Towards an advanced observation system for the marine Arctic in the framework of the Pan-Eurasian Experiment (PEEX)

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Abstract. The Arctic marine climate system is changing rapidly, seen as warming of the ocean and atmosphere, decline of sea ice cover, increase in river discharge, acidification of the ocean, and changes in marine ecosystems. Socio-economic activities in the coastal and marine Arctic are simultaneously changing. This calls for establishment of a marine Arctic component of the Pan-Eurasian Experiment (MA-PEEX). There is a need for more in-situ observations on the marine atmosphere, sea ice, and ocean, but increasing the amount of such observations is a pronounced technological and logistical challenge. The SMEAR (Station Measuring Ecosystem-Atmosphere Relations) concept can be applied in coastal and archipelago stations, but in the Arctic Ocean it will probably be more cost-effective to further develop a strongly distributed marine observation network based on autonomous buoys, moorings, Autonomous Underwater Vehicles (AUV), and Unmanned Aerial Vehicles (UAV). These have to be supported by research vessel and aircraft campaigns, as well as various coastal observations, including community-based ones. Major manned drifting stations may occasionally serve comparable to terrestrial SMEAR Flagship stations. To best utilize the observations, atmosphere-ocean reanalyses need to be further developed. To well integrate MA-PEEX with the existing terrestrial/atmospheric PEEX, focus is needed on the river discharge and associated fluxes, coastal processes, as well as atmospheric transports in and out of the marine Arctic. More observations and research are also needed on the specific socio-economic challenges and opportunities in the marine and coastal Arctic, and on their interaction with changes in the climate and environmental system. MA-PEEX will promote international collaboration, sustainable marine meteorological, sea ice, and oceanographic observations, advanced data management, and multidisciplinary research on the marine Arctic and its interaction with the Eurasian continent.

1. Introduction

During the recent decades the Arctic air temperatures have increased two or three times as fast as the global mean (AMAP, 2017a; Overland et al., 2017). This is called the Arctic amplification of climate warming. The warming has been strongest in winter with the maxima over sea ice, whereas in summer the warming has been weaker with the maxima in terrestrial Arctic and Greenland ice sheet (Figure 1). The atmospheric warming is associated with strong sea ice decline (Döscher et al., 2014):

since the early 1980s, the September sea ice extent had decreased by approximately 40% and the cold season sea ice thickness by approximately 50% (Kwok and Cunnigham, 2015). Since 1950s, the decrease in sea ice area has almost linearly followed the increase of the cumulative CO_2 emissions (Notz and Stroeve, 2016). Aerial coverage of terrestrial snow pack in early summer has decreased even twice faster than September sea ice coverage (Derksen et al., 2015), enhancing permafrost thawing (Lawrence et al., 2015). Precipitation has increased over most of the terrestrial Arctic (Vihma et al., 2016). On the basis of climate model projections, during this century we can expect accelerating warming, snow and ice melt, and increase in precipitation (AMAP, 2017a).

Major environmental impacts related to climate warming include ocean acidification (AMAP, 2013), changes in biochemical cycles (Shakhova et al. 2007; Harada, 2016), such as the availability of nutrients, and numerous changes in marine ecosystems, e.g. in primary production (Petrenko et al., 2013), phytoplankton biomass and species composition, and fish species diversity (AMAP, 2017b). Primary production in the entire ice-free Arctic basin has increased by ~16% during 1998–2010, which is primarily a result of the drastic sea ice decline, but also due to the continuous growth of phytoplankton annual productivity, which has been approximately 32% higher than during 1959-2005 (Petrenko et al., 2013). In the marginal zone of the Arctic Ocean the primary production has increased less primarily due to the influence of river-runoff increase, ensuing water turbidity and worsening of water quality (Pozdnyakov et al., 2007). The higher gross primary production would affect air-sea fluxes of CO_2. Also an increase in the overall biological production including the production of higher trophic level organisms and fish populations could be foreseen (Doney et al., 2012). The warmer surface waters may enable the invasion of new species, which may dramatically impact the sensitive Arctic ecosystem by changing the pelagic food webs, energy flows and biodiversity. This aspect is very relevant for the regulation of international fisheries in the Arctic. The melting of permafrost together with increasing precipitation in the Arctic river basins may lead to flooding, and increasing the amount of freshwater and allochthonous materials in the Arctic shelves, and further in the Arctic Basin. All these processes may further impact the Arctic Ocean marine ecosystems, their productivity, and the key biogeochemical cycles in the region.

Mostly due to sea ice decline, economic interest in the marine Arctic has strongly increased. In particular, decrease of sea ice along the Northern Sea Route (NSR) will allow intensifying navigation, which is already occurring in the western parts of the route (Liu and and Kronbak, 2010). Although transit navigation through the entire NSR is still very limited and restricted to a short season in late summer – early autumn, there is a growing interest towards more extensive transit navigation (Smith and Stephenson, 2013). This interest and associated increase in Arctic research and technology development have been particularly strong among Asian countries: China, Japan and South-Korea. The Chinese initiative One Belt One Road (Tsui et al., 2017) together with the Chinese-Russian Ice Silk Road (Sørensen and Klimenko, 2017) are and will be facilitating the ongoing economic changes in the Arctic regions. In addition to navigation, economic interest towards the Arctic Ocean and its marginal seas is also growing due to the large off-shore hydrocarbon resources, fisheries, and tourism (AMAP, 2017b). The increasing industrial and transport activities generate large risks for the sensitive Arctic environment. The environmental impacts of increasing economic activities include worsening of air and water quality. Even more alerting than gradual trends is the increasing risk of accidents that may result in major oil spills.

Increases in navigation, other offshore activities, aviation, and tourism call for more accurate and extensive operational forecasts for weather, sea ice, and ocean conditions in the Arctic. These needs are recognized by the international community, and one of the concrete responses is enhancement of observational and modelling activities in the Arctic during the Year of Polar Prediction (YOPP, in 2017-2019) of the World Meteorological Organization, (WMO, 2013). Also, the Copernicus Marine and Atmospheric Services have since 2014 provided monitoring and short-term forecasting on global scale, including the Arctic (von Schuckmann et al., 2016). The services use various models, satellite data and available in situ data that are delivered in near real-time. However, the quality of the Copernicus services in the Arctic is uncertain, partly due to lack of in situ data. Above all, more data on atmospheric pressure, wind, temperature, and humidity as well as sea ice concentration

should be collected and assimilated to numerical weather prediction (NWP) and sea ice – ocean models (Inoue et al., 2013; 2015).

Changes in the Arctic have impacts also on non-Arctic regions with respect to weather and climate (Mori et al., 2014; Kug et al., 2015; Overland et al., 2015) as well as economics, above all in the transport (Furuichi and Otsuka, 2013) and hydrocarbon sectors (McGlade, 2012). Hence, ensuring a sustainable development of the Arctic maritime environment is not only important to the local and indigenous communities who reside in the Arctic but it is a global-scale societal need and challenge. The first practical steps needed include identification of processes of a high research priority and establishment of a coherent, coordinated, comprehensive observation system.

The Pan-Eurasian Experiment (PEEX) is a program to study large-scale research topics from a system perspective to fill the key gaps in our understanding of the interactions and feedbacks in the land–atmosphere–aquatic–society continuum (Lappalainen et al., 2014; 2016; 2018). The regional focus of PEEX has so far been in the Eurasian continent. PEEX has a hydrological component addressing terrestrial waters but not yet a marine component. Due to the importance of the marine Arctic in the climate system and the increased economic interest in the Arctic regions, it is vital that PEEX includes an active marine component, addressing physical and ecosystem processes in the ocean, sea ice, and marine atmosphere, and their alterations due to climate and environmental drivers. The Marine Arctic Component of PEEX (MA-PEEX) should be based on a combination of distributed, mostly autonomous, observations and flagship stations following the SMEAR (Station Measuring Ecosystem-Atmosphere Relations) concept, successfully applied in the Eurasian continent. The system is to be designed in collaboration with other programs addressing the present and future observation networks in the Arctic, including the Sustaining Arctic Observation Networks (SAON) and the Arctic Monitoring and Assessment Program (AMAP) established by the Arctic Council, the European Commission project Integrated Arctic Observation System (INTAROS), and several other programmes and networks.

The objective of this paper is to design the MA-PEEX, schematically illustrated in Figure 2. This requires identification of the actual research needs and the state of existing observations in relation to the needs (Section 2), evaluation of the information available on the basis of atmospheric and ocean reanalyses (Section 3), evaluation of the relevant socio-economic aspects that both affect and are affected by climate and environmental changes (Section 4), and assessment of the challenges, emerging opportunities, and concrete actions needed (Section 5). MA-PEEX is aimed to be integrated with the well-established structure and activities of the terrestrial and atmospheric components of PEEX. This requires particular attention to linkage and feedback processes, such as atmospheric transports in and out of the Arctic, river discharge, and various other coastal processes.

2. Existing observations and processes to be studied

Numerous processes are acting in the marine Arctic climate system: in the ocean, sea ice, and atmosphere. Many of these processes act on a subgrid-scale, and they accordingly need to be parameterized in Earth system models and operational NWP, ocean and sea ice models (Vihma et al., 2014). However, there is also a strong need to better understand synoptic and hemispherical-scale processes (Zhang et al., 2004; Overland et al., 2016), which, among others, link the marine and terrestrial Arctic. Process understanding is hampered by the sparsity of observations from the marine Arctic. This is related to the high cost of observations, difficult accessibility to the measurement sites, and the harsh environment for instruments. Below we first introduce some of the most important multidisciplinary observation systems in the marine Arctic (Section 2.1). Then we describe the key processes in the atmosphere, sea ice, and ocean, as well as the observations available to understand and quantify them (Sections 2.2 to 2.5).

2.1 Multidisciplinary observation platforms

Multidisciplinary observations of the coupled atmosphere – sea ice – ocean system are mostly based on coastal stations, drifting ice stations, and research cruises. The primary coastal stations in the MA-PEEX domain include the Villum Station Nord in Greenland, Ny Ålesund and Barentsburg in Svalbard, Cape Baranova at the coast of the Kara Sea, and Tiksi at the coast of the Laptev Sea. Providing long time series of key climate variables at fixed locations, these stations are cornerstones of the coastal Arctic observation system. The coastal station data have been applied in numerous studies addressing the Arctic atmosphere, sea ice, and ocean, described in Sections 2.2 to 2.5.

Considering the central Arctic Ocean, drifting ice stations have played a major role in the history of observations. The first in the series of the Soviet Union "North Pole" stations was operated in 1937-1938, followed by 30 stations during 1950-1991. In this century, Russia has continued to perform the comprehensive monitoring of the natural environment of the Central Arctic and studies of the physical processes that determine its state. These studies are especially important in terms of improving climate models. To obtain the new data about the above-mentioned processes, complex hydrometeorological observations had been organized at the drifting stations "North Pole-32" to "North Pole-40" in 2003 – 2014 (Figure 3). The most important western drifting stations have been the Surface Heat Budget over the Arctic Ocean (SHEBA) in 1997-1998 (Uttal et al., 2002), the Tara expedition during the International Polar Year in 2007-2008 (Gascard et al., 2008), and the Norwegian N-ICE expedition in the European Marginal Ice Zone in winter 2015 (Granskog et al., 2016). The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) will be the next major international experiment in 2019-2020, where the focus is studies of Arctic climate and ecosystem processes (http://www.mosaicobservatory.org/). Drifting stations provide unique possibilities to study the ocean, sea ice, snow, and atmosphere in the central Arctic.

Analogously to drifting ice stations, research vessel collect multidisciplinary observations from the marine Arctic. These are however, restricted to monthly time scales and biased towards summertime. Important cruises in the Eurasian sector of the Arctic have been carried out above all by Russian, Norwegian, German, Swedish and, more recently, Chinese and Japanese research vessels.

Regular observations on the atmosphere, sea ice, and ocean are also collected by drifting buoys deployed above all by International Arctic Buoy Programme (IABP). The present (November 2018) distribution of buoys is shown in Figure 4. The buoy observations on sea level pressure are important to detect the synoptic-scale pressure field, which is needed for initialization of NWP models (Inoue et al., 2013; 2015), atmospheric forcing for ocean and sea ice models, and for climatological and meteorological research. The buoy network is, however, often too sparse in the Eurasian sector of the Arctic Ocean (as in Figure 4). Various buoy applications are described more specifically in Sections 2.3 and 2.4, as well as in Appendix 1.

2.2 Marine atmosphere

The most important atmospheric processes over the marine Arctic can be divided into the following categories: (a) atmospheric boundary layer turbulence and exchange processes at the air-ice and air-water interfaces, (b) aerosol and cloud physics, (c) synoptic-scale cyclones and Polar lows, (d) orographically and thermodynamically driven processes over coastal regions, (e) circumpolar heat and moisture budgets, (f) stratosphere-troposphere coupling, (g) local and large-scale processes affecting air quality, and (h) Arctic – midlatitude linkages affecting weather and climate. In addition to process studies, there is need for climate-scale monitoring of key variables, which requires long-term observations taken at coastal stations or numerous consecutive drifting ice stations and buoys.

Small-scale processes over the sea, such as (a) and (b) above, can be best studied on the basis of observations from drifting ice stations (Section 3.1), research cruises, and research aircraft, but the spatial and temporal coverage of the data available is

limited. Good temporal coverage over recent years is achieved at coastal observatories, which gather plenty of valuable data on small-scale atmospheric processes over the coastal zone of the Arctic Ocean, including cloud and aerosol physics, radiative transfer, and atmosphere-surface exchange processes (Makshtas and Sokolov, 2014; Uttal et al., 2016; Grachev et al., 2018). Atmospheric observations taken at drifting stations and research cruises have been crucial to better understand small-scale processes related to the vertical structure of the Arctic atmosphere (Serreze et al., 1992; Palo et al., 2017), surface fluxes (Jordan et al., 1999; Persson et al., 2002; Andreas et al., 2010a,b), cloud physics (Tjernström et al., 2012; Shupe et al., 2013; Sedlar and Shupe, 2014), and aerosols (Tjernström et al., 2014). Coastal radiosonde sounding observations have been applied in studies of meteorological processes over the ocean (Maistrova et al., 2003; Tetzlaff et al., 2013). Research aircraft observations have been an important source of information on air-ice momentum flux and aerodynamic surface roughness (Lüpkes et al., 2013), atmospheric boundary layer physics, in particular the evolution of stable boundary layer during on-ice flows (Brümmer and Thiemann, 2001; Tisler et al., 2008) and the growth of convective boundary layer during off-ice flows (Chechin and Lüpkes, 2017), as well as mesoscale processes, such as low-level jet formation, during flows parallel to the ice margin (Guest et al., 2018). Moreover, aircraft observations have been applied to study the radiative and microphysical properties of the Arctic clouds (Ehrlich et al., 2008; Schäfer et al., 2015), the optical characteristics of the sea ice surface (Tschudi et al., 2001), and surface-atmosphere fluxes of greenhouse gases as well as latent and sensible heat (Kohnert et al., 2014; Hartmann et al., 2018).

Meso- and synoptic-scale processes, such as (c) and (d) above, can be studied on the basis of distributed observations but, due to their sparsity, in most cases observations have to be supplemented by model/reanalysis products. Among others, coastal mesoscale processes, such as wind channeling, katabatic and barrier winds, tip jets, and gap flows have been studied on the basis of high-resolution model products and observations (Reeve and Kolstad, 2011; Moore et al., 2016). Presently most studies on Arctic cyclones are based on model/reanalysis products (Sepp and Jaagus, 2011; Rinke et al., 2017), and this is the case also for large-scale processes, such as (e) to (h) above. Model/reanalysis products are available in a regular grid and therefore much more convenient to analyse than irregularly spaced observations. There is, however, a strong need for observations to evaluate the model/reanalysis products (Condron et al., 2006; Chung et al., 2013).

A common problem for research on all processes (a) to (h) is the limited amount of in-situ data on the vertical structure of the Arctic atmosphere. Satellite remote sensing on the vertical profiles of air temperature and humidity provide an attractive source of information. However, the vertical resolution of satellite remote sensing products is too coarse to study small-scale process and the role of the atmospheric boundary layer in larger-scale processes, and problems remain in remote sensing of cloud water and ice contents over sea ice. In situ observations on vertical profiles are needed for more accuracy and better resolution. In the marine Arctic out of the coastal zone, radiosonde soundings up to the altitudes of 15-30 km and tethersonde soundings up to 1-2 km are restricted to research cruises (Lüpkes et al., 2010; Brooks et al., 2017) and manned ice stations (Tjernström and Graversen, 2009; Vihma et al., 2008; Jakobson et al., 2013). In addition, lidars, sodars, cloud radars, and scanning microwave radiometers have been used to observe the vertical profiles of wind, temperature, humidity, cloud properties, and aerosols, but such data are restricted to a few campaigns (Tjernström et al., 2012; Mielke et al., 2014).

In-situ observations in the marine Arctic include several technical and environmental challenges, such as riming of instruments, darkness of the Polar night, instability of sea ice as a measurement field (leads may open within the field, causing danger for instruments and people), tilting of weather masts due to sea ice motions, low clouds and fog hampering airborne (research aircraft, Unmanned Aerial Vehicle, and tethered balloon) operations, Polar bears' interest towards the measurement devices, and disturbance of the airflow caused by ships and other constructions on ice stations (largest in conditions of stably-stratified boundary layer typical of the Arctic). Despite of these challenges, there is a strong need for more in-situ observations to better understand and quantify atmospheric processes and their interactions in the marine Arctic.

2.3 Sea ice

There are several dynamic and thermodynamic processes that need to be better understood to sufficiently quantify the state and change of the Arctic sea ice cover. Considering sea ice thermodynamics, the key processes are (a) sea ice formation and growth, including snow accumulation on top of sea ice and formation of granular ice types, and (b) sea ice and snow melt, including processes affecting ice and snow albedo, aerosol deposition on snow and ice, and evolution of melt ponds. Possibilities to observe the spatial distribution and temporal evolution of sea ice, snow and melt ponds in the Arctic Ocean have recently improved due to better satellite remote sensing methods (Spreen and Kern, 2017), airborne electromagnetic mapping methods (Haas et al., 2009), sea ice mass-balance buoys (Perovich et al., 2014), and community-based observations (Eicken et al. 2014; example at arctic-aok.org). In remote sensing, challenges still remain, among others, in distinguishing between melt ponds and leads under cloudy skies, as well as between surface snow and clouds. Layers of granular ice, formed due to refreezing of flooded or partly melted snow pack, on top of columnar ice may be detected using mass-balance buoy data supported by thermodynamic modelling (Cheng et al., 2014). Such layers may become more common due to thinning sea ice and increasing precipitation, favouring heavier snow load on top of thin ice, which increases the occurrence of flooding (Borodkin et al, 2016; Granskog et al., 2017). Under present conditions of decreased ice concentration and thickness, an influence of the ocean heat on the ice cover is increasing, providing positive feedback on a seasonal time scale (Ivanov et al., 2016). This effect is particularly important for the Atlantic sector of the Arctic Ocean, where inflowing warm waters facilitate an upward heat flux towards the ice base. This has occurred in recent winters in the Nansen Basin, reducing sea-ice formation (Polyakov et al., 2017).

Observational data on ice concentration and extent are satisfactory since the advent of passive microwave satellite remote sensing data in 1978 with a daily temporal resolution. Information on the evolution of ice thickness is, however, less accurate, the data consisting of submarine observations from several decades before year 2000 and satellite remote sensing data during the last two decades. Passive and active microwave instruments provide information on multiyear ice coverage, which can be used as a proxy for ice thickness (Comiso, 2012). Since about 2004, more accurate information is available from satellite altimeters applying lidars and radars at a resolution of about 25 km (Kwok et al., 2009). From the point of view of the atmospheric response to changes in sea ice cover, the most important sea ice variables are ice concentration and fraction of thin (less than 0.5 m) ice. Passive microwave L-band data from the Soil Moisture and Ocean Salinity satellite have shown unique capability to measure thickness of thin ice less than 0.5 m (Kalescke et al., 2012). Ice concentration is particularly important in conditions of a compact ice cover (> 90% ice concentration) in winter (Lüpkes et al., 2008). Also the flaw polynyas along the Russian shelf in winter are important. They open and close repeatedly during the winter, depending on wind direction and speed, and causing new ice formation during opening and ice rafting and ridging during closing (Dmitrenko et al., 2001).

Information on different ice types, floe size distribution, leads, and the snow pack on top of sea ice are collected during research cruises, ice stations and aircraft campaigns, as well as by satellite remote sensing methods. Considering exchange processes at the air-snow, air-ice, snow-ice, and ice-water interfaces, such as surface and basal fluxes of momentum, heat, freshwater, CO_2, and CH_4, direct observations are very limited, mostly restricted to specific field campaigns based on manned ice stations. However, data collected with sea ice mass-balance buoys allow possibilities for indirect estimation of the heat exchange at air-snow/ice and ice-water interfaces (Lei et al., 2018). The surface albedo is critical for the snow and sea ice mass balance during the melt season. It can be observed via remote sensing methods (Riihelä et al., 2013), but in-situ observations are needed to develop better model parameterizations for the dependence of albedo on physical properties of snow, ice, and melt ponds (Perovich and Polashenski, 2012). Further, better observations are needed on light penetration through snow and ice, which is important for the ecosystems in and below the ice (Kauko et al., 2017).

Considering atmospheric and oceanic forcing on sea ice dynamics, the best source of process-level information are simultaneous observations on the vectors of wind, ocean current, and sea ice drift (Leppäranta, 2011). In lieu of such data, sea

ice drift observations, based on buoys or satellite remote sensing, combined with reanalysis products for the wind and ocean currents yield valuable information at least on regional scales (Spreen et al., 2011; Vihma et al., 2012). Small-scale processes of sea ice dynamics, including deformation, rafting, ridging, and breaking of ice flows, are more difficult to observe, but advance has been made using ice-station observations on the internal stress of the ice field (Weiss et al., 2007) as well as seismometer (Marsan et al., 2012) and ice radar observations (Karvonen, 2016). Radar observations are good for detection of leads and ice ridges in areas where high-resolution (< 10 m) Synthetic Aperture Radar images are obtained. To cover larger areas, satellite remote sensing observations are needed, but challenges remain in detection of ice ridges. Large-scale evolution of the ice field results from a combination of thermodynamic and dynamic forcing, storms representing extreme cases of the latter (Itkin et al., 2017). Quantification of their relative contributions is still a challenge. This is partly related to inaccuracy of sea ice thickness data. Also, the thermodynamic and dynamic forcing factors may often support each other, for example when strong winds advect warm, moist air masses to the over sea ice, simultaneously generating melt and ice advection away from the study region (Alexeev et al., 2017).

In further development of sea ice observations, MA-PEEX should give a high priority to sea ice thickness and snow cover on top of sea ice, which are of a high climatological importance, as well as to sea ice ridges, whose occurrence and properties are important for navigation.

2.4 Ocean physics

Understanding the ocean heat and freshwater budgets is important for understanding the entire Arctic climate system and ecosystems, in particular their inter-annual and decadal variations. Most physical, chemical and biological processes in the Arctic Ocean are influenced by the quantity and geochemical quality of freshwater. However, the uncertainties in the heat and freshwater budgets of the Arctic Ocean and its marginal seas are not well quantified (Carmack et al., 2016). Different studies have yielded different results, but it is challenging to distinguish between differences originating from the lack and uncertainty of observations from those originating from temporal variations on inter-annual and decadal scales.

The Arctic Ocean stratification is characterised by a stably-stratified low-salinity surface layer, which results from positive net precipitation and freshwater inflow from the Arctic rivers, Greenland ice sheet, and the Pacific through the Bering Strait (Rudels 2012). The thickness of the surface layer is limited by a strong halocline underneath and varies on seasonal-to-decadal time scales and across the basin. The freshwater stored in the Arctic Ocean surface layer is either accumulated in the Beaufort Gyre or transported out of the basin via the Fram Strait and, in smaller amounts, via the Canadian archipelago. Warm and saline Atlantic water flows into the Arctic Ocean mainly through Fram Strait in the West Spitsbergen current and St. Anna Trough. Formation of different water masses, characterized by combinations of temperature and salinity, in various parts of the Arctic Ocean takes place via heat loss to the atmosphere and freshening via precipitation and mixing with melt water and riverine water (Ivanov and Aksenov, 2013; Rudels et al., 2014). Tides and wind waves in the Arctic Ocean are important for the climate, coastal erosion, and navigation. Tides contribute to mixing of water masses, further affecting sea ice melt (Luneva et al., 2015) and the global ocean conveyer belt with potential impacts on the Arctic and global climate (Holloway and Proshutinsky, 2007). Other small-scale processes important for climate include exchange of momentum, heat, and salt at the ice–ocean interface, brine formation (Bourgain and Gascard, 2011), diapycnal mixing (Rainville et al., 2011), double diffusive convection (Sirevaag and Fer, 2012), as well as (sub-) mesoscale eddies and fronts (Timmermans et al., 2012).

Multidisciplinary in situ data in the Arctic Ocean are collected mainly during icebreaker expeditions, aircraft surveys, and manned drifting platforms. However, these activities are irregular in time, very expensive, biased to the summer season, and hence poorly suited for providing regular long-term monitoring data. Moorings have been deployed at key locations in the gateways and rims of the Arctic Ocean (Figure 5), but they mainly deliver physical parameters from fixed depths in a delayed mode (Beszczynska-Möller et al., 2011). Nevertheless, observations have allowed documenting of Atlantic Water warm pulses

in this century (Polyakov et al., 2011) and revealing the strong seasonal cycle in the intermediate Atlantic Water layer deep below the ocean surface, which was not directly measured before (Ivanov et al., 2009; Dmitrenko et al., 2009). The SST field over the open ocean is fairly accurately known during the satellite era. Decadal and inter-annual changes of wind wave fields in the Barents and White seas in the period 1979-2010 have been estimated on the basis of the NCEP/CFSR reanalysis and numerical models. Information on the wave statistics and validation techniques applied are provided by Medvedeva et al. (2015), Myslenkov et al. (2015; 2017) and Korablina et al. (2016). The maximum of significant wave height reaches 15-16 m in the Barents Sea and 4-5 m in the White Sea. Model experiments for storm surges in the Barents and White seas have shown that most of the highest surges are formed after a passage of a Polar low (Korablina et al., 2016). The Onega Bay in the White Sea and the Haipudyr Bay in the Barents Sea were found as areas of the most frequent formation of surges over the last decades.

Considering spatial differences, the availability of oceanographic data is comparatively good in the Barents Sea, Bering Sea, and Greenland/Norwegian Sea, whereas there are far less data from the less accessible central and eastern parts of the Arctic Ocean and Russian shelves. Extended spatial coverage of the upper Arctic Ocean observations is provided by the Ice-Tethered Buoys (ITP), which allow high resolution profiling in the uppermost 800-1000 m layer and straightforward transmittance of data via satellite.

To understand the hydrography of the Arctic Ocean, it is important to have good observations of the river discharge. In Eurasian Arctic, the number of monitoring stations for river discharge reached its maximum during the 1980s, when about 74% of the total non-glaciated Pan-Arctic was monitored (Shiklomanov and Shiklomanov 2003). Later, there was significant decline in gauges in Russia mostly due to population decreases in high-altitude areas, loss of qualified personnel, and insufficient financial support (see Section 4). The total Pan-Arctic area monitored decreased by 67% from 1986 through 1999, and in Russia the decrease was 79% (Shiklomanov et al. 2002). More recently, the situation has improved by the Arctic-RIMS (Rapid Integrated Monitoring System, http://rims.unh.edu), which allows to characterize water budgets across the pan-Arctic drainage region. In addition, the historical archives of the Global Runoff Data Centre and R-ArcticNET (A Regional, Electronic, Hydrographic Data Network For the Arctic Region) allow monitoring of changes in the hydrological cycle.

As a summary, process understanding and quantification of the state and changes of the Arctic Ocean circulation, heat and freshwater budgets, as well as small- and meso-scale processes are limited by the insufficient amount of observations. A specific challenge for in situ observations of the ocean is that only a part of the data are available in real time, whereas a lot of data can only be gathered when the instruments are recovered from the ocean.

2.5 Ocean chemistry and ecosystems

With increasing CO_2 partial pressure in the atmosphere, the capacity of the world oceans to uptake CO_2 continues to decrease as the reaction of CO_2 dissolution gradually tends to saturation. Under such conditions, the planetary greenhouse effect enhances. In turn, the ensuing surface ocean temperature growth leads to a shift of dissociated calcite, $CaCO_3$, to its solid phase (Chen and Tang 2012). Thus, the actual balance between dissociated and suspended phases of CO_2 becomes an issue of paramount importance (Seinfeld and Pandis, 2016). Shifts in the exchange of CO_2 between the aquatic medium and the boundary layer above are highly consequential also in terms of acidification of seas. In combination with the co-occurring external forcings, both processes are conducive to a variety of alterations in marine hydrobiological processes. Among the latter are the formation of nutrients uptakable by phytoplankton, rates of intracellular metabolism, primary production, and reshufflings in phytoplankton species composition and abundance (Bates and Mathis, 2009).

Because of immense sizes (up to millions of square kilometers) of *E. huxleyi* bloom areas (Figure 6) and their active spatio-temporal dynamics, exclusively satellite observations are capable of providing adequate information on this phenomenon and its consequences. Due to recently developed methodologies and image processing algorithms, space-borne means are highly efficient in quantification of many parameters characterizing the features and properties of *E. huxleyi* blooms, such as (*i*) the

bloom area, (*ii*) duration of blooming (exact dates of bloom outburst and disappearance), (*iii*) content of the alga-produced inorganic carbon within the bloom, (*iv*) increase of partial pressure of dissolved carbon dioxide (CO_2) with regard to its background values, and (*v*) increase of CO_2 content in the atmospheric column over the bloom. For such purposes Ocean Colour Climate Change Initiative (OC-CCI) satellite data yield reliable information, from which quantification of the above parameters (*i- iv*) is feasible, whereas Orbiting Carbon Observatory 2 data are better for quantification of parameter (*v*). Satellite OC-CCI data permit to retrieve the time series of parameters (*i- iv*) since 1998 for all marine environments where the phenomenon occurs. Moreover, employment of data from various other optical and microwave satellite sensors permit to enrich the data on parameters (*i-v*) with the accompanying/supplementary data on a number factors that can condition the development of the phenomenon, such as water surface temperature, water salinity, near-surface wind speed and direction, ice edge and ice-fee area, cloud fraction, and downward solar radiation in the PAR spectral range. This allows to reveal the major bloom-forcing environmental factors and prioritize them and, with the application of climate models, to predict the phenomenon dynamics in the forthcoming several decades (Kondrik et al., 2017, 2018a,b,c).

Nitrogen, phosphorus, iron and silicon are indispensable in primary production processes. Organic carbon is the principal forage for heterotrophic bacteria. Thus, the balance in input of the above substances controls the net carbon dioxide content in marine ecosystems. Allochtonous dissolved organic matter (ADOM) is also highly important in establishing the status quo of the light regime in such waters. The input and spread of the above elements are ultimately important for the marine ecosystem workings not only within the outfall of the major Eurasian rivers and adjacent shelf zones but across the entire Arctic Ocean.

Observations on the surface fluxes, carbonate system, other biogeochemical variables, and food chain are mostly restricted to scientific cruises and sparse coastal observations. However, bio-optical sensor suites are developed for ITPs for ecosystem monitoring (Laney et al., 2014). In moorings, biogeochemical sensors are still very limited; only in the Fram Strait, the key region for Arctic-Atlantic exchanges, a multi-disciplinary moored observatory has been implemented for long-term ecosystem monitoring (Soltwedel et al., 2005).

2.6 Linkages between the marine Arctic and Eurasian continent

The linkages between the marine Arctic and Eurasian continent can be broadly divided in three groups (a) large-scale atmospheric transports and teleconnections, (b) river discharge, and (c) atmospheric and oceanic mesoscale processes in the coastal zone. Considering (a), there is continuous atmospheric transport of heat, moisture (Dufour et al., 2016), pollutants (Bourgeois and Bey, 2011; Law et al., 2015), and other aerosols (Ancellet et al., 2014; Popovicheva et al, 2017) between the Eurasian continent and the marine Arctic. Most of the transport is carried out by planetary waves and transient cylones, but also the mean meridional circulation, related to the Polar cell, contributes to the transports. Planetary waves include both propagating and quasi-persistent features in the atmospheric pressure field, such as the Siberian high-pressure pattern (Tubi and Dayan, 2013). Heat and moisture are transported both northwards and southwards, but the net transport across latitudes 60 and 70°N is northwards over most of Eurasia. However, southward net moisture transport occurs in summer in the belt between 40 and 140°E (Naakka et al., 2019). In addition to transports, planetary wave patterns generate teleconnections from the marine Arctic to Eurasian continent, as far as southern China (Uotila et al., 2014). Due to the Arctic amplification of climate warming, individual cold-air outbreaks from the central Arctic to mid-latitudes have become less cold on the circumpolar scale (Screen, 2014). However, several studies suggest that Arctic changes, in particular the sea ice loss in the Barents and Kara seas, favours more frequent occurrence of winter cold-air outbreaks in central and eastern Eurasia (Mori et al., 2014; Kug et al., 2015; Jaiser et al., 2016; Vihma, 2017). The sea ice loss from the Arctic Ocean has also resulted in increased evaporation from the Arctic Ocean (Boisvert and Stroeve, 2015), and some studies suggest that this has caused increased snow fall in Siberia (Cohen et al., 2014).

Considering the coastal and archipelago zone of northern Eurasia, the atmospheric processes include coastal effects on the wind field, which are driven or steered by orographic and thermal effects (Moore, 2013). A remarkable change during recent decades is the intensification of the summertime frontal zone along the Siberian coast (Crawford and Serreze, 2016). In summer the terrestrial Arctic has warmed much faster than the marine Arctic (Figure 1), increasing the north-south temperature gradient. However, the Arctic coastal frontal zone is not a region of cyclogenesis, but favours intensification of cyclones formed over Eurasia (Crawford and Serreze, 2016).

Via river discharge, freshwater as well as dissolved and particulate matters are transported from the Eurasian continent to the Arctic Ocean. River discharge impacts the sea ice and ocean, including the water quality (Sonke et al., 2018), water column light climate (Pozdnyakov et al., 2007; Carmack et al., 2016), storm surges (Wicks and Atkinson, 2017), and coastal erosion (Overduin et al., 2014). Degradation of permafrost has recently led to increased runoff, erosion and associated transport of total suspended mater and nutrients and refractory organic carbon release, which has a significant impact on both regional and global carbon and biochemical cycles (Shakhova et al. 2007). Interaction of these processes in the changing climate system is complex, but we expect to see that increasing primary production and water turbidity will result in heat accumulation in the upper layers of the coastal ocean, strengthening of the thermal the stability, and shallowing of the thermocline. This will also cause some increase of alkalinity and buffering against CO_2 driven ocean acidification (Lenton and Watson, 2000). Considering sediment and water quality components, only approximately 10% of the catchment area is monitored. The main datasets are based on regional studies recently performed in Lena (Hölemann et al. 2005), Ob (Shakhova et al. 2007), and Amur (Levshina 2008; Chudaeva et al. 2011) rivers, and summarized in reviews (Savenko 2006; Bagard et al. 2011; Pokrovsky et al. 2015). The existing datasets underestimate the fluxes of particulate heavy metals from the Siberian rivers to the Arctic Ocean due to sampling infrequency and uncertainties in sampling procedures (Chalov et al., 2018). To improve estimates of fluvial export, multiyear chemicals data sets from a coordinated sampling program have been collected since 2003 under ArcticGRO program at the six largest Arctic rivers (Holmes et al. 2012; McClelland et al. 2016). Since 2018 under PEEX umbrella, the ArcticFLUX project provides estimates of dissolved and particulate organic matter, nutrients and metals fluxes based on unprecedented dense river cross-section samples at the outlets of four largest Siberian rivers (Ob, Yenisey, Lena and the Kolyma) multiple times per year (Figure 7).

Coastal erosion processes in the Arctic Ocean lead inter alia to inundation of the terrestrial coastal zone, which is due to wind driven breaking of the fast ice and exposure of the coast to marine wave action (Section 2.4), destruction of coastal forefront soil, and formation of a sloping bank. As a result, extensive areas of terrestrial permafrost become submarine permafrost. Because of ensuing warming, submarine permafrost starts thawing. The bottom thermal conditions thus change, and the processes of release of CO_2, methane, and other volatile substances from thawing submarine permafrost start developing on very large scales (Overduin et al., 2016). Despite the importance of this process, we have limited knowledge on submarine permafrost distribution, its thermal state, as well as rates of greenhouse gas liberation and transport up into the atmosphere (Ping et al., 2011). Karlsson et al. (2016) suggest that terrestrial matter dominates in both water column and surface sediment of Arctic rivers compared to marine matter released from the sea floor.

As a summary, the present observation network is sufficient to detect synoptic-scale processes in the atmosphere, but improvement is needed to detect coastal mesoscale flow features and to better quantify the magnitudes, vertical profiles, and trajectories of atmospheric transports. Considering river discharge, due to the dominating role of largest rivers, only 12 hydrologic gauges are sufficient to capture 91% of total monitored area and 85% of total monitored discharge. However, for a detailed description of the state of Arctic land surface hydrology and its effects on the ocean, it is necessary to record the discharge also from much smaller sub-basins. There is also a strong need for more observations on coastal erosion and its consequences.

3. Atmospheric and ocean reanalyses

The most complete information on the state of the marine Arctic climate system is based on combinations of observations and model results. Such combinations are produced via data assimilation to generate (a) analyses for initial conditions of operational forecasts and (b) reanalyses, where the same operational model version and data assimilation system is applied over a long historical period. Hence, reanalyses are more coherent in time, as the results are not affected by changes in the operational model version and data assimilations method. Reanalyses consist of time series of the three-dimensional state of the atmosphere and ocean on a regular grid. Broadly applied atmospheric reanalyses include the global ones produced by European, U.S., and Japanese agencies and the regional Arctic System Reanalyses. A regional high-resolution reanalysis for the European Arctic is under work. Although these are the best sources of information on the past state of the Arctic atmosphere, reanalyses include also challenges, in particular in the Arctic, where the observational coverage is limited. Major errors occur in near-surface air temperature and wind, as well as air moisture (Lüpkes et al., 2010; Jakobson et al., 2012; Lindsay et al., 2014) and clouds (Makshtas et al., 2007; Lindsay et al., 2014). The problems are related, among others, in modelling of mixed-phase clouds, stably-stratified atmospheric boundary layer over ice and snow, and the boundary layer in conditions of very heterogeneous surface temperature distribution.

Global and regional ocean reanalysis products are increasingly used in polar research, but their quality has only recently been systematically assessed (Uotila et al. 2018). First results reveal consistency with respect to sea ice concentration, which is primarily due to the constraints in surface temperature imposed by atmospheric forcing and ocean data assimilation. However, estimates of Arctic sea-ice volume suffer from large uncertainties, and the ensemble mean does not seem to be a robust estimate (Chevallier et al. 2017). On average, ocean reanalyses tend to have a relatively low heat transport to the Arctic through Fram Strait and, as a result, cooler than the observed Atlantic water layer. These results emphasise the importance of atmospheric forcing, air-ocean coupling protocol and sea-ice data assimilation for the product performance.

The example illustrated in Figure 8 highlights the ocean reanalyses performance in terms of ocean salinity in the Eurasian basin. In the surface layer, the top 100 m, their salinities disagree the most due to differences in the surface layer freshwater balance. The freshwater originates from melted sea ice, atmospheric precipitation, river runoff and to a limited extent from the Pacific. Also, the amount of inflow of saline Atlantic water affects the basin salinity profile. Notably, the multi-product mean appears relatively close, although too fresh, to the observational products in contrast to many individual reanalyses. This feature is common to many climate model ensembles.

Large salinity disagreements in the surface layer do not co-vary with the corresponding temperature disagreements (not shown), which are the largest in the Atlantic Water layer below (300-700 m). The surface layer temperatures typically stay close to the freezing point around the year, and are also strongly constrained by the prescribed atmospheric near-surface temperatures used to drive many of the ocean reanalyses. For the products shown in Figure 8, these air temperatures are based on atmospheric reanalyses, mostly ERA-Interim. A notable exception is the Ensemble Coupled Data Assimilation System, version 3 (ECDA3) which is a coupled atmosphere-ocean product with the atmosphere relaxed towards NCEP-NCAR renanalysis. However, in addition to large ocean temperature discrepancies compared to other products (not shown), ECDA3 also has the largest salinity disagreement in the Eurasian Basin (Figure 8b).

The accuracy of Eurasian Basin surface layer salinity in ocean reanalyses is strongly affected by the Siberian river runoff. Currently all reanalyses use a variety of adjusted runoff climatologies. This is clearly a shortcoming, and improving the practice is one of the objectives of MA-PEEX. The use of inter-annually varying runoff data ideally based on all available observations would be a major step towards a more realistic Arctic Ocean reanalysis, in particular when combined with better precipitation, wind and temperature data from the latest atmospheric reanalyses.

4. Socio-economic evolution in the marine and coastal Arctic

In general, PEEX is interested in developing methods and concepts for integrating natural sciences and societal knowledge as a part of Earth system sciences. The present socio-economic component of PEEX includes research on energy policy changes and their effect on the greenhouse gas emissions, especially in the Russian Arctic and Siberian regions (Lappalainen et al., 2016; 2018). PEEX has a modelling framework with an objective to link the energy consumption to emission models and current IPCC Representative Concentration Pathway scenarios, and then run climate models. Climate models provide input for the air quality, climate and aerosol predictions. This framework is relevant also for the marine and coastal Arctic. The marine Arctic is expected to become increasingly important from the socio-economic point of view, which will significantly broaden the socio-economic research activities of PEEX. The socio-economic importance of marine Arctic is related to sustainable livelihoods of the local communities as well as future prospects for increasing navigation, fisheries, and oil and gas drilling (International Maritime Organization, 2016).

Contemporary socio-economic conditions for the development of coastal areas of Arctic and northeastern Eurasia (coastal areas of the Bering and Okhotsk Seas) are characterized by considerable contrasts (Vlasova and Petrov, 2010). On one hand, the oil and gas areas of the Yamalo-Nenets and Nenets Autonomous Okrugs have a strong economic momentum due to the development of new, non-depleted hydrocarbon fields and the implementation of new Liquefied Natural Gas (LNG) projects addressing European and Asian markets (Glomsrod et al., 2015). On the other hand, the coastal areas of Arctic Asia, including the Arctic regions of Yakutia, the territories of the Chukotka Autonomous Okrug, the Kamchatka Region and the Magadan Region, are characterized by a long-lasting loss of population and only a limited implementation of point-based short- and medium-term projects in gold mining as well as extraction of polymetals and coal (Hill and Gaddy, 2003). Between these poles of economic success and depression, intermediate conditions occur in the Murmansk Region (Myllylä et al., 2008), the Arkhangelsk Region and the northern parts of the Krasnoyarsk Region, in which, for decades of industrial development, powerful territorial-production complexes (Rutt, 1986) have been created in the fields of maritime transport, mining industry, and timber processing. All three regions have accumulated significant industrial material assets, and skilled human resources in the industrial sector (Bolotova and Stammler, 2010). At the same time there are many environmental and closely connected socio-cultural problems inherent in these old industrial districts of the Russian Arctic (Orttung, 2018). In the most accessible Murmansk and Arkhangelsk Regions, tourism has been developing for the last two decades. An important role belongs to mutual recognition of these territories under the umbrella of the Barents Region Initiative, which is one of the most successful and energetic cross-border cooperation examples in the circumpolar Arctic.

Contrast is also characteristic for the situation in navigation issues along the Northern Sea Route. Years 2016 and 2017 have exceeded the peak of the Soviet-era transport in 1986, when 6.5 million tons were transported. However, in the 1980s this was achieved via a uniform operation along the entire Northern Sea Route, but now it is achieved mainly via transportation on the western parts of the Northern Sea Route. There the opening of new offshore and onshore hydrocarbon fields and the construction of a completely new port and the city of Sabetta have enhanced the regional development (Huskey et al., 2014). The situation is very different in the eastern sector (east of Dikson) of the Northern Sea Route. There are no major new projects onshore, although exploration work on the Kara Sea shelf, the Laptev Sea and, in the future, East Siberian and Chukchi Seas is and will be steadily intensifying. A completely different story is in the Sea of Okhotsk, where for more than 15 years has been an industrial production of hydrocarbons for export markets.

Against the backdrop of the strongest polarization of socio-economic development of the coastal areas of the Arctic and the northern Far East (northeast Asia), a common trend is emerging for all the territories – that is, "hydrocarbonization" of economy. The economic profile of several territories, which were previously largely based on small-scale reindeer husbandry and fisheries, is gradually beginning to shift to hydrocarbon economy under the influence of new discoveries of gas and oil both offshore and onshore. This will require very thorough and much more numerous distribution of stationary and mobile

research activities of the natural environment and climate, their changes, and the impact of these changes on the risks of economic activity on land and at sea as well as on the livelihood and culture of the local communities. Such integrated research has been conducted for many years in the delta of Lena, on the basis of the Tiksi settlement. However, the scale of the new economic development and the formation of entirely new industrial regions on land and shelf of the Arctic will require much more intensive and regular research of the Eurasian Arctic. Examples of numerous and not completely understandable new environmental events, such as craters in the Yamal, unexpected releases of gas hydrates (Bogoyavlenskiy et al., 2017), and frequent accidents of oil and gas pipelines under the influence of thawing permafrost demonstrate the need to increase interdisciplinary research efforts to understand the general patterns of development of natural-economic systems in the highly unstable modern Eurasian Arctic.

Another important and relatively new trend is the processes of gradual consolidation of the coastal municipal formations of Eurasian Arctic, as evidenced, for example, by the recent establishment of the Association of Coastal Municipalities of the Arctic Zone of Russia (Rasmussen, 2011). Common challenges related, among others, to climate change and its effects on socio-economic stability of these territories will contribute to such consolidation. In Section 6 (Item F), we suggest concrete research needs in this multifaceted socio-economic situation.

As a summary, a sustainable socio-economic development is needed to keep the Eurasian coastal Arctic populated (Laruelle, 2014), which also favours development and maintenance of high-quality observation network for weather, climate and environment. A major challenge is that, in a short time perspective, the strongest economic development is obtained via oil and gas industry, but it simultaneously increases the risk of environmental and socio-economic hazards, such as oil spills (EPPR, 2017), and accelerates climate warming with dangerous consequences (AMAP, 2017a,b).

5. Discussion: The way forward

The knowledge on physical, biogeochemical, and ecosystem processes in the Arctic Ocean and the overlying atmosphere is limited. Improvement of the observing system is, however, a pronounced technological and logistical challenge. In the design of MA-PEEX, the SMEAR concept, successfully applied in PEEX (Lappalainen et al., 2018), can be applied in coastal and archipelago stations, such as Tiksi, Cape Baranova, Ny Ålesund, Barentsburg, and Villum Station Nord. A key question in the design of the observation system for the offshore regions is, if instead of the SMEAR concept it will be more cost-effective to further develop a strongly distributed marine observation network. The trend in marine observations, both globally and in the Arctic, has been towards increasing application of autonomous buoys, moorings, autonomous underwater vehicles (AUVs), and unmanned aerial vehicles (UAVs), and the relative importance of centralized observations in research vessels and ice stations has simultaneously decreased. In the Arctic these trends have been enhanced by the sea ice decline.

Here we propose how to proceed and what actions are concretely needed to develop MA-PEEX. Particularly important is that MA-PEEX will be well integrated with the existing atmospheric, terrestrial, and socio-economic components of PEEX. This requires special attention to the linkage processes, such as atmospheric teleconnections and transports in and out of the Arctic, river discharge and related transports of dissolved and particulate matter, as well as various coastal processes. Further, it is vital that MA-PEEX will be developed in close collaboration with all relevant programs and projects active in the study region. In addition to close international collaboration, the way forward includes opportunities arising from development of new technology, community-based observations, improved data management, and better atmosphere-ocean reanalyses. Further, there is a strong need for cross-disciplinary research to obtain comprehensive understanding on the interactions between the physical climate system, ecosystems, and socio-economics, which all are changing rapidly. The principal concrete actions needed are as follows.

A. MA-PEEX will work towards establishment of improved and sustainable Arctic observation infrastructure. This includes the following: (i) regular research cruises, (ii) monitoring of the riverine biogeochemical flux at the outlets of the largest Arctic rivers based on prototype established under the ArcticFLUX project under the PEEX umbrella project (see section 2.6) (iii) regular deployment of various autonomous instruments (See B below) in the Arctic Ocean, (iv) maintenance of radiosonde sounding network in the MA-PEEX domain and supporting it by enhanced vertical profiling of the atmosphere using ground-based remote sensing devices and UAVs, and (v) establishment of a mechanism for ships navigating the Arctic to collect and share routine weather, sea state, and sea ice observations.

We realize that establishment of this infrastructure includes several challenges. First, most of the existing marine Arctic data, including both atmospheric and ocean observations, are collected under time limited research projects. The challenge is to reach long-term sustainability, monitoring enhancement, and harmonization of the Arctic observations, to improve the scientific understanding of the complex and sensitive Arctic environment. This is also the objective of the ongoing EU project INTAROS (http://www.intaros.eu). Close collaboration with INTAROS will therefore provide an excellent starting point for MA-PEEX. Other potential key collaborators for MA-PEEX include the Argo program (a global array of autonomous instruments measuring subsurface ocean properties; Riser et al. (2016)), Arctic Coastal Dynamics project (Lantuit et al., 2012), and the Arctic Regional Ocean Observing System (Sandven et al., 2005).

Further, systematic studies are needed to keep the evolving observation network optimal. MA-PEEX should adopt the YOPP approach to carry out model experiments to quantify the benefit of various observations on weather, sea ice and sea state forecasts, and optimize the observation network accordingly. MA-PEEX should also consider the optimization from the points of view of climate and ecosystem research and related information services.

B. MA-PEEX will effectively utilize new observation methods.

Recent advances in observation technology generate improved possibilities to quantify the state of the atmosphere, cryosphere, and the ocean. There is potential for a more extensive application of UAVs for atmospheric research, new types of buoys for sea ice research, as well as ice-tethered profilers and AUVs for ocean research. Several devices are already available and tested in harsh Arctic conditions, and the technology is developing fast. The opportunities arising are described in more detail in Appendix 1. However, challenges remain in financing spatially and temporally extensive observations. Their cost-effectiveness needs to be concretely proved. In addition, there are challenges in data sharing, and a concrete need to solve legal and administrative problems related to observations across territorial waters and marine economic zones. In this respect, MA-PEEX shall collaborate with the Arctic Council (AMAP, 2012).

C. In collaboration with local and indigenous people, MA-PEEX will further develop community-based observation systems in the coastal regions of the marine Arctic. Some community-based observing systems have been established in all Arctic countries (Gofman 2010; Johnson et al. 2016; Danielsen et al. 2017). In Appendix 2 we summarize a present systems in Greenland, which are among the most advanced and may serve as an example to develop analogous systems in the other parts of the MA-PEEX domain. With more human activities in the marine Arctic and rapidly improving technological possibilities for data transmission (e.g., via mobile phones), there will be increasing opportunities for community members to contribute to collection of data and improvement of understanding of the state and change of the marine Arctic (Eicken et al. 2014; Johnson et al. 2015).

D. MA-PEEX will establish a coordinated, multidisciplinary, sustained, open access data management system.

The Arctic in situ data are presently managed in a large diversity of levels, reflecting the many types of observing systems, which differ in the technical solutions adopted and in the maturity and organization of their various components. Advance in data management can be made by building connections between distributed data repositories. Initiatives such as AMAP,

IABP, Arctic ROOS, Copernicus Marine Services, INTAROS, as well as SAON committees, the Arctic Data Committee and Committee on Observations and Networks, will all contribute to the overall collection of data as well as dissemination and management of data from the Arctic. MA-PEEX is expected to particularly benefit from the support provided by Arctic Data Committee to adopt, implement and develop (where necessary) data and metadata standards. To ensure that research data are soundly managed, the European Commission has recently published data management guidelines for the Horizon 2020 projects (Wilkinson et al., 2016). The guidelines help to make the research data findable, accessible, interoperable and reusable (FAIR). It requires that the data are accompanied by rich metadata and are uniquely identified by persistent identifiers. The FAIR principles will be applied as much as possible for the multidisciplinary data produced in MA-PEEX.

E. MA-PEEX will contribute to new reanalyses and effectively utilise them in research.

The emergence of large number of atmosphere, ocean and coupled reanalysis products shows a major promise, and they are becoming an increasingly valuable resource for researchers of the marine Arctic. MA-PEEX will make its observations available for atmospheric and oceanic reanalyses, and apply the observations in evaluation of existing and new reanalyses. With more powerful computational resources, models can be run with higher precision being able to resolve smaller flow features with less need for a subgrid-scale parameterization. For example, significant improvement in the realism of ocean reanalyses is expected, as the ocean models increasingly start to resolve ocean eddies. Further, reanalyses will be increasingly based on ensemble forecasting, and more sophisticated data assimilation methods, such as the four-dimensional variational assimilation, are constantly being developed and applied. Fast development is expected particularly for sea-ice data assimilation, with emerging utilization of adjoint methods and observations on sea-ice thickness (in addition to sea-ice concentration) (Koldunov et al. 2017). Finally, coupled reanalyses products are becoming increasingly available. They realistically resolve air-ice-ocean interactions compared to their stand-alone atmosphere and ocean counterparts (Zhang et al., 2017; Uotila et al., 2018), and one can expect that their realism will further improve due to intensive development efforts. However, there are numerous variables, above all related to atmospheric composition and ocean biogeochemistry, which are not included in presently available reanalyses. Advance in observations is crucial to provide a basis for their inclusion in reanalyses. Further, a concrete action towards more realistic Arctic Ocean reanalysis is to use temporally varying river runoff data based on all available observations.

F. MA-PEEX will address actual socio-economic research questions in the marine and coastal Arctic. These include (a) reasons for differences between the rapidly developing western part of the Russian coastal Arctic and the economically stagnated eastern part, (b) challenges and risks related to the development of offshore oil and gas fields, and (c) the potential instability in the interaction of environmental, socio-cultural and economic conditions due to large-scale projects for the creation of new ports and transport corridors in the Eurasian Arctic. In (a) – (c), MA-PEEX will progress, among others, by establishing a close research coordination between the new activities in the Arctic in those in the Sakhalin region, where there is more than 15 years of experience in the development of industry on the shelf. Investigation of the similarities and differences of these regions will yield new knowledge on the Arctic specificity in the interaction of natural and economic systems.

Further, better weather and marine services are needed to enable environmentally and socially responsible growth. The environmental risks associated with Arctic offshore activities are closely tied to adequate anticipation of adverse weather and ice conditions. How and to what extent the Arctic service level will unfold depends also on the international cooperation regarding regulations and their enforcement regarding environmental protection and transport safety in the Arctic. Closer interaction between model developers, forecast and service providers, and end-users should include

interactive elicitation of user needs, stepwise co-development of needs and capabilities, and assessment of service improvement response thresholds.

In addition, to promote sustainable development, MA-PEEX should evaluate the potential for renewable energy production in the coastal Russian Arctic, including mapping of wind power resources, as already done in parts of the MA-PEEX domain (Starkov et al., 2000; Tammelin et al., 2013).

As a summary, MA-PEEX will promote international collaboration, sustainable marine meteorological, sea ice, and oceanographic observations, advanced data management, and multidisciplinary research on the marine Arctic and its interaction with the Eurasian continent.

Appendices

Appendix 1. Opportunities arising from new observation technology

Rapidly developing observation technology opens new opportunities to study the Arctic atmosphere, ocean, and sea ice. Considering the atmosphere, small, cost-effective UAVs can be applied to observe vertical profiles of air temperature as well as wind speed and direction up to 2-3 km (Reuder et al., 2012) even in winter conditions over sea ice (Jonassen et al., 2015; Figure A1). Large sophisticated UAVs, such as the Global Hawk, can operate on circumpolar scales in the Arctic, also releasing dropsondes (Intrieri et al., 2014). The fast technological development in the field is expected to continue, but there are challenges related to financing of extensive UAV activities and to legal regulations, in particular for flights crossing the borders of national air spaces (AMAP, 2012). Another potentially useful method for meteorological observations is Controlled Meteorological Balloon, already tested in harsh Polar conditions (Hole et al., 2016). Further, we expect better possibilities for atmospheric and Earth surface observations also via advance in performance and instrumentation of manned research aircraft. We also expect further advance in ground/ship/ice-based remote sensing of the Arctic atmosphere, as the methods introduced in Section 2.2 are progressively improving. Further, recent advance in satellite remote sensing has yielded better information on the temperature and humidity profiles over ice and snow (Perro et al., 2016).

There is promising development in autonomous ocean observing systems, which can significantly improve the capacity to collect data from the Arctic seas. Ice-Tethered Profilers (ITPs) provide high-quality upper-ocean observations available from the central Arctic throughout the year (Toole et al., 2011). ITPs offer a platform that can carry a cluster of instruments with capability to transmit data via satellite in near real-time. Bio-optical sensor suites are developed for the ITPs for ecosystem monitoring (Laney et al., 2014). Development of geo-positioning systems has made it possible to apply gliders and floats below Arctic sea ice (Lee et al., 2013; Sagen et al.,2017), although European gliders have not yet been tested in ice-covered Arctic seas. New opportunities are also arising from regional networks for acoustic thermometry and passive acoustic observations (Mikhalevsky et al. 2015; Worcester et al., 2015).

Sea ice mass-balance buoys are already widely used to monitor the evolution of snow depth and ice thickness on ice floes drifting in the Arctic (Perovich et al., 2014). A new type of mass-balance buoys consists of a high-resolution (2 cm) thermistor chain from the ocean through ice and snow to atmosphere (Jackson et al., 2103). Its cost-cutting design makes it possible to deploy a large array buoys to investigate regional snow and sea ice thickness distribution in the Arctic Ocean. An automatic algorithm has been developed to derive the snow depth and ice thickness from the temperature measurements (Liao et al., 2018). Advance is also expected via more extensive utilization of seismometer observations in sea ice research. These can record signals generated by ocean waves and swell propagating in sea ice, and yield information on the dependence of wave

propagation on ice thickness (Marsan et al., 2012), which may further allow estimation of the average ice thickness and its evolution on a regional scale. Further, seismic measurements can complement satellite observations on sea ice deformation.

Observed shifts in river discharge and geochemical fluxes due to permafrost degradation, which is not monitored in the existed scarce gauging network, emphasize the importance of surrogate techniques in freshwater magnitude and quality observations. In particular, the remote sensing of both water runoff and water composition offers a powerful and reliable tool to enhance our understanding of hydrological impacts in major Arctic river systems.

In general, there are good perspectives for continuous development of technology of autonomous vehicles, observations and data transmission.

Appendix 2. Community-based observations in Greenland

In all countries around the Arctic, there are community-based observing systems (Gofman 2010; Johnson et al. 2016; Danielsen et al., 2017; online atlas available at arcticcbm.org). With more people coming to the marine areas of the Arctic, there will be increasing opportunities for community members to contribute to better understand the marine Arctic ecosystems and their biotic and abiotic components (Eicken et al. 2014; Johnson et al. 2015; Nordic Council of Ministers 2015; Fidel et al. 2017; Johnson et al. 2018).

To understand the different potential uses and sources of community-based data on the marine Arctic, it is necessary to know the different kinds of community-based observing approaches that are used. These monitoring approaches range from programs involving community members only in data collection ("contributory citizen science" *sensu* Bonney et al. (2009)) with the design, analysis and interpretation undertaken by professional researchers, to entirely autonomous monitoring systems run by community members (Table A1; Danielsen et al. 2009).

Citizen science approaches where community members are involved only in data collection are particularly useful when large numbers of people are required to collect data across wide geographical areas and on a regular basis. This capitalizes on the strength of gathering the most data possible, even if the accuracy or precision of each individual data point may not be as high as that obtained by highly trained professionals. Monitoring approaches with more profound involvement of community members (the collaborative approaches in Table A1) are typically useful: (1) where community members have significant interests in natural resource use; (2) when the information generated can have an impact on how one can manage the resources and the monitoring can be integrated within the existing management regimes; and (3) when there are policies in place that enable decentralized decision-making.

To illustrate the potential uses of data from community based observing in marine areas of the Arctic, we provide below an example from Greenland. The Greenland Ministry of Fisheries and Hunting has established a simple, field-based system for observing and managing resources developed specifically to enable Greenlandic fishers and hunters to document trends in living resources and to propose management decisions themselves (Danielsen et al. 2014; searchable database available at https://eloka-arctic.org/pisuna-net/). The system was designed to build upon existing informal observing methods, and it includes most of the aspects that are believed to make knowledge generation initiatives 'culturally appropriate' (Pulsifer et al. 2011). At the national level in Greenland, there is considerable scope for collecting community member observations from this system and using them to track wider trends in the abundance of resources while at the same time increasing community members' voice in higher-level decision-making (Table A2). Data from community-based observing could potentially be aggregated to generate larger-scale overviews of, for instance, species range and phenology, habitat condition, opportunities and threats, the impacts of management interventions, and the delivery of benefits such as wildlife resources to the community members from the natural ecosystems.

As well as providing data to inform natural resource management decisions, community-based observing has the potential to shed valuable light on environmental changes at national and even pan-Arctic scales (Huntington et al. 2013; Chandler et

al. 2016). The Greenland example described above is one such system currently in development, which has been explicitly designed to allow such upwards movement of data, and ultimately to permit larger-scale analyses. To the extent that systems like this can be implemented and replicated, important gaps in the monitoring of coastal areas of the Arctic seas can be plugged, at relatively low cost, while at the same time increasing community members' input to higher-level decision-making.

Most importantly, for community-based information to be useful at larger scales, monitoring schemes will need to be established in more sites and regions (Danielsen et al. 2005). Results can also only be synthesized where many programmes have monitored the same attributes. They need not all use a single standardized technique – this would be difficult given the importance of the monitoring schemes being autonomous, and would preclude schemes from being responsive to local circumstances and needs. However, it is important that only a relatively small number of methods, each well replicated, is used across the set of studies to be analysed. Provided this is the case then meta-analytical techniques can be used to check (and if necessary adjust) for differences in results being due to differences in field methods.

Author contributions. T. Vihma led the design and coordination of the manuscript and wrote a major part of it. P. Uotila wrote Sections 3 and 5E, and prepared Figure 8. S. Sandven wrote large parts of Section 2.4 and contributed to several other sections. D. Pozdnyakov wrote most of Section 2.5 and contributed to Section 1. A. Makshtas, V. Ivanov and I. Frolov contributed to Section 2 and planned Figure 3. A. Pelyasov wrote Section 4. R. Pirazzini wrote Section 5D and contributed to Section 2. F. Danielsen and A. Albin wrote Section 5C and Appendix 2. H. Lappalainen contributed to Section 2.5. S. Chalov, S. Dobrolyubov, V. Arkhipkin, and S. Myslenkov wrote parts of Sections 2.4 and 2.6, and Chalov prepared Figure 7. B. Cheng contributed to Section 2.3. The idea to write the manuscript came from M. Kulmala. He, together with H. Lappalainen and T. Petäjä, contributed to integration of the plans of MA-PEEX to the activities of the other components of PEEX.

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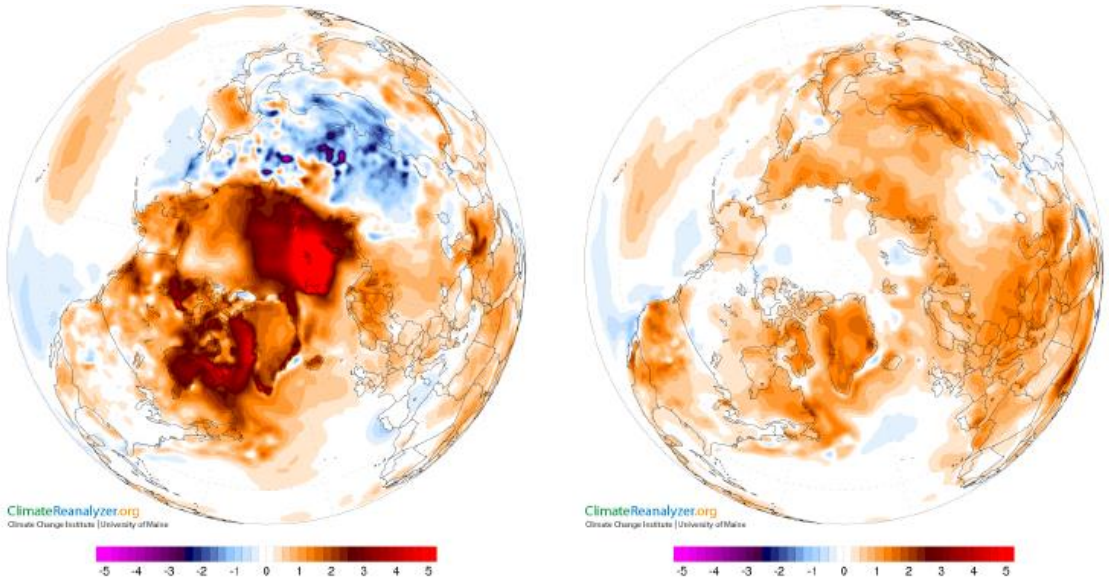

Figure 1. Differences in winter (DJD, left panel) and summer (JJA, right panel) 2-m air temperature between the periods 2000-2015 and 1979-1999 according to ERA-Interim reanalysis. Figure drawn applying Climate Reanalyzer.

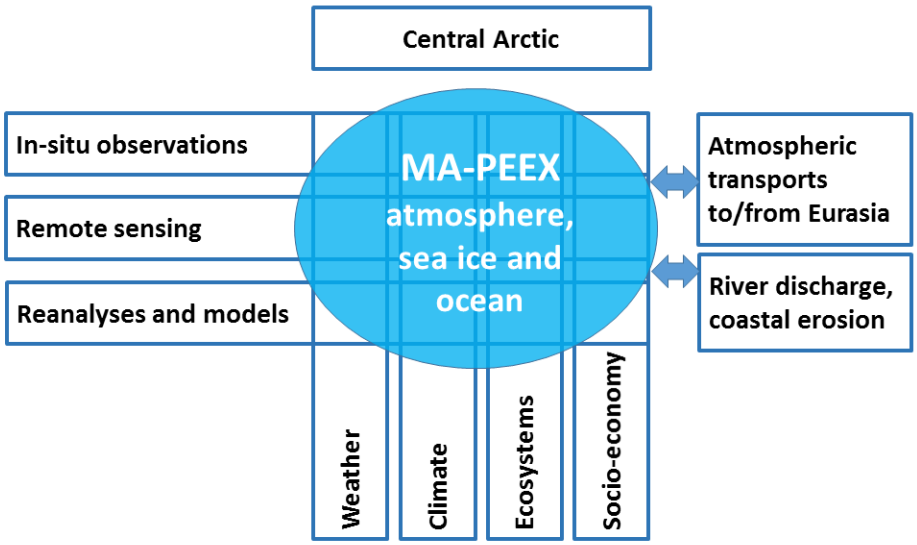

Figure 2. Schematic illustration of the marine Arctic component of PEEX (MA-PEEX)

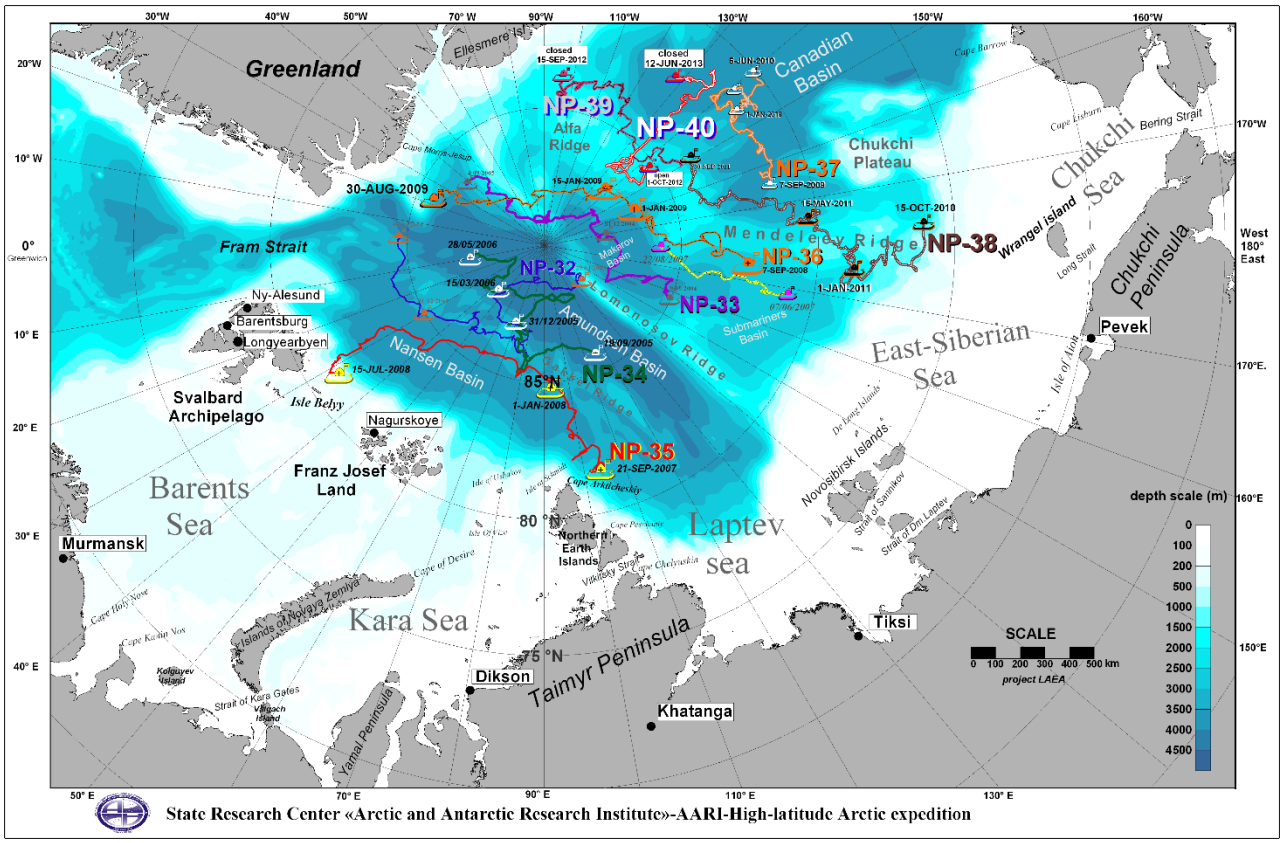

Figure 3. Trajectories of Russian "North Pole" drifting stations in 21st century.

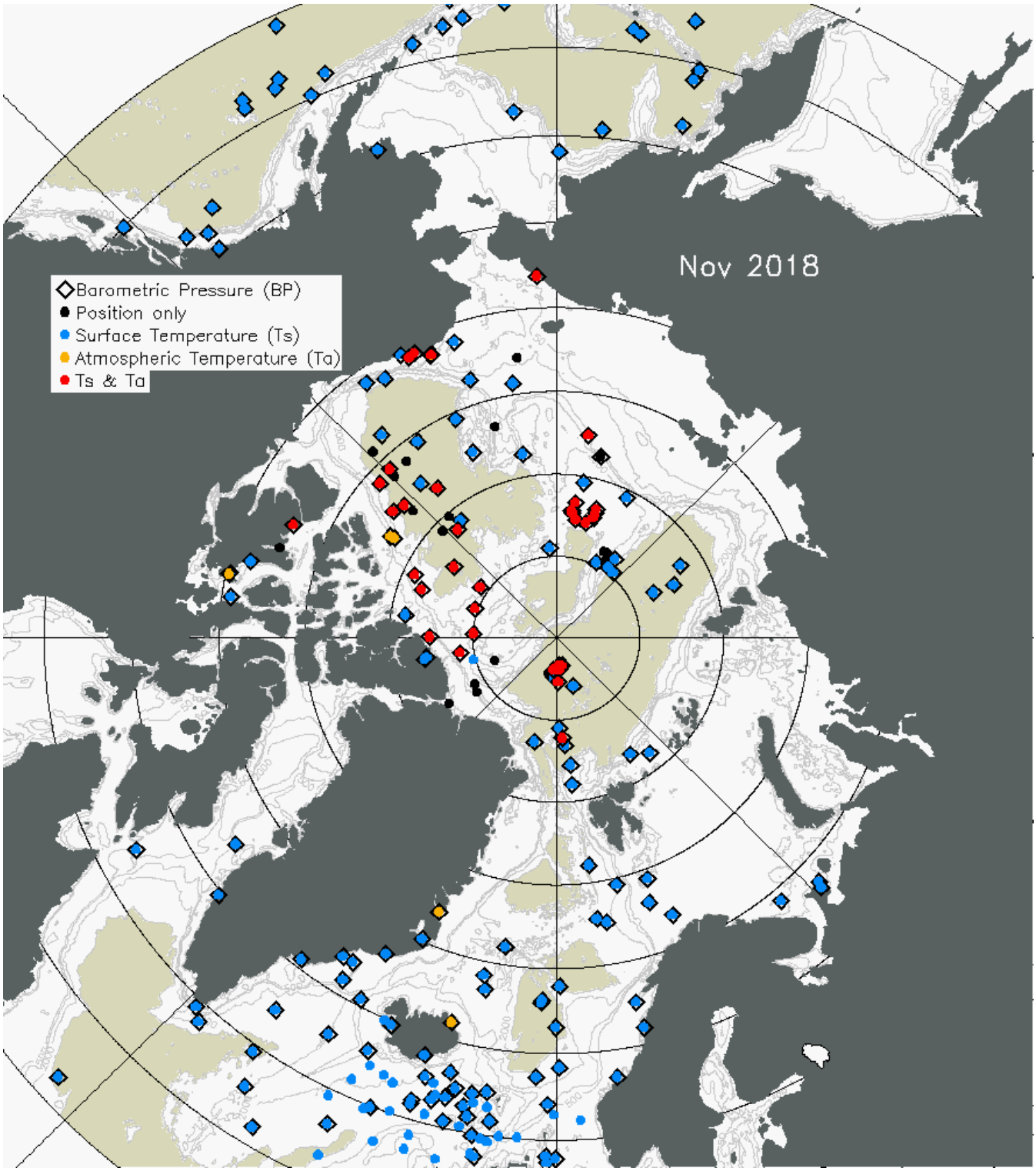

Figure 4. Distribution of sea ice and ocean buoys in November 2018. Reproduced from http://iabp.apl.washington.edu/monthly_maps.html with permission.

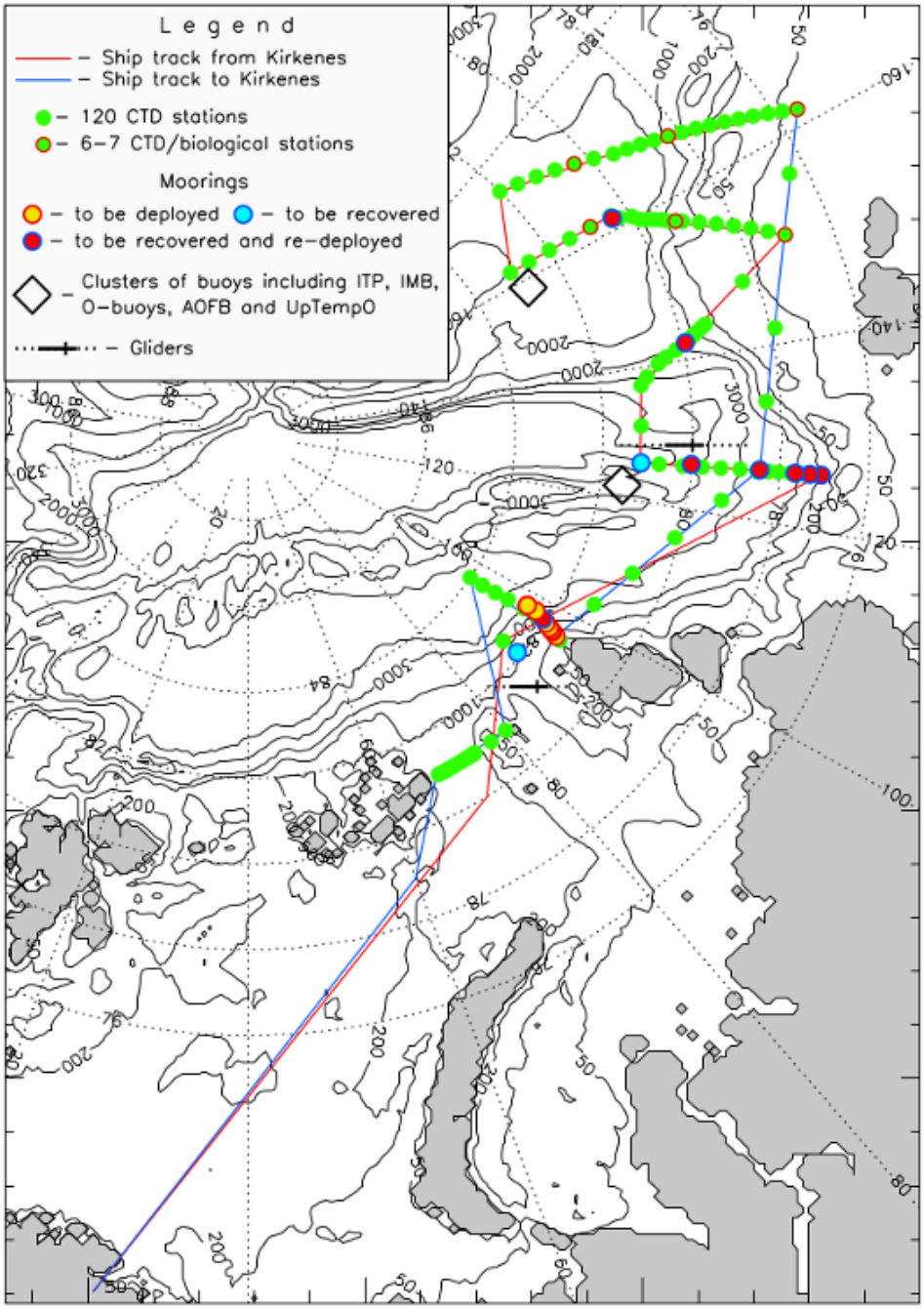

Figure 5. Oceanographic observations carried out during the Nansen and Amundsen Basins Observational System (NABOS) cruise in summer 2015, including CTD profiles, biological stations, deployment and recovery of moorings, as well as deployment of buoys and gliders. Source: http://research.iarc.uaf.edu/NABOS2/cruise/2015/. Reproduced with permission from Igor Polyakov, the University of Alaska Fairbanks.

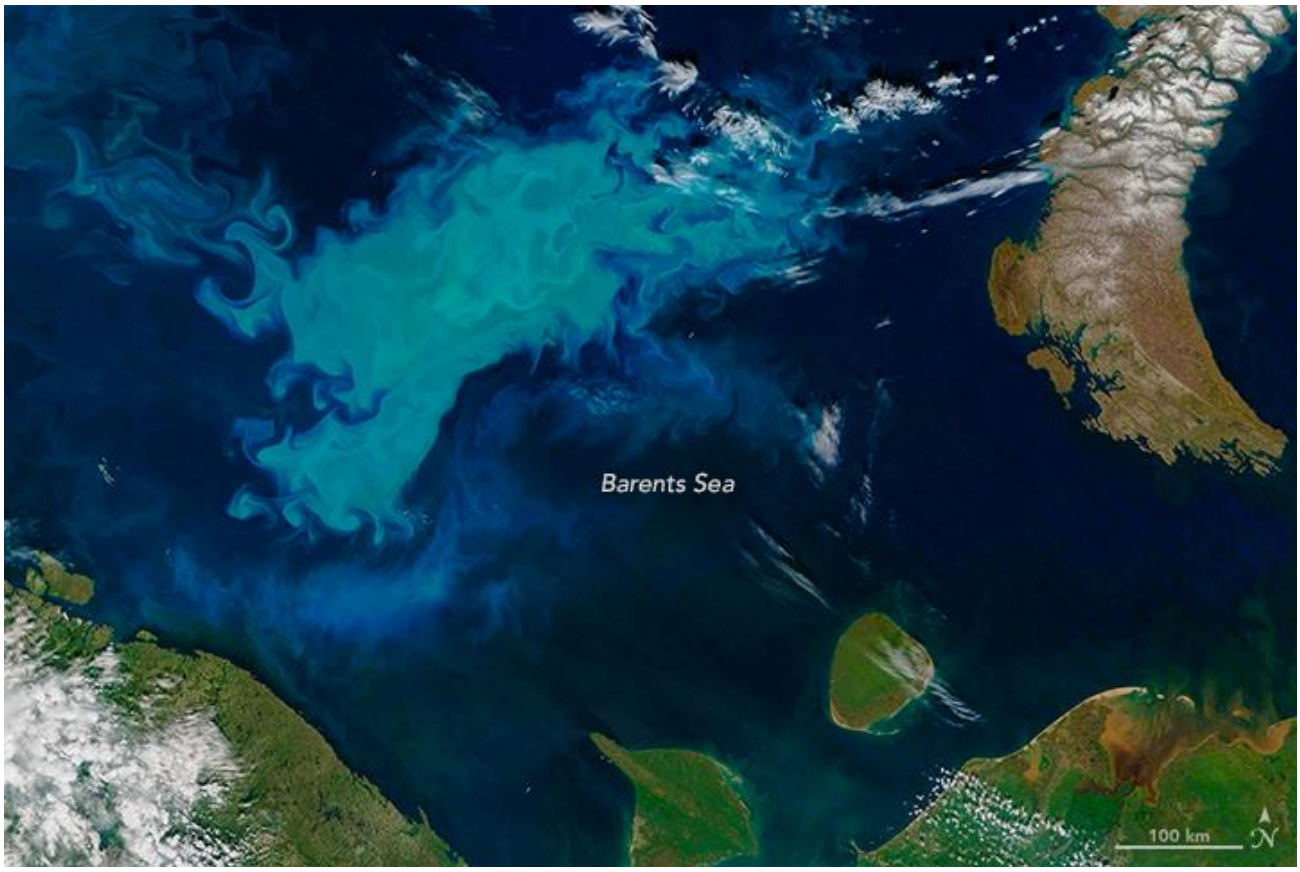

Figure 6. A phytoplankton bloom in the Barents Sea acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite on 6 July 2016. The phytoplankton may contain coccolithophores. The image is from the Rapid Response imagery from the Land, Atmosphere Near real-time Capability for EOS (LANCE) system operated by the NASA/GSFC/Earth Science Data and Information System (ESDIS).

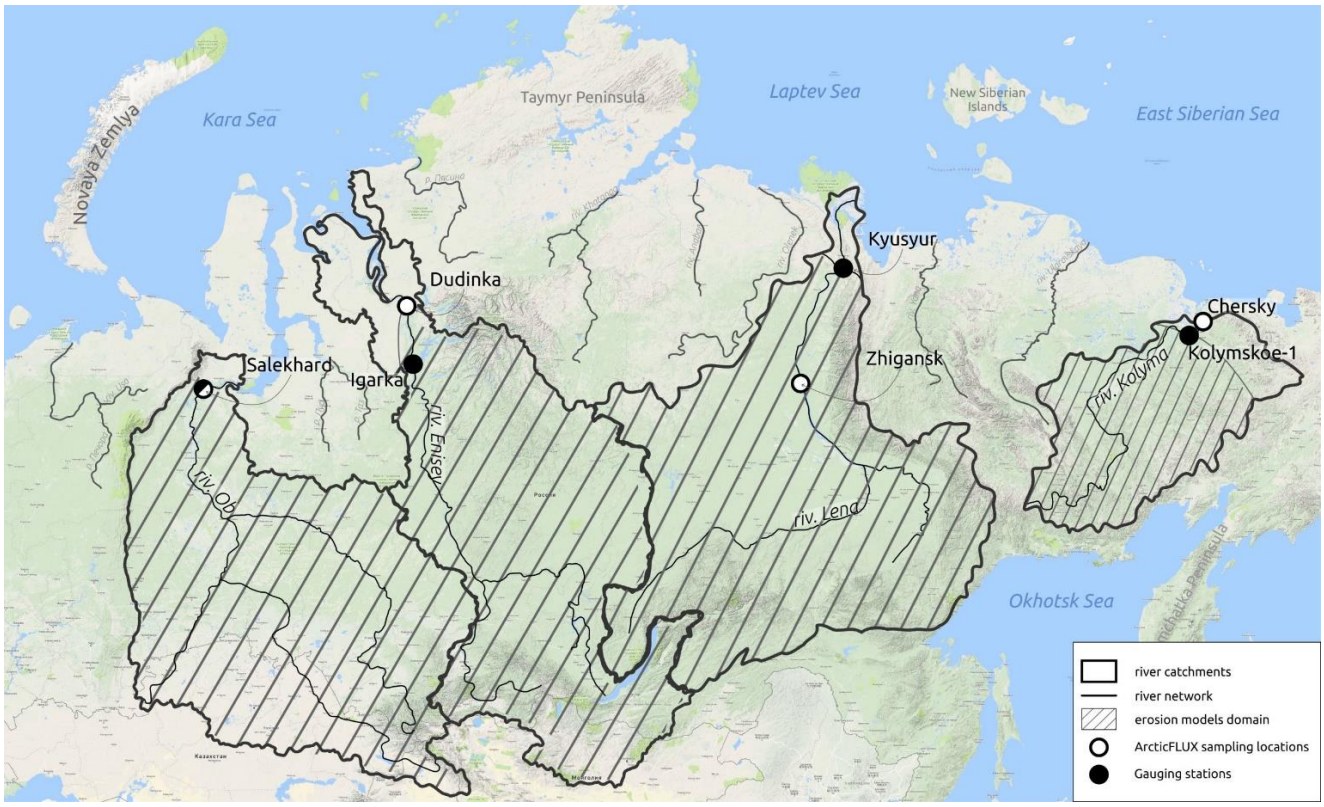

Figure 7. Map delineating great Siberian rivers studied in the ArticFLUX project under the PEEX umbrella to monitor erosion and biogeochemical fluxes into the Arctic Ocean.

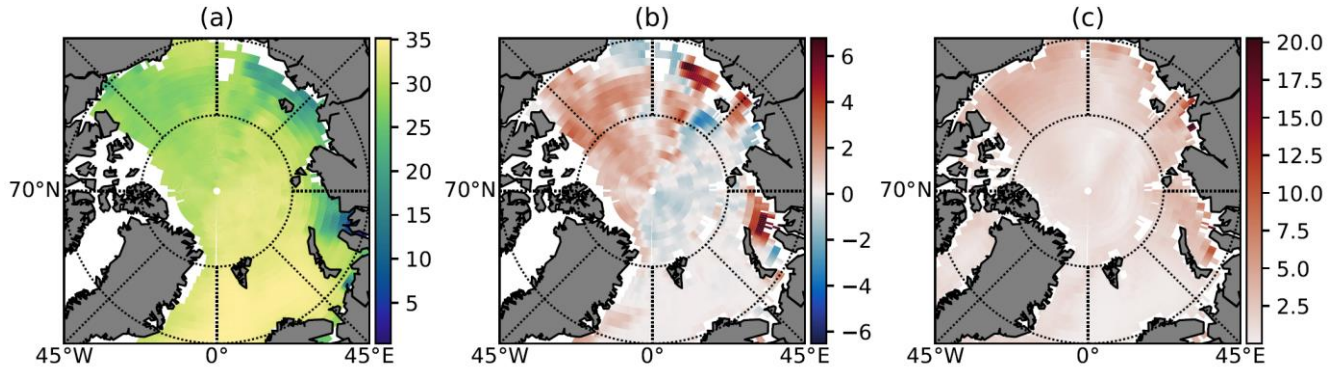

Figure 8. (a) Average surface salinity in based on Sumata et al. (2018) observed climatology, (b) mean departure of four ocean reanalysis from the climatology selected from Uotila et al. (2018), and (c) the salinity spread of four ocean reanalysis. The figure illustrates that the Arctic Ocean salinity uncertainty is the highest on the Siberian shelf, in particular close to the large rivers. This high uncertainty highlights the need for more measurements from the region.

Figure A1. Small Unmanned Meteorological Observer (SUMO), which is used to measure vertical profiles of air temperature, humidity and wind speed up to the height of 2-3 km. Photo Priit Tisler, Finnish Meteorological Institute.

Table A1. Arctic and sub-Arctic natural resource monitoring schemes across a spectrum of possible monitoring approaches based on the relative participation of different actors (modified from Danielsen et al. 2009; Huntington et al. 2013). The relative role of community members in the monitoring systems increases from bottom to top between the five categories of monitoring systems.

Category	**Arctic examples**	**Description**
Fully autonomous local monitoring	Customary conservation regimes, e.g., in Canada (Ferguson et al. 1998, Moller et al. 2004)	The whole monitoring process – from design, to data collection, to analysis, and finally to use of data for management decisions – is carried out autonomously by local stakeholders
Collaborative monitoring with local data interpretation	Arctic Borderlands Ecological Knowledge Co-op, Canada (Eamer 2004); Community-based monitoring by Inuvialuit Settlement Region, Canada (Huntington 2011); Opening Doors to the Native Knowledge of the Nenets, Russia (www.arcticcbm.org); Piniakkanik Sumiiffinni Nalunaarsuineq (PISUNA), Greenland (Danielsen et al. 2014; www.pisuna.org)	Locally based monitoring involving local stakeholders in data collection, interpretation or analysis, and management decision making, although external scientists may provide advice and training. The original data collected by local people remain in the area being monitored, but copies of the data may be sent to professional researchers for in-depth or larger-scale analysis
Collaborative monitoring with external data interpretation	Integrated Ecosystem Management (ECORA), Russia (Larsen et al. 2011)	Local stakeholders involved in data collection and monitoring-based management decision making, but the design of the scheme and the data analysis and interpretation are undertaken by external scientists
Externally driven monito-toring with local data collectors	Environmental Observations of Seal Hunters, Finland (Gofman 2010); Fávllis Network, Norway (Gofman 2010); Monitoring of breeding eider *Somateria mollissima*, Greenland (Merkel 2010); The Piniarneq fisheries catch and hunting report database, Greenland	Local stakeholders involved only in data collection stage, with design, analysis and interpretation of monitoring results for decision-making being undertaken by professional researchers, generally far from the site
Externally driven, researcher executed monitoring	Multiple scientist-executed natural resource monitoring schemes with no involvement of the local stakeholders	Design and implementation conducted entirely by professional scientists who are funded by external agencies and generally reside elsewhere

Table A2. Comparison of community members' perceptions and trained scientists' assessments of trends in the abundance of 18 marine attributes in NW Greenland 2009-2011 (Danielsen et al. 2014). Legend: ↑, increased abundance; ↓, declining abundance; ⇔, no major change in the abundance; ‡, increased abundance reported in some areas, decline in other areas; Few data, there are little or no abundance data available; , correspondence between community members' and scientists' assessments; ( ), probable correspondence between community members' and scientists' assessments but the time, area and/or temporal/spatial scale of the assessments do not match; ⦸, no correspondence. D, Disko Bugt; N.a., not applicable; U, Uummannaq Fjord. *For latin names and details see Danielsen et al. (2014) and https://eloka-arctic.org/pisuna-net/.

	Attributes	Percep-tions*	Scientists' assessments	Source of scientists' assessments*	Correspon-dence
Fish	Atlantic cod, D	‡	Few data	Siegstad 2011	N.a.
	Wolffish *spp.*, D	↑	↑/⇔	Siegstad 2012	( )
	Greenland halibut	↑	↓/⇔	Siegstad 2011; 2012	⦸
Marine mammals	Ringed seal	↓	Few data	Boertmann 2007; Rosing-Asvid 2010	N.a.
	Harp seal, D	↑	↑	Department of Fisheries and Oceans 2010; Rosing-Asvid 2010	
	Narwhale	‡	Few data	North Atlantic Marine Mammal Commission 2012	N.a.
	Humpback whale	↑	↑	Heide-Jørgensen *et al.* 2011	( )
	Minke whale, D	↑	↑	Heide-Jørgensen *et al.* 2010	( )
	Minke whale, U	⇔	Few data	No information	N.a.
Birds	Common eider	↑	↑	Chaulk *et al.* 2005; Merkel 2010	( )
	White-tailed eagle, D	↑	Few data	No information	N.a.
	Large gulls*, D	↑	Few data	Boertmann 2007	N.a.
	Arctic tern, D	↑	⇔	Boertmann 2007; Egevang & Frederiksen 2011	⦸
	Brünnich's guillemot, breeding	↓	↓	Burnham *et al.* 2005; Labansen & Merkel 2012	
	Little auk, D	↑	Few data	Egevang & Boertmann 2001; Boertmann 2007	N.a.
Other	Winter sea-ice*, U	↓	↓	Danish Meteorological Institute	
	Offshore ships, U	↑	↑	Arctic Marine Shipping Assessment 2009	( )
	Trawling, D	↑	Few data	No information	N.a.