise directions across all audited wind speeds. The wind direction sensor and vane alignment had <3.9 degrees composite error for all wind directions, meeting quality control requirements. The lower detection limit (LDL) for the RM Young wind speed is 0.4 m/s. Undetected wind is reported as half of the LDL, or 0.2 m/s, and in these instances the wind direction is reported as NaN. The ½LDL correction is applied to the original 1-minute data, not to any further averaged data (e.g. 5-minute or hourly).

Temperature, Relative Humidity

Temperature and relative humidity are measured with a Campbell Scientific CS215-L50-PT probe housed inside a RM Young 6-Plate Solar Radiation Shield mounted on the meteorological tower at 5.6 m height above the surface using the factory calibration. An audit was performed by the Colorado Department of Public Health and Environment (CDPHE) of the accuracy of the temperature and relative humidity readings on 15 October 2021. The instrument passed in all audit criteria with temperature reading accuracy having an error of 0.0 degrees C (passing is <2 degrees C), and relative humidity having a 2.6% error (passing is <5%). The manufacturer stated resolution of the CS215-L temperature measurement is 0.01 degree Celsius. The stated relative humidity resolution is 0.03%.

Solar radiation

Incoming solar radiation is monitored with an Apogee SP-110-SS pyranometer on the meteorological tower at 5.4 m height above the surface. The sensor dome is cleaned every 2 months.

Ozone (O₃)

Ozone is recorded with a Thermo Fisher Scientific model 49C UV absorption monitor. Ambient air is sampled from an inlet mounted at 5.1 m height above ground. The sampling line consists of 7 m length, ¼ inch o.d., 5/32 inch i.d. PFA tubing, equipped with an inlet PFA filter holder that houses a 5 micron Teflon membrane filter. Inlet filters are replaced every two months. The time resolution of the ozone monitoring is one minute. The monitoring and calibration protocol follow the federal regulatory monitoring requirements according to the specifications of '40 Code of Federal Regulations (CFR) Part 58'.

The calibration scale is referenced against an EPA Region 8 primary ozone reference standard. The level 2 standard was last referenced against an EPA Region 8 primary ozone reference standard on 4 May 2022 and 21 Feb 2024. Daily zero and span checks are performed automatically using a Thermo Fisher Scientific 49C calibrator unit. These checks are performed at night by introducing the calibration gases through the calibration valve of the instrument. First, zero air is introduced for 6 minutes, followed by 80 ppb of ozone for 6 more minutes. Two hours later, a mid-range check at 50 ppb is performed for 6 minutes. Quarterly, a full range linearity check is performed using the same calibrator unit. Six different levels of ozone are introduced: 0 ppb, 25 ppb, 50 ppb, 100 ppb, 200 ppb, 400 ppb. Also quarterly an inlet check is performed by feeding the calibrator output through the inlet filter on the tower and the entire inlet line to the instrument, and then running a standard calibration check. Yearly, a calibration check is performed using a level 2 standard (a Thermo Fisher Scientific 49C calibrator unit) following the same protocol as for the quarterly checks. From calibration check performance, the following correction has been applied to the data:

Start	End	Slope	Intercept
07/20/2022 17:00 UTC	10/14/2022 01:00 UTC	1.018	-0.9

An audit of the 49C was performed by the Colorado Department of Public Health and Environment (CDPHE) on 15 October 2021. The instrument passed all audit criteria with a calibration agreement slope 0.992 and an offset of -0.20 ppb, meeting EPA measurement quality requirements. The lower detection limit (LDL) for ozone is 1 ppb as reported by the instrument manufacturer. Measurements below this value are replaced with ½ of the LDL, 0.5 ppb. The ½LDL correction is applied to the original 1-minute data, not to any further averaged data (e.g. 5-minute or hourly). Uncertainty is calculated as the greater of 1.6 ppb or 3.9% for 1-minute data and was assessed within the range of 0 ppb to 400 ppb.

Methane (CH₄)

Methane was monitored with a Picarro G2301 cavity ring down spectrometer until 4 November 2021. The procedure was as follows: Ambient air is sampled at 400 scc/min from an inlet at 5.1 m height. The sampling line consists of 7 m length, ¼ inch o.d., 5/32 inch i.d. PFA tubing, equipped with an inlet PFA filter holder that houses a 5 micron Teflon membrane filter. Membrane filters are replaced every

two months. The manufacturer's calibration settings are applied. Calibration checks are conducted every 49 hours by introducing a breathing air grade ambient air gas mixture from a compressed tank (2413 ppb CH₄). The CH₄ mole fraction of this test atmosphere has been cross-referenced against the NOAA Global Atmospheric Monitoring Laboratory (GML) CH₄ scale and is estimated to have an accuracy error of <2 ppb. After ~3 months of use the test atmosphere is again cross-referenced to the NOAA GML scale to account for potential drift. Every 6 months, a calibration check is performed with an 1852.18 ppb CH₄ primary standard from NOAA (certification date 04/2015). Uncertainty up to 11/2021 was calculated as the greater of 4.68 ppb or 0.19% for 1-minute data and was assessed within the range of 1827.3 ppb to 3072.8 ppb. Uncertainty for measurements starting 04/2024 will be evaluated in Q1 2025.

Nitrogen Oxides (NO_x)

NO and NO₂ are monitored with a Teledyne Model API T200UP chemiluminescence analyzer. This analyzer uses a photolytic converter for the NO₂ determination. The sampling line consists of 7 m length, ¼ inch o.d., 5/32 inch i.d. PFA tubing equipped with a PFA filter holder that houses a 5 micron Teflon membrane filter. Membrane filters are replaced every two months. The sampling inlet is mounted on the meteorological tower at 5.1 m height. The monitoring and calibration protocol follow the federal regulatory monitoring requirements according to the specifications of '40 Code of Federal Regulations (CFR) Part 58'. Calibrations are performed using dynamic dilution and titration of a 10.00 parts per million (ppm) NO primary EPA-grade standard (EPA protocol grade gas, Praxair, production date 03/20/2020) with a Thermo Fisher Scientific 146i Multi-gas Calibrator equipped with a Gas Phase Titration system (GPT). The output of the calibrator is introduced through the span port of the instrument. Zero air is generated by running compressed air through Sofnofil and Charcoal scrubbers. Quarterly, full calibrations of the NO_x analyzer are performed using the output of the calibrator to introduce span gas to the span port of the instrument and zero air through the zero air port of the analyzer. For these calibrations, a zero adjustment is made first, followed by NO and NO_x span adjustments using 180 ppb NO. Then, a 6-level linearity check is performed (0 ppb NO, 20 ppb NO, 40 ppb NO, 80 ppb NO, 120 ppb NO, 180 ppb NO). The conversion efficiency adjustment is done next, at 2 different levels using the GPT: 150 ppb NO₂ (for 180 NO_x) and 20 ppb NO₂ (for 40 ppb NO_x). Weekly, calibration checks are performed for zero, a single span value of 160 ppb NO, and a single NO₂ mid-point value using the same calibrator connected to the span port of the analyzer, with the zero air sourced via the calibrator into the span port of the analyzer. An audit was performed by CDPHE on 15 October 2021. The instrument passed all audit criteria for flow rates, NO/NO_x, and gas-phase titration NO conversion efficiency, and met EPA measurement quality requirements. The detailed report is available upon request. The lower detection limit reported by the manufacturer for NO, NO₂, and NO_x is 0.05 ppb. Measurements below this value are replaced with ½ of the LDL, 0.025 ppb. The ½LDL correction is applied to the original 1-minute data, not to any further averaged data (e.g. 5-minute or hourly). Uncertainty for all NO_x measurements is calculated as the greater of 0.5 ppb or 5.5% for 1-minute data and was assessed within the range of 0 ppb to 500 ppb.

Hydrogen Sulfide (H₂S)

H₂S is analyzed by gas-phase ultraviolet fluorescence with a Teledyne T101 analyzer in air that is pulled at 650 scc/min from an inlet mounted at 5.1 m height above ground. The sampling line

consists of 8 m length, ¼ inch o.d., 5/32 inch i.d. PFA tubing equipped with an inlet PFA filter holder that houses a 5 micron Teflon membrane filter. Membrane filters are replaced every two months. Calibrations are performed by dynamic dilution of a 2.44 parts per million (ppm) H₂S primary EPA-grade standard (EPA protocol grade gas, Praxair, production date 03/18/2020), using a Thermo Fisher Scientific 146i Multi-gas Calibrator. Weekly zero and span checks are performed by an operator. The output of the calibrator is introduced through the zero or span valve of the instrument, respectively. Zero air is generated from a Parker zero-air generator followed by passing through Sofnofil and Charcoal scrubbers. Zero air is introduced first for 10 min, followed by 100 ppb H₂S for 15 min. Every 6 months, a 5-level linearity check is performed (0 ppb, 25 ppb, 50 ppb, 75 ppb, 100 ppb). The lower detection limit reported by the manufacturer is 0.4 ppb. Measurements below this value are reported as ½ of the LDL, 0.2 ppb. The ½LDL correction is applied to the original 1-minute data, not to any further averaged data (e.g. 5-minute or hourly).

Particulate Matter

A GRIMM EDM180 monitor is used for measuring particulate matter (PM). This analyzer measures particles in the 0.25 – 32 µm (micrometer) size range by a laser scattering technique. Air is sampled from an inlet stack protruding approximately 1 m above the instrument shelter roof at ~1.2 L/min. The instrument has EPA certification, and the protocol follows requirements for regulatory PM monitoring. Two size ranges are reported: PM₁₀ (coarse particles) for all particle mass smaller than 10 µm, and PM_{2.5} (fine particles) for all particle mass smaller than 2.5 µm. Weekly flow rate checks and zero tests using a 0.05 micron particle filter are performed by an operator at the sample inlet. Every 6 months, a field test is performed by an operator to check the instrument performance. For these tests, an aerosol test mixture is generated with a GRIMM Field Test Kit 185 by atomizing a diluted polystyrene latex standard suspension (1 micron and 2.5 micron, Durag Inc, PN 4030200 and 4030201). The test mixture is introduced directly into the instrument inlet. During this 6-month maintenance, the sample inlet pipe is also cleaned and internal filters replaced as needed. The lower detection limit for PM₁₀ and PM_{2.5} is 0.1 µg/m³ as reported by the manufacturer. Measurements below this value are replaced with ½ of the LDL, 0.05 µg/m³. The ½LDL correction is applied to the original 1-minute data, not to any further averaged data (e.g. 5-minute or hourly). Uncertainty is calculated as 17% for PM₁₀ and 15.5% for 1-minute data.

Volatile Organic Compounds

Volatile Organic Compounds (VOCs) are monitored with a custom-made preconcentration system interfaced to an Agilent 8860 gas chromatograph (GC) using a flame ionization detector (FID) detector and Agilent 5977 mass spectrometer (MS) (until April 2024). Sample air is pulled from an inlet at 5.1 m above ground on the meteorological tower at a purge rate of 1.5 L/min. The sampling line consists of 8 m length, ¼ inch o.d., 5/32 inch i.d. PFA tubing, equipped with an inlet PFA filter holder that houses a 5 micron Teflon membrane filter which is replaced every two months. The sampling line is inside a conduit heated to 40°C. Hourly, VOCs are extracted over a 10-minute time window at 40 cc/min. To preconcentrate VOCs, sample air is directed through a Peltier-cooled water freezeout trap that is held at -45°C. The dried air then flows through an ozone scrubber that contains

sodium-thiosulfate-impregnated glass wool, replaced annually. VOCs are then extracted from the downstream air flow on a micro-adsorbent trap (Carboxen 1000 and Carboxen 1016) held at -40°C. VOCs are transferred by rapid heating of the micro-adsorbent trap to 290°C and purged onto the GC column.

From the start of measurements until April 2024, a PoraBOND Q GC column (50 m, 0.53 mm i.d., 10 µm film) was used. After temperature-programmed separation, about 10% of the sample is directed to the MS and 90% to the FID.

Starting May 2024, the MS was removed from the system and the GC column was changed to an alumina PLOT GC column (Al₂O₃/KCl PLOT, 50 m, 0.53 mm i.d., 15 µm film thickness).

Compound identification and quantification are accomplished with the FID using PeakSimple software (SRI Instruments, version 4.88). Within PeakSimple, specifically programmed peak integration is done automatically following each run. The tabulated peak area results are processed by automated scripts using monthly updated calibration carbon response factors (CRF) and effective carbon numbers (ECN) to calculate mixing ratios, which are reported in real time on the program website.

Approximately 20 - 30 VOCs are traced and quantified routinely.

From the start of measurements until April 2024, 20 VOCs were quantified:

ethane
ethene
propane
propene
acetaldehyde
i-butane
n-butane
acetylene
acetone
i-pentane
n-pentane
cyclopentane
n-hexane
isoprene
n-heptane
benzene
toluene
ethyl-benzene
m&p-xylene
o-xylene

Beginning in May 2024 the GC column type was change and the list was expanded to 33 compounds (while losing acetone and acetaldehyde):

ethane
ethene
propane
cyclopropane
propene
i-butane
n-butane
acetylene
trans-2-butene
1-butene
i-butene
cis-2-butene
cyclopentane
i-pentane
n-pentane
1,3-butadiene
trans-2-pentene
1-pentene
cyclohexane
2-methylpentane
3-methylpentane
n-hexane
isoprene
C7H16_alkane_isomers*
n-heptane
benzene
2,2,4-trimethylpentane
C8H18_alkane_isomers*
n-octane
toluene
ethyl-benzene
m&p-xylene
o-xylene

*C7H16_alkane_isomers includes:

2,2-dimethylpentane
2,4-dimethylpentane
methylcyclohexane
2,2,3-trimethylbutane
3,3-dimethylpentane
ethylcyclopentane
2,3-dimethylpentane
3-ethylpentane
3-methylhexane

2-methylhexane

*C₈H₁₈_alkane_isomers includes:

4-methylheptane

n-propylcyclopentane

2-methylheptane

3-methylheptane

A subset of selected VOC tracers are plotted on the web portal (<https://www.bouldair.com/broomfield.htm>). Data represent the 10-minute mean VOC mole fractions over the 10-minute sample collection period, with the recorded time stamp at the middle of that sampling period.

The calibration scale is tied to the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) VOCs scale, using a certified multicomponent 10-ppb primary standard (Table 1) acquired from the U.K. National Physics Laboratory (NPL, calibration date 2/7/2020) – the central calibration laboratory for VOCs recommended by WMO-GAW program. The calibration standard is run weekly by an operator. Calibration carbon response factors (CRF) are updated monthly using the averaged result of the NPL standard samples run the prior month, and are applied to the previous month's data record retroactively. Realtime data use the CRF values continuing from the prior month. Compounds not in the NPL standard use the average CRF value of the respective carbon number alkanes or alkenes (e.g. i-butene's CRF is the average CRF of trans-2-butene, 1-butene, and cis-2-butene).

In addition, a 200-ppb NPL standard and a high mole fraction VOC standard dilution curve are run annually to check for the linearity of the instrument response at high levels. The high mole fraction standard (635.4 ppb ethane, 640.6 ppb propane, 532.1 ppb i-butane, 532.1 n-butane, 320.8 ppb i-pentane, 320.8 ppb n-pentane) is diluted to various mixing ratios to create an instrument response curve (ratio of the measured/expected mole fraction vs. measured mole fraction). A zero air (blank) sample and a lab-calibrated multi-component working standard are run every 65 runs (~every three days). Zero-air is generated with a custom-built catalytic system using platinum on alumina pellets heated to 380C.

Table 1: National Physics Laboratory VOC calibration standard composition.

Database component name	mole fraction (ppbv)	Uncertainty (ppbv)	Name on certificate
ethane	9.85	0.20	
ethene	9.67	0.20	
propane	9.73	0.20	
propene	9.68	0.20	
i-butane	9.91	0.25	2-methylpropane
acetylene	10.10	0.50	ethyne
n-butane	9.83	0.20	
trans-2-butene	9.86	0.20	trans-but-2-ene
1-butene	9.81	0.20	but-1-ene

cis-2-butene	9.83	0.20	cis-but-2-ene
i-pentane	9.70	0.20	2-methylbutane
n-pentane	9.74	0.20	
1_3-butadiene	9.94	0.20	1,3-butadiene
trans-pent-2-ene	9.79	0.20	
pent-1-ene	9.95	0.20	
2-methylpentane	10.22	0.21	
n-hexane	10.22	0.21	
isoprene	10.18	0.21	
n-heptane	10.24	0.21	
benzene	9.68	0.20	
2_2_4-trimethylpentane	9.61	0.20	2,2,4-trimethylpentane
n-octane	9.64	0.20	
toluene	9.41	0.24	
ethyl-benzene	10.18	0.26	
m&p-xylene	19.80	0.50	m-xylene+p-xylene
o-xylene	9.74	0.25	
1_3_5-trimethylbenzene	9.53	0.24	1,3,5-trimethylbenzene
1_2_4-trimethylbenzene	9.68	0.25	1,2,4-trimethylbenzene
1_2_3-trimethylbenzene	10.00	0.25	1,2,3-trimethylbenzene

VOC data are reported in nanomoles per mole by volume (nmol mol^{-1} , i.e. 10^{-9}). The more commonly used unit ppb (parts-per-billion by volume) is used as a surrogate.

VOC lower detection limits (LDL) were calculated from the smallest, reliably identifiable FID peak area and the compound CRFs calculated monthly from the weekly standard runs. Since the calculation of LDL varies with the instrument response calibrated monthly, the lowest values seen in the data will also vary monthly. Representative lower detection limits from March 2023 are provided in Table 2. VOC species with no detected or quantifiable peak in the GC chromatograms are recorded as $\frac{1}{2}$ of the lower detection limit (which similarly vary monthly).

Table 2: VOCs lower detection limits.

VOC	LDL Value (ppb)
ethane	0.021
ethene	0.020
propane	0.014
propene	0.014
i-butane	0.010
n-butane	0.010
acetylene	0.028
i-pentane	0.008
n-pentane	0.008

n-hexane	0.007
isoprene	0.008
n-heptane	0.007
benzene	0.007
Toluene	0.007
ethyl-benzene	0.010
m&p-xylene	0.010
o-xylene	0.011

VOC data corrections:

Zero-air blank subtractions

Blanks are assessed from the periodic collection of the VOC-scrubbed zero air runs. Blank peak area subtractions are determined using the mean peak area of zero air runs during a particular time window that a detectable peak is present for a given compound. Most often this is delineated on a monthly basis, or following significant system work (e.g. installation of a new absorbent trap). Most VOCs show no blank peak and are below the limit of detection, or well below the response seen in ambient levels, and are therefore deemed negligible. Blank peak area subtractions have been applied and are accounted for in the data set.

Chromatogram co-elutions

m- / p- xylene

Two xylene isomers, meta-xylene and para-xylene, elute very closely together in the chromatogram and often cannot be separated as individual peaks. The results for these isomers are therefore reported at the sum of both, m&p-xylene.

i-pentane / isoprene

i-pentane and isoprene elute very closely together in the chromatogram and can be difficult to separate as individual peaks. During the summer months growing season (approximately May through October) with higher levels of isoprene, the compounds are more easily integrated separately and both compounds are reported. When the peaks are unable to be separated, both compounds are not be reported (defined as NaN). The growing season is defined looking at the isoprene data from nearby stations, as 05/21/2021 00:00:00 to 10/10/2021 00:00:00; 05/10/2022 00:00:00 to 10/30/2022 00:00:00; 05/09/23 00:00:00 to 10/21/23 00:00:00. In the winter non-growing season with little to no isoprene, the i-pentane peak is reported and isoprene is reported as NaN.

The i-pentane/isoprene coelution issue ended starting May 2024 when the GC column type was changed.

propene / methyl chloride

Propene and methyl chloride (CH₃Cl) are unable to be separated with the GC column and therefore co-elute. A constant 0.173 ppb mixing ratio is subtracted from the propene value to account for that co-elution and the relatively constant concentration of CH₃Cl in the atmosphere. This was estimated

by comparing the measurement of propene/ CH_3Cl at BSE with nearby stations on clean windy days when propene was zero at nearby stations and most VOC levels were near zero, across the 2-3 years of sampling at BSE. The propene/methylchloride coelution issue ended starting May 2024 when the GC column type was changed.