FRAM - FRontiers in Arctic marine Monitoring

Visions for Permanent Observations in a Gateway to the Arctic Ocean

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***Abstract*—Our ability to understand the complex interactions of biological, chemical, physical, and geological processes in the ocean and on land is still limited by the lack of integrative and interdisciplinary observation infrastructures. The main purpose of the planned open-ocean infrastructure FRAM (FRontiers in Arctic marine Monitoring) is permanent presence at sea, from surface to depth, for the provision of near real-time data on climate variability and ecosystem change in a marine Arctic system. The Alfred-Wegener-Institut – Helmholtz-Zentrum für Polar- und Meeresforschung (AWI), together with partner institutes in Germany and Europe, aims at providing such infrastructure for the polar ocean as a major contribution to the grand challenges of Earth observation and environmental status. The FRAM Ocean Observing System targets the gateway between the North Atlantic and the Central Arctic, representing a highly climate-sensitive and rapidly changing region of the Earth system. It will serve national and international tasks towards a better understanding of the effects of change in ocean circulation, water mass properties and sea-ice retreat on Arctic marine ecosystems and their main functions and services. FRAM will implement existing and next-generation sensors and observatory platforms, allowing synchronous observation of relevant ocean variables, as well as the study of physical, chemical and biological processes in the water column and at the seafloor. Experimental and event-triggered platforms will complement observational platforms. Products of the infrastructure are continuous long-term data with appropriate resolution in space and time, as well as ground-truthing information for ocean models and remote sensing. FRAM will integrate and develop already existing observatories, i.e. the oceanographic mooring array HAFOS (Hybrid Arctic/Antarctic Float Observing System) and the Long-Term Ecological Research (LTER) site HAUSGARTEN.**

Keywords—Arctic Ocean; Fram Strait; Long-Term Ecological Research; Observing System; Interdisciplinary; Climate Change; HAFOS; HAUSGARTEN

I. INTRODUCTION

Measurements of physical, chemical and biological variables of the Earth system are the only mean to objectively determine its natural dynamics and the effects of Global Change on different spatial and temporal scales. Furthermore, observational data are essential for the validation of remote sensing products, as well as climate and ocean models. Large international programs such as the Global Earth Observation System of Systems (GEOSS) are currently being established to achieve this urgent goal. Their success depends on the implementation and support of national observation infrastructure in regional hot spots of change. Germany, and especially the Helmholtz Association, contributes to global Earth observations by supplying various types of research platforms such as ships, satellites, airplanes, ocean drifters, and networks of activities at specific research sites. With its focus on integrated multidisciplinary ocean observation in the Arctic, the FRAM Ocean Observing System is proposed as a unique contribution of national and international relevance.

FRAM is proposed as a large-scale investment into a submarine infrastructure to enable year-round and long-term observations with partial near real-time data access in Fram Strait, the main gateway between the Atlantic and Arctic Ocean. It will comprise both Eulerian and Lagrangian observatory components, linked through integrated data pipelines for multidisciplinary synoptically measurements, supporting comprehensive syntheses. FRAM will integrate classical physicochemical measurements, contemporary biogeochemical and biooptical sensing methods, as well as biological observations. At any time, new technologies could be integrated. Interactive and intelligent event-triggered data recording, innovative solutions for energy supply and tailored solutions for data transmission and near-real time access will make FRAM a highly advanced observing system. FRAM will provide access to, and exchange with, a broad range of user groups, including the maritime technology, remote sensing, ocean modeling and ecosystem assessment communities.

II. SCIENTIFIC BACKGROUND AND OBJECTIVES

Polar Regions play a central role for the global climate. In recent decades, the Arctic Ocean has experienced dramatic changes in three main processes of global climatic importance,

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(1) the poleward oceanic heat flux into the Arctic Ocean, (2) the freshening of the Central Arctic and an increasing export of freshwater towards the North Atlantic, and (3) the strong reduction of multi-year sea ice.

A large-scale shift towards warmer conditions in the Arctic Ocean has been observed since the early 1990s. Observations in Fram Strait revealed distinctive temperature increases in two periods (1998 - 2000, and 2003 - 2006), with a net increase over the last decade of 1°C [1]. A mean value of 36 ± 6 TW for the years 1997 through 2009 and an increase in the order of 10 TW in the recent decade were estimated using a stream-tube approach to estimate the oceanic heat flux through Fram Strait [2]. The intrusion of anomalously warm Atlantic water could be traced over Arctic shelves [3], along the Arctic continental margin [4], and into the central Arctic [5], [6]. A substantial warming was also observed in the Atlantic Water recirculating in Fram Strait. The observed warming could have consequences for an escape of methane gas from the seabed along the West Spitsbergen continental margin [7].

At the same time, substantial changes have been observed in the storage and distribution of Arctic freshwater in the upper few hundred meters, which is delivered by the Eastern Greenland Current (EGC) to the North Atlantic in the form of liquid freshwater or sea ice through Fram Strait or the Canadian Archipelago. During summer months, the liquid freshwater content of the deeper part of the Arctic Ocean (excluding shelves) increased by 8400 ± 2000 km^3 between 1992 - 1999 and 2006 - 2008 [8]. Changes in the freshwater content and distribution obviously also led to a shift in the position of the transpolar drift [9], [10].

Model simulations show also that these changes have the potential to influence the Atlantic Meridional Overturning Circulation (MOC), by reduced convection in the deep-water formation regions of the North Atlantic [11] – [13]. However, despite extensive efforts to estimate oceanic fluxes through the critical gateways, it was so far not possible to balance seawater and freshwater budgets. Therefore, the proposed FRAM Ocean Observing System, employing different autonomous systems, providing data with sufficient spatial resolution and including the surface layer, may substantially improve the available estimates of oceanic fluxes through Fram Strait.

The extension of sea ice has a crucial influence on the Earth's heat balance [14], but also substantially affects the marine Arctic ecosystem, including its productivity, biogeochemical fluxes, as well as all trophic levels from bacteria to fish, seabirds, and mammals. A notable shift in the plankton community of the eastern Fram Strait from diatom- dominated assemblages to a dominance of coccolithophorids and other forms of the nanoplankton, might indicate first effects of increased water temperatures and a decreasing ice-coverage [15]. This shift is also corroborated by variations in large zooplankton species, which showed an increase of warm adapted organisms in recent years [16]. The observed changes in the composition of primary producing phytoplankton, their grazers, and in the quality of settling particles are expected to impact higher trophic levels, as well as the benthos.

The "Atlantification" scenario, which is currently suggested as the most likely outcome of Global Change in the Fram Strait, may lead to the retention of particles in the upper water column and less food reaching the seafloor [17]. It is possible that the entire benthic community will be impoverished, which is currently studied by quantifying *in situ* carbon fluxes and consumption by the community in comparison to the last decade [18].

The seafloor as ultimate sediment trap reflects such changes not only in biogeochemical processes, but also in the composition of benthic communities and in the geological record [19]. Benthic studies in Fram Strait so far focused on sediment-bound bacteria and the metazoan community, covering all size classes from the meio- to the megafauna. Inter-annual variability in the benthic community structure could be related to food availability. This is also evident from bathymetric distribution patterns of meiofauna [20], macrofauna [21] – [23], and megafauna, which display a high degree of zonation [24]. Recently, the analysis of seafloor photographs taken in the eastern Fram Strait (approximately 2500 m water depth) in 2002, 2004, and 2007 indicates a striking decline in megafaunal densities with time in this phase of ocean warming and sea-ice retreat, indicating that the biological processes in surface waters and the deep ocean are directly coupled [25]. Increases in the $\delta^{15}N$ signature of predatory fish between 2004 and 2008 [26] indicate changes at the base of the benthic food chain. *In situ* experiments [27] – [31] are urgently needed to enhance our knowledge on ecosystem resilience in a period of rapid Climate Change, and to identify indicator species, communities and processes for the "Atlantification" process.

Based on knowledge gaps, the overarching scientific goals for long-term studies in the marine Arctic include:

- to provide daily near-real time data on ocean surface and deep-water properties.
- to obtain observations to link variations of daily (e.g., relevant for the preconditioning for phytoplankton blooms) to inter-annual (e.g., relevant to decipher decadal trends) time-scales to processes in the atmo-, cryo-, hydro-, bio- and geosphere.
- to quantify budgets and transports of energy and matter at different spatial and temporal resolution from events to seasonal dynamics, inter-annual differences and decadal changes.
- to study interactions and feedback mechanisms between the cryosphere, hydrosphere, biosphere, and geosphere.
- to reveal the mechanisms which shape biodiversity of pelagic and benthic communities.
- to contribute data for an assessment of ecosystem functions, services and the role of biodiversity therein.

- to study the resilience of Arctic marine organisms and to identify indicator species for community changes.
- to decipher how Climate Change mechanisms in the North Atlantic and the Arctic Ocean are coupled.
- to provide data for assessing the quality of remote sensing products and models simulating current and future changes in the Arctic Ocean.

III. Description of the Proposed Facility

The main aim of the interdisciplinary FRAM Ocean Observing System is to be permanently present at sea for the provision of integrated and interdisciplinary data. The proposed infrastructure will implement and maintain cutting-edge synergetic observation platforms for polar, marine and Global Change research in the ocean, and – as a prototype for large scale integrative, autonomous observatories – will lay the foundation for sustainable monitoring and management of the oceanic environment. Continuous observations will be provided at the interface between hydrosphere, cryosphere and atmosphere, as well as hydrosphere and geosphere, to determine the huge seasonal and inter-annual changes in freshening, stratification and deep convection related to warming and ice melt, and their consequences for productivity, biological and physical carbon uptake, export and burial, as well as other ecosystem functions, including biodiversity. The observing system will facilitate the comprehensive recording of processes also during winter time or during episodic, extreme events that are presently severely under-sampled, but can have major influence on the trajectories of seasonal development. The components to be installed will help to better understand the consequences of the rapid warming of the Arctic atmosphere, which has proceeded twice as fast as the global mean during the past decades [32], with a continuing trend of Arctic amplification.

Hence, to meet all the above requirements, the FRAM Ocean Observing System will consist of arrays of autonomous, stand-alone components, which will be installed, maintained and replaced during expeditions with research vessels. These expeditions will also enable the internal and external user communities to complement the autonomous monitoring with ship-borne measurements, *ad hoc* experiments, and field studies. The observatory would be unique in its combination of synoptical Eulerian (i.e., fixed in place) and Lagrangian (i.e., drifting) system components, as well as remotely navigated systems working under ice, in open water and on the deep seafloor.

FRAM will integrate and develop already existing observatories such as the oceanographic mooring array HAFOS (Hybrid Arctic/Antarctic Float Observing System) and the Long-Term Ecological Research (LTER) site HAUSGARTEN (Fig. 1). The mooring array has been maintained since 1997. It covers a 300 km wide section, crossing the Fram Strait at 78°50’N with a spatial resolution between 10 and 30 km [33]. Currently, all moorings are instrumented at standard levels: subsurface (~50 m), the level of the AW water layer (~250 m), the level of the AW lower boundary (~750 m), the deep water level (~1500 m, where available), and the near bottom level (~10 m above the seafloor). Each mooring carries three to seven instruments including current meters, acoustic current profiler, temperature and salinity sensors, and bottom pressure recorders. The instruments record the data internally while moored. In addition, HAFOS builds on vertically profiling floats located by acoustic means using moored RAFOS sound sources as backbone and is complemented by a suite of moored automated systems and sea gliders.

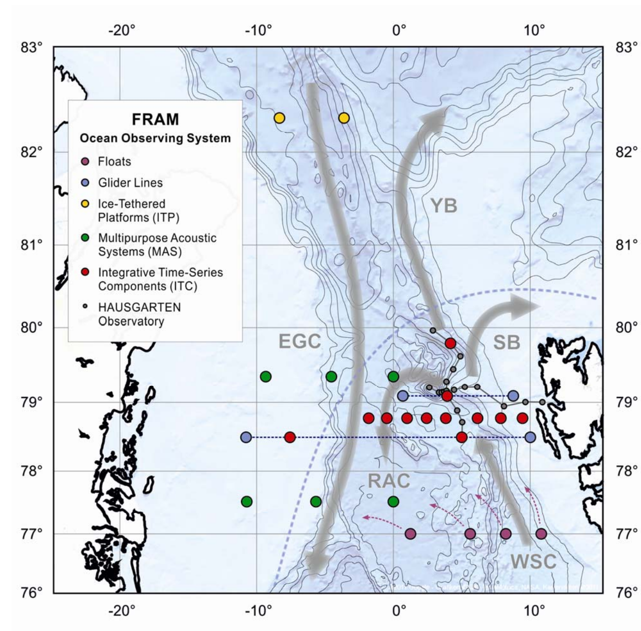

Figure 1. The Ocean Observing System FRAM and its main components (EGC: East Greenland Current, RAC: Return Atlantic Current, WSC: West Spitsbergen Current, SB: Svalbard Branch, and YB: Yermak Branch of the WSC; glider lines and float tracks are schematic representations and can vary with the currents; dashed blue line: mean summer ice edge).

The deep-sea observatory HAUSGARTEN was established in 1999 [34]. It consists of 17 permanent sampling sites along a depth transect from 1000 to 5500 m and a latitudinal transect following the 2500 m isobaths for approximately 150 km. The central HAUSGARTEN station at 2500 m water depth serves as an experimental area for biological *in situ* experiments. Multidisciplinary research activities at HAUSGARTEN and cover almost all compartments of the marine ecosystem from the pelagic zone to the benthic realm, with some focus on benthic processes. These studies include many parameters which are not yet available for autonomous observations, such as community biomass, structure and function, but which are critical for the valuation of ecosystem status and services such as productivity.

Within the FRAM Ocean Observing System, single HAFOS and HAUSGARTEN sites will be developed to so-called Integrative Time-series Components, ITCs (Fig. 2). An ITC will consist of moorings equipped with physical, biogeochemical and biological sensor packages (e.g., temperature, salinity, turbidity, oxygen, transmission, light, fluorescence, pCO_2) sending data for near-real time data transmission. The moorings will include up to 10 instruments per mooring such as rotor and acoustic current meters, acoustic current profilers, temperature and salinity sensors, bottom pressure recorders, acoustic passive recorders, as well as biogeochemical and optical sensors. An ITC will also host different type of sampling devices, as well as visual and acoustic recorders, which will produce samples and data to be retrieved by expeditions with R/V Polarstern and other research vessels. These range from classical tools (e.g., sediment traps, time lapse camera) to next-generation instruments such as *in situ* fluorometers, flow cytometers, incubating productivity systems water and sediment samplers, *in situ* filtration pumps and other systems allowing monitoring production, biodiversity and community function.

A suite of variables that can be measured electronically will be transmitted in near-real time. Besides the classical oceanographic/physical characteristics, these variables comprise a suite of *in situ* biological (e.g., fluorescence, absorption) and biogeochemical parameters (e.g., O_2, CO_2). For near-real time data transfer by satellite, acoustic modems have been developed (e.g., in the European Integrated Project DAMOCLES) and already implemented in the oceanographic mooring array during the European project ACOBAR (ACoustic technology for OBserving the interior of the ARctic Ocean). Instrumentation for variables, which need to be analyzed in the lab (e.g., sediment trap materials) will produce samples which are fixed and stored, and are retrieved by research expeditions. In addition to scientific data, FRAM could also supply data of operational use, particularly from near- surface measurements (e.g., reflectance, temperature, salinity, meteorological information), and some other services (e.g., sound sources for navigation and tomography, and satellite validation). Furthermore, it is planned to comply to European policies of marine ecological observation such as the Marine Strategy Framework Directive; FRAM would be one of the first high seas observatories to do so.

Accordingly, in addition to the ITCs, several sound sources and receivers will be implemented in international cooperation into a Multipurpose Acoustic System (MAS) used for 3D tomography, navigation of sea gliders under ice and passive listening to ambient noise from sea ice and marine mammals.

Observations have to be year-round, including the winter and spring phases that are hardly accessible by ship, and have to cover a wide range of temporal and spatial resolution. Due to the

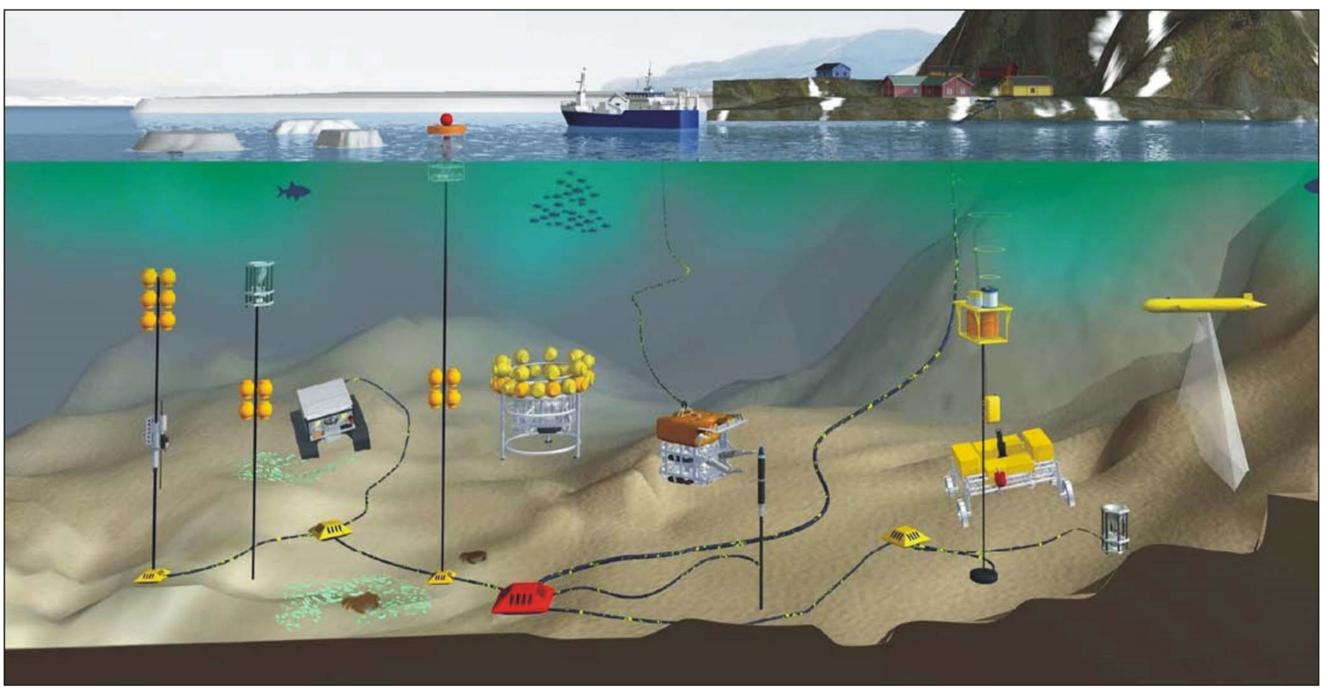

Figure 2. Scheme of a study site with FRAM integrative time-series components

(Source: KDM brochure „Ocean observatories for Earth system sciences in the key region Atlantic-Arctic Ocean“, 2011) sea-ice coverage and rough climatic conditions, in particular in winter, such near-surface year-round measurements represent a major technological challenge, which will be approached in different ways such as profiling systems on top of moorings, gliders profiling in open water and under the sea-ice, wave gliders measuring at sea-surface during the period of open water, and various multi-sensor Ice-Tethered Platforms (ITPs) floating southwards with the ice leaving the Arctic Ocean in western parts of the Fram Strait.

Briefly, the FRAM Ocean Observing System would include:

- >8 year-round Integrative Time-series Components (ITCs) composed of oceanographical and acoustic moorings with current meters, physical, biogeochemical and biooptical sensor packages, and profiling systems on winches for observations in the subsurface and surface layers.
- >4 Integrative Time-series Components (ITCs) with visual and acoustic units and event recording/sampling capacities for plankton and benthos.
- >10 mobile systems (AUV, sea gliders, floats and Ice-Tethered Platforms, ITPs) for year-round operation, with physical and biogeochemical sensors.
- A Multipurpose Acoustic System (MAS) for navigation, sound recording etc.
- Satellite-modem links for data exchange and interfaces for future connections to nodes of underwater cable networks.
- 1-2 benthic crawler systems for year-round sampling (sediments, photography).

With a regular replacement of instruments every 1-3 years, depending on user needs and the individual endurance of the instruments, we would be able to sustain the FRAM Ocean Observing System for >20 years. The autonomous modular set-ups would allow to react rapidly to modernizations and new developments in marine technology, and to scientific progress in system understanding at any time. Furthermore, the system should be open and flexible for external users to add components to the installed infrastructure. In addition, some of the modules will be equipped at an early stage with interfaces to potentially profit from planned underwater cabling for interactive high bandwidth data communication and energy supply.

IV. DATA FLOW AND DATA MANAGEMENT

While the degree of autonomy of all instruments with regard to power supply and data storage will be very high, all observational data can be linked in the FRAM database and can be integrated over a wide range of scales in space and time via data queries with flexible binning options. Quality controlled data will be archived and made available by the permanent data archive PANGAEA (www.pangaea.de), the central archive of the Publishing Network for Geoscientific & Environmental Data. Observational data will be compatible for distribution to or queries by other established data distribution systems (e.g. Argo, SeaDataNet, GenBank etc.). Archiving issues already considered by the World Data Center for Marine Environmental Sciences (WDC MARE) during the ESONET project include content-based indexing, distributed database management, alerting, feature recognition, various levels of access to data, and web-based modeling. Accordingly, the infrastructure for making FRAM data available to the scientific community is already solved. However, we have the additional goal to comply with GEOSS standards, and to encourage and train internal and external user communities to do so.

Data shall be freely accessible for registered users via an internet portal. Data access limitations will be defined case by case, tailored to the respective project or disciplinary needs. All published data, results and information will be available electronically. The near-real time data will be made available through an Argo-type web portal hosted for the project, flagged for the status of quality control, and will be available for queries and browsing via online visualization, including event- and feature-search tools, and preliminary statistical analyses.

Additionally, as a management tool, an internal web site would be maintained which could display the status of the deployment and the flow of available data, as well as user requests. The status of the system will be assed annually to take into account the performance of the deployed instruments, the potential change of natural conditions (e.g., decreasing/increasing ice cover), further development of technology (e.g., cable technology, acoustic underwater navigation and communication) and engagement of international partners. Furthermore, the web portal will offer opportunities for media and the public to obtain information, images, visualization of results for educative uses.

V. CONCLUDING REMARKS

The proposed infrastructure will allow improving methods for near-real time observations of oceanic processes, visualization of the ocean environment, and integration of new methods from the areas of robotics, nanotechnology and marine genomics. A main novelty of the FRAM Ocean Observing System will be the integration of biogeochemical and ecological data to assess ecosystem responses to global change processes in the Arctic region. Challenges are a near-surface access, the reliable operation of underwater platforms, improvement of the long-term performance of instruments and sensors, long-term energy supply, and minimization of energy consumption, development of procedures to prevent corrosion and fouling, interactive access to all functions of an instrument, as well as the online, near-real time transfer of high quality data to international open-access data bases.

The FRAM Ocean Observing System is designed to provide multi-parameter data of oceanographic, biogeochemical and biological variables, allowing the identification and monitoring a wide range of indicators and features relevant for the analysis of natural and man-made ocean dynamics. It will also provide opportunities to implement innovative physical, biogeochemical, biooptical and biological observational systems and experimental set-ups.

Short- and intermediate-term upgrades and integrations with novel technologies for underwater observations will allow this observatory to become a central national and international facility for both ocean and polar research. This will also ensure its high standard, allowing a potential future integration into future underwater cable networks and other international developments in ocean observation. Furthermore, in consideration of the international long-term goals concerning Arctic observation the proposed observatory would be a key contribution to the ESFRI project SIOS (www.sios-svalbard.org), as well as to SAON (Sustaining Arctic Observing Networks) and the international open-ocean observatory network OceanSites.

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