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Tidal benthic mesocosms simulating future climate change scenarios in the field of marine ecology

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Abstract

Increasing human activities cause local to global changes in sea surface temperatures, ocean acidity, eutrophication, and rising sea levels. Many laboratory experiments investigate the effects of these regime shifts on single species and single stressors, showing variable responses within and among species, while different combinations of stressors can have synergistic, additive or antagonistic effects. Large-scale multi-species and multi-stressor experiments can more reliably predict future ecosystem changes. A unique mesocosm facility was developed and set up at the AWI Wadden Sea Station – Sylt, Northern Germany to investigate the particular effects of future climate changes on predominant marine intertidal communities. Each of 12 benthic mesocosms serves as an independent experimental unit with novel techniques of tide and current simulations as well as multi parameter measurement systems to simulate multi-factorial climate change scenarios including the combination of warming, acidification, nutrient enrichment, and sea level rise. Temperature, pH, oxygen, and salinity can be continuously monitored and logged, while discretely collected samples of total alkalinity, light availability, chlorophyll *a* (Chl *a*), nutrients and seston supplement these online datasets. Herein we demonstrate the functionality of the new benthic mesocosm system including first experimental results on the responses of *Fucus vesiculosus forma mytili*, and its associated community to the combination of warming, ocean acidification, and increased nutrient enrichment.

Due to increasing human activities, especially by burning fossil fuels, our climate is changing at an accelerating rate, leading to a global impact on the abiotic and biotic components of the marine ecosystem (Field 2014). To direct political decisions and actions on a local as well as global scale, one of the most important aims of research is to reliably predict future ecosystem changes and its implications (Derous et al. 2007). Trustworthy information is, however, not only very urgently needed but also very challenging to obtain due to complex interactions within and between the closely related abiotic and biotic components of a system (Wahl et al. 2011).

Many investigations have been undertaken in the field of climate change research, however most of these experiments were run in laboratory settings, mainly with single species and single components of climate change, i.e., single stressors (Harley et al. 2006; Walther 2010; Wernberg et al. 2012). Their often restricted realism makes extrapolation to the natural situation problematic (Stewart et al. 2013). While field observations (Kowalski et al. 2009; Winde et al. 2014) or field experiments (Campbell and Fourqurean 2011) can reveal important information in a more realistic way and with a higher bio-complexity on the community level, they are more an observational point of view where directed and precise manipulation of the system is difficult. They tend to be impractical for experimental handling, less controllable and have a low potential to reliably predict future consequences. This unavoidably generates a trade-off between space, time and the complexity in the different experimental approaches. Mesocosms have the potential to close the gap between these two approaches and are recommended as an effective tool for more reliable, near natural climate change experiments at the community level (Stewart et al. 2013).

Mesocosms are large enough to enclose a particular proportion of a natural community with the ability to investigate biotic interactions and biogeochemical processes under controlled experimental conditions with the advantage of true replication. Moreover, they allow an interdisciplinary way of addressing research questions, bringing together different disciplines within one facility, e.g., marine ecology,

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Fig. 1. Overview of the Sylt benthic mesocosm facility, showing the 12 tanks during the Summer-2014 experiment.

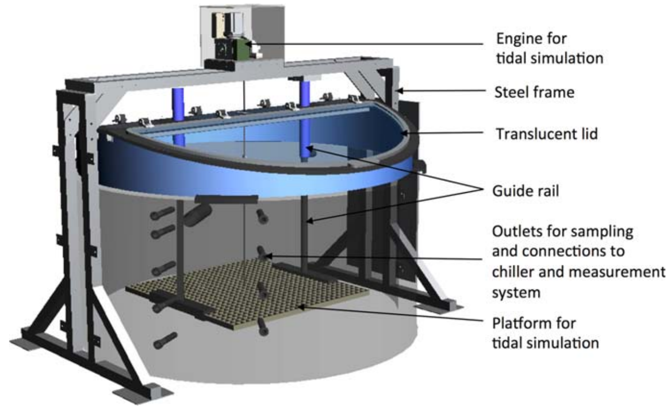

Fig. 2. Schematic of a single mesocosm unit with its components.

physiology, biogeochemistry or molecular biology. Only few constraints reveal in mesocosm experiments. Confounding factors such as lower light availability, wall effects, limited space as well as the exclusion of higher trophic levels likely influencing trophic interactions (Mine Berg et al. 1999; Petersen and Berg 2009). Another important constraint in many available mesocosm facilities to date is the lack of tidal and current simulations, with possible non-natural implications for tidal communities such as extended periods of submersion, reduced water mixing and constant grazing pressure. Despite these few constraints, mesocosms remain a valuable tool for climate change experiments at the community level and can contribute important information that cannot be provided by any other approach (Hendriks et al. 2010; Yvon-Durocher and Allen 2012; Wahl et al. 2015). Considering the great potential of benthic mesocosm facilities within the field of climate change research, very few facilities exist and even fewer are equipped with continuous monitoring systems.

Here, we demonstrate the setup and functioning of the newly developed benthic mesocosm facility at the AWI Wadden Sea Station Sylt, Germany, with a novel integrated tidal and current simulation system and a multi parameter measurement system (MPMS). We present all single hardware compartments, possible manipulation of the different physical parameters as well as physico-chemical data obtained during the first experiments ran in 2013 and 2014. With its new developments this facility has a great potential to investigate the effects of multiple stress scenarios at the community level within a near natural setting to predict more reliably future consequences of climate.

Materials and methods

General set up

The mesocosm facility was set up in August 2013 outdoors on solid ground next to the AWI Wadden Sea Station on the Island of Sylt (55°01′19.2″N, 8°26′17.7″E; Fig. 1). It consists of 12 round tanks, made of UV stabilized high-density polyethylene (HDPE; Spranger Kunstoffe, Plauen, Germany). Each of 12 tanks serves as independent experimental unit. Hull and bottom of each tank has a double wall construction, insulated with 10 cm of Styrofoam to increase energy efficiency and to be independent from exterior air temperature fluctuations. Each tank has an inner diameter of 170 cm and is 85 cm high, with a net water volume of 1800 L.

The outdoor facility is constantly exposed to ambient light conditions. To avoid an introduction of unwanted material such as air-transported dune sand or bird faeces, and to maintain a constant atmospheric O_2 and CO_2 pressure in the headspace, each mesocosm is covered with a translucent lid (Fig. 2), allowing 90% of the photosynthetically active radiation (PAR) to penetrate (LI-250, LI192-SA Quantum Sensor, LI-COR, Lincoln, Nebraska, U.S.A.). The lid is constructed of HDPE and translucent double wall polycarbonate with a slope of 22% to avoid accumulation of condensate, rain and dirt.

All tanks are supplied with non-filtered seawater from the AWI Wadden Sea Station facilities (Fig. 3). Seawater is pumped from 50 m offshore via a storage tank in four subsequent 1000 L tanks, which are located in the second floor of the institute. From here the seawater falls by gravity to the mesocosm facility. The residence time in the storage tanks is around 5 h and result in reduced sediment loads, preventing an undesired accumulation of sediment in the experimental tanks. The Sylt mesocosms can be run as closed or open systems with an adjustable flow through volume of 1–3000 L per day. The wastewater is directed back into the sea. Water samples can be obtained through the sampling outlet in the tank wall of each tank at around 40 cm depth (Fig. 2).

Manipulation and monitoring of environmental parameters is computer controlled. Information technology (IT) facilities are installed in a container next to the mesocosms. A multi parameter measurement system (Fig. 4a–c) continuously monitors temperature, conductivity, pH and dissolved oxygen. For service works in the tanks during an experiment,

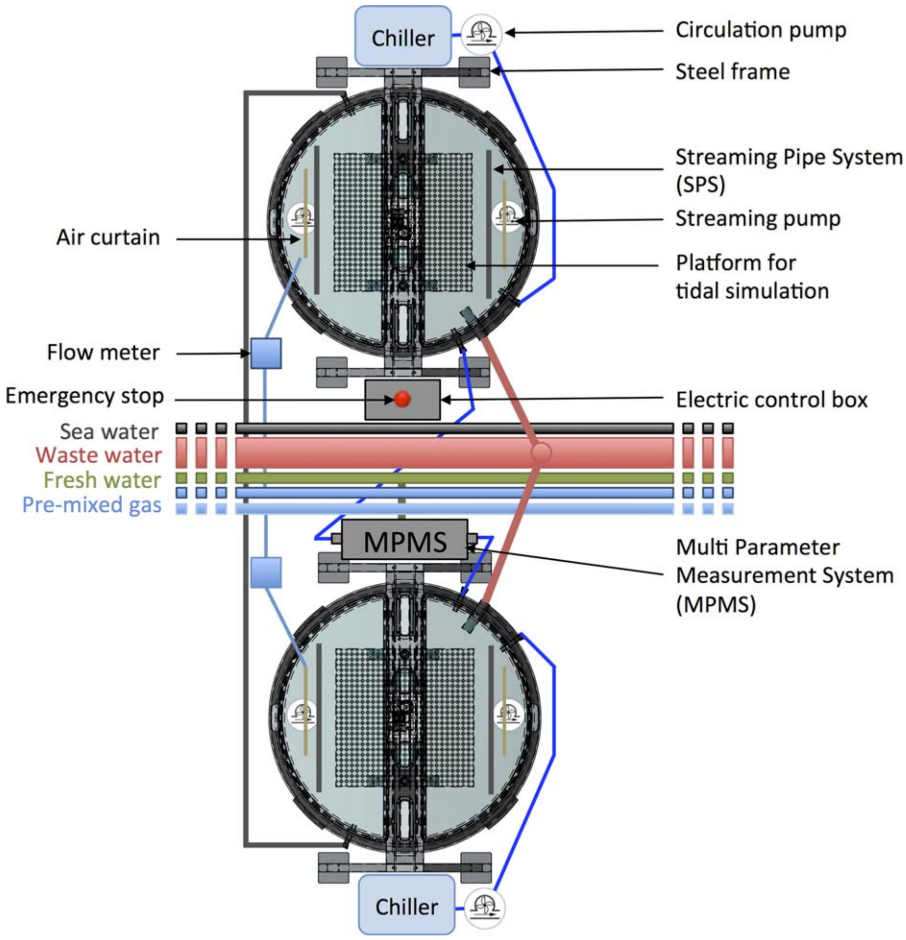

Fig. 3. Schematic overview of one of the six mesocosm tank pairs with their components and connections.

all electric loads with 220 V can be switched off for each pair of tanks, separately. One of the main components, the tidal simulation system, simulates changing water level and changing current direction simultaneously in each tank (Fig. 5). A CO_2-mixing facility, heaters and coolers, as well as the tidal simulation system allow the simulation of diverse climate scenarios.

The system is reliably operated in all but the harsh winter months due to the possibility of damages from severe temperatures ($< -5°C$). In some parts of the system the water is not continuously flowing as the chance of freezing may negatively affect or even damage the system.

Tidal simulation system

The computer-controlled tidal simulation system (Fig. 5) consists of two parts, the first simulating changing water levels and the second changing the current situation during changes from high to low tide and vice versa. The tidal rhythm can be set as sinus or straight function.

To simulate changing water levels, a 1 m^2 grating platform (glass-fibre reinforced plastic, GRP), on which the organisms can be planted, is lifted up and down in the water column, with a constant volume of water in the tanks (Fig. 2). A wire cable and a 220 V engine (Spranger Kunststoffe, Plauen, Germany), attached to a massive steel frame, are constructed to lift the platform with weights up to 250 kg (Fig. 2), allowing work with sediments, stones or other heavy substrates. A guide rail stabilizes the up and down movements of the platform (Fig. 2). The maximum tide range can be set from 0 cm (low tide, no water) to 70 cm (high tide) and the platform is moved stepwise (e.g., for a 6 h tidal period from 0 cm to 60 cm: 1 cm every 6 min). Amplitude, time and type of tide can be regulated with the software without additional mechanical adjustments. Emergency stop buttons are installed between each pair of mesocosms and stop the tide simulation engine immediately in case of problems.

The naturally occurring tidal currents are simulated with the second part of the tidal simulation system. To produce a streaming, which is evenly distributed over the whole water body, two streaming pipe systems are opposing each other in the tanks (Fig. 5). Each system consists of a 60 × 110 cm pipe grid of six horizontal and two vertical PVC-U pipes

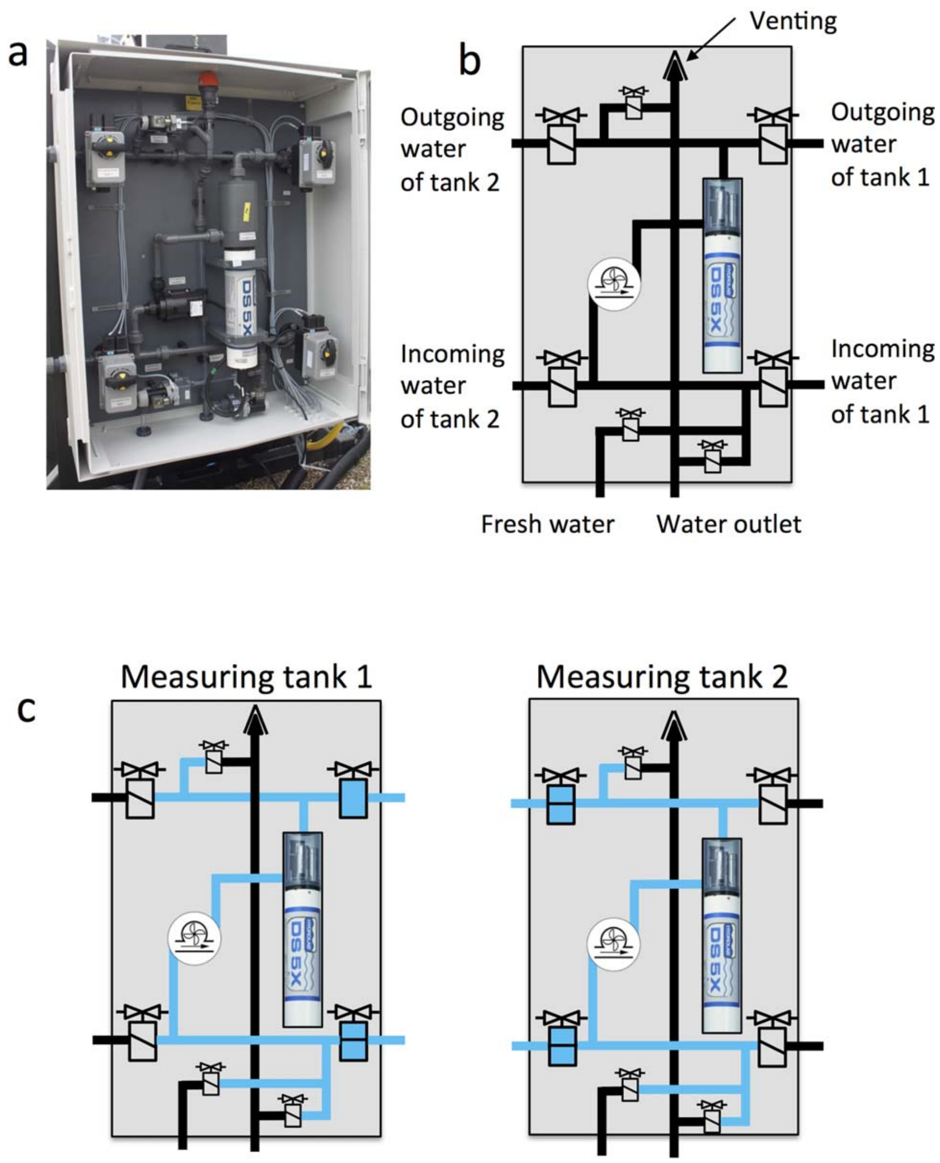

Fig. 4. Foto (**a**) and diagram (**b**) of the multi parameter measurement system and (**c**) an illustration of the alternating pathways for water while parameters of one of the tanks are measured.

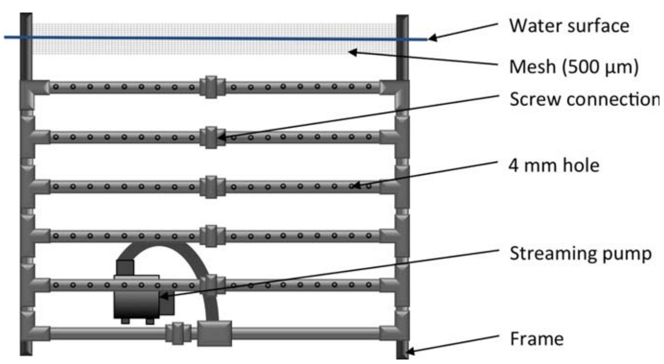

Fig. 5. One of two streaming pipe systems, which are installed opposite to each other in each mesocosm.

(20 mm diameter; Georg Fischer Piping Systems, Schaffhausen, Switzerland). Screw connections in the middle of each pipe allow easy cleaning of the system. Through a total number of 125 holes (4 mm diameter) in the grid, a directed and evenly distributed stream of water (Eco Runner 12000, Aqua medic, Bissendorf, Germany; pumping capacity of 12,000 L per hour) is produced for every vertical position of the grating platform in the water column. To achieve this, the pump is connected to the lowest pipe of the streaming pipe systems where the highest ambient water pressure is present. At the bottom of the tank the high pressure of the pump compensates the high ambient water pressure, while near the surface the pressure of the pump, as well as the ambient water pressure is reduced. This creates almost the

same current velocity by each single pipe. The current velocity produced is around 10 cm/s, measured in the middle of the tank without any biota (Flo Mate 2000, Hach/Marsh Mc Birney, Loveland, U.S.A.). Direction of the current changes with tides and the round shape of the tanks ensure that reflected water runs back along the walls of the tank without interfering with the investigated communities.

Multi parameter measurement

Each two tanks share one Multi Parameter Measurement System (MPMS; Fig. 4a,b). The system consists of a Hydrolab DS5X Probe (OTT Messtechnik GmbH, Kempten Germany), which continuously measures temperature, conductivity, pH and dissolved oxygen. Water is pumped (Eco runner 2700, Aqua Medic, Bissendorf, Germany) from either tank 1 or 2 through the measurement chamber of the Hydrolab DS5X back into the tank. The water gently passes by the sensors in the measurement chamber and a value for each parameter is logged every minute. Electric ball valves and magnetic valves enable the switch between tank 1 and 2 (Fig. 4c). To avoid a mixing of the water between the two tanks and to avoid a fast growing biofilm affecting the sensors, the system is completely emptied and flushed with fresh water between each switching interval, with the use of magnetic valves. Time intervals for measurements in each experimental tank can be adjusted to ensure sensors have stabilized and provide reliable values (30 min proved to be optimal for our needs). Verification of drifting or sensors degradation is done by additional manual measurements (pH - pH330i SenTIX81, WTW, Weilheim, Germany; oxygen - Knick Portamess 911 Cond, Berlin, Germany). In case of significant deviations, the sensors are calibrated or replaced and the measured values of the MPMS are corrected by the manual measurements of the hand-held sensors.

In addition, to the parameters logged by the MPMS, samples of total alkalinity (TA), nutrients, Chl *a*, seston and trace elements (iron, molybdenum, and silicate) were performed regularly using the sampling outlets in the wall of the mesocosms.

Software

The software (Labview based, 4H-Jena engineering, Jena, Germany) controls and regulates temperature, tides, currents, energy supply and the MPMS. All logged data from the MPMS are saved automatically as text files and can easily be plotted for a quick check of the measured parameter. Furthermore, a failure notification is integrated, which automatically sends out personalized e-mails in case of system malfunction or if logged parameter deviate from the set thresholds. The system can also be set to different operation modes: SIMULATION mode simulates an experimental run with the predetermined settings of temperature or pH; PLANT mode sets all platforms to the highest position and allows easy access for planting and handling the material on the platforms; SERVICE mode allows for calibration of the MPMS probes; EXPERT mode gives access to more advanced functions and settings, e.g., manual control of the MPMS, temperature or tidal system.

Temperature and pCO$_2$ adjustment

Each tank is equipped with an external cooling unit (Titan 2000 or Titan 4000 Aqua Medic, Bissendorf, Germany) connected via a pump (Eco Runner 2700, Aqua Medic, Bissendorf, Germany). Water runs continuously through the chiller (Eco Runner 2700, Aqua Medic, Bissendorf, Germany), while cooling is automatically switched on or off. Three heaters (Titanium heater 500 W, Aqua Medic, Bissendorf, Germany) are installed directly in each tank. The software regulates cooling devices and heaters to achieve the desired temperatures in each tank. Due to the fact that two tanks share one measuring system, it is not possible to simultaneously obtain continuous temperature values in both of these tanks. While the temperature in tank 1 is measured tank 2 is uncoupled from the continuous temperature measurements. By integrating water amount, heat capacity, heat output and difference between measured and desired temperature, the software calculates and regulates the necessary heat amount for the uncoupled period.

To manipulate pCO$_2$ in seawater, each mesocosm is continuously and directly aerated with pre-mixed gas, provided by a central CO$_2$-mixing facility from the institute (GMZ 750, HTK, Hamburg, Germany). Pure CO$_2$ is mixed with compressed air to the required pCO$_2$ value. A 60 cm air curtain, installed behind each streaming pipe system, aerates the water body continuously with 800 L per hour, controlled with an upstream flow meter (qflow 140, Vögtlin Instruments AG-flow technology, Aesch Bl, Swiss). Direct aerating facilitates the dissolution of CO$_2$ in seawater allowing a flow through of large amounts of ambient (CO$_2$ poor) seawater from the facility. A 500-μm, horizontal suspended mesh (Fig. 5) traps air bubbles that accumulate at the water surface between the streaming pipe system and the tank wall, to avoid an influence on the experimental system. The installed mesh did not affect the light availability in the tanks. The lid ensures similar atmospheric and seawater pCO$_2$ concentrations and reduces the amount of CO$_2$ required for the experiments. The CO$_2$-mixing facility is checked and calibrated every year.

2013–2014 assessments

The Sylt mesocosms were in operation from October 2013 to December 2014 during four experimental investigations simulating different seasons and different combinations of environmental stressors (Table 1). Each incubated community consisted of the dominant components of a local Wadden Sea community; the brown alga *Fucus vesiculosus f. mytili*, the pacific oyster *Crassostrea gigas*, the blue mussel *Mytilus edulis*, the periwinkles *Littorina littorea* and *Littorina mariae*, and amphipods of the genus *Gammarus* spp. Algae were bind with wire to the frame, mussels were kept in small

Table 1. Periods of investigations of the four experiments in 2013 and 2014.

Season	Time	Duration (weeks)	Treatment
Autumn-2013	29 Oct 2013–10 Dec 2013	7	Acidification + warming
Spring-2014	10 Apr 2014–25 Jun 2014	11	Acidification + warming
Summer-2014	17 Jul 2014–24 Sep 2014	10	Acidification + warming + nutrients
Autumn-2014	16 Oct 2014–17 Dec 2014	8	Acidification + warming + nutrients

baskets on the frame and the rest was free in the tanks. Natural biomass in the field differed between seasons and was adjusted in the mesocosms to mimic the natural population density for the experiments. Within each experiment, the biomass for all species was consistent among the 12 experimental units. The flow through of seawater from the Wadden Sea allowed additional recruitment and settlement of different organism groups such as barnacles, mussels, tunicates, worms, and algae.

In the Autumn-2013 and Spring-2014 experiments, we applied fully crossed experimental designs with both factors, temperature and pCO_2. To mimic the actual field temperatures, the software calculates a daily and yearly temperature sinus function based on the input of daily and yearly maximum and minimum temperatures (LabVIEW 2013, National Instruments Germany GmbH, München, Germany). The input values of daily temperatures were adjusted at least once a week to actual values measured in the field. Thus, ambient temperatures followed seasonal patterns and warming was achieved by adding a delta value of 5°C to the ambient temperatures. This led to the following four treatment combinations: (1) ambient, to mimic today's situation, (2) warm, (ambient temperature +5°C) as expected for 2100 according to the RCP8.5 temperature scenario of the fifth IPCC report (Field 2014), (3) acid (ambient temperature and 1000 ppm pCO_2) expected for 2100 according to the RCP8.5 scenario of the fifth IPCC report and (4) warm + acid (ambient temperature +5°C and 1000 ppm pCO_2), the combination of increased temperatures and acidification to represent the most realistic future scenario (Field 2014). Each treatment combination was replicated three times.

In the Summer- and Autumn-2014 experiments, we applied partly crossed designs where the factors temperature, acidification, and nutrients were combined in the following four treatment combinations: (1) ambient (ambient temperature, pCO_2 and nutrients), (2) nutrients (ambient temperature and pCO_2 but doubled concentration of the last 7 yr (2006–2013) means of PO_4^{3-}, NO_2^-, NO_3^-, Si), (3) warm + acid (+5°C, 1000 ppm pCO_2 but ambient nutrients), and (4) warm+acid+nutrients (+5°C, 1000 ppm pCO_2 and doubled nutrients).

Between experiments, all tanks, pipes and hoses were emptied and thoroughly cleaned. Cleaning was done with a high pressure cleaner to remove as much biota as possible, to reduce possible undesired interactions before starting the next experiment. Settled barnacles and tunicates were detached by hand. Except for the Summer-2014 experiment, with very high temperatures (> 28°C) and the addition of nutrients, we did not have many problems with fouling.

During the 2014 experiments, we conducted 24-h sampling campaigns at the end of each experiment to follow the diurnal, physico-chemical fluctuations in the mesocosms with changing conditions of light, temperature, and biological activity. Temperature, pH, and salinity were measured and additional samples were taken every other hour from all treatments to determine TA, dissolved inorganic carbon (DIC), nutrients, metals, and trace elements.

TA samples were filled bubble-free in 250 mL Winkler bottles and measured immediately after sampling with a titration unit combined with a sample changer (Titroline Alpha Plus, SI Analytics, Mainz, Germany). TA measurements were corrected using certified seawater standards (Dickson, Scripps Institution of Oceanography, San Diego, U.S.A.; Dickson et al. 2003). Chl *a* was measured weekly with a bbe AlgaeLabAnalyser (bbe Moldaenke, Schwentinental, Germany). Nutrient samples were filtered through 0.45 μm Minisart syringe filter (Sartorius SFCA, Sartorius, Göttingen, Germany); samples were stored at −20°C until measurements were performed using a QuAAtro nutrient analyzer (SEAL Analytical GmbH, Norderstedt, Germany; Winde et al. 2014). Accuracy and precision of the nutrient analyses were checked by replicate analyses of standard solution (Winde et al. 2014).

During the Summer-2014 experiment, the system was accidentally shut down due to a lightning strike next to the facility. The resulting overvoltage damaged the interface module, connecting pc and mesocosms. Since the temperature regulation and tidal simulation were no longer working, external temperature computers (T-Computer, Aqua Medic, Bissendorf, Germany) were installed on every tank the next morning. The CO_2 mixing facility and water supply work independently from the control system and were not affected by the lightning. An additional lightning protection module was installed with the replacement of the interface module.

This work focuses on the introduction of this new mesocosms facility and the essential abiotic and biotic parameters measured during the experiments to demonstrate the functionality of the system. All other data obtained on the

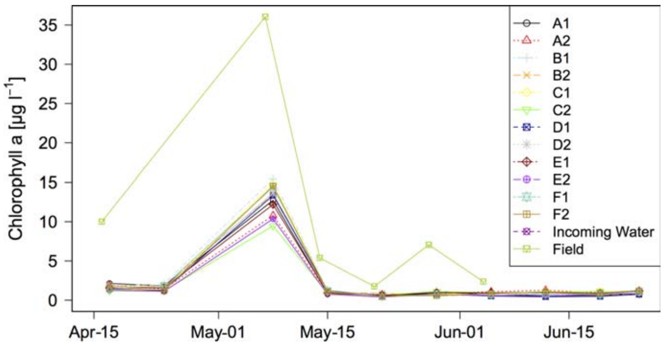

Fig. 6. Chl *a* concentration during the Spring-2014 experiment for every individual mesocosm, the incoming water and field samples.

community changes under the different climate change scenarios will be presented in detail elsewhere.

Results and discussion

Chlorophyll *a*

Chl *a* values in the mesocosms during the Spring-2014 experiment (Fig. 6) show the occurrence of the natural algal spring bloom equally in all tanks (peak at the 8th of May), however, with reduced amplitudes compared with field measurements. The maximum concentrations of Chl *a* measured were 15.6 μg L^{-1} and 36.1 μg L^{-1} in the mesocosms and in the field, respectively. Chl *a* decreased after the spring bloom and varied around 2 μg L^{-1} in all mesocosms until the end of the experiment. A second spring bloom occurred in the field in end of May 2014 (Chl *a* of up to 7.05 μg L^{-1}; Fig. 6) but could not be detected in the incoming water, as well as in the mesocosms. The lower amplitude of the first spring bloom and the absence of the second spring bloom in the mesocosms are likely due to water transport and storage before it is delivered to the mesocosms. Another possible explanation could be the intake of seawater. While field samples of Chl *a* were taken at the surface, the seawater inlet for the supply to the mesocosms is placed at 2–4 m depths, depending on the tide. Biological activity in the filed is, however, mainly concentrated in the surface layers, as is the Chl *a* concentration (Ryther 1956). However, lots of planktonic species as well as settled barnacles and tunicates, were found during the experiments, suggesting that enough food for the filter feeders was available. In all experiments, we found less than 5% of the dominant filter feeders (*Mytilus edulis* and *Crassostrea gigas)* dead in the ambient treatments. A further explanation of the reduced Chl *a* concentration could be the reduced light availability in the tanks. Although 90% of the photosynthetically active radiation penetrates the lid, shading effects from the sidewalls of the tanks cannot be avoided. Nevertheless, the successful simulation of the first plankton bloom and apparently abundant phytoplankton and zooplankton species in the tanks, as well as settled barnacles and tunicates at the end of the experiments, demonstrates a strong coupling of the mesocosms and the natural water body of the Wadden Sea. Installing a pump with a direct pipe, connecting the Wadden Sea and the mesocosm facility, should reduce the effects of seawater transport and storage on the Chl *a* concentration as it is done in the Kiel Outdoor Benthocosm (KOB) facility (Wahl et al. 2015). However, without sedimentation tanks the amount of sediment in the Sylt mesocosms would massively increase and unintentional change the biogeochemistry of the water, including the carbonate system.

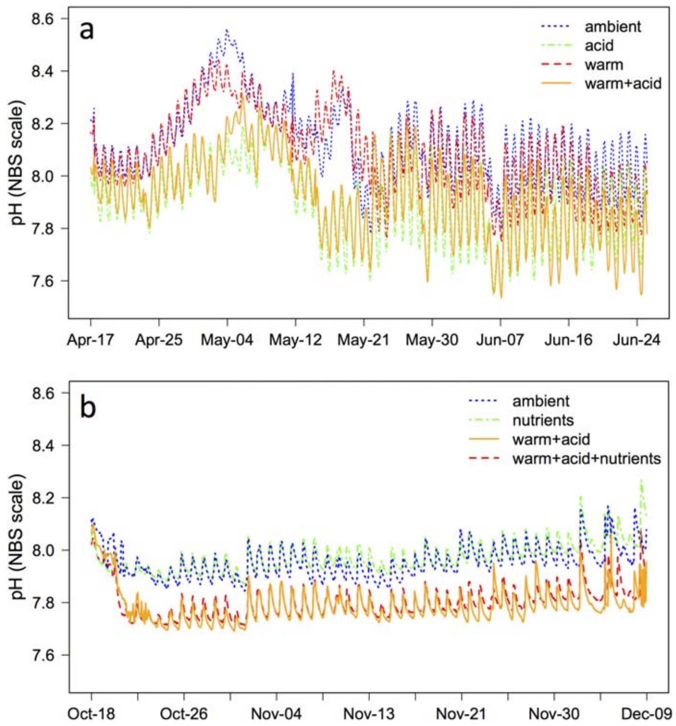

Fig. 7. Daily fluctuations of pH$_{NBS}$ measured by the multi parameter measurement system during the Spring-2014 (**a**) and the Autumn-2014 (**b**) experiments. pH values shown are hourly means.

Furthermore, we found higher growth rates for *Fucus vesiculosus* in our ambient treatments compared with controls in the field and no signs of light deficiency on the macroalgae during our experiments. While it is still a tank experiment, with some confounding factors, we believe that the lower light availability did not negatively affect the experimental treatments.

Seawater pH

The daily pH fluctuations during the Spring-2014 experiment ranged up to 0.5 pH units per treatment (NBS scale; Fig. 7a). This was likely due to the natural photosynthetic activity and respiration processes of the biotic components in the tanks (Duarte et al. 2013) with minimum pH values in the early morning and maximum pH values in the late afternoon. During the algae bloom of early May, pH reached its highest values of 8.55. Daily pH fluctuations measured

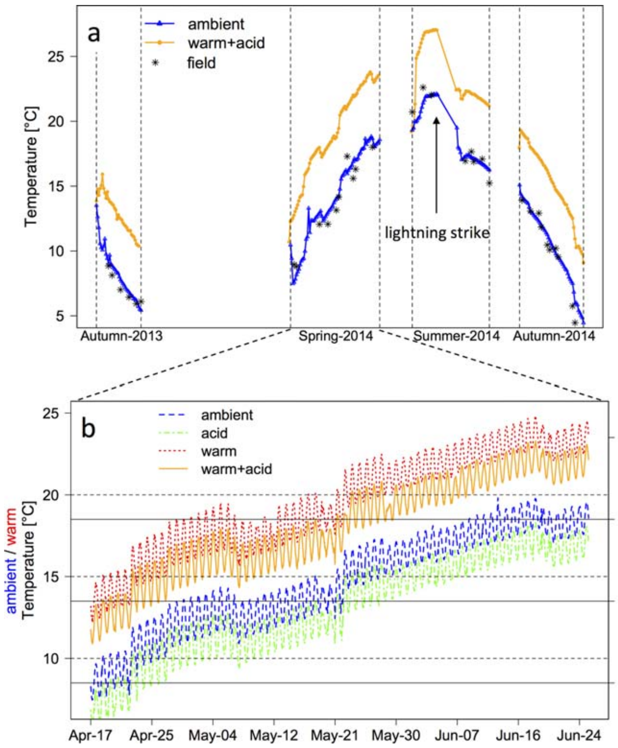

Fig. 8. Daily mean temperatures measured by the multi parameter measurement system during the four experiments in 2013 and 2014 including field temperatures (**a**) and diel fluctuations of water temperatures (means per hour) during the Spring-2014 experiment (**b**). The lines of ambient (blue) and acid treatments (green) as well as those of warm (red) and warm + acid (orange) treatments are overlapping due to the same temperature regimes, the right *y*-axis was therefore shifted downward by 1.5°C (**b**).

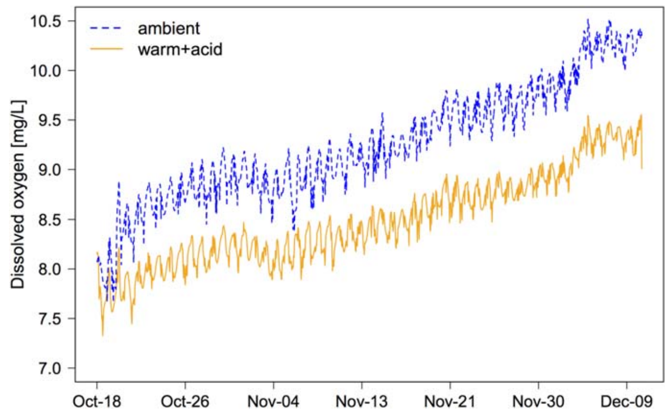

Fig. 9. Daily fluctuations of dissolved oxygen concentrations measured by the multi parameter measurement system during the Autumn-2014 experiment in an ambient and a warm treatments. The oxygen values shown are means per hour.

during the Autumn-2014 experiment (Fig. 7b) varied by up to 0.2 units. This much lower variation compared with the Spring-2014 experiment was likely due to reduced temperatures (Fig. 8a) and less sunlight available due to the lower solar angle during that season.

The observed daily fluctuations in seawater pH demonstrate that the naturally occurring variability observed in the field (Saderne et al. 2013) can also be simulated in the mesocosms experiments (Fig. 7a,b), albeit with slightly reduced amplitudes. Nevertheless, the important pH fluctuations could be simulated in our system, which suggests that the amount of incoming, pre-mixed gas and water was not too high to buffer the whole biotic activity within the mesocosms. Furthermore, extremely high fluctuations arising from too high biomass-water-ratios were not observed. The CO_2 mixing facility produced stable treatments during the conducted experiments. The pH within the acid treatments (1000 ppm $p$$CO_2$) was consistently 0.2–0.3 pH units lower compared with the ambient treatment. This is consistent with the predictions of the fifth ICCP report for the year 2100, where a decreasing pH up to 0.35 units is predicted (IPCC 2013). After the four experiments, single pH sensors started to drift and had to be replaced. However, as the CO_2 mixing facility acts independently of the pH sensors, the drifting values did not affect the treatments themselves.

Temperature

Throughout all four experiments in 2013 and 2014, a minimum temperature of 5°C was only observed at the end of both autumn experiments, in the beginning of December (Fig. 8a). A maximum temperature of 28°C was reached at the beginning of August 2014 in the warm treatment. During the Summer-2014 experiment, the values were not continuously logged by the MPMS between the 12th and 26th of August (Fig. 8a) due to the lightning strike next to the facility, which damaged the control system.

The yearly (Fig. 8a) and diurnal variations (Fig. 8b) in water temperature in the Sylt mesocosms accurately followed the calculation made by the software. A continuous difference of 5°C between the ambient and warm treatments was maintained with the existing cooling and heating devices at all time during the experiments. Although the temperature simulation is very accurate and reliable, we are aware that even with a lot of adjustments, it only roughly reflects the temperature conditions in the field. All small-scale in situ fluctuations are neglected with this type of simulation.

Oxygen

Oxygen concentrations shown here for the Autumn-2014 experiment (Fig. 9) constantly increased from 7.5 mg L^{-1} to 9.25 mg L^{-1} and from 8.0 mg L^{-1} to 10.25 mg L^{-1} in the ambient and the warm + acid treatment, respectively. This is most likely due to decreasing water temperatures during the experiment. The difference between ambient treatment and warm treatments, was consistently highest about 1.0 mg L^{-1} due to the 5°C difference in temperature. Biotic activity, as seen for pH values, induced diurnal variations in oxygen

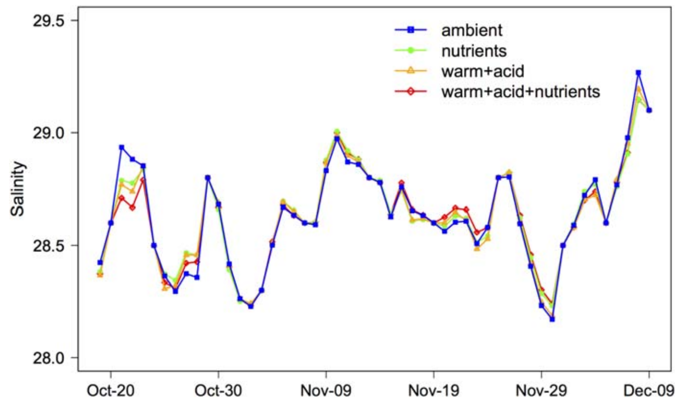

Fig. 10. Fluctuations in salinity during the Autumn-2014 experiment with the four different treatments. Shown are means per day.

concentrations in the tanks, with an increase of oxygen from dawn to the late afternoon, followed by a decrease until the next morning. We never found any evidence for anoxic conditions in the mesocosms during the conducted experiments.

Salinity

The salinity, here shown for the Autumn-2014 experiment measured by the MPMS showed only marginal differences between the different treatments (Fig. 10). The salinity fluctuations within the experiment ranged from 28.2 to 29.3.

Nutrients (PO_4^{3-}, Si and, NO_3^-)

During the 24 h sampling campaign of December 2014, we took nutrient samples every 2 h. Figure 11 shows the concentration of PO_4^{3-}, Si and , NO_3^- during that period. It illustrates the addition of nutrients (red and green lines) at around 3 pm, followed by a strong increase in the concentrations until 5 pm with a gradual subsequent decrease. Part of the added nutrients was likely washed out due to the water flow through while the rest was reduced by the biota in the tanks. The treatments without the addition of nutrients (orange and blue lines) stayed constant over the 24 h (Fig. 11a–c).

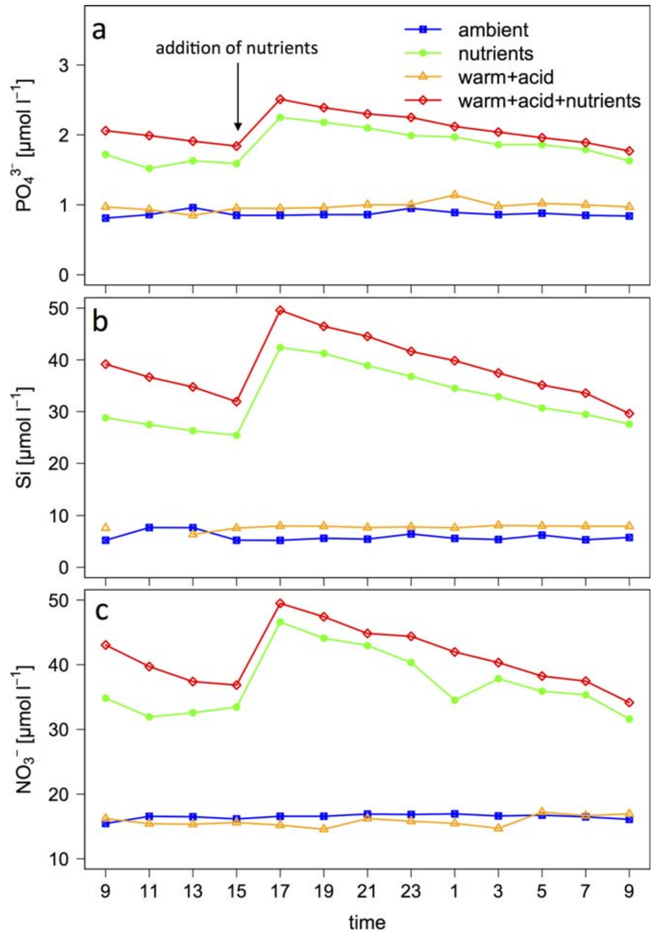

Fig. 11. Nutrient measurements during a 24 h sampling campaign during the Autumn-2014 experiment for (**a**) PO_4^{3-}, (**b**) Si and (**c**), NO_3^-.

Conclusions and perspectives

The great potential of mesocosm studies to acquire new knowledge in the context of climate change and its consequences is well known and a reason for the increasing number of new mesocosm facilities worldwide (Stewart et al. 2013). Understanding the complex correlations between abiotic factors, biodiversity dynamics, and ecosystem processes is crucial to gain knowledge on possible shifts in the functioning of ecosystems (Loreau et al. 2001). This requires an experimental design, which is controllable, near natural, replicable and feasible at the same time, and based at the community level.

The few transportable pelagic mesocosm facilities that exist allow conducting the same experiments in different aquatic systems around the world (Mostajir et al. 2013; Riebesell et al. 2013). For benthic systems, however, such transportable facilities do not exist. Nevertheless, to reliably predict the consequences of future ecosystem changes, it remains essential to investigate the impact of future changes in the different systems under natural conditions, elucidating local as well as generic patterns in the response to these changes. For the Baltic Sea, a similar system compared with the Sylt mesocosms exists already at the GEOMAR in Kiel (Germany). The KOB system consists of six rectangle tanks, with a direct water supply, a hood for each tank and works as well with benthic communities under environmental stress. It did not have a tidal simulation system but a wave generator (Wahl et al. 2015). However, for the Wadden Sea such mesocosm system did not exist before.

The Wadden Sea along the coasts of Germany, Denmark and the Netherlands is one of the most productive marine ecosystems in the world and home to numerous plant and animal species but, at the same time, a heavily used recreational area for humans. It is one of the largest, coherent tidal flat area systems in the world and serves as nursery ground for fish and shrimps as well as important feeding ground for millions of migrating birds (Reise et al. 2010). That is why it is important to investigate the response of this exceptional system to future changes and this can be done with this new mesocosm facility.

The mesocosms at the AWI Wadden Sea Station were effectively running during the four experiments with good functionality of all components, it therefore can be recommended as a tool for a variety of experiments in the field of marine biology. Monitoring and controlling the physico-chemical conditions is one of the most important features for climate change experiments. This is done in several comparable, but still different ways (Mostajir et al. 2013; Riebesell et al. 2013; Leblud et al. 2014; Wahl et al. 2015). The MPMS of the Sylt mesocosms is very adaptable, as it can be equipped for different experimental approaches with further sensors (e.g., turbidity, chlorophyll, ammonium, nitrate or chloride). The newly developed tidal simulation system works well and provides new possibilities for mesocosm experiments in coastal systems and tidal areas. It is an important additional feature for near natural mesocosm experiments and not existing in this way in any other mesocosm facility worldwide.

Numerous different types of mesocosm facilities exist, each made with special features for a specific purpose. The targeted purpose of this facility are climate change experiments with benthic communities in tidal areas, but there are far more possibilities for applications. In addition to investigate benthic assemblages, it is possible to investigate pelagic systems with this facility. Although the water depth is only 80 cm, one can test the response of planktonic species to increasing temperatures, acidification or nutrient enrichment as it has been done with comparable mesocosm facilities (Kim et al. 2006; Lewandowska et al. 2014; Paul et al. 2015). The round design of the tanks is favourable for experiments with smaller fish species, juvenile fish, fish larvae or jellyfish, compared with rectangle shaped tanks where it is hard to produce circular flows. Additionally further stressors or stress combinations can be applied, such as deoxygenation, changes in salinity, changes in turbidity or heat waves. In addition to simulate the tides, it is possible to mimic future sea level rise scenarios with an adjustment of the tidal simulation system. Investigations with non-native species are possible, but they have to be run without a flow-through mode or with an appropriate treatment of the wastewater to avoid an introduction of new species into the Wadden Sea.

So far, the system works with estimated temperatures, calculated by the software, which does not reflect exactly the conditions in the field. To achieve a higher parallelism with field conditions, including natural small-scale fluctuations, which have the potential to modulate environmental stress (Dufault et al. 2012; Cornwall et al. 2013; Wahl et al. 2015), we suggest installing additional sensors in the field. These would continuously transmit the measured values to the system to improve the simulation of field conditions in the tanks. Direct water supply has great advantages and should be favoured for such experiments (Wahl et al. 2015), but was not possible to build for our system. This adjustment could be considered for future experiments, which focus on small-scale fluctuations of the system. The total costs for the Sylt mesocosms without maintenance and personnel expenses were around 250 K Euro.

The innovations introduced by this facility are the simultaneous control of the important environmental parameters, the manipulation of multiple stressors, their combination with a newly developed tidal simulation system, and the capability to conduct experiments with inshore benthic communities.

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