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Coastal-SMEAR — introduction to infrastructure and capacity of the atmospheric observatory in Tvärminne, Finland

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Long-term observations of coastal ecosystems and atmosphere are crucial for addressing global challenges like air pollution, water, energy, and food supply. Coastal environments are ecological hotspots acting as greenhouse gas sinks/sources, emitting volatile organic compounds (VOCs) and trace gases, and impacting marine aerosol formation. The Tvärminne Zoological Station (TZS) in the northern Baltic Sea has a long history of marine biology observations. In 2022, a comprehensive atmospheric observatory was established at TZS, leading to the creation of coastal-SMEAR (Station for Measuring Earth surface – Atmosphere Relations). Equipped with advanced instrumentation, the key aim of this station is to understand potential feedbacks between coastal ecosystems and the atmosphere. Initial results indicate that the sea-air exchange of aerosol precursor gases, VOCs and CO_2 at the coast are highly dynamic, influenced by meteorological and biological conditions. Establishing SMEAR stations in different coastal environments would greatly help to understand coastal ecosystem-atmosphere feedbacks.

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Introduction

Background — need for the coastal-SMEAR

In a rapidly changing world, it is challenging to understand and adapt to the grand challenges that are evidently spread globally. The grand challenges are related to the availability of clean air, water, food, and energy as well as planetary health (https://www.wcrp-climate.org/grand-challenges/). The intertwining nature of these challenges and their connection to global changes (Kulmala *et al.* 2015, Lappalainen *et al.* 2022, Nolan *et al.* 2018, Laughner *et al.* 2021, Wang *et al.* 2023, IBPES https://www.ipbes.net/nexus/media-release) calls for an integrated approach to multidisciplinary research and well-designed solutions (Kulmala *et al.* 2023a, Kulmala *et al.* 2021). Atmospheric interactions with the biosphere, lithosphere and hydrosphere govern many of these challenges. Thus, it becomes crucial to understand the atmospheric processes as, for example, aerosol-related processes are the largest single source of uncertainty in quantifying human-caused changes in Earth's radiative forcing (IPCC 2021). The coastal ecosystems are significant for carbon capture and mitigation of climate change. To be able to understand these processes and address interrelated grand challenges, we need continuous, comprehensive open data from the atmosphere and marine systems of the coastal realm.

The ocean acts as a carbon sink absorbing about 31% of atmospheric CO_2 emissions (Gruber *et al.* 2019). The subsequent ocean acidification not only disturbs the ocean and coastal water chemistry, but it can influence the marine and coastal atmosphere as well, leading to a disturbance in the ocean's capacity to act as a sink. A healthy coastal water ecosystem can capture and store significant amounts of atmospheric carbon through the accumulation of vegetation and long-term sediment burial (Mcleod, E. *et al.* 2011). However, some of the carbon is returned to the atmosphere as CH_4 after undergoing metabolization (Al-Haj *et al.* 2020), creating an offset in the GHG sink estimate of these ecosystems (Bastviken *et al.* 2011). Studies have shown that if a coastal ecosystem starts to degrade it could lead to more CH_4 emissions (Fig. 1), offsetting the climate benefits and the overall capacity of oceans to act as carbon sink (Roth *et al.* 2023). While current conservation efforts emphasize long-term carbon storage, they often overlook key variables affecting radiative forcing, such as short-lived climate forcers (SLCFs) like methane and volatile organic compounds (VOCs) (Szopa *et al.* 2021). The GHGs contribute to warming, while aerosols and their precursors have a cooling effect, introducing uncertainty in assessing human impacts on Earth's climate. Thus, we advocate for a more comprehensive approach that includes a synchronized study of marine and atmospheric parameters as a long-term approach to tackle climate crises. This approach involves setting up an atmospheric observatory that would enable us to obtain a comprehensive data on climate change induced changes to coastal environments. This involves the study of the feedback mechanisms and integrated process understanding. These processes include, e.g., new particle formation (NPF), carbon fluxes and different feedbacks. University of Helsinki (UH) has decades-long experience of building permanent comprehensive scientific stations around the world i.e., Station for Measuring Earth surface and Atmosphere Interactions (SMEAR), performing cutting-edge atmospheric science with state of art instruments alongside capacity building in forest and urban sites. UH has four such SMEAR stations in Finland (Hari *et al.* 1994, Hari and Kulmala 2005) and two in China (Liu *et al.* 2020). The observation stations at various locations are of prime importance for the global observation networks. For example, there are a number of organizations and research infrastructures using the data of the long-term measurements carried out at the SMEAR I — nature reserve in Värriö, SMEAR II — boreal forest in Hyytiälä, and SMEAR III — urban site in Helsinki.

With the existing long-term marine ecosystem observations at the Tvärminne Zoological Station (TZS), Finland, we decided to establish an atmospheric observatory at TZS, to create a comprehensive research observatory and data base for long-term observations of ecosystem-atmosphere relations, i.e. a coastal-SMEAR. Our expectation is that the establishment of

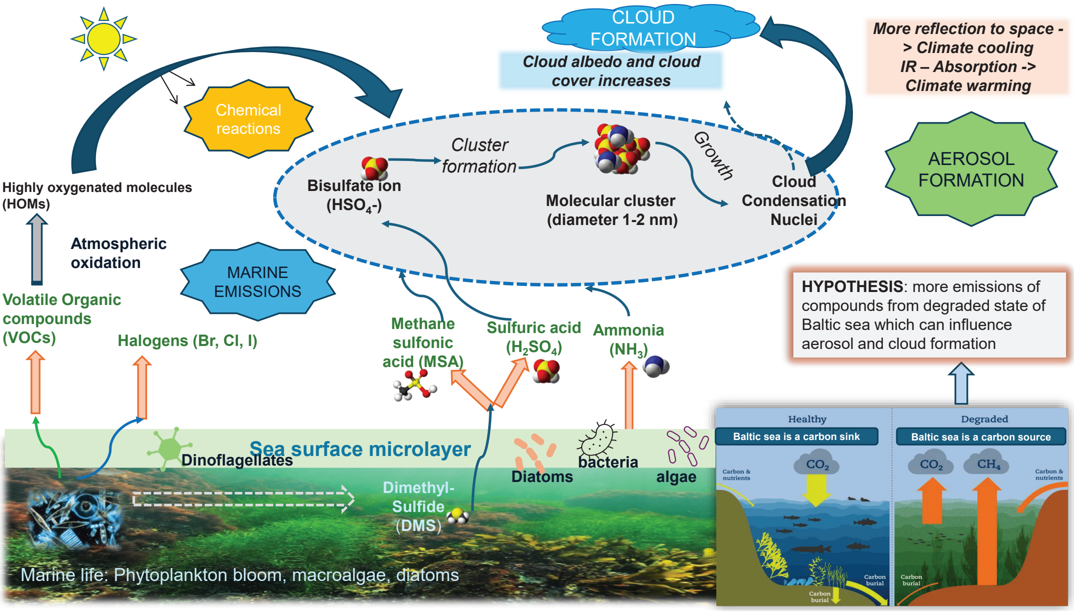

Fig. 1. Schematics showing the marine emissions, their sources and impact on atmospheric chemistry — concept of coastal SMEAR at Tvärminne (CoastClim).

the coastal-SMEAR will produce findings that highlight the interconnectedness of the coastal biodiversity, atmospheric responses and climate change, emphasizing that effective conservation measures must address these aspects simultaneously. The new coastal atmospheric laboratory houses a comprehensive set of instrumentation to collect data to understand aerosol-climate feedback processes in the coastal environment.

An active atmospheric research focus is on how atmospheric particles (aerosols) are formed in the atmosphere. Various studies have been published on the role of sulphuric acid in new particle formation (NPF) in various regions of the world (Riipinen *et al.* 2007, Paasonen *et al.* 2010, Nieminen *et al.* 2014). Even gaseous organic compounds (Huang *et al.* 2021) play an important role in NPF as indicated by the field measurements in Hyytiälä. The global BVOC (Biogenic Volatile Organic Compounds) emissions are dominated by terpenes (isoprene (C_5H_8), 594 Tg C a^{-1}, monoterpenes ($C_{10}H_{16}$), 95 Tg C a^{-1}, and sesquiterpenes ($C_{15}H_{24}$), 20 Tg C a^{-1} (Sindelarova *et al.* 2014), which are mainly emitted by vegetation and can be influenced by meteorological conditions, such as temperature and light (Guenther *et al.* 1995, Kaser *et al.* 2013). Most of the above-mentioned studies are focussed on the inorganic trace gases and BVOCs emitted from the terrestrial sources and their role in NPF. However, the role of emissions from marine sources in NPF is largely unknown. Studies have shown that there is a strong marine biogenic influence on the marine aerosols (Anttila *et al.* 2010, Spracklen *et al.* 2008). Secondary organic aerosol (SOA) over the marine regions can be formed by the oxidation products of BVOCs (including halogen and sulphur-containing compounds) emitted by e.g. phytoplankton, and these can form sulphuric acid (SA), methane sulphonic acid (MSA), oxygenated VOCs, iodic acid-sulphuric acid (IA-SA) clusters, etc (Yassaa *et al.* 2008, Kim *et al.* 2017 , He *et al.* 2021, He *et al.* 2023).

Coastal NPF may lead to the formation of cloud condensation nuclei (Casan *et al.* 2025, Wollesen *et al.* 2024) but how much they would affect the radiation budget globally is a question which is yet to be answered. Every year the Baltic Sea is extensively affected by the spring and summer phytoplankton blooms, suggesting it could be a hot spot for VOC emissions. The dearth of measurements of VOCs in the marine boundary layer has raised questions on how the marine environment is impacted or can impact the overlying atmosphere. VOC emissions at the interface between air and soil, snow or ocean play a major role in atmospheric oxidation processes, gas-particle transfer and the formation of SOA. Some VOCs produce low-volatility vapours through the process of autoxidation (Ehn *et al.* 2014), which rapidly forms highly oxygenated molecules (HOMs) that act as important precursor vapours leading to NPF (Fig. 1). Extensive studies have been performed for terrestrial VOC fluxes but much less attention has been given to the marine emissions of VOCs (Yu and Li 2021). Focussing our attention specifically to the Baltic Sea, the lacuna is that no studies have attempted to capture the seasonality of the VOC emissions from the recurring blooms and how they impact aerosol formation. A recent study showed that when the air mass travelled over the water bodies surrounding Helsinki, having higher residence times of the air mass over the cyanobacterial/algal blooms, the air mass was enriched with biogenic SA and/or IA initiating the formation of small clusters of particles at the measurement site (Thakur *et al.* 2022).

The datasets like VOCs, aerosol size distributions and GHGs generated at the station using state of art instrumentation to analyse feedback processes and provide clarity on the total impact of the coastal ecosystem on carbon uptake and aerosol formation. Modelling studies can utilize this data to assess surface and cloud albedos in the long run, enabling quantification of the CarbonSink+, a concept introduced by Kulmala *et al.* (2020). The concept of CarbonSink+ combines the effects of CO_2 fertilization and aerosol-induced diffuse radiation enhancement on photosynthesis which is then responsible for influencing ecosystem (in this case the marine ecosystem) carbon uptake. Interactions between aerosol particles and ecosystem similar to CarbonSink+ are yet to be understood in the coastal zone. The measurement systems at the station enables comprehensive monitoring of marine emissions — such as VOCs, dimethyl sulphide (DMS), and greenhouse gases — and their role in aerosol formation and modification of the atmospheric radiative budget. By simultaneously measuring atmospheric parameters, water chemistry, and coastal biological activity, we aim to understand how environmental changes, including rising sea surface and air temperatures and thereafter eutrophication, influence marine biogeochemical processes. Understanding these marine biogeochemical processes better directs us to gain insight into the Charlson-Lovelock-Andreae-Warren (CLAW, Charlson *et al.* 1987) and Continental-Biosphere-Atmosphere-Clouds-Climate feedback, COBACC (Kulmala *et al.* 2004, 2014) hypothesis. The CLAW hypothesis proposes a climate feedback loop linking phytoplankton activity to cloud formation whereas the COBACC (Continental-Biosphere-Atmosphere-Clouds-Climate) feedback loop puts forward a hypothesis that increased CO_2 level leads to more efficient photosynthesis, and more active plants emitting BVOCs, which then contribute to formation and growth of atmospheric aerosol particles, influencing solar radiation and photosynthesis, and feedback on the carbon sink (and CO_2) via the diffuse radiation fertilization effect. Specifically, we are examining how warming and eutrophication in the Baltic Sea may stimulate phytoplankton and cyanobacterial blooms, thereby increasing DMS emissions. Once released, DMS is oxidized in the atmosphere to sulphur dioxide (SO_2) and subsequently to sulphate aerosols, which can act as cloud condensation nuclei (CCN). These CCN influence cloud albedo and, consequently, Earth's radiative balance. Despite evidence supporting components of the DMS–CCN–cloud albedo feedback mechanism, a complete, globally validated framework remains lacking (Ayers and Cainey, 2007). The coastal SMEAR station provides an essential platform to observe and quantify these processes in a real-world coastal environment, offering valuable data to assess and refine the CLAW hypothesis and examine COBACC hypothesis under increasing emissions from the sea, with changing climate scenarios. Furthermore, significant gaps and contradictions persist, including a lack of quantitative understanding of new particle formation processes in the marine atmospheric boundary layer.

Thus, to understand the greenhouse gas sources and sinks in coastal area, sea to air emission processes of trace gases, their oxidation and their role in aerosol formation, the feedback

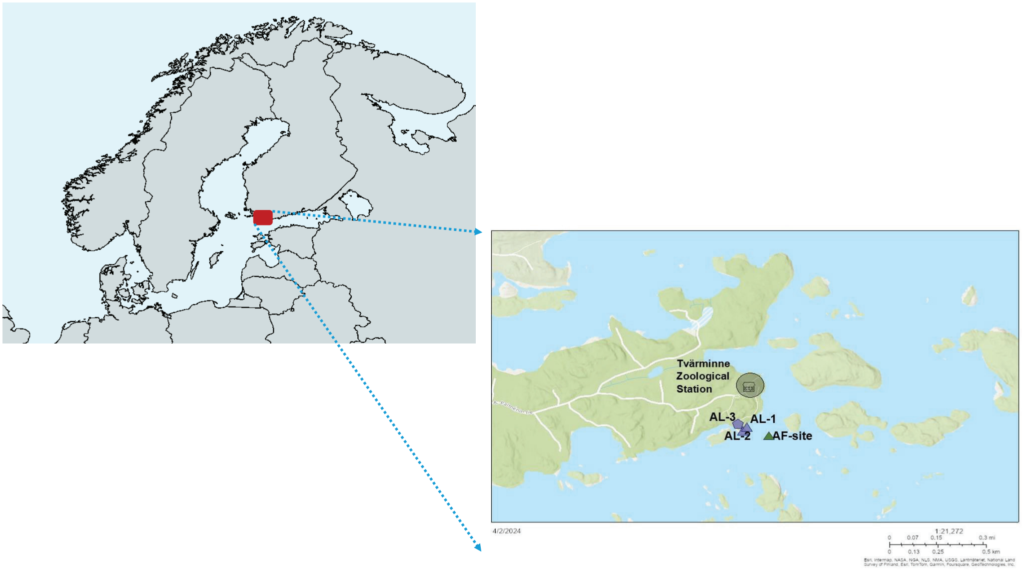

Fig. 2. Location showing the site of the atmospheric observatory at the coast of Tvärminne. Note the trailers marked as atmospheric lab: AL-1 and AL-2 are located ~10m from the coast, AL-3 in a container housed 160 m away from the coast and AF site, which situated on a small island, 130 m from AL-1 and Al-2.

loops and integration we have set up a permanent atmospheric laboratory at the Tvärminne Zoological Station (TZS) on the Finnish coast of the Baltic Sea in 2022, within the umbrella of "CoastClim" (Centre for Coastal Ecosystem and Climate Change Research, https://coastclim.org), which is a collaboration between the University of Helsinki and Stockholm University. The location, infrastructure and instruments of the coastal-SMEAR are explained in the following section, while examples of some preliminary results from coastal-SMEAR are discussed in the Results section.

Material and methods

Location and facilities

The atmospheric observatory is hosted by the Tvärminne Zoological Station (TZS, University of Helsinki). TZS is located in Tvärminne on the Hanko peninsula, often marked as the northern point of the line separating the Baltic Sea proper from the Gulf of Finland (Alenius *et al.* 1998, Fig. 2). Established in 1902, TZS serves as a pivotal site for studying long-term environmental change (Goebeler et al 2022). This site has a brackish seawater environment (salinity approx. 6g kg^{-1} of water), with expansive archipelagos comprised by diverse habitats that offer a prime depiction of the Baltic Sea ecosystem and serves as a valuable point of reference for comparing coastal ecosystems across Europe. TZS has a fully equipped marine laboratory, multiple research vessels, sampling gear, diving facilities, aquarium facilities, and extensive long-term databases from the marine realm. Marine research conducted at TZS concentrates on exploring the biodiversity and operational mechanisms of the Baltic Sea ecosystem, alongside examining the anthropogenic stressors influencing its dynamics (Kremp *et al.* 2008, Rousi *et al.* 2013, Villnäs *et al.* 2013, Spilling *et al.* 2014, Jokinen *et al.* 2015, Kauppi *et al.* 2015, Lammerant *et al.* 2024, Uth *et al.* 2024). This research spans across various disciplines, including ecology, ecophysiology, ecotoxicology, taxonomy, and behavioural and evolutionary biology. The establishment of the atmospheric laboratory at the site facilitates strong collaborative science spanning across different disciplines to understand the coastal ecosystem and its impact on the overlying atmosphere. The details of the marine research are explained in the Marine observations section.

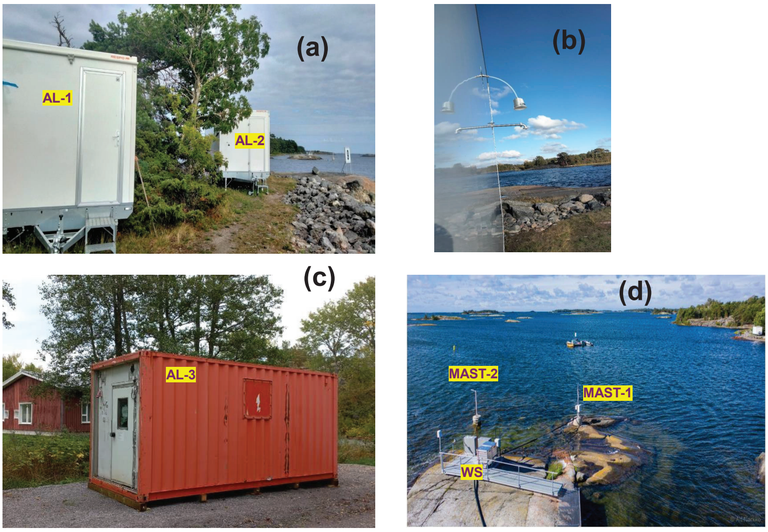

Fig. 3. (**a**) The Trailers AL-1 and AL-2 at the coast; (**b**) inlets of the mass spectrometers facing the coast; (**c**) Metal container, AL-3,150 m away from the coast; (**d**) Aerial photograph of the AF site with eddy covariance masts (Mast-1 and Mast-2) and weather station (WS) with the trailers in the background in the right.

Atmospheric Observatory

The atmospheric observatory aims to measure GHG fluxes, molecular clusters, VOCs, aerosol number and size distributions, and trace gases like CO, NO_x, O_3 and SO_2. The atmospheric observatory consists of two movable trailers, one metal container and an eddy covariance setup. Each of the trailers is ~15m^3 in capacity (3.1 × 2.2 × 2.2 m) and are temperature and humidity controlled by air conditioning units, and temperature and humidity sensors. The trailers were installed in 2022. The trailers (Type-fRespo 320-1D) are named as Atmochem Lab (AL) 1 and 2 (Fig. 2) and house particle size analysers (1–40 nm) and mass spectrometers with inlets facing the coast (Fig. 3a and b). The AL-1 houses the Neutral cluster and Air ion Spectrometer (NAIS) and Vocus-Proton Transfer Reaction-Mass Spectrometer (PTR-MS) (Table 1). The inlet of the NAIS is at 2.2 m a.m.s.l. and that of Vocus-PTR-MS is 2 m a.m.s.l. The second similar trailer, placed next to the first, houses a Multischeme chemical-ionization-atmospheric pressure interface- Time of Flight mass spectrometer (MION-CIMS), Particle Size Magnifier (PSM), air dryer units, compressors and vacuum pump systems (Table 1). The labs are thermally insulated (EPS insulation). AL-1 and 2 are placed 15 m from the coast (Fig 3a) with inlets facing the coast (Fig. 3b). The trace gas analysers (O_3, NO_x, SO_2 and CO) and aerosol instrumentation (10 nm – 20 microns) are installed in a metal container, Atmogas Lab, AL-3 (Fig. 3c). This metal container (Fig. 3c, AL-3) was placed 150 m from the coast in 2023. The observatory also houses two atmospheric eddy covariance masts and a weather station measuring meteorological parameters and fluxes of CO_2 and methane (Fig. 3d) at the Atmoflux (AF) site of the atmospheric observatory, which is situated on a small island, 130 m from AL-1 and AL-2 (Fig. 2).

Instruments in the Atmochem and Atmogas Lab

Gas phase instruments

MION-CIMS

The MION-CIMS is a long ToF with a mass resolving power of ~9000 coupled to a recently developed multi-scheme chemical ionization inlet (MION, Karsa Ltd., Rissanen *et al.* 2019) was used to analyse the molecular composition of inorganic and organic vapours. Chemical ionization (CI) is a soft ionization method (Gross, 2017) often employed in aerosol research (Ehn *et al.* 2014, Lopez-Hilfiker *et al.* 2014). More specifically the MION inlet ionizes molecules through clustering with ions like bromide and nitrate (Rissanen *et al.* 2019). During the 60 min cycles of measurements, MION-CIMS switches modes between nitrate (NO_3^-, 12 min), bromide (Br^-, 12 min), and ambient (measuring natural ions, 30 min) modes, followed by 6 min of ion-filter zeroing before switching from ambient mode to the next mode. Gaseous organic compounds were sampled via a stainless-steel tube (2.54 cm. outer diameter) of ca. 0.9 m length and a flow rate of 20 L min^{-1}. Due to the large inlet diameter and high flow rate, losses of organic vapours are expected to be negligible. Through the fast switching between the two reagent ion schemes, Br^- and NO_3^-, both less and more oxygenated VOCs (including highly oxygenated molecules, HOMs) can be measured, as well as sulfuric acid (H_2SO_4) and its clusters, e.g. $(H_2SO_4)_n(NH_3)_y$ in the range of 60–1000 amu (Rissanen *et al.* 2019, Huang *et al.* 2021). The MION-CIMS is housed in the trailer AL-2 (Fig. 4a).

Vocus PTR-MS

Mass spectrometry techniques are commonly used to study organic compound composition (Nash *et al.* 2006). Proton-transfer-reaction mass spectrometry (PTR-MS) is commonly used to measure VOCs in the atmosphere (Yuan *et al.* 2017). The Vocus PTR-MS, with its improved chemical ionization source, offers enhanced sensitivity for detecting a wide range of VOCs and their oxygenated products, and it can detect a broader spectrum of VOCs (even diterpenes) and their oxygenated products (up to six to eight oxygen atoms for monoterpene oxidation products, Li *et al.* 2020). It may, however, not be ideal for detecting HOMs or dimers due to potential instrument fragmentation and losses in sampling lines (Li *et al.* 2020, Riva *et al.* 2019). In Vocus-PTR-MS, VOCs enter a drift-tube ion–molecule reactor (IMR), and they are ionized via proton transfer from hydronium ions (H_3O^+) produced in a separate ion source. A hollow-cathode ion source is common in these mass spectrometers, but Tofwerk's Vocus uses a conical, low-pressure discharge source (Krechmer *et al.* 2018). Frequent background calibrations were made every 2 h in addition to weekly multipoint calibrations using a standard calibration gas. The Vocus is housed in the trailer AL-1 (Fig. 4b).

Trace Gas Analysers

The container AL-3 houses a set of different trace gas analysers, which are calibrated monthly using a calibrator unit and ozone generator

Table 1. List of instruments, parameters and other details on measurement for the atmospheric laboratory housed in trailers AL-1 and AL-2, and container AL-3.

Instruments	Parameter	Resolution	Inlet height (a.m.s.l)	Measurement started
AL-1 Instruments				
NAIS	Aerosols: ions (0.8–40 nm) and particles (2–40 nm)	10 sec	2.2 m	25.02.2022
Vocus-PTR-MS	Concentration of VOCs and their oxygenated products (m/z 10-m/z 500)	5 sec	2 m	25.07.2022
AL-2 Instruments				
MION-CIMS	Concentration of inorganic and organic vapors,highly oxygenated molecules (m/z 60-m/z 1000)	5 sec	2 m	17.07.2022
PSM	Particle concentration and size distribution from 1–3 nm	1 sec	1.5 m	18.07.2022
AL-3 Instruments				
DMPS	Particle concentration and size distribution from 10–800 nm	5 min	4 m	31.01.2024
APS	Particle concentration and size distribution from 0.5–20 microns	5 min	4 m	20.12.2023
Gas analyzers	Concentration of O_3, NO_x, SO_2 and CO	10 min	4 m	17.12.2023

Fig. 4. Gas phase instruments: (**a**) MION-CIMS; (**b**) Vocus PTR-MS; and (**c**) Trace gas analyzer and their calibration systems.

housed in the same rack (Fig. 4c). NO_x (NO and NO_2) is measured using a NO_x analyser (Teledyne API, model T200P, photolytic). SO_2, CO and O_3 are measured with a SO_2 analyser (43i-TLE, ThermoFisher), a CO analyser (Teledyne API, model T300) and ozone analyser (Teledyne API, T400, photometric), respectively. A gas calibrator unit is used to calibrate the different gas analysers (CMK5 Touch/ 4PG /O_3(GPT-MFC)/PH). The pump for compressed dry air for the analysers and a vacuum pump (described in the Affiliated facilities section) are housed in a separate small pump room inside AL-3. It is well ventilated by an exhaust fan system to prevent overheating of the room due to running pumps and compressor systems.

Particle Phase Instruments

NAIS, PSM, DMPS and APS

Several instruments based on different technologies are deployed to measure the particle size distribution from 1 to 20 000 nm (Fig. 5). A PSM (Airmodus Ltd.) is used to measure the size distribution from 1–3 nm particles (Vanhanen *et al.* 2011). Particles from 2 nm to 40 nm and ions from 0.8 nm to 40 nm are measured using a NAIS (Airel Ltd.) (Mirme & Mirme, 2013). Particles from 10 to 800 nm are measured with a custom-made DMPS (differential mobility particle sizer, Aalto *et al.* 2001). The particles from 500 nm to 20 000 nm are measured with an APS (Aerodynamic Particle Sizer; Model 3321, TSI). The DMPS and APS instruments have Nafion dryers which dry the aerosol sample flow to 15–20% RH at the inlet.

Atmoflux Site-Eddy covariance masts and the weather system

There are two atmospheric eddy covariance mast systems on a small rocky island 130 m from the ALs at the coast, one mast with the sonic anemometer and gas analysers and the other mast is the net radiometer. On the island, also the pyranometer, PAR quantum sensor and air temperature and relative humidity probe are installed. The details of the instruments and the variables measured are shown in Table 2.

Marine observations

In close vicinity (100 m) to the Atmospheric observatory, a range of key physical (temperature and salinity) and biogeochemical (chlorophyll-*a*, turbidity, coloured dissolved organic matter, dissolved oxygen, and partial pressure of CO_2 and CH_4) parameters in seawater are continuously being measured via an intake pipe at 4 m depth (sandy habitat with mixed macrophyte vegetation, Table 3). This setup is under development and will be described in detail elsewhere. In the same area, soft sediment macrofauna, macrophytes and macroalgae (bladder wrack *Fucus vesiculosus*) and associated invertebrate epifauna, phytoplankton and zooplankton are being monitored. At the TZS long-term hydrography monitoring site Storfjärden (30 m depth), approx. 1.5 km from the Atmospheric observatory, seawater temperature and salinity has been measured since 1926 (Goebeler *et al.* 2022). Currently CTD profiles are measured daily during the ice-free season with an automated profiling buoy, with monthly measurements of water column nutrients, chlorophyll-*a*, oxygen, and Secchi depth. Soft sediment macrofauna is monitored twice a year. These marine observations are conducted by TZS staff and CoastClim researchers. The marine parameters that would be used to understand the sea-air interactions and carefully interpret the long-term data sets of aerosol size distribution and chemi-

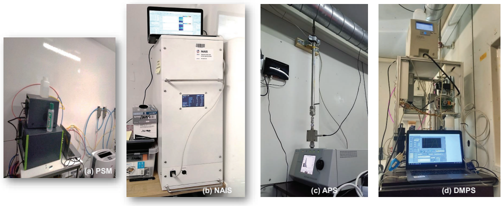

Fig. 5. Aerosol measurement instruments: (**a**) NAIS installed in AL-1; (**b**) PSM installed in AL-2; (**c**) APS installed in AL-3; and (**d**) DMPS installed in AL-3.

cal composition of the atmosphere is listed in Table 3. These marine and atmospheric measurements existing under one umbrella allows to build a unique data set for studies of marine ecosystem-atmosphere interactions driving the concept of coastal SMEAR. Further, simultaneous measurements of sea water properties and atmospheric variables will enable us to connect changes in atmospheric chemistry with the state of the sea so that we can for example understand how eutrophication and sea surface temperature can influence carbon fluxes and aerosol formation at the coast.

Affiliated facilities

Electricity system at the coast

A total of 24 kW of electricity is supplied to the AL-1 and AL-2. The power line has 35-amp fuses, for 3 phases, at 230 volts. Weatherproof electrical cables run from the main station power supply to the Atmospheric Labs/trailers. The safety circuit breakers and UPSs are placed in the ALs to ensure safe and smooth running of the instruments.

Table 2. List of variables and Instruments at the Atmoflux site (AF site)

Variable	Instrument	Height above mean sea level	Auxiliary information
Fluxes			
Sensible heat flux, Latent heat flux, Momentum flux, Friction velocity, CO_2 flux, H_2O flux	METEK uSonic-3 Scientific, LI-7200RS, LI-COR	4.2 m	
CH_4 flux	METEK uSonic-3 Scientific, Picarro G2311-f	4.2 m	
Meteorology			
Wind speed, Wind direction, Sonic temperature	METEK uSonic-3 Scientific	4.2 m	
Air temperature, Relative humidity	Vaisala HMP155	4.0 m	
Precipitation	OTT HydroMet Pluvio2, Tretyakov-type wind shield		250 m from the EC site. Maintained by the Finnish Meteorological Institute
Radiation			
Global and Reflected shortwave radiation	Kipp & Zonen CNR4	3.3 m	Spectral range 300–2800 nm
Total and Diffuse irradiance	Delta-T SPN1	3.0 m	Spectral range 400–2700 nm
Photosynthetically active radiation	Kipp & Zonen PQS1	3.0 m	Spectral range 400–700 nm

Pumps, Compressed air and Calibration gases

Compressed and dried air is needed by MION-CIMS, the PSM, DMPS and APS. One compressor system is installed within AL-3 (housed in a separate pump room) and another is installed within AL-2, where the MION-CIMS and PSM are housed. The compressor-dryer system consists of an oil-free air compressor (Flairmo), equipped with a gas tank (25 L at max. pressure of 10 bar). The maximum output flow rate of the compressor is 75 lpm. The compressed air is directed to the dryer (SMC IDF4E-10 air dryer, IDF Refrigerated Dryer, with dew point of −51°C). The dryer is in compliance with the Montreal Protocol Regulations and uses refrigerants R134a and R407C to prevent any climate damage. The dried and compressed air is then directed to the PSM and MION-CIMS. The MION-CIMS uses a very small flow of 108 ml per min in total for the reagent flows (Br^- and NO^{3-}). Oil-free vacuum pumps are used for creating vacuum for the inlet flow of PSM (3.5–4.0 lpm), MION-CIMS (20 lpm). Two 3KVA UPS (Eaton) are installed in the AL-2 so that the MION-CIMS and the compressor-drier system can run for ~30 min in the case of interruption of power supply and one 3KVA UPS (Eaton) installed in AL-1 to backup the operation of Vocus-PTR-MS. The gas cylinders are in an outdoor weatherproof storage near the AL-2. The gases include high purity SO_2, synthetic air, nitrogen for SA calibration (for MION-CIMS), and Vocus PTR-MS calibration gas mixture (20 component mixture with each component at nominally 1 μmol mol^{-1} (ppm) in a balance of nitrogen).

Data Backup system and data quality control

The instruments have independent data acquisition systems and computers except the gas analysers and APS. A well-developed data integration and backup system for routine data quality check and data backup has been built. The real-time raw data are automatically uploaded to a University of Helsinki group server. The backing up of the data is scheduled per hour via automated scripts and data transfer platforms. A high priority is given on the data quality, which forms an integral part of the continuous observations. The smooth and uninterrupted running of the instruments are ensured by checking the diagnostic parameters of all the instruments daily and an updated logbook is maintained.

Capacity and First Results

The synchronized marine and atmospheric observations give us capacity to investigate multiple processes, feedbacks and interactions in coastal environments. Here we show some of the first results within the umbrella of coastal-SMEAR. This section describes the meteorological conditions prevailing at the site, followed by the chemical speciation in air at the coastal site. We also show the first results of VOC fluxes, like isoprene and α-pinene, emitted out from the coastal waters, which may act as precursors to oxidized organics in the atmosphere contributing to NPF. The section, "CO_2 fluxes and Carbon-Sink+ at the coastal site" describes the seasonal and diurnal variability of CO_2 fluxes and local aerosol production which could be useful in

Table 3. Marine parameters measured continuously in the atmospheric observatory as part of coastal SMEAR

Parameters /Variables	Facilities/Equipment
*Marine VOC flux	Tenax TA - Carbopack B sorbent tube samples with analysis through TD-GC-MS
Temperature, salinity of water column	Seabird salinograph SBE 045
pCO_2 and pCH_4	LI-7810, LI-COR
Chlorophyll-*a*, turbidity, and phycocyanin	TriLux, Chelsea
Colored dissolved organic matter	UviLux, Chelsea

*campaign based measurements

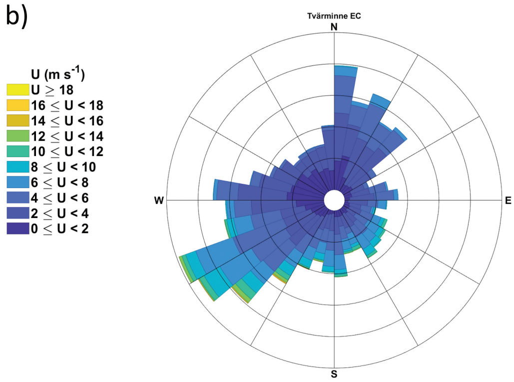

Fig. 6. (**a**) Meteorological parameters at TZS from January–December 2023. Note T_w is the water temperature; T_a is the air temperature; P_a is the atmospheric pressure, RH is the relative humidity. (**b**) Windrose plotted for the year 2023.

evaluating the overall impact of Carbonsink+. We conclude in the Results section by describing how these variables measured at the station can contribute to feedback loops based on CLAW and COBACC hypotheses at the coast of the Baltic Sea.

Meteorological conditions

The meteorological conditions at TZS are typical for any Finnish location at the Southern coast bordering the Gulf of Finland. The basic meteorological parameters for 2023 are summarized in Fig. 6a. Below zero temperatures prevailed from December to March, where the minimum temperature recorded was in mid-January, –18ºC. Spring marks the onset of comparatively warmer temperatures as compared to previous months, above 5ºC, with maximum temperature in first weeks of August reaching 25ºC. During the year, almost 90% of the time the relative humidity remained above 60%. Precipitation reached its maximum in late August and mainly sunny (clear sky) conditions were recorded from mid-April to July. The windrose plotted for the year 2023 (Fig. 6b) showed the wind direction with the maximum frequency was south-west followed by north-northeast. The south-west direction indicates that the wind coming to the station is mostly passing over the Gulf of Finland and the northern Baltic Sea indicating a dominant marine wind. Highest wind speeds of 12–16 m sec^{-1} are also recorded from this sector, suggesting an efficient transfer of the marine emissions to the station site. Nevertheless, the second dominant wind direction, NNE, which is mostly continental air masses that have travelled over the forest and rural areas.

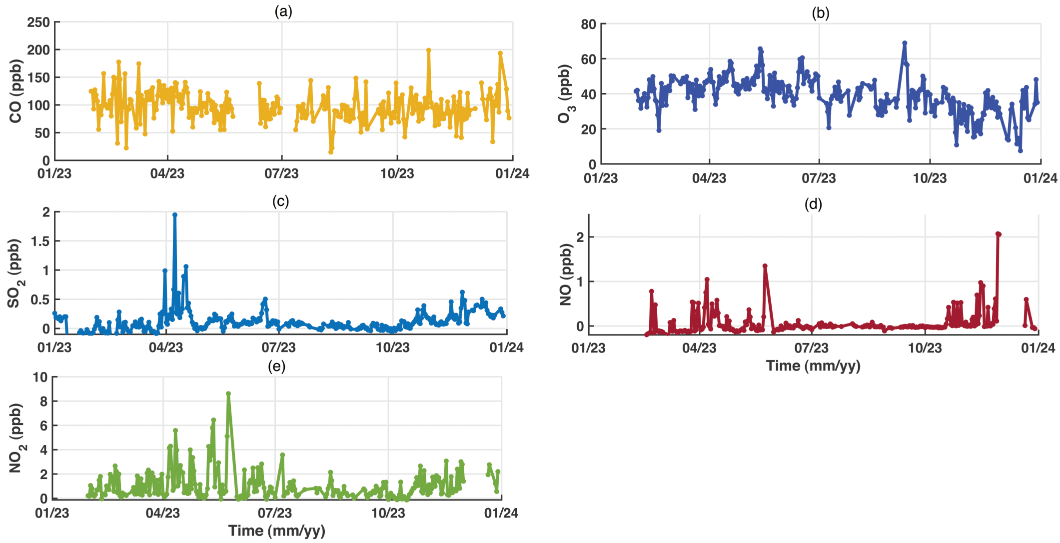

Fig. 7. Time series plot for different trace gases.

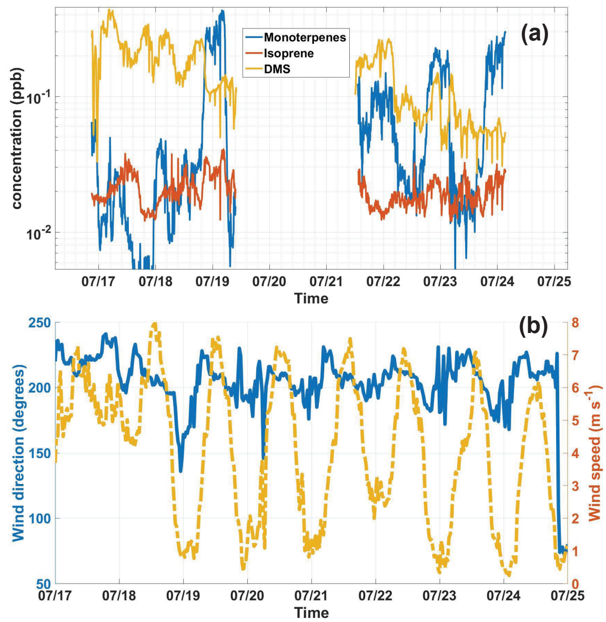

Fig. 8. (**a**) Time series of the concentration of isoprene, monoterpenes and DMS during the marine air mass intrusion period, 17–24 July 2024. (**b**) Wind direction and wind speed during the period 17–24 July 2024 (30 min average). Marine sector (200–250 degrees) chosen for the data analysis.

Chemical Speciation of ambient air

Trace gases

A time series plotted for daily median concentrations of trace gases (CO, SO_2, NO_2, O_3 and NO) for approx. one year (2023) period is shown (Fig. 7). The concentration of CO remained relatively stable throughout the year (Fig. 7a). Some seasonal variability was noted for O_3 (Fig. 7b). Comparatively higher concentrations of O_3 are seen in March–April (as compared to winter), with concentrations reaching up to 65 ppb. The spring peak could be due to the recovery of O_3 through photochemical production (Dibb *et al.* 2003). We again observe the O_3 concentration going up to 65 ppb in mid-August and then decrease over the autumn and winter months.

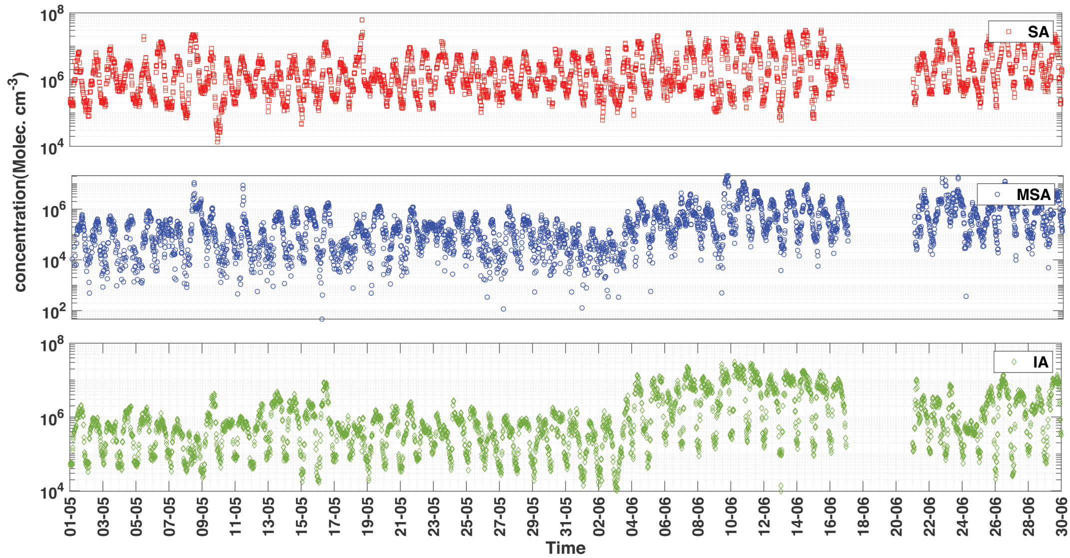

Fig. 9. Time series of concentrations of sulphuric acid (SA), Methanesulphonic acid (MSA), Iodic acid (IA) from 01 May–30 June 2024.

The SO_2 concentrations were ranging between 0.05–2 pbb (Fig. 7c), with the maximum concentration seen during the springtime. The range of concentrations of trace gases found in this study are well within the threshold, limit and critical value mentioned in the national guidelines and WHO air quality threshold values (https://en.ilmatieteenlaitos.fi/air-quality-index; Antilla and Tuovinen, 2010; https://www.hsy.fi/en/air-quality-and-climate/air-protection-and-health/air-quality-regulations/). The need for a background site monitoring the standard gaseous pollutants is crucial for the national air quality monitoring program (Kukkonen *et al.* 1999, Anttila *et al.* 2003).

Volatile Organic Compounds

A snapshot of the data for three target compounds, DMS, monoterpenes and isoprene were chosen as the main representative VOCs from the Vocus-PTR-MS. A time series plot of the concentrations of these species (Fig. 8a) is analysed for July 17–24, 2023. This time slot was particularly chosen as the winds were from the marine sector (200º–250º, Fig. 8b). During a relatively low wind speed day (17 July), DMS concentration dominated. While this coastal site itself can be the source of DMS, being a more stable gaseous species as compared to isoprene or monoterpenes it can also be transported from further away. The atmospheric lifetime of DMS can range from less than one day to up to five days (Ghahreman *et al.* 2019). Isoprene has a lifetime of one to two hours (Chauhan and Sharma, 2023), and monoterpenes have a lifetime of one hour to several hours (Peräkylä *et al.* 2014). When the wind speed was relatively higher during the daytime (> 6 m s^{-1}) monoterpenes were either equal or higher than DMS, with a daytime concentration range of 0.1–0.4 ppb. Isoprene was noted to be an order of magnitude lower than DMS and monoterpenes on most of the days (0.01–0.03 ppb). The correlation plots of DMS with isoprene and monoterpenes did not show any significant corelation (see Fig. S1a and b in Supplementary Information), indicating different sources. Isoprene can be produced by heterotrophic bacteria (Fall and Copley, 2000), marine cyanobacteria, phytoplankton and seaweeds (Exton *et al.* 2013), whereas DMS can be produced by its cellular precursor dimethyl sulfoniopropionate (DMSP) in algae and bacteria (Curson *et al.* 2017). Marine algae have been noted to be sources of monoterpenes both in the field and laboratory studies (Yassaa *et al.* 2008,Wise *et al.* 2003). However, a good cor-

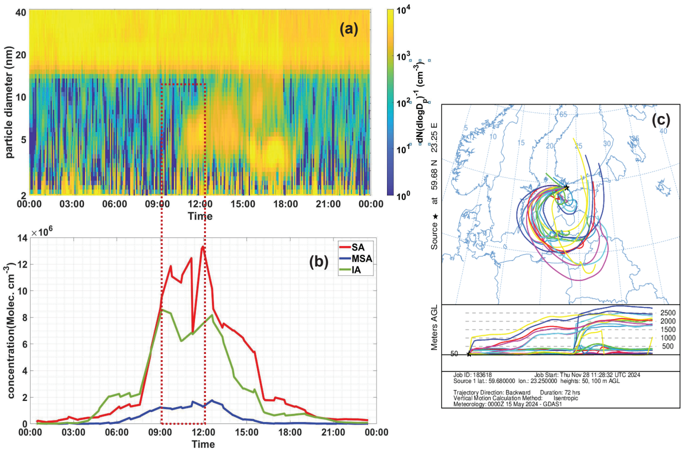

Fig. 10. (**a**) Ion Burst event, number size distribution data recorded by NAIS; (**b**) Diurnal plot for concentrations of SA, MSA, IA for the event; (**c**) 5-day back trajectory analysis done by HYSPLIT.

relation (r^2= 0.97) was noted for isoprene and monoterpenes for datapoints when high monoterpene concentrations (> 0.1 ppb, see Fig. S1c in Supplementary Information) was recorded. It may indicate an additional, possibly marine influence on the monoterpene and isoprene concentrations during these days.

The complexity of processes governing the emissions is not only at the air-sea interface but also above this interface. The northside of the atmospheric Labs, AL-1 and AL-2 is also marked by sparse forest and vegetation, indicating a possible (and large) terrestrial source of these organics directly for the overlying atmosphere. The combined influence of the airmass origin, meteorological parameters, biology (macrophytes) and even the lifetime of the gaseous species would determine the concentration and impact of these gases at the coast. To further explore the sources of some VOCs we carried out campaign-based flux measurements at the coast described in the following section.

Precursor gases and their role in NPF

The diurnal variation of chemical species like sulphuric acid (SA), iodic acid (IA), methane sulphonic acid (MSA) and organics (HOMs) was investigated (Fig. 9 and Fig. S1 in Supplementary Information) for the period of June 2024. This period was chosen as this is the starting month of summer cyanobacterial bloom. It was observed that SA concentration remained the highest, ~1.2×10^7 molec. cm^{-3} as compared to MSA and IA at least until the first week of June. The algal barometer which describes the cyanobacterial development over the weeks using the data from the Finnish monitoring sites monitored by Finnish environment institute (see Fig. S2 in Supplementary Information; https://tarkka.syke.fi/eo-tarkka/?ver=0&lang=fi), showed that cyanobacterial bloom barometer increased after 12 June. This was well synchronized with the 2–3 fold increase of MSA and IA concentrations. Along with the increasing abundance of algal blooms, sea surface temperatures also increase from the first week of June to mid-June (Fig. 9) which could have promoted the release of DMS and iodine from the exposed macroalgae surrounding the coastal station. DMS and iodine are produced by algae which act as precursor gases to form MSA and iodic acid after undergoing oxidation processes in the atmosphere (Thakur *et al.* 2022 and references therein). High iodine emission could be expected over the Baltic Sea region due to the presence of the macroalgal species which are well established and adapted there despite its low salinity (Kautsky & Kautsky, 2000, Schagerström *et al.* 2014). The rocky shorelines of the northern Baltic Sea, including those at Tvärminne, provide ample habitat for several species of macroalgae, including the bladderwrack *Fucus vesiculosus* (Kautsky & Kautsky 2000, Torn *et al.* 2006, Attard *et al.* 2019). Previous studies have documented that

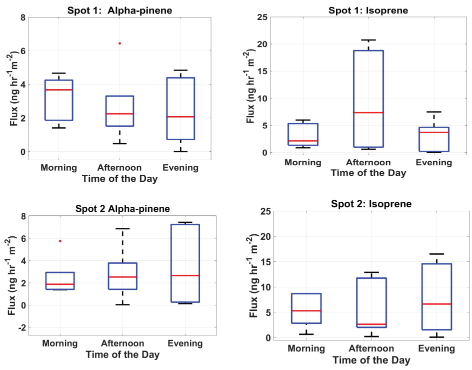

Fig. 11. α-pinene and isoprene flux at both the spots, Spot 1 with abundant macroalgae and Spot 2 with less macroalgae. The red line shows the median flux value, the upper end and lower end of the box demonstrates the 75th and 25th percentile, respectively. The whiskers show the variability in the data.

certain macroalgae contain high levels of iodine, of which the kelp *Laminaria digitata* stores the highest amount (Ar Gall *et al.* 2004, Küpper *et al.* 1998).

The dataset for HOM from the MION-CIMS was unfortunately not working optimally before December 2023, as it was influenced by water clusters. To present good quality data we chose to use the 2024 summer dataset for HOMs. DMS data was used from 2023 as during this time the Vocus PTR was working very well. Based on different air masses arriving at the site, different NPF events were noted during May-June 2024. 5-day back trajectories were plotted using global data assimilation system (GDAS) data and the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein *et al.* 2015). When the air masses were mostly marine, circling over the Southwestern Gulf of Finland and Northern basin of the Baltic Sea before arriving at the site, an ion burst was noted (Fig. 10). These bursts appearing at small sizes (2–4 nm) are indicative of local clustering processes in contrast to regional events, where it is possible to follow the growing particle mode for several hours (Dada *et al.* 2018, Dal Maso *et al.* 2005). Intense burst events are frequently observed at coastal sites accompanied with high concentrations of IA (O'Dowd *et al.* 2002, Rong *et al.* 2020, Sipilä *et al.* 2016, Thakur *et al.* 2022). Here we describe a burst event that was observed on 16 May 2024. During the start of the first burst event both SA and IA concentration increased to 12×10^6 cm^{-3} and 8×10^6 cm^{-3}, respectively, from a concentration of 2×10^6 cm^{-3}. A similar event was recorded near SMEAR III station in Helsinki during marine air mass intrusion when IA concentration was higher and/or equal to SA concentration indicating that marine emissions are capable of initiating local clustering of ions and can form aerosol particles which may or may not grow to climate relevant sizes (Thakur *et al.* 2022). We also note that no increase in the signal intensity of organic molecules was observed before or during the first burst (Fig.S3 a–b in Supplementary Information) but an increase in the signal of organic molecules during the second burst of particles (15:00–18:00 hrs, Fig. S3c in Supplementary Information) was observed. It could indicate that the evening burst was more driven by organics at the coast. Further investigation is needed on the molecular cluster composition of the organics and oxidative species would help to better explain the role of organics in the burst events at the coast.

However, when a regional event, where local clustering of ions leads to formation and growth of aerosol particles to climate relevant sizes (Dal maso *et al.* 2005) occurred on 7 May 2024 (Fig. S4 in Supplementary Information), the air arriving at the site was coming mostly from the land areas of northern Finland with only a few trajectories over the Gulf of Bothnia. SA concentration increases from 1.5×10^6 cm^{-3} to 5×10^6 cm^{-3} during the nucleation (9:00-12:00 hrs). The air mass analysis indicates a terrestrial source of SA during this event. The IA and MSA concentrations remained low throughout the event ($0.2–0.5\times10^6$ cm^{-3}).

Campaign Results — VOC flux measurements

The observatory is also a good site for intensive field studies to assess parameters that are not continuously measured at the site, as the field studies can benefit greatly from the supporting continuous observations. As an example of such a study, we performed a field experiment using floating

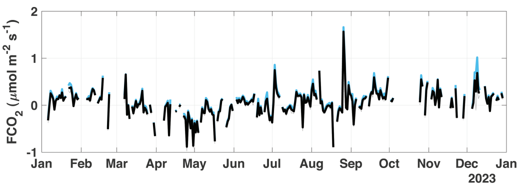

Fig. 12. Carbon dioxide fluxes at the coast from January–December 2023, calculated using the data from LI-COR sensors and eddy covariance technique. the blue line indicates random uncertainty of the flux estimated with the Finkelstein and Sims (2001) method. Black line indicates the daily average fluxes for each month.

glass chambers for VOC flux measurements over macroalgae and phytoplankton rich waters at the site from 30 May to 8 June 2022. Purified air was passed through the chamber and VOC samples were collected from the air exiting the chamber in Tenax TA-Carbopack B sorbent tubes which were later analysed using a thermal-desorption instrument connected to a gas chromatograph with a mass selective detector (Mäki *et al.* 2017, Helin *et al.* 2020). This method can provide a flux estimate from VOCs diffusing out from the water into the air, though care must be taken to measure also appropriate zeros given that VOCs can be emitted also from various materials as well as people handling the sample tubes. Two locations were selected for a pilot study: Spot 1 with more abundant macroalgae and Spot 2 with less abundant macroalgae. The sampling spots were selected by a visual inspection of the abundance of macroalgae. Each location was sampled in the morning, afternoon and evening over the sampling days to study diurnal variations. The uncertainty of the Tenax TA-Carbopack B sorbent tubes in the measurements ranges between 7–10% (Hellén *et al.* 2023). The limitation for using this offline sampling method is that it can be subjected to some contamination during the handling of the tubes if utmost care has not been taken, which can raise the absolute uncertainty range. The results showed highest flux for isoprene as compared to α-pinene in general at both the spots (Fig. 11). Median fluxes in the location with abundant macroalgae (Spot 1) for α-pinene was observed to be 2.6–4.0 ng hr^{-1}m^{-2} whereas for isoprene it ranged from 2.1 to 7.3 ng hr^{-1} m^{-2} (Fig. 11). However, the maximum values of fluxes for both isoprene and α-pinene was observed on this Spot 1 in the afternoon, with isoprene showing fluxes of 18.8 ng hr^{-1} m^{-2}. The spot 2 also showed high isoprene fluxes as compared to α-pinene, with median fluxes ranging between 2.6 to 6.6 ng hr^{-1}m^{-2}, with the highest median fluxes reported in the evening. The highest median fluxes at Spot 2 for α-pinene was 2.6 ng hr^{-1}m^{-2}, observed during the evening, however not varying much from the afternoon fluxes. Overall, fluxes of isoprene and α-pinene were quite similar between the two spots and between different times, which may reflect the fact that diffusion of these VOCs up to the surface (and further into the air) is a slower process than mixing of the water. We expect that the timescales relevant for diffusion of VOCs to the surface from where they can evaporate are long enough that the water may have time to flow and mix between areas, and therefore the VOC concentrations can reflect a larger emission area than simply the biology observed at the two spots. Further investigation on the sources, sea surface composition, ambient temperatures, and other processes influencing the biogenic VOC emission from the sea surface needs to be critically evaluated. Furthermore, the oxidation of these BVOCs in the atmosphere which could lead to the formation of HOMs is needed to link these emissions to aerosol formation at the TZS coast.

CO_2 fluxes and CarbonSink+ at the coastal site

The interest to study CO_2 fluxes from the oceans lies in the fact that they are responsible for sequestering approximately 1/4 of anthropogenic carbon emissions annually (Terhaar *et al.* 2022). Here we report CO_2 air-sea fluxes from January to December 2023 (Fig. 12), calculated using the data from LICOR sensors and eddy covariance technique, supported by the flux parametrization based on the wind speed measurements from the AF site (refer to Fig. 3). The flux footprint (given as 80%) extends to about 200 m upwind from the flux tower. The CO_2 flux shows that during spring the coastal region was a net sink of CO_2 whereas during summer and winter it was a net source. The growth of phytoplankton during the

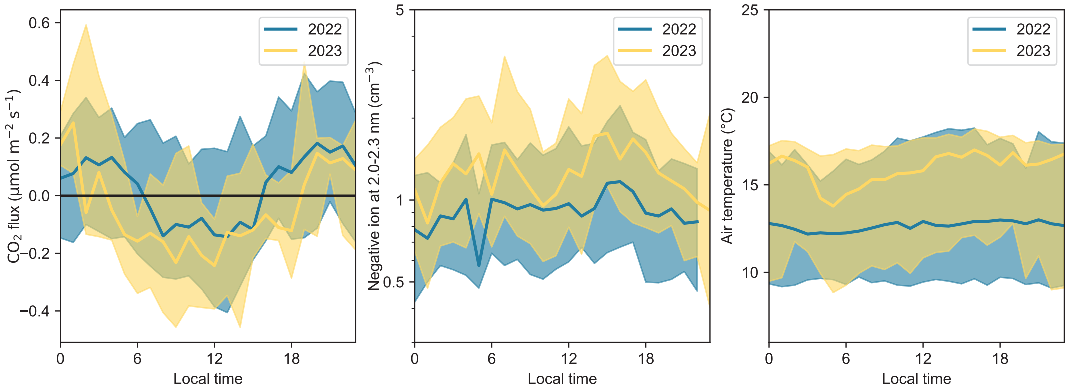

Fig. 13. The hourly data of CO_2 fluxes from eddy covariance measurement, negative ions at 2.0–2.3 nm measured by NAIS, and air temperature in the growing season in 2022 and 2023. The line and shadowed areas are median values and 25% and 75% percentiles, respectively.

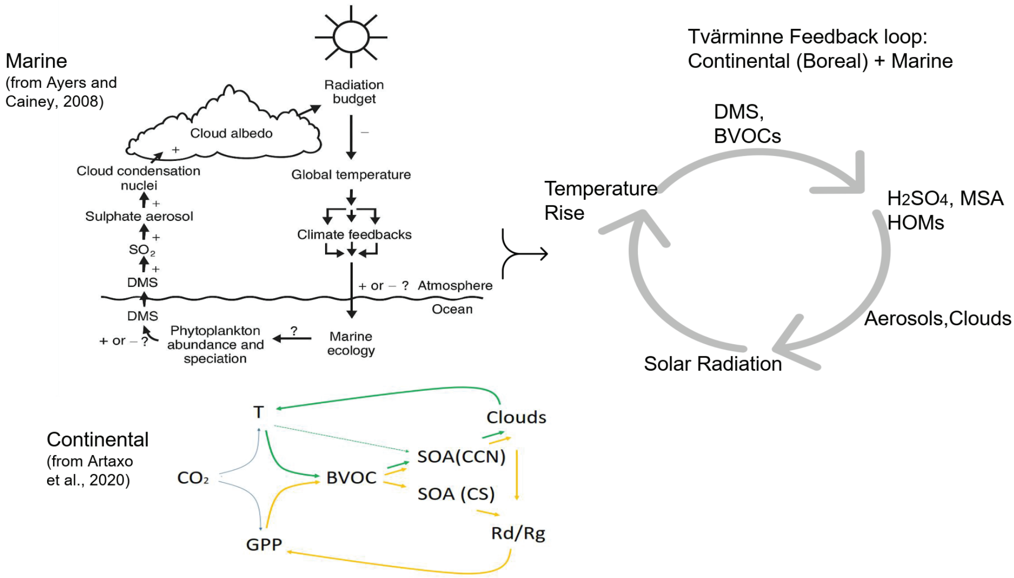

Fig. 14. Combining CLAW (marine) and COBACC (continental) feedback loop hypotheses towards Baltic Sea feedback loop.

spring reduces the partial pressure of pCO_2 in water, so a pressure gradient may develop at the air-sea interface, making the water in spring a net sink (Carvalho *et al.* 2021). However, during the summer and autumn the coastal region seems to transit to a net source. This change can be attributed to the mesoscale physical processes like mesoscale eddies, significantly influencing coastal dynamics, nutrient transport, and biological productivity (Ito *et al.* 2016) which can be quite complex in coastal regions. The complexity also extends to inland waters, where studies have shown that daily and seasonal variability of pCO_2 is high in lakes and rivers (Han *et al.* 2020, Xu *et al.* 2019, Yang *et al.* 2019), due to the strong influence of the ambient environment and river discharge (Marce *et al.* 2015).

We also studied CO_2 flux for two years (2022 and 2023) at the TZS station along with negative ion concentrations and ambient temperatures to understand the effect of growth season on the CO_2 fluxes and on local ion clustering in the atmosphere. If using a daily mean air temperature of 5°C for five consecutive days as a threshold for growing season, the growing season started in April and ended in October or November. There were 210 and 188 days of growing season in 2022 and 2023, respectively. During the growing season, the coastal area was a net CO_2 sink in the daytime (Fig. 13), at a rate between 0.0 to –0.2 µmol m^{-2} s^{-1}, which was much smaller than that in the boreal forest (Kolari *et al.* 2022) and open peatland (Alekseychik *et al.* 2021) in Finland, but close to that observed for macroalgae habitats on the island of Askö in the Baltic Sea (Roth *et al.* 2023). The nighttime CO_2 emission may largely compensate the daytime uptake. Apart from CO_2 uptake, other factors, e.g. aerosol production and albedo, can also influence an ecosystem's contributions to climate. These factors should also be included in evaluating net climate effects from ecosystems, i.e., the overall effect of CarbonSink+ (Kulmala *et al.* 2020). Negative ions in 2.0–2.3 nm size range are assumed as a relatively reliable proxy of local intermediate ion clustering and aerosol production (Kulmala *et al.* 2024, Tuovinen *et al.* 2024). In the growing season, the median values of the negative ion cluster concentration range between 0.5 and 1.7 cm^{-3}, distinctly lower than the inland ecosystems, such as forests and peatland (Kulmala *et al.* 2024). There were also annual variations of both CO_2 fluxes and local aerosol production. Accompanying the lower air temperature in 2022, the net CO_2 uptake rate and daytime negative ions concentration were both smaller than that in 2023.

Feedback loops

Observations at TZS are relevant for understanding of complex multidisciplinary problems and climate feedback mechanisms like the CLAW and COBACC hypotheses, both based on biosphere-atmosphere interactions. The activities at TZS station will generate data to connect both CLAW and COBACC loops to the regulation of global climate interlinked by aerosol formation (Fig. 14). It is well-known that both the sulphuric acid and HOMs play an important role in the formation and growth of aerosol particles over vast areas covered by boreal forest (Kulmala *et al.* 2013, Ehn *et al.* 2014, Garmash and Ezhova *et al.* 2024). The measurement results we show here also report the emission of BVOCs like isoprene and monoterpenes from the coastal waters. Further, the results also show that SA and organics can have increased concentration during particle burst events indicating local sources can have influence in particle formation which may or may not lead to growth of particles. These results from TZS can be connected to crucial climate variables, such as cloud characteristics, radiation and temperature, and further to ecosystem-related processes at the coast of Baltic Sea, completing the Baltic Sea feedback loop. So far, these feedbacks related to the sulphur cycle (CLAW) and biogenic emissions (COBACC) and related processes have been considered separately from each other especially at the marine sites. However, in the areas relatively near seas and oceans, the contribution of marine and continental sources to aerosol formation and growth are tightly linked. A recent study (Jonge *et al.* 2024) shows that DMS originating from the ocean has much larger influence on aerosol population (including CCN) at the forest stations in Sweden and Finland than previously thought. Therefore, a new approach emerges which suggests the combination of continental and marine factors in the feedback mechanisms (Fig. 14). Stemming from the aerosol-related parts of the COBACC feedback loop (Ezhova *et al.* 2018, Petäjä *et al.* 2022, Räty *et al.* 2023, Kulmala *et al.* 2023, Blichner *et al.* 2024), the ability of atmospheric aerosol to interact with solar radiation and clouds and strengthen ecosystems' carbon sink led to the concept of CarbonSink+ (Kulmala *et al.* 2020). Furthermore, there are different sources of aerosol particles in different ecosystems and represent different carbon sinks, the concept developed towards a broader one, CarbonSink+ Potential (Kulmala *et al.* 2024), which encompasses the ability of any ecosystem to serve as a carbon sink and produce aerosol particles, with the ultimate aim to understand and quantify the effect of different ecosystems on climate. The effect of local aerosol emissions from different ecosystems (boreal, marine, etc) on regional (and ultimately global) carbon uptake and their CarbonSink+ Potential is an

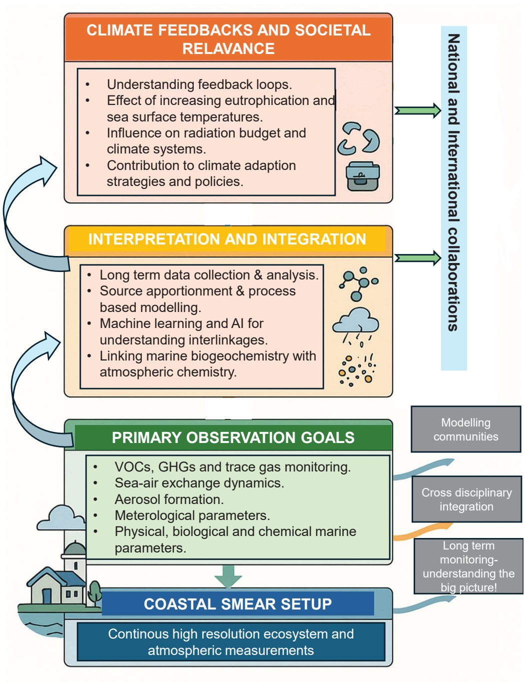

Fig. 15. Roadmap summarizing the station and observatory activities, goals and relevance.

important next step in climate science to which the research infrastructure at TZS aims to contribute.

Conclusions

There exists societal awareness of the big and very well documented impacts of climate change on the Baltic Sea and the global oceans. However, there is far less awareness and knowledge of the role of oceans and coastal regions impacting atmospheric composition and chemical processes, e.g. changed greenhouse gas exchange and aerosol formation with associated climate impacts (radiative properties, cloud formation etc). We have established a coastal SMEAR for continuous observations of the ecosystem-atmosphere interactions to address these challenges. We present some preliminary results on the emissions and related aerosol formation. With longer time series, we will be able to apportion concentrations measured at the station to their sources and source regions, e.g. between marine, coastal, and terrestrial sources. The data being collected will help to explain the impact of the changing Baltic Sea ecosystem (due to climate change and human activities) on greenhouse gas exchange, aerosol formation pathways, and feedback loops like CLAW and COBACC. The establishment of the coastal SMEAR could exemplify how the problem of eutrophication and sea surface temperature increase in the Baltic Sea not only alters habitat quality and ecological processes, but also influence the chemistry of the atmosphere above the oceans. From the local impact of sea upwelling (Lehmann *et al.* 2012) on carbon uptake and CO_2, CH_4 and VOC emissions to the regional impact of sea and forest emissions on formation of clouds over forest, and further on global climate — coastal-SMEAR provides an important convergence point for the study of complex atmosphere-sea interactions.

The sophisticated instruments and high-end facilities will provide us with enormous amounts of high-quality data to understand the long-term trends of VOCs, GHGs, organic gases, inorganic trace gases and aerosol formation pathways linked to the changing health of the Baltic ecosystem. The enormity of the data set generated with numerous complex interdependent variables generated within the air-sea system in Coastal-SMEAR will require the involvement of machine learning, artificial intelligence, and modelling approaches to resolve and understand the interlinkages of the various components of the marine and continental climate feedback loop (Fig. 15). In the future, we will involve diverse collaborations both from field measurement sites at national and global marine/coastal sites and modelling community to meet the environmental grand challenges (Fig. 15).

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Data accessibility: The recent data figures for meteorology, eddy covariance, aerosol size distribution data, trace gases data and water quality physical parameters can be downloaded and visualised from https://wiki.helsinki.fi/xwiki/bin/view/SMEAR/The%20SMEAR%20Wikispace/Tv%C3%A4rminne%20data/. The raw and archived datasets for above mentioned parameters can be requested by the author of this paper. In future more open data sets would be provided for free download from https://smear.avaa.csc.fi/.

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