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Controlled release testing of commercially available methane emission measurement technologies at the TADI facility

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S1 Experimental Setup

S1.1 Participant Testing Schedule

Table S1. Schedule of participants and the week(s) that they participated in.

Week	Drone Teams	Aircraft and Satellite Teams	Continuous Monitoring Teams
Week 1 (June 17-21, 2024)	Aeromon, GSMA	GHGSat	Sensirion
Week 2 (June 24-28, 2024)	SeekOps	GHGSat	Sensirion
Week 3 (September 9-13, 2024)		GHGSat	Sensirion, SENSIA, SLB
Week 4 (September 16-20, 2024)	Flylogix	GHGSat	Sensirion, SENSIA, SLB

S1.2 TADI Test Site Description

TADI (TotalEnergies Anomaly Detection Initiative) is a research and development platform located in Lacq, France, specifically dedicated to testing and experimenting with gas leak detection and quantification technology.[1] Owned and operated by TotalEnergies, TADI was constructed to evaluate technologies aimed at improving safety and minimizing gas emissions on oil and gas production sites. TADI is located on an industrial SEVESO 3 site with active industrial activity around it. The leak points are located within dismantled oil and gas equipment, such as drum pipes, valves, wellheads, flanges, level gauges, etc. Originally designed for safety research in 2015, the site quickly evolved into being capable of testing greenhouse gas emission measurement technologies. The site can test gas detection and quantification capabilities of several types of gases, including methane. Since 2016, TADI and the Methane Emission Technology Evaluation Center (METEC) from Colorado State University have built a strong scientific collaboration. In 2023, TADI and METEC partnered to develop an international protocol for qualification of methane emissions technologies.[2]

The TADI site is made up of the gas release platform and the surrounding area. The gas release platform is an ATEX zone and contains all the leak points. The gas release platform is 40m wide, and 50m in length, for area of 2000 m^2. There are two regions of the platform: TADI North and TADI South. TADI North can release methane flowrates of 0.0036 kg h^{-1} to 21.6 kg h^{-1}. TADI South can release flowrates from 0.54 kg h^{-1} to 1080 kg h^{-1} of methane. Other gases have different flowrate limitations due to safety and other constraints. The methane flow rate limit depends on the length of time the gas is released, as gas is supplied via CNG bottles. The equipment on TADI can provide 226 different leak scenarios, with different combinations of equipment, location on equipment, outlet diameter, and inlet diameter. There is a meteorological station permanently on TADI site, a 2d wind anemometer and a ZX 300 wind

LIDAR. These data are not intended to be shared during testing, as performers must use their own equipment in the same configuration as during measurement campaigns.

Figure S1 contains a map of the test site. The releases are controlled from an operation room directly north of the platform. The control room was under the jurisdiction of the TADI site engineer, and no participants were allowed in the control room to maintain the blind nature of the experiment. The Stanford team and any participants onsite were housed in a work room dedicated to the campaign set back from the platform. Due to its location on an active industrial site (INDUSLACQ), personal protective equipment (PPE), a gas mask, and a personal gas detector were required when anywhere on the industrial site except for the control room and campaign headquarters. Figure S2 depicts the gas release platform.

Figure S1. Map of the TADI test site.
The gas release platform is indicated in red, the gas release control room in green, and the campaign headquarters in blue.

Figure S2. Side view of TADI gas release platform.
The methane storage tanks are in the front of the picture, looking northeast. Note the control room (blue storage containers) in the upper left.

S1.2.1 TADI Team

There was a team of dedicated engineers and researchers associated with TADI that helped plan and execute the experiment. Catherine Juéry, Vincent Blandin, Yvan Faucher, and Jordi Jourde were invaluable in ensuring a safe and seamless execution of the experiments.

S1.3 Methane Release Schedule and Emission Rates

Table S2. Intended daily release schedule.

Release Number	Start Time (Local)	End Time (Local)
1	9:00	9:45
2	10:00	10:45
3	11:00	11:45
4	12:00	12:45
5	13:30	14:15
6	14:30	15:15
7	15:30	16:15
8	16:30	17:15

Methane release flowrates ranged from 0 kg h^{-1} (so-called "zero release") to 310 kg h^{-1}. The gas used in the experiment was sourced by the TADI team and was specified at ≥99% CH_4 composition. The release rates were different every week. Table S3 contains the daily and weekly total number of releases. The lower number of releases on Mondays (<8) was due to the safety briefing conducted Monday morning each week as participants arrived onsite for the first time.

Table S3. Daily, weekly, and campaign total number of releases.

Week	Number of Releases per Day					Weekly Total Number of Releases
	Monday	*Tuesday*	*Wednesday*	*Thursday*	*Friday*	
Week 1	7	9	8	8	8	40
Week 2	7	8	8	8	4	35
Week 3	6	9	9	8	5	37
Week 4	6	8	9	9	8	40
Campaign Total						152

For a particular release, the TADI site participant would refer to the schedule and prepare the leak location during the break between releases. This would involve both physical operations (opening or closing valves, changing pipe configurations) and inputting the desired release characteristics in the control room (flowrate, location). The TADI site estimated a specific uncertainty between actual flowrate and the specified flowrate for methane for each release. The average uncertainty was 3.23%. There were two zero releases schedule for each week, and two to four satellite scale releases, depending on the week.

S1.3.1 Zero Releases

There were two zero releases pre-scheduled for each week. These releases aim to test for false positive detections. Because false positives were not the primary focus of the testing campaign, only two release periods were designated as zero releases. Table S4 contains the summary of actual number of zero releases conducted during each week, which can differ from the pre-scheduled two releases. Notably, Week 2 only had one zero release due to the Friday afternoon releases being canceled.

S1.3.2 Satellite Releases

As discussed above, there were several releases each week that were specifically targeted to the GHGSat-C satellites. Due to the higher detection limit of satellites, these releases were designed to be high-volume releases. Other participants were not aware of the satellite schedule, nor which overpasses were selected by the Stanford and TADI teams and therefore did not know the timing of the high-volume releases.

During the June campaign, several of the satellite-designated releases occurred during cloud cover of the site, resulting in the satellite not being able to measure methane. To minimize the emissions impacts of the experiment and to reduce costs, the September campaign included alternative-satellite releases. These were flowrates designed to be used specifically if cloud coverage at the site made it impossible for the satellite to obtain a measurement. If clouds were present at the satellite overpass time, the alternative-satellite amount was released instead. The Stanford and TADI teams made the decision to proceed with either the satellite-scale or alternative-satellite release rate within an hour of the target overpass time, given local conditions.

Table S4. Summary of zero releases and satellite-designated releases by week.

Week	Number of Zero Releases	Number of Satellite Releases
1	2	3
2	1[a]	3
3	2	1[b]
4	2	2

[a] *Week 2 only has 1 zero release because of the decision to cancel Friday afternoon releases.*
[b] *Week 3 only has 1 satellite release because of cloud conditions.*

S1.3.3 Drone Releases

During weeks with multiple drones (Week 1), we attempted to make sure that each drone participant had the opportunity to measure a high-volume and zero-release. The original schedule had this occurring, with the Stanford team specifying which drone participant was to begin measuring the first release of the day, with the assumption that the drone participants would measure every other release (i.e. one drone team measured all the odd-numbered releases for the day and the other participant would measure all the even-numbered releases). However, due to weather and equipment malfunctions, the drone participants did not measure releases in a predictable manner, meaning that the planned distribution of releases for each participant could not be managed. This resulted in one drone participant not measuring a high-volume release.

Complete schedules of methane releases with release start and end times, flowrates, and uncertainties can be found in the following tables.

S1.3.4 Methane release flowrates and schedules

Table S5. Week 1 methane release flowrates and times

Week	Date	Release Start	Release end	Flowrate (kg h^{-1})	Uncertainty (%)
1	6/17/24	11:07:00	11:53:30	28.26	3.3
1	6/17/24	12:05:00	12:51:00	0.66	7
1	6/17/24	13:05:45	13:52:00	20	0.67
1	6/17/24	14:00:00	14:48:30	8.28	11.08
1	6/17/24	15:00:00	15:46:00	1.49	3.15
1	6/17/24	16:00:00	16:47:30	16.46	0.69
1	6/17/24	16:57:05	17:48:30	56.7	1.73

1	6/18/24	9:08:00	9:54:00	41	2.32
1	6/18/24	10:05:05	10:51:30	28.26	3.3
1	6/18/24	11:03:00	11:49:00	4.45	7.54
1	6/18/24	12:00:30	12:46:30	8.28	11.08
1	6/18/24	13:00:00	13:46:00	47.66	2.02
1	6/18/24	14:04:05	14:51:00	3.83	8.82
1	6/18/24	15:05:45	15:33:00	1.95	12.72
1	6/18/24	15:38:00	16:25:00	126	1.38
1	6/18/24	16:41:00	17:35:15	4.46	7.54
1	6/19/24	9:00:50	9:47:10	16.95	0.69
1	6/19/24	10:00:45	10:49:10	1.92	2.48
1	6/19/24	11:01:45	11:48:00	115	1.49
1	6/19/24	12:00:30	12:47:00	0	0
1	6/19/24	13:02:20	13:48:10	38.52	2.46
1	6/19/24	14:01:15	14:50:30	5.6	6.01
1	6/19/24	15:02:00	15:48:00	103.2	1.63
1	6/19/24	16:02:15	16:50:00	8.28	0.85
1	6/20/24	9:00:00	9:47:30	13.59	6.76
1	6/20/24	10:03:05	10:49:00	24.01	3.86
1	6/20/24	11:00:30	11:51:30	16.92	5.72
1	6/20/24	12:03:00	12:51:00	43.49	2.19
1	6/20/24	13:07:00	13:53:05	5.63	6.01
1	6/20/24	14:08:00	14:56:00	20	0.67
1	6/20/24	15:14:10	16:30:00	101.8	1.65
1	6/20/24	16:18:00	17:05:30	13	0.73
1	6/21/24	9:00:15	9:47:30	1.1	4.12
1	6/21/24	10:02:45	10:49:00	27.84	3.35
1	6/21/24	11:04:00	11:56:30	5.38	1.07
1	6/21/24	12:10:00	13:04:00	0	0
1	6/21/24	13:13:30	14:01:20	40.63	2.34
1	6/21/24	14:12:00	15:05:00	0.01	2
1	6/21/24	15:15:20	16:06:00	15.15	6.07
1	6/21/24	16:29:30	17:19:40	3.95	8.5

Table S6. Week 2 methane release flowrates and times

Week	Date	ReleaseStart	ReleaseEnd	Flowrate (kg h^{-1})	Uncertainty (%)
2	6/24/24	11:08:45	11:55:00	0.59	7.86
2	6/24/24	12:00:00	12:45:00	136.6	1.29
2	6/24/24	13:02:00	13:45:00	24.83	3.74
2	6/24/24	14:01:25	14:48:30	0.89	5.07
2	6/24/24	15:01:15	15:53:30	46.2	2.08
2	6/24/24	16:05:15	16:51:00	19.23	0.68
2	6/24/24	17:00:15	17:49:00	32.18	2.91
2	6/25/24	9:02:00	9:48:00	0.77	6.02
2	6/25/24	10:03:00	10:49:00	1.95	2.43
2	6/25/24	11:05:00	11:51:00	8.2	11.17
2	6/25/24	12:05:00	12:51:15	32.1	2.92
2	6/25/24	13:35:00	14:21:00	50.42	1.92
2	6/25/24	14:35:00	15:22:00	21.7	4.26
2	6/25/24	15:33:00	16:19:00	54.95	1.78
2	6/25/24	16:39:00	17:34:30	1.48	3.15
2	6/26/24	8:55:00	9:43:00	1.62	2.88
2	6/26/24	10:01:00	10:52:00	1.33	3.47
2	6/26/24	11:00:00	11:50:00	9.71	0.8
2	6/26/24	13:03:10	13:51:10	4.83	1.15
2	6/26/24	14:00:00	14:52:20	0.01	2
2	6/26/24	15:01:20	15:49:30	44.02	2.17
2	6/26/24	16:03:00	16:50:00	8.55	10.71
2	6/26/24	17:01:00	17:47:00	0	0
2	6/27/24	8:56:00	9:44:00	37.59	2.51
2	6/27/24	10:09:00	10:55:00	42.06	2.26
2	6/27/24	11:06:00	11:56:30	0.57	7.86
2	6/27/24	12:09:00	12:55:00	8.55	10.71
2	6/27/24	13:29:00	14:15:00	13.91	6.62
2	6/27/24	14:35:00	15:22:00	37.59	2.51
2	6/27/24	15:33:15	16:19:15	81.3	2.01
2	6/27/24	16:35:30	17:24:05	1.44	3.22
2	6/28/24	9:00:00	9:47:30	2.98	1.67
2	6/28/24	10:10:40	10:56:00	0.32	2
2	6/28/24	11:02:30	11:49:15	189	1.03
2	6/28/24	12:03:30	12:51:00	19.23	0.68

Table S7. Week 3 methane release flowrates and times

Week	Date	ReleaseStart	ReleaseEnd	Flowrate (kg h^{-1})	Uncertainty (%)
3	9/9/24	11:02:30	11:50:10	56.7	1.73
3	9/9/24	12:05:00	12:52:30	31.36	2.98
3	9/9/24	13:23:55	14:16:00	5.57	1.05
3	9/9/24	14:30:30	15:20:45	0	0
3	9/9/24	15:25:15	16:15:40	0.18	2
3	9/9/24	16:42:00	17:36:30	13.38	0.72
3	9/10/24	8:45:00	9:31:00	0.92	4.88
3	9/10/24	9:45:15	10:31:00	2.02	2.35
3	9/10/24	10:40:00	11:26:00	79.2	2.05
3	9/10/24	11:45:00	12:31:00	17.8	5.19
3	9/10/24	12:44:00	13:36:30	6.77	0.94
3	9/10/24	13:44:15	14:30:00	1.85	2.57
3	9/10/24	14:44:00	15:30:00	28.16	3.31
3	9/10/24	15:44:00	16:30:00	4.47	1.22
3	9/10/24	16:46:00	17:36:00	0.45	9.66
3	9/11/24	8:35:15	9:22:00	54	1.81
3	9/11/24	9:34:00	10:20:30	31.36	2.98
3	9/11/24	10:37:50	11:25:00	1.01	4.54
3	9/11/24	11:34:00	12:22:00	20.18	3.67
3	9/11/24	12:37:00	13:25:00	0.02	2
3	9/11/24	13:34:15	14:22:00	0.62	7.41
3	9/11/24	14:34:15	15:20:15	0.7	6.64
3	9/11/24	15:34:00	16:22:00	44.07	2.17
3	9/11/24	16:34:00	17:23:00	51.12	1.9
3	9/12/24	9:16:15	10:02:00	19.74	0.68
3	9/12/24	10:06:00	10:54:00	13.38	0.72
3	9/12/24	11:07:30	11:55:00	4.14	1.29
3	9/12/24	12:00:00	12:46:15	37.1	2.54
3	9/12/24	13:28:00	14:15:00	50.88	1.91
3	9/12/24	14:31:00	15:17:00	1.3	3.56
3	9/12/24	15:28:00	16:15:00	210	0.96
3	9/12/24	16:30:45	17:17:30	26.85	3.46

3	9/13/24	8:45:00	9:32:00	0	0
3	9/13/24	9:49:00	10:35:00	3.4	1.5
3	9/13/24	10:45:00	11:31:05	1.47	3.15
3	9/13/24	11:45:00	12:33:00	308.2	0.8
3	9/13/24	12:45:00	13:34:00	20.18	0.67

Table S8. Week 4 methane release flowrates and times

Week	Date	ReleaseStart	ReleaseEnd	Flowrate (kg h^{-1})	Uncertainty (%)
4	9/16/24	11:00:00	11:46:10	0.57	2.21
4	9/16/24	11:59:00	12:47:00	56.7	1.73
4	9/16/24	12:59:00	13:45:00	11.17	0.76
4	9/16/24	13:59:30	14:46:00	28.71	3.95
4	9/16/24	14:59:00	15:45:00	21.64	4.28
4	9/16/24	15:59:00	16:45:00	9.23	0.81
4	9/17/24	9:00:30	9:46:00	0.9	5.07
4	9/17/24	9:59:00	10:46:00	7.3	0.9
4	9/17/24	10:59:00	11:50:00	79.2	2.05
4	9/17/24	11:59:30	12:49:30	5.5	1.06
4	9/17/24	13:00:00	13:46:30	0	0
4	9/17/24	13:58:30	14:45:00	54	1.81
4	9/17/24	14:58:00	15:44:00	0.02	2
4	9/17/24	15:47:00	16:44:00	44	2.17
4	9/18/24	8:51:30	9:37:00	0.5	8.97
4	9/18/24	9:44:30	10:31:00	38.47	2.46
4	9/18/24	10:45:00	11:31:15	1.45	3.22
4	9/18/24	11:44:00	12:33:00	52.94	1.84
4	9/18/24	12:45:00	13:25:30	0.29	2
4	9/18/24	13:30:00	14:16:00	8.25	0.85
4	9/18/24	14:29:00	15:15:45	0.19	2
4	9/18/24	15:30:00	16:17:00	290	1.67
4	9/18/24	16:31:20	17:19:45	0.73	6.31
4	9/19/24	8:45:00	9:32:30	28.71	3.25
4	9/19/24	9:45:00	10:31:00	1.63	2.88
4	9/19/24	10:44:00	11:32:00	2.01	2.35
4	9/19/24	11:44:00	12:31:30	4.14	1.29

4	9/19/24	12:44:00	13:32:30	49.01	1.97
4	9/19/24	13:46:00	14:34:00	1.14	3.99
4	9/19/24	14:44:00	15:31:00	80.1	1.67
4	9/19/24	15:44:30	16:34:00	8.25	0.85
4	9/19/24	16:44:10	17:36:00	26.4	3.52
4	9/20/24	8:45:15	9:31:00	3.3	1.53
4	9/20/24	9:45:00	10:34:00	38.47	2.46
4	9/20/24	10:45:00	11:33:00	34.4	2.73
4	9/20/24	11:46:15	12:33:00	1	4.54
4	9/20/24	12:46:50	13:33:00	17.93	0.68
4	9/20/24	13:51:00	14:20:00	0	0
4	9/20/24	14:32:30	15:20:00	54	1.81
4	9/20/24	15:32:30	16:41:00	250.8	0.87

Safety limitations allowed only one drone and one aircraft flying in the air at a time to ensure that no mid-air collision occurs. This results in some drone teams having fewer datapoints than ground vehicle or fixed sensors. During weeks with more than one drone (Week 1), the drone teams switched off measuring the releases. Only one aircraft was scheduled for each week.

S1.4 Participant Scheduling

Participant Week assignments were decided based on participant availability and test site constraints. Because the participants were going to measure concurrently, we aimed to achieve a mix of different measurement techniques in each week. Additionally, more constraints were placed on drones and aircraft. The Stanford and TADI team limited participation to two drones per week and one aircraft per week to ensure that each team had the opportunity to measure a significant number of releases while maintaining safe operations.

There were some difficulties in scheduling participants. Because the TADI site is located on a Seveso 3 industrial site, there are several restrictions and certifications placed on the operation of drones within the site and aircraft flying above it.[i] This resulted in some participants that had expressed initial interest being unable to participate in the experiment, citing difficulties with obtaining the necessary permissions for operation.

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[i] SEVESO 3 industrial site refers to an industrial facility that falls under the regulations of the Seveso III Directive (Directive 2012/18/EU), meaning it handles large quantities of dangerous substances and is required to implement strict safety measures to prevent major accidents and minimize their consequences on people and the environment.

S1.4.1 GHGSat Scheduling

Specific scheduling was needed for GHGSat measurements due to the larger detection limit and pre-set overpass times of the satellites. Two weeks before each campaign in June and September, the GHGSat team sent us the TADI overpass schedule for that timeframe. We would then indicate which overpasses we would target releases for, given the other constraints on the daily release schedule discussed above. Other teams were not informed of this data, as it might give them information about planned sizes.

S2 Participant & Technology Descriptions

Eight commercial teams participated in the testing across four weeks. Their methane detection and quantification solutions were deployed via satellite, aircraft, drone, vehicle, and fixed ground sensors and cameras. Descriptions of each participant's technology and team can be found in Sect. S2.1. These descriptions are based off interviews conducted with each participant during their week of testing, participant submissions to technology and method surveys included with their results, and publications. Table S9 contains the specific technology deployed by each participant.

Table S9. Participant name, solution name, and technology type.

Participant Type	Participant	Solution Name	Technology Type
Commercial	*Aeromon*	Aeromon BH-12	Drone
Commercial	*GSMA*	AUSEA	Drone
Commercial	*Flylogix*	Flylogix Asset-level Methane emissions report	Drone
Commercial	*SeekOps*	TDLAS (SeekIR) Sensor	Drone
Commercial	*GHGSat*	GHGSat-C2, C3, C4, C5, C7, and C8 (GHGSat-C)	Satellite
Commercial	*Sensirion*	Nubo Sphere	Continuous Monitor
Commercial	*SLB*	Methane Lidar Camera	Continuous Monitor
Commercial	*SENSIA*	Mileva 33	Continuous Monitor
Academic	*DTU*	N/A	Vehicle
Academic	*UHEI*	N/A	Vehicle
Academic	*UU/LSCE/CYI/RHUL*	N/A	Vehicle
Academic	*Empa/UZH*	AVIRIS-4	Aircraft
Academic	*FAAM*	N/A	Aircraft

Many of the participants have participated in previous testing at TADI or in single-blind controlled release experiments conducted by Stanford. Previous testing may have resulted in more familiarity with the testing methods and site configuration.

Table S10. Previous controlled release testing of the participants.

Solution	Previously Tested by Stanford	Previously Tested on TADI or TotalEnergies Sites
Aeromon BH-12	No	No
GSMA AUSEA	No	Yes
Flylogix	No	Yes
SeekOps SeekIR	Yes	Yes
GHGSat-C	Yes	Yes
Sensirion Nubo Sphere	Yes	Yes
SLB Methane Lidar Camera	No	Yes
SENSIA Mileva 33	No	Yes

The Stanford tests were all single-blind controlled release experiments. SeekOps was tested in the Stanford/EDF Mobile Monitoring Challenge in 2018 (Ravikumar et al., 2019).[3] GHGSat's C-series (GHGSat-C) satellites were tested during experiments in 2021 and 2022 (Sherwin et al., 2023, Sherwin et al., 2024).[4,5] Sensirion's Nubo Sphere point sensor network was also tested in 2022 (Chen et al., 2024).[6]

S2.1 Technology Descriptions

S2.1.1 Aeromon BH-12 (Aeromon Oy)

Aeromon Oy measured methane using an in-situ sensor attached to a drone. Their modular BH-12 measuring device supports a series of attached sensors to allow for simultaneous measuring of different compounds. In the experiment, the drone hosted a tunable diode laser spectrometer that measured methane concentrations. The drone also supported a miniaturized 3d anemometer. Aeromon installed a fixed 2d wind and weather station on the test site for meteorological data. They deployed their sensor on a drone operated by contractor Skeye. The target gas concentration, location, altitude, wind speed and direction at sampling position and timestamp was measured with Aeromon BH-12 measuring device with sensor modules for CH_4 and wind speed/direction. The methane sensor has a reported detection limit of 0.19 ppm above ambient background. This mobile setup was carried around the test site with DJI M300 drone. The stationary weather station was installed at location (43.412777, -0.643708, 10 m AGL). Aeromon's stationary 2D anemometer was used only half of their testing week (Wednesday-Friday) due to the airline losing the mast in transit. Vaisala WXT combined with Aeromon BH-12 was used.

The mass flow rate measurements can be divided into two different approaches, Reverse Dispersion Modelling (RDM) and Mass Balance (MB). RDM is suitable for cases where a plume from individual source can be separated from the background and there's no turbulent dilution between the source and the measurement point. MB is suitable for any type of combination of sources and dilution processes. In both cases the first step is to map out the entire plume from the source by measuring horizontal measurement lines downwind from the source. The lines are repeated at different altitudes to cover the plume(s) from source area completely. The altitude step is predetermined and kept constant. Aim is to repeat these full fence line walls at least 3 times with MB approach. For RDM at least 10 good repetitions from the plume centerline region are expected for analysis. In this campaign there was a time limitation for each test and for this reason the upwind reference was not measured separately. The background level was measured before and after the tests and it was found to be zero above the ambient background with all tested wind directions. In this campaign only MB approach was used at the end for quantification as the source area could not be reached due to EX restrictions. The boundary conditions for mass flow rate quantification are as follows: 1) the average wind speed over the measurement time must be between 1 - 15 m/s, preferably 2-10 m/s and 2) wind persistence, P, should be > 0.9 (In accordance with EN 17628, wind persistence, P, defined as the ratio of the magnitude of the wind-vector to the scalar wind speed.)

Aeromon Oy provides services to verify and quantify emissions from industrial plants. They deploy UAV-assisted emission monitoring solutions through their platform of the BH-12 measuring device and the analytics system Aeromon Cloud Service™. Aeromon is based in Finland and operates globally.[7]

S2.1.2 University of Reims Champagne-Ardenne (GSMA) AUSEA

The GSMA laboratory deployed a UAS-based methane measurement technology in Week 1 of this campaign. Their Airborne Ultra-light Spectrometer for Environmental Application (AUSEA) sensor (Bonne et al., 2024; Joly et al., 2016, 2020) embarked on a multi-copter UAS.[8–10] The sensor technology was developed by GSMA and TotalEnergies.[11]

This sensor is an open path laser absorption spectrometer that measures in situ CO_2 and CH_4 concentrations at 24 Hz, using two DFB interband cascade laser diodes in the mid-infrared spectral region (near 3 μm). Air temperature, pressure and relative humidity parameters are recorded and used by the inversion process to derive gas concentrations from recorded spectra, accounting for their spectroscopic effects on the CO_2 and CH_4 absorption lines. Vertical profiles of wind speeds and directions were monitored in parallel with a ZX-300 wind Lidar operating from the ground. The lidar integrates a 2D sonic anemometer at 1.5 m above ground level, which complements the laser-based measurements at 11 heights (120m, 100m, 80m, 70m, 60m, 50m, 40m, 38m, 30m, 20m and 10m), providing wind profiles at an approximative temporal resolution of 18s.

The UAS was operated by contractor ROAV7. The flight paths consist in a succession of horizontal transects at different altitudes covering a plume cross-section in a vertical plane approaching the orthogonal of the wind direction. The horizontal and vertical extents of the flight path is expected to cover the entire cross-section of the plume. The fluxes were derived from the wind and concentrations measurements based on a Lagrangian mass balance approach. The fluxes are estimated as the integral of the product of the wind speed component orthogonal to the monitoring plane and of the concentration enhancements within the plume compared to the background level (measured outside the plume). In previous controlled release experiments at TADI, this method could detect leaks with emission fluxes down to 0.01 g/s (Bonne et al., 2024).[8]

The Molecular and Atmospheric Spectrometry Group (GSMA) is a joint research unit between the National Center for Scientific Research (CNRS) and the University of Reims, both institutions in France. The GSMA is an interdisciplinary laboratory that combines fundamental and applied spectroscopy and its application to atmospheric and planetary sciences.[12]

S2.1.3 Flylogix

Flylogix deployed a drone-mounted sensor. They used an Aeris Strato sensor, a mid IR range laser absorption methane spectrometer, to sample methane concentrations in the air at 5 Hz. Wind data were measured using a Davis weather station fixed on the ground. A DJI M300 drone flew in a rectangular pattern around the platform, completing several paths around the perimeter at different heights. Plumes were quantified using a mass balance approach. Contractor Air Control Entech operated the drone. Flylogix typically conducts offshore measurements using a fixed-wing drone, and their technology was adapted to the conditions at TADI.

Flylogix Holdings Limited (Flylogix) is a U.K. based company that utilizes unmanned aircraft in remote operations. Their core business is conducting emissions and safety monitoring of offshore platforms in the North Sea.[13] Their typical operations involve long-distance flights using fixed wing drones.

S2.1.4 SeekOps SeekIR

SeekOps deployed a drone-mounted sensor. They used a tunable diode laser absorption spectrometer in the midwave infrared range and coupled this with wavelength modulation spectroscopy to detect methane concentrations. Their sensor employs absorption spectroscopy, utilizing a tunable diode laser (TDL) situated within an open cavity flanked by two mirrors. This configuration extends the laser's path length, enhancing its sensitivity to CH_4's absorption characteristics. Accurate determination of parameters such as pressure, temperature, wavelength, and path length enables the calculation of the target species' concentration through observed changes in spectral intensity. In this setup, the TDL serves as the source of initial spectral intensity, while a photovoltaic detector, attuned to the laser's spectral region, measures photons unabsorbed by methane molecules. Wavelength Modulation Spectroscopy (WMS) modulates both the laser's intensity and wavelength at a specific frequency, optimizing the signal-to-noise ratio. Employing filters for high frequencies enables the demodulation of the detected response, thus quantifying the methane concentration within the open cavity. The drone flight path consisted of transects of the plume spaced at 1m height intervals. This data was input into proprietary algorithms using a mass-balance approach to quantify emissions. The drone was flown by contractor ROAV7.

SeekOps delivers tailored emissions monitoring solutions and services to participants in both traditional and renewable energy industries. They are located in Austin, Texas, USA.[14]

S2.1.5 GHGSat-C (GHGSat)

GHGSat was a participant in all four weeks of the campaign. The GHGSat-C constellation is explicitly designed for methane sensing and deploys a patented imaging interferometer. At the time of testing, there were 12 GHGSat-C satellites in orbit.[15] The field of view of the sensors is 12 km-wide with a claimed detection limit of 100 kg h^{-1} at 3 m/s winds and a spatial resolution of around 25m.[5] The specific instruments used in this testing were the WAF-P instrument on GHGSat-C4, GHGSat-C5, and GHGSat-C7. Each release previously agreed on has been coordinated with a single satellite overpass, which yields a retrieval domain covering approximately 10 km x 15 km area. Once the data was downlinked, it was processed and reviewed for quality. If the quality was good, the georeferencing accuracy was validated and emissions were identified. For every emission identified, a mask was created using a semi-automatic floodfill algorithm to isolate the emission from the background. This mask was used to estimate the source rate using the Integrated Mass Enhancement method (Varon et al. 2018).[16]

GHGSat Inc., is the participant of the GHGSat-C satellite constellation. GHGSat combines greenhouse gas emissions monitoring from space, aircraft services, and emissions analytics to deliver emissions intelligence for participants, governments, and regulators.[17]

S2.1.6 Sensirion Nubo Sphere (Sensirion Connected Solutions)

In this study, Sensirion Connected Solutions (SCS) operated a fixed-point continuous monitoring system for all four testing weeks. They installed twelve *in situ* methane sensors on six poles around the test site. Each pole had a sensor at 1.5m and 5m above ground. The six sensors at 1.5m were used for reporting purposes. The extended cartridges mounted at 5m height above ground were purely installed for data collection purposes for post-processing, but their signals were not ingested into the algorithms. Each instrument deployed Sensirion Connected Solutions' Nubo Sphere™ sensor node, which uses a photoacoustic-based laser spectroscopy sensing technology to detect methane concentrations.[18] The Nubo Sphere sensor node has two slots for sensing cartridges and LTE connection for real-time data transmission. The cartridge can be exchanged for maintenance or upgrading. All devices are installed above ground, and a 2D ultrasonic wind sensor is included on one pole. No additional meteorological data is collected. In previous controlled release testing, the Nubo Sphere sensor network has detected releases > 0.1 kg h^{-1} with 90% probability of detection.[6] In detail, the solution consists of three components: the sensor hardware, the data analytics, and the real-time user dashboard.

Sensirion Connected Solutions AG is part of Sensirion Holding AG that specializes in sensor-based services and solutions for emission monitoring in the energy sector. They integrate proprietary sensor technology, data analytics, and user interfaces to provide insights into emissions. Their headquarters are in Stäfa, Switzerland and Chicago, Illinois, USA.[19]

S2.1.7 SLB Methane Lidar Camera

SLB participated in both weeks of the campaign in September. The SLB methane lidar camera uses tunable diode lidar (TDLidar), which combines the advantages of a range of gas-detection technologies to enable remote spectroscopy and ranging with low-power semiconductor diode lasers. It uses differential absorption lidar (DIAL) technology to quantify methane emissions; tunable diode laser absorption spectroscopy (TDLAS), which can detect very low methane concentrations; and time-correlated single-photon counting (TCSPC), which enables long-range, low-power, eye-safe imaging. The camera emits a laser beam to scan for emissions within finite conical fields of view and iterates through scan plans to cover all emission sources. Wind speed and direction are measured using an anemometer connected to the camera at ~7.5 m height above ground. Upon leak detection, the camera uses a mass balance algorithm to quantify the mass emission rate.[20] The methane lidar camera is a licensed product of QLM Technology Ltd. In this experiment, the camera was mounted on a tall structure on the platform to get a vantage point above most of the equipment. The camera was installed on a pole connected to the walkway railing on top of the yellow tank at the northwest corner of TADI at ~9 m height above ground. SLB optimizes the standard commercial installation location and height for their camera and anemometer to avoid obstacles in the wind field and along the camera's line of sight. Due to facility restrictions on allowed installation locations at TADI, SLB installed their anemometer closer to a large tank and at a much higher height than their standard installations, and their camera at a much lower height.

SLB, formerly known as Schlumberger, is a global technology and oilfield services company in the energy sector. They have a global footprint in more than 100 countries and employees representing almost twice as many nationalities, and work on developing and scaling energy systems. SLB's methane elimination services cover the spectrum end to end, including monitoring emissions from satellites, drones, or on the ground.[21]

S2.1.8 SENSIA Mileva 33 (SENSIA Solutions)

SENSIA's Mileva 33 imaging sensor measured releases during both weeks of the September campaign. They deployed an infrared optical gas imaging (OGI) camera in the spectral band of 3.2-3.4µm, fixed at 9m above ground on a tower onsite at TADI, which scans through pre-set camera angles to detect the release. SENSIA's technology does not require any additional instrumentation apart from the OGI camera (e.g. an anemometer). Their approach leverages proprietary AI and computer vision analytics for automatic and unattended detection and quantification of emissions. The camera was installed on a pole connected to the walkway railing on top of the yellow tank at the northwest corner of TADI at ~9 m height above ground.

SENSIA is a European company based in Madrid that designs and manufactures advanced infrared imaging solutions. Their mission is to support industry in their safety and sustainability goals.[22]

S2.2 Flight Participant Descriptions

Several participating drone and aircraft teams used contractors to pilot their operations. Below finds the description of these contract flight participants.

S2.2.1 ROAV7

ROAV7 is a company specializing in drone-based data acquisition and processing. They operate in a variety of different fields, including offshore, infrastructure, renewable energies, raw materials, and agriculture in Europe and Africa. Their European operation is based in Le Havre, France.[23]

S2.2.2 Skeye

Skeye offers drone survey and inspection services. They provide solutions for geographic data acquisition, industrial inspections, and aerial imagery. They operate globally and have offices in the U.K. and the Netherlands.[24]

S2.2.3 Air Control Entech

Air Control Entech is a remote inspection technology company, mostly focused on offshore O&G platform operations. They deploy innovative robotics, including custom-engineered UAVs, to find remote inspection solutions. The company is based in Aberdeen, Scotland.[25]

S2.2.4 Swiss Flight Services

Swiss Flight Services SA is a private Swiss company based in Colombier that operates its own fleet under the authority of the Swiss Federal office of Civil Aviation. They are an experienced service provider for aerial surveys such as photogrammetry, laser scanning, and remote sensing in general.[26]

S2.3 Participant Technology Survey Responses

This section contains descriptions of the participants as reported in the Data Reporting Template spreadsheet.

S2.3.1 Aeromon Technology Survey Responses

Company	Aeromon Oy
Product name	Aeromon BH-12
(1) Please provide a detailed description of system configuration and primary components including the sensor and deployment platform. Additionally, the location (latitude, longitude, height) of auxiliary components such as meteorological station or any other equipment installed at or near the Test Center must be recorded.	Target gas concentration, location, altitude, wind speed and direction at sampling position and timestamp was measured with Aeromon BH-12 measuring device with sensor modules for CH4 and wind speed/direction. Methane sensor has a detection limit of 0.19 ppm above ambient background. This mobile setup was carried around the test site with DJI M300 drone. Stationary weather station was installed at location (43.412777, -0.643708, 10 m AGL). Vaisala WXT combined with Aeromon BH-12 was used.

(2) Please record the model number of each primary component in (1), if applicable.	BHMD-0164 and BHMD-0170 as mobile measurement device and backup. BHMD-0149 as weather station device.
(3) Please record the software revision installed on the components in (1), including performer-specific software components, revisions, or customizations	CPU code version in BHMD devices "2024.04"
(4) Please record the revision number of any software analytics installed offsite. For example software to convert concentration maps to mass emission quantification estimates during the experiments.	ACS (Aeromon Cloud Service) 2.0
(5) Please provide a detailed description of the methodology used during emission detection/quantification surveys.	The mass flow rate measurements can be divided into two different approaches, Reverse Dispersion Modelling (RDM) and Mass Balance (MB). RDM is suitable for cases where a plume from individual source can be separated from the background and there's no turbulent dilution between the source and the measurement point. MB is suitable for any type of combination of sources and dilution processes. In both cases the first step is to map out the entire plume from the source by measuring horizontal measurement lines downwind from the source. The lines are repeated at different altitudes to cover the plume(s) from source area completely. The altitude step is predetermined and kept constant. Aim is to repeat these full fence line walls at least 3 times with MB approach. For RDM at least 10 good repetitions from the plume centreline region are expected for analysis. In this campaign there was a time limitation for each test and for this reason the upwind reference was not measured separately. The background level was measured before and after the tests and it was found to be zero above the ambient background with all tested wind directions. In this campaign only MB approach was used at the end for quantification as the source area could not be reached due to EX restrictions. The boundary conditions for mass flow rate quantification are as follows: 1) the average wind speed over the measurement time must be between 1 - 15 m/s, preferably 2-10 m/s and 2) wind persistence, P, should be > 0.9 (In accordance with EN 17628, wind persistence, P, defined as

	the ratio of the magnitude of the wind-vector to the scalar wind speed.)
(6) Please provide the confidence level at which emission detection data are reported. (e.g., 95% CI, +/- 1 sigma)	95% Cl
(7) Please record the number of personnel participating in the surveys and their roles. Any remote personnel participating in the survey in any fashion should be documented as part of the survey team in this section. Names of individual personnel are not required.	1) Payload participant. 2) Reporter. These two may also be the same person.
(8) For hyperspectral technologies, describe how plume length is determined for quantification.	-
(9) If wind speed is used in computing total emission rate, please describe how the wind estimate is obtained, including the precise instrument or wind reanalysis product used.	For MB approach the perpendicular wind speed vector in relation to the measurement line is measured with Trisonica Mini sensor. The sensors are tested and compared to calibrated Vaisala WXT weather station in both controlled and field conditions. Drones downwash effect on onboard wind speed measurement is measured and compensated mathematically. The wind stability is analyzed from fixed weather station data in all quantification cases.
(10) If uncertainty is reported, where is it coming from? Is it from calculations, reported data, experimentation, etc.	Uncertainty of Aeromon's MB approach combines the measurement uncertainties of the methane sensor concentration measurement (defined according to CEN TS 17660), wind sensor

	and drone location throughout the entire fenceline wall with result-to-result deviation between full fenceline walls.

S2.3.2 GSMA Technology Survey

Company	J1 - GSMA - LabCom LYNNA
Product name	AUSEA
(1) Please provide a detailed description of system configuration and primary components including the sensor and deployment platform. Additionally, the location (latitude, longitude, height) of auxiliary components such as meteorological station or any other equipment installed at or near the Test Center must be recorded.	AUSEA is a technology combining : (1) A IR Spectrometer measuring CH_4 and CO_2 @ 24Hz frequency, (2) a DJI M300/M350 RTK drone, (3) a Wind Lidar to measure wind speed and direction profiles located at all time on the ground at the position [lat:43.41286, lon:-0.64340], (4) a tablet for real time concentration monitoring (5) specific quantification software
(2) Please record the model number of each primary component in (1), if applicable.	(1) AUSEA sensor i210 and i207 have been used, (2) Drone DJI M350 RTK, (3) Lidar ZX 300
(3) Please record the software revision installed on the components in (1), including performer-specific software components, revisions, or customizations	Software ADMIN V20221024 has been used for real time monitoring and operation management
(4) Please record the revision number of any software analytics installed offsite. For example software to convert concentration maps to mass emission quantification estimates during the experiments.	Software AUSEA Calculator V5.1.2 has been used for data analysis and emission quantification.
(5) Please provide a detailed description of the methodology used during emission detection/quantification surveys.	Flight with ladder pattern have been used to sample CO_2 and CH_4 concentrations on a cross section of the emission plume with a specific vertical step and with a global size aiming at ensuring that all the plume is sampled. Sampling completion is made thanks to the concentration real time monitoring. Wind is measured such as providing an estimation of the wind speed at the drone location. Concentrations, positions and wind data are mixed to provide an emission quantification using a mass balance method.

(6) Please provide the confidence level at which emission detection data are reported. (e.g., 95% CI, +/- 1 sigma)	Uncertainty of a single measurement is established at +/- 40% according to previous control releases experiments.
(7) Please record the number of personnel participating in the surveys and their roles. Any remote personnel participating in the survey in any fashion should be documented as part of the survey team in this section. Names of individual personnel are not required.	2 people on the field to manage drone flights and sampling control. 1 data analyst to run quantification software and provide analyzed figures.
(8) For hyperspectral technologies, describe how plume length is determined for quantification.	N/A
(9) If wind speed is used in computing total emission rate, please describe how the wind estimate is obtained, including the precise instrument or wind reanalysis product used.	Wind is measured using a ZX 300 Wind Lidar at 11 heights : 120m 100m 80m 70m 60m 50m 40m 38m 30m 20m 10m . Data are interpolated in time to match sampling time. Data are interpolated between measurements level along the altitude to match the drone position and extrapolated under the minimum altitude supposing a neutral wind profile.
(10) If uncertainty is reported, where is it coming from? Is it from calculations, reported data, experimentation, etc.	Single quantification uncertainty comes from a combination of previous TADI and METEC experiments conducted with AUSEA. When several quantifications have been used to produce the final quantification, uncertainty is calculated with the following formula: with Ci a single quantification and n the number of quantifications $$\frac{\sqrt{\sum_i^n (0.4.C_i)^2}}{n\left[\frac{\sum_i^n C_i}{n}\right]}$$

S2.3.3 Flylogix Technology Survey Responses

Company	Flylogix Holdings Ltd
Product name	Flylogix Asset-level Methane emissions report

(1) Please provide a detailed description of system configuration and primary components including the sensor and deployment platform. Additionally, the location (latitude, longitude, height) of auxiliary components such as meteorological station or any other equipment installed at or near the Test Center must be recorded.	DJI Mavic M300 Aeris MIRA Strato LDS - Natural Gas Davis Vantage Pro2 weather station (~3m above ground)
(2) Please record the model number of each primary component in (1), if applicable.	
(3) Please record the software revision installed on the components in (1), including performer-specific software components, revisions, or customizations	
(4) Please record the revision number of any software analytics installed offsite. For example software to convert concentration maps to mass emission quantification estimates during the experiments.	Flylogix Methane Analysis script - Quadcopter v0.4
(5) Please provide a detailed description of the methodology used during emission detection/quantification surveys.	This is a standard mass balance method using Gauss's Law to calculate the methane flux, see e.g. `Application of Gauss's theorem to quantify localized surface emissions from airborne measurements of wind and trace gases', S. Conley et al.: Atmos, Meas. Tech. 10, 3345-3358, 2017.
(6) Please provide the confidence level at which emission detection data are reported. (e.g., 95% CI, +/- 1 sigma)	3-sigma
(7) Please record the number of personnel participating in the surveys and their roles. Any remote personnel participating in the survey in any fashion should be documented as part of the survey team in this section. Names of individual personnel are not required.	Drone Pilot, Data Processing Engineer
(8) For hyperspectral technologies, describe how plume length is determined for quantification.	

(9) If wind speed is used in computing total emission rate, please describe how the wind estimate is obtained, including the precise instrument or wind reanalysis product used.	We used a Davis Vantage 2 Pro Weather station with WeatherLink telemetry system to store the data An calibration offset was applied to the wind direction to centralise the plume downwind
(10) If uncertainty is reported, where is it coming from? Is it from calculations, reported data, experimentation, etc.	The methane uncertainty is obtained by analysis of the 'background' Methane measurement data to get bias and variance of the sensor The wind speed and direction uncertainty is obtained from a combination of the specs of the Davis Vantage 2 Pro Weather station and the statistics of the data measured

S2.3.4 SeekOps Technology Survey Responses

Company	SeekOps
Product name	TDLAS (SeekIR) sensor
(1) Please provide a detailed description of system configuration and primary components including the sensor and deployment platform. Additionally, the location (latitude, longitude, height) of auxiliary components such as meteorological station or any other equipment installed at or near the Test Center must be recorded.	
(2) Please record the model number of each primary component in (1), if applicable.	
(3) Please record the software revision installed on the components in (1), including performer-specific software components, revisions, or customizations	
(4) Please record the revision number of any software analytics installed offsite. For example software to convert concentration maps to mass emission quantification estimates during the experiments.	

(5) Please provide a detailed description of the methodology used during emission detection/quantification surveys.	Our sensor employs absorption spectroscopy, utilizing a tunable diode laser (TDL) situated within an open cavity flanked by two mirrors. This configuration extends the laser's path length, enhancing its sensitivity to CH4's absorption characteristics. The underlying physical principle, governed by the Beer-Lambert Law, elucidates how spectral intensity variation at a given wavelength – after traversing a sample – relates to the physical parameters of the sample, including initial spectral intensity and path length (Hanson, 2016). Accurate determination of parameters such as pressure, temperature, wavelength, and path length enables the calculation of the target species' concentration through observed changes in spectral intensity. Our sensor incorporates a multi-pass optical cell (a Herriott Cell) to augment the laser's path length, thereby enhancing the sensitivity to variations in concentration, temperature, or pressure. This Herriott Cell consists of two highly reflective concave mirrors, precisely aligned to reflect the desired wavelength of light. Such an arrangement enables the laser beam to undergo multiple reflections within the cavity, significantly extending the interaction path with the sample gas and improving the detection sensitivity. In this setup, the TDL serves as the source of initial spectral intensity, while a photovoltaic detector, attuned to the laser's spectral region, measures photons unabsorbed by methane molecules. To further refine the process, Wavelength Modulation Spectroscopy (WMS) modulates both the laser's intensity and wavelength at a specific frequency, optimizing the signal-to-noise ratio and facilitating a calibration-free approach to laser diagnostics. This method allows for the establishment of calibration factors at the time of manufacture, which remain valid throughout the instrument's lifespan. Employing filters for high frequencies enables the demodulation of the detected response, thus quantifying the methane concentration within the open cavity.
(6) Please provide the confidence level at which emission detection data are reported. (e.g., 95% CI, +/- 1 sigma)	

(7) Please record the number of personnel participating in the surveys and their roles. Any remote personnel participating in the survey in any fashion should be documented as part of the survey team in this section. Names of individual personnel are not required.	FSM (Field Service Manager), DSP (Drone Service Provider), DA (Data Analyst), Environmental Scientist.
(8) For hyperspectral technologies, describe how plume length is determined for quantification.	The advent of modern enterprise-grade drones, equipped with anti-collision sensors, enables close, safe proximity to operational equipment, ensuring thorough and safe operational coverage without endangering personnel or disrupting ongoing site activities. We estimate a plume's length by employing the Navier-Stokes equations to model fluid movements and their interactions. This approach necessitates numerous measurements and assumptions to accurately address the inverse problem. We apply the law of conservation of mass to estimate methane's mass flow from specific equipment. This method is predicated on three fundamental assumptions: 1. The targeted area is confined within a well-defined engineering control volume. 2. Essential parameters, such as the density and velocity of wind, can be either directly measured or accurately modeled. 3. The variance in mass flowrate is attributed exclusively to the specified area of interest. Employing the conservation of mass principle, we express the mass flowrate of emissions, $\dot{m}_{emissions}$, as the differential between the mass flowrates along the downwind, $\dot{m}_{out}$, and upwind surfaces, $\dot{m}_{in}$. $\dot{m}_{emissions}=\dot{m}_{out}-\dot{m}_{in}$ Moreover, to compute the mass flowrate, we integrate across the control volume: $\dot{m}_{emissions} = \iint \rho \ (\chi_{yz} - \chi_b) \ v(z) \cdot \hat{n} \ dx \ dz$ Here, ρ represents CH_4's density under specific temperature and pressure conditions, χ_{yz} indicates CH_4 concentration in parts-per-million by volume (ppmv) at each measurement point, χ_b

	refers to the background CH4 concentration, and (v(z)) denotes the wind vector's normal component at varying altitudes throughout the engineering control volume. The resultant mass flowrates, expressed in grams per second (g/s) or standard cubic feet per hour (SCFH), incorporate standard corrections for temperature and pressure.
(9) If wind speed is used in computing total emission rate, please describe how the wind estimate is obtained, including the precise instrument or wind reanalysis product used.	Wind velocity measurements utilized in our calculations are derived from an on-site stationary anemometer, complemented by a wind profile model tailored to local surface characteristics. Airdata is used for wind reanalysis.
(10) If uncertainty is reported, where is it coming from? Is it from calculations, reported data, experimentation, etc.	We report a standardized +/- 30% uncertainty (influenced by wind variability).

S2.3.5 GHGSat Technology Survey Responses

Company	GHGSAT
Product name	DATA.SAT
(1) Please provide a detailed description of system configuration and primary components including the sensor and deployment platform. Additionally, the location (latitude, longitude, height) of auxiliary components such as meteorological station or any other equipment installed at or near the Test Center must be recorded.	WAF-P instrument on GHGSat-C4, GHGSat-C5, and GHGSat-C7
(2) Please record the model number of each primary component in (1), if applicable.	NA
(3) Please record the software revision installed on the components in (1), including performer-specific software components, revisions, or customizations	GHGSat-C3+ Firmware version: 10.29.4 GHGSat-C3+ Observation script for : N5138CC1.GSB
(4) Please record the revision number of any software analytics installed offsite. For	Retrievals toolchain version 14.3.0 Source rate retrieval version 0.15.5

example software to convert concentration maps to mass emission quantification estimates during the experiments.	
(5) Please provide a detailed description of the methodology used during emission detection/quantification surveys.	Each release previously agreed on has been coordinated with a single satellite overpass, which yields a retrieval domain covering approximately 10 km x 15 km area. Once the data was downlinked, it was processed using our retrievals toolchain. It was then reviewed for quality. If the quality was good, we validated the georeferencing and identified any emission. A mask was created using a semi-automatic floodfill algorithm. This mask was used to estimate the source rate using our source rate retrieval algorithm.
(6) Please provide the confidence level at which emission detection data are reported. (e.g., 95% CI, +/- 1 sigma)	+/- 1 sigma
(7) Please record the number of personnel participating in the surveys and their roles. Any remote personnel participating in the survey in any fashion should be documented as part of the survey team in this section. Names of individual personnel are not required.	Satellite observations are programmed in advance and do not require active participation by personnel.
(8) For hyperspectral technologies, describe how plume length is determined for quantification.	The length of the detected plume used for source rate retrievals varies from case to case, and is determined using an internal algorithm. Our algorithm retrieves the square root of the plume mask area.
(9) If wind speed is used in computing total emission rate, please describe how the wind estimate is obtained, including the precise instrument or wind reanalysis product used.	OpenWeatherMap
(10) If uncertainty is reported, where is it coming from? Is it from calculations, reported data, experimentation, etc.	Our source rate error includes: (1) Wind error, (2) Measurement/data error, (3) error from the IME model (as described in Varon et al. (2018, 2019)

S2.3.6 Sensirion Technology Survey Responses

Company	Sensirion Connected Solutions
Product name	Nubo Sphere

(1) Please provide a detailed description of the system configuration and primary components including the sensor type and deployment platform. Please also indicate the location (latitude, longitude, height) of all components, including meteorological stations or any other equipment installed at or near the Test Center.	The **fixed-point Nubo Sphere sensor network is an end-to-end solution for real-time monitoring** of methane emissions in the oil & gas industry. It is designed as a future-proof and easy-to-use solution and aims to change the state-of-the-art in methane emission monitoring. It has never been easier to reliably detect, locate and quantify unintended methane emissions down to less than 1kg/h. The deployment of real-time, continuous methane concentration measurement technology enables detection of emissions much earlier than was previously possible through human interaction. This enables fast, accurate and cost-saving damage control through rapid incident response actions for increased safety and a reduced environmental burden. In detail, the solution consists of three components: the sensor hardware, the data analytics, and the real-time user dashboard. 1. The **Nubo Sphere sensor node** has two slots for sensing cartridges and LTE connection for real-time data transmission. The cartridge can be easily exchanged for maintenance or upgrading. For the IMEO/Stanford test campaign a methane (CH_4) **sensing cartridge deploying a photoacoustic-based laser spectroscopy sensing technology** has been used. Thanks to the solar panel, low-power electronics and the state-of-the-art lithium-ion batteries, the nodes work fully autonomously without the need to deploy electric power cables even in the most adverse conditions. The compact size ensures easy deployment wherever needed. At least one of the nodes is, in addition to the methane sensor, equipped with a wind meter in order to measure the local wind speed and direction at any time. 2. Our **advanced analytics** system continuously applies algorithms based on physical modelling to the refined data to detect any emission as early as possible. The models further allow for automatic and reliable localization and quantification of emissions. 3. The status of all sites can be easily monitored on the **intuitive dashboard** in any web browser or smartphone. Sites where action is required can be easily identified, and their status can be tracked during the repair process. The best mitigation action can be easily determined based on the intuitive data visualization of the location and size of any emission event. If critical emission events are detected, the user receives notifications to enable a team to react rapidly.

	All devices are installed 2 meters above ground with a single wind sensor installed at device cc1-602xgp-0d-27-29. No additional meteorological data is collected.
(2) Please record the model number of each primary component in (1), if applicable.	not applicable
(3) Please record the software revision installed on the components in (1), including performer-specific software components, revisions, or customizations	Version 2.20.0
(4) Please record the revision number of any software analytics installed offsite. For example software to convert concentration maps to mass	not applicable

emission quantification estimates during the experiments.	
(5) For a site the size of this test facility, roughly 4 acres, how many sensors would you typically install for a customer?	This could vary depending on the amount of equipment that is installed on-site along with wind conditions, topology and the participant's performance requirements (e.g. fast detection or accurate quantification). A rough estimate can be from 4-8 devices.
(6) For camera-based systems, what is angular field view in the x, y, and z directions?	not applicable
(7) a) Under what conditions will the system not provide results? How are such instances be indicated (e.g. NaN)? b) Will an error code be reported indicating the reason for a non-measurement? c) Make sure to indicate instances of partial or fully missing data in the "Missing Data Reporting" sheet to ensure these are not erroneously marked as false negatives.	a) If there is an off-site emission, system will not send an alert email low wind speeds below 1 m/s typically b) Yes, those emissions are labeled as "cannot estimate". c) There was no data loss
(8) Describe the conditions under which you create an alarm notifying a customer, as in the "Alarm" column of the data reporting sheet.	Alert email is sent once emissions is confirmed. Within that alert email the following information is provided: Site name Emission start time Emission rate Emission coordinates
(9) Please provide the confidence level at which emission detection data are reported. (e.g., 95% CI, +/- 1 sigma)	+/- 2 sigma
(10) Please record the number of personnel participating in the surveys and their roles. Any remote personnel participating in the survey in any fashion should be documented as part of the survey team in this section. Names of individual personnel are not	Total of 3 people. 1 Field Application Engineer, 1 Algorithm Engineer, 1 Key Account Manager

required.	
(11) If wind speed is used in computing total emission rate, please describe how the wind estimate is obtained, including the precise instrument or wind reanalysis product used.	The wind estimate is obtained by using ultra sonic anemometer which gathers information of wind speed and direction.
(12) If uncertainty is reported, where is it coming from? Is it from calculations, reported data, experimentation, etc.	Calculations

S2.3.7 SLB Technology Survey Responses

Company	SLB
Product name	Methane Lidar Camera
(1) Please provide a detailed description of the system configuration and primary components including the sensor type and deployment platform. Please also indicate the location (latitude, longitude, height) of all components, including meteorological stations or any other equipment installed at or near the Test Center.	The SLB methane lidar camera detects and quantifies methane emissions using tunable diode lidar technology, which combines aspects of tunable diode laser absorption spectroscopy with differential absorption lidar and time-correlated single photon counting. The camera was installed on a pole connected to the walkway railing on top of the yellow tank at the northwest corner of TADI at ~9 m height above ground. The approximate latitude, longitude of the camera were (43.413155, -0.642936) The camera is connected to an anemometer installed next to the camera at ~7.5 m height above ground.
(2) Please record the model number of each primary component in (1), if applicable.	SN 23-0035, QL1101
(3) Please record the software revision installed on the components in (1), including performer-specific software components, revisions, or customizations	3.2.10
(4) Please record the revision number of any software analytics installed offsite. For example software to convert concentration maps to mass emission quantification estimates during the experiments.	qlm-ch4-analysis_v0.2.1.2

(5) For a site the size of this test facility, roughly 4 acres, how many sensors would you typically install for a customer?	1-2 cameras depending on facility geometry, complexity, number of emission sources, and monitoring requirements
(6) For camera-based systems, what is angular field view in the x, y, and z directions?	The camera is installed on a pan-tilt stage that changes the nominal direction of the camera, directing the camera to different emission sources. The stage has the capability to pan 360 degrees and tilt vertically. Each scan (field of view) by the camera covers a conical field of view with a maximum full cone angle of 23 degrees. The full cone angle depends on the zoom.
(7) a) Under what conditions will the system not provide results? How are such instances be indicated (e.g. NaN)? b) Will an error code be reported indicating the reason for a non-measurement? c) Make sure to indicate instances of partial or fully missing data in the "Missing Data Reporting" sheet to ensure these are not erroneously marked as false negatives.	The camera will not provide results if it is not connected to a power source, if there is a hardware malfunction, if the cloud platform provider or cellular network incurs disruptions, or if there is an undocumented software bug. The camera will create internal error codes in these situations. Redundancies are built into the software services to avoid data loss.
(8) Describe the conditions under which you create an alarm notifying a customer, as in the "Alarm" column of the data reporting sheet.	Customers configure their own alarm notification criteria. Generally customers request notification based on emission rate, emission duration, and emissions above baseline.
(9) Please provide the confidence level at which emission detection data are reported. (e.g., 95% CI, +/-1 sigma)	The camera reports the mean emission rate. Typical uncertainties are within a factor of 2.
(10) Please record the number of personnel participating in the surveys and their roles. Any remote personnel participating in the survey in any fashion should be documented as part of the survey team in this section. Names of individual personnel are not required.	2 people on-site to install, 1 person to configure the device and fix the misalignment after the camera got bumped, 1 person to write the report
(11) If wind speed is used in computing total emission rate, please describe how the wind estimate is obtained, including the precise instrument or wind reanalysis product used.	Real time wind speed and direction are measured by an anemometer installed on site with the camera.
(12) If uncertainty is reported, where is it coming from? Is it from calculations, reported data, experimentation, etc.	The camera does not report uncertainty estimates for each emission event. Previous controlled release tests indicate

	the one sigma uncertainty in emission rate quantification is around a factor of two.

S2.3.8 SENSIA Technology Survey Responses

Company	SENSIA SOLUTIONS
Product name	Mileva 33
(1) Please provide a detailed description of the system configuration and primary components including the sensor type and deployment platform. Please also indicate the location (latitude, longitude, height) of all components, including meteorological stations or any other equipment installed at or near the Test Center.	The system deployed consists of SENSIA's IR camera with a pan and tilt positioner to point the camera to different areas across the facility. The data from the camera is processed on an edge computer running SENSIA's proprietary software, RedLook, that detects and quantifies the emissions in real time.
(2) Please record the model number of each primary component in (1), if applicable.	Mileva 33: SEN.F23.01.00.54.000.002
(3) Please record the software revision installed on the components in (1), including performer-specific software components, revisions, or customizations	RedLook Fix Software v1.22
(4) Please record the revision number of any software analytics installed offsite. For example software to convert concentration maps to mass emission quantification estimates during the experiments.	No additional instrumentation or software was used apart from the equipment deployed on-site. RedLook reports were generated in real-time and submitted immediately after the end of the campaign.
(5) For a site the size of this test facility, roughly 4 acres, how many sensors would you typically install for a customer?	For this facility just 1 camera is enough. Even for larger facilities 1 camera can provide coverage at full performance up to distances of 250-300 meters, provided there is direct line of site to the monitored equipment.
(6) For camera-based systems, what is angular field view in the x, y, and z directions?	With the pan and tilt, the camera can cover 360 degrees in the y axis (pan), and 90 degrees in the z axis (tilt)
(7) a) Under what conditions will the system not provide results? How are such instances be indicated (e.g. NaN)? b) Will an error code be reported indicating the reason for a non-measurement? c) Make sure to indicate instances	When the camera is switched off or not operative. If the camera is powered and software running and configured, the system provides results.

of partial or fully missing data in the "Missing Data Reporting" sheet to ensure these are not erroneously marked as false negatives.	
(8) Describe the conditions under which you create an alarm notifying a customer, as in the "Alarm" column of the data reporting sheet.	The alarms are fully customizable and are configured during the commissioning according to client's requirements and needs.
(9) Please provide the confidence level at which emission detection data are reported. (e.g., 95% CI, +/- 1 sigma)	RedLook quantification estimates include uncertainty indicators represented as higher and lower quantification values per reading. This uncertainty is determined case by case by the analytics based on image parameters of the plume.
(10) Please record the number of personnel participating in the surveys and their roles. Any remote personnel participating in the survey in any fashion should be documented as part of the survey team in this section. Names of individual personnel are not required.	2. Project manager and AI engineer.
(11) If wind speed is used in computing total emission rate, please describe how the wind estimate is obtained, including the precise instrument or wind reanalysis product used.	Wind speed is not an input required for RedLook's quantification. Imaging-based parameters retrieved from the plume provide the required inputs for RedLook quantification CNN to provide accurate quantification estimates.
(12) If uncertainty is reported, where is it coming from? Is it from calculations, reported data, experimentation, etc.	The uncertainty of each quantification output is estimated by RedLook's AI analytics through the analysis of parameters such as plume geometric factors, radiometric contrast, plume dynamics, among others. By continuously refining its AI models with real-world data, RedLook enhances its accuracy, reliability, and ability to provide actionable insights for methane emissions monitoring.

S3 Field Data Collection

S3.1 Field Data Collection Procedures

Information about release flowrate, location, start and end time was recorded onsite by the site engineer. Deviations from the schedule were recorded by hand on the printed schedule and by the Stanford team. For each release, the input flowrate and associated uncertainty was recorded. The TADI site personnel delivered this information to the Stanford team after the completion of each week.

Weather conditions, temperature, and prevailing windspeed and direction was recorded on site every morning and afternoon. Wind data on the TADI site was also collected using the TADI ZX 300 Wind Lidar measurement device, with measurement heights set to 10m, 20m, 38m, 50m, 75m, 100m, 125m, 150m, 180m, 240m, and 300m. Initially, it was not planned to share this wind data with the participating teams as each team had to use their own equipment as part of their technology deployment. However, to challenge the performers' results and especially their wind measurements, the TADI team decided to provide this information. Section S3.2 details the weather conditions. Flowrate information and detailed methane release schedules with location, start and end times, stabilization times, equipment numbers, and orientation can be found in Sect. S1.3.

S3.2 Weather Conditions

Tables S11, S12, and S13 contain the weather, temperature, and wind conditions for each morning and afternoon during the campaign as recorded by the TADI site engineer using a 2d METEK meteorological station. More precise measurements of wind speed and direction were taken using the wind lidar measurement device. Analysis of the wind lidar measurement data is described in the Results section.

Table S11. Daily weather conditions.

Week	Time of Day	Daily Weather Condition Recordings				
		Monday	*Tuesday*	*Wednesday*	*Thursday*	*Friday*
1	*Morning*	Sunny, no clouds	Partly cloudy	Cloudy, wet,	Very rainy	Very cloudy with some rain
	Afternoon	Sunny, no clouds	Partly cloudy	Cloudy, without rain	Rainy	Very cloudy with some rain
2	*Morning*	Sunny, some clouds	Sunny	Cloudy	Cloudy	Cloudy
	Afternoon	Sunny, no clouds	Sunny	Cloudy	Cloudy	Cloudy
3	*Morning*	Continuous rain	Cloudy, some sun	Cloudy	Rainy	Cloudy
	Afternoon	Non-continuous rain	Sunny, some clouds	Drizzle	Cloudy, some showers, sunny late afternoon	Sunny, some clouds
4	*Morning*	Sunny, some clouds	Mist	Slightly cloudy	Partly cloudy	Partly cloudy

	Afternoon	Sunny, several clouds	Cloudy	Sunny, some clouds	Sunny, some clouds	Some clouds, rain showers

Table S12. Daily temperature conditions.

Week	Time of Day	Daily Temperature Recordings (°C)				
		Monday	*Tuesday*	*Wednesday*	*Thursday*	*Friday*
1	*Morning*	30	22-24	18-22	15-16	18-19
	Afternoon	32-35	31-32	23-25	15-16	18-20
2	*Morning*	23-25	26-28	26-28	22	20-22
	Afternoon	27-30	32-34	38	30	30
3	*Morning*	16	16	17	13	11-12
	Afternoon	18-19	21-23	19	20-22	20-22
4	*Morning*	9-10	11-12	11-12	14	16-17
	Afternoon	21-22	22-23	25-26	23-25	18-19

Table S13. Daily wind conditions.

Week	Time of Day	Daily Wind Conditions (m/s, direction)				
		Monday	*Tuesday*	*Wednesday*	*Thursday*	*Friday*
1	*Morning*	3-3.5 ESE	1.4-2.6 SW	1-3, W/WSW	No speed measuring, SSE	3.5-5.5 W/WSW
	Afternoon	1.5-3.7, E/ESE	2-3.5, E/ENE	3-4 WSW	2-2.5 E/SE	3.5-5.5 W/WSW
2	*Morning*	2-3.5 N	2-3.0 S/SSE/E	1-3 E	3-4 W/WNW	1.5-2.0 W/WNW
	Afternoon	2.5-3.0 E	4.5-5 E	2.5-3.5 E	3-4 W/WNW	N/A
3	*Morning*	3.5-5 W	0.5-1 SW, later 1.5-3	3-4 SW, later 3.5-5 SW	1-2 SW	1-2 SW
	Afternoon	2-3 W	1.5-2 NE, later 2.5-3.5 SW	3-4 SW	3-4 SW	3-4 SW
4	*Morning*	1-2 SW	1-2 SW	1-2 ESE	1-2 ENE	1-2 SSE
	Afternoon	2-4 SW	1-2 SW	1-2 E	2-3 E	1-2 SW

In addition to the daily record of wind conditions, high-resolution wind data was collected using the ZX 300 Wind Lidar and released to all teams as part of the unblinding process. Figure S3 contains example releases with relatively better and worse wind conditions. In general, steady wind directions and moderate, steady wind speeds are preferred for most techniques, as they allow for more straightforward analysis. Very low winds and frequently changing wind directions tend to be difficult for most, if not all, analyzed techniques. Because of the natural experimental design (e.g., at a field site rather than in a controlled wind tunnel), we had no control over variation in wind quality across weeks.

S3.3 Wind Rose Plots

Wind data are plotted in a wind rose plot, which provides information on wind speed and wind direction during the time of a specific release. Wind rose plots for each release over the four weeks of testing can be found below. Overall, wind conditions varied widely throughout each week and between each week of testing. Week 4 was particularly difficult, with average wind speeds that were very low and large variation of wind direction.

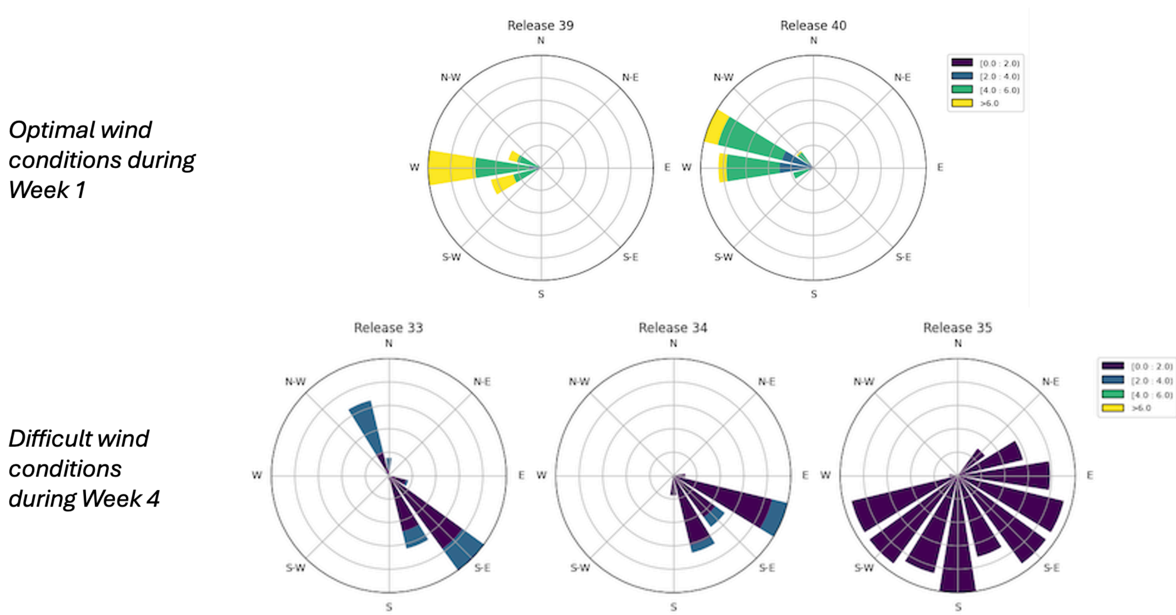

Figure S3. Wind rose plots characterizing the wind conditions during specific releases in Week 1 and 4. Low wind speeds and high variance of direction correspond to difficult conditions, while steadier winds with higher speeds and consistent direction are more optimal for measurement.

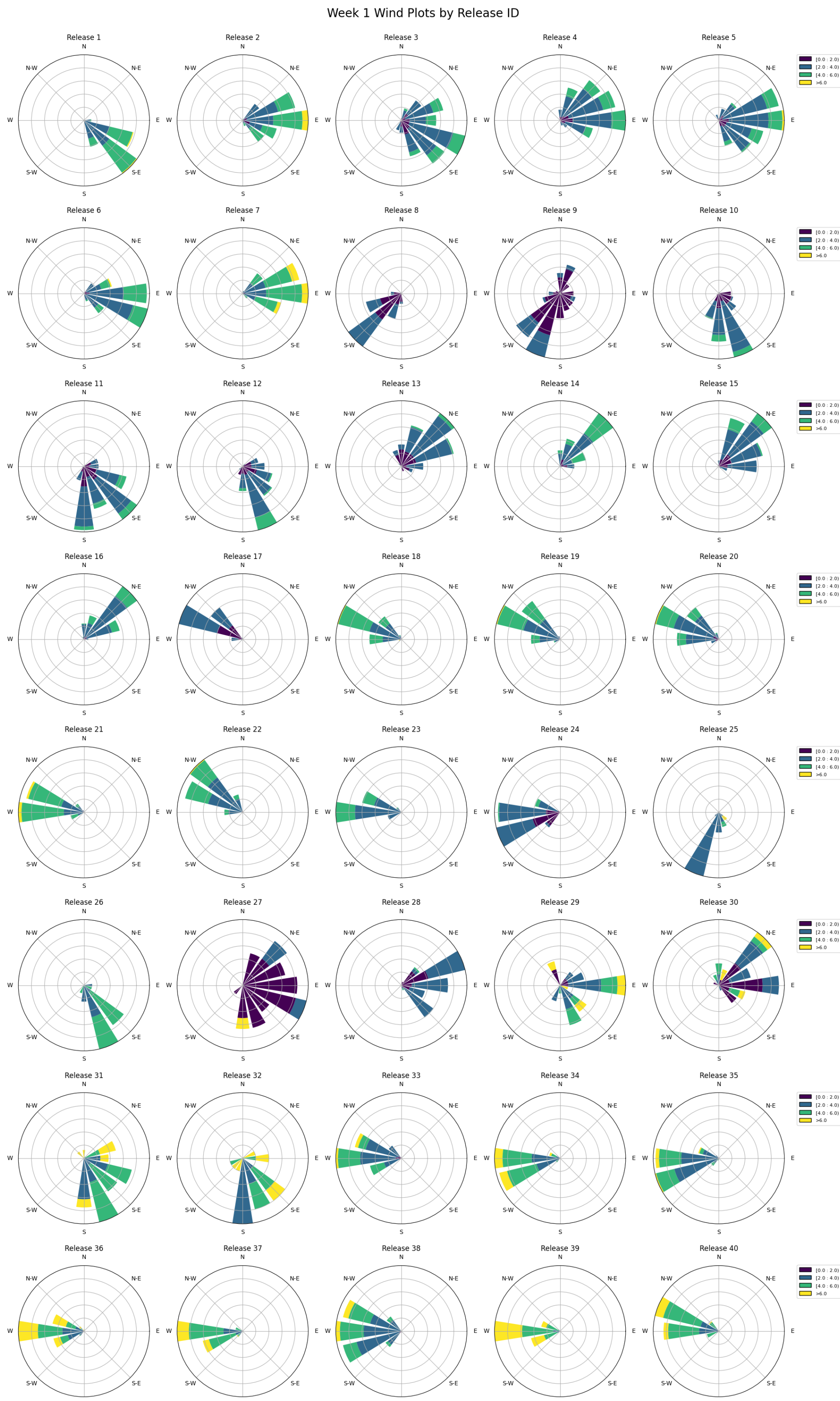

Figure S4. Week 1 wind rose plots by release.

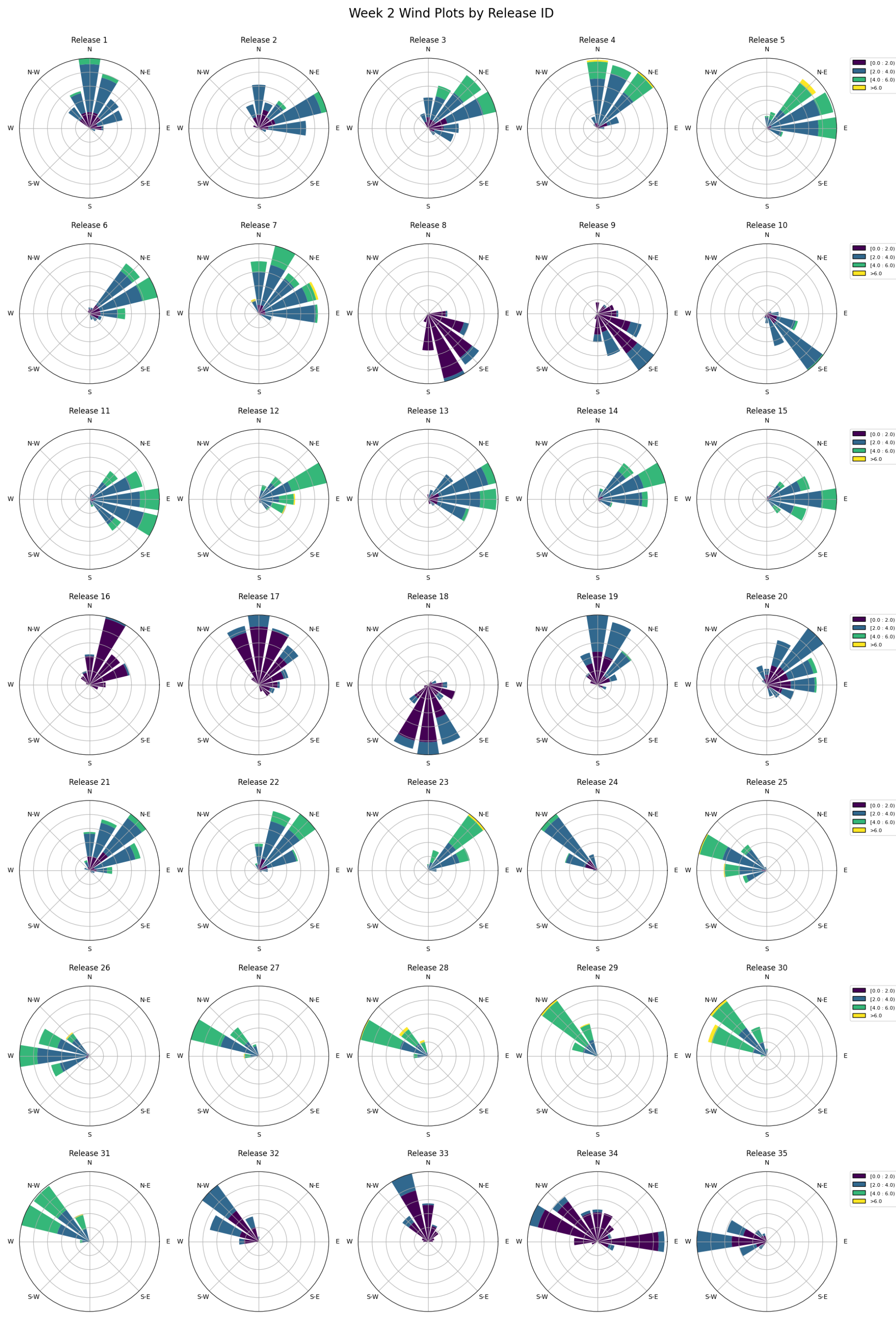

Figure S5. Week 2 wind rose plots by release.

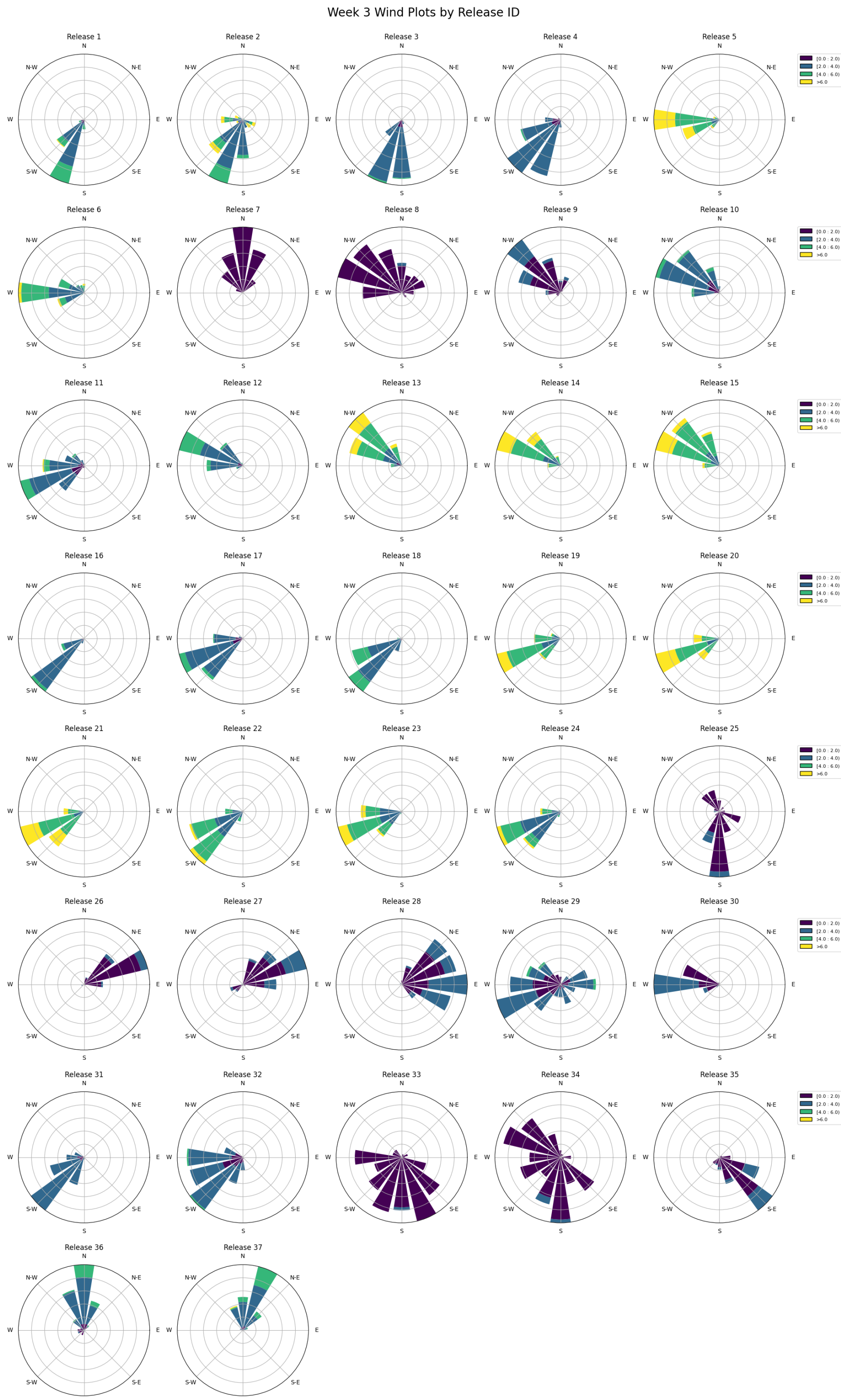

Figure S6. Week 3 wind rose plots by release.

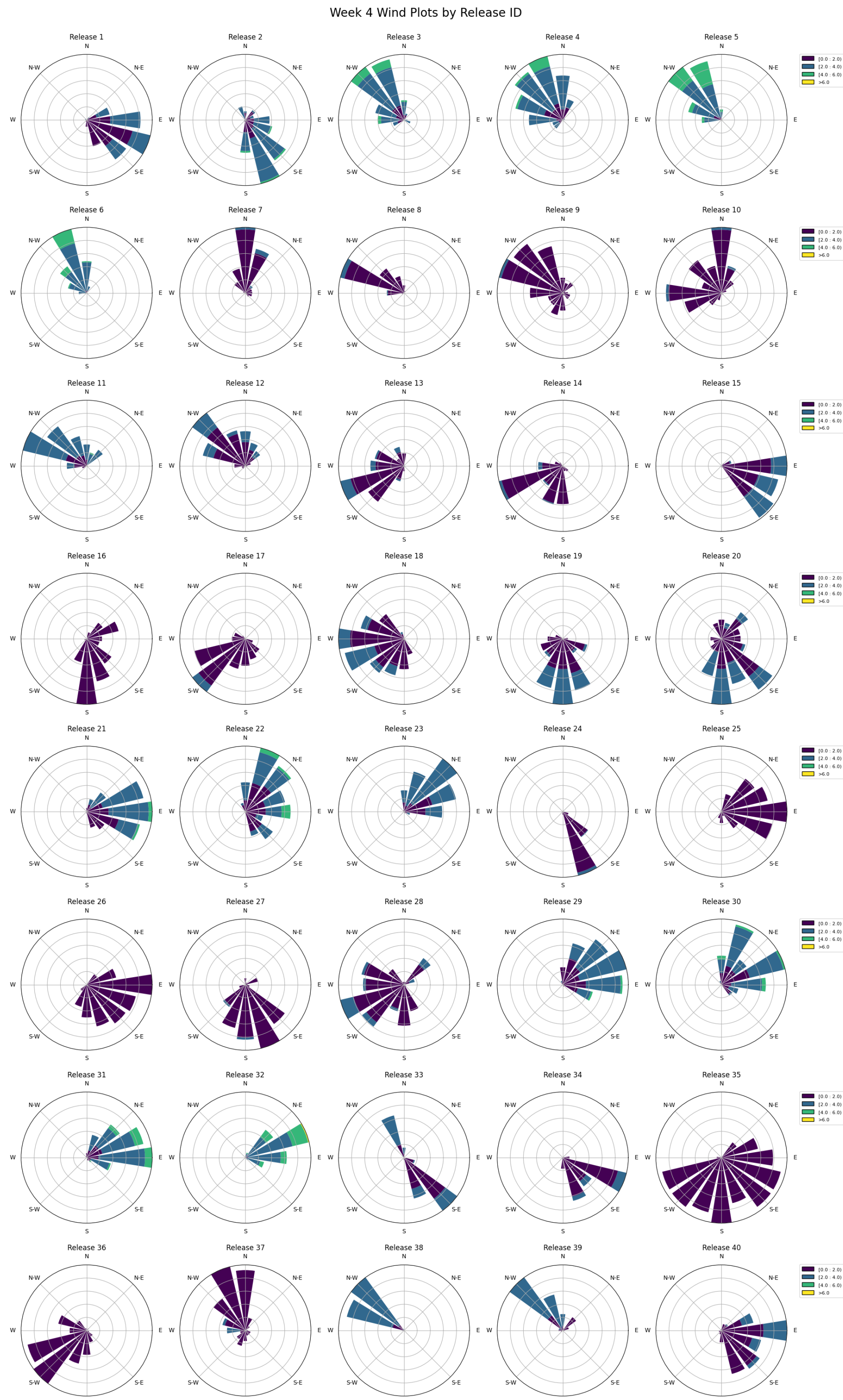

Figure S7. Week 4 wind rose plots by release.

S4 Participant Data Collection, Reporting, and Filtering

Throughout their week(s) participating in the campaign, the participants measured the methane releases to provide an estimate of the release flowrate. Each participant's measurement technique is described in Sect. S2.1, and in more detail submitted by participants in Sect. S2.3. Participants were allowed four weeks from the completion of each testing week to submit results for that week. Not all teams were able to perform analysis within four weeks, and we allowed additional time to reply given the provision that we would record the timing of response. We provided a Data Reporting Template to each participant with instructions on how to submit results. Table S14 contains the result submission dates of each participant.

Table S14. Results reporting dates and submission dates by participant and week.

Week	Due Date	Team	Result Submission Date
1	July 22, 2024	GHGSat	July 18, 2024
		Sensirion	July 22, 2024
		Aeromon	July 22, 2024
		GSMA	July 22, 2024
2	July 29, 2024	GHGSat	July 25, 2024
		Sensirion	July 29, 2024
		SeekOps	July 29, 2024
3	October 14, 2024	GHGSat	October 7
		SENSIA	September 23, 2024
		Sensirion	October 14, 2024
		SLB	October 9, 2024
4	October 21, 2024	GHGSat	October 7, 2024
		SENSIA	September 23, 2024
		SLB	October 9, 2024
		Sensirion	October 17, 2024
		Flylogix	October 21, 2024

The Data Reporting Template also included sections for each participant to fill out with more detailed information on their technology, measurement techniques, and analysis methods. There were separate templates for each technology group: drone, vehicle, continuous monitor (fixed ground sensor), and aircraft/satellite. Additionally, each participant was sent the schedule ("Release Schedule") of the releases with start and end times and asked to fill out two columns verifying if they (1) measured the release ("Measurement Taken") and (2) were able to quantify the emission rate ("Quantification Status"). This information was then used to classify the releases, discussed in more detail in Sect. 4.1. Additionally, each team had the opportunity to point out if there were any specific issues with the quantification or detection of each release, such as wind or weather conditions or equipment malfunction. Each team was invited to submit as much additional information as they desired to, such as plume images, concentration paths, or any other context-providing document.

S4.1 Participant Submission & Data Cleaning

Participants were asked to submit two documents: (1) the data reporting template with release rate estimates ("Results") and (2) a schedule of releases with information about whether participants had measured a particular release ("Schedule"). Although instructions were given on how to fill out these documents, each participant had a slightly different interpretation, leading to differences in how each team submitted release estimates. The Stanford team developed three different criteria to filter and categorize each participants results: a strict data filtering criterion (Strict QC), the Stanford team's criteria (Stanford QC), and a participant-submitted criteria (Participant QC). Results estimates were categorized into one of three types of estimates: releases that teams measured and submitted a non-zero methane emission rate ("non-zero estimates"), releases for which teams submitted a methane emission rate of 0 kg h^{-1} ("zero estimates"), and releases for which teams did not submit any estimate ("N/A estimates"). Participants submitted zero-estimates differently (e.g. some reported in an estimate methane emission rate of 0 kg h^{-1}, while others reported them as failed quantifications), resulting in the creation of the three different categorization methods (Strict QC, Stanford QC, and Participant QC). Unless otherwise specified, the Stanford QC process was the default method used for data included in analysis.

S4.1.1 Data filtering and categorization methods

The three different QC methods used the information that teams submitted in the Schedule document to categorize a release estimate into non-zero, zero, or N/A. This used the information in the three columns in the Schedule: (1) Measurement Taken, (2) Quantification Status, and (3) Explanation. The difference in each method is in how they treat releases that were submitted as failed quantifications. The Strict QC criteria considered every release that was measured as passing QC, and assigned release rates of 0 kg h^{-1} to every release that did not have an associated estimate submitted. The Stanford QC criteria assigned either 0 kg h^{-1} or N/A to releases that were reported as failed quantifications, depending on the explanation that the participant provided. The Participant QC criteria only included release estimates that had an associate methane emission rate submitted by the participant. This information is summarized in Table S15.

Table S15. Participant release estimate filtering criteria

Release Schedule Column[a]		**QC Criteria**		
Measurement Taken	*Quantification Status*	*Strict QC*	*Stanford QC*	*Participant QC*
YES	Completed	As reported	As reported	As reported

YES	Failed	Zero	Depends on Explanation	N/A
NO	N/A	N/A	N/A	N/A

[a] The criteria uses the information provided in the "Release Schedule" document. Participants were to turn in this document along with the Data Reporting Template that contained their estimated emission rates.

Participants occasionally did not report measurements for some releases they had measured due to quality issues with the measurements and subsequent analysis. Examples of data quality issues include low wind speeds, cloud coverage, and equipment malfunction. Additionally, some participants reported releases that were below their detection limits as failed quantifications, while others reported in release rates of 0 kg h^{-1} . The Stanford QC process aimed to address this difference in reporting. In general, failed quantifications with explanations related to detection capabilities or low signals were categorized as zero-estimates while other issues were categorized as N/A (Fig. S8). The participant-specific release estimate categorization for releases with entries in the Explanation column using the Stanford QC criteria is described in Sect. S4.1.2-9, and flow rate charts for each specific participant are provided below. The QC flags included by each participant are also included in a table.

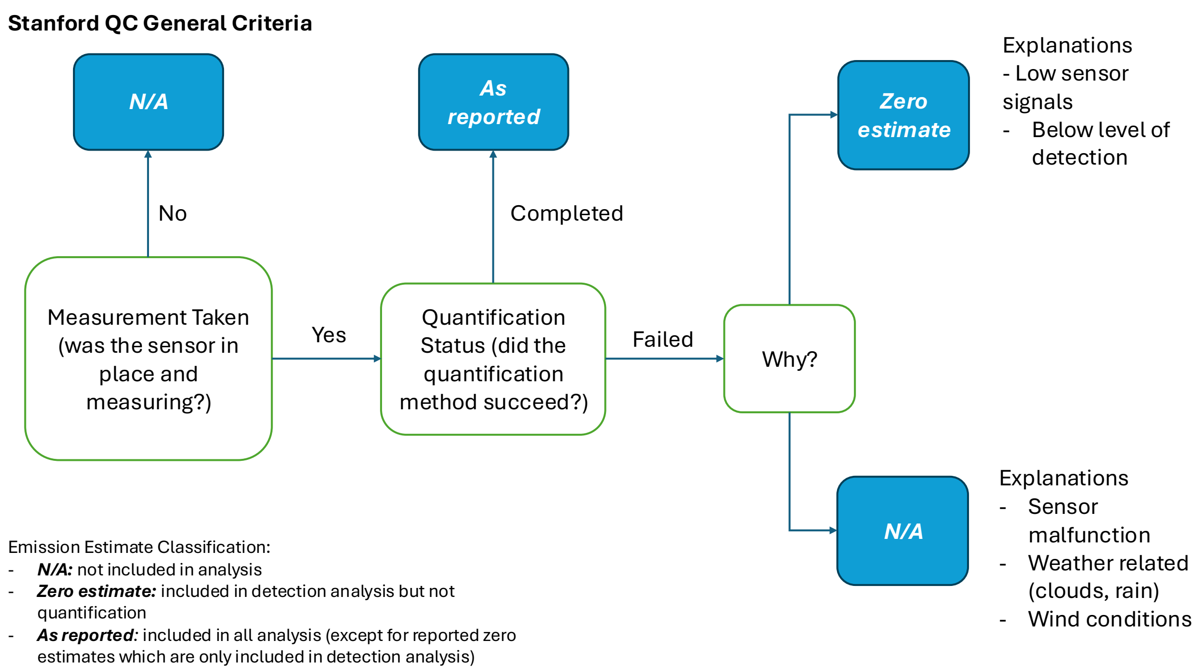

Figure S8. Stanford QC process release estimate classification criteria.

S4.1.2 Aeromon BH-12 Data Cleaning

Aeromon's stationary 2D anemometer was used only half of their testing week (Wednesday-Friday) due to the airline losing the mast in transit. Aeromon initially reported estimates for 18 releases but updated their submission to a total of 9 releases passing their QC process due to a misunderstanding of when they would receive the wind data from TADI. Their weather station was delayed in arriving at TADI because of shipping issues, so they could not provide estimates for the first two days because of this missing data.

Table S16. Aeromon QC flags with number of releases and associated estimated emission rate.

QC Flag	Number of Releases	Stanford QC Assigned Emission Rate (kg h^{-1})
Other drone team was flying	15	N/A
Unable to confirm if wind conditions are within boundary conditions due to missing weather station data	9	N/A
Wind conditions outside boundary conditions momentarily during test, but average wind speed sufficient	6	As reported
Rain	4	N/A
Nonconformity (not enough data due to rain + average wind speed <1 m/s + wind persistence below 0.9)	2	N/A
Wind conditions outside boundary conditions momentarily during test, average wind speed barely meeting the boundary of 1 m/s	1	As reported
Nonconformity (not enough data due to rain + wind persistence below 0.9)	1	N/A
close to detection limit (High uncertainty is due to all the detections above ambient background were close to sensor detection limit) + interrupted by rain + wind conditions outside boundary conditions momentarily during test, but average wind speed sufficient	1	As reported
close to detection limit (High uncertainty is due to all the detections above ambient background were close to sensor detection limit) + wind conditions outside boundary conditions momentarily during test, but average wind speed sufficient	1	As reported

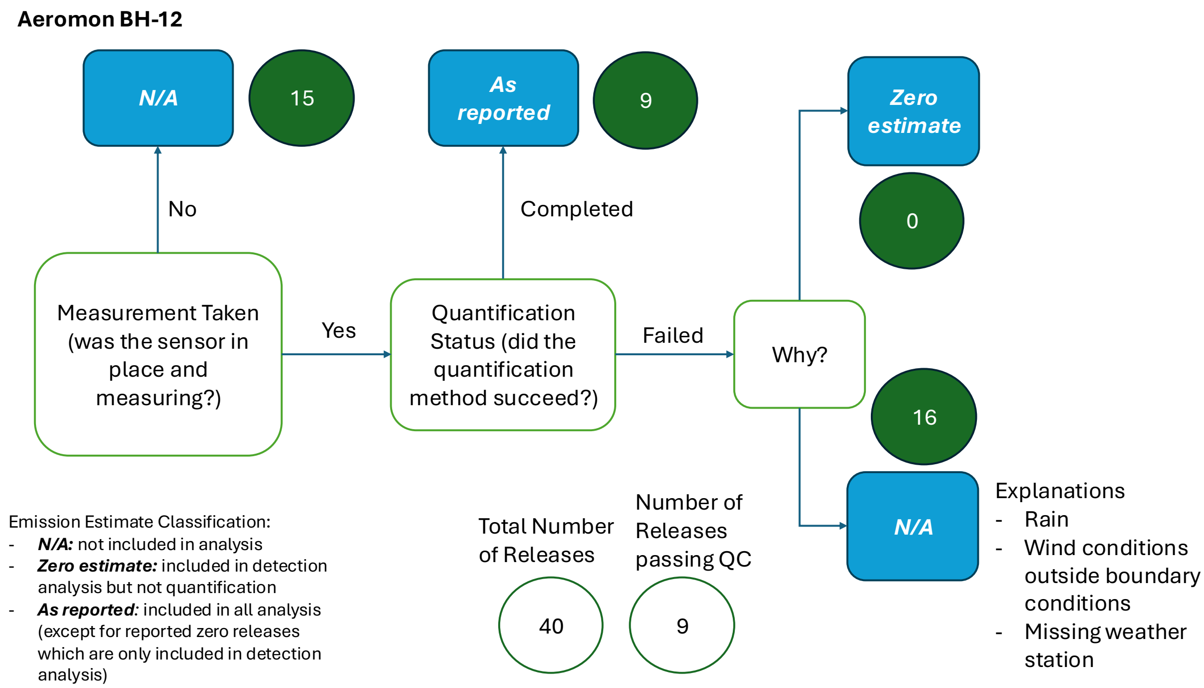

Figure S9. Data cleaning process flowchart for Aeromon.

S4.1.3 GSMA AUSEA Data Cleaning

Table S17. GSMA QC flags with number of releases and associated estimated emission rate.

QC Flag	Number of Releases	Stanford QC Assigned Emission Rate (kg h^{-1})
Other drone team operating	21	N/A
Rain	4	N/A
Flight aborted due to the rain	1	N/A
Sensor switch	1	N/A

GSMA AUSEA Sensor

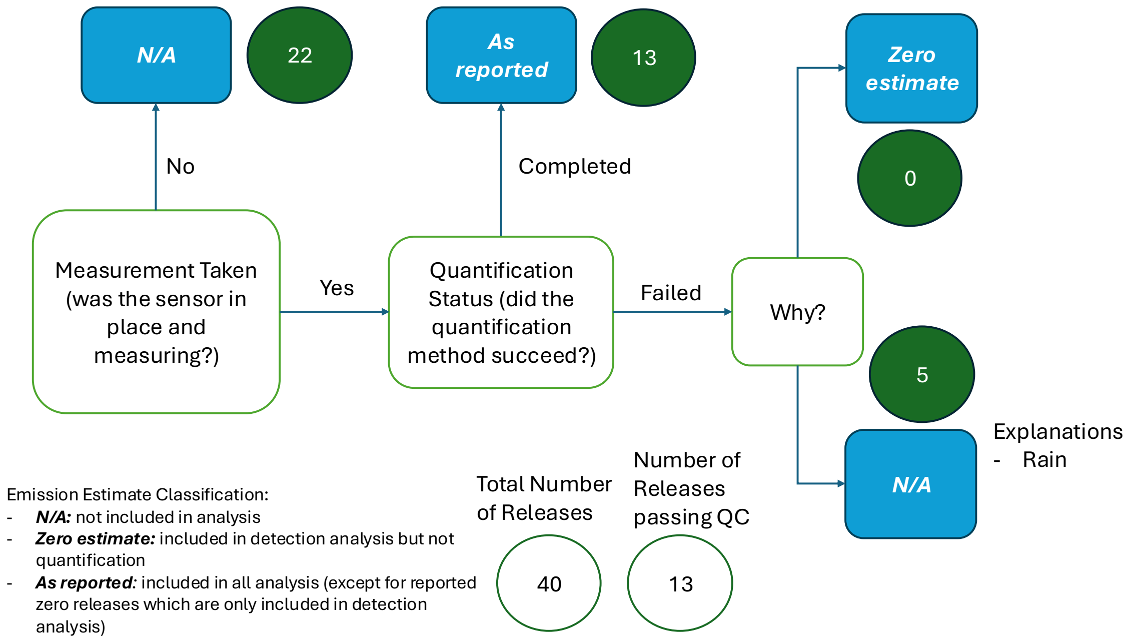

Figure S10. Data cleaning process flowchart for GSMA.

S4.1.4 Flylogix Data Cleaning

Flylogix submitted a complementary report to explain their difficulties in applying their flight protocol, adapted for offshore platforms, on the TADI site. Additionally, they submitted analyses for three releases as examples of their standard procedures.

Table S18. Flylogix QC flags with number of releases and associated estimated emission rate.

QC Flag	Number of Releases	Stanford QC Assigned Emission Rate (kg h^{-1})
Demobilised for other commitments	9	N/A
Setting up	6	N/A
Charging	6	N/A
Hosting VIPs and charging[a]	2	N/A

[a] "Hosting VIPs" refers to the visit by UN officials and other stakeholders that took place during Week 4.

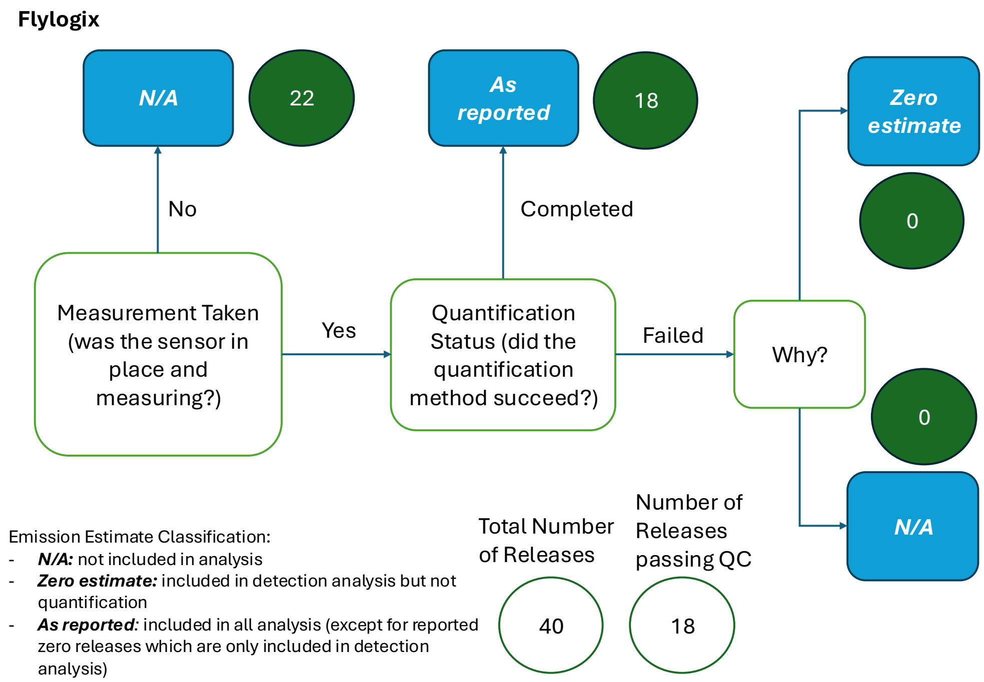

Figure S11. Data cleaning process flowchart for Flylogix.

S4.1.5 SeekOps SeekIR Data Cleaning

SeekOps reported results for all drone flights that they took, even if 2 flights were during the same release. They reported a totaled estimate for those flights in the Release Schedule, but the Data Reporting spreadsheet contains information per flight, not per release. The estimated emission rate used was the one they reported in the Release Schedule spreadsheet.

Table S19. SeekOps QC flags with number of releases and associated estimated emission rate.

QC Flag	Number of Releases	Stanford QC Assigned Emission Rate (kg h^{-1})
UAV not in air during this timeframe	5	N/A

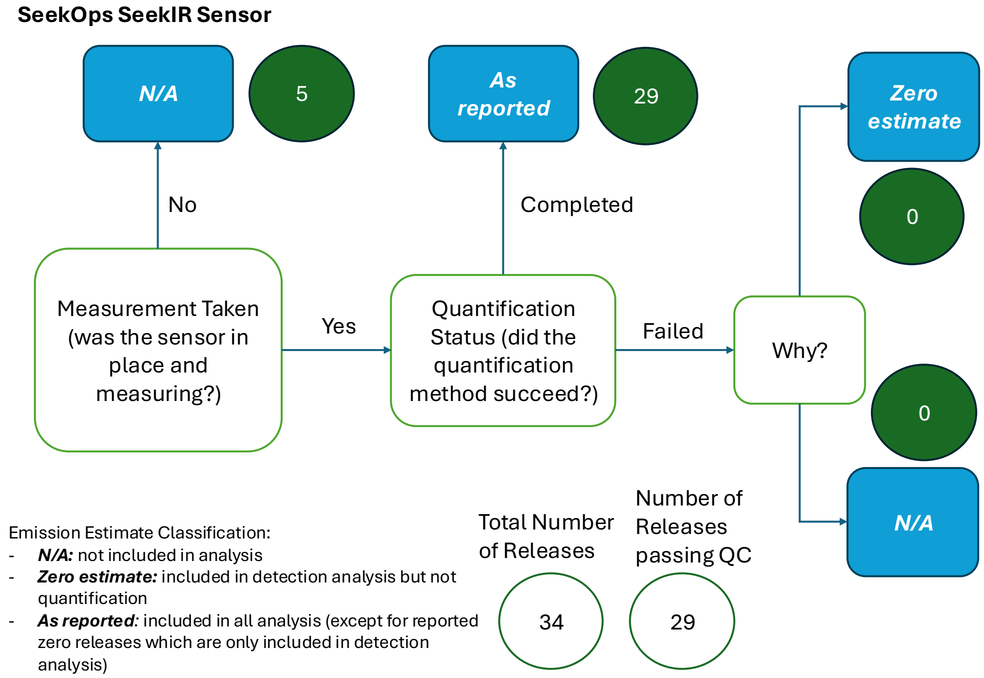

Figure S12. Data cleaning process flowchart for SeekOps.

S4.1.6 GHGSat-C Data Cleaning

GHGSat-C was tasked to estimate the flow rate at TADI twelve times during the four weeks of testing and submitted one release rate estimate.

Table S20. GHGSat-C QC flags with number of releases and associated estimated emission rate.

QC Flag	Number of Releases	Stanford QC Assigned Emission Rate (kg h^{-1})
Bad weather – Cloudy	11	N/A
Partially cloudy, area over site clear	1	As reported

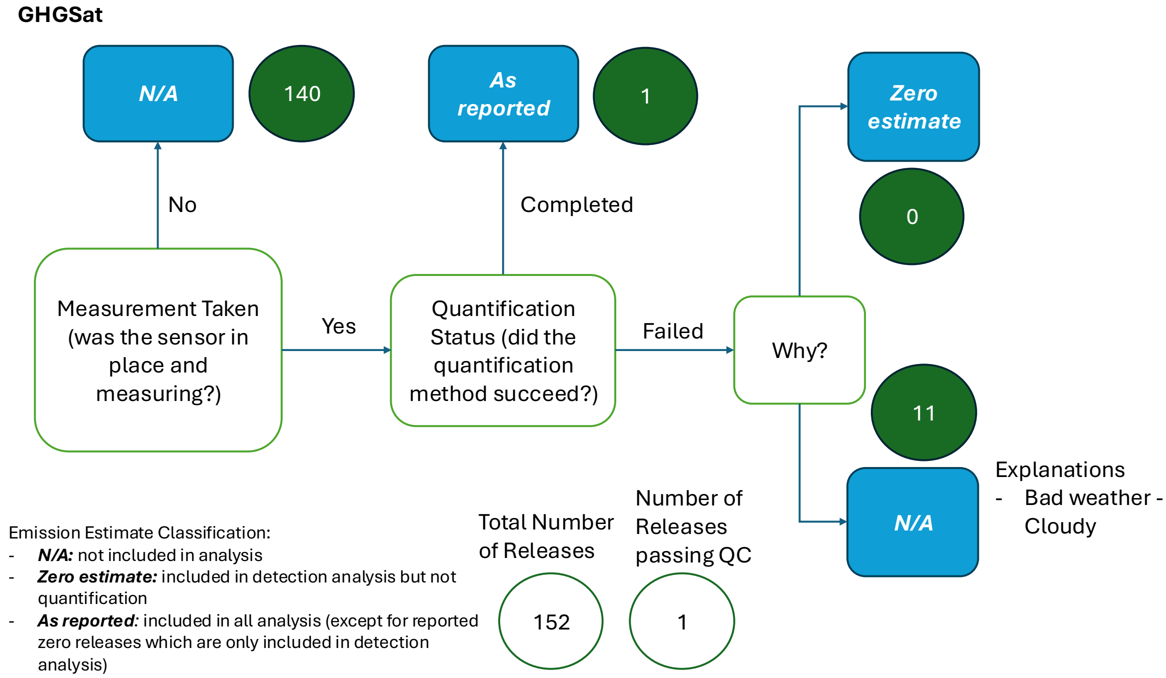

Figure S13. Data cleaning process flowchart for GHGSat-C.

S4.1.7 Sensirion Nubo Sphere Data Cleaning

All failed quantifications related to low signals on sensors are categorized as zero-releases, while the rest are treated as N/A. In their submitted Week 2 Schedule, Sensirion reported a "NO" in the Measurement Taken column with an explanation of "no signals measured". This was treated as a zero-release using both the Stanford and Strict QC criteria.

Table S21. Sensirion QC flags with number of releases and associated estimated emission rate.

QC Flag	Number of Releases	Stanford QC Assigned Emission Rate (kg h^{-1})
Installation not yet finished	5	N/A
Emission duration + poor wind conditions	10	N/A
Emission duration + unchanging wind conditions	6	N/A
No / Low signals measured on sensors	11	0

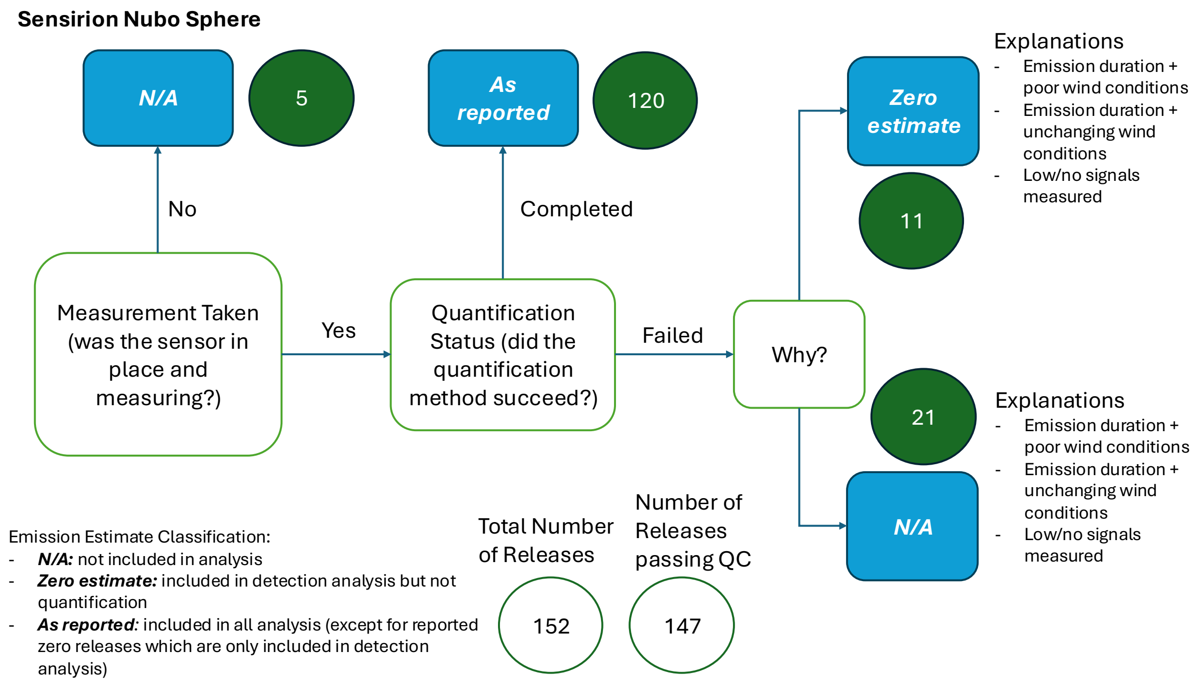

Figure S14. Data cleaning process flowchart for Sensirion Nubo Sphere.

S4.1.8 SLB Methane Lidar Camera Data Cleaning

SLB reported estimates below their level of detection (LOD) as failed quantification measurements.

Table S22. SLB QC flags with number of releases and associated estimated emission rate.

QC Flag	Number of Releases	Stanford QC Assigned Emission Rate (kg h^{-1})
Below LOD or obscured	10	0
Camera had been likely bumped by other participants working in the area	2	N/A

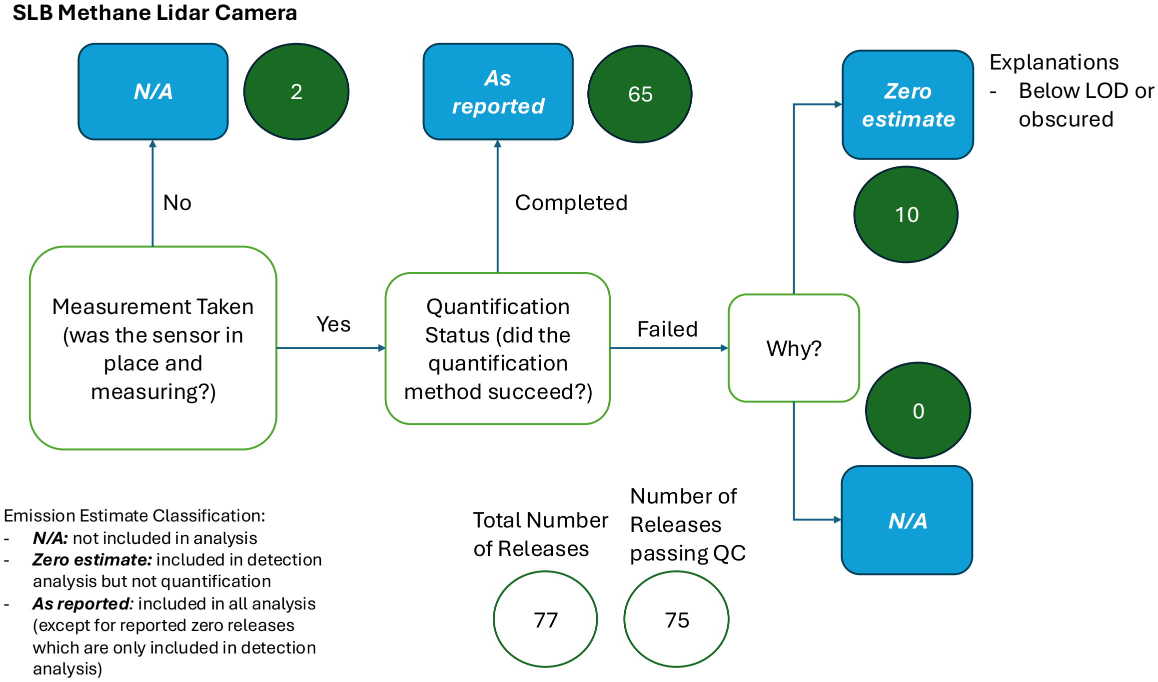

Figure S15. Data cleaning process flowchart for SLB Methane Lidar Camera.

S4.1.9 SENSIA Mileva 33 Data Cleaning

SENSIA only submitted the Data Reporting Template with their results and did not submit an associated release schedule as asked. They included all estimated emission rates including undetected releases as zeroes in their results. There was some reported installation and de-installation time.

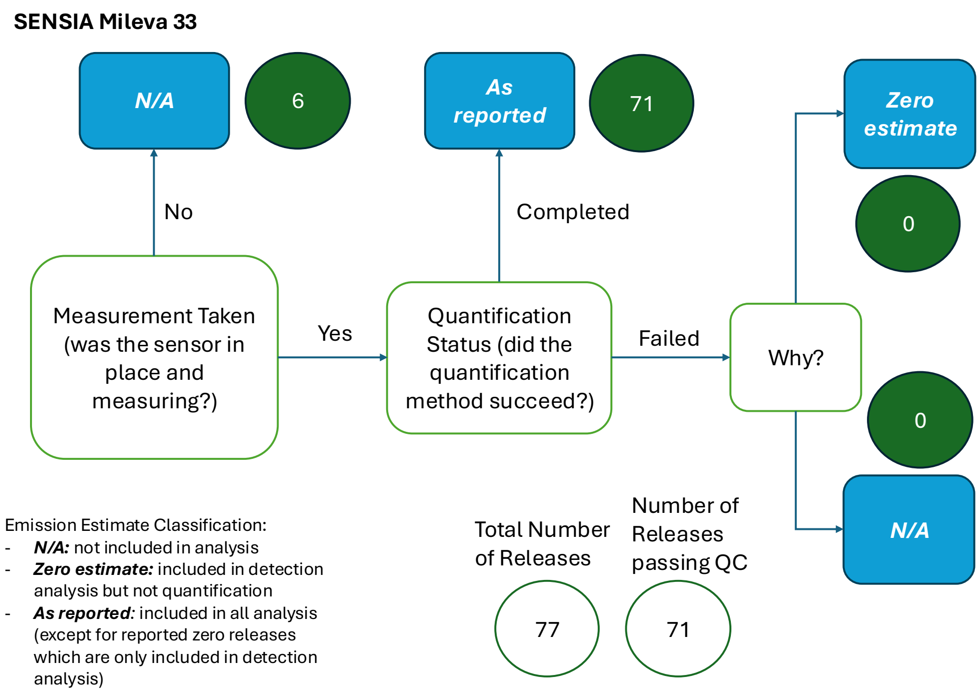

Figure S16. Data cleaning process flowchart for SENSIA Mileva 33.

S4.2 Data classification

Table S23 summarizes the release estimates that pass the data filtering and categorization process for each of the QC methods. Note that in many cases the Stanford QC and Participant QC processes result in the same number of zero and non-zero release estimates. Table S24 contains the minimum and maximum true release rates measured by each team. This does not mean that the team necessarily submitted an estimate for this true release rate, only that they were measuring during the release.

Table S23. Release counts by participant through the filtering process.

Solution	Scheduled Releases[a]	Measured Releases[b]	Strict QC Passing Estimates[c]			Stanford QC Passing Estimates			Participant QC Passing Estimates		
			Zero	*Non-Zero*	*Total*	*Zero*	*Non-Zero*	*Total*	*Zero*	*Non-Zero*	*Total*
Aeromon BH-12	20	21	12	9	21	0	9	9	0	9	9
GSMA AUSEA	20	14	2	12	14	1	12	13	1	12	13
Flylogix	40	18	3	15	18	3	15	18	3	15	18
SeekOps SeekIR	34	29	0	29	29	0	29	29	0	29	29
GHGSat-C	12[d]	12	11	1	12	0	1	1	0	1	1
Sensirion Nubo Sphere	152	147	27	120	147	11	120	131	0	120	120
SLB Methane Lidar Camera	77	75	10	65	75	10	65	75	0	65	65
SENSIA Mileva 33	77	71	4	67	71	4	67	71	4	67	71

[a] Scheduled releases refers to the total number of releases available for each performer occurring during the assigned week(s) of testing.
[b] Measured releases is the number of releases that the participants measured during the testing periods. This is the same as the total number of releases passing the Strict QC criteria.
[c] QC passing estimates is the number of measured estimates that passed the three QC methods, divided into zero and non-zero estimates by participant (i.e. the classification of the release rate submitted by the participant, which could be different than the true release rate). The Stanford QC passing releases are those included in the analysis in this paper (highlighted in gray).
[d] Satellite overpass frequency was determined based on the available overpasses of the TADI site and the timing of the overpasses, which is why only 12 releases corresponded to real overpasses.

Table S24. Maximum and minimum true release rates measured and passing the Stanford QC process.

Solution	Maximum Release Rate Measured [kg h^{-1}]	Minimum Release Rate Measured [kg h^{-1}]	Maximum Release Rate Passing Stanford QC [kg h^{-1}]	Minimum Release Rate Passing Stanford QC [kg h^{-1}]
Aeromon BH-12	126.0	0.0	115.0	0.0
GSMA AUSEA	47.66	0.0	47.66	0.0
Flylogix	290.0	0.0	290.0	0.0
SeekOps SeekIR	136.6	0.0	136.6	0.0

GHGSat-C	308.2	17.8	136.6	136.6
Sensirion Nubo Sphere	308.2	0.0	308.2	0.0
SLB Methane Lidar Camera	308.2	0.0	308.2	0.0
SENSIA Mileva 33	308.2	0.0	308.2	0.0

The release schedules were planned so each participant would measure during a satellite-scale and zero-release, but due to equipment and weather issues this was not possible for every participant.

S4.3 Solution Uncertainties

Table S25 contains the confidence level associated with the upper and lower emission rate estimates submitted with participants' results, as well as the sources of uncertainty that they include in their quantification estimates.

Table S25. Uncertainty types associated with participant quantification of release flowrates.

Solution	Confidence Level	Uncertainty Source
Aeromon BH-12	95% CI	Uncertainty of Aeromon's MB approach combines the measurement uncertainties of the methane sensor concentration measurement (defined according to CEN TS 17660), wind sensor and drone location throughout the entire fenceline wall with result-to-result deviation between full fenceline walls
GSMA AUSEA[a]	± 40%	Single quantification uncertainty has been established in prior controlled release campaigns on TADI (2019, 2021) and 1 on METEC (2022). It is based on the global average of the absolute error of quantification: AUSEA measured rate compared with actual rate. It includes all wind speed and methane rate conditions.
Flylogix	3-sigma	The methane uncertainty is obtained by analysis of the 'background' Methane measurement data to get bias and variance of the sensor The wind speed and direction uncertainty is obtained from a combination of the specs of the Davis Vantage 2 Pro Weather station and the statistics of the data measured
SeekOps SeekIR[a]	± 30%	They report a standardized ± 30% uncertainty (influenced by wind variability)
GHGSat-C	1-sigma	Source rate error includes: (1) Wind error, (2) Measurement/data error, (3) error from the IME model (as described in Varon et al. (2018, 2019)

Sensirion Nubo Sphere	2-sigma	Calculations
SLB Methane Lidar Camera[b]	1-sigma	The SLB methane lidar camera estimates emission rates within a ± factor of two. The uncertainty is based on previous METEC tests.
SENSIA Mileva 33[a]	Analytical	Calculations from the analytics obtained during the estimation of the leak rate.

[a] GSMA, SeekOps, and SENSIA did not report the confidence level (e.g., 1-sigma, 2-sigma) associated with their percentage estimates. 95% CI is roughly 2-sigma.
[b] The SLB Methane Lidar Camera described their uncertainty generally but did not include upper and lower bounds for estimates in their reporting.

S5 Detection Results

S5.1 Release Classification Criteria

The ability of methane detection technologies to correctly identify the presence of emissions is a fundamental requirement for effective emissions monitoring and mitigation. In this section, we evaluate the detection performance of each participant by categorizing reported measurements as true positives (TP), false positives (FP), true negatives (TN), or false negatives (FN). True positives indicate successful detection of a known release, while false negatives represent missed detections. Conversely, false positives occur when a participant reports a detection where no release was present, and true negatives confirm correct identification of zero-release events. The general criteria for these designations can be found in Table S26.

Table S26. General release categorization criteria into TP, TN, FP, and FN.

Categorization	True Release Rate	Participant Estimated Release Rate[a]
TP	>0	>0
TN	0	0
FP	0	>0
FN	>0	0

[a] The participant release rate refers to the reported release rate or release rate assigned during the data categorization process.

Figure S17 visualizes the distribution of estimate categorizations for each participant for small (0-50 kg h^{-1}) and large (50-350 kg h^{-1}) release rates.

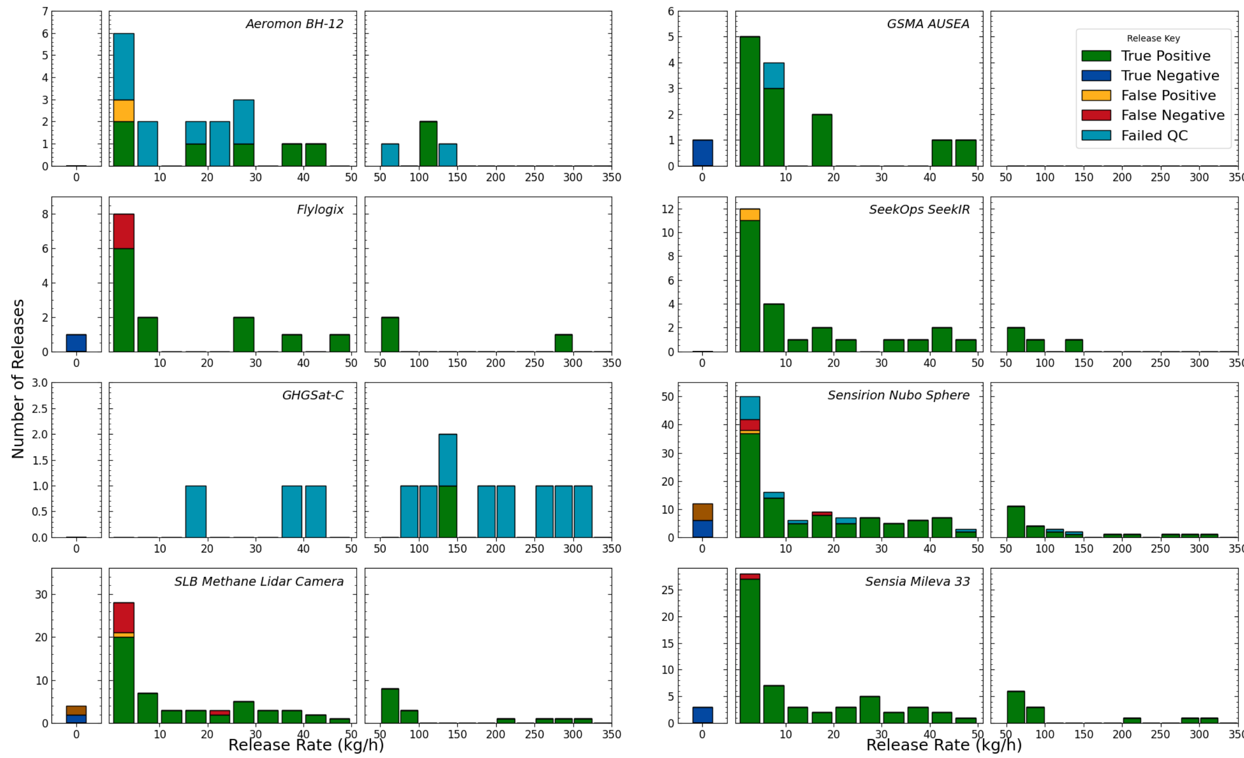

Figure S17. Distribution of measured release categorizations by participant. The colors represent different result classifications: true positive, true negative, false positive, false negative, and failed QC process. The y-axis is the number of measured releases, and the x-axis corresponds to the binned methane release flowrate. Note the different y-axis scales per row.

S5.2 Detection Capabilities Under 5 kg h^{-1}

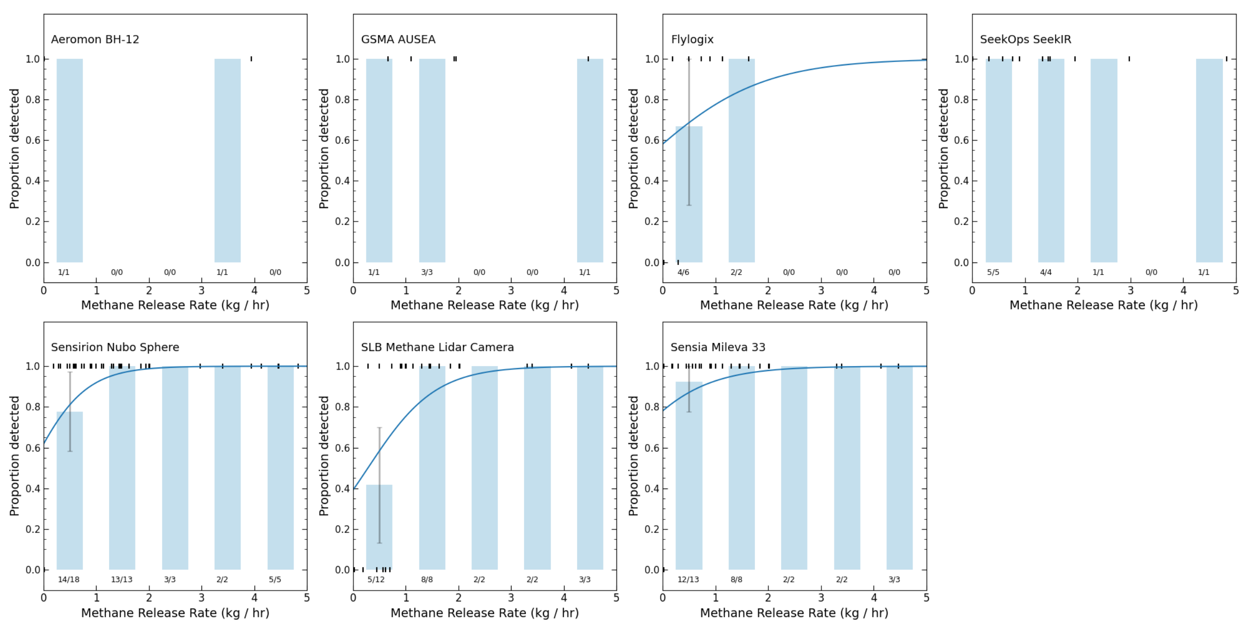

Figure S18. Detection capabilities below 5 kg h^{-1}.

This figure shows the probability of detection for participant-quantified releases. Each release is marked by a vertical line at y = 0 if not detected and y = 1 if detected, ordered along the x-axis by release volume. Blue bars indicate the proportion of detected releases within each bin, with error bars representing 95% confidence intervals based on a binomial distribution. The darker blue line is the best fit of a logistic regression model on the probability data. GHGSat-C is excluded due to not measuring any releases below 5 kg(CH_4) h^{-1}. The x-axis is based on the true release rate.

S5.3 Distribution of Detected Releases

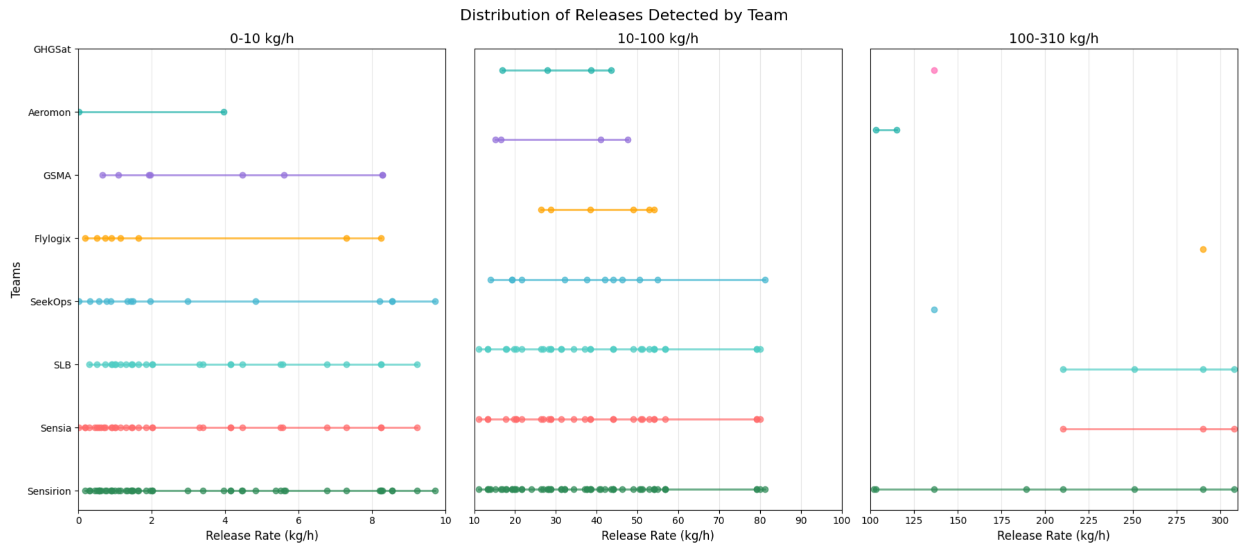

Figure S19. Distribution of detected releases by team.

S6 Quantification Results

S6.1 Additional Parity Plots

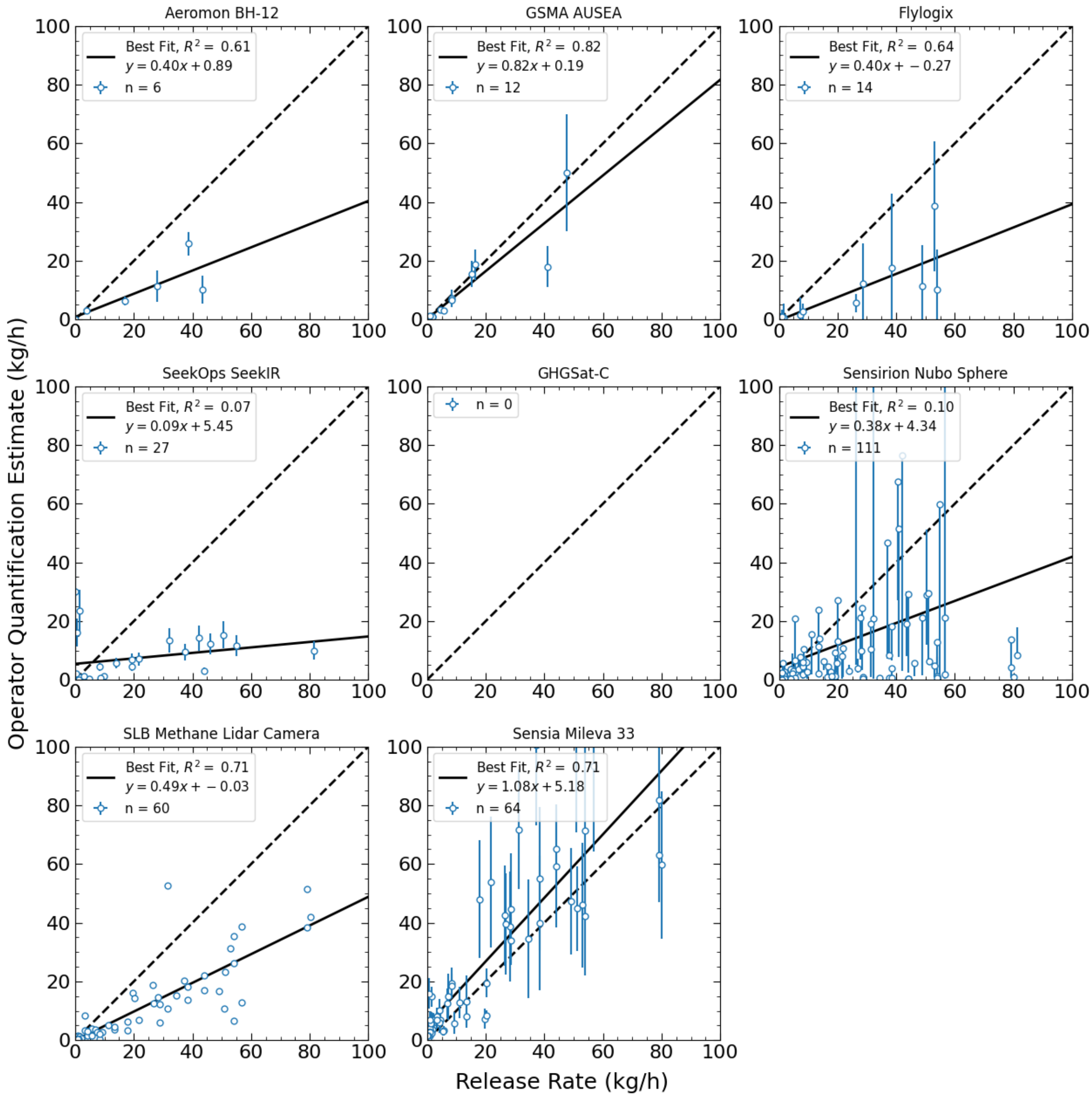

Figure S20. Parity plots with true release rates of <100 kg h^{-1}

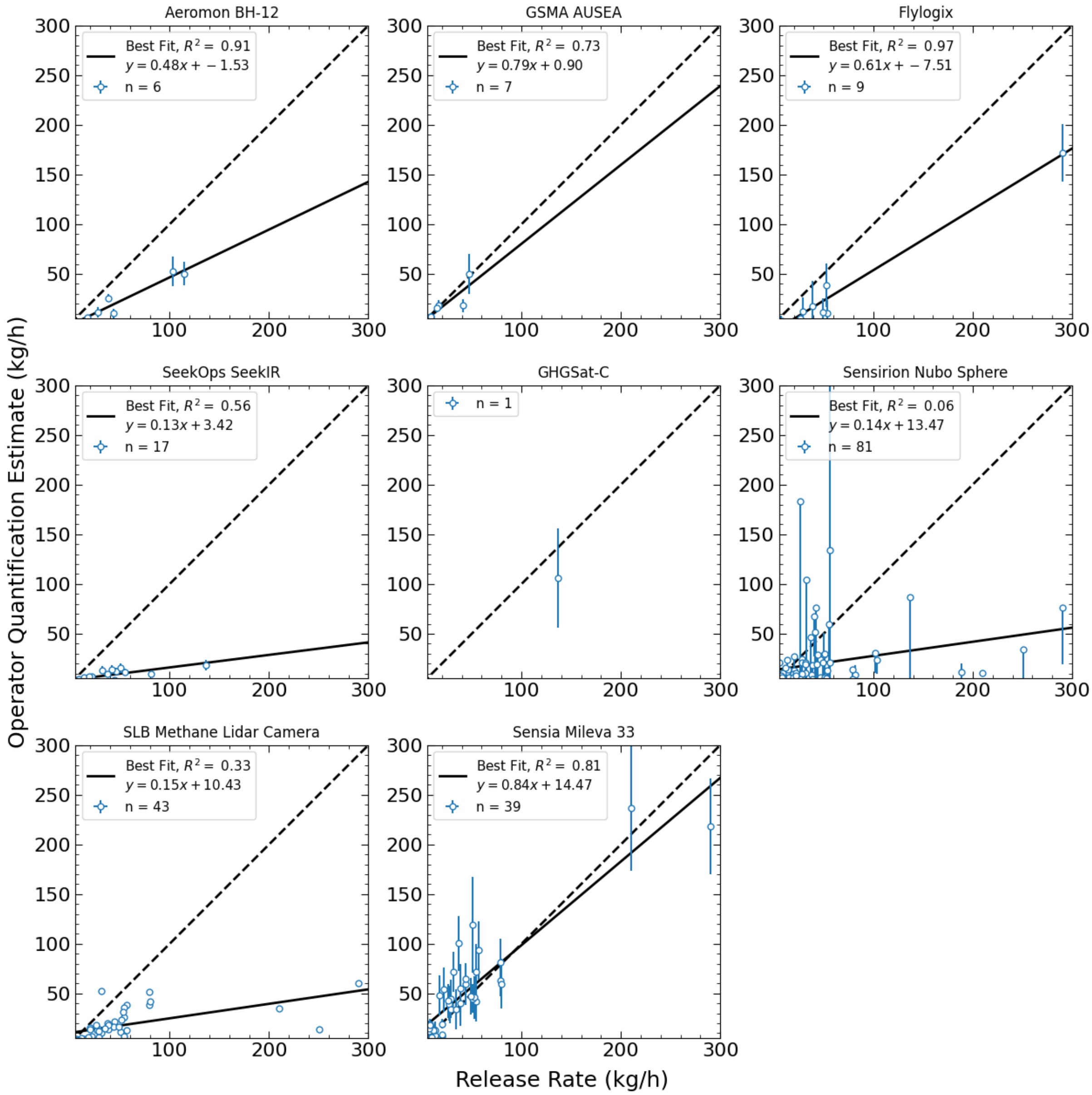

Figure S21. Parity plots with true release rates > 10 kg h^{-1}

S6.2 Participant Parity Plots

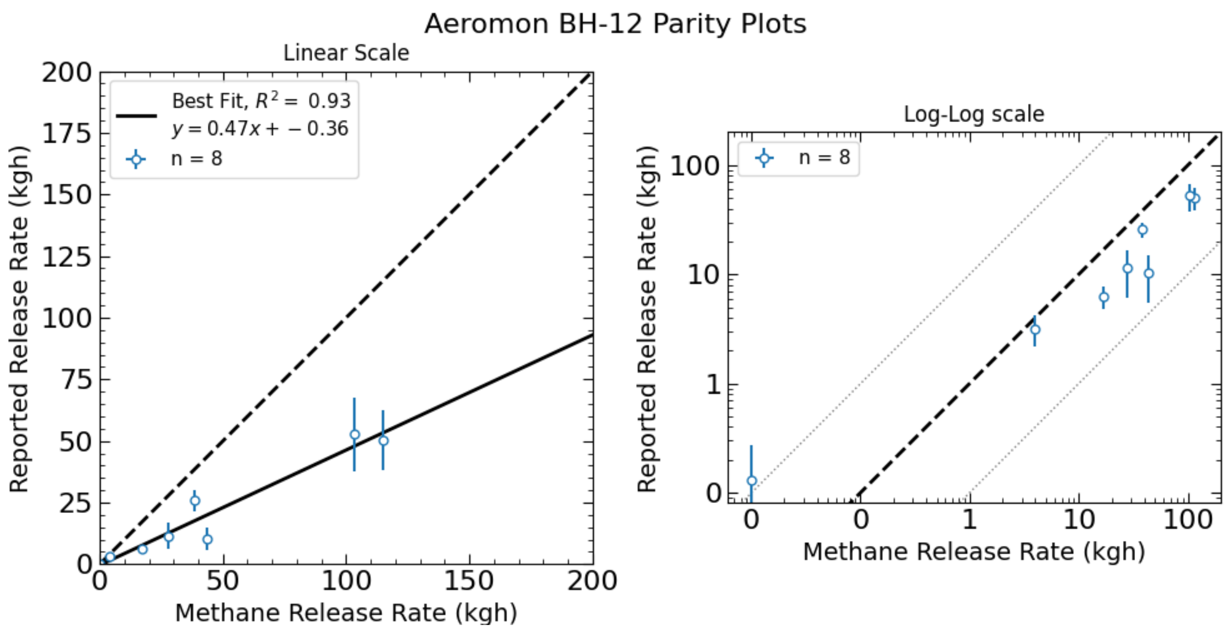

Figure S22. Aeromon BH-12 parity plot.

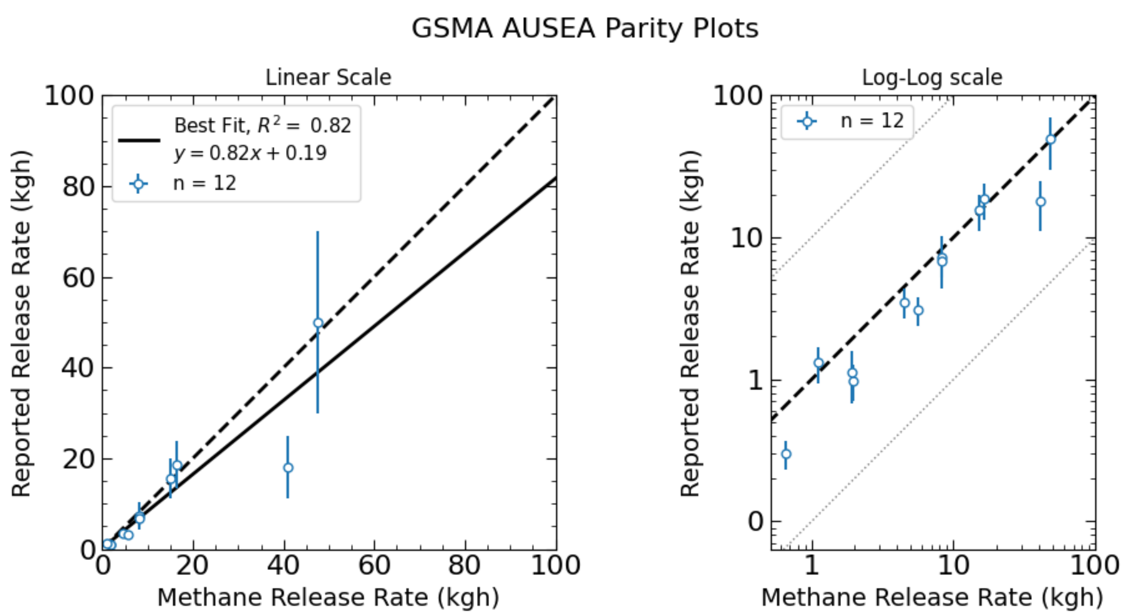

Figure S23. GSMA AUSEA parity plot.

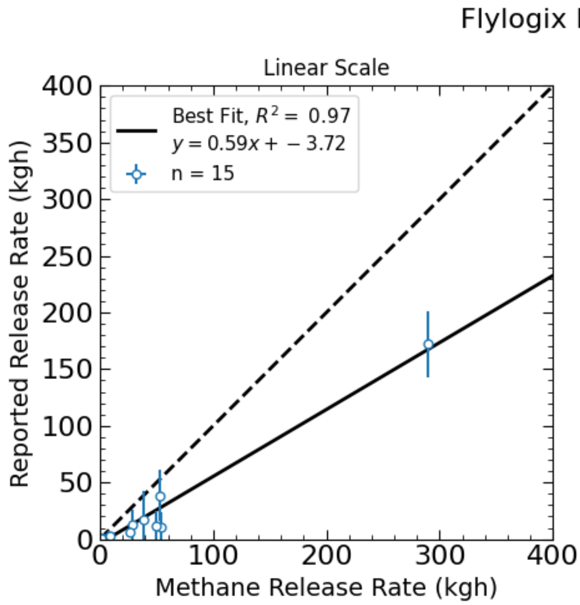

Figure S24. Flylogix parity plot.

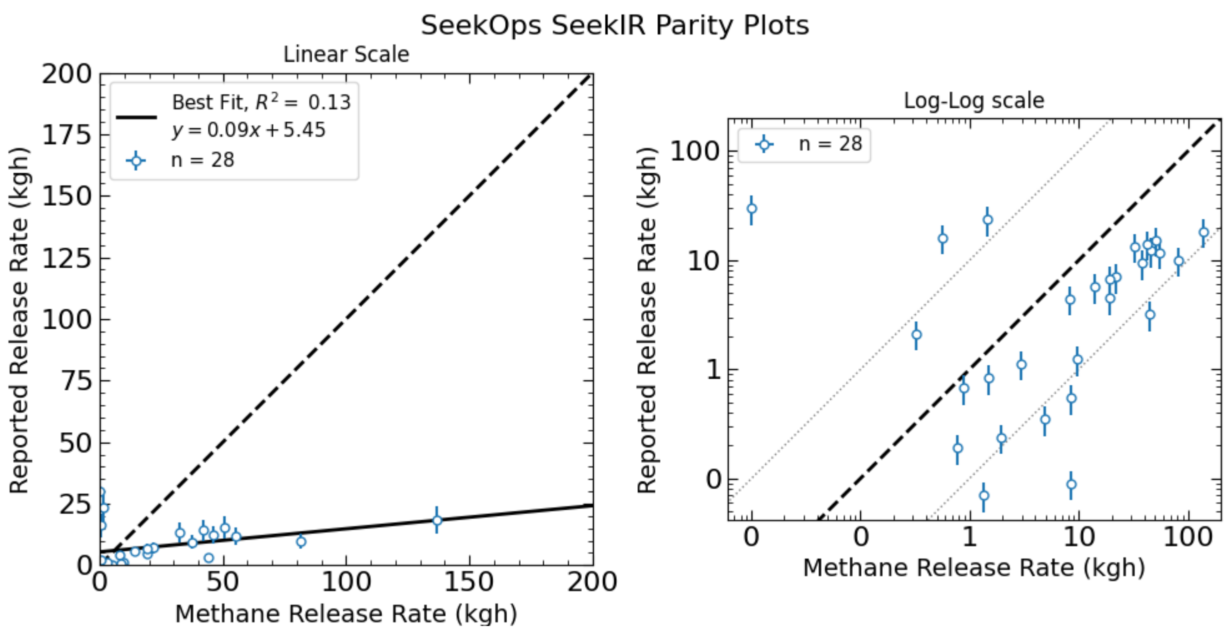

Figure S25. SeekOps SeekIR parity plot.

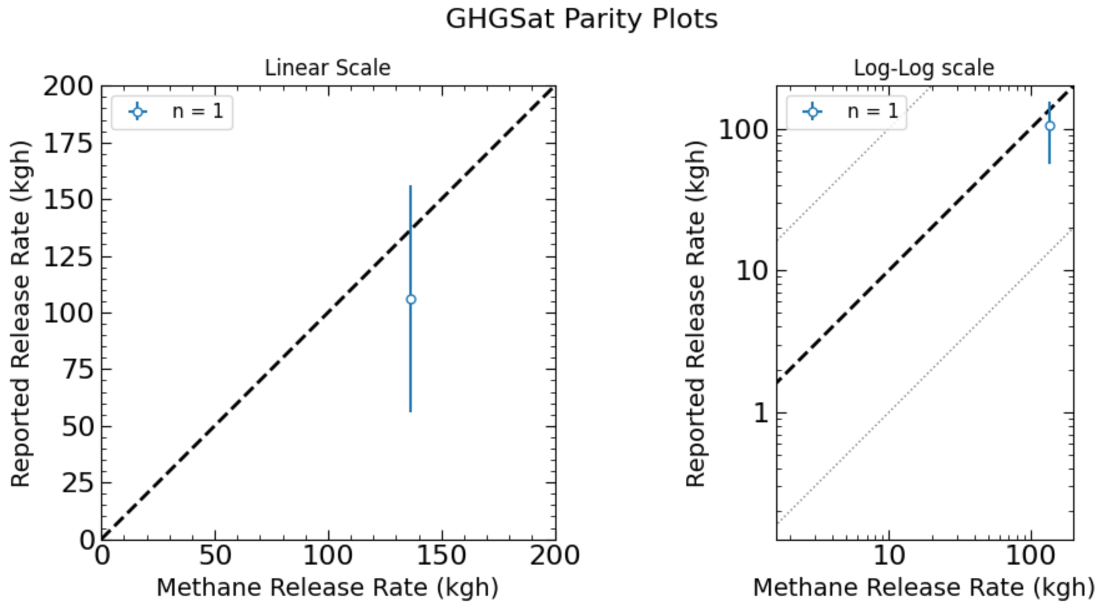

Figure S26. GHGSat-C parity plot.

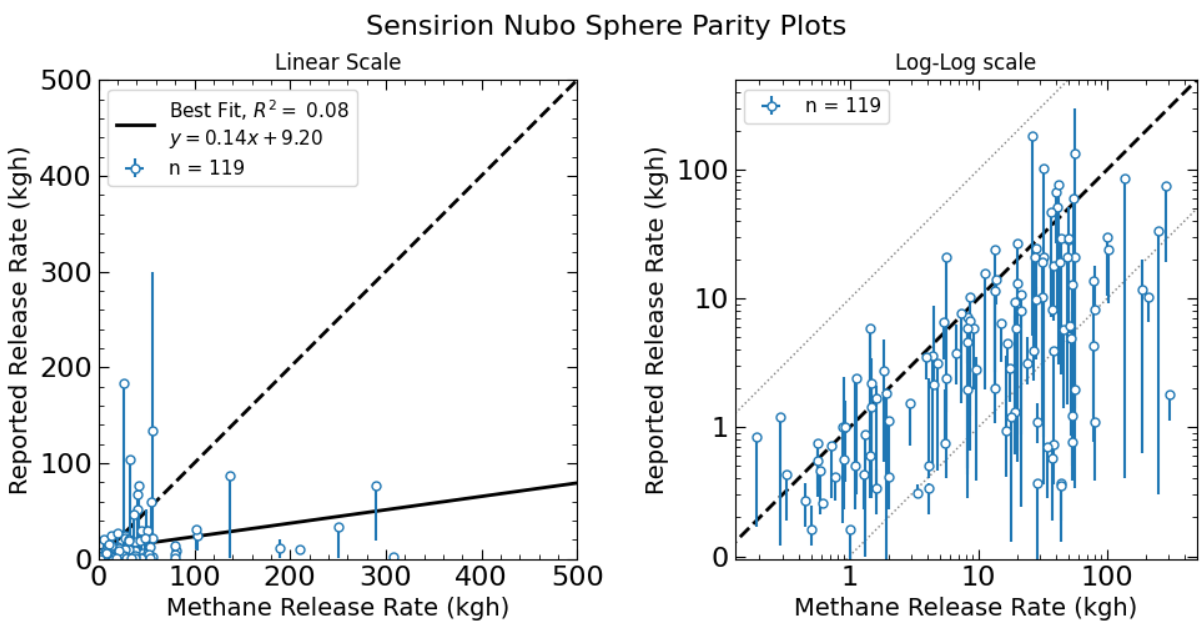

Figure S27. Sensirion Nubo Sphere parity plot.

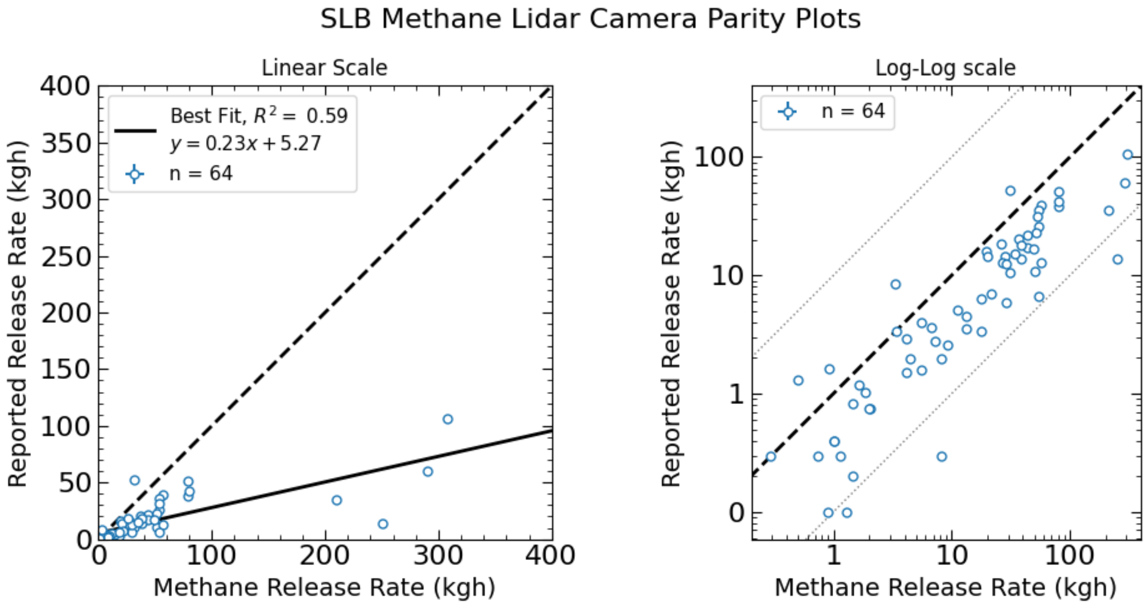

Figure S28. SLB Methane Lidar Camera parity plot.

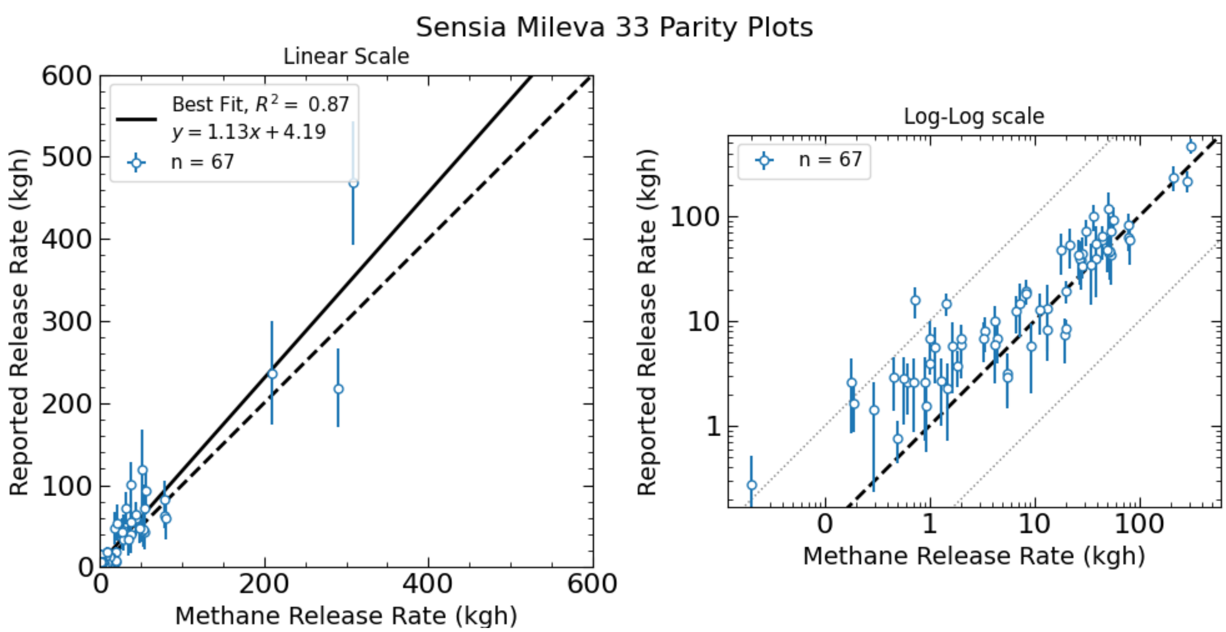

Figure S29. Sensia Mileva 33 parity plot.

S7 Wind Condition Analysis

Wind conditions significantly influence methane plume behavior, affecting detection and quantification accuracy. Variability in wind speed, direction, and turbulence can distort plume shape and movement, making accurate measurement more challenging—especially under rapidly changing conditions. This section analyzes measurement performance across bins of average wind speed, wind speed CoV, and wind direction CoV to identify where different technologies perform best or face limitations. Results are shown both by participant and in aggregate, though data point counts vary across participants.

Wind data were collected using TADI's ZX 300 Wind Lidar at 20 m height and were not available to participants until after unblinding. Wind statistics were calculated for each release window. Coefficient of variation (CoV), defined as the standard deviation normalized by the mean, was used to assess variability. Figures S29, S30, and S31 show parity plots colored by wind speed and variability bins

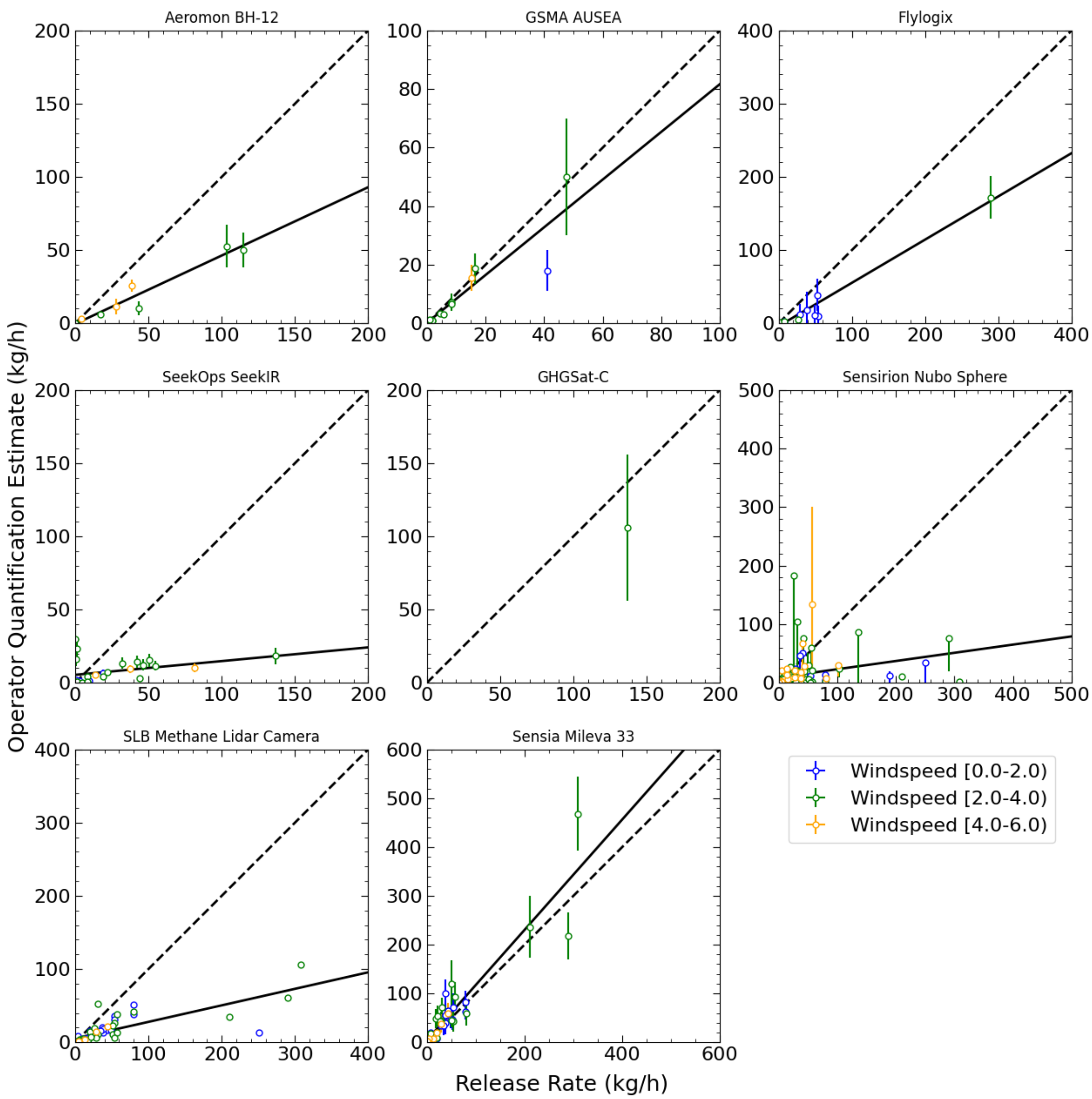

Figure S30. Parity plots with average wind speeds.
The average windspeeds are binned into low [0-2.0 m/s), medium [2-4 m/s) and high [4-6 m/s) windspeed bins.

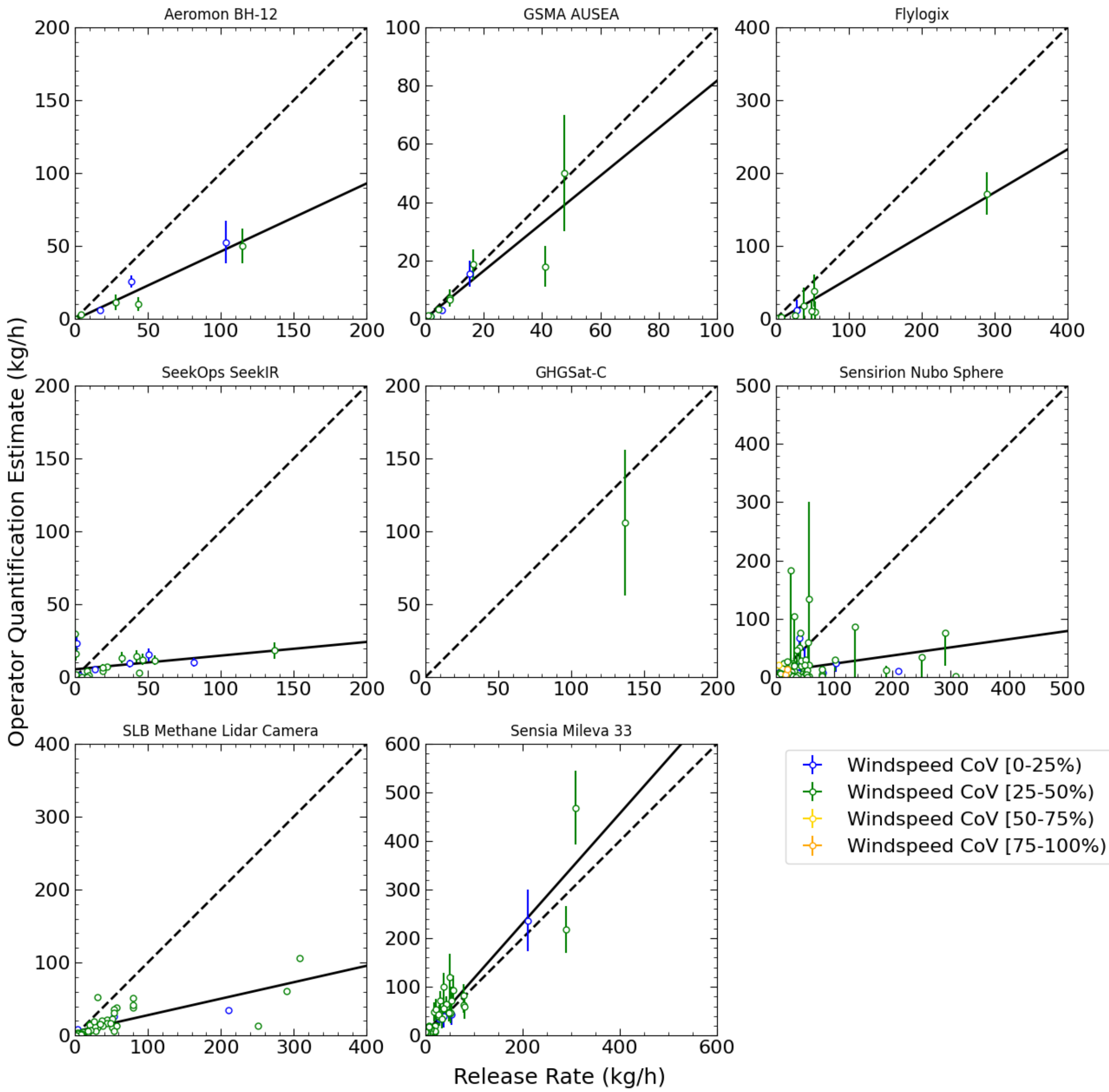

Figure S31. Parity plots with wind speed coefficient of variation (CoV).
The average wind speed CoVs are binned into low [0-25%), medium [25-50%), high [50-75%), and extreme [75-100%) wind speed CoV ranges.

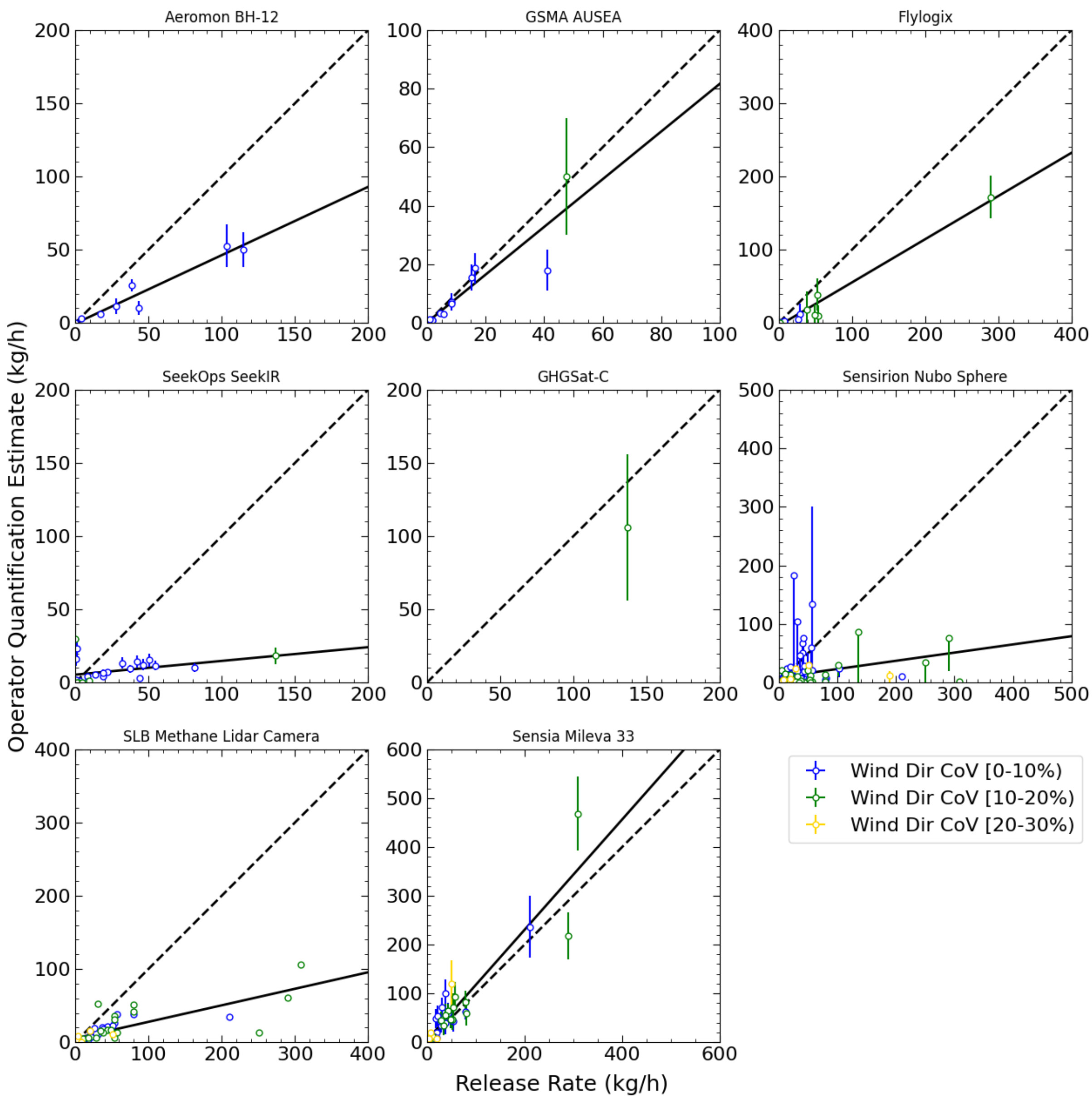

Figure S32. Parity plots with wind direction coefficient of variation (CoV).
The average wind direction CoVs are binned into low [0-10%), medium [10-20%), and high [20-30%) wind direction CoV ranges.

In addition to providing context about each of the quantification estimates submitted by a participant, this wind analysis allowed us to investigate the impact of varying wind conditions on quantification performance. For example, to view the impact of average wind speed on quantification ability, a participant's estimates were categorized into different average wind speed bins and the best fit line was recalculated using only those data points, yielding a slope and R^2 value for each bin. These calculations were performed for each participant and average wind speed, wind speed CoV, and wind direction CoV bin. Table S27 summarizes these results. The scale and sometimes direction of improvement varies by participant. Additionally, many of the participants had only a few data points in a bin; although slope and R^2 values were calculated for any bin with >1 datapoint, it is difficult to draw any conclusion (see Table

S28 for the number of data points in each bin for each participant). The impact of wind conditions on quantification performance is more evident and robust when combining the release rate estimates across all participants. In general, quantification performance improves as average wind speed increases, wind speed CoV decreases, and wind direction CoV decrease. Improved performance is indicated by best fit line slopes closer to 1.00 and R^2 values closer to 1.

Table S27. Slope (R^2) values of the linear model fit on releases across technology types and wind analysis bins.

	Wind Speed Average Bins			**Wind Speed CoV Bins**		**Wind Direction CoV Bins**		
Solution	**[0-2) m/s**	**[2-4) m/s**	**[4-6) m/s**	**[0-25%)**	**[25-50%)**	**[0-10%)**	**[10-20%)**	**[20-30%)**
Aeromon BH-12	-	0.49 (0.96)	0.60 (0.87)	0.51 (0.96)	0.43 (0.96)	0.47 (0.93)	-	-
GSMA AUSEA	-	1.08 (0.99)	-	1.14 (0.98)	0.81 (0.81)	0.51 (0.71)	-	-
Flylogix	0.40 (0.59)	0.60 (1.00)	-	-	0.59 (0.97)	0.33 (0.84)	0.61 (0.97)	-
SeekOps	0.30 (0.76)	0.07 (0.06)	0.06 (0.07)	0.04 (0.02)	0.10 (0.17)	0.11 (0.14)	0.08 (0.12)	-
GHGSat-C[a]	-	-	-	-	-	-	-	-
Sensirion Nubo Sphere	0.12 (0.24)	0.12 (0.05)	0.45 (0.16)	0.05 (0.03)	0.16 (0.09)	0.23 (0.05)	0.15 (0.36)	0.03 (0.03)
SLB Methane Lidar Camera	0.14 (0.27)	0.25 (0.72)	0.54 (0.97)	0.15 (0.76)	0.24 (0.60)	0.24 (0.62)	0.22 (0.57)	0.15 (0.24)
SENSIA Mileva 33	1.03 (0.78)	1.12 (0.86)	1.26 (0.95)	1.11 (0.99)	1.14 (0.85)	1.09 (0.88_	1.14 (0.87)	2.28 (0.88)
All Solutions	0.24 (0.27)	0.54 (0.46)	0.61 (0.35)	0.65 (0.47)	0.45 (0.41)	0.69 (0.45)	0.44 (0.45)	0.14 (0.05)

[a] Values are provided for bins that had more than one quantification estimate occurring under those wind conditions. GHGSat-C only submitted one estimate, so a linear trend could not be fit to the data.

Table S28. Number of data points in the bins of average wind speed, wind speed CoV, and wind direction CoV used in analysis.

	Wind Speed Average Bins			**Wind Speed CoV Bins**		**Wind Direction CoV Bins**		
Solution	**[0-2) m/s**	**[2-4) m/s**	**[4-6) m/s**	**[0-25%)**	**[25-50%)**	**[0-10%)**	**[10-20%)**	**[20-30%)**
Aeromon BH-12	5	3	0	5	3	8	0	0
GSMA AUSEA	10	1	1	9	3	11	1	0
Flylogix	9	6	0	14	1	8	7	0

SeekOps	18	7	3	21	7	22	6	0
GHGSat-C	1	0	0	1	0	1	0	0
Sensirion Nubo Sphere	57	45	17	98	18	75	38	6
SLB Methane Lidar Camera	33	27	4	57	7	32	27	5
SENSIA Mileva 33	33	25	9	59	8	38	24	5
All Solutions	207	155	49	340	65	249	142	20

S7.1 Wind Parity Plots by Participant

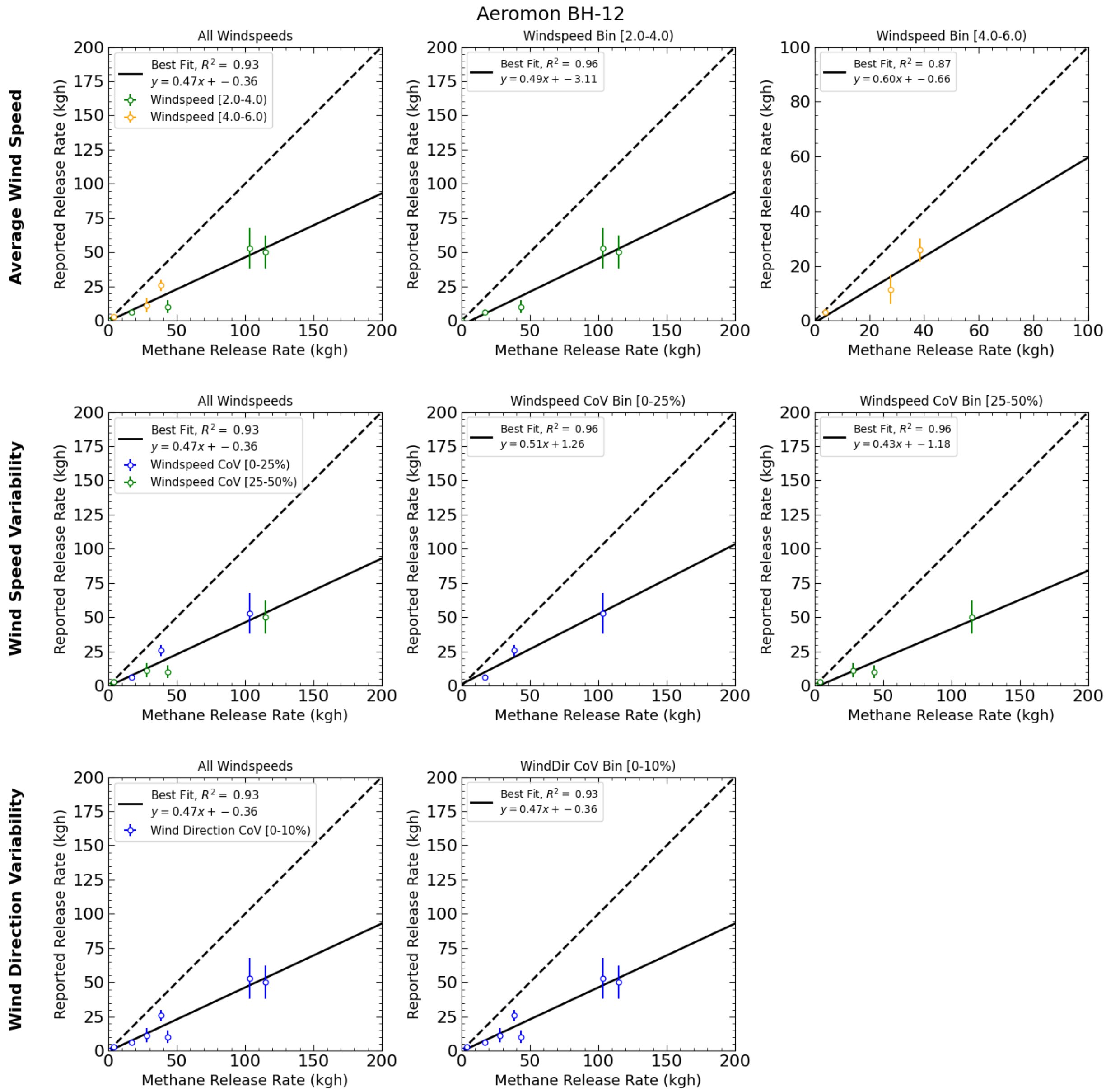

Figure S33. Aeromon quantification data by wind condition bin.

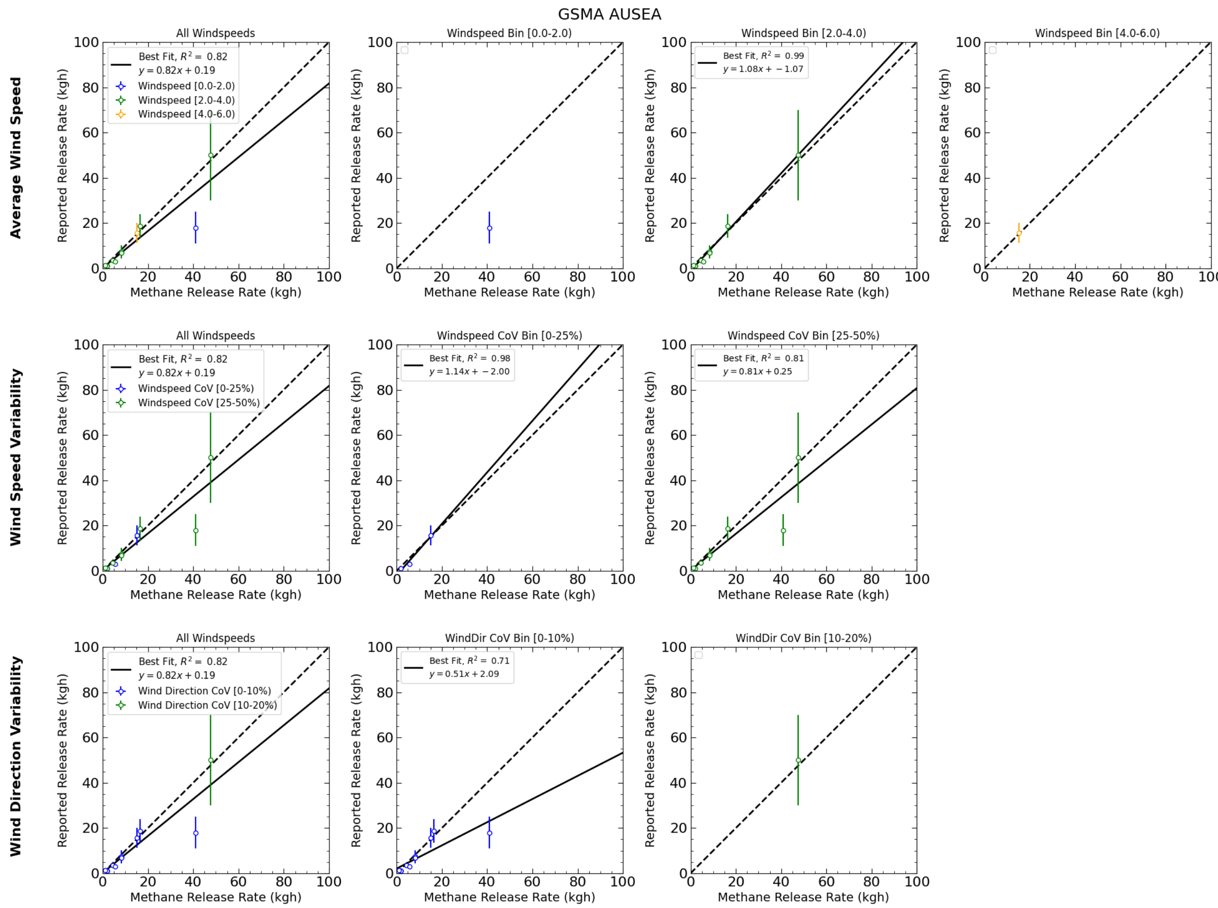

Figure S34. GSMA AUSEA quantification data by wind condition bin.

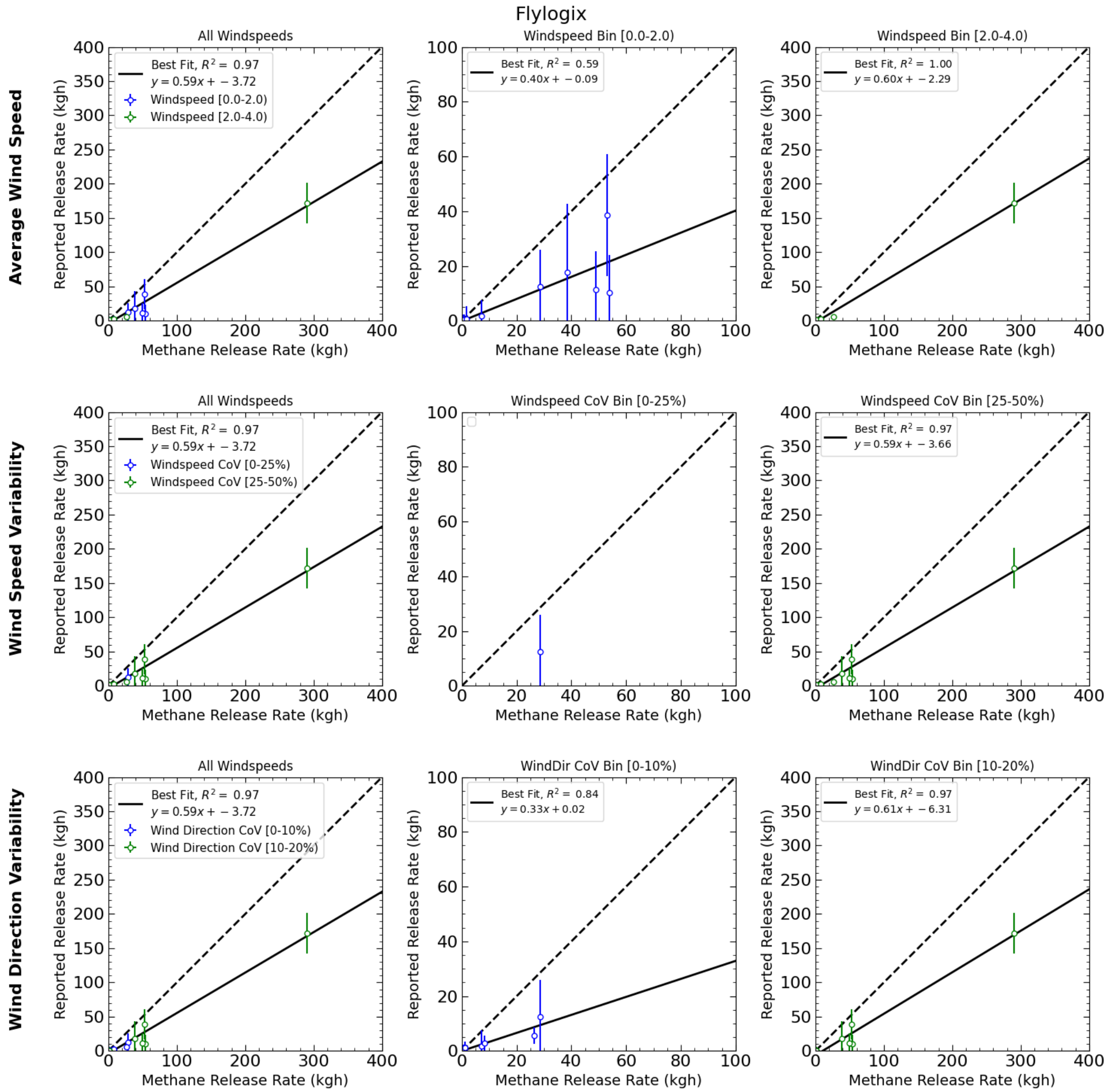

Figure S35. Flylogix quantification data by wind condition bin.

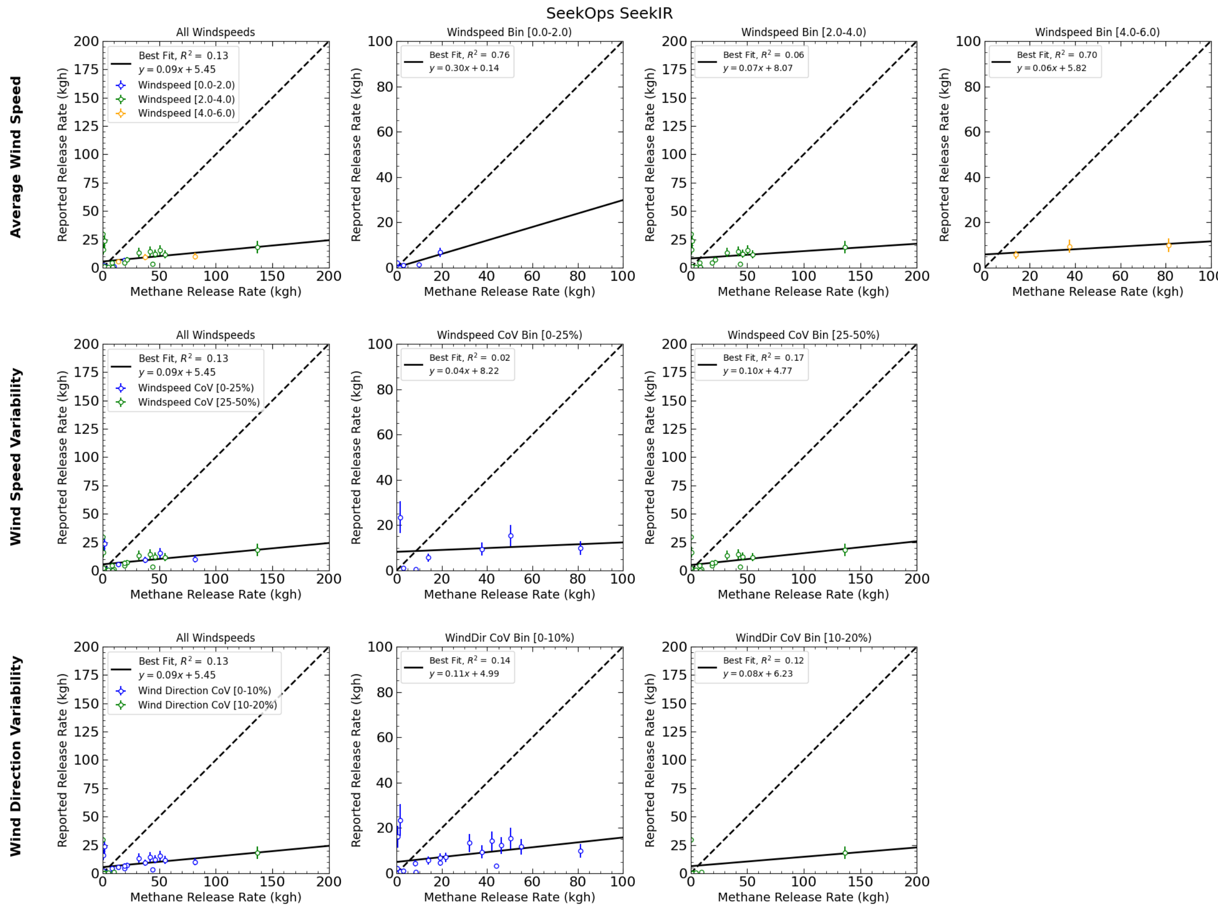

Figure S36. SeekOps SeekIR quantification data by wind condition bin.

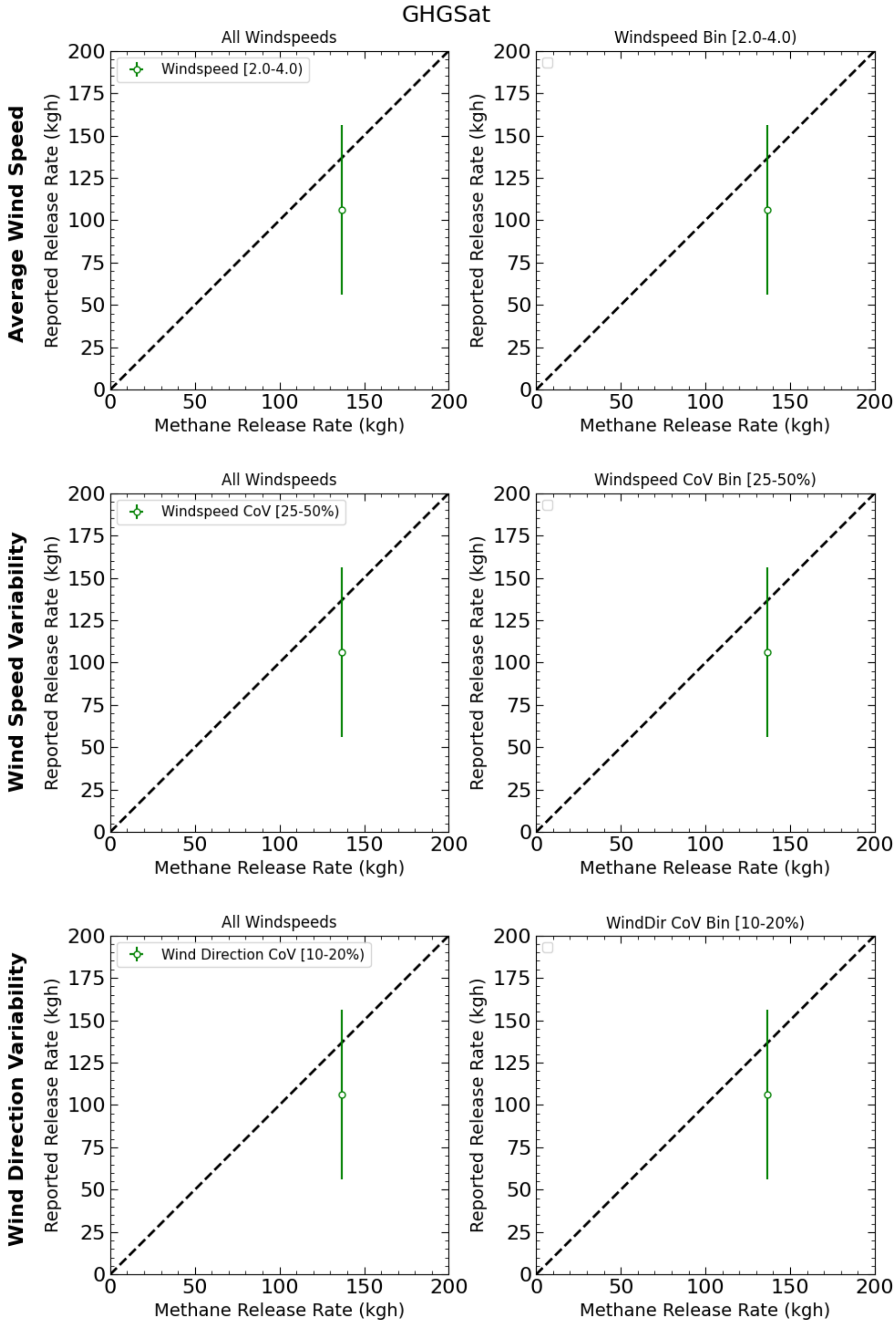

Figure S37. GHGSat-C quantification data by wind condition bin.

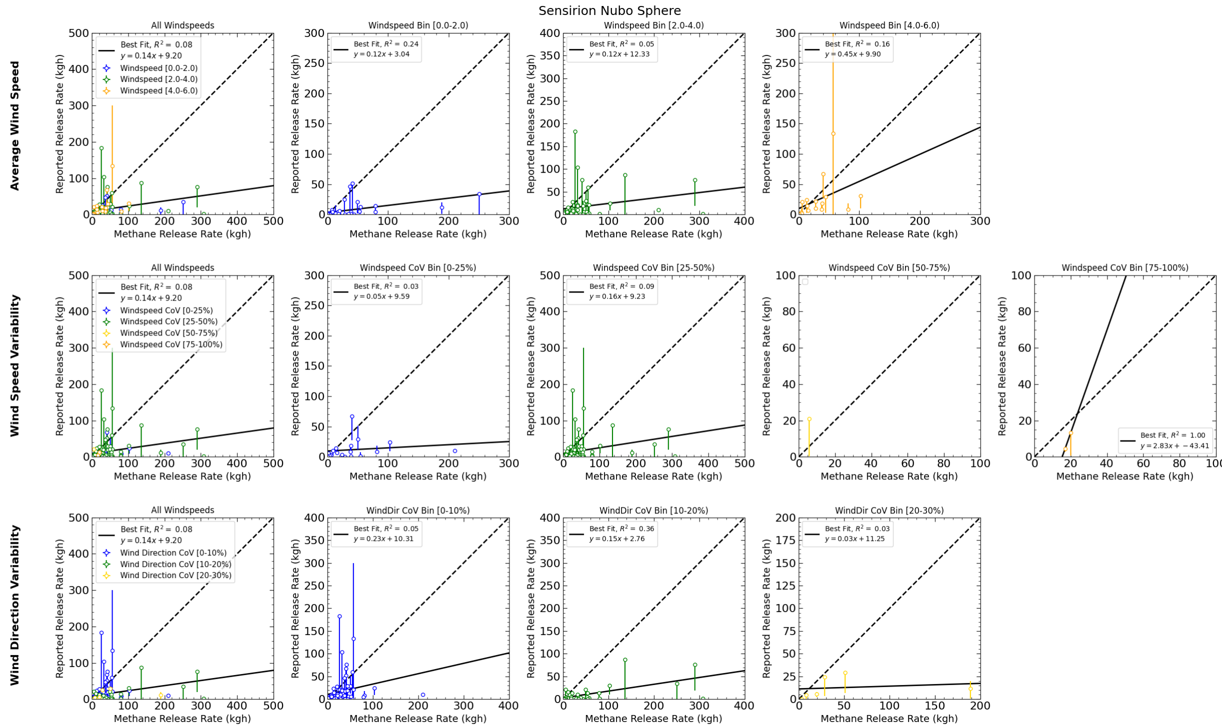

Figure S38. Sensirion Nubo Sphere quantification data by wind condition bin.

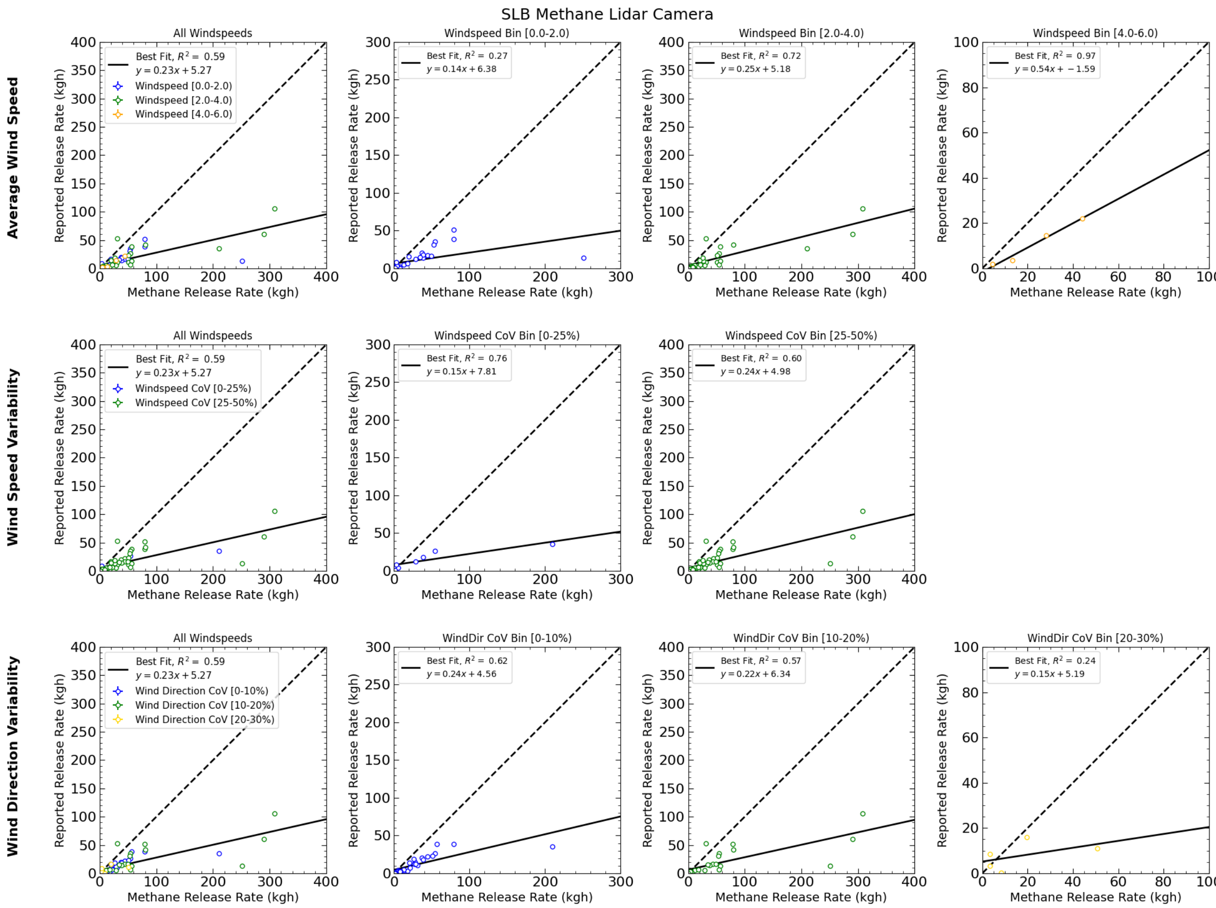

Figure S39. SLB Methane Lidar Camera quantification data by wind condition bin.

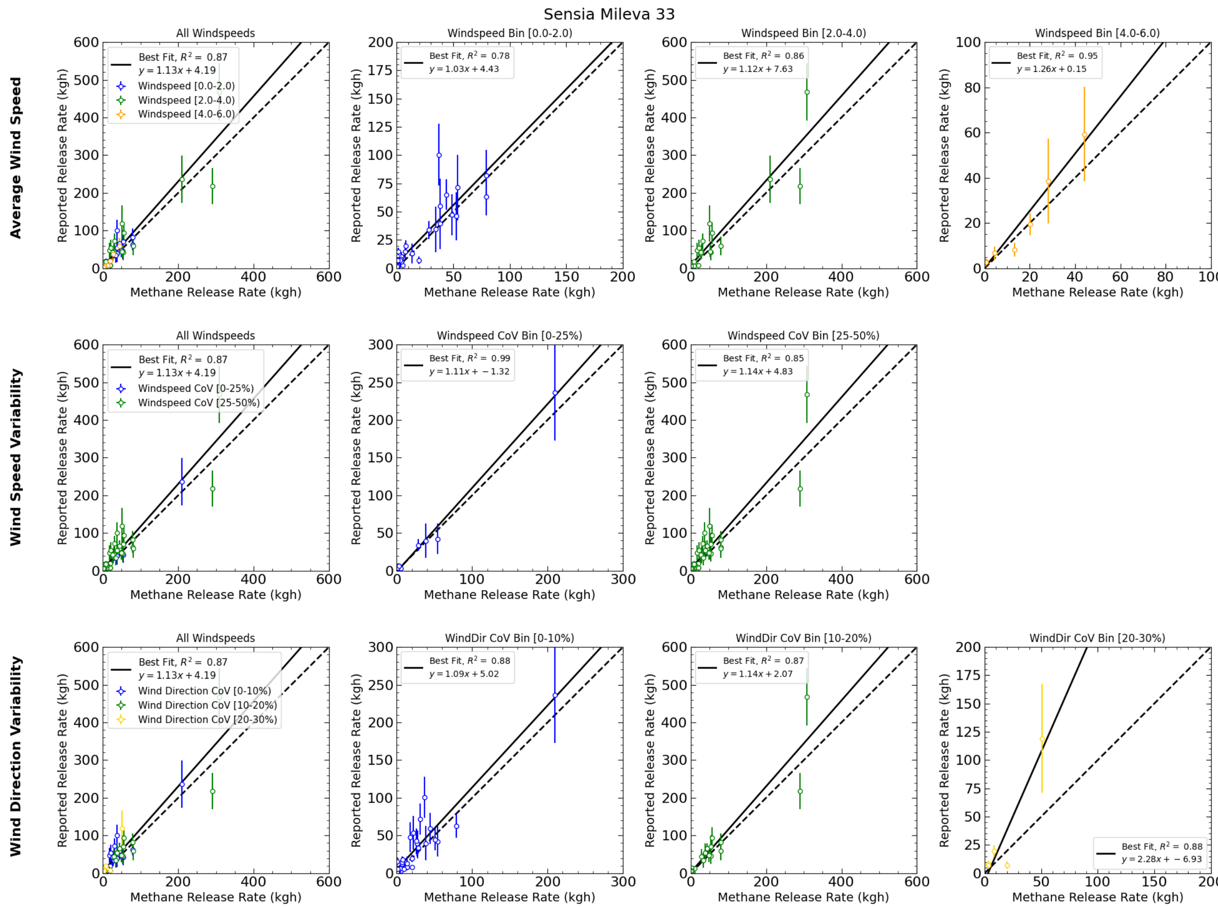

Figure S40. SENSIA Mileva 33 quantification data by wind condition bin.

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(1) *TADI: A test center with international reach in Lacq | ETABLISSEMENT PAU LACQ*. https://cstjf-pau.totalenergies.fr/en/our-expertise/leveraging-digital-innovation/tadi-test-center-international-reach-lacq (accessed 2025-01-29).

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