



BOWTIE: ship-based measurements of atmosphere and ocean within the moist tropical Atlantic

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Abstract. As part of BOWTIE (German: Beobachtung von Ozean und Wolken - Das Trans ITCZ Experiment), the German research vessel *FS Meteor* navigated the moist tropics of the Atlantic Ocean for 40 days in summer 2024, with an east-west trajectory. The journey started in the port of Mindelo, Cape Verde, on August 16, and finished in the port of Bridgetown, Barbados, on September 24. The objective was to measure properties of the atmosphere, upper-ocean, and air-sea interface within the Intertropical Convergence Zone (ITCZ), under a variety of wind, convection, and sea surface temperature regimes. Using a set of 29 instruments/platforms, BOWTIE sampled the near-surface conditions of the atmosphere and ocean with high temporal resolution. This included continuous measurements of: the 2-D wind field within the lowest 2 km of the atmosphere, near-surface ocean currents, cloud and precipitation properties. Profiles of the ocean state and atmospheric thermodynamics and kinematics were obtained both continuously and at discrete intervals. Furthermore, dedicated stations sampled biochemical properties of the upper-ocean. Complementing BOWTIE observations, *FS Meteor* hosted further dedicated field campaigns for



3D cloud and precipitation properties, as well as intensive measurements of the atmospheric boundary layer. This manuscript provides an overview of the extensive instrumentation and data collected during BOWTIE. In addition, it addresses two key aspects based on these observations. First, it examines the range and uncertainties of selected quantities measured by multiple instruments, including column-integrated water vapor, rain detection, surface ocean currents, and sea surface temperature. Second, it illustrates the diversity of sampled weather regimes through two representative cases: calm doldrum conditions and a gusty, precipitating convective state.

1 Introduction

In 1974, the "Global Atmospheric Research Program's Atlantic Tropical Experiment" (GATE) marked a milestone by using 39 ships within three observational phases to collect atmospheric and surface measurements in the tropical Atlantic to understand the role of tropical weather systems in the large-scale flow (Mason, 1975; Greenfield and Fein, 1979). GATE was also one of the first programs to collect measurements of the atmospheric boundary layer (Wylie and Ropelewski, 1980) and the upper-ocean (Philander and Düing, 1980) in different wind and convection regimes, from stormy to calm-wind conditions. 50 years after GATE, the "Beobachtung von Ozean und Wolken - Das Trans ITCZ Experiment" (BOWTIE; Klocke et al., 2026c) aims at understanding the mechanisms involved in the development of atmospheric convection within the Atlantic Intertropical Convergence Zone (ITCZ), and its impact on the atmosphere and upper-ocean state, including marine biology. To accomplish its objective, BOWTIE used the German research vessel *FS Meteor* to travel across the moist region in the tropical Atlantic, mapping the inner region and edges of the ITCZ. BOWTIE measured the full depth of the troposphere and the upper 2 km of the ocean simultaneously. Aside from traditional instrumentation (e.g., radiosondes, ocean Conductivity-Temperature-Depth-Oxygen), BOWTIE used a variety of state-of-the-art remote sensing techniques to continuously measure thermodynamic and dynamic properties of the free troposphere (humidity, temperature, wind), the 3D cloud and precipitation field, and aerosols. BOWTIE also intensively measured the 2-D wind field continuously at different levels in the first two kilometers above the ocean, and near-surface properties of the atmosphere and ocean, such as near-surface ocean currents. In this sense, BOWTIE sampled the small-scale variability in processes at play in the free troposphere, the atmospheric boundary layer, and the upper ocean to analyze their small-scale processes.

As part of the "Organized Convection and EarthCARE Studies over the TRopical Atlantic" (ORCESTRA; Stevens et al., 2026), BOWTIE contributes to answering a broader question: What is the role of small-scale processes within the ITCZ on the energetics and water budget on the large-scale circulation? The interest in the ITCZ is sparked by its role in the water and energy budget of the tropics (Simpson, 1992). While current computational resources allow for explicit simulation of deep convection and meso-scale circulation, several processes remain unresolved, such as atmospheric turbulence, cloud-radiation interaction, and the continuous exchange of momentum and energy in the air-sea interface. These unresolved processes have uncertain influences on the representation of the ITCZ in global km-scale models (Takasuka et al., 2024; Segura et al., 2025). It is in this context that the measurements of BOWTIE are important. The continuous high-temporal-resolution measurements of the marine atmospheric boundary layer and the upper-ocean permit quantification of the components of air-sea coupling (winds,



ocean currents, surface properties), and their variability in energy exchange. These measurements provide data critical for answering questions regarding the role of the doldrums - highlighted in early wind atlases (Maury, 1864) and re-emphasized in recent studies (Klocke et al., 2017; Windmiller, 2024) - in the formation of clouds and precipitation and the effect of convection on momentum and heat transfer across the air-sea interface. The route of the BOWTIE cruise was designed to perform sampling in different wind and cloud conditions within the ITCZ. During its 40-day journey, *FS Meteor* encountered doldrums, regions populated by shallow cumulus, cumulus congestus, and cumulonimbus. This provides adequate sampling to analyze the different stages of atmospheric convection and their interaction with the marine boundary layer and the upper-troposphere.

The purpose of this manuscript is to present the data collected during BOWTIE, a 40-day journey of *FS Meteor* in the ITCZ, and provide an overview of the different instruments and measured variables. We also discuss whether differences in the measurement of similar variables by different instruments are related to the instrumentation itself (remote sensing, bulk properties, in-situ observations) or to physical explanations. Moreover, two case studies are presented to illustrate potential uses of BOWTIE data.

The structure of the manuscript is as follows. Section 2 describes the track of *FS Meteor* during BOWTIE, and briefly summarizes the coordination between BOWTIE and other ORCETRA's subcampaigns. The technical details of the instruments installed on board *FS Meteor* and used during BOWTIE are described in Section 3. The comparison of measurements of column-integrated water vapor, rain detection, ocean surface currents, and sea surface temperature measurements obtained by different instruments is in Section 4. Section 5 shows the two cases of contrasting weather regimes: the calm doldrums and the gusty precipitation convection state.

2 *FS Meteor* cruise track and stations

The *FS Meteor* is a German research vessel used for scientific purposes in different research fields, such as marine meteorology, marine biology, and physical oceanography, among others. It was built in 1986 and can accommodate 28 scientists, allowing cruises with a maximum duration of 50 days¹. The BOWTIE campaign officially started on August 10, 2024; however, due to global logistics issues, *FS Meteor* departed the port of Mindelo on August 16, 2024, at 06:00 local time (Figure 1a). Measurements commenced shortly after leaving port. The final destination was the port of Bridgetown in Barbados, where *FS Meteor* arrived on September 24, 2024, at 08:00 local time. (Figure 1b). Measurements were terminated the evening prior to arrival.

2.1 Track

As *FS Meteor* traveled westward from Cape Verde to Barbados, it also performed north-south excursions to sample near the northern and southern edges of the ITCZ, as shown in Figure 2 and Figure 3. In Figure 3, *FS Meteor*'s track shows meridional excursions, which can be divided into three stages in which the longitudinal movement is small compared to the latitudinal

¹For more information about *FS Meteor*, visit <https://www.lfd.uni-hamburg.de/en/meteor.html>, latest access: 24-04-2026

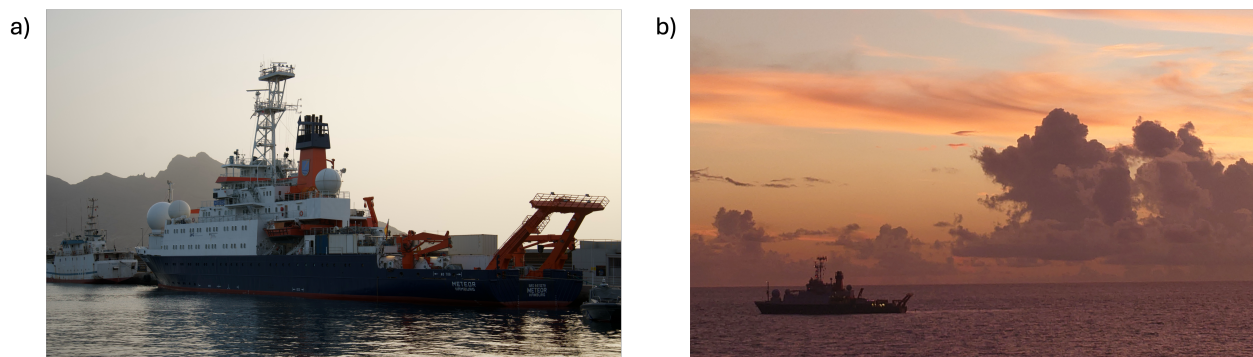


Figure 1. *FS Meteor* in the port of Mindelo (a; Credit: Philipp Henning), and near the coast of Barbados (b; Credit: Yuting Wu).

one. During the first stage from August 16 to September 1, *FS Meteor* deployed two gliders, a WireWalker, and a drift buoy on August 18 (Figures 2c, 3) near a mooring at 11.5°N , 23°W of the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA; Servain et al., 1998). *FS Meteor* navigated southward until August 23, then steamed northward until August 28, when additional instruments and personnel were collected in Praia, Cape Verde. *FS Meteor* then again headed south and recovered the oceanographic instruments after their 11-day deployment on August 29–30. *FS Meteor* continued heading south until September 1 and then turned to travel west along a latitude of 8.5°N .

After continuing a westward trajectory for several days, the second stage of north-south excursion occurred near a longitude of 38°W between September 6 and September 11. After deploying three gliders, the WireWalker, and a drift buoy (Figure 2c, 3e) near a Pirata mooring at 8°N , 38°W on September 6, *FS Meteor* navigated northward until September 9. After September 9, *FS Meteor* returned southeastward, arriving at 8°N and 36°W on September 11. The 2° of longitudinal difference between the initial and the end of the second stage (Figure 2c) occurred because the deployed oceanographic instruments were displaced eastward by the North Equatorial Countercurrent. *FS Meteor* then headed northwest on September 12.

The third and final stage of north-south excursion occurred near a longitude of 47°W from September 15 to September 18. On September 15, two gliders, the WireWalker, and a drift buoy were deployed for the third and final time at 10°N and 47°W (Figure 2c, 3g). *FS Meteor* then followed a southward trajectory until 6°N , where it arrived on September 17. *FS Meteor* then returned northward to recover the oceanographic instruments on September 18 (Figure 2c) at 10°N and 46.5°W . This was the last meridional excursion for *FS Meteor*. After this point, *FS Meteor* headed northwest until it reached Barbados on September 23.

2.2 Stations

Stations are defined as time periods during which a specialized instrument was deployed to perform measurements. The term may also refer to the specific time at which an instrument was launched. Instrument stations indicate that these instruments did not operate continuously through the campaign. For the atmosphere, this applies to radiosondes, microtops, and drones. The launch times of radiosondes and the deployment times of drones are recorded, and their locations are shown in Figure 2b.

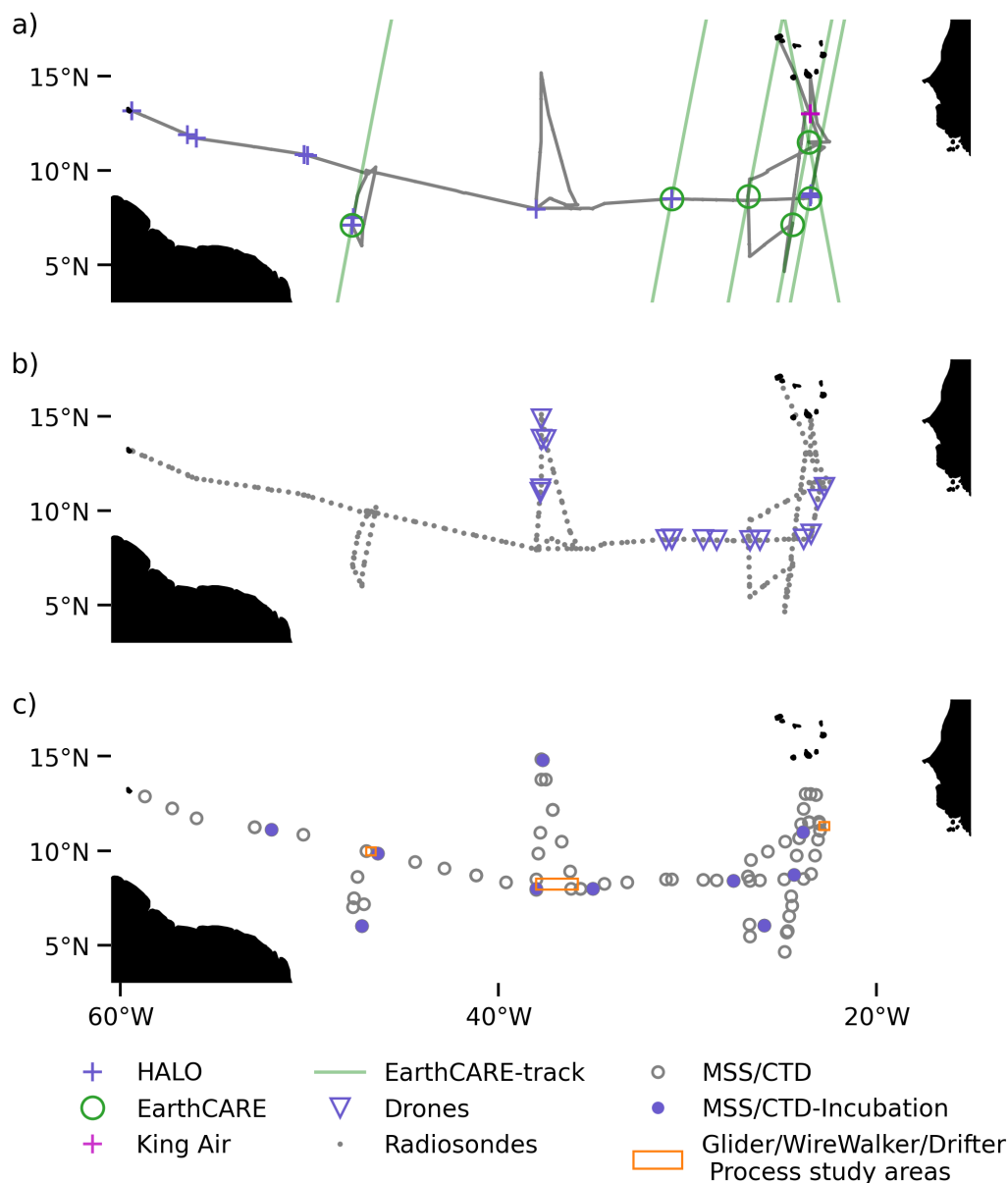


Figure 2. a) *FS Meteor*'s trajectory during the BOWTIE campaign (gray solid line) and intersection with HALO (blue crosses) and King Air (magenta crosses) flights. EarthCARE tracks (green line) overpassing *FS Meteor*'s trajectory are shown with green circles. b) Radiosonde launch locations are shown with gray dots and locations where drones were deployed are shown with blue triangles. c) Conductivity-temperature-pepth-oxygen (CTDO) measurement locations are shown with gray unfilled circles, CTDO measurements that included biology samples are shown with blue-filled circles, and the areas that gliders, WireWalkers, and drifters sampled are enclosed by orange rectangles.

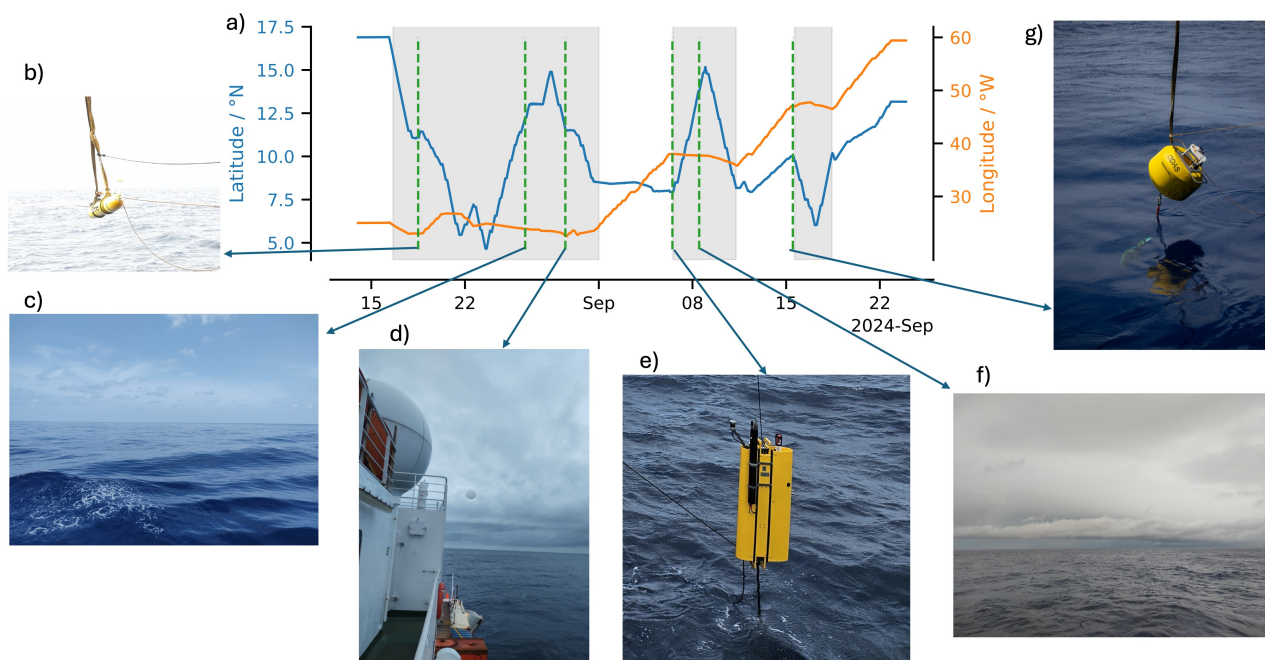


Figure 3. a) *FS Meteor*'s trajectory in the BOWTIE campaign. b) Glider being launched on August 18 (Credit: Philipp Henning). c) Photo taken on August 26, during a doldrum event. d) Photo taken on August 29, during a strong wind regime. e) Launch of the WireWalker on September 6. f) Photo taken on September 8, the day that a precipitation gust-front occurred. g) WireWalker being launched on September 15.

For ocean measurements, conductivity-temperature-depth-oxygen (CTDOs), microstructure profiling system (MSS), the gliders, the drift buoy, the WireWalker, the plankton bottle nets, the UVP camera, and nutrients measurements are classified as station-based observations. CTDO measurements required the ship to remain stationary. At selected CTDO-stations, additional instruments - such as those for nutrient measurements, the UVP camera, and plankton bottle nets - were also deployed (Figure 2c). In contrast, the MSS measurements required the ship to move slowly with a small displacement. The location of the MSS measurements are shown in Figure 2c. Gliders, drift buoys, and the WireWalker are autonomous instruments that were deployed for extended periods and subsequently recovered. During BOWTIE, these platforms were deployed at three distinct locations, referred to as process study areas (Figure 2c, Figure 3).

During CTDO stations, drones were also deployed. Moreover, some of the radiosonde deployments also coincided with CTDO and MSS stations. To take advantage of simultaneous measurements, the BOWTIE collection includes records of the time that CTDO, MSS, radiosondes, and drones were deployed and the time the measurements finished². The information on the time when CTDO and MSS were conducted, as well as the time when drones were deployed, is included in YAML files³. This allows the user to easily select data from other simultaneous measurements, e.g., radiosondes.

²<https://doi.org/10.82246/bafybeianebwhw4uzkqnaekl5kyoau7hubxaens7azrftgqtz2mccciejle>, Segura and Wing (2026), latest access: 24-04-2026

³<https://doi.org/10.82246/bafybeiekpjsfkslf2drgqtigah7a2y33zuzv6tjlrwgsxqv6plwebbnr5m>, Segura (2026b), latest access: 24-04-2026



2.3 BOWTIE and ORCESTRA's sub-campaigns

2.3.1 PICCOLO and STRINQS

As part of the ORCESTRA campaign, BOWTIE coordinated efforts on board *FS Meteor* with two other sub-campaigns, PICCOLO (Wing et al., in preparation) and STRINQS. PICCOLO installed the Colorado State University Sea-Pol radar (Rutledge et al., 2019) on *FS Meteor* to measure precipitation and hydrometeor properties of convective storms. Sea-Pol operated continuously during the trajectory of *FS Meteor*. STRINQS used unmanned aerial vehicles (drones) to sample the thermodynamics and dynamics in the first 1.5 km of the atmosphere with fine temporal and vertical resolution. The primary objective of STRINQS was to demonstrate the employability of drones from a research vessel to characterize the state of the atmospheric boundary layer in high-resolution. Drones were deployed at 17 dedicated stations during the *FS Meteor*'s trajectory as shown in Figure 2b. Due to technical problems, the drones were not deployed after September 9.

2.3.2 PERCUSION and CELLO

BOWTIE coordinated measurements with the PERCUSION and CELLO sub-campaigns of ORCESTRA (Stevens et al., 2026) and EarthCare satellite overpasses as illustrated in Figure 2a. In total, six overpasses by the EarthCARE satellite were coordinated during BOWTIE. For more details, refer to Klocke et al. (2026c).

The PERCUSION campaign (Persistent EarthCare Underflight Studies of the ITCZ and Organized Convection) employed the German research aircraft HALO to conduct measurements in and across the ITCZ. In addition to in situ observations of thermodynamic variables and wind, HALO was equipped with an extensive suite of passive and active remote sensing instruments, including a 35 GHz radar and a high-spectral-resolution water vapor DIAL lidar. The campaign featured circular flight patterns with extensive dropsonde deployments to characterize mesoscale vertical motion. HALO operated from Sal (Cape Verde) in the eastern tropical Atlantic during the first phase and from Barbados in the western tropical Atlantic during the second phase of the PERCUSION campaign. In total, 17 overpasses and 7 additional close approaches were achieved. Beyond its scientific objectives, PERCUSION emphasized a comprehensive validation of the EarthCARE mission (Groß et al., 2026).

The CELLO campaign (Cloud and EarthCARE caL/vaL Observations) focused primarily on the validation of EarthCARE retrievals. Led by a Norwegian initiative, it utilized the Romanian INCAS King Air aircraft operating from Praia (Cape Verde) to perform in situ measurements of aerosols, clouds, and precipitation. Flights were conducted along the EarthCARE ground track. Three coordinated overpasses of *FS Meteor* were realized.

To facilitate the selection of data acquired during coordinated measurements with PERCUSION and CELLO, a YAML file was created to document the timing of these events. Depending on the observing platform, different types of coordination were implemented. For EarthCare and the King Air aircraft, coordination consisted of overpasses above *FS Meteor*. Similarly, HALO conducted coordinated overpasses of *FS Meteor*. In addition, certain coordinated flight patterns positioned *FS Meteor*

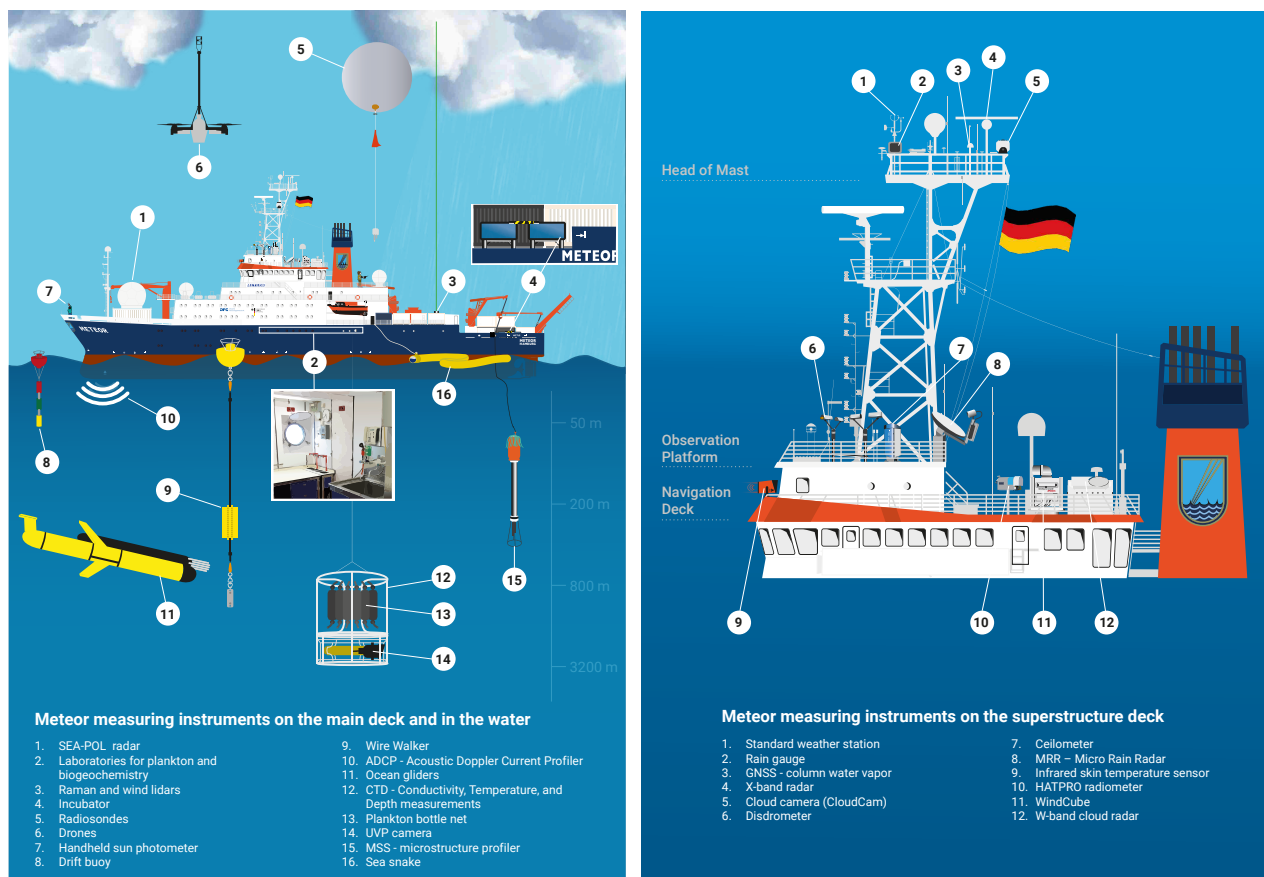


Figure 4. Schematic of the instrumentation used in BOWTIE and its placement on the ship.

within circular flight tracks executed by HALO. All coordination events and their corresponding metadata are also compiled in a CSV file⁴.

3 Instrumentation and processing

145 To accomplish BOWTIE's objective, continuous measurements of the atmosphere and ocean were made using 29 instruments (Tables 1, 2 and 3), of which 23 were a BOWTIE contribution, 4 are permanent instruments onboard *FS Meteor*, and one each were contributed by PICCOLO and STRINGS. Figure 4 shows a schematic of the instruments used in BOWTIE and their location on the ship. Many instruments operated continuously, but discrete measurements of both the ocean and atmosphere were also taken by 11 instruments during stations, detailed in Figures 2b,c, and described in Section 2.2.

⁴<https://doi.org/10.82246/bafybeianebwhw4uzkqnaekl5kyoau7hubxaens7azrftgqtz2mccciejle>, Segura and Wing (2026), latest access: 24-04-2026



150 In the final BOWTIE dataset⁵, datasets are generally named after the corresponding instrument, with a few exceptions as
 noted in Table 1. For clarity, each instrument is assigned a specific marker in this table. The variables are organized as follows:
 time and position variables are listed in Table 4, ship orientation variables in Table 5, atmospheric variables in Table 6, and
 oceanic variables in Table 7. The variables shown in Table 6 and Table 7 represent only a subset of the complete dataset. For a
 comprehensive overview of all available variables, please refer to the ORCESTRA data browser⁶. In the following, we briefly
 155 describe the instruments.

3.1 Permanent instruments - Davis Ship System

The Davis Ship System (DSHIP) includes data from standard meteorological instruments as well as the ship's position, head-
 ing, roll, pitch, and heave, referred to as ship orientation. Data was extracted from the ship server using the Python package
shippspy (Köhler 2024). The extracted DSHIP data has a temporal resolution of 1 minute.

160 Meteorological data

The Ship's Meteorological Office is a permanent institution on the *FS Meteor* and is operated by the German Weather Service.
 One of its countless tasks is the continuous measurement of meteorological parameters. An extensive number of measuring
 instruments are available for this purpose.

165 **Wind direction and wind speed:** 2-dimensional ultrasonic anemometers (type 4.3810, Thies) are installed on both the
 port and starboard sides of the ship, with resolution of 0.1° and 0.1 m s^{-1} , respectively; mounted at 35.3 m above the
 waterline in the mast top.

Air temperature and relative humidity: Temperature and humidity sensor with integrated transmitter (type EE33, E
 and E Elektronik), with a resolution of 0.1 K and 0.1%, respectively; installed at 28.3 m above waterline.

170 **Water temperature:** Pt100 sensor in a weld-in housing (type 2020.0000, Theodor Friedrichs) installed on both the port
 and starboard sides; resolution of 0.1 K; located 2.1 m below the waterline.

Global shortwave radiation: Pyranometer (CM11, Kipp & Zonen); mounted at the mast top, 35 m above the waterline.

UVE and UVA radiation: UV radiometer (UV-S-EA-T, Kipp & Zonen); mounted at the mast top 35 m above the
 waterline.

Longwave radiation: Pyrgeometer (CG4, Kipp & Zonen); mounted at the mast top, 35 m above the waterline.

175 **Air pressure:** Digital barometer (PTB220, Vaisala) with a resolution 0.1 hPa; installed at the on-board weather station
 11.1 m above the waterline.

⁵<https://latest-orcestra--campaign-org.ipns.dweb.link/products/METEOR/>, latest access: 24-04-2026)

⁶<https://browser.orcestra-campaign.org> (latest access: 24-06-2026)



Precipitation: Ship rain gauge (SRM450, Eigenbrodt; designed by Prof. Hasse) and a precipitation monitor (Thies), both mounted at the mast top at around 35 m above the waterline. Precipitation rate is additionally derived from the visibility sensor (PWD22, Vaisala), which combines a capacitive measurement system with optical forward-scatter measurements, enabling the detection of light precipitation types such as drizzle.

The meteorological measurement data are processed on the meteorological computer (METCO) located in the ship's meteorological office. All signals from the meteorological sensors are collected, analyzed, quality-controlled, averaged, and stored on this system. Two mLog 08 data loggers, installed in sub-distribution units on the masthead and on the radar platform (one platform below the masthead), are used to record analog and digital sensor signals. These signals are digitized locally and transmitted to the METCO via RS422 data telegrams. The processed measurement data are then fed into the DSHIP on-board data network, where they are made available to the scientific research crew.

Ship orientation

The navigation data is the record of two fiber-optic gyrocompasses (Navigat X MK1 and Navigat 2100) and the integrated system Seapath 320+. Those instruments comprise the navigation system. The two gyrocompasses measure the ship's pitch, roll, and heading. The Navigat 2100 is the principal sensor, and in case of failure, the Navigat X MK1 is used. The Seapath 320+ additionally uses the motion unit MRU 5 and two GPSs antennas to provide highly-accurate pitch, roll, heading, and heave of the ship. The MRU 5 sensor is installed in the center of gravity of the ship.

Pure Sea-water system

A thermosalinograph (TSG) is an automated sea near-surface temperature and salinity measurement system using a water intake. Two TSG systems are permanently installed on *FS Meteor* and are operated in parallel. System 1 draws water from the port side while system 2 draws water from the starboard side of the vessel. Both water intakes are located 5 m below the water line, approximately 4 m behind the bow of the vessel on each respective side of the hull. Each system consists of a conductivity cell with an internal temperature sensor, an external temperature sensor, and a debubbler that removes air bubbles from the input water stream. The external temperature sensors are mounted on the water inlets. Data are logged every ten seconds.

During the cruise, both systems showed acceptable flow speeds between $48.5\text{--}56\text{ l min}^{-1}$. In post-processing, the temperature and salinity data from the TSG were calibrated against CTDO profile data taken during the cruise and salinity measurements from daily water samples drawn from the TSG flow and analyzed with a Guildline Autosol salinometer on board. Quality control, post-processing, and data publication were carried out by the Deutsche Allianz Meeresforschung Underway data project. For data availability and a detailed data processing report, the reader is referred to Schlundt et al. (2025). The final thermosalinograph data is not part of DSHIP data, being a separate data set.



3.2 Specialized instrumentation for BOWTIE

In addition to the instruments permanently installed on *FS Meteor*, the ship was equipped with specialized instrumentation to target BOWTIE's scientific questions. These were installed in Mindelo and removed from the ship after the cruise. We distinguish between instruments measuring in the atmosphere or the ocean, continuously measuring instruments, instruments measuring at discrete intervals during stations, or autonomous instruments deployed for several days before retrieval.

3.2.1 Continuous measurements of the atmosphere

Raman LIDAR: The Raman lidar of the Max-Planck-Institut für Meteorologie (MPI-M) provides continuous vertical profiles of atmospheric properties. Backscatter profiles at 3 wavelengths (0.355, 0.532, and 1.064 μm) provide information about cloud-base altitude and a qualitative aerosol vertical distribution. Additional information on depolarization reveals non-spherical particle shapes to identify ice clouds and mineral dust layers. The backscatter in off wavelengths (Raman) frequencies near 0.355 and 0.532 μm provides quantitative profiles of aerosol extinction, temperature, and water vapor. Under clear-sky conditions or thin cloud presence, the Raman lidar can give profile information up to 29 km above sea level. Under thick clouds, profiles have a good accuracy up to cloud base. If rain is detected, measurements are stopped.

Microwave radiometer: The microwave radiometer type RPG-HATPRO (Radiometer Physics GmbH - Humidity And Temperature PROfiler) Generation 5 named LIMHAT, retrieves tropospheric humidity and temperature profiles by detecting atmospheric microwave emission. The brightness temperatures are measured by the passive remote-sensing instrument at two different frequency ranges with 14 channels. Specifically, brightness temperatures are measured at the centers and slopes of the absorption line of water vapor (22.23-31.4 GHz) and of oxygen (51.26-58.0 GHz) by seven channels each. The newly developed retrieval algorithm, which is based on ERA5 reanalysis data over the tropical and subtropical Atlantic, not only provides profiles of humidity and temperature but also column-integrated water vapor (IWV) and liquid water path (LWP). Reliable retrievals of tropospheric profiles and integrated quantities are only possible under non-rainy conditions. The accuracy of temperature profiles within the lowest 1.5 km can be improved by using off-zenith observation under lower elevation angles, which was done every 15 min. The same instrument was operated onboard *FS Meteor* during EUREC⁴A (Schnitt et al., 2024). For BOWTIE, the microwave radiometer was installed on the starboard side of the navigation deck at 15.8 m above sea level to avoid sea spray influence. Most of the time, the microwave radiometer was in zenith-pointing mode (at 90-degree elevation angle). However, within every 15 minutes, the microwave radiometer performs a two-minute-long atmospheric boundary layer scan at elevation angles of 90°, 30°, 19.2°, 14.4°, 11.4°, 8.4°, 6.6°, 5.4°, 4.8°, and 4.2°.

W-Band cloud radar: A bistatic frequency modulated continuous wave (FMCW) radar of type RPG-FMCW-94-DP by RPG (Küchler et al., 2017) was operated during BOWTIE. Similar to the microwave radiometer, and to avoid sea spray influence, the cloud radar was installed on the starboard side of the navigation deck at 15.8 m above sea level.



In addition to active remote-sensing in the W-band (94 GHz) a passive radiometer channel at 89 GHz is integrated into the radar-radiometer system. During its deployment on the *FS Meteor*, the radar was passively stabilized by a cardanic mount, the performance of which was investigated by Kalesse-Los et al. (2023) based on its first deployment during EUREC⁴A. The small wavelength of the radar (3.2 mm) is optimal for detecting backscatter from cloud droplets, ice particles, and drizzle or rain drops above the vertically-pointing radar. The radar (named LIMRAD94) was operated with different chirp programs with temporal resolutions of 2 s and range resolution of 14-55 m extending from an altitude of 100 m up to 12 km.

Based on recordings of the high-resolution radar Doppler spectra, radar moments like radar reflectivity, mean Doppler velocity, spectrum width, and skewness are derived. Under non-rainy conditions or during rain with low precipitation rates and moderate IWV values in the atmosphere, the radar signal can penetrate clouds fully, which allows the determination of cloud base height and cloud top height. During heavy rain, the radar signal gets fully attenuated in the lowermost radar range gates, which severely hampers the radar measurements during rain. Similar issues of strong signal attenuation hinder the detection of mid- and high-level clouds in situations with high values of IWV.

Other difficulties arise when deploying the Doppler radar onboard a research vessel due to the constant movement along all axes of motion. To minimize the influence of horizontal wind on the measured radar Doppler velocities, the radar was mounted in a two-axis cardanic stabilisation platform. In this mount, the radar oscillates freely up to $\pm 20^\circ$ in two directions. Steel plates with a total weight of 150 kg are mounted directly below the radar to keep the oscillation amplitude small. Radar attitude angles are continuously sampled at about 0.2 Hz by an accelerometer with an accuracy of 0.02° built into the radar itself. Unfortunately, this sensor is not suitable for usage on constantly moving platforms, as the radar was originally designed for deployment on land. Therefore, an additional motion sensor was installed at the steel plates, which is a sensor fusion of accelerometer, gyroscope, and magnetometer using the Madgwick Algorithm (Madgwick, 2010) designed for use in constantly moving environments. This sensor samples at 20 Hz. Statistical analysis of the motion sensor data is still under research. To check the performance of the cardanic mount, the radar was strapped down multiple times during the cruise for several hours, so that no free-swinging was possible.

In addition to the pitch and roll movement, the heave of the vessel induces a bias in the vertical direction of motion, leading to a continuous shift of the Doppler spectrum in a positive/negative direction (depending on up- or downward heave). In post-processing, the heave-related errors are corrected by a heave-correction as done in Kalesse-Los et al. (2023), which is based on Acquistapace et al. (2022) but directly applied to unaveraged Doppler spectra instead of the mean Doppler velocity. Other post-processing steps of the radar data include filtering of clutter and ghost echoes, as well as Doppler spectra unfolding. Cloudnet processing was applied, as described in Section 3.2.5, and additional flags for ghost echoes and rain attenuation were included. A rain detection flag is set within the Cloudnet categorize files. It is set to true when the reflectivity in the fourth range gate (at 165 m) exceeds 3.1 dBZ and the Mean Doppler Velocity is negative.



Micro rain radar: The Micro rain radar (MRR), type MRR-PRO by Metek (Meteorologische Messtechnik GmbH) is a compact frequency modulated continuous wave (FMCW) Doppler radar operating at 24 GHz (Peters et al., 2005). It was installed in the observational deck at an elevation of 20.66 m above sea level. The temporal resolution was set to 10 s and the range resolution to 10 m. Minimum and maximum measurement height were 126 m and 1.4 km, respectively. If operated on land or on a stabilization platform on a research vessel, quantities like profiles of rain rates and drop size distributions could be retrieved from profiles of radar Doppler spectra. However, because the MRR was a) not stabilized during the cruise and b) had to be tilted by 7 degrees due to an obstacle at the installation location, the data cannot be sufficiently corrected for ship movement. Instead, it is only used as a surface rain flag when detecting reflectivities > 3 dBz in the fourth lowest range gate (at 156 m). Due to artifacts, data in the lowest three range gates are discarded.

Ceilometer: The ceilometer (Lufft, CHM 15k) is an optical-based instrument, using a YAG solid-state laser at a 1064 nm wavelength. It measures atmospheric parameters such as cloud base height (allowing three cloud layers), atmospheric boundary layer height, penetration depth, and vertical visibility. The operating range is 15 km, detecting high cloud layers and cirrus clouds. The frequency of measurements is 10 s. The ceilometer was mounted on the observational deck at an altitude of 20.66 meters above sea level.

Cloud Camera: The all-sky camera is a self-made imager containing a Mobotix Camera (S15D) with an optical fisheye-lens sensor (B016, 180°-180°) mounted in an outdoor housing. This camera records a full sky image every 10 seconds with a resolution of 1280x960 pixel in JPG-format and sends these pictures to a network-connected computer, where the files are stored in daily zip files for further processing.

Sea-Pol: The Colorado State University (CSU) Sea-Going Polarimetric (Sea-Pol) radar is a polarimetric, scanning C-band radar that provides measurements of the kinematic and microphysical structure of precipitation (Rutledge et al., 2019). Sea-Pol incorporates an inertial navigation unit (INU), which measures ship motion and sends compensation commands to the antenna positioner that continuously stabilize the radar scanning plane. The deployment of Sea-Pol on the *FS Meteor* was supported by the US National Science Foundation (NSF) through the PICCOLO campaign. The 5-cm wavelength (5.65 GHz) transmitter and 4.3 m antenna yield a 1-degree beam width for high-resolution polarimetric measurements at ranges up to 120 km, with longer range measurements out to 245 km at lower resolution. C-band is an excellent wavelength for precipitation measurements due to the optimal combination of spatial resolution, sensitivity, attenuation, Doppler, and polarimetric capability. Sea-Pol provides measurements of radar reflectivity, differential reflectivity, differential phase, correlation coefficient, and Doppler velocity, which are used to retrieve detailed hydrometeor characteristics, convective structure, and atmosphere flow fields. Standard derived products include rain rates and hydrometeor identification.

The Sea-Pol scanning strategy during PICCOLO as part of the BOWTIE cruise consisted of a set of fixed and user-selected scanning angles to provide a balanced combination of unbiased statistics and optimization in specific scenarios (i.e., multi-platform sampling). The fixed scanning angles included a long-range (245 km) low-elevation (0.5°) surveillance scan; horizontal Plan-Position-Indicator (PPI) scans at multiple elevations for high-resolution volumetric coverage



out to 120 km; and a quasi-vertical profile at 45° elevation. The user-selected angles included vertical Range-Height-Indicator (RHI) scans at multiple azimuths for more detailed vertical structure of convection or additional volume scans. During the first 12 days of the cruise (August 16 - August 28), Sea-Pol was limited to single-polarization retrievals due to a broken part. The part was successfully replaced on August 28, and dual-polarization data was collected for the remaining 28 days of the cruise. More details on the scanning strategy, processing techniques, and data products can be found at https://seapol.colostate.edu/data/PICCOLO/qc_data/level4/PICCOLO_Sea-Pol_readme.pdf (latest access: 24-04-2026).

Disdrometer: Two optical disdrometers (PARSIVEL, or PARTicle Size and VELOCITY; Löffler-Mang and Joss, 2000) were installed on the observation deck of *FS Meteor* at an elevation of 20.66m above sea level, placed perpendicular to each other. The time resolution is 1 min. The quality control procedure was performed separately for each of the disdrometers and is adapted from the process used in 2022's Prediction of Rainfall Extremes Campaign in the Pacific campaign (PRECIP; details of PRECIP can be found <http://precip.org/>, latest access: 24-04-2026), which follows the approach of Taiwan's Central Weather Administration. The procedure flags drop size distributions with high or low fall velocities - outside 0.5x to 1.5x of the fall velocity-diameter relationship derived in Brandes et al. (2002). This leads to a flagging of extremely large drops, and high wind contamination as described in Friedrich et al. (2013a, b). Aside from the individual measurements of rain rate, a merged version of rain rate using the two disdrometers has been constructed, using the maximum rain rate between the two disdrometers at each time step, and after the quality control was applied.

Wind lidar: The wind lidar is an Abacus Laser Litra S/S+ Module type and was integrated into the Raman Lidar system for BOWTIE. The transmitter-receiver of the lidar was fixed on an angular-stabilized mount, ensuring almost vertical pointing during the ship cruising. It has a range of 8 to 14 km, depending on the amount of aerosol present. The repetition frequency is adjustable over range of 8 to 50 kHz, and the lidar operates at a wavelength of 1550 nm.

WindCube: A Windcube 200S was installed on an active stabilization platform OS4000 (Offshore Gyro Stabilization Mount, provided by Ecole Centrale de Nantes), designed to automatically stabilize the lidar's pitch and roll, with the lidar head sitting at 18.3 m above sea level. The Windcube 200s is a long-range, scanning laser-based system that can create a 3D map of wind in the atmosphere. Its range can extend up to 10 km, but requires sufficient aerosol presence and the absence of (thick) clouds. In practice, during BOWTIE, good signal-to-noise ratios are achieved up to 1-1.2 km when the lidar signal is pointed at zenith, while the range of horizontal scans extends to 6-10 km away from the ship.

The Windcube performed alternating scanning modes to retrieve both the vertical wind profile and the spatial heterogeneity of wind created by convective circulations. The vertical wind profile was measured using the Doppler Beam Swinging (DBS) mode, which involves pointing the lidar beam at four azimuth angles (0,90,180,270) under an elevation angle of 80°, followed by one vertical beam. Groups of 6 DBS scans (~ 75 s) were carried out every ten minutes, allowing the retrieval of continuous ~ 15 s temporal resolution wind profiles with a height resolution of 25m from 68.4m above sea level upward.



During the remainder of the ten minutes, Plan Position (PPI) scans were made involving horizontal scans away from the ship's starboard in a sector spanning 10° to 110° azimuth and at 7 elevation angles between -0.5° and 4° . These provide heterogeneity in radial wind speed at 50 m range resolution, as well as one mean wind profile across the surface layer for different distances away from the ship. To support the wind profile retrieval and sample the vertical structure of the boundary layer within the azimuthal sector, three Range-Height Indicator scans were performed from -0.5° elevation to 11.5° elevation at azimuths of 20° , 60° , and 100° and a range resolution of 50 m. The stabilization platform reduced pitch and roll values from $\approx 4^\circ$ to 0.4° , and was thus critical for the PPI scans. During the final part of the cruise, as indicated by data flags, the stabilization platform was dysfunctional and disabled. While motion-stabilization is not critical for DBS wind profiles when averaged over 10 min, scrutiny is advised.

Global Navigation Satellite System - GNSS: IWV values were retrieved from raw GNSS measurements acquired on board the *FS Meteor* through the estimation of tropospheric signal propagation delays. The observations were collected using the C-Nav3050 GNSS receiver connected to a NovAtel NAVAN2004T antenna, used for the vessel navigation. Raw GNSS code and phase data were recorded at a 30 s sampling interval. The retrieval methodology closely follows that described in Bosser et al. (2021, 2022). Its main principles, as well as recent updates, are briefly reviewed here. The analysis was performed using precise point positioning with ambiguity resolution based on the GipsyX software package (version 2.2; Bertiger et al., 2020). JPL products, including orbits, clock corrections, phase biases, and wide-lane corrections, were used, considering the GPS constellation only, to estimate receiver positions and tropospheric zenith total delays (ZTD) at a 30 s temporal resolution. ZTDs were estimated using Vienna Mapping Functions 1 (VMF1) mapping functions and Vienna Mapping Functions 3 (VMF3) a priori delays (Re3data.Org, 2016), with temporal variations constrained by a random walk of $25 \text{ mm}^2 \text{ h}^{-1}$. After estimation, ZTDs were screened for outliers and subsequently converted into IWV following a classical procedure (Bevis et al., 1992), using ERA5 surface pressure data (Hersbach et al., 2020) and the weighted mean atmospheric temperature of the moist column provided by TU Wien (Re3data.Org, 2016).

3.2.2 Station measurements of the atmosphere

Radiosondes: 327 radiosondes were launched during BOWTIE, from which 327 ascending and 318 descending trajectories were recorded. Of the 327 radiosondes, 253 were contributed by BOWTIE, 35 from PICCOLO, and 39 from the German Weather Service (DWD). The types of radiosonde used were Vaisala RS41-SGPe for BOWTIE and DWD, and RS41-SGP for PICCOLO. Due to the delay leaving port, the first 3 radiosondes were launched while *FS Meteor* was still in the Mindelo harbor and without any regular frequency. Those are also part of the data set. From August 16 at 10:50 UTC, when the first radiosonde was launched in the open sea, the launches had a frequency of 3 hours. The last radiosonde was launched on September 24 at 01:50 UTC. The use of two ground stations, one from DWD and one installed by BOWTIE, permitted a launch frequency such that the balloon reached the top of the troposphere at 0 UTC, 3 UTC, 6 UTC, 9 UTC, 12 UTC, 15 UTC, 18 UTC, or 21 UTC. This means that the launches occurred one hour and 20 minutes before the target observation time. The ground station installed by BOWTIE is a Sounding System MW41



connected to a Vaisala Portable Antenna Set CG31 and an automatic weather station measuring pressure and temperature. Wind velocity, wind direction, and sea water temperature were taken from the DSHIP data. Launches using the ground station from DWD used meteorological data from the DSHIP data. Out of the 8 daily launches, one was done by the DWD's personnel. 17 Additional radiosondes were launched in coordination with EarthCARE, HALO, and King Air overpasses. The postprocessing of the raw data was done using the Python package pysonde (Schulz et al., 2024). For more information about the radiosondes used in BOWTIE, please refer to Winkler et al. (2026).

Microtops: Sunphotometer instruments of MPIM/NASA and IOPAN collect atmospheric column properties for aerosol and water vapor. Samples are collected in a labor-intensive handheld operation and are only possible when the sun is not obscured by clouds. This means that aside from clear-sky conditions, partly cloudy conditions were also sampled. Data were transmitted to http://aeronet.gsfc.nasa.gov/new_web/maritime_aerosol_network.html (latest access: 24-04-2026) from where sampled data and derived products (e.g. aerosol fine-mode fraction) can be viewed or downloaded within hours.

Drones: Four quadcopter drones designed for meteorological measurements were contributed by STRINQS. These drones were capable of measuring relative humidity, temperature, pressure (2 sets of sensors), and 3D winds. For the latter, the drones were equipped with a sonic anemometer that was fixed on a vertical mast, keeping the anemometer a bit more than 1 m from the propellers. Sampling strategies varied in each station according to the number of drones that flew in coordination. In general, the sampling strategies included horizontal and vertical trajectories, and the sampling area was limited to a radius of ~ 3 km around the ship and an altitude up to 1.5 km. The drone measurements were taken exclusively when the ship was stationed, most often synchronous with CTDO measurements.

3.2.3 Continuous measurements of the ocean

ISAR: The infrared SST autonomous radiometer (ISAR) is an infrared ocean temperature-measuring system. It employs two reference blackbody cavities to maintain the radiance calibration of a special Heitronics KT15.85D radiometer. ISAR measures the in situ skin temperature to an accuracy of 0.1 K. ISAR is composed of a fore-optics system, a detector and blackbody calibration subsystem, an internal control and data acquisition computer subsystem, an environmental protection subsystem incorporating a storm shutter, and an external RS485 interface to which additional atmosphere and ocean sensors may be connected, powered, and data collected. For more information, refer to Donlon et al. (2008).

Sea snake: The sea snake is a nickname for a floating air-filled rubber tube that was towed off the port side of the mid-ship deck with an exposed slow-response thermistor attached toward the end of the tube, and another foot or so of tube connected past the sensor to keep it from sinking (see Fairall et al. (1997) for more details). The slow-response thermistor is purposefully deployed within the ship wake so that, as the ship sails and the water churns up around the hull, the nominal 5 cm depth floating sensor gives the average temperature of the subskin layer, below the interfacially cooled skin (Fairall et al., 1996, 1997). By recording averages on a 1-second scale and responding relatively more slowly than other fast thermistors commercially available or the TSG, the sea snake does not get sidetracked by the temperature



of instantaneously passing air bubbles beneath the surface or air while cresting atop a momentary wave. The sensor stays just beneath the surface. The ship underway hull TSG temperature measurements (see above) are expected to be equal to the snake measurements at night, when diurnal warm layers are absent (Gentemann et al., 2009), which is how the snake was checked for calibration during this cruise. Since the sea snake measurements were within 0.002 K of the TSG under these conditions, no corrections were applied.

Marine X-band radar: The Hereon marine radar system (Horstmann et al., 2021), developed by Helmholtz-Zentrum Hereon, is a high-resolution X-band radar designed for detailed observation of ocean surface physical properties. Operating at 9.4 GHz, it captures both backscatter intensity and phase information, enabling advanced analysis of sea surface dynamics. The radar uses short 50 ns pulses to achieve a spatial resolution of approximately 7.5 m and supports pulse repetition frequencies up to 2 kHz with Vertical-Vertical polarization and a rotating antenna capable of 360° scans at 30 rpm. The data products include surface currents (Lund et al., 2018), significant wave height (Carrasco et al., 2024), wave energy dissipation (Streßer et al., 2022), air-sea interaction (Streßer et al., 2026), as well as individual wave tracking and short-term wave forecasts (Carrasco et al., 2025).

During BOWTIE, the Hereon marine radar system was configured to generate geolocated backscatter intensity maps, which serve as the basis for deriving relative surface roughness and two-dimensional surface current fields. The surface current retrieval method is based on the linear wave dispersion relation by examining the temporal and spatial evolution of the wave field. Local currents induce Doppler-shifted wave frequencies, which are analyzed to infer surface current velocities, achieving a root-mean-square error of 0.04 ms⁻¹ (Lund et al., 2018).

Upper-ocean velocities: Underway current measurements of the upper-ocean were taken continuously throughout the cruise using two vessel-mounted acoustic Doppler current profilers (vmADCPs). A 75 kHz Teledyne RD Instruments Ocean Surveyor provided velocity data with high vertical resolution, while the measurements from a 38 kHz Ocean Surveyor reached deeper at the cost of coarser vertical resolution. Both instruments were mounted into the vessel's hull 5 m below the water line. To reduce acoustic interference, the transducer of the 75 kHz vmADCP was installed at 45° relative to the ship's axis, while the 38 kHz vmADCP transducer was not rotated.

The measurement range of the 75 kHz vmADCP was from 17 m to 750 m depth with a vertical resolution of 8 m. The 38 kHz vmADCP recorded data from 53 m to below 1600 m depth at vertical intervals of 32 m. Both systems were run in narrow-band mode, allowing larger depth coverage but somewhat reducing accuracy (Fischer et al., 2003). As detailed in section 3.1, *FS Meteor* provides a navigational data stream of high-quality position, heading, pitch, and roll data. The misalignment angles and gain factors determined from water track calibrations during post-processing (Kopte et al., 2024a, b) showed constant values with respect to time and low standard deviations for both instruments, indicating high data quality. Quality control, post-processing, and data publication were carried out in the framework of the underway research data project of the German Marine Research Alliance (DAM). A detailed data processing report is available in Kopte et al. (2024c, d).



3.2.4 Station measurements of the ocean

Conductivity-temperature-depth-oxygen (CTDO) measurements: CTDO measurements were acquired using a Seabird 911plus system equipped with dual temperature-conductivity-oxygen sensors. The system was attached to a 24-bottle water sampling rosette with 10 l Niskin bottles. During some stations, where bottle nets were attached, the number of bottles was reduced. Water sampling, processing, and calibration followed GO-SHIP recommendations (Swift, 2010; McTaggart et al., 2010; Uchida et al., 2010) and included the recommended steps of Data Conversion, Sensor Time-Alignment, Creation of Bottle Files, Outlier Removal, Pressure Sensor Filtering, Conductivity Cell Thermal Mass Correction, Ship Roll Correction, and Deck Offset Correction by Loop Editing, as well as Derivation of Calculated Properties. After these steps, conductivity and oxygen readings were calibrated against values determined with salinometry and Winkler titration, respectively. Finally, the downcast data was averaged over 1 dbar wide intervals.

In addition to the CTDO system, a Wetlabs FLNTU fluorometer measuring chlorophyll *a* fluorescence and turbidity, a Photosynthetically Active Radiation (PAR) sensor manufactured by Biospherical Instruments, and a Seabird/Satlantic Submersible Ultraviolet Nitrate Analyzer (SUNA) were attached to the rosette. SUNA data was processed following the procedures outlined in Sakamoto et al. (2009, 2017) and calibrated against nitrate measurements from discrete water samples taken during the cruise. The manufacturer's calibration was applied to the chlorophyll *a*, turbidity, and PAR data in the published data sets.

Vessel-based ocean turbulence observations: Ocean turbulence profiles were taken after or prior to CTDO stations to quantify the dissipation rate of turbulent kinetic energy and infer rates of turbulent mixing. The vessel-based loosely-tethered microstructure profiling system (MSS) used during the cruise was manufactured by Sea & Sun Technology and consisted of a profiler (MSS90-D, S/N 73), a winch having about 800 m of cable, and a data interface. The profiler was equipped with three microstructure shear sensors, a fast-response temperature sensor, an acceleration sensor, and two tilt sensors, as well as conductivity (Sea & Sun Tech.), temperature (Sea & Sun Tech.), pressure (Keller), turbidity (Seapoint) and optical oxygen (Sea & Sun Tech.) sensors sampling with a lower response time. The profiler was optimized to sink at a rate of 0.5-0.6 m s⁻¹.

In total, 243 microstructure profiles were collected. Usually, 3 profiles from the surface to 150-200m depth were collected at each MSS station. At 13°N, 23°45'W, a 15-hour station was conducted on August 26-27, where 54 profiles were taken. All data were collected without a protection cage to reduce vibrations of the profiler during descent. Standard post-processing algorithms (Lueck et al., 2024; Fer et al., 2024) were used to determine the rate of kinetic energy dissipation of turbulence in the water column.

Ocean glider: An integral component of the three process studies (Figure 2c) was the deployment of ocean gliders to sample the variability of hydrography, turbulence, oxygen, nutrients and various other parameters at high spatial resolution within the ITCZ. Ocean gliders are autonomous underwater vehicles that use buoyancy-driven gliding to move through the ocean while carrying different sensor packages (Figure 4). Two or three Teledyne Webb Research



Slocum gliders (ifm09, ifm14, ifm50) were deployed in each of the process study areas and retrieved after 3 to 11 days. All gliders were equipped with temperature, conductivity, pressure, oxygen, chlorophyll and turbidity sensors. In addition, microstructure probes (MicroRider, manufactured by Rockland Scientific) were mounted to the gliders and an optical nitrate sensor (SUNA, manufactured by Satlantic) was mounted to glider ifm14. Glider ifm50 also carried an Underwater Vision Profiler (see below).

The gliders were programmed to sample different parts of the water column. One glider (ifm50) sampled the upper 200 m while either circling a PIRATA buoy at 23°W and 38°W or attempting to stay at one position at 10°N, 48°W. Another glider (ifm09 or ifm14) followed the drifting buoy to provide information about ocean turbulence along with the buoy's velocity measurements. Maximum sampling depth for these missions were between 350 m and 700 m. A third glider deployed in the P2 process study region (38°W) followed the WireWalker to provide reference turbulence data.

The microstructure probes attached to the gliders carried two microstructure shear and two microstructure temperature sensors as well as a fast-responding accelerometer and a tilt sensor. Altogether, 2102 hydrographic profiles and 1658 turbulence profiles were collected by the gliders during the three process studies.

Drift Buoy: As part of the three process studies (Figure 2c, Figure 3), a drifting buoy equipped with a downward-looking acoustic Doppler current profiler (300 kHz) and seven temperature and salinity sensors (Seabird Microcats) was deployed to measure near-surface current and hydrographic variability. The drift buoy was designed to measure time series of velocity and hydrography within and below the surface mixed layer. The aim was to study phenomena such as near-inertial and internal waves and to complement the measurements taken by the gliders and the WireWalker (see below). The acoustic Doppler velocity profiler was mounted at a depth of 3 m below the buoy. The temperature and salinity recorders were attached at depths of 3 m, 13 m, 18 m, 23 m, 33 m, 43 m, and 53 m to a wire carrying a 50 kg weight at the bottom. A GPS receiver was attached to the buoy, which recorded its position every second in order to determine the absolute velocities from the drifting current profiler. Additionally, a GPS receiver with automated Iridium-SBD transmission was installed to track the path of the buoy during the whole drift.

WireWalker: The WireWalker is a freely drifting platform profiling the water column up to a depth of 1000m. The system consists of a surface buoy, a steel cable with weights, and the WireWalker itself. Due to a one-way clamping mechanism within the WireWalker, it “walks” down the wire whenever waves move the buoy up and down. The clamps are released when the WireWalker arrives at the end of the cable and hits the “turn-around bumper”. As it is buoyant, it floats upwards. Usually, data is collected on the upcast as it is a smoother and steadier movement. The WireWalker was deployed during the three process studies, carrying a UVP-6 Plankton camera, a microstructure probe, and a conductivity-temperature-depth (CTD). On the first deployment, a Fluorescence and an oxygen sensor were additionally installed. All three deployments were successful and gathered valuable data from the surface to a depth of 750m.

Plankton bottle nets: The bottle net is an innovative tool designed to collect microplankton samples from any depth, including depths exceeding 4000 meters—areas where such sampling has not previously been conducted. The device consists of an external PVC and stainless steel frame housing a 20 μ m plankton net. During BOWTIE, four bottle nets



were mounted on the CTDO frame, with each replacing two Niskin bottles from the oceanographic rosette sampler. Samples were collected exclusively during the CTDO's ascent, with one sample taken per deployment across four depth intervals: 0–100 m, 100–200 m, 200–300 m, and 300–600 m. At each target depth, the bottle net was opened to filter seawater, and organisms were collected. Once sampling was complete at the designated depth, the bottle was closed to prevent additional water intake during the ascent to the surface. Onboard, the collected samples were retrieved, preserved with Lugol's solution, and prepared for further analysis. Sampling was conducted entirely during the day or at night to avoid interference from the zooplankton's daily vertical migration. These samples will be scanned and will undergo taxonomic identification to study microplankton diversity. The collected data will contribute to a deeper understanding of the active carbon pump and the composition of plankton communities.

Underwater vision profiler: The UVP-6 is the sixth iteration of the Underwater Vision Profiler. It is an underwater camera to study larger particles and zooplankton ($> 100 \mu\text{m}$). It is illuminated with a red laser and uses a 5 MP black-and-white camera. The images are directly filtered for regions of interest, limiting the amount of storage space necessary on board the system. The UVP6 exists in two versions, one with low power requirements and a framerate of 1.3 images per second, and a high frequency one with a framerate of about 20 Hz. The WireWalker was equipped with one UVP-6 HF, while one Glider was equipped with the low-power version. Additionally, another HF was installed on the CTDO rosette by Geomar / LOV. After analysis, the UVP-6 data comprises particle properties (e.g., size, form, solidity) as well as plankton taxonomy and abundance data.

CPICS: The CPICS is an underwater camera that has a higher resolution than the UVP6 (12.3 MP compared to 5MP) and records in color instead of black and white, with a framerate of about 6 images per second. Due to its telecentric lens with a magnification of 0.9, the imaged volume is considerably smaller than that of the UVP6, but with much higher resolution, permitting more detailed analysis of the captured particles and zooplankton. Unfortunately, our CPICS had a small leakage after only a few days, hindering any further deployments. The CPICS was installed on the Rosette.

Nutrients: Water samples were collected from the Niskin bottles of the CTDO to perform concentration measurements of inorganic and organic nitrogen and phosphorus compounds, rate measurements of primary productivity, nitrogen fixation, and phosphonate utilization using stable-isotope incubations, with and without nutrient supplementation, microbial community analyses using state-of-the-art metagenomic and transcriptomic sequencing, and cell-specific activity measurements of keystone microbial groups using nanoSIMS.

3.3 Cloudnet processing

The microwave radiometer and W-band cloud radar were operated by Leipzig University. In combination with data from the Lufft CHM 15K ceilometer operated by MPI-M, the microwave radiometer data and cloud radar data were processed using the Cloudnet processing scheme (Illingworth et al., 2007; Tukiainen et al., 2020) to obtain atmospheric properties in the vertical column above *FS Meteor*. The Cloudnet processing was done on the Cloudnet data portal (<https://cloudnet.fmi.fi>, latest), where auxiliary information on profiles of atmospheric temperature and pressure from ECMWF-IFS is available along the ship track.



Cloud radar observations were corrected for atmospheric attenuation by water vapor. Cloudnet products include a profile-based target classification separated into pixels containing ice, liquid, aerosol, and precipitation. The temporal resolution of Cloudnet products is 30 s and the vertical resolution is the same as the cloud radar resolution (on the order of a few tens of meters). Cloudnet also provides retrievals of microphysical cloud properties such as liquid water content, ice water content, and effective radius of droplets and ice particles. During the two-minute-long atmospheric boundary layer scans of the microwave radiometer (termed “MWR multiple pointing” times in Cloudnet), Cloudnet does not use the microwave radiometer data and thus labels the liquid water path as “Invalid LWP”, which in turn prohibits the determination of liquid water content (LWC) during the MWR scan times.

4 Insights from instrumentation

As described above, BOWTIE included multiple instruments that measured similar variables. This redundancy was intentional, to allow for identifying and mitigating systematic errors, provide backups in case of instrument failure, and ensure the robustness of results. Here, we explore complementary measurements of four quantities - column-integrated water vapor, rain detection, surface current, and sea surface temperature - as an example of how different instruments can be combined to assess data reliability.

Integrated Water Vapor

IWV is an important variable for characterizing the local environment, as it is intimately coupled to tropical rainfall (Bretherton et al., 2004). It is, therefore, a variable of special emphasis in this campaign for analysis of the convective environment. IWV is derived from four different instruments: radiosondes, microwave radiometers, microtops, and GNSS (Figure 5).

Multiple approaches were tested for calculating integrated water vapor from radiosondes (not shown), from the following equation

$$\text{IWV} = \int_{z_{base}}^{z_t} q \rho dz,$$

where q is specific humidity (mass of water vapor per mass of total air) and ρ is air density, calculated accounting for moisture effects consistent with Schulz and Stevens (2018). While z_{base} is generally taken to be the lowest available measurement, for this comparison we take $z_{base} = 30$ m to match the elevation of the radiometer. The change from 0–30 m amounts to a mean decrease 0.37 kg m^{-2} for the radiosonde dataset, bringing it closer to that of the radiometer.

For all conditions (Figure 5a), the instruments with the most regular sampling – radiosondes, radiometers, and GNSS – differ by approximately 2 kg m^{-2} , with radiosondes being moister. IWV retrieved from GNSS and microwave radiometer is similar. Microtops is closer to radiosonde, differing by only -0.72 kg m^{-2} , but this measurement was taken irregularly throughout the campaign.

The additional panels of Figure 5 separate the comparison into clear-sky, cloudy, and raining conditions, identified through a combination of rain gauge, ceilometer, and cloud radar data. Measurements using microtops were pointing directly at the

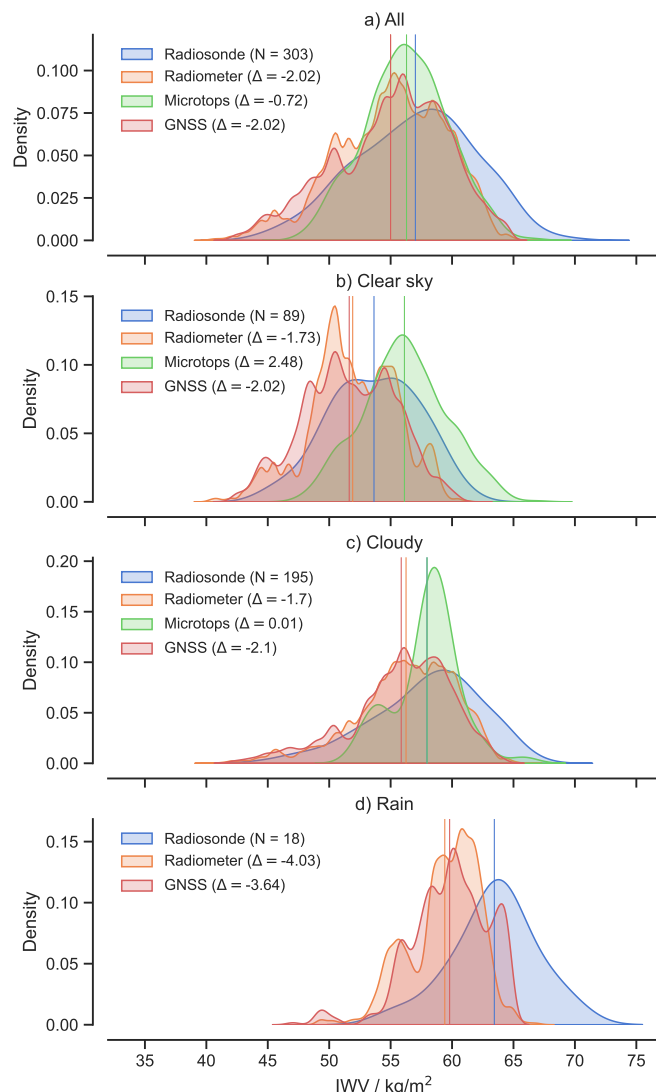


Figure 5. Kernel density estimate (KDE) plots of IWV estimated from multiple datasets (see legend), with means indicated by vertical lines and deviations (Δ) from that of the radiosondes indicated in the legend. The complete dataset (a) is separated into clear-sky (b), cloudy (c), and rain conditions (d). The sample size for the radiosondes (N) in each category is indicated in the legends.

sun, even under partly cloudy conditions, explaining microtop measurements in the cloudy category. Figures 5b-d depict IWV increase from clear-sky to raining conditions, as expected, with mean IWV from radiosondes increasing from about 54–
 570 64 kg m^{-2} . Values of IWV from GNSS and microwave radiometer are about 2 kg m^{-2} lower than radiosonde-derived values in clear-sky and cloudy conditions. Interestingly, IWV derived from microtops is substantially moister than radiosondes in clear-sky conditions ($\Delta \approx 2.5 \text{ kg m}^{-2}$), but the difference is near 0 kg m^{-2} in cloudy conditions.

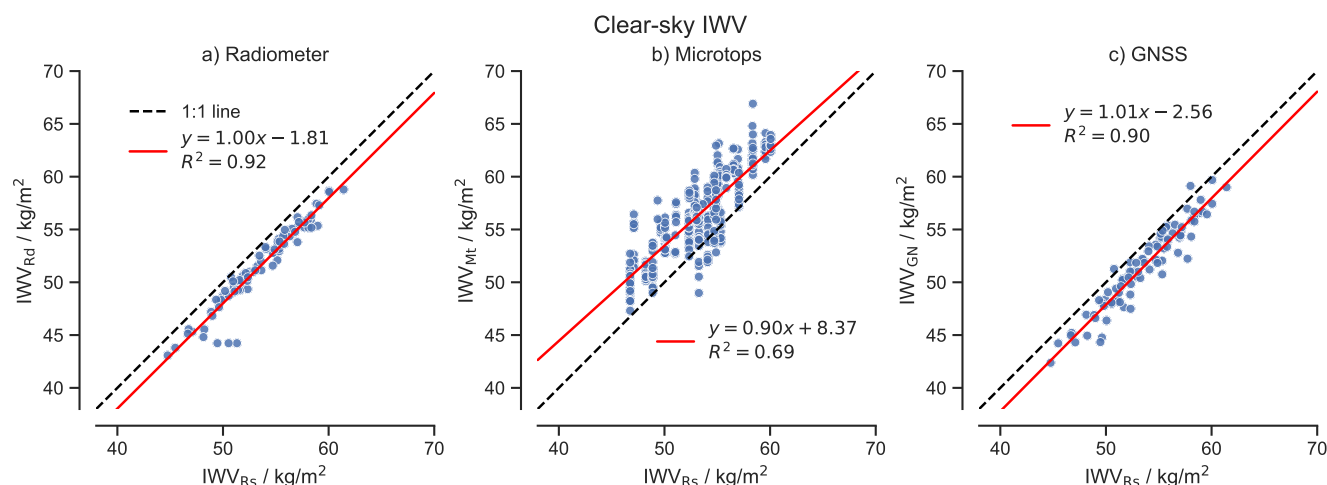


Figure 6. Radiosonde I WV (IWV_{Rd} ; kg m^{-2}) plotted against I WV from the a) radiometer (IWV_{Ra}), b) microtops (IWV_{Mt}), and c) GNSS (IWV_{GN}) in clear-sky conditions, with measurements temporally matched between datasets using a nearest-neighbor approach. One-to-one and linear regression lines are depicted.

The remote-sensing-based I WV estimates are less trustworthy due to attenuation in cloudy and rainy conditions, so we therefore assess the relationship between radiosonde and the other measurements in clear-sky conditions in Figure 6. With clear-sky conditions isolated, the difference between radiosondes and the radiometer is found to be constant, with the slope of the best-fit line being 1. I WV derived from microtops is substantially greater than that of radiosondes at low values of I WV, with the gap decreasing at a rate of 0.1 kg m^{-2} per unit I WV. Consistent with Figure 5, GNSS exhibits a very consistent difference from radiosondes that is nearly invariant with I WV.

It remains unclear what explains the gap of $\sim 2 \text{ kg m}^{-2}$ between radiosonde and the other measurements. The RS41 radiosondes used here are considered a highly accurate benchmark in situ measurement to which other instruments are compared and often calibrated (Sun et al., 2021). Data users should bear these differences in mind, and future work should investigate their possible causes.

Rain detection

The exact quantification of surface rain is very difficult, especially on a moving platform like a ship. Spatial variability, especially on small scales, as well as the method to quantify precipitation, can lead to different results in measured rain amount (Yuter and Parker, 2001). However, one can expect that the detection of rain is more likely to be similar among the instruments; that is, the simple question of whether it is raining or not. Here we compare rain observations obtained by the micro rain radar, the cloud radar, two disdrometers, and the rain gauge station for the period between August 18, 06:00 UTC, and September 21, 23:59 UTC.



590 One of the variables derived from the micro rain radar (manually) and the cloud radar (within the Cloudnet processing) is a rain detection flag, which is set to 0 for no rain and 1 for rain, as illustrated in Section 3.1.2. The micro rain radar has a temporal resolution of 1 second, whereas the Cloudnet-processed cloud radar data has a temporal resolution of 30 seconds. To homogenize our analysis, we use three different time windows: 1 minute, 5 minutes, and 10 minutes. In each window, the rain detection flag is one (1) if rain is detected at least once in the window; otherwise, the rain detection flag is zero (0).

595 For the rain gauge and the two disdrometers, the time series of rain rate is used to construct the rain detection flag. Following the analysis of the micro rain radar and the cloud radar data, three different time windows are chosen: 1 minute, 5 minutes, and 10 minutes. In each window, the rain detection flag is 1 when the rain rate is larger than 0 mm h^{-1} at least once. The rain detection flag is 0 when rain rate is zero in the entire window.

Based on the 1-minute, 5-minute, and 10-minute rain detection time series, the total number of times that five, four, three, and two instruments detected rain simultaneously is computed. Likewise, the total number of times that a single instrument detected rain is calculated. The frequency is shown in Figure 7. The total number of times that rain was detected (referred to as events) during 1-minute, 5-minute, and 10-minute periods is 6681, 1641, and 939, respectively. The percentage of events detected by five, four, three, two, or only one instrument is similar regardless of the time step used. Nearly 33% of the events were detected simultaneously by the five different instruments. About 18% of the time, rain was observed by 4 instruments, while around 13% of the time, it was observed by 3 or 2 instruments only. The percentage of events detected by only one instrument is 23%.

Events detected by only one instrument are not homogeneously partitioned among all the instruments, as shown in Figure 7d-f. In this category, the micro rain radar is the instrument with the highest detection rate of rain, independent of the time resolution. Considering the 1-minute time step, the micro rain radar accounts for 80% of the events in which only one instrument detected rain, followed by the rain gauge, with 16%. The two disdrometers and the cloud radar are the only instruments to detect rain in less than 3% of the one-instrument-only events. From the two disdrometers, the one with the laser aligned perpendicular to the ship's motion (disdrometer 1) did not detect rain alone (0%), while the one with the laser aligned parallel to the ship's motion accounted for 2.5% of the events. For the 5-minute and 10-minute time steps, 70% of the rain events are only detected by the micro rain radar, and 27% are only detected by the rain gauge.

615 The differences in the detection of rain across the instruments can be explained by several factors. While rain gauges and disdrometers measure rain in situ near the surface at their respective installation point, the micro rain radar and the cloud radar are remote-sensing instruments from which rain detection is derived at an altitude of $\sim 160 \text{ m}$ above the ship. This difference in the height of the precipitation measurement, combined with the facts that (i) rainfall can partially or fully evaporate in dry surface layers (Kalesse-Los et al., 2023) and (ii) ship steaming speed and horizontal wind velocity can induce turbulence effects around the in-situ rain sensors, can lead to notable differences in the rain detections. Full evaporation of precipitation in the lowest 160 meters can occur during light rain/drizzle with small drop sizes and very dry subcloud layers.

The alignment of the disdrometers also seems to play a role in the detection of rain. The disdrometer with the laser aligned perpendicular to the ship's motion detected rain less often than the disdrometer with the laser parallel to the ship's motion. The perpendicularly-aligned disdrometer also recorded a smaller rain rate than the parallel one 98.4% of the time.



625 The difference in rain detection between the micro rain radar and the cloud radar can be attributed to the similar reflectivity
threshold used to state whether rainfall occurred or not. For both instruments, rain occurrence is set to true if the radar reflectiv-
ity at ~ 160 m (fourth radar range gate) is greater than 3.1 dBZ. However, in rain, the radar reflectivity measured by the micro
rain radar is greater than that of the cloud radar because for drops larger than about 1.2 mm, the Rayleigh assumption is no
longer valid for the higher-frequency cloud radar. Instead, scattering of larger particles occurs in the Mie regime, in which the
630 linear relation between scattering cross section and particle size is not true, leading to reduced reflectivities. Furthermore, the
cloud radar suffers from stronger attenuation effects caused by high IWV values, as well as cloud droplets and rain itself, also
leading to reduced observed reflectivities. Consequently, the micro rain radar detects rain onset earlier and rain end later. For
example, on August 21, rain onset by the micro rain radar was detected at 23:14 UTC, whereas the cloud radar only started to
detect rain at 23:46 UTC (Figure 8a) when the reflectivity threshold was reached (Figure 8b). Before that time, the cloud radar
635 observed falling drops in the lowest radar range gates (Figure 8c), but the reflectivity values were too low to set the rain flag to
true. Decreasing the reflectivity threshold value in the cloud radar would thus allow an earlier detection of rain, as indicated by
the 0 dBZ reflectivity contour line in (Figure 8b).

Overall, this analysis provides an estimate of the rain detection uncertainty, which can arise due to the differences in each
instrument's sensitivity, measurement principles, effective measurement volumes (smaller for in-situ sensors than for radars),
640 and post-processing.

Ocean surface currents

During the BOWTIE experiment, ocean surface currents were measured using two systems: vessel-mounted ADCPs (vmAD-
CPs) and an X-band marine radar (see Section 3.2.3). VmADCPs are subject to inherent limitations when resolving near-surface
currents, as their installation below the ocean surface, combined with the instrument blanking distance, results in blind zones in
645 the upper water column. These layers are further degraded by ship-induced bubble clouds and residual inaccuracies in motion
compensation. Consequently, the shallowest reliable current estimate obtained from the 75 kHz vmADCP corresponds to a
depth-averaged measurement spanning approximately 13 m to 21 m.

Current measurements derived from X-band marine radar are inferred by analyzing the evolution of the wave field in the
frequency–wavenumber domain and identifying the most probable current velocities consistent with the wave dispersion re-
650 lation. The retrieved current, therefore, represents a depth-averaged flow weighted by the wave-induced orbital motion, rather
than a direct measurement at a fixed depth. A key question associated with this approach is the effective sensing depth of the
retrieved currents. According to Lund et al. (2015), this depth corresponds to approximately 7.8% of the dominant wavelength
for a linear vertical current profile, and 4.4% of the wavelength for a logarithmic current profile. Assuming a logarithmic
current profile and a typical dominant wavelength of 80 m, the effective depth of the retrieved current is approximately 3.5 m.

655 A direct comparison between the two sensors is inherently challenging because vmADCP measurements are collected di-
rectly at the vessel location, whereas radar observations cannot be acquired at the same position and time due to vessel-induced
imaging disturbances. As a result, radar-derived currents at this location are available only before or after the vessel's presence.
To address this limitation, a workaround strategy is employed in which radar and ADCP measurements are aggregated into

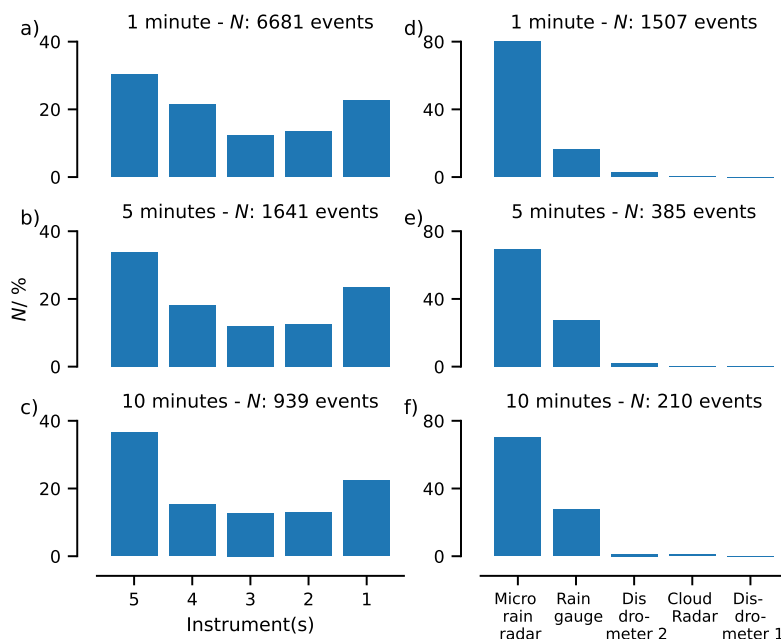


Figure 7. The relative frequency in percentage of times that rain was detected simultaneously by 5, 4, 3, 2, and only 1 instrument using time series of 1-minute time step (a), 5-minute time step (b), and 10-minute time step (c). Relative frequency in percentage of times that rain was detected by only one instrument in a 1-minute time step (d), 5-minute time step (e), and 10-minute time step (f). The instruments are the micro rain radar, the cloud radar, the rain gauge station, and the combination of two disdrometers. The absolute number of times N that rain was detected is shown in the title of each panel.

time windows sufficiently long to ensure that the vessel fully traverses the target location. In this study, the data are grouped into 15-minute intervals, within which all available measurements are temporally averaged. The averaged radar and vmADCP currents are then directly compared.

Figure 9 illustrates the resulting comparison between both instruments, where the x-axis represents vmADCP measurements and the y-axis radar-derived currents. Panel 9a shows the eastward component of the surface current, while panel 9b displays the northward component. The color scale denotes the number of observations contributing to each bin. The rectangle in the upper-left corner summarizes the statistical comparison between both sensors, including bias, standard deviation, RMSE, and the Pearson correlation coefficient. The dashed black line indicates the one-to-one correspondence between both measurements: data points above the line represent stronger radar-derived currents, whereas points below the line indicate weaker radar currents relative to the vmADCP. As expected, a systematic trend is observed, with radar-derived surface currents (representative of approximately 3.5 m depth) exceeding vmADCP currents measured at 17 m depth, consistent with vertical shear induced by wind drag in the uppermost ocean layer.

The application of quality-control criteria in Figure 9 is summarized as follows. The vmADCP provides a quality flag ranging from 0 to 9; only measurements classified as good data (QC = 1) or probably good data (QC = 2) are retained for

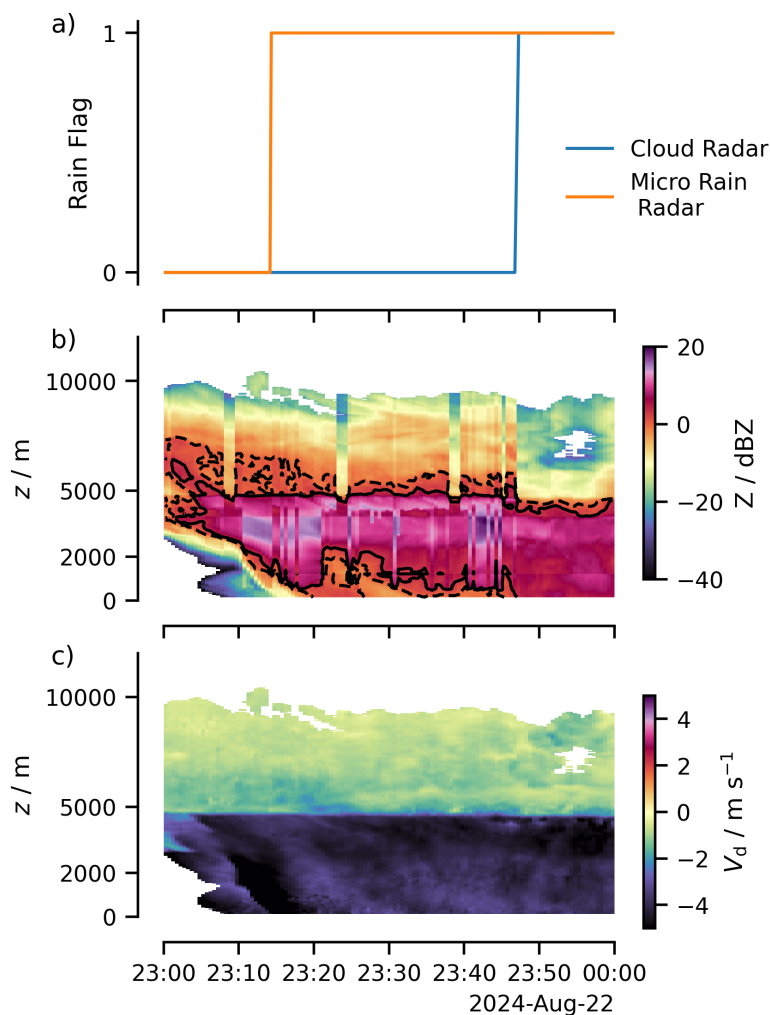


Figure 8. Precipitation event on August 21st, 2024. a) Rain detection flag for the micro rain radar (orange) and the cloud radar (blue). 0 refers to no rain detected, and 1 refers to rain detected. b) Radar reflectivity time-height plot of the cloud radar (color shading). The 0 and 3.1 dBZ lines are shown in black dashed and solid lines, respectively. c) Mean Doppler Velocity time-height plot of the cloud radar. Melting layer height is indicated by a strong increase in Mean Doppler Velocity at around 5000 m.

the analysis. Radar-derived currents are quality-controlled using the signal-to-noise ratio (SNR), where higher values indicate greater confidence. Only radar measurements with $SNR > 5$ are considered in the comparison.

675 Sea surface temperature measurements

The temperature of the sea surface is an important quantity because of its use in the calculation of the exchange of energy and moisture between the ocean surface and the air. It is known that measurements of what is referred to as sea surface temperature

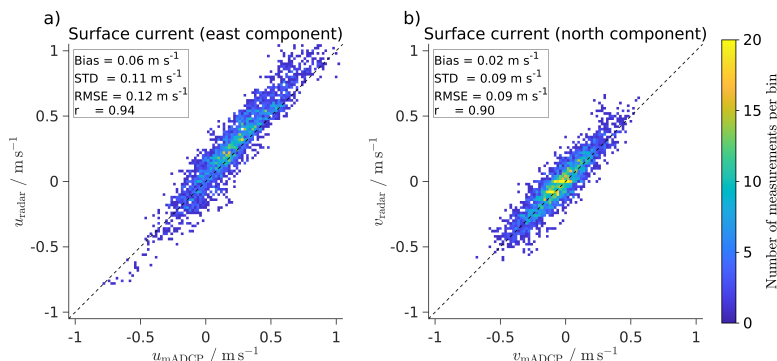


Figure 9. Comparison of quality-controlled vmADCP and X-band radar-derived ocean surface currents. VmADCP measurements at 17 m depth (x-axis) are compared with radar-derived currents representative of approximately 3.5 m depth (y-axis). Panel (a) shows the eastward component, and panel (b) the northward component. The color scale represents the number of observations per bin. The dashed black line marks the one-to-one correspondence, and the inset rectangles report bias, standard deviation, RMSE, and Pearson correlation coefficient.

(SST) can vary with depth (Saunders, 1967; Fairall et al., 1996), reflecting different processes in the first meters of the upper-ocean. At the air-sea interface (skin), molecular heat conduction is the principal mechanism of heat transfer. Because it is thin, its heat capacity is low, making the skin tenths of a degree colder than a few centimeters (sub-skin) or even a few meters (bulk) below the skin (Saunders, 1967). Below the skin layer, turbulence efficiently distributes heat, allowing the vertical temperature gradient to be small; however, in the presence of light wind regimes and daytime conditions of net heat input, turbulence decreases, and heat is trapped in the first meters of the upper-ocean. If insolation is strong, the temperature stratification is strong, developing a diurnal warm layer (Price et al., 1986; Fairall et al., 1996). This results in warmer temperatures in the sub-skin layer than in both the bulk measurements and the skin layer (Minnett, 2003). It is also possible for the skin layer to be warmer than the bulk measurements. Given this background, the measurements during BOWTIE are analyzed to identify 1) whether BOWTIE measurements are consistent with these expectations, and 2) possible errors in the measurements.

The three products used are from ISAR, the thermosalinograph, and the sea snake, all of which incorporate quality flags (see section 3.2.1). ISAR measures the skin layer temperature (SST_{skin}), the sea snake measures the sub-skin layer temperature at 5 cm ($SST_{5\text{cm}}$), and the Thermosalinograph measures the bulk temperature at 5 m ($SST_{5\text{m}}$) below the ocean surface. For ISAR, the quality levels chosen are “acceptable_quality” and “best_quality”, which are attributes of the “quality_level” class inside the ISAR dataset. The thermosalinograph and the sea snake share a similar class for the flag of quality level, “TEMP_QC”. Only measurements with a flag of “good_data” and “probably_good_data” are selected. Figure 10a shows the time series of SST_{skin} , $SST_{5\text{cm}}$, and $SST_{5\text{m}}$ during the BOWTIE campaign. At first view, there is a good agreement between $SST_{5\text{cm}}$ and $SST_{5\text{m}}$, except in certain periods related to light wind regimes, such as on August 26 (see section 5.1). The skin layer is colder than the sub-skin layer or the bulk measurements most of the time. While this is expected, SST_{skin} can be more than 1 K colder



than the sub-skin layer or the bulk measurements, which is much colder than previous observations (e.g., Robinson et al., 1984; Minnett, 2003; Fairall et al., 2026).

To further analyze how much colder the ISAR-measured skin layer is according to ISAR, we compute the difference between the skin layer and bulk measurements ($SST_{\text{skin}} - SST_{5\text{cm}}$) at night (between 22 and 5 local time), as well as the difference between the sub-skin layer and the bulk measurements ($SST_{5\text{cm}} - SST_{5\text{m}}$). These hours were selected to avoid any influence of diurnal warm layers. Moreover, only time steps when all three instruments have measurements are taken into account. Figure 10b depicts the typical temperature structure of the upper-ocean. As expected, the difference between the sub-skin layer and bulk measurements is small, with a mean difference of 0.008°C and a standard deviation of 0.09°C . The skin layer is tenths of a degree colder than the sub-skin layer most of the time, with a mean difference of -0.6°C and a standard deviation of 0.5°C . The large standard deviation in the difference between the skin and the sub-skin layer (cold layer) is due to measurements in which the skin layer was colder than the sub-skin layer by 1°C . Restricting to values of $\Delta SST_{\text{skin}-5\text{cm}} > -1^{\circ}\text{C}$ gives a standard deviation of 0.17°C and a mean of -0.43°C , which is in the range of expected values. Possible factors for a much colder skin layer ($\Delta SST_{\text{skin}-5\text{cm}} < -1^{\circ}\text{C}$) than expected, such as changes in downwelling longwave radiation or in factors controlling surface heat fluxes (wind speed, relative humidity, and temperature), are not different from other nights where $\Delta SST_{\text{skin}-5\text{cm}} \geq -1^{\circ}\text{C}$. The development of the too cold layer ($\Delta SST_{\text{skin}-5\text{cm}} < -1^{\circ}\text{C}$) during the night is 4.7% of the total measurement during night hours. Figure 10b shows that the occurrence of too cold skin layers is not explained by wind speed. While rain can cool the skin layer (Witte et al., 2023) or introduce noise in the measurements, there were no rain events over the ship when $\Delta SST_{\text{skin}-5\text{cm}} < -1^{\circ}\text{C}$. Therefore, we do not currently have an explanation for why the ISAR skin temperature measurements are sometimes unexpectedly cold.

To analyze the development of diurnal warm layers and how they are observed in BOWTIE, a similar analysis is conducted for daytime hours, from 10 to 18 local time (Figure 10c). The difference between the sub-skin temperature and the bulk temperature (shading in Figure 10c) is notably larger under conditions of light wind speed. The maximum difference was 2.43°C , on August 26 during light wind conditions. At the time of the maximum $\Delta SST_{5\text{cm}-5\text{m}}$, the skin layer was 0.44°C colder than the sub-skin layer. This means that the skin layer was 2°C warmer than the bulk measurements. The picture of $SST_{5\text{m}} < SST_{\text{skin}} < SST_{5\text{cm}}$ is typical of diurnal warm layers. However, Figure 10c also shows that in certain periods, not always, the skin was warmer than the sub-skin layer ($\Delta SST_{\text{skin}-5\text{cm}} > 0$). The maximum $\Delta SST_{\text{skin}-5\text{m}}$ (2.34°C) on August 26 coincides with a skin layer 0.81°C warmer than the sub-skin layer. $\Delta SST_{\text{skin}-5\text{cm}} > 0$ has been observed in the mid-latitudes and is called a “warm skin event” (Jia and Minnett, 2023). The fact that the skin layer is warmer than the sub-skin layer indicates an input of energy into the ocean, and could be associated with a reduction in surface heat fluxes or an increase in downwelling longwave radiation. The former is the most probable due to the light winds. Nevertheless, $\Delta SST_{\text{skin}-5\text{cm}}$ can be smaller than -1 K during the daytime (a too cold skin layer), and this accounts for 4% of the measurements during the day. Only one of the too cold skin layers during daytime is related to a rainfall event; we lack an explanation for the other instances of these cold ISAR skin temperature measurements.

Overall, BOWTIE’s measurements of near-surface ocean temperatures at different depths are, in general, consistent with expectations regarding a cold skin layer and the development of diurnal warm layers under light wind conditions. However,



there are instances of too cold skin layers from the ISAR measurements ($\Delta\text{SST}_{\text{skin}-5\text{cm}} < -1^\circ\text{C}$) that should be taken with caution. Including all measurements, too cold layers account for 15% of the measurements.

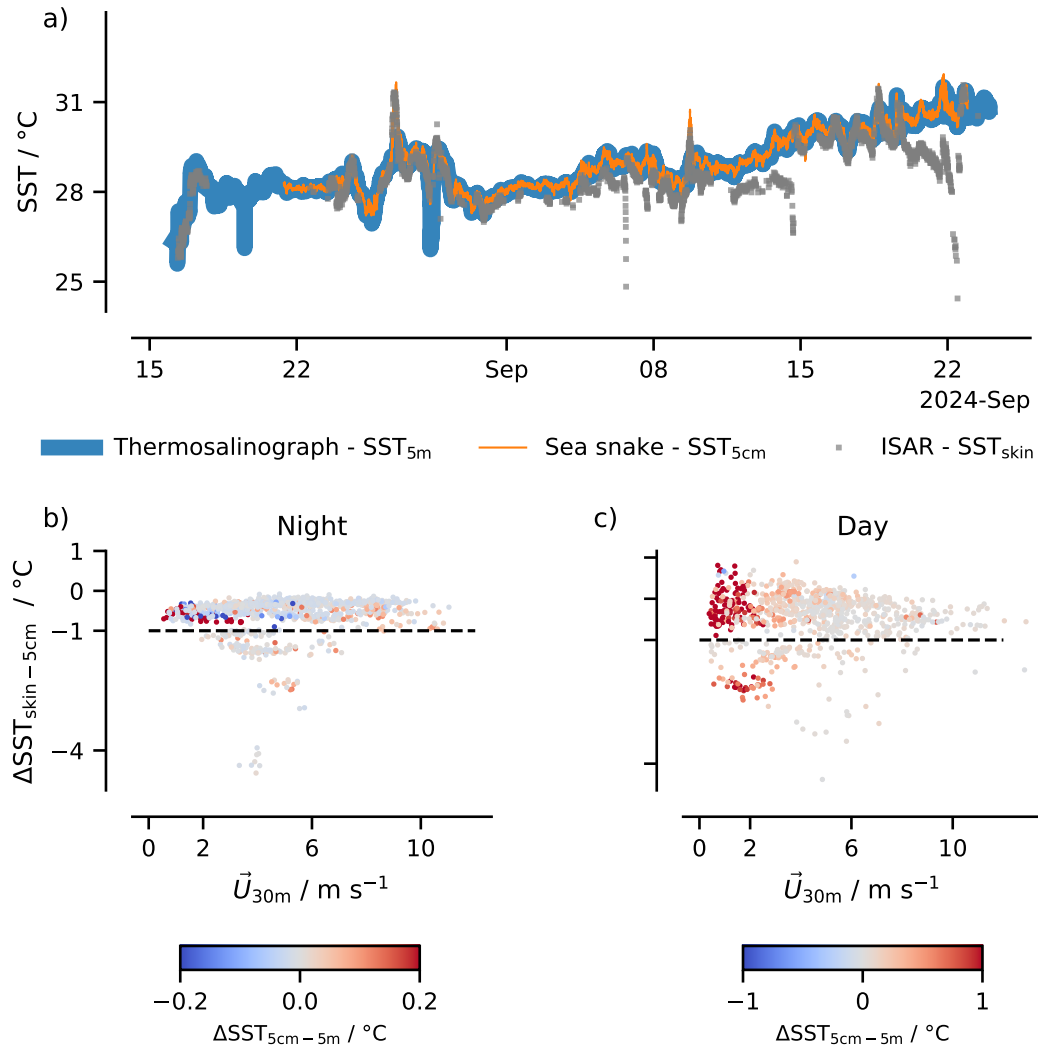


Figure 10. Ocean temperature measurements at the skin (SST_{skin} ; ISAR), 5 cm ($\text{SST}_{5\text{cm}}$; sea snake) and 5 m ($\text{SST}_{5\text{m}}$; thermosalinograph) during BOWTIE. a) Time series for the entire campaign of SST_{skin} (thick solid blue line), $\text{SST}_{5\text{m}}$ (Solid orange line), and SST_{skin} (gray thick dots). b) Scatter plot of the difference between SST_{skin} and $\text{SST}_{5\text{cm}}$ ($\Delta\text{SST}_{\text{skin}-5\text{m}}$ y-axis) and wind speed measured at 30 m above water line ($\vec{U}_{30\text{m}}$; x-axis) colored by $\Delta\text{SST}_{5\text{cm}-5\text{m}}$. The analysis is done for nighttime hours, from 22 to 5 local hours. The dashed black line indicates a $\Delta\text{SST}_{\text{skin}-5\text{m}}$ of -1°C . c) Similar to b) but for daytime hours, from 10 to 18 local hours. In b,c) only time steps in which the three instruments have valid measurements are taken into account.



5 Case studies of the inner ITCZ

735 In this section, case studies were selected to show the possible atmospheric and oceanic processes that can be studied using the BOWTIE data collection.

5.1 Doldrums

One atmospheric mesoscale phenomenon targeted by BOWTIE is the doldrums, which are characterized by weak surface winds. The BOWTIE data collection permits characterization of doldrums and their impact on the atmosphere and ocean.
 740 Figure 11 shows a doldrum event on August 26. After 11:46 UTC, the anemometers measured wind speeds with magnitudes smaller than 3 m s^{-1} for about 12 consecutive hours (23:57 UTC); this was one of the longest doldrum events observed by BOWTIE. The sky conditions were mostly clear until late afternoon, as the ceilometer detected only a small amount of clouds most of the day. The weak wind and mostly clear-sky conditions resulted in a diurnal warm layer, in which the sub-skin ocean temperature measured by the sea snake was up to 2.34°C warmer than the bulk temperature measured by the thermosalinograph.
 745 This was the strongest diurnal warm layer measured during the campaign, as discussed above in Section 4.3.

It is possible to characterize the vertical structure of the atmosphere when doldrums occur. Figure 12 shows the temporal evolution of wind speed, specific humidity, and potential temperature of the first kilometer measured by the radiosondes. Light winds occurred throughout the first kilometer of the atmosphere. As the wind speed decreased after 11 UTC, the atmospheric boundary layer became warmer and drier.

750 5.2 Precipitation and gust front

The characterization of different convective systems is also an objective for BOWTIE. On September 8, around 12 UTC, the disdrometer detected precipitation rates greater than 5 mm h^{-1} , indicating the presence of intense precipitation (Figure 13a). This is confirmed by Sea-Pol, in which the quasi-vertical scan revealed that high precipitation intensities occurred below 5 km altitude (Figure 13b). The Cloudnet retrieval also indicated substantial liquid water content in the lowest few km (Figure 13c).
 755 Sea-Pol's scanning capabilities provide information on the 3-D structure of precipitation (Figure 14). Range-height indicator (RHI) scans of the squall line indicate that it consisted primarily of congestus (echo tops of 5-7 km), though some deeper convection is found further from the ship (Figure 14c). Dual-polarimetric measurements reveal microphysical characteristics of the precipitation; for example, higher differential reflectivity (ZDR) values (Figure 14d) indicate a larger average size of the raindrops. An increase in both reflectivity and ZDR towards the surface indicates collision-coalescence processes. The areas
 760 where ZDR is higher, and reflectivity is lower near the surface, are likely due to size sorting, where the bigger drops fall faster than the smaller ones, though faster evaporation of smaller drops could also contribute.

During that precipitation event, the ship-board anemometer measured a sharp increase in wind speed of about 10 m s^{-1} (Figure 13d), indicating that this precipitation event was associated with a gust front. This may be caused by evaporation of precipitation before it reaches the surface, cooling the air and leading to a downdraft that spreads horizontally as a gust front
 765 when it hits the surface. Following the passage of the leading edge of the gust front and the occurrence of precipitation, the

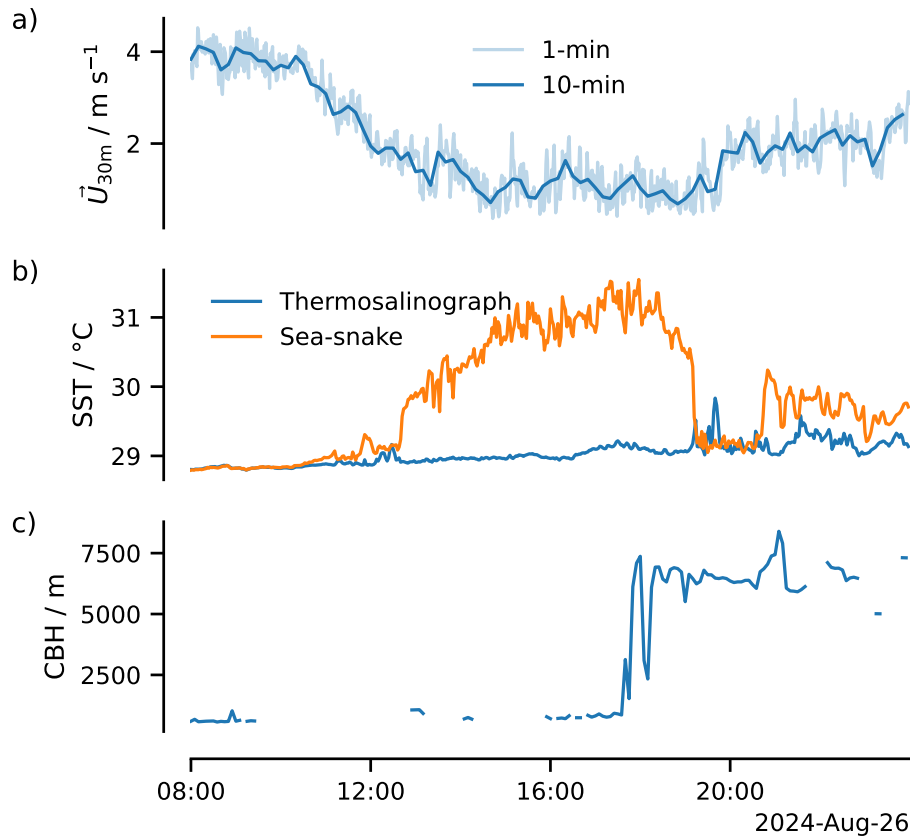


Figure 11. Doldrums: Time series of a) wind speed ($\vec{U}_{30m}$) with 1-minute time step (light blue) and 10-minute mean (dark blue), b) sea surface temperature (SST) from the thermosalinograph (blue line) and sea snake (orange line), and c) cloud base height from ceilometer (CBH; blue line). Wind speed and SST from the thermosalinograph are part of the DShip data.

boundary layer cooled significantly, as shown by a drop of 4 K in air temperature measured by the ship-board thermometer (Figure 13e).

6 Summary

During the Beobachtung von OZean und Wolken - Das Trans ITCZ Experiment (BOWTIE) campaign, the *FS Meteor* navigated in the moistest tropical Atlantic for 40 days (Klocke et al., 2026c). *FS Meteor* departed from the port on Mindelo on August 16, 2024 at 06:00 local time and arrived at the port of Bridgetown in Barbados on September 24, 2024 at 08:00 local time. BOWTIE utilized 29 instruments to measure different properties of the atmosphere, upper-ocean, and air-sea interface. Radiosondes were launched every 3 hours and provided profiles of the atmosphere up to 30 km. Standard meteorological instruments and thermosalinographs on board provided observations of near-surface variables in the atmosphere and upper-ocean with high

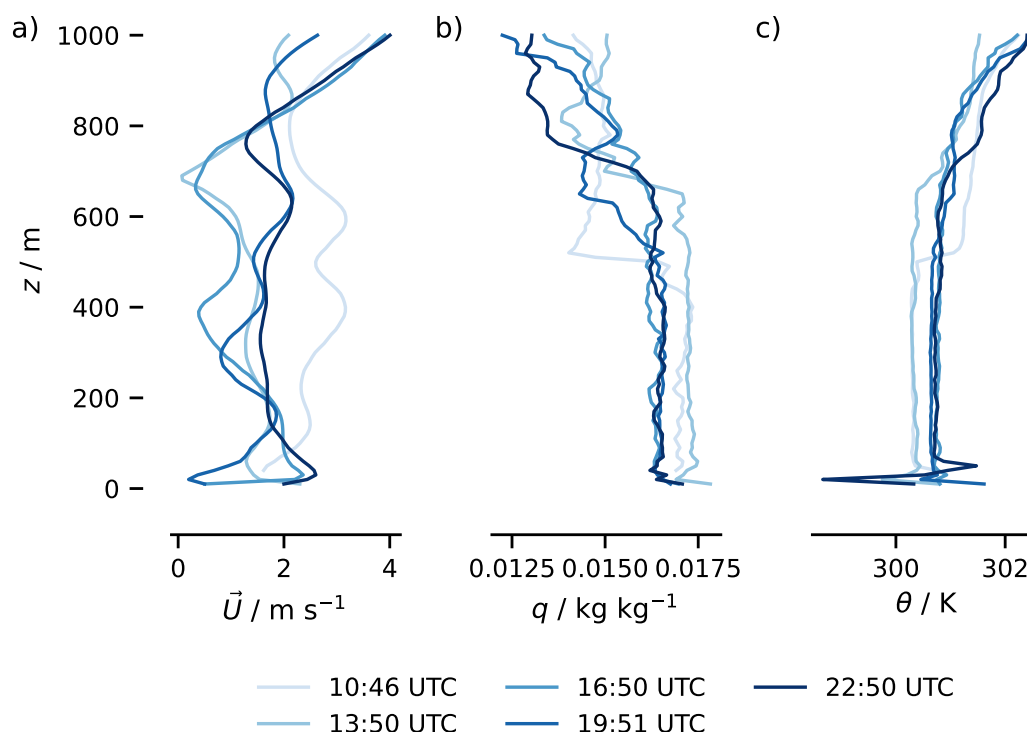


Figure 12. Doldrums: temporal evolution of a) wind speed ($\vec{U}$), b) specific humidity (q), and c) potential temperature (θ) from radiosondes. Colors indicate the time in UTC when the radiosonde was launched.

temporal resolution. Profiles of ocean properties down to 2 km depth were obtained during dedicated CTDO stations, and autonomous oceanographic platforms (gliders, a WireWalker, and a drift buoy) were deployed three times in specific study areas. Instruments using remote sensing techniques provided high temporal resolution profiles of thermodynamic and dynamic properties of the troposphere. Cloud, hydrometeor, and aerosol properties were also sampled. The 2-D wind field within the first two km above the surface and 2-D currents near the ocean surface were also measured by remote sensing techniques, as well as profiles of ocean currents down to 1.6 km depth. The close collaboration with the PICCOLO campaign permitted measurements of precipitation and hydrometeor properties not only over *FS METEOR* but within the surrounding area, as far away as 245 km from the ship, by using the Sea-Pol radar. Drones deployed by the STRINQS campaign in dedicated stations mapped profiles of the first 1.5 km of the atmosphere. Most of the data is available in a common repository found at <https://latest-orchestra--campaign-org.ipns.dweb.link/> (latest access: 24-04-2026). In this manuscript, only a small fraction of the data has been used in case studies and example analyses. A global view of the data can be found in the ORCESTRA data browser (<https://browser.orchestra-campaign.org/#/?s=>, latest access: 24-06-2024).

The large number of instruments in BOWTIE and the fact that some of the instruments measured similar or related variables allow us to characterize uncertainties in the measurements. Four examples were selected: 1) column-integrated water vapor, 2)



rain detection, 3) ocean surface currents, and 4) sea surface temperature measurements. The comparison of IWV shows that the four relevant instruments - radiosondes, microwave radiometer, microtops, and the GNSS - differ in their measurement by 2 kg m^{-2} . The difference varies depending on the environment (clear-sky, cloudy, and rainy), as environmental conditions affect the accuracy of the instruments using remote sensing techniques. The rain detection analysis indicates that remote sensing instruments (micro rain radar, cloud radar) tend to detect rain more frequently than surface-measured-rainfall instruments (rain gauge and disdrometers). This could be related to possible rain evaporation, strong winds, and ship movements, which could reduce the detection of rain by surface-measured-rainfall instruments. Post-processing procedures can also contribute to differences between remote sensing instruments.

The difference in the ocean current measured by the X-band radar (near-surface) and the ADCP (17 m depth) agrees with expectations. The X-band radar measured stronger currents than the ADCP, and this does not depend on the velocity of the ship. It is observed that most of the time, the zonal current shear tends to be greater than the meridional one.

The measurements of ocean temperature at different depths, skin (ISAR), sub-skin (5 cm depth; sea snake), and bulk 5 m depth (thermosalinograph), show the expected cold skin and the development of diurnal warm layers. The latter occur during light wind regimes. However, there are times when the skin layer is unexpectedly colder than the sub-skin layer by more than 1 K. At the moment, we lack a physical explanation for this behavior, and caution should be taken regarding the ISAR measurements.

To illustrate the different wind/convection/sea surface temperature regimes that can be encountered within the ITCZ, two case studies are shown: a doldrum event and a precipitation event associated with a gust front. These case studies provide an example of how multiple instruments from BOWTIE can be leveraged to provide a comprehensive characterization of such events, which is a first step for a deeper understanding. This manuscript serves as a reference for the data collected in BOWTIE and documents the suite of instruments and measured variables. The extensive measurements of the atmosphere, ocean, and air-sea interface across different environments may be leveraged by future studies to investigate questions about atmospheric convection and its interaction with the upper-ocean.

7 Data availability

The BOWTIE data is shared using the InterPlanetary File System (IPFS), which allows addressing, routing, and transferring data on the web. Every data set, as well as each version of a given dataset, has a unique identifier in IPFS. This allows tracking of the data that is used. The latest version of the data can always be accessed via <https://latest-orchestra--campaign-org.ipns.dweb.link/> (latest access: 24-06-2024). A global view of the data can be found in the ORCESTRA data browser (<https://browser.orchestra-campaign.org>, latest access: 24-04-2026). Moreover, BOWTIE's data sets follow the Climate and Forecast (CF) data conventions.

Specific datasets used in this paper are listed below, along with their IPFS content identifiers.



Data set: DOI and citation

Data set / DOI	Citation
DSHIP https://doi.org/10.82246/bafybeib5awa3le6nxi4rgepn2mwxi733aazpkmgtpa3uc2744gxv7op44	Segura (2026a)
RAPSODI https://doi.org/10.82246/bafybeid7cnw62zmzfgxcvc6q6fa267a7ivk2wcchbmkyk4kdi5z2yj2w4	Winkler et al. (2026)
Cloudnet https://doi.org/10.82246/bafybeidtfyua2vmmrpnhl6nj57x2ynowaceghdapyetc6lnrpjii2tlli	Foth (2026a)
Disdrometer 1 https://doi.org/10.82246/bafybeicrrokylnpcyjgs52c6526otqbqxcxhmkt6mkqovya2xvt2n3yo54	Colón-Burgos (2026a)
Disdrometer 2 https://doi.org/10.82246/bafybeiaacc53awulhrtttkdwd6uktvb3bfbsyac5g4ww7rkujigkalmkfe	Colón-Burgos (2026b)
Disdrometer merged https://doi.org/10.82246/bafybeihjcwsecgpmjsxoo5peqafnuqfnalu3ya3vtibwl7qkm76izsnuei	Colón-Burgos (2026c)
Sea Snake https://doi.org/10.82246/bafybeieoosfm33u47expejxhccectau4oxrp2jg4efzrqn743af6tzxide	Dengler (2026a)
GNSS https://doi.org/10.82246/bafybeifanfvmxia7nfeuros7gl3ouv3qb5cmg4dczl6ekkjuk7gv66w424	Bosser (2026)
Sunphotometer https://doi.org/10.82246/bafybeifw2qrevl4ckmncq4zqpwiwvrcgketyyyjap5po7xkvkykjh5jpa	Lind et al. (2026)
ISAR https://doi.org/10.82246/bafybeibei32rn7fcyrrhxx3gfsdz2yonze6rpqvvyih2avpxb74qqqlqss4	UoS (2026)
Rain gauge https://doi.org/10.82246/bafybeievu3hvrmbc7bh6fv4xqsx3kzsreokwnsk2mfz62xp2fspyzrrta	Stelzner and Klocke (2026)
ADCP ocean currents (38 kHz) https://doi.org/10.82246/bafybeieli3hwulxcvqqan2f62lfajswqzbbbhmueenjaubc6zfxukjc2ke	Klocke et al. (2026a)
ADCP ocean currents (75 kHz) https://doi.org/10.82246/bafybeia4pgtryncxt4pexfs2gyvgxn4cob43mfijkdo2alwcxgorpfn3va	Klocke et al. (2026b)
Level 4 Gridded Sea-Pol Radar Data Rainrate 2D https://doi.org/10.82246/bafybeigv34pws3t5wlmnatcnnavfsfie5zyd6j36eyv57qsh6f7usn5kg4	Bell et al. (2026a)
Level 4 Gridded Sea-Pol Radar Data RHI 2D https://doi.org/10.82246/bafybeigbngdrbifkqry3hsqilx4rywi3pu4a6vf2fraf4bql3qyzoosh2m	Bell et al. (2026b)
Level 4 Gridded Sea-Pol Radar Data Composite 2D	Bell et al. (2026c)



Data set / DOI	Citation (Continued)
https://doi.org/10.82246/bafybeigdehy7635uywpwipv5xdlvgnlbncvuyudajwejawn2llirbp2vyq	
Level 4 Gridded Sea-Pol Radar Data QVP 1D	Bell et al. (2026d)
https://doi.org/10.82246/bafybeifhwxvq4kh66dry6wo4s7auvdbfhur4gtmhwonw6ru2w537j53xiy	
Ceilometer	Jansen (2026)
https://doi.org/10.82246/bafybeia74wnxe2nxwkcmespzjckqwt25tyhcknah3xqxexeevbsdiawzom	
Conductivity-Temperature-Depth-Oxygen (CTDO)	Dengler (2026b)
https://doi.org/10.82246/bafybeihoghhgi655g7arw2ubtpudbq4c4hwpjlrwghcex3snu7f36imjgq	
Microwave radiometer (HATPRO - single point)	Foth (2026b)
https://doi.org/10.82246/bafybeihc63mpkfatnvl6z5hze2eijzwqr6o3ohubhi5i66dvos4qjcssvu	
Microwave Radiometer (HATPRO - multiple point)	Foth (2026c)
https://doi.org/10.82246/bafybeihddiylirtiv64yo74wzt7zok545yowhiuu23kjonvz2wl57eunze	
Raman lidar light (fast product - 2 min smoothing)	Serikov (2026a)
https://doi.org/10.82246/bafybeidhokylvrnu447th4z3npevzflfmtjsva2icf7gbyp7mmsyeyeknhm	
Raman lidar light (slow product - 58 min smoothing)	Serikov (2026b)
https://doi.org/10.82246/bafybeie754xlr57yw2vnqrneuh23vsalzagfputvjnbqnsi4fvyjjtfrq	
X-band radar (surface derived ocean currents)	Boedewadt et al. (2026)
https://doi.org/10.82246/bafybeig3znybjnw6tzt5ek6acavwmkvd6rl7bo6mpbbfhkhweq5oexs3ja	
WindCube (horizontal wind profiles from scanning wind lidar)	Nuijens (2026)
https://doi.org/10.82246/bafybeieggj743jwgsahtv56hb7ier245mxnxy56zl5bdr3iltzmm4ik4a	
Wind lidar Litra S (raw data)	Serikov (2026c)
https://doi.org/10.82246/bafybeibg3e7kodnqrgjs5576soeq7gwcqjzdity56zlmz2bw27ucrip4fe	
Wind lidar Litra S (heave-corrected with asynchronous ship motion)	Serikov (2026d)
https://doi.org/10.82246/bafybeiaonfwwrbianryo4nejd4fyfjqcrofo6wciz62aeuzpeplcqu6zqe	
Wind lidar Litra S (heave-corrected with synchronous ship motion)	Serikov (2026e)
https://doi.org/10.82246/bafybeigh4aqyy3zmqhqe4y53zknarkmy7rwe6sctcwskuyw4paap6kxm	
Micro rain radar (rain flag)	Foth (2026d)
https://doi.org/10.82246/bafybeie2zhy2rkepcqh6tc5lk75blv372rvpfnnrhysyl6efscdgmugld4a	
Thermosalinograph (salinity and temperature)	Schlundt (2026)
https://doi.org/10.82246/bafybeife55jwmknrq7heen6mu3vayxxl3m2xuqb6ekofm5pw7whpsxh4mq	
<i>FS Meteor</i> log	Segura and Wing (2026)
https://doi.org/10.82246/bafybeianeabwhw4uzkqnaekl5kyoau7hubxaens7azrftgqtz2mccciejle	
<i>FS Meteor</i> stations (time at which CTDO, MSS, UAV stations occurred)	Segura (2026b)
https://doi.org/10.82246/bafybeiekpjsfkslf2drqqtigah7a2y33zuzv6tjlrwgsxqv6plwebbnr5m	



820 The scripts used to produce the figures in this manuscript are in (Segura et al., 2026)

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Table 1. Name of the data set in the catalog (<https://latest-orchestra--campaign-org.ipns.dweb.link/products/METEOR/>, latest access: 24-04-2026) and the associated symbol. The name also represents the instrument or platform used during the campaign. If not, the name of the instrument or platform is indicated in parentheses. The exception is DSHIP, which represents a collection of instruments (see section 3).

Instrument / Platform / Name in collection	Symbol	Instrument / Name in collection	Symbol
Atmosphere			
DSHIP	•	LICHT-LIDAR_b (Raman-lidar)	△
LICHT-LIDAR_t (Raman-lidar)	▽	HATPRO (Microwave_radiometer)	□
MRR_rainflag (micro rain radar)	◇	Ceilometer	×
Cloudcamera (Cloud Camera)	★	Cloudnet (W-band cloud radar)	◁
WindLidar-Abacus	▷	Disdrometer	†
Rain_gauge (PWD22)	‡	Sunphotometer (Microtops)	○
GNSS_IWV (GNSS)	*	Radiosondes	∫
Sea-Pol	⊕	WindCube	≈
Ocean			
DSHIP	•	CTDO	⊖
ADCP	⊕	ISAR_SST (ISAR)	⊙
SeaSnake (sea snake)	⊗	Thermosalinograph	⊗
Marine X-band Radar Derived Currents	→		



Table 2. Instruments taking continuous measurements in the atmosphere and the upper-ocean. The symbols indicate the associated name of the data set as shown in Table 1.

Instrument / Platform	Sensor name	Comment
Weather station (●)	2-D Ultrasonic Anemometer Thies	one on port, one on starboard at 35.3 m above water line
	E+E EE33	One on port, one on starboard at 28.3 m above water line
	Vaisala PTB220	On starboard 11.1 m above water line
	Ship rain gauge SRM450	Bowside, 34.1 m above water line
	Pt 100 type 2020	One on port, one on starboard at 2 m below water line
Radiation (●)	Pyranometer CM11 Kipp & Zonen	Rear side, 35 m above water line
	Pyrgeometer CG4 Kipp & Zonen	Rear side, 35 m above water line
Navigation System (●)	Navigat X MK1 / Navigat 2100 (FOG)	Measures roll, pitch, and heading
	Seapath 300	Integrate the MRU 5 sensor and two GPSs
	Position sensor MRU 5	Measures roll, pitch, heading, and the heave
	GPS Simrad HS50 (GPS-Kompass)	
	GPS Shipmate GN30-2 (Hersteller Simrad)	
Pure seawater system	SBE 21 SeaCAT Thermosalinograph (⊙)	Inside, one on port, one on starboard
	SBE 38 Digital Oceanographic Thermometer (●)	Outside, one on port, one on starboard, 5m below water line
Lidar	Raman Lidar (▽,△)	Mounted over stabilization platform
	Abacus Later Litra S/S+ - Wind- (>)	Mounted over stabilization platform
WindCube Lidar ≈	Specialized lidar	Observation deck
Sea-Pol radar (⊕)	C-band (5.65 GHz, 5-cm wavelength)	PICCOLO
GNSS (*)	GPS C-Nav3050	Estimation of integrated water vapor (Bosser et al., 2021, 2022)
Microwave radiometer (□)	RPG-HATPRO-G5	Observation deck (15.8 m)
W-Band cloud radar (<)	RPG-FMCW-94-DP	Observation deck
Micro rain radar (◇)	MRR-PRO	Observation deck
Ceilometer (×)	CHM 15K	Observation deck
Cloud Camera (★)	Mobotix Camera (S15D)	
	optical fisheye lens sensor (B016)	
Disdrometer (†)	OTT Parsivel2	Two on observation deck
Thermosalinograph (⊙)	Sea-Bird SBE21 and SBE38	intakes on port and starboard side at 5 m depth.
ISAR (⊙)	Heitronics KT15.85D radiometer	Observational deck; starboard
Sea snake (⊗)	slow-response thermistor	nominal 5 cm depth; port side of the mid-ship deck
X-band radar (→)	X-band (9.4 GHz) Horstmann et al. (2021)	Observational deck
ADCP (⊕)	Ocean Surveyor 38kHz	depth range from 53m to 1600m at 32m vertical resolution
	Ocean Surveyor 75 kHz	depth range from 17m to 750m at 8m vertical resolution



Table 3. Instruments used in stations for taking measurements in the atmosphere and the ocean in specific locations. The symbols indicate the associated name of the data set as shown in Table 1.

Instrument / Platform	Sensor name	Comment
Radiosondes (l)	Vaisala Radiosondes RS41-SGPe or RS41-SGP Vaisala DigiCORA Sounding System MW41 Sounding processing system SPS311G Portable antenna set CG31 Ground check subsystem RI41 Deutscher Wetterdienst (DWD) System	see Winkler et al. (2026)
Microtops sun photometer (o)	Dpro Scientific model 540 Microtops II	Part of the Maritime Aerosol Network
Uncrew aerial vehicle (UAV)	Drones	STRINGS
CTDO (e)	Seabird 911plus (S, T, P sensors) Seabird oxygen sensor SBE 43 Wetlabs FLNTU fluorometer/turbidity PAR sensor by Biospherical instrument Seabird Deep Submersible Ultraviolet Nitrate Analyzer	Attached to 24-bottle water sampling rosette with Niskin bottles
MSS	MSS90-D Profiler by Sea & Sun Technology	shear, fast-response temperature, tilt, conductivity, oxygen sensors
Glider	Teledyne Webb Research Slocum G2 gliders Rockland MicroRider 1000 turbulence probes Underwater Vision Profiler for gliders	ifm03, ifm14, ifm50
Drift Buoy	Teledyne-RDI Workhorse 300 kHz ADCP five Seabird MicroCat SBE 37	depth range from 6m to 122m at 4m resolution temperature, salinity, pressure
WireWalker	surface float, 800m cable by Del Mar Oceanographic RBR CTDO logger Underwater Vision Profiler 6 Rockland MicroRider 1000 turbulence probe	
Plankton bottle nets	bottle nets	Mounted in CTDO frame
UVP camera	Underwater Vision Profiler 6	Mounted in CTDO



Table 4. The names of the variables used to indicate time and position, and their respective nomenclature in the data set. All data sets have time, longitude, and latitude as variables. For the other variables, the symbol or symbols next to the name in the data set and between parentheses indicate which data set is used. The symbols are according to Table 1.

Variable	Name in the dataset	Variable	Name in the dataset
Time and position			
time	time	longitude	lon
latitude	lat	altitude/height	alt ($\nabla, \Delta, \lambda, \square, \triangleleft, \approx$)
time of launch	launch_time (?)	time during flight	flight_time (?)
longitude of launch	launch_lon (?)	longitude during flight	flight_lon (?)
latitude of launch	launch_lat (?)	latitude during flight	flight_lat (?)
depth	DEPTH ($\oplus, \otimes$)		

Table 5. The names of the variables used to indicate the ship orientation, and their respective nomenclature in the data set. The symbol or symbols next to the name in the data set and between parentheses indicate which data set is used. The symbols are according to Table 1.

Variable	Name in the dataset	Variable	Name in the dataset
Ship orientation			
ship speed	ship_speed (●)	ship heading	ship_heading (●)
ship heave	ship_heave (●)	ship pitch	ship_pitch (●)
ship roll	ship_roll (●)	eastward ship velocity	U_SHIP ($\oplus$)
northward ship velocity	V_SHIP ($\oplus$)		



Table 6. The names of the measured atmospheric variables, and their respective nomenclature in the data set. The symbol or symbols next to the name in the data set and between parentheses indicate which data set is used. The symbols are according to Table 1.

Variable	Name in the dataset	Variable	Name in the dataset
Meteorology			
air temperature	ta (●, ∇, √, □)	potential temperature	theta (√, □)
dew point temperature	dp (●, √)	equivalent potential temperature	theta_e (□)
air pressure	p_air, p (●, √)	wind speed	wspd (●, √, ≈)
wind direction	wdir (●, √, ≈)	vertical wind	wind (▷)
eastward wind speed	u (√)	northward wind speed	v (√)
relative humidity	rh (●, ∇, √, □)	specific humidity	q (√)
water vapor mixing ratio	mr (∇, △, √)	absolute humidity	rho_w (□)
column-integrated water vapor	iwv (*, □)	water vapor	water_vapor (cm) (○)
liquid water path	lwp (□, <)	liquid water content	lwc (<)
ice water content	iwc (<)	longwave radiation	lwr (●)
shortwave radiation	swr (●)	UV radiation	uv (●)
air mass	air_mass (○)		
Aerosols			
PM1 ambient aerosol	pm1 (●)	PM2.5 ambient aerosol	pm2d5 (●)
PM10 ambient aerosol	pm10 (●)	Particle backscatter at 355, 532 nm	bp355, bp532 (△)
aerosol optical depth 340, ..., 1640 nm	aod_340nm, ..., aod_1640nm (○)		
Clouds			
cloud cover - total	tcc (×)	cloud cover - base	bcc (×)
cloud base height	cbh (×, <)	cloud depth	cdp (×)
cloud top height	cth (□, <)	radar reflectivity	Z (<)
doppler velocity	v (<)		
Precipitation			
rain rate	rain_rate (†, ‡, <, ⊕)	rain_flag (◇, <)	



Table 7. The names of the measured oceanic variables, and their respective nomenclature in the data set. The symbol or symbols next to the name in the data set and between parentheses indicate in which data set is used. The symbols are according to Table 1.

Variable	Name in the dataset	Variable	Name in the dataset
Sea water			
sea surface temperature	sst_skin ($\odot, \otimes$)	sea water temperature	TEMP ($\ominus$)
	sst_2m_port ($\bullet$)	sea water pressure	PRES ($\ominus$)
	sst_2m_board ($\bullet$)	sea water density	rho_port ($\bullet$)
	TEMP - at 5m - ($\oslash$)		rho_board ($\bullet$)
eastward sea water velocity	U ($\oplus, \mapsto$)	northward sea water velocity	V ($\oplus, \mapsto$)
sea floor depth	sea_floor_depth ($\bullet$)	salinity	p_sal ($\oslash, \ominus$)
sea water turbidity	TURB ($\ominus$)	dissolved oxygen	dox2 ($\ominus$)
photosynthetically active radiation	PAR ($\ominus$)	chlorophyll concentration	FLU2 ($\ominus$)

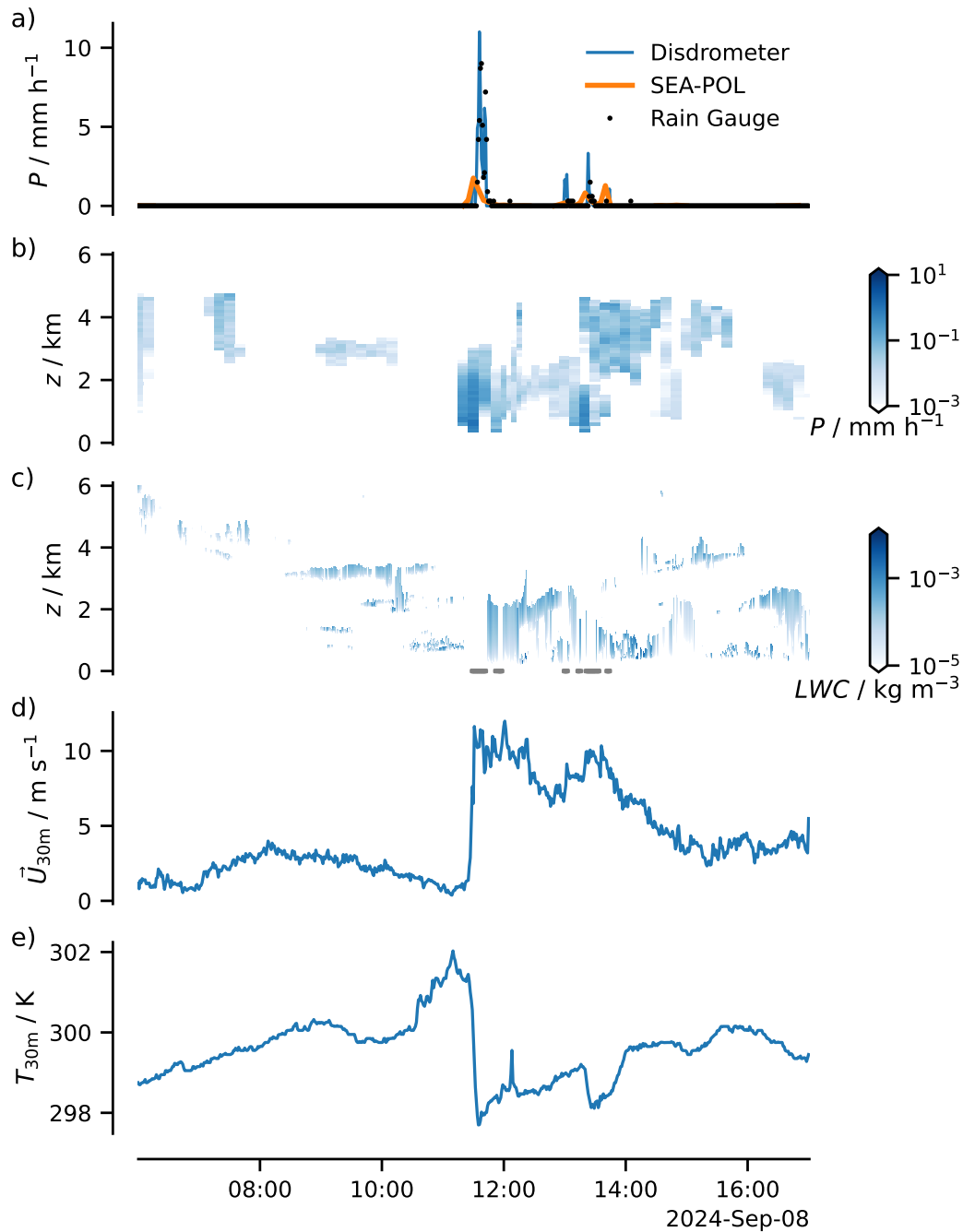


Figure 13. September 8 case study. a) Precipitation intensity (P) from the disdrometer (blue line), rain gauge (black dots), and average within 1 km of the ship from the Sea-Pol low-level scan (orange line). Temporal evolution of b) the vertical structure of precipitation from the Sea-Pol quasi-vertical profile and c) the vertical structure of liquid water content (LWC) from the CloudNet retrieval. The gray dots in the third row indicate when the LWC retrieval is not possible due to rain detection. Time series of d) wind speed ($\vec{U}_{30\text{m}}$) and e) temperature ($T_{30\text{m}}$) from DShip data.

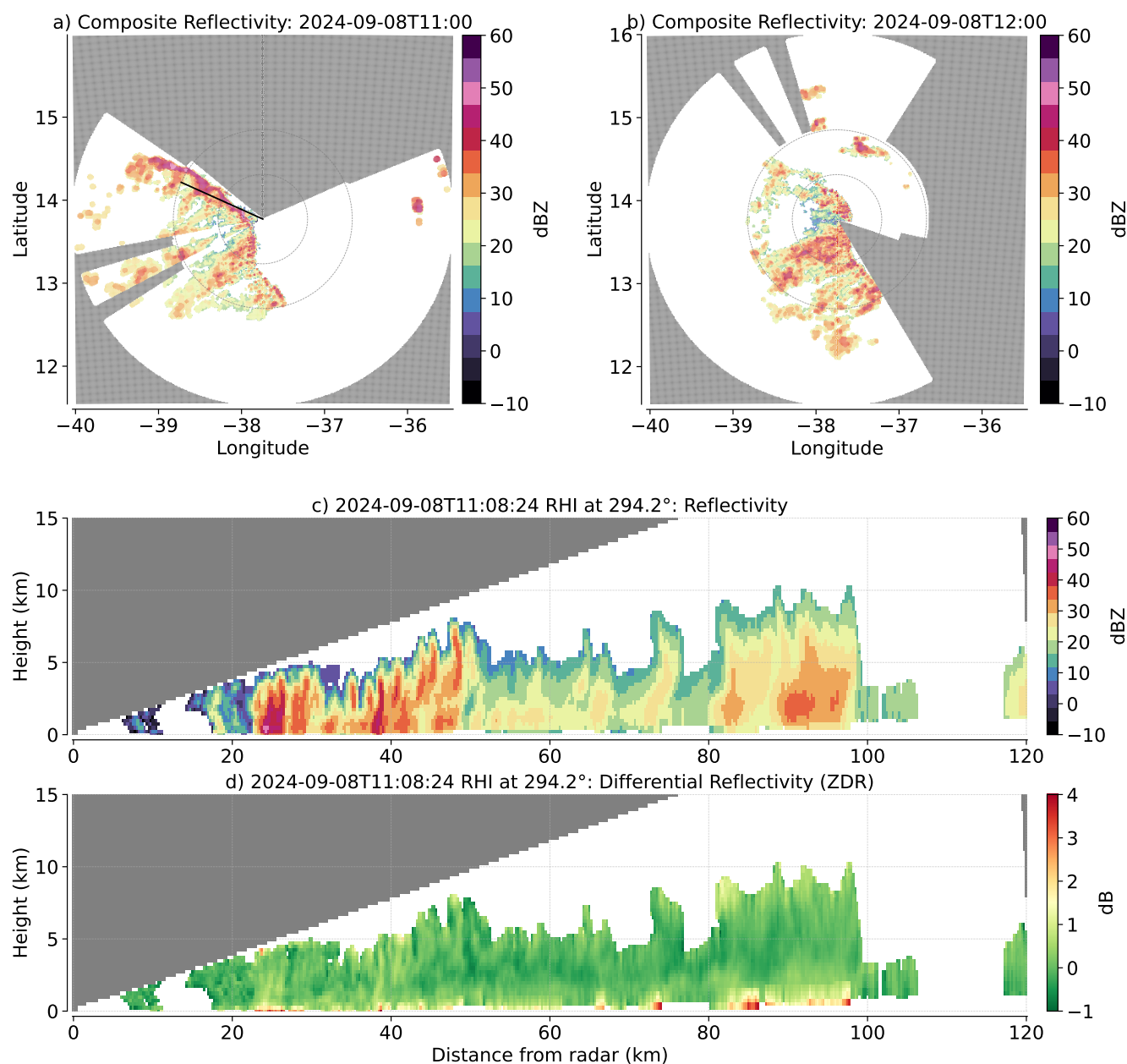


Figure 14. September 8 case study. Spatial distribution of convection a) before (11 UTC; panel a) and b) after (12 UTC) passage of gust front as depicted by Sea-Pol composite reflectivity. Range rings are shown at 60 km and 120 km. Bottom two rows are range-height indicator plots (RHI) showing vertical structure of the squall line at 11:08 UTC, at an azimuth of 294.2° (black line in a) based on reflectivity (c; dBZ) and differential reflectivity (d; dB).