Using Small Swarm-Capable AUVs for Submesoscale Eddy Measurements in the Baltic Sea

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***Abstract*—This paper presents an approach using small and swarm-capable autonomous underwater vehicles (AUVs) as flexible measurement devices for observing oceanic submesoscale eddies. The robots equipped with environmental sensors are placed near interesting oceanographic structures to measure the water column along different trajectories. The robots communicate acoustically while diving in a saw tooth pattern underneath the surface. This measurement strategy enables high-resolution sensor data on the one hand and a fast reaction to changing conditions in the observed region on the other hand.**

I. Introduction

Submesoscale surface dynamics influence the world's oceans in a considerable way and the effects from generation to decay of small eddies are still object of research. For large scale investigations, satellite altimetry measurements of ocean surface topography are used to understand global relations. Furthermore, the synthetic aperture radar (SAR) serves as a usual measuring device to study oceanographic structures with a diameter as small as 1 km over long-term time series, but they do not provide enough dynamically relevant information [1], [2]. Hence, flexible towed and ship-mounted instruments as well as X-Band radar are used in addition to perform in-situ measurements but needed ship-times are very expensive [3]. Therefore, autonomous underwater vehicles (AUVs) are becoming more important for tasks in the field of autonomous investigations. Regularly available robot platforms such as the Slocum Glider [4] or the REMUS AUV [5] have benefits regarding robustness and equipped payloads, but are big in size and it is not possible to react to rapidly changing conditions fast enough while investigating small turbulence eddies. Thus, this paper presents an approach to use small, swarm-capable and fast AUVs for observing oceanic submesoscale eddies to overcome the limitations of ship-based measurement devices and to achieve an investigation strategy to cover a larger area in a short time period.

II. Expedition Clockwork Ocean

In order to better understand the importance of submesoscale eddies and fronts for the ocean's energy cascade from global scales down to turbulence as well as their likely significant role in phytoplankton production, the Expedition Clockwork Ocean was carried out in Danish waters between the islands of Bornholm and Usedom in

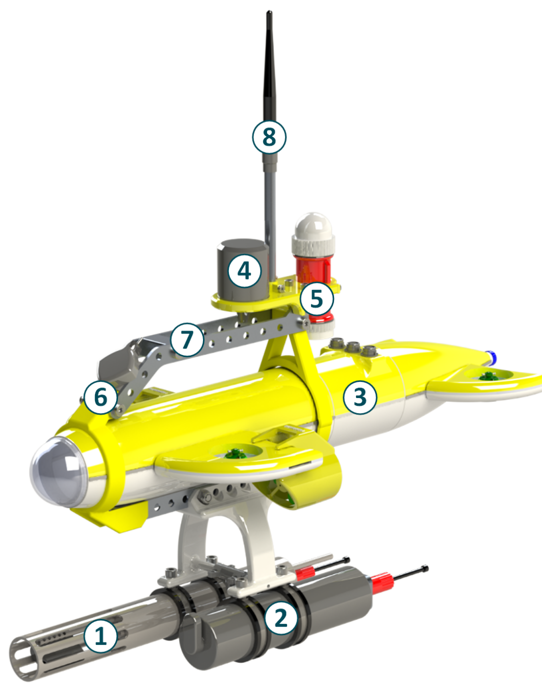

Fig. 1. Monsun Underwater Robot equipped with the expansion set suitable for open sea missions as part of the Expedition Clockwork Ocean. Its extended with an interface module (3) to connect a CTD probe (1) and an acoustic modem (2) underneath the robot. At the top an aluminium handle (7) for releasing and recovering the robot from a ship is mounted. Furthermore, the acoustic transducer (4) a flashlight (5) a GPS antenna (6) and a large WiFi antenna (8) are linked to the handle.

June 2016 [6]. The aim was to find submesoscale eddies and provide high-resolution remote sensing data from an airplane and airship (Zeppelin NT) thus complementing and guiding in situ observations with 4 vessels and additional AUVs. The resulting resolution is on the order of a few metres and minutes simultaneously allowing to observe eddies repeatedly from generation to decay. Several different instruments were used on various platforms to detect the ocean's stratification and potential energy, the kinetic energy, as well as biogeochemical parameters and phytoplankton distribution.

During the Expedition, a motor glider equipped with infra-red cameras localized interesting structures at the ocean surface from the air and based on this information an airship was sent to the most promising ones. The Zeppelin NT was equipped with infra-red and hyper-spectral cameras and used for stationary measurements above the eddy or submesoscale structure. It could measure temperature fluctuations within $0.03\,°\mathrm{C}$ on the surface and transmit the data to all other members of the expedition in real time. With the help of this information, the development and behaviour of the measured eddy can be studied on the one hand and the various research vessels can be guided to interesting points on the other hand. First, the vessels set non propelled measurement buoys adrift, which follow the currents in the area and record sequential GPS positions every second. The ship based measurements are enriched with radar and ADCP data. To achieve a view under the surface and to survey the water column inside submesoscale eddies, various types of sensors are combined in towed instrument chains. The instruments are attached to the chain at ten levels of depth and measure temperature, salinity, oxygen concentrations and chlorophyll. A depressor weight is attached at the lower end, which pulls the chain downward even at the considerable speed of $10\,\mathrm{kn}$ and keeps it at a depth of up to $50\,\mathrm{m}$. The towed instrument chain measures how much potential energy exists in the eddy and how micro algae are influenced by it. Additionally, a Scanfish at the end of one instrument chain allows for depth adjustments of the full chain to change the orientation of sensors and spatial resolution.

For autonomous measurements, MONSUN AUVs and Slocum Gliders were additionally inserted in the centre of the water feature. The gliders equipped with similar sensors followed trajectories slowly through the area and recorded full data profiles for the whole measuring day. Respectively, the MONSUN AUVs were placed in the centre of the eddy and operated as an experimental robot team to measure different trajectories with changing depth and velocity values. Hence, a swarm of AUVs can be seen as a modular extension of a towed instrument chain. The robots orientation can be changed due to wireless and acoustic communication immediately and thus ship costs could be minimized.

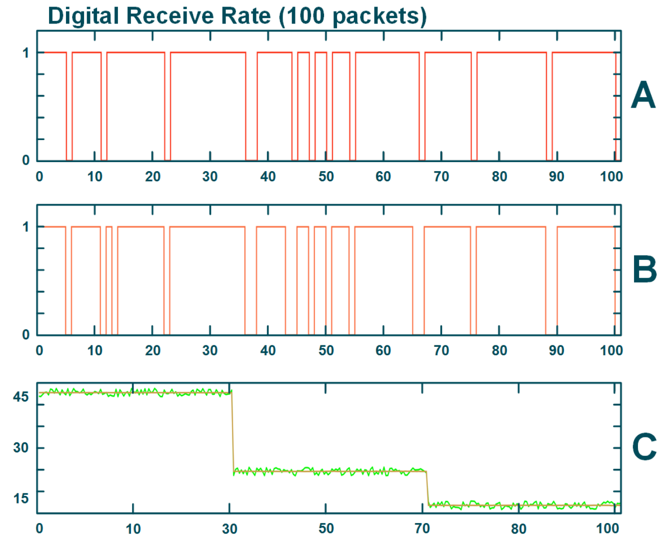

Fig. 2. Reliability tests of the communication channel and accuracy of distance measurements conducted in a local waterbody. Two AUVs were fixated in three different scenarios with distances ranging from $45\,\mathrm{m}$ down to $10\,\mathrm{m}$. The plots A and B display the digital receive rate from messages from MONSUN 1 to MONSUN 2 and respectively vice versa over 100 packets. Plot A shows a receive rate of $87\,\%$ and plot B a rate of $83\,\%$ with no noticeable difference in regard to the three different distances. Plot C shows the measured Distance in green color in regard to the absolute distance between the AUVs. The mean square error is hereby 0.29 with the biggest outlier being $0.49\,\mathrm{m}$.

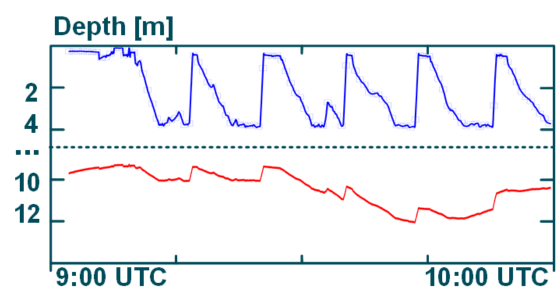

Fig. 3. The MONSUN AUVs traverse an observed path given by information from the airship above. The robot at the surface specifies the path on the basis of GPS positions and communicates course and desired depth values to the submerged robot acoustically. Under water, the AUV follows in a sawtooth pattern down to $4\,\mathrm{m}$ to measure the entire water column. The plot at the top shows the depth values in blue measured by the diving robot and the distance between the two robots in red recorded by acoustic communication. Together, a distance of $896\,\mathrm{m}$ was covered with an average speed of $1.1\,\mathrm{kn}$ without moving apart.

III. MONSUN UNDERWATER ROBOT

The investigations of small oceanographic structures require flexible possibilities to insert sensor devices in the area of application. The environmental data has to be enriched with precise position estimations and the short lifetime of small turbulence eddies demands a fast deployment and propulsion of robots. To meet the mentioned requirements, the MONSUN AUVs designed by the University of Lübeck were used and further developed for this mission. The robot has a modular design and is thus adaptable to a large field of tasks in environmental monitoring and inspection missions [7]. The swarm-capable MONSUN robot is with a length of $80\,\mathrm{cm}$ small in size and able to follow trajectories autonomously on its own or in a team. With a weight of $8\,\mathrm{kg}$ it is easy to handle by one person and needs no extra equipment to place it in the mission area. The hull is made from fibreglass reinforced plastics and is pressure resistant down to $100\,\mathrm{m}$. For propulsion, it uses four brushless motors for vertical and two for horizontal movements while diving with a positive buoyancy. With the help of two bajonette closures, the interior of the robot is easily accessible in a short time period. As main controller a 64 bit Quad Core ARM Cortex-A53 running a Linux Ubuntu operating system is used, which enables to program the robot with the help of the Robot Operation System (ROS). The battery capacity up to $60\,\mathrm{Wh}$ allows for an operation time up

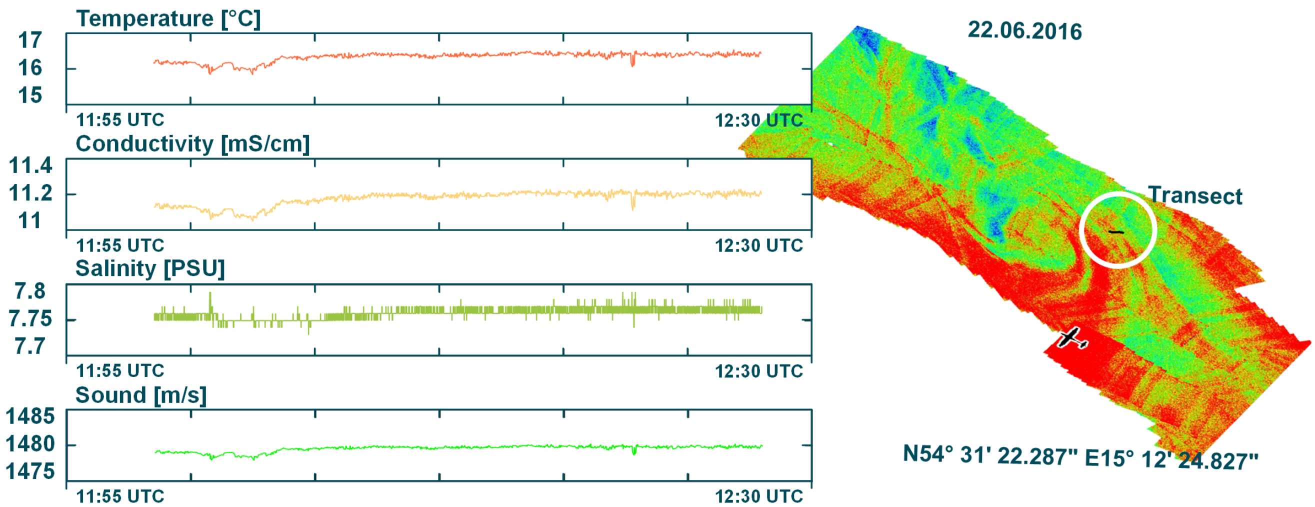

Fig. 4. Results of the first measurement day 60 km south of Bornholm. The airship discovered an spiral eddy with a diameter of more then 3 km and a first test run with one MONSUN robot was performed. An IR image provided by the airship of the area of investigation is depicted at the right. A distance of 360 m at the edge of the eddy was measured while driving with a velocity of 0.4 kn against the current. Temperature and conductivity fluctuations at the beginning were recorded, thus proving the first successful operation of the AUV. Measured speed of sound allows for simultaneous distance measurements.

to 5 h with an average speed of 1.5 kn. The robots feature a modular design and were adapted easily to the requirements of the *Clockwork Ocean* expedition [8]. The Figure 1 illustrates a robot equipped with an expansion set suitable for open sea missions. In the centre of the robot an interface module is placed to supply waterproof plug-in locations for external devices. It is used to integrate a CTD probe and an acoustic modem. The modem achieves a data rate of up to 13.9 kbit/s and operates in a frequency band from 18 to 34 kHz which enables underwater communication to coordinate the swarm on the one hand and an online data transmission to the surface on the other hand. Especially under rough sea conditions, it is complicated to insert small AUVs near a ship to place them in the area of application. Therefore, the MONSUN open sea expansion set contains an aluminium handle at the top to snap in a boat hook for safe release and recover of the robot from a boat with high bulwark. At the end of the handle a flashlight and a large WiFi Antenna are mounted at the top for better reception. Furthermore the GPS antenna is placed at the top of the so called tower enabling a good signal reception rate while driving at the surface under rough conditions. All in all, the expansion set allows for an open sea application of the robot which is used as an upgrade for the conventional measuring devices of the Expedition Clockwork Ocean.

IV. EXPERIMENTS

After receiving geo-referenced infrared image data taken by the Zeppelin or the airplane Stemme, the MONSUN deployment boat heads to the vicinity of the area of interest. A graphical user interface is meanwhile used to plan missions on sea charts. A set of waypoints can be assigned to the MONSUN AUVs along with parameters like total mission time. In order to simplify the planning task, the sea charts can be overlayed with IR image data. Based on the temperature gradients and the direction of movement observed from the overlays, the operator is planning a transect. The waypoints of the transect are assigned to one MONSUN AUV. After deployment the robot is navigating to the waypoints on the surface via GPS localization. Meanwhile a CTD probe is used to gather essential data for oceanology such as conductivity, temperature, depth and resulting values like density. However, this surface information is of lesser interest, as the IR imaging and radar data is already providing a lot of data. A second MONSUN is therefore supposed to follow the surface AUV on a submerged path to provide data of the below water layers. A simple submerged transect is albeit supplying only data for a single layer. Hence, the submerged MONSUN is adjusting diving depth in a sawtooth pattern. The AUV is then surveying the complete transverse section for a given maximum diving depth. For each diving depth the data can be interpolated between sample points later. This strategy results in more spatial information, despite using only one additional survey vehicle, with the drawback of lesser temporal resolution for a specific water layer.

A big challenge of this approach is following the surface MONSUN and to accurately geo-reference the gathered data since the submerged robot is not able to use GPS localization. Relying solely on dead reckoning navigation will result in high misalignment between the two AUVs. Due to sensor drift and signal noise of the used IMU, navigation gets increasingly more inaccurate the longer the traveled distance. The nature of the mission introduces another issue. Eddys or similiar oceanographic structures can move in unpredictable ways and might force the operator to make adjustments to the mission like planning new transects. Using for example a glider to survey the structure might therefore prove ineffective due to

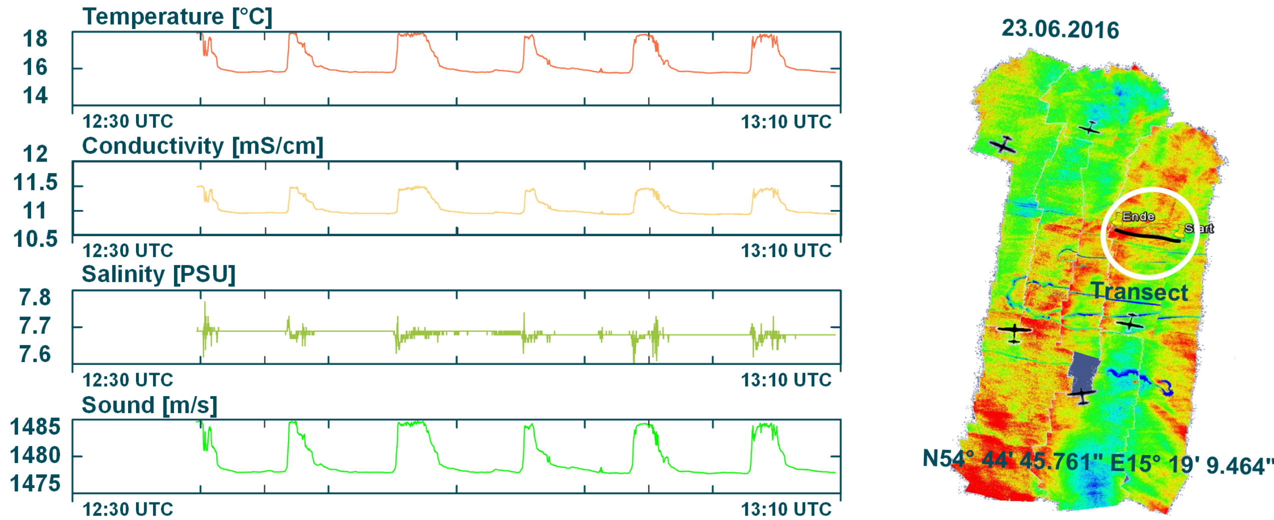

Fig. 5. Results of the second measurement day $37\,\mathrm{km}$ south east of Bornholm. A cyanobacteria bloom together with a large temperature front at the edge of a large eddy was discovered by the airship. Two robots performed various measurement runs through the discovered front and a combined distance of $1896\,\mathrm{m}$ with a velocity of $1.5\,\mathrm{kn}$ were travelled. The second robot followed the first robot in a distance of $10\,\mathrm{m}$ and performed a sawtooth pattern down to a depth of $5\,\mathrm{m}$, which can be easily seen in the plots on the left.

long mission time caused by the low velocity of the vehicle. Acoustic communication was therefore chosen to allow mission adjustments to the submerged AUVs. The acoustic communication channel is lossy and features low bandwidth data transfer. Upon receiving an acoustic data set, an acknowledgement is sent back to the origin of the message. Thus, the AUVs have better means to discern the correct propagation of messages. The low bandwidth is still enough to provide other AUVs with useful meta-data about the current mission to improve the follow behaviour and allow for adjustments of the mission. In addition to sending data, the acoustic communication can be used to measure the distance between communication partners in a point-to-point scenario. By measuring the round-trip-time of the acoustic signal and using the data of the CTD probe to determine the sound velocity underwater, an accurate distance can be calculated. Tests to determine the reliability of the communication channel and the accuracy of the the distance measurements were conducted in a local waterbody. In the test two AUVs were fixated in three different positions. In the first scenario the distance was set to $45\,\mathrm{m}$, in the second to $25\,\mathrm{m}$ and in the third to $10\,\mathrm{m}$. Upon receiving a message a response is sent at once. For a set of 100 packets sent for each scenario the average message receive rates were determined. Figure 2 shows the digital receive rate from MONSUN 1 to MONSUN 2 in plot A and vice versa in plot B. In the first case, the average receive rate was $87\,\%$ and in the second case $83\,\%$. The three different distances were not noticeably influencing the receive rates. Receive rates of above $80\,\%$ are high enough to warrant a periodic exchange of meta data between the AUVs. The accuracy of the measured distances is displayed in plot C. The green line represents the measured distances in regard to the absolute AUV distances. With a mean square error of 0.29 and the biggest outlier being a difference of $0.49\,\mathrm{m}$ the measurements are highly accurate when compared with the accuracy of basic GPS localization. When surveying an oceanographic structure, the acoustic communication is used to aid the submerged AUV. Meta-data like the current heading of the surface AUV and the maximum diving depth of the sawtooth-pattern are send. This information improves the follow behaviour and allows for adjustments or even cancel the current mission. Meanwhile, the distance measurements are used to minimize the displacement of the two AUVs with a PID controller. If the the robots move too far apart, speed and course adjustments can be made to correct the distance between the robots. Figure 3 displays the sawtooth pattern of the submerged AUV as the blue line while also showing the inter-AUV distance in red. The two MONSUNs traversed a planned transect based on IR image data of the airship. On the surface, navigation is conducted based on GPS positions and mission data is sent to the submerged AUV via the acoustic channel. Underwater, the second MONSUN followed in a sawtooth pattern down to a depth of $4\,\mathrm{m}$ in order to survey the water column. The desired inter-AUV distance was set to $10\,\mathrm{m}$ with the biggest outliers being around $\pm\ 2\,\mathrm{m}$. The data was recorded for a course distance of $896\,\mathrm{m}$ with an average AUV velocity of $1.1\,\mathrm{kn}$.

V. RESULTS AND CONCLUSION

The Expedition Clockwork Ocean was carried out in Danish waters south of the island of Bornholm in June 2016 with an overall expedition time of 10 days. Due to changing weather conditions and the airships sensitivity to strong winds, a total number of five measurement days were performed. The MONSUN AUVs were deployed on three days during this time period and a large data set with CTD, GPS po-

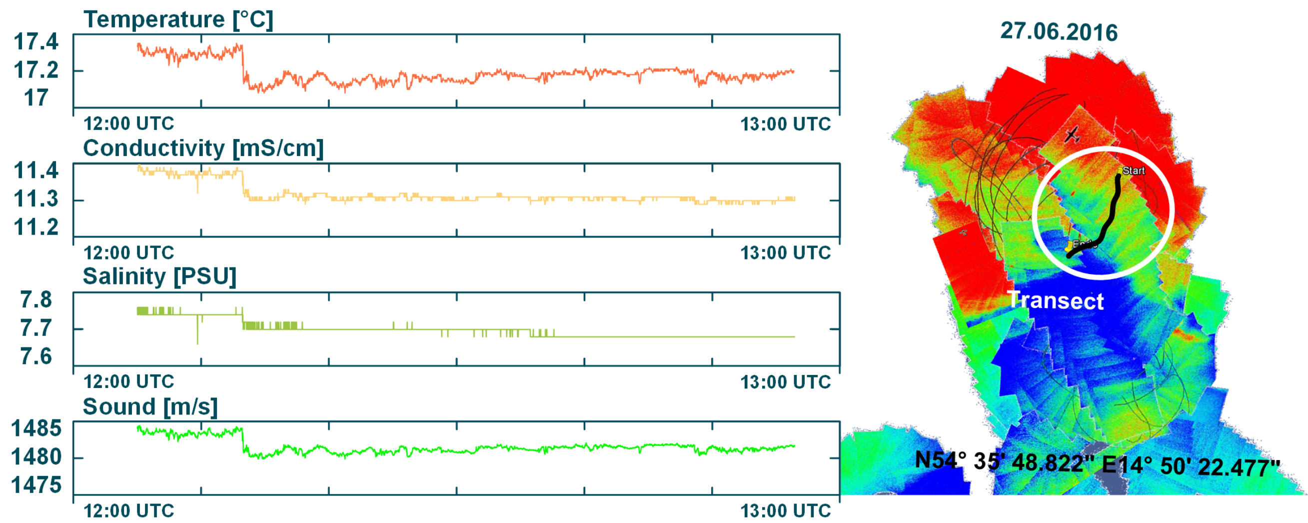

Fig. 6. Results of the third measurement day $55\,\mathrm{km}$ south of Bornholm. During a time period of $12\,\mathrm{h}$ a full lifetime of a small spiral eddy was investigated from generation to decay. The MONSUN robots performed measurements runs in the centre of the eddy and traversed together a distance of $896\,\mathrm{m}$ with a velocity of $1.1\,\mathrm{kn}$. The drop in the measured environmental data indicate the crossing of an oceanographic front associated with a filament of the eddy.

sitioning and acoustic communication data was gathered by three robots. At the first measurement day with contribution of MONSUN AUVs a large rotating spiral eddy was found $60\,\mathrm{km}$ south of Bornholm. Figure 4 illustrates an infra-red image delivered by the airship of the area of investigation and plots of the measured CTD data of the surface AUV. Highlighted in the IR map is a small transect travelled by the AUVs. The first test run was used for adapting the system to the currents and conditions in open sea eddies. Therefore, the robots travelled with a comparably slow velocity of $0.4\,\mathrm{kn}$ and covered a short transect of $360\,\mathrm{m}$. Nevertheless, temperature and conductivity fluctuations at the beginning were recorded, thus proving the first successful operation of the system. The second operation was performed a day later only $37\,\mathrm{km}$ south east of Bornholm. Easily seen from the airship, a cyanobacteria bloom together with a sharp temperature front at the edge of a large eddy was discovered. Depicted in Figure 5 is one transect in black travelled through the front, which is recognisable as a red corridor in the IR image. After analysing the first operation a day earlier, the robots behaviour was improved and a combined distance of $1896\,\mathrm{m}$ with an average velocity of $1.5\,\mathrm{kn}$ was covered. A second robot followed the MONSUN at the surface in a depth of $5\,\mathrm{m}$ while holding a distance of $10\,\mathrm{m}$. The sawtooth pattern can be seen in the plotted CTD data in the left of Figure 5 as well. The data proved that the temperature front is not only at the surface near the swimming cyanobacteria, but rather recognisable in a depth of $5\,\mathrm{m}$. The last measuring day with contribution of MONSUN robots was the 27th of Juni. At this day a full lifetime of a small spiral eddy was investigated from generation to decay $55\,\mathrm{km}$ south of Bornholm. Here, the robots travelled a combined distance of $896\,\mathrm{m}$ with a velocity of $1.1\,\mathrm{kn}$ and the CDT data together with the IR image illustrated in Figure 6 indicate a crossing of an oceanographic front associated with a filament of the eddy.

Finally, this paper presented the autonomous underwater robot MONSUN and its successful operation as part of the Expedition Clockwork Ocean for submesoscale eddy measurements in the Baltic sea. Various measurement runs were performed and a large data set supporting the investigation of this ocean phenomenon was collected.

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