Atmospheric
Chemistry
and Physics

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, which is seen in the 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 the 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 for 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 (AUVs), and unmanned aerial vehicles (UAVs). These have to be supported by research vessel and aircraft campaigns, as well as various coastal observations, including community-based ones. Major manned drift-

ing stations may occasionally be 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, and 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.
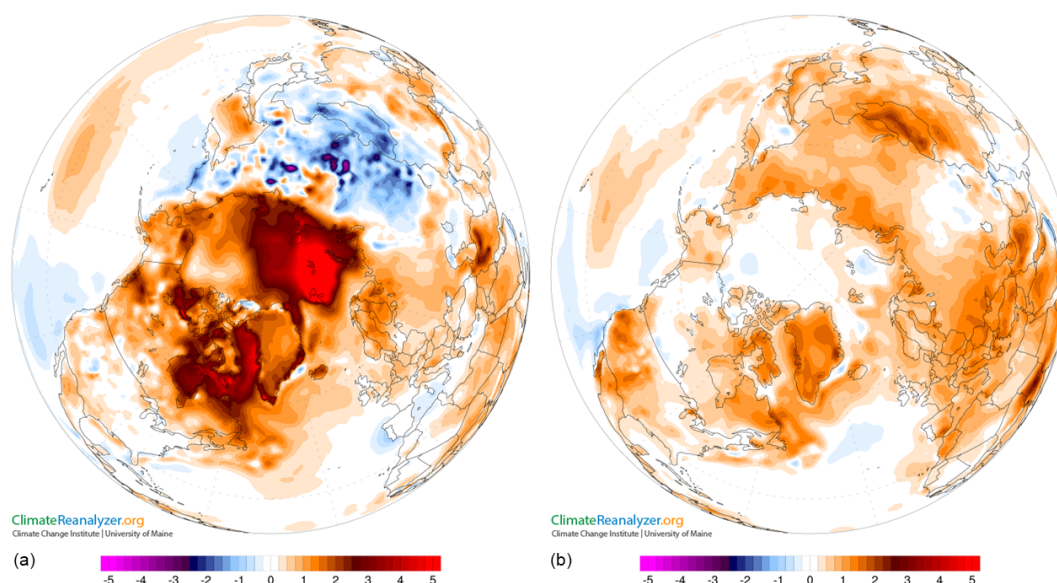
Figure 1. Differences in winter (DJF, **a**) and summer (JJA, **b**) 2 m air temperature (in °C) between the periods 2000–2015 and 1979–1999 according to ERA-Interim reanalysis. Figure drawn applying Climate Reanalyzer.

1 Introduction

During the recent decades the Arctic air temperatures have increased 2 or 3 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 the terrestrial Arctic and Greenland ice sheet (Fig. 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 in the cumulative CO_2 emissions (Notz and Stroeve, 2016). Aerial coverage of terrestrial snowpack in early summer has even decreased 2 times 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 % dur-

ing 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 increases in 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, the decrease in sea ice along the Northern Sea Route (NSR) will allow the intensification of 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 Stephen-

son, 2013). This interest and associated increase in Arctic research and technology development has been particularly strong among Asian countries: China, Japan, and South Korea. The Chinese initiative One Belt One Road (Tsui et al., 2017) and 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 offshore 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 the 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 the 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 Environment Monitoring Service has since 2014 provided monitoring and short-term forecasting on a 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 a 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 into 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 the identification of processes of a high research priority and establishment of a coherent, coordinated, comprehensive observation system.

The Pan-Eurasian Experiment (PEEX) is a programme 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-medium–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
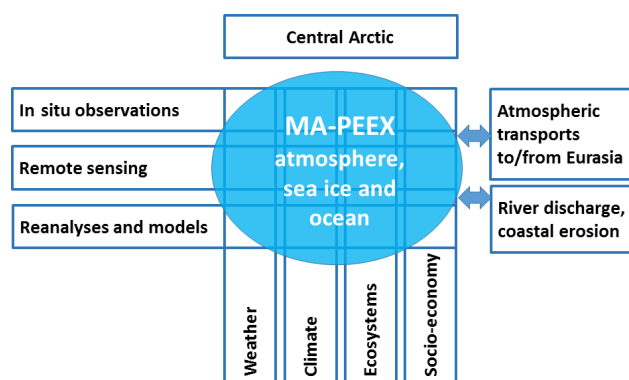

Figure 2. Schematic illustration of the marine Arctic component of PEEX (MA-PEEX).

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 for Measuring Ecosystem–Atmosphere Relations) concept, successfully applied in the Eurasian continent. The system is to be designed in collaboration with other programmes addressing the present and future observation networks in the Arctic, including the Sustaining Arctic Observation Networks (SAON) and the Arctic Monitoring and Assessment Programme (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 Fig. 2. This requires identification of the actual research needs and the state of existing observations in relation to the needs (Sect. 2); evaluation of the information available on the basis of atmospheric and ocean reanalyses (Sect. 3); evaluation of the relevant socioeconomic aspects that both affect and are affected by climate and environmental changes (Sect. 4); and assessment of the challenges, emerging opportunities, and concrete actions needed (Sect. 5). The aim of MA-PEEX is its integration 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 (Sect. 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 (Sect. 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 Sect. 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 (Fig. 3). The most important western drifting stations have been the Surface Heat Budget of 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/, last access: 4 February 2019). Drifting stations provide unique possibilities to study the ocean, sea ice, snow, and atmosphere in the central Arctic.

Analogously to drifting ice stations, research vessels collect multidisciplinary observations from the marine Arctic. These are, however, restricted to monthly timescales 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 the International Arctic Buoy Programme (IABP). The present (November 2018) distribution of buoys is shown in Fig. 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 Fig. 4). Various buoy applications are described more specifically in Sect. 2.3 and 2.4, as well as in Appendix A.

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 (Sect. 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 re-
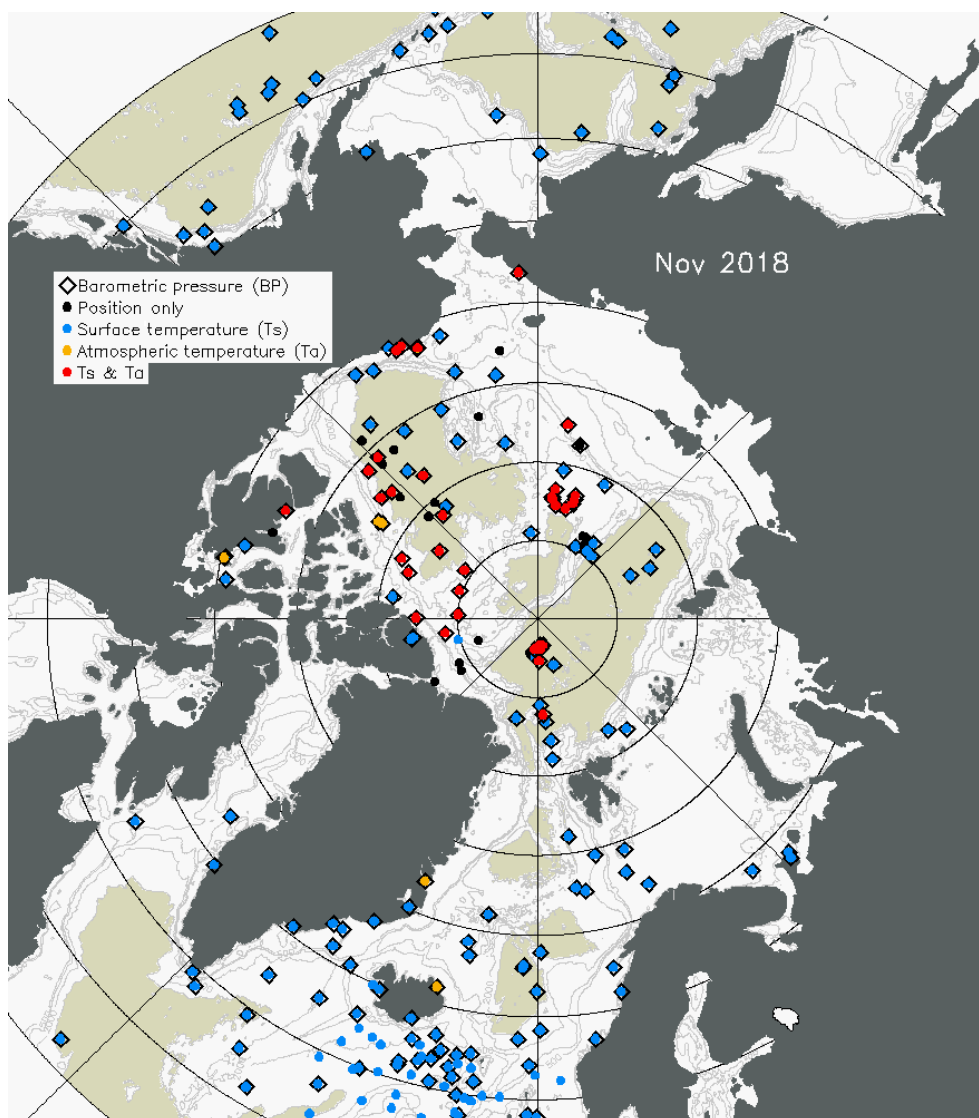
Figure 3. Trajectories of Russian "North Pole" drifting stations in the 21st century.

lated 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); and 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 and/or reanalysis products. Among others, coastal mesoscale processes, such as wind channelling, 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 and/or 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 and/or reanalysis products are available in a regular grid and are therefore much more convenient to analyse than irregularly spaced observations. There is, however, a strong need for observations to evaluate the model and/or 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 provides an attractive source of information. However, the vertical resolution of satellite remote sensing products is too coarse to study small-scale processes and the role of the atmospheric

Figure 4. Distribution of sea ice and ocean buoys in November 2018. Reproduced from http://iabp.apl.washington.edu/monthly_maps.html (last access: 4 February 2019) with permission.

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 vehicles, UAVs; 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 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 in 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 snowmelt, 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 https://arctic-aok.org/, last access: 4 February 2019). 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 snowpack, 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, the influence of the ocean heat on the ice cover is increasing, providing positive feedback on a seasonal timescale (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). However, there is also a negative feedback that plays a role in winter, because thinner ice grows faster (Petty et al., 2018).

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, with 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 a unique capability to measure thicknesses 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 snowpack on top of sea ice is 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 is 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 advances have 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 the detection of ice ridges. Large-scale evolution of the ice field results from a combination of thermodynamic and dynamic forcing, with 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 the 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 drift and 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 and those originating from temporal variations on inter-annual and decadal scales.

The Arctic Ocean stratification is characterized 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 timescales 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 Arctic Archipelago. Warm and saline Atlantic water flows into the Arctic Ocean mainly through the 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 meltwater 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 the mixing of water masses, further affecting sea ice melt (Luneva et al., 2015) and the thermohaline circulation with potential impacts on the Arctic and global climate (Holloway and Proshutinsky, 2007). Other small-scale processes important for climate include the 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), and (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 (Fig. 5), but they mainly deliver physical parameters from fixed depths in a delayed mode (Beszczynska-Möller et al., 2011). Nevertheless, observations have allowed the documentation of Atlantic water warm pulses in this century (Polyakov et al., 2011) and the revelation of 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 sea surface temperature (SST) field over the open ocean is fairly accurately known during the satellite era. Decadal and inter-annual changes in wind wave fields in the Barents and White seas in the period 1979–2010 have been estimated on the basis of the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) reanalysis and numerical models. Information on the wave statistics and validation techniques applied is 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 and Norwegian Sea, whereas there are far fewer 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 profilers (ITPs), 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 the 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 Sect. 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 been improved by the Arctic-RIMS (Rapid Integrated Monitoring System, http://rims.unh.edu, last access: 4 Febru-
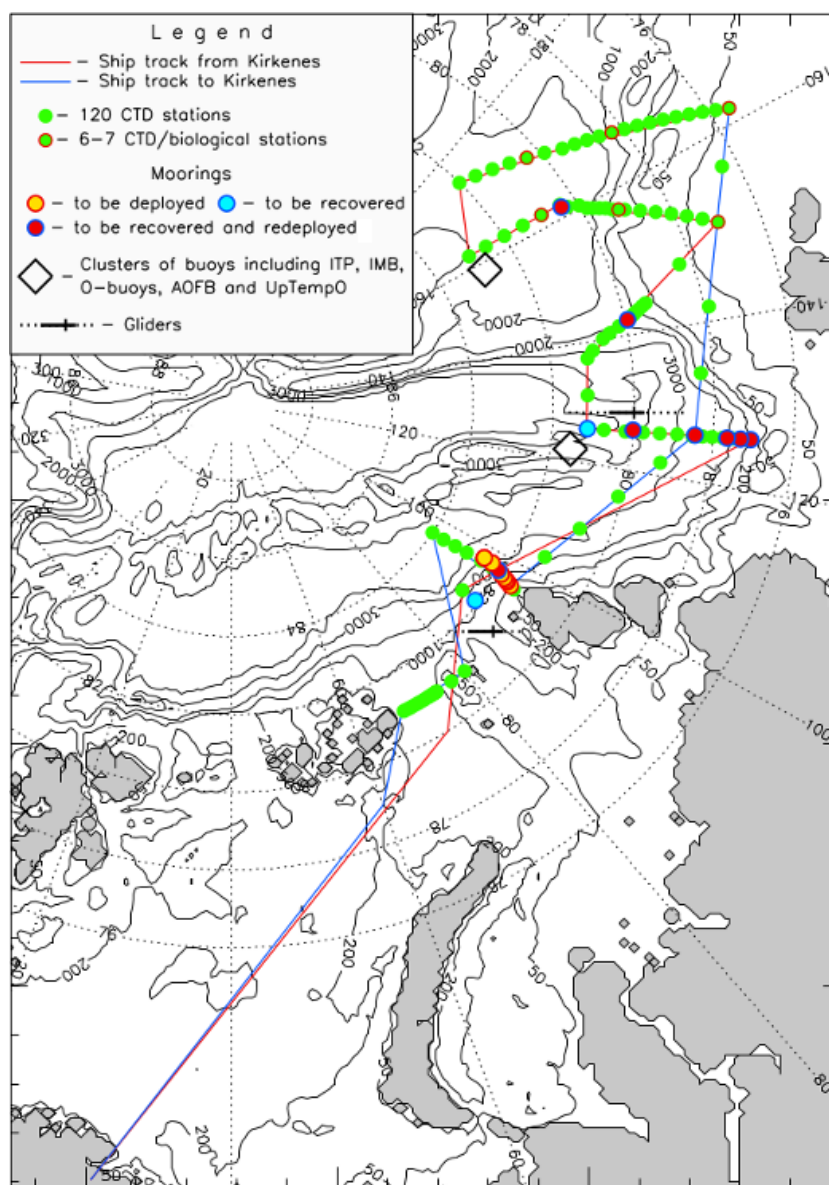
Figure 5. Oceanographic observations carried out during the Nansen and Amundsen Basins Observational System (NABOS) cruise in summer 2015, including CTD profiles, biological stations, deployment and recovery of moorings, and deployment of buoys and gliders. Source: http://research.iarc.uaf.edu/NABOS2/cruise/2015/ (last access: 23 January 2019). Reproduced with permission from Igor Polyakov, the University of Alaska Fairbanks.

ary 2019), which allows the characterization of 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 Hydrometeorological Data Network for the pan-Arctic Region) allow monitoring of changes in the hydrological cycle.

As a summary, process understanding and quantification of the state and changes in the Arctic Ocean circulation, heat and freshwater budgets, and small- and mesoscale 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 is enhanced. In turn, the ensuing surface ocean temper-

ature growth leads to a shift in 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 the 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 kilometres) of *E. huxleyi* bloom areas (Fig. 6) and their active spatio-temporal dynamics, only 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 the (i) 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 in partial pressure of dissolved carbon dioxide (CO_2) with regard to its background values, and (v) increase in 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 parameters (v). Satellite OC-CCI data permit the retrieval of the time series of parameters (i)–(iv) since 1998 for all marine environments where the phenomenon occurs. Moreover, the employment of data from various other optical and microwave satellite sensors permits the enrichment of the data on parameters (i)–(v) with 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-free area, cloud fraction, and downward solar radiation in the PAR spectral range. This allows us 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. Allochthonous 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 impor-

tant 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 multidisciplinary 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 into 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 cyclones, 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 the 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, favour a 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 snowfall 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 oro-

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 of the Land, Atmosphere Near-real-time Capability for EOS (LANCE) system operated by the NASA Goddard Space Flight Center (GSFC) Earth Science Data and Information System (ESDIS).

graphic 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 (Fig. 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, and dissolved and particulate matter 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). The degradation of permafrost has recently led to increased runoff, erosion, and associated transport of total suspended matter 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). The 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, the strengthening of the thermal the stability, and the shallowing of the thermocline. This will also cause some increase in 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 the Lena (Hölemann et al., 2005), Ob (Shakhova et al., 2007), and Amur rivers (Levshina, 2008; Chudaeva et al., 2011) 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 chemical datasets from a coordinated sampling programme have been collected since 2003 under the Arctic-GRO programme at the six largest Arctic rivers (Holmes et al., 2012; McClelland et al., 2016). Since 2018 under the PEEX umbrella, the ArcticFLUX project has provided estimates of dissolved and particulate organic matter, nutrients, and metals fluxes based on unprecedented dense river cross-section samples at the outlets of the four largest Siberian rivers (Ob, Yenisey, Lena, and the Kolyma) multiple times per year (Fig. 7).

Coastal erosion processes in the Arctic Ocean lead inter alia to inundation of the terrestrial coastal zone, which is due to the wind-driven breaking of the fast ice and ex-
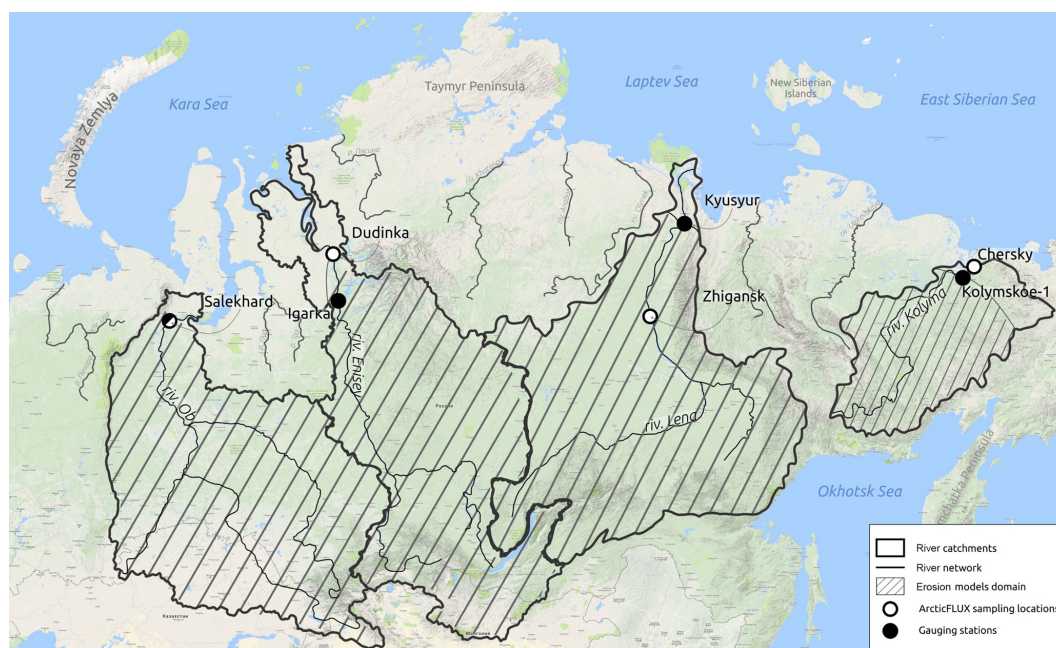
Figure 7. Map delineating great Siberian rivers studied in the ArticFLUX project under the PEEX umbrella to monitor erosion and biogeochemical fluxes into the Arctic Ocean.

posure of the coast to marine wave action (Sect. 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, and 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 the 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 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 the total monitored area and 85 % of the 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, US, and Japanese agencies and the regional Arctic System Reanalysis. 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 also include 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, to the 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 the Fram Strait, which, as a result, is cooler than the observed Atlantic water layer. These results emphasize the importance of atmospheric forcing, the air–ocean coupling protocol, and sea ice data assimilation for the product performance.

The example illustrated in Fig. 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 Fig. 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 reanalysis. 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 (Fig. 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, for instance. 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 the marine Arctic is related to the 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 the Arctic and northeastern Eurasia (coastal areas of the Bering and Okhotsk seas) are characterized by considerable contrasts (Vlasova and Petrov, 2010). On the one hand, the oil and gas areas of the Yamalo-Nenets and Nenets Autonomous Okrug 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-term 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 Krai region, in which, for decades of industrial development, powerful territorial-production complexes (Rutt, 1986) have been created in the fields of maritime transport, mining, 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 sociocultural 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 the mutual recognition of these
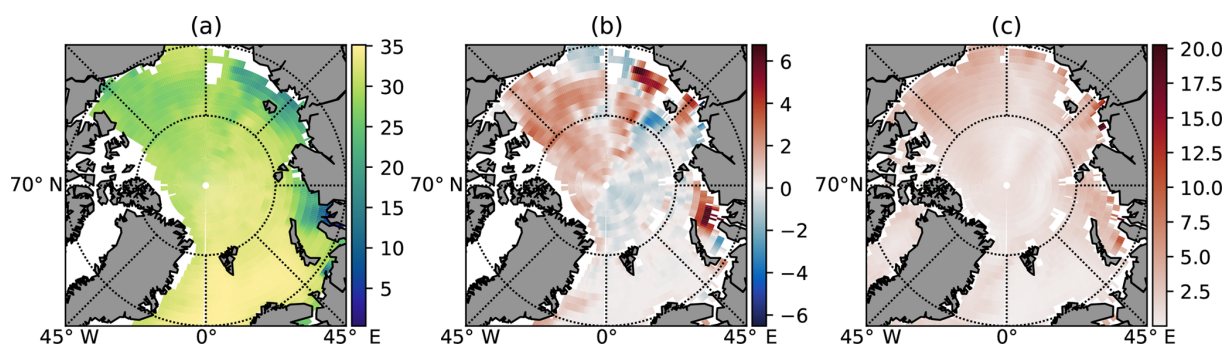
Figure 8. (a) Average surface salinity in based on Sumata et al. (2018) observed climatology, **(b)** mean departure of the four-ocean reanalysis from the climatology selected from Uotila et al. (2018), and **(c)** the salinity spread of the four-ocean reanalysis. The figure illustrates that the Arctic 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.

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 t 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, the 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, the "hydrocarbonization" of the 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 the 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 the 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 on the 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 Peninsula, 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 process of gradual consolidation of the coastal municipal formations of the Eurasian Arctic, as evidenced, for example, by the recent establishment of the Association of Arctic Municipalities in 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 Sect. 5 (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 the development and maintenance of a 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 the 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 whether 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, and various coastal processes. Further, it is vital that MA-PEEX be developed in close collaboration with all relevant programmes 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 a comprehensive understanding of the interactions between the physical climate system, ecosystems, and socio-economics, which are all changing rapidly. The principal concrete actions needed are as follows.

a. MA-PEEX will work towards the 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 the prototype established under the ArcticFLUX project under the PEEX umbrella project (see Sect. 2.6), (iii) regular deployment of various autonomous instruments (see b below) in the Arctic Ocean, (iv) maintenance of the radiosonde sounding network in the MA-PEEX domain and its support 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 the 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, last access: 23 January 2019). Close collaboration with INTAROS will therefore provide an excellent starting point for MA-PEEX. Other potential key collaborators for MA-PEEX include the Argo programme (a global array of autonomous instruments measuring subsurface ocean properties; Riser et al., 2016), the Arctic Coastal Dynamics project (Lantuit et al., 2012), and the Arctic Regional Ocean Observing System (ROOS; 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, and ice-tethered profilers and AUVs for ocean research. Several devices are already available and have been tested in harsh Arctic conditions, and the technology is developing fast. The opportunities arising are described in more detail in Appendix A. However, challenges remain in financing spatially and temporally extensive observations. Their cost-effectiveness needs to be concretely proven. 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; John-

son et al., 2016; Danielsen et al., 2017). In Appendix B we summarize the 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 the collection of data and improvement of the understanding of the state and change in 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. Advances in data management can be made by building connections between distributed data repositories. Initiatives such as AMAP, IABP, Arctic ROOS, Copernicus Marine Environment Monitoring Service, and INTAROS, as well as the SAON 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 the 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 be accompanied by rich metadata and be 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 utilize them in research.

The emergence of the large number of atmosphere, ocean, and coupled reanalysis products shows 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 will apply the observations in the 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, signifi-

cant 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. Advances in observations are 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, sociocultural, 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 and those in the Sakhalin region, where there are 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 the 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, cryospheric, and oceanographic observations; advanced data management; and multidisciplinary research on the marine Arctic and its interaction with the Eurasian continent.

Data availability. Reanalysis products of air temperature applied in Fig. 1 are available from Climate Reanalyzer at https:// climatereanalyzer.org/ (last access: 11 February 2019). Ocean reanalysis products and observations of sea surface salinity applied in Fig. 8 are available at https://icdc.cen.uni-hamburg.de/1/daten/ reanalysis-ocean/oraip.html (last access: 11 February 2019).

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.

Appendix A: 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; Fig. 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 the use of a controlled meteorological balloon, which has already been tested in harsh polar conditions (Hole et al., 2016). Further, we expect better possibilities for atmospheric and Earth-surface observations also via advances in performance and instrumentation of manned research aircraft. We also expect further advances in ground-, ship-, and ice-based remote sensing of the Arctic atmosphere, as the methods introduced in Sect. 2.2 are progressively improving. Further, recent advances in satellite remote sensing have yielded better information on the temperature and humidity profiles over ice and snow (Perro et al., 2016).

There are promising developments in autonomous ocean-observing systems, which can significantly improve the capacity to collect data from the Arctic seas. Ice-tethered profilers 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 the 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). The de-

velopment 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 the 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). Advances are 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 existing 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 on major Arctic river systems.

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

Appendix B: 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 http://www.arcticcbm.org/, last access: 23 January 2019). With more people coming to the marine areas of the Arctic, there will be increasing opportunities for community members to contribute to better understanding of the marine Arctic ecosystems and their biotic and abiotic components (Eicken et al., 2014; Johnson et al., 2015, 2018; Nordic Council of Ministers, 2015; Fidel et al., 2017).

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 observ-

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 the 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 the Inuvialuit Settlement Region, Canada (Huntington, 2011); opening doors to the native knowledge of the Nenets, Russia (http://www.arcticcbm.org, last access: 8 February 2019); Piniakkanik Sumiiffinni Nalunaarsuineq (PISUNA), Greenland (Danielsen et al., 2014; http://www.pisuna.org, last access: 23 January 2019).	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 Ecosystems Management Approach to Conserve Biodiversity and Minimize Habitat Fragmentation (ECORA), Russia (Larsen et al., 2011).	Local stakeholders involved in data collection and monitoring-based management decision-making, with the design of the scheme, the data analysis, and interpretation being undertaken by external scientists.
Externally driven monitoring with local data collectors	Environmental observations of seal hunters, Finland (Gofman, 2010); Fávllis Network, Norway (Gofman, 2010); monitoring of breeding of the eider *Somateria mollissima*, Greenland (Merkel, 2010); the Piniarneq fisheries catch and hunting report database, Greenland.	Local stakeholders involved only in data collection stage, with the design, analysis, and interpretation of the 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.

ing approaches that are used. These monitoring approaches range from programmes involving community members only in data collection ("contributory citizen science", 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, Hunting, and Agriculture 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.

Table A2. Comparison of community members' perceptions and trained scientists' assessments of trends in the abundance of 18 marine attributes in NW Greenland during 2009–2011 (Danielsen et al., 2014).

	Attributes	Perceptions*	Scientists' assessments	Source of scientists' assessments*	Correspondence
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 (2012); Rosing-Asvid (2010)	
	Narwhal	↕	Few data	North Atlantic Marine Mammal Commission (2012)	N.a.
	Humpback whale	⇑	⇑	NAMMCO (2008)	(?)
	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 and Frederiksen (2011)	–
	Brünnich's guillemot, breeding	⇓	⇓	Burnham et al. (2005); Labansen and Merkel (2012)	
	Little auk, D	⇑	Few data	Egevang and Boertmann (2001); Boertmann (2007)	N.a.
Other	Winter sea ice*, U	⇓	⇓	Danish Meteorological Institute	
	Offshore ships, U	⇑	⇑	AMSA (2009)	(?)
	Trawling, D	⇑	Few data	No information	N.a.

⇑: 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; No entry: 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 Bay; N.a.: not applicable; U: Uummannaq Fjord. * For latin names and details, see Danielsen et al. (2014) and https://eloka-arctic.org/pisuna-net/ (last access: 23 January 2019).

org/pisuna-net/, last access: 23 January 2019.). 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.

References

Alexeev, V. A., Walsh, J. E., Ivanov, V. V., Semenov, V. A., and Smirnov, A. V.: Warming in the Nordic Seas, North Atlantic storms and thinning Arctic sea ice, Environ Res. Lett., 12, 084011, https://doi.org/10.1088/1748-9326/aa7a1d, 2017.

AMAP: Enabling Science use of Unmanned Aircraft Systems for Arctic Environmental Monitoring, in: Arctic Monitoring and Asessment Programme (AMAP), edited by: Crowe, W., Davis, K. D., la Cour-Harbo, A., Vihma, T., Lesenkov, S., Eppi, R.,

Weatherhead, E. C., Liu, P., Raustein, M., Abrahamsson, M., Johansen, K.-S., and Marshall, D., Oslo, 30 pp., 2012.

AMAP: AMAP Assessment 2013: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 2013.

AMAP: Snow, Water, Ice and Permafrost in the Arctic (SWIPA), Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 269 pp., 2017a.

AMAP: Adaptation Actions for a Changing Arctic: Perspectives from the Barents Area. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 267 pp., 2017b.

AMSA: Arctic Marine Shipping Assessment, Arctic Council, 2009.

Ancellet, G., Pelon, J., Blanchard, Y., Quennehen, B., Bazureau, A., Law, K. S., and Schwarzenboeck, A.: Transport of aerosol to the Arctic: analysis of CALIOP and French aircraft data during the spring 2008 POLARCAT campaign, Atmos. Chem. Phys., 14, 8235–8254, https://doi.org/10.5194/acp-14-8235-2014, 2014.

Andreas, E. L., Horst, T. W., Grachev, A. A., Persson, P. O. G., Fairall, C. W., Guest, P. S., and Jordan, R. E.: Parametrizing turbulent exchange over summer sea ice and the marginal ice zone, Q. J. Roy. Meteor. Soc., 136, 927–943, https://doi.org/10.1002/qj.618, 2010a.

Andreas, E. L., Persson, P. O. G., Jordan, R. E., Horst, T. W., Guest, P. S., Grachev, A. A., and Fairall, C. W.: Parameterizing turbulent exchange over sea ice in winter, J. Hydrometeorol., 11, 87–104, https://doi.org/10.1175/2009JHM1102.1, 2010b.

Bagard, M. L., Chabaux, F., Pokrovsky, O. S., Viers, J., Prokushkin, A. S., Stillea, P., Rihsa, S., Schmitt, A.-D., and Dupré, B.: Seasonal variability of element fluxes in two Central Siberian rivers draining high latitude permafrost dominated areas, Geochim. Cosmochim. Ac., 75, 3335–3357, https://doi.org/10.1016/j.gca.2011.03.024, 2011.

Bates, N. R. and Mathis, J. T.: The Arctic Ocean marine carbon cycle: evaluation of air-sea CO_2 exchanges, ocean acidification impacts and potential feedbacks, Biogeosciences, 6, 2433–2459, https://doi.org/10.5194/bg-6-2433-2009, 2009.

Beszczynska-Möller, A., Woodgate, R., Lee, C., Melling, H., and Karcher, M.: A synthesis of exchanges through the main oceanic gateways to the Arctic Ocean, Oceanography, 24, 82–99, https://doi.org/10.5670/oceanog.2011.59, 2011.

Bogoyavlenskiy, V., Bogoyavlenky, I., and Nikonov, R.: Results of aerial, space and field investigations of large gas blowouts near Bovanenkovo field on Yamal peninsula, Arctic: economy and environment, 3, 1–17, 2017 (in Russian).

Boertmann, D.: Grønlands Rødliste 2007, Nuuk, Greenland: DMU and Greenland Home Rule, 156 pp, https://www2.dmu.dk/pub/groenlands_roedliste_2007_dk.pdf, 2007 (in Danish with English Summary).

Boisvert, L. N. and Stroeve J. C.: The Arctic is becoming warmer and wetter as revealed by the Atmospheric Infrared Sounder, Geophys. Res. Lett., 42, 4439–4446, https://doi.org/10.1002/2015GL063775, 2015.

Bolotova, A. and Stammler, F.: How the North Became Home: Attachment to Place Among Industrial Migrants in Murmansk Region, in: Migration in the Circumpolar North, edited by: Huskey, L. and Southcott, C., CCI Press/University of Arctic, 193–219, 2010.

Bonney, R., Cooper, C., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K. V., and Shirk, J.: Citizen science: A developing

tool for expanding science knowledge and scientific literacy, Bioscience, 59, 977–984, 2009.

Borodkin, V. A., Makshtas, A. P., and Bogorodsky, P. V.: Coastal fast ice of the Shokalski Strait Ice and snow, 56, 525–532, https://doi.org/10.15356/2076-6734-2016-4-525-532, 2016.

Bourgain, P. and Gascard, J. C.: The Arctic Ocean halocline and its interannual variability from 1997 to 2008, Deep-Sea Res. Pt. I, 58, 745–756, 2011.

Bourgeois, Q. and Bey, I.: Pollution transport efficiency toward the Arctic: Sensitivity to aerosol scavenging and source regions, J. Geophys. Res., 116, D08213, https://doi.org/10.1029/2010JD015096, 2011.

Brooks, I. M., Tjernström, M., Persson, P. O. G., Shupe, M. D., Atkinson, R. A., Canut, G., Birch, C. E., Mauritsen, T., Sedlar, J., and Brooks, B. J.: The turbulent structure of the Arctic summer boundary layer during ASCOS, J. Geophys. Res., 122, 9685–9704, https://doi.org/10.1002/2017JD027234, 2017.

Brümmer, B. and Thiemann, S.: Arctic wintertime on-ice air flow, Bound.-Lay. Meteorol., 104, 53–72, 2002.

Burnham, W., Burnham, K. K., and Cade, T. J.: Past and present assessments of bird life in Uummannaq District, West Greenland, Dansk Ornitologisk Forenings Tidsskrift, 99, 196–208, 2005.

Carmack, E., Yamamoto-Kawai, M., Haine, T. W. N., Bacon, S., Bluhm, B. A., Lique, C., Melling, H., Polyakov, I. V., Straneo, F., Timmermans, M.-L., and Williams, W. J.: Fresh water and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans, J. Geophys. Res.-Biogeo., 121, 675–717, https://doi.org/10.1002/2015JG003140, 2016.

Chalov, S. R., Shuguang, L., Chalov, R. S., Chalova, E. R., Chernov, A. V., Promakhova, E. V., Berkovitch, K. M., Chalova, A. S., Zavadsky, A. S., and Mikhailova, N.: Environmental and human impacts on sediment transport of the largest Asian rivers of Russia and China, Environ. Earth Sci., 77, 274, https://doi.org/10.1007/s12665-018-7448-9, 2018.

Chandler, M., See, L., Copas, K., Bonde, A. M. Z., Lopez, B. C., Danielsen, F., Legind, J. K., Masinde, S., Miller Rushing, A. J., Newman, G., Rosemartin, A., and Turak, E.: Contribution of citizen science towards international biodiversity monitoring, Biol. Conserv., 213, 280–294, https://doi.org/10.1016/j.biocon.2016.09.004, 2016.

Chaulk, K. G., Robertson, G. J., Collins, B. T., Montevecchi, W. A., and Turner, B.: Evidence of recent population increases in common eiders breeding in Labrador, J. Wildlife Manage., 69, 805–809, 2005.

Chechin, D. and Lüpkes, C.: Boundary-layer development and low-level baroclinicity during high-latitude cold-air outbreaks: A simple model, Bound.-Lay. Meteorol., 162, 1–26, https://doi.org/10.1007/s10546-016-0193-2, 2017.

Chen, Y. and Tang, D. L.: Eddy-Feature Phytoplankton Bloom Induced by a Tropical Cyclone in the South China Sea, Int. J. Remote Sens., 33, 7444–7457, https://doi.org/10.1080/01431161.2012.685976, 2012.

Cheng, B., Vihma, T., Rontu, R., Kontu, A., Kheyrollah, P. H., Duguay, C., and Pulliainen, J.: Evolution of snow and ice temperature, thickness and energy balance in Lake Orajärvi, Northern Finland, Tellus A, 66, 21564, https://doi.org/10.3402/tellusa.v66.21564, 2014.

Chevallier, M., Smith, G. C., Dupont, F., Lemieux, J.-F., Forget, G., Fujii, Y., Hernandez, F., Msadek, R., Peterson, K. A., Storto, A., Toyoda, T., Valdivieso, M., Vernieres, G., Zuo, H., Balmaseda, M., Chang, Y.-S., Ferry, N., Garric, G., Haines, K., Keeley, S., Kovach, R. M., Kuragano, T., Masina, S., Tang, Y., Tsujino, H., and Wang, X.: Intercomparison of the Arctic sea ice cover in global ocean–sea ice reanalyses from the ORA-IP project, Clim. Dynam., 49, 1107–1136, https://doi.org/10.1007/s00382-016-2985-y, 2017.

Chudaeva, V. A., Shesterkin, V. P., and Chudaev, O. V.: Water quality and protection: Trace elements in surface water in Amur River basin, Water Resour., 38, 650–661, https://doi.org/10.1134/S0097807811050034, 2011.

Chung, C. E., Cha, H., Vihma, T., Räisänen, P., and Decremer, D.: On the possibilities to use atmospheric reanalyses to evaluate the warming structure in the Arctic, Atmos. Chem. Phys., 13, 11209–11219, https://doi.org/10.5194/acp-13-11209-2013, 2013.

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., and Jones, J.: Recent Arctic amplification and extreme mid-latitude weather, Nat. Geosci., 7, 627–637, 2014.

Condron, A., Bigg, G. R., and Renfrew, I. A.: Polar mesoscale cyclones in the Northeast Atlantic: comparing climatologies fromERA-40 and satellite imagery, Mon. Weather Rev., 134, 1518–1533, https://doi.org/10.1175/MWR3136.1, 2006.

Crawford, A. D. and Serreze, M. C.: Does the summer Arctic frontal zone influence Arctic Ocean cyclone activity?, J. Climate, 29, 4977–4993, https://doi.org/10.1175/JCLI-D-15-0755.1, 2016.

Danielsen, F., Burgess, N. D., and Balmford, A.: Monitoring matters: examining the potential of locally-based approaches, Biodivers. Conserv., 14, 2507–2542, 2005.

Danielsen, F., Burgess, N. D., Balmford, A., Donald, P. F., Funder, M., Jones, J. P. G., Alviola, P., Balete, D. S., Blomley, T., Brashares, J., Child, B., Enghoff, M., Fjeldså, J., Holt, S., Hübertz, H., Jensen, A. E., Jensen, P. M., Massao, J., Mendoza, M. M., Ngaga, Y., Poulsen, M. K., Rueda, R., Sam, M., Skielboe, T., Stuart-Hill, G., Topp-Jørgensen, E., and Yonten, D.: Local participation in natural resource monitoring: a characterization of approaches, Conserv. Biol., 23, 31–42, 2009.

Danielsen, F., Topp-Jørgensen, E., Levermann, N., Løvstrøm, P., Schiøtz, M., Enghoff, M., and Jakobsen, P.: Counting what counts: using local knowledge to improve Arctic resource management, Polar Geogr., 37, 69–91, 2014.

Danielsen F., Enghoff, M., Magnussen, E., Mustonen, T., Degteva, A., Hansen, K. K., Levermann, N., Mathiesen, S. D., and Slettemark, Ø.: Citizen science tools for engaging local stakeholders and promoting local and traditional knowledge in landscape stewardship, chap. 4, in: The Science and Practice of Landscape Stewardship, UK, edited by: Bieling, C. and Plieninger, T., Cambridge University Press, 2017.

Department of Fisheries and Oceans: Current Status of Northwest Atlantic Harp Seals, (Pagophilus groenlandicus), DFO Can. Sci. Advis. Sec. Sci. Advis. Rep., 2011/070, 2012.

Derksen, C., Brown, R., Mudryk, L., and Luojus, K.: Arctic – Terrestrial Snow, State of the Climate in 2014, B. Am. Meteorol. Soc., 96, 133–135, 2015.

Dmitrenko, I. A., Hoelemann, J. A., Kirillov, S. A., Berezovskaya, S. L., and Kassens, H.: Role of barotropic sealevel changes in

current formation on the eastern shelf of the Laptev Sea, Dokl. Earth Sci., 377, 243–249, 2001.

Dmitrenko I., Kirillov, S., Ivanov, V., Woodgate, R., Polyakov, I., Koldunov, N., Fortier, L., Lalande, C., Kaleschke, L., Bauch, D., Hölemann, J., and Timokhov, L.: Seasonal modification of the Arctic Ocean intermediate water layer off the eastern Laptev Sea continental shelf break, J. Geophys. Res., 114, C06010, https://doi.org/10.1029/2008JC005229, 2009.

Doney, S. C., Ruckelshans, M., and Duffy, J. E.: Climate change impacts on marine ecosystems, Annu. Rev. Mar., 4, 11–37, https://doi.org/10.1146/annurev.-marine-04.1911-11611, 2012.

Döscher, R., Vihma, T., and Maksimovich, E.: Recent advances in understanding the Arctic climate system state and change from a sea ice perspective: a review, Atmos. Chem. Phys., 14, 13571–13600, https://doi.org/10.5194/acp-14-13571-2014, 2014.

Dufour, A., Zolina, O., and Gulev, S. K.: Atmospheric moisture transport to the Arctic: Assessment of reanalyses and analysis of transport components, J. Climate, 29, 5061–5081, https://doi.org/10.1175/JCLI-D-15-0559.1, 2016.

Eamer, J.: Keep it simple and be relevant: the first nine years of the Arctic Borderlands Ecological Knowledge Co-op, in: Bridging Scales and Knowledge Systems, edited by: Reid, W. V., Berkes, F., Wilbanks, T., and Capistrano, D., Island Press, Washington, DC, 185–206, 2006.

Egevang, C. and Boertmann, D.: The Greenland Ramsar sites, a status report, NERI Technical Report No. 346, National Environmental Research Institute, Roskilde, Denmark, 2001.

Egevang, C. and Frederiksen, M.: Fluctuating breeding of Arctic terns, Sterna paradisaea, Arctic and High-Arctic colonies in Greenland, Waterbirds, 34, 107–111, 2011.

Ehrlich, A., Bierwirth, E., Wendisch, M., Gayet, J.-F., Mioche, G., Lampert, A., and Heintzenberg, J.: Cloud phase identification of Arctic boundary-layer clouds from airborne spectral reflection measurements: test of three approaches, Atmos. Chem. Phys., 8, 7493–7505, https://doi.org/10.5194/acp-8-7493-2008, 2008.

Eicken, H., Kaufman, M., Krupnik, I., Pulsifer, P., Apangalook, L., Apangalook, P., Weyapuk J. R., and Leavitt, J.: A framework and database for community sea ice observations in a changing Arctic: An Alaskan prototype for multiple users, Polar Geogr., 37, 5–27, 2014.

EPPR (Arctic Council Working Group: Emergence Prevention, Preparedness, and Response): Field Guide for Oil Spill Response in Arctic Waters, 2nd edn., 443 pp, 2017.

Ferguson, M. A. D., Williamson, R. G., and Messier, F.: Inuit knowledge of long-term changes in a population of Arctic tundra caribou, Arctic, 51, 201–219, 1998.

Fidel, M., Johnson, N., Danielsen, F., Eicken, H., Iversen, L., Lee, O., and Strawhacker, C.: INTAROS Community-based Monitoring Experience Exchange Workshop Report, Yukon River Inter-Tribal Watershed Council (YRITWC), University of Alaska Fairbanks, ELOKA and INTAROS, Fairbanks, 18 pp., 2017.

Furuichi, M. and Otsuka, N.: Cost Analysis of the Northern Sea Route (NSR) and the Conventional Route Shipping, IAME 2013, Marseille, France, 3–5 July 2013, 2013.

Gascard, J. C., Festy, J., le Gogg, H.,Weber, M., Bruemmer, B., Offermann, M., Doble, M., Wadhams, P., Forsberg, R., Hanson, S., Skourup, H., Gerland, S., Nicolaus, M., Metaxin, J. P., Grangeon, J., Haapala, J., Rinne, E., Haas, C., Heygster, G., Jakobson, E., Palo, T., Wilkinson, J., Kaleschke, L., Claffey, K., Elder, B., and Bottenheim, J.: Exploring Arctic Transpolar Drift During Dramatic Sea Ice Retreat, EOS Trans., 89, 21–28, 2008.

Glomsrod, S., Mänpää, I, Lindholt, L., and Mc Donald, H.: Arctic economies within the Arctic nations, chap. 4, in: The Economy of the North, Statistics Norway 2017, 37–77, 2015.

Gofman, V.: Community based monitoring handbook: lessons from the Arctic, CAFF CBMP Report No. 21, Conservation of Arctic Flora and Fauna (CAFF), Akureyi, Iceland, 2010.

Grachev, A. A., Persson, P. O. G., Uttal, T., Akish, E. A., Cox, C. J., Morris, S. M., Fairall, C. W., Stone, R. S., Lesins, G., Makshtas, A. P., and Repina, I. A.: Seasonal and latitudinal variations of surface fluxes at two Arctic terrestrial sites, Clim. Dynam., 51, 1793–1818, https://doi.org/10.1007/s00382-017-3983-4, 2018.

Granskog, M. A., Assmy, P., Gerland, S., Spreen, G., Steen, H., and Smedsrud, L. H.: Arctic research on thin ice: Consequences of Arctic sea ice loss, Eos T. Am. Geophys. Un., 97, 22–26, https://doi.org/10.1029/2016EO044097, 2016.

Granskog, M. A., Rösel, A., Dodd, P. A., Divine, D., Gerland, S., Martma, T., and Leng, M. J.: Snow contribution to first-year and second-year Arctic sea ice mass balance north of Svalbard, J. Geophys. Res.-Oceans, 122, 2539–2549, https://doi.org/10.1002/2016JC012398, 2017.

Guest, P., Persson, P. O. G., Wang, S., Jordan, M., Jin, Y., Blomquist, B., and Fairall, C.: Low-Level Baroclinic Jets over the New Arctic Ocean, J. Geophys. Res., 123, 4074–4091, https://doi.org/10.1002/2018JC013778, 2018.

Haas, C., Lobach, J., Hendricks, S., Rabenstein, L., and Pfaffling, A.: Helicopter-borne measurements of sea ice thickness, using a small and lightweight, digital EM system, J. Appl. Geophys., 67, 234–241, 2009.

Harada, N.: Review: Potential catastrophic reduction of sea ice in the western Arctic Ocean: Its impact on biogeochemical cycles and marine ecosystems, Global Planet. Change, 136, 1–17, https://doi.org/10.1016/j.gloplacha.2015.11.005, 2016.

Hartmann, J., Gehrmann, M., Kohnert, K., Metzger, S., and Sachs, T.: New calibration procedures for airborne turbulence measurements and accuracy of the methane fluxes during the AirMeth campaigns, Atmos. Meas. Tech., 11, 4567–4581, https://doi.org/10.5194/amt-11-4567-2018, 2018.

Heide-Jørgensen, M. P., Witting, L., Laidre, K. L., Hansen, R. G., and Rasmussen, M.: Revised estimates of minke whale abundance in West Greenland in 2007, SC/61/AWMP 4, available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.533.718&rep=rep1&type=pdf, 2010.

Hill, F. and Gaddy, C.: The Siberian Curse: How Communist Planners Left Russia Out in the Cold, Brookings Institution Press, Washington, DC, 304 pp., 2003.

Hole, L. R., Bello, A., Roberts, T., Voss, P., and Vihma, T.: Atmospheric Measurements by Controlled Meteorological Balloons in Coastal Areas of Antarctica, Antarct. Sci., 28, 387–394, https://doi.org/10.1017/S0954102016000213, 2016.

Hölemann, J. A., Schirmacher, M., and Prange, A.: Seasonal variability of trace metals in the Lena River and the southeastern Laptev Sea: Impact of the spring freshet, Glob. Planet. Change, 48, 112–125, https://doi.org/10.1016/j.gloplacha.2004.12.008, 2005.

Holloway, G. and Proshutinsky, A.: Role of tides in Arctic Ocean/ice climate, J. Geophys. Res., 112, C04S06, https://doi.org/10.1029/2006JC003643, 2007.

Holmes, R. M., McClelland, J. W., Peterson, B. J., Tank, S. E., Bulygina, E., Eglinton, T. I., Gordeev, V. V., Gurtovaya, T. Y., Raymond, P. A., Repeta, D. J., Staples, R., Striegl, R. G., Zhulidov, A. V., and Zimov, S. A.: Seasonal and Annual Fluxes of Nutrients and Organic Matter from Large Rivers to the Arctic Ocean and Surrounding Seas, Estuar. Coast., 35, 369–382, https://doi.org/10.1007/s12237-011-9386-6, 2012.

Huntington, H. P.: The local perspective, Nature, 478, 182–183, 2011.

Huntington, H. P., Danielsen, F., Enghoff, M., Levermann, N., Løvstrøm, P., Schiøtz, M., Svoboda, M., and Topp-Jørgensen, E.: Conservation through community involvement, in: Arctic Biodiversity Assessment, edited by: Meltofte, H., Conservation of Arctic Flora and Fauna (CAFF), Akureyi, Iceland, 644–647 2013.

Huskey, L., Mäenpää, I., and Pelyasov, A.: Economic Systems, Arctic Human Development Report, Regional Processes and Global Linkages, Tema Nord, 151–180, 2014.

Inoue, J., Enomoto, T., and Hori, M. E.: The impact of radiosonde data over the ice-free Arctic Ocean on the atmospheric circulation in the Northern Hemisphere, Geophys. Res. Lett., 16, 864–869, 2013.

Inoue, J., Yamazaki, A., Ono, J., Dethloff, K., Maturilli, M., Neuber, R., Edwards, P., and Yamaguchi, H.: Additional Arctic observations improve weather and sea-ice forecasts for the Northern Sea Route, Sci. Rep., 5, 16868, https://doi.org/10.1038/srep16868, 2015.

International Maritime Organization: Polar Code, International Code for Ships Operating in Polar Waters, 83 pp., 2016.

Intrieri, J. M., de Boer, G., Shupe, M. D., Spackman, J. R., Wang, J., Neiman, P. J., Wick, G. A., Hock, T. F., and Hood, R. E.: Global Hawk dropsonde observations of the Arctic atmosphere obtained during the Winter Storms and Pacific Atmospheric Rivers (WISPAR) field campaign, Atmos. Meas. Tech., 7, 3917–3926, https://doi.org/10.5194/amt-7-3917-2014, 2014.

Itkin, P., Spreen, G., Cheng, B., Doble, M., Girard-Ardhuin, F., Haapala, J., Hughes, N., Kaleschke, L., Nicolaus, M., and Wilkinson, J.: Thin ice and storms: Sea ice deformation from buoy arrays deployed during N-ICE2015, J. Geophys. Res.-Oceans, 122, 4661–4674, https://doi.org/10.1002/2016JC012403, 2017.

Ivanov, V., Alexeev, V., Koldunov, N. V., Repina, I. A., Sandoe, A. B., Smedsrud, L. H., and Smirnov, A.: Arctic Ocean Heat Impact on Regional Ice Decay: A Suggested Positive Feedback, J. Phys. Oceanogr., 46, 1437–1456, https://doi.org/10.1175/JPO-D-15-0144.1, 2016.

Ivanov, V. V. and Aksenov, E. O.: Atlantic Water transformation in the eastern Nansen Basin: observations and modelling, Problemy Arktiki, 1, 72–87, 2013 (in Russian with English abstract).

Ivanov, V. V., Polyakov, I. V., Dmitrenko, I. A., Hansen, E., Repina, I. A., Kirillov, S. S., Mauritzen, C., Simmons, H., and Timokhov, L.A.: Seasonal Variability in Atlantic Water off Spitsbergen, Deep-Sea Res. Pt. I, 56, 1–14, https://doi.org/10.1016/j.dsr.2008.07.013, 2009.

Jackson, K., Wilkinson, J., Maksym, T., Meldrum, D., Beckers, J., Haas, C., and Mackenzie, D.: A novel and low cost sea ice mass balance buoy, J. Atmos. Ocean. Tech., 30, 2676–2688, https://doi.org/10.1175/JTECH-D-13-00058.1, 2013.

Jaiser, R., Nakamura, T., Handorf, D., Dethloff, K., Ukita, J., and Yamazaki, K.: Atmospheric winter response to Arctic sea ice changes in reanalysis data and model simulations, J. Geophys. Res., 121, 7564–7577, https://doi.org/10.1002/2015JD024679, 2016.

Jakobson, E., Vihma, T., Palo, T., Jakobson, L., Keernik, H., and Jaagus, J.: Validation of atmospheric reanalyzes over the central Arctic Ocean, Geophys. Res. Lett., 39, L10802, https://doi.org/10.1029/2012GL051591, 2012.

Jakobson, L., Vihma, T., Jakobson, E., Palo, T., Männik, A., and Jaagus, J.: Low-level jet characteristics over the Arctic Ocean in spring and summer, Atmos. Chem. Phys., 13, 11089–11099, https://doi.org/10.5194/acp-13-11089-2013, 2013.

Johnson, N., Alessa, L., Behe, C., Danielsen, F., Gearheard, S., Gofman-Wallingford, V., Kliskey, A., Krümmel, E.-M., Lynch, A., Mustonen, T., Pulsifer, P., and Svoboda, M.: The contributions of community-based monitoring and traditional knowledge to Arctic observing networks: Reflections on the state of the field, Arctic, 68, 1–13, 2015.

Johnson, N., Behe, C., Danielsen, F., Krümmel, E.-M., Nickels, S., and Pulsifer, P. L.: Community-based Monitoring and Indigenous Knowledge in a Changing Arctic. A review for the Sustaining Arctic Observing Networks, Arctic Council, Inuit Circumpolar Council, Ottawa, 2016.

Johnson, N., Fidel, M., Danielsen, F., Iversen, L., Poulsen, M. K., Hauser, D., and Pulsifer, P.: INTAROS Community-based Monitoring Experience Exchange Workshop Report Québec City, Québec, ELOKA, Yukon River Inter-Tribal Watershed Council (YRITWC), University of Alaska Fairbanks, and INTAROS, Québec City, Québec, 28 pp., 2018.

Jonassen, M. O., Tisler, P., Altstädter, B., Scholtz, A., Vihma, T., Lampert, A., König-Langlo, G., and Lüpkes, C.: Application of remotely piloted aircraft systems in observing the atmospheric boundary layer over Antarctic sea ice in winter, Polar Res., 34, 25651, https://doi.org/10.3402/polar.v34.25651, 2015.

Jordan, R. E., Andreas E. L., and Makshtas A. P.: Heat budget of snow-covered sea ice at North Pole 4, J. Geophys. Res., 104, 7785–7806, 1999.

Kaleschke, L., Tian-Kunze, X., Maaß, N., Mäkynen, M., and Drusch, M.: Sea ice thickness retrieval from SMOS brightness temperatures during the Arctic freeze-up period, Geophys. Res. Lett., 39, L05501, https://doi.org/10.1029/2012GL050916, 2012.

Karlsson, E., Gelting, J., Tesi, T., van Dongen, B., Andersson, A., Semiletov, I., Charkin, A., Dudarev, O., and Gustafsson, Ö.: Different sources and degradation state of dissolved, particulate, and sedimentary organic matter along the Eurasian Arctic coastal margin, Global Biogeochem. Cy., 30, 898–919, https://doi.org/10.1002/2015GB005307, 2016.

Karvonen, J.: Virtual radar ice buoys – a method for measuring fine-scale sea ice drift, The Cryosphere, 10, 29–42, https://doi.org/10.5194/tc-10-29-2016, 2016.

Kauko, H. M., Taskjelle, T., Assmy, P., Pavlov, A., Mundy, C. J., Duarte, P., Fernández-Méndez, M., Olsen, L. M., Hudson, S. R., Johnsen, G., Elliott, A., Wang, F., and Granskog, M. A.: Windows in Arctic sea ice: Light transmission and ice algae in a refrozen lead, J. Geophys. Res.-Biogeo., 122, 1486–1505, https://doi.org/10.1002/2016JG003626, 2017.

Kohnert, K., Serafimovich, A., Hartmann, J., and Sachs, T.: Airborne Measurements of Methane Fluxes in the Alaskan and Canadian Tundra with the Research Aircraft Polar 5, Rep. Prog. Phys., 673, ISSN 1866-3192, 2014.

Koldunov, N. V., Köhl, A., Serra, N., and Stammer, D.: Sea ice assimilation into a coupled ocean–sea ice model using its adjoint, The Cryosphere, 11, 2265–2281, https://doi.org/10.5194/tc-11-2265-2017, 2017.

Kondrik, D. V., Pozdnyakov, D. V., and Johannessen, O. M.: Satellite evidence that E. huxleyi phytoplankton blooms weaken marine carbon sinks, Geophys. Res. Lett., 45, 846–885, https://doi.org/10.1002/2017GL076240, 2018a.

Kondrik, D. V., Pozdnyakov, D. V., and Pettersson, L. H.: Tendencies in Coccolithophorid Blooms in Some Marine Environments of the Northern Hemisphere according to the Data of Satellite Observations in 1998–2013, Izvestiya, P. Soc. Photo.-Opo. Ins., 53, 955–964, 2018b.

Kondrik, D., Kazakov, E., and Pozdnyakov, D.: A synthetic satellite dataset of E. huxleyi spatio-temporal distributions and their impacts on Arctic and Subarctic marine environments (1998–2016), Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-101, in review, 2018c.

Korablina, A., Arkhipkin, V., Dobrolyubov, S., and Myslenkov S.: Modeling storm surges and wave climate in the White and Barents Seas/EMECS 11 – Sea Coasts XXVI Joint conference, p. 184, 2016.

Kug, J.-S., Jeong, J.-H., Jang, Y.-S., Kim, N.-M., Folland, C. K., Min, S.-K., and Son, S.-W.: Two distinct influences of Arctic warming on cold winters over North America and East Asia, Nat. Geosci., 8, 759–762, https://doi.org/10.1038/NGEO2517, 2015.

Kwok, R. and Cunningham, G. F.: Variability of Arctic sea ice thickness and volume from CryoSat-2, Philos. T. Roy. Soc. A, 373, 20140157, https://doi.org/10.1098/rsta.2014.0157, 2015.

Kwok, R., Cunningham, G. F., Wensnahan, M., Rigor, I., Zwally, H. J., and Yi, D.: Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008, J. Geophys. Res., 114, C07005, https://doi.org/10.1029/2009JC005312, 2009.

Labansen, A. L. and Merkel, F. R.: Kolonien i Diskobugten i fare for udryddelse, Sermitsiaq, 2012 (in Danish).

Lantuit, H., Overduin, P. P., Couture, N., Wetterich, S., Aré, F., Atkinson, D., Brown, J., Cherkashov, G., Drozdov, D., Forbes, D. L., Graves-Gaylord, A., Grigoriev, M., Hubberten, H. W., Jordan, J., Jorgenson, T., Ødegård, R. S., Ogorodov, S., Pollard, W. H., Rachold, V., Sedenko, S., Solomon, S., Steenhuisen, F., Streletskaya, I., and Vasiliev, A.: The Arctic Coastal Dynamics Database: A New Classification Scheme and Statistics on Arctic Permafrost Coastlines, Eastuar. Coast., 35, 383–400, 2012.

Lammers, R. B., Shiklomanov, A. I., Vörösmarty, C. J., Fekete, B., M., and Peterson, B. J.: Assessment of contemporary Arctic river runoff based on observational discharge records, J. Geophys. Res., 106, 3321, https://doi.org/10.1029/2000JD900444, 2001.

Laney, S. R., Krishfield, R. A., Toole, J. M., Hammar, T. R., Ashjian, C. J., and Timmermans, M. L.: Assessing algal biomass and bio-optical distributions in perennially ice-covered polar ocean ecosystems, Polar Sci., 8, 73–85, https://doi.org/10.1016/j.polar.2013.12.003, 2014.

Lappalainen, H. K., Petäjä, T., Kujansuu, J., Kerminen, V.-M., Shvidenko, A., Bäck, J., Vesala, T., Vihma, T., de Leeuw, G., Lauri, A., Ruuskanen, T., Lapshin, V. B., Zaitseva, N., Glezer, O., Arshinov, M., Spracklen, D. V., Arnold, S. R., Juhola, S., Lihavainen, H., Viisanen, Y., Chubarova, N., Chalov, S., Filatov, N.,Skorokhod, A., Elansky, N., Dyukarev, E., Esau, I., Hari, P., Kotlyakov, V., Kasimov, N., Bondur, V., Matvienko,

G., Baklanov, A., Mareev, E., Troitskaya, Y., Ding, A., Guo, H., Zilitinkevich, S., and Kulmala, M.: Pan Eurasian experiment (PEEX) – a research initiative meeting the grand challenges of the changing environment of the northern Pan-Eurasian Arctic-boreal areas, Geography, Environment, Sustainability, 7, 13–48, 2014.

Lappalainen, H. K., Kerminen, V.-M., Petäjä, T., Kurten, T., Baklanov, A., Shvidenko, A., Bäck, J., Vihma, T., Alekseychik, P., Andreae, M. O., Arnold, S. R., Arshinov, M., Asmi, E., Belan, B., Bobylev, L., Chalov, S., Cheng, Y., Chubarova, N., de Leeuw, G., Ding, A., Dobrolyubov, S., Dubtsov, S., Dyukarev, E., Elansky, N., Eleftheriadis, K., Esau, I., Filatov, N., Flint, M., Fu, C., Glezer, O., Gliko, A., Heimann, M., Holtslag, A. A. M., Hõrrak, U., Janhunen, J., Juhola, S., Järvi, L., Järvinen, H., Kanukhina, A., Konstantinov, P., Kotlyakov, V., Kieloaho, A.-J., Komarov, A. S., Kujansuu, J., Kukkonen, I., Duplissy, E.-M., Laaksonen, A., Laurila, T., Lihavainen, H., Lisitzin, A., Mahura, A., Makshtas, A., Mareev, E., Mazon, S., Matishov, D., Melnikov, V., Mikhailov, E., Moisseev, D., Nigmatulin, R., Noe, S. M., Ojala, A., Pihlatie, M., Popovicheva, O., Pumpanen, J., Regerand, T., Repina, I., Shcherbinin, A., Shevchenko, V., Sipilä, M., Skorokhod, A., Spracklen, D. V., Su, H., Subetto, D. A., Sun, J., Terzhevik, A. Y., Timofeyev, Y., Troitskaya, Y., Tynkkynen, V.-P., Kharuk, V. I., Zaytseva, N., Zhang, J., Viisanen, Y., Vesala, T., Hari, P., Hansson, H. C., Matvienko, G. G., Kasimov, N. S., Guo, H., Bondur, V., Zilitinkevich, S., and Kulmala, M.: Pan-Eurasian Experiment (PEEX): towards a holistic understanding of the feedbacks and interactions in the land-atmosphere-ocean-society continuum in the northern Eurasian region, Atmos. Chem. Phys., 16, 14421–14461, https://doi.org/10.5194/acp-16-14421-2016, 2016.

Lappalainen, H. K., Altimir, N., Kerminen, V., Petäjä, T., Makkonen R., Alekseychik, P., Zaitseva, N., Bashmakova, I., Kujansuu, J., Lauri, A., Haapanala, P., Mazon, S. B., Borisova, A., Konstantinov, P., Chalov, S., Laurila, T., Asmi, E., Lihavainen, H., Bäck, J., Arshinov, M., Mahura, A., Arnold, S., Vihma, T., Uotila, P., de Leeuw, G., Kukkonen, I., Malkhazova, S., Tynkkynen, V., Fedorova, I., Hansson, H. C., Dobrolyubov, S., Melnikov, V., Matvienko, G., Baklanov, A., Viisanen, Y., Kasimov, N., Guo, H., Bondur, V., Zilitinkevich, S., and Kulmala, M.: Pan-Eurasian Experiment (PEEX) program: an overview of the first 5 years in operation and future prospects, Geography, Environment, Sustainability, 11, 6–19, https://doi.org/10.24057/2071-9388-2018-11-1-6-19, 2018.

Laruelle, M.: Russia's Arctic Strategies and the Future of the Far North, Armonk, NY, USA, 250 pp., 2014.

Larsen, T. S., Kurvits, T., and Kuznetsov, E.: Lessons learned from ECORA – An integrated ecosystem management approach to conserve biodiversity and minimize habitat fragmentation in the Russian Arctic, CAFF Strategy Series Report No. 4, 2011.

Law, K. S., Stohl, A., Quinn, P. K., Brock, C., Burkhart, J., Paris, J.-D., Ancellet, G., Singh, H. B., Roiger, A., Schlager, H., Dibb, J., Jacob, D. J., Arnold, S. R., Pelon, J., and Thomas, J. L.: Arctic Air Pollution: New Insights From POLARCAT-IPY, B. Am. Meteorol. Soc., 95, 1873–1895, https://doi.org/10.1175/BAMS-D-13-00017.1, 2015

Lawrence, D. M., Koven, C. D., Swenson, S. C., Riley, W. J., and Slater, A. G.: Permafrost thaw and resulting soil moisture changes regulate projected high-latitude

CO_2 and CH_4 emissions, Environ. Res. Lett., 10 094011, https://doi.org/10.1088/1748-9326/10/9/094011, 2015.

Lee, O., Eicken, H., Kling, G., and Lee, C.: A Framework for Prioritization, Design and Coordination of Arctic Long-term Observing Networks: A Perspective from the U.S. SEARCH Program, Arctic, 68, 76–88, https://doi.org/10.14430/arctic4450, 2015.

Lei, R., Cheng, B., Heil, P., Vihma, T., Wang, J., Ji, Q., and Zhang, Z.: Seasonal and interannual variations of sea ice mass balance from the Central Arctic to the Greenland Sea, J. Geophys. Res., 123, 2422–2439, https://doi.org/10.1002/2017JC013548, 2018.

Lenton, T. M. and Watson, A. J.: Red eld revisited: 1. Regulation of nitrate, phosphate, and oxygen in the ocean, Global Biogeochem. Cy., 14, 225–248, 2000.

Leppäranta, M.: The drift of sea ice, 2nd edn., Heidelberg, Springer-Verlag, 350 pp., 2011.

Levshina, S. I.: Dissolved and suspended organic matter in the Amur and Songhua River water, Water Resour., 35, 716–724, https://doi.org/10.1134/S0097807808060110, 2008.

Liao, Z., Cheng, B., Zhao, J., Vihma, T., Jackson, K., Yang, Q. Yang, Y., Zhang, L., Li, Z., Qiu, Y., and Cheng, X.: Snow depth and ice thickness derived from SIMBA ice mass balance buoy data using an automated algorithm, Int. J. Digit. Earth, https://doi.org/10.1080/17538947.2018.1545877, 2018.

Lindsay, R., Wensnahan, M., Schweiger, A., and Zhang, J.: Evaluation of seven different atmospheric reanalysis products in the Arctic, J. Climate, 27, 2588–2606, 2014.

Liu, M. and Kronbak, J.: The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe, J. Transp. Geogr., 18, 434–444, 2010.

Luneva, M. V., Aksenov, Y., Harle, J. D., and Holt, J. T.: The effects of tides on the water mass mixing and sea ice in the Arctic Ocean, J. Geophys. Res.-Oceans, 120, 6669–6699, https://doi.org/10.1002/2014JC010310, 2015.

Lüpkes, C., Vihma, T., Birnbaum, G., and Wacker, U.: Influence of leads in sea ice on the temperature of the atmospheric boundary layer during polar night, Geophys. Res. Lett., 35, L03805, https://doi.org/10.1029/2007GL032461, 2008.

Lüpkes, C., Vihma, T., Jakobson, E., König-Langlo, G., and Tetzlaff, A.: Meteorological observations from ship cruises during summer to the central Arctic: A comparison with reanalysis data, Geophys. Res. Lett., 37, L09810, https://doi.org/10.1029/2010GL042724, 2010.

Lüpkes, C., Gryanik, V. M., Rösel, A., Birnbaum, G., and Kaleschke, L.: Effect of sea ice morphology during Arctic summer on atmospheric drag coefficients used in climate models, Geophys. Res. Lett., 40, 446–451, https://doi.org/10.1002/grl.50081, 2013.

Maistrova, V., Colony, R., Nagurny, A., and Makshtas, A.: Long-term trends of temperature and specific humidity of free atmosphere in the North Polar Region, Proceedings of the Russian Academy of Science, 391, 112–116, 2003.

Makshtas, A. P. and Sokolov, V. T.: Research Station "Cape Baranov Ice Base" – summer field season in 2014, Russian Polar Research, 3, 10–12, 2014 (in Russian).

Makshtas, A. P., Atkinson, D., Kulakov, M., Shutilin, S., Krishfield, R., and Proshutinsky, A.: Atmospheric forcing validation for modeling the central Arctic, Geophys. Res. Lett., 34, L20706, https://doi.org/10.1029/2007 GL031378, 2007.

Marsan, D., Weiss, J., Larose, E., and Metaxian, J. P.: Sea-ice thickness measurement based on the dispersion of ice swell, J. Acoustic. Soc. Am., 131, 80–91, 2012.

McGlade, C. E.: A review of the uncertainties in estimates of global oil resources, Energy, 47, 262–270, https://doi.org/10.1016/j.energy.2012.07.048, 2012.

McClelland, J. W., Holmes, R. M., Peterson, B. J., Raymond, P. A., Striegl, R. G., Zhulidov, A. V., Zimov, S. A., Zimov, N., Tank, S. E., Spencer, R. G. M., Staples, R., Gurtovaya, T. Y., and Griffin, C. G.: Particulate organic carbon and nitrogen export from major Arctic rivers, Global Biogeochem. Cy., 30, 629–643, 2016.

Medvedeva, A. Y., Arkhipkin V. S., Myslenkov, S. A., and Zilitinkevich, S. S.: Wave climate of the Baltic Sea following the results of the SWAN spectral model application, Moscow University Bulletin, Series 5, Geography, 1, 12–22, 2015.

Merkel, F. R.: Evidence of recent population recovery in common eiders breeding in Western Greenland, J. Wildlife Manage., 74, 1869–1874, 2010.

Mielke, M., Zinoviev, N. S., Dethloff, K., Rinke, A., Kustov, V. J., Makshtas, A. P., Sokolov, V. T., Neuber, R., Maturilli, M., Klaus, D., Handorf, D., and Graeser, J.: Atmospheric winter conditions 2007/08 over the Arctic Ocean based on NP-35 data and regional model simulations, Atmos. Chem. Phys. Discuss., 14, 11855–11893, https://doi.org/10.5194/acpd-14-11855-2014, 2014.

Mikhalevsky, P. N, Sagen, H., Worcester, P., Baggeroer, A. B., Orcutt, J., Moore, S. E., Lee, G. M., Vigness-Raposa, K. J., Freitag, L., Arrott, M., Atakan, K., Beszczynska-Möller, A., Duda, T. F., Dushaw, B. D., Gascard, J. C., Gavrilov, A. N., Keers, H., Morozov, A. K., Munk, W. H., Rixen, M., Sandven, S., Skarsoulis, E., Stafford, K. M., Vernon, F., and Yuen, M. Y.: Multipurpose Acoustic Networks in the Integrated Arctic Ocean Observing System, Arctic, 68, 11–27, https://doi.org/10.14430/arctic4449, 2015.

Moller, H., Berkes, F., Lyver, P. O., and Kislaioglu, M.: Combining science and traditional ecological knowledge: monitoring monitoring populations for co-management, Ecol. Soc., 9, 2004.

Moore, G. W. K.: The Novaya Zemlya Bora and its impact on Barents Sea air-sea interaction, Geophys. Res. Lett., 40, 3462–3467, https://doi.org/10.1002/grl.50641, 2013.

Moore, G. W. K., Bromwich, D. H., Wilson, A. B., Renfrew, I., and Bai, L.: Arctic System Reanalysis improvements in topographically forced winds near Greenland, Q. J. Roy. Meteor. Soc., 142, 2033–2045, https://doi.org/10.1002/qj.2798, 2016.

Mori, M., Watanabe, M., Shiogama, H., Inoue, J., and Kimoto, M.: Robust Arctic sea-ice influence on the frequent Eurasian cold winters in past decades, Nat. Geosci., 7, 869–873, https://doi.org/10.1038/ngeo2277, 2014.

Myllylä, Y., Andreev, O., and Rautio, V.: Where are the Hubs and Gateways of Development?, in: Developments in Murmansk Oblast, edited by: Rautio, V. and Tykkyläinen, M., Russia's Northern Regions on the Edge. Kikimora, Publications, 182–199, 2008.

Myslenkov, S. A., Platonov, V. S., Toropov, P. A., and Shestakova, A. A.: Simulation of storm waves in the Barents Sea, Moscow University Bulletin, Series 5, Geography, 6, 65–75, 2015.

Myslenkov, S. A., Stoliarova, E. V., Markina, M. Y., Kiseleva, S. V., Arkhipkin, V. S., Gorlov, A. A., and Umnov, P. M.: Seasonal and interannual variability of the wave energy flow in the Barents

Sea, Alternative Energy and Ecology (ISJAEE), 19–21, 2017 (in Russian).

Naakka, T., Nygård, T., Vihma, T., Sedlar, J., and Graversen, G.: Atmospheric moisture transport between mid-latitudes and the Arctic: Regional, seasonal and vertical distributions, Int. J. Climatol., in press, 2019.

Nordic Council of Ministers: Local knowledge and resource management, Tema Nord 2015, Copenhagen, Denmark, 2015.

Notz, D. and Stroeve, J.: Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission, Science, 354, 747–750, https://doi.org/10.1126/science.aag2345, 2016.

Orttung, R. (Ed.): Sustaining Russia's Arctic Cities, Resource Politics, Migration and Climate Change, Berghahn Books, 254 pp., 2018.

Overduin, P. P., Strzelecki, M. C., Grigoriev, M. N., Couture, N., Lantuit, H., St.-Hilaire-Gravel, D., Günther, F., and Wetterich, S.: Coastal changes in the Arctic, Geological Society, London, Special Publications, 388, 103–129, https://doi.org/10.1144/SP388.13, 2014.

Overduin, P. P., Wetterich, S., Günther, F., Grigoriev, M. N., Grosse, G., Schirrmeister, L., Hubberten, H.-W., and Makarov, A.: Coastal dynamics and submarine permafrost in shallow water of the central Laptev Sea, East Siberia, The Cryosphere, 10, 1449–1462, https://doi.org/10.5194/tc-10-1449-2016, 2016.

Overland, J., Francis, J., Hall, R., Hanna, E., Kim, S.-J., and Vihma, T.: The Melting Arctic and Mid-latitude Weather Patterns: Are They Connected?, J. Climate, 28, 7917–7932, https://doi.org/10.1175/JCLI-D-14-00822.1, 2015.

Overland, J. E., Dethloff, K., Francis, J. A., Hall, R. J., Hanna, E., Kim, S.-J., Screen, J. A., Shepherd, T. G., and Vihma, T.: The Melting Arctic and Midlatitude Weather Patterns: Forced Chaos and a Way Forward, Nat. Clim. Change, 6, 992–999, https://doi.org/10.1038/nclimate3121, 2016.

Overland, J. E., Hanna, E., Hanssen-Bauer, I., Kim, S.-J., Walsh, J. E., Wang, M., Bhatt, U. S., and Thoman, R. L.: Surface air temperature, in: Arctic Report Card 2017, http://www.arctic.noaa.gov/Report-Card (last access: 21 December 2018), 2017.

Palo, T., Vihma, T., Jaagus, J., and Jakobson, E.: Observations on temperature inversion over central Arctic sea ice in summer, Q. J. Roy. Meteor. Soc., 143, 2741–2754, https://doi.org/10.1002/qj.3123, 2017.

Perovich, D. K. and Polashenski, C.: Albedo evolution of seasonal Arctic sea ice, Geophys. Res. Lett., 39, L08501, https://doi.org/10.1029/2012GL051432, 2012.

Perovich, D. K., Richter-Menge, J. A., Polashenski, C., Elder, B., Arbetter, T., and Brennick, O.: Sea ice mass balance observations from the North Pole Environmental Observatory, Geophys. Res. Lett., 41, 2019–2025, https://doi.org/10.1002/2014GL059356, 2014.

Perro, C., Lesins, G., Duck, T. J., and Caddedu, M.: A microwave satellite water vapour column retrieval for polar winter conditions, Atmos. Meas. Tech., 9, 2241–2252, https://doi.org/10.5194/amt-9-2241-2016, 2016.

Persson, P. O. G., Fairall, C. W., Andreas, E. L., Guest, P. G., and Perovich, D. K.: Measurements near the Atmospheric Surface Flux Group tower at SHEBA: Near-surface conditions and surface energy budget, J. Geophys. Res., 107, 8045, https://doi.org/10.1029/2000JC000705, 2002.

Petrenko, D., Pozdnyakov, D., Johannessen, J., Counillon, F., and Sychov, V.: Satellite-derived multi-year trend in primary production in the Arctic Ocean, Int. J. Remote Sens., 34, 3903–3937, 2013.

Petty, A. A., Holland, M. M., Bailey, D. A., and Kurtz, N. T.: Warm Arctic, increased winter sea ice growth?, Geophys. Res. Lett., 45, 12922–12930, https://doi.org/10.1029/2018GL079223, 2018.

Ping, C.-L., Michaelson, G. J., Guo, L., Torre Jorgenson, M., Kanevskiy, M., Shur, Y., Dou, F., and Liang, J.: Soil carbon and material fluxes across the eroding Alaska Beaufort Sea coastline, J. Geophys. Res., 116, G02004, https://doi.org/10.1029/2010JG001588, 2011.

Pokrovsky, O. S., Manasypov, R. M., Loiko, S., Shirokova, L. S., Krickov, I. A., Pokrovsky, B. G., Kolesnichenko, L. G., Kopysov, S. G., Zemtzov, V. A., Kulizhsky, S. P., Vorobyev, S. N., and Kirpotin, S. N.: Permafrost coverage, watershed area and season control of dissolved carbon and major elements in western Siberian rivers, Biogeosciences, 12, 6301–6320, https://doi.org/10.5194/bg-12-6301-2015, 2015.

Polyakov, I. V., Pnyushkov, A. V., Alkire, M. B., Ashik, I. M., Baumann, T. M., Carmack, E. C., Goszczko, I., Guthrie, J., Ivanov, V. V., Kanzow, T., Krishfield, R., Kwok, R., Sundfjord, A., Morison, J., Rember, R., and Yulin, A.: Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean, Science, 356, 285–291, 2017.

Polyakov, I. V., Alexeev, V. A., Ashik, I. M., Bacon, S., Beszczynska-Möller, A., Carmack, E. C., Dmitrenko, I. A.., Fortier, L.,. Gascard, J.-C, Hansen, E., Hölemann, J., Ivanov, V. V., Kikuchi, T., Kirillov, S., Lenn, Y.-D.., McLaughlin, F., Piechura, J., Repina, I., Timokhov, L. A., Walczowski, W., and Woodgate, R.: NOWCAST: Fate of early-2000's Arctic warm water pulse, 2011, B. Am. Meteorol. Soc., 92, 561–565, https://doi.org/10.1175/2010BAMS292I.I, 2011.

Popovicheva, O. B., Makshtas, A. P., Movchan, V. V., Persiantseva, N. M., Timofeev, M. A., and Sitnikov, N. M.: Aerosol component of the atmospheric surface layer according observations of the expedition "North-2015", Problems of Arctic and Antarctic, N4, 57–65, ISSN: 0555-2648, 2017 (in Russian).

Pozdnyakov, D. V., Johannessen, O. M., Korosov, A. A., Pettersson, L. H., Grassl, H. G., and Miles, M. W.: Satellite evidence of ecosystem changes in the White Sea: A semi-enclosed arctic marginal self sea, Geophys. Res. Lett., 34, L08604, https://doi.org/10.1029/2006GL028947, 2007.

Pulsifer, P. L., Laidler, G. J., Taylor, D. R. F., and Hayes, A.: Towards an indigenist data management program: Reflections on experiences developing an atlas of sea ice knowledge and use, Can. Geogr., 55, 108–124, 2011.

Rainville, L., Lee, C. M., and Woodgate, R. A.: Impact of wind-driven mixing in the Arctic Ocean, Oceanography, 24, 136–145, 2011.

Rasmussen R. O. (Ed.): Megatrends, Tema Nord 2011, Nordic Council of Ministers, Copenhagen, 205 pp., 2011.

Reeve, M. A. and Kolstad, E. W.: The Spitsbergen South Cape tip jet, Q. J. Roy. Meteor. Soc., 137, 1739–1748, https://doi.org/10.1002/qj.876, 2011.

Reuder, J., Jonassen, M. O., and Olafsson, H.: The small unmanned meteorological observer SUMO: recent developments and applications of a micro-UAS for atmospheric boundary layer research, Acta Geophys., 60, 1454–1473, 2012.

Riihelä, A., Manninen, T., and Laine, V.: Observed changes in the albedo of the Arctic sea-ice zone for the period 1982–2009, Nat. Clim. Change, 3, 895–898, doi:1.1038/nclimate1963, 2013.

Rinke, A., Maturilli, M., Graham, R. M., Matthes, H., Handorf, D., Cohen, L., Hudson, S. R., and Moore, J. C.: Extreme cyclone events in the Arctic: Wintertime variability and trends, Environ. Res. Lett., 12, 094006, https://doi.org/10.1088/1748-9326/aa7def, 2017.

Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbeoch, M., Gilbert, D., Xu, J., Pouliquen, S., Thresher, A., Le Traon, P.-Y., Maze, G., Klein, B., Ravichandran, M., Grant, F., Poulain, P. M., Suga, T., Lim, B., Sterl, A., Sutton, P., Mork, K.-A., Joaquin Velez-Belch, P., Ansorge, I., King, B., Turton, J., Baringer, M., and Jayne, S. R.: Fifteen years of ocean observations with the global Argo array, Nat. Clim. Change, 6, 145–153, 2016.

Rosing-Asvid, A.: Grønlands sæler, Ilinniusiorfik Undervisningsmiddelforlag: Nuuk, Greenland, 146 pp., 2010.

Rudels, B.: Arctic Ocean circulation and variability – advection and external forcing encounter constraints and local processes, Ocean Sci., 8, 261–286, https://doi.org/10.5194/os-8-261-2012, 2012.

Rudels, B., Korhonen, M., Schauer, U., Pisarev, S., Rabe, B., and Wisotzki, A.: Circulation and transformation of Atlantic water in the Eurasian Basin and the contribution of the Fram Strait inflow branch to the Arctic Ocean heat budget, Progr. Oceanogr., 132, https://doi.org/10.1016/j.pocean.2014.04.003, 2014.

Rutt, S.: The Soviet Concept of the Territorial-Production Complex and Regional Development, Town Planning Rev., 57, 425–439, 1986.

Sagen, H., Worcester, P. F., Dzieciuch, M. A., Geyer, F., Sandven, S., Babiker, M., Beszczynska-Möller, A., Dushaw, B. D., and Cornuelle, B.: Resolution, identification, and stability of broadband acoustic arrivals in Fram Strait, J. Acous. Soc. Amer., 141, 2055, https://doi.org/10.1121/1.4978780, 2017.

Sandven, S., Johannessen, O.-M., Fahrbach, E., Buch, E., Cattle, H., Toudal Pedersen, L., and Vihma, T.: The Arctic Ocean and the Need for an Arctic GOOS, EuroGOOS Publication No. 22, 50 pp., 2005.

Savenko, V.: Chemical composition of World River's suspended matter, GEOS, Moscow, 175 pp., 2006 (In Russian).

Schäfer, M., Bierwirth, E., Ehrlich, A., Jäkel, E., and Wendisch, M.: Airborne observations and simulations of three-dimensional radiative interactions between Arctic boundary layer clouds and ice floes, Atmos. Chem. Phys., 15, 8147–8163, https://doi.org/10.5194/acp-15-8147-2015, 2015.

Screen, J. A.: Arctic amplification decreases temperature variance in northern mid- to high-latitudes, Nat. Clim. Change, 4, 577–582, https://doi.org/10.1038/nclimate2268, 2014.

Sedlar, J. and Shupe, M. D.: Characteristic nature of vertical motions observed in Arctic mixed-phase stratocumulus, Atmos. Chem. Phys., 14, 3461–3478, https://doi.org/10.5194/acp-14-3461-2014, 2014.

Seinfeld, J. H. and Pandis, S. N.: Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, 1195, New York: John Willey & Sons, 2016.

Sepp, M. and Jaagus, J.: Changes in the activity and tracks of Arctic cyclones, Clim. Change, 105, 577–595, 2011.

Serreze, M. C., Kahl, J. D. W., and Schnell, R. C.: Low-level temperature inversions of the Eurasian Arctic 5 and comparisons with Soviet drifting stations, J. Climate, 8, 719–731, 1992.

Shakhova, N., Semiletov, I., and Bel'cheva, N.: The great Siberian rivers as a source of methane on the Russian Arctic shelf, Dokl. Earth Sci., 415, 734–736, https://doi.org/10.1134/S1028334X07050169, 2007.

Shiklomanov, A. I., Lammers, R. B., and Vörösmarty, C. J.: Widespread decline in hydrological monitoring threatens Pan-Arctic Research, Eos T. Am. Geophys. Un., 83, 13–17, https://doi.org/10.1029/2002EO000007, 2002.

Shiklomanov, I. A. and Shiklomanov, A. I.: Climatic change and the dynamics of river runoff into the Arctic Ocean, Water Resour., 30, 593–601, https://doi.org/10.1023/B:WARE.0000007584.73692.ca, 2003.

Shupe, M. D., Persson, P. O. G., Brooks, I. M., Tjernström, M., Sedlar, J., Mauritsen, T., Sjogren, S., and Leck, C.: Cloud and boundary layer interactions over the Arctic sea ice in late summer, Atmos. Chem. Phys., 13, 9379–9399, https://doi.org/10.5194/acp-13-9379-2013, 2013.

Siegstad, H.: Sammendrag af den biologiske rådgivning for 2012 for fiskebestande med relation til grønlandske fiskerier, Greenland Institute of Natural Resources, Nuuk, Greenland, 2011.

Siegstad, H.: Rådgivning om fiskebestande, available at: http://www.natur.gl/fileadmin/user_upload/FiSk/Raadgivning/1._Fiskeraadgivningen_2012.pdf, (last access: 26 January 2016), 2012.

Sirevaag, A. and Fer, I.: Vertical heat transfer in the Arctic Ocean: The role of double-diffusive mixing, J. Geophys. Res., 117, C07010, https://doi.org/10.1029/2012jc007910, 2012.

Smith, L. C. and Stephenson, S. R.: New Trans-Arctic shipping routes navigable by mid-century, P. Natl. Acad. Sci. USA, 110, E1191–E1195, https://doi.org/10.1073/pnas.1214212110, 2013.

Soltwedel, T., Bauerfeind, E., Bergmann, M., Budaeva, N., Hoste, E., Jaeckisch, N., von Juterzenka, K., Matthiessen, J., Mokievsky, V., Nöthig, E.-M., Quéric, N.-V., Sablotny, B., Sauter, E., Schewe, I., Urban-Malinga, B., Wegner, J., Wlodarska-Kowalczuk, M., and Klages, M.: HAUSGARTEN: Multidisciplinary investigations at a deep-sea, long-term observatory in the Arctic Ocean, Oceanography, 18, 46–61, https://doi.org/10.5670/oceanog.2005.24, 2005.

Sonke, J. E., Teisserenc, R., Heimbürger-Boavida, L.-E., Petrova, M., Marusczak, N., Le Dantec, T., Chuparov, A., Li, C., Thackray, C., Sunderland, E., Tananaev, N., and Pkrovsky, O.: Eurasian river spring flood observations support net Arctic Ocean mercury export to the atmosphere and Atlantic Ocean, P. Nat. Acad. Sci. USA, 115, 11586–11594, https://doi.org/10.1073/pnas.1811957115, 2018.

Sørensen, C. T. N. and Klimenko, E.: Emerging Chinese-Russian cooperation in the Arctic – Possibilities and constraints, SITRI Policy Paper, No. 46, Stockholm International Peace Research Institute, 43 pp., ISBN 978-91-85114-92-4, 2017.

Spreen, G. and Kern, S.: Methods of satellite remote sensing of sea ice, in: Sea Ice, edited by: Thomas, D. N., 3rd edn., Wiley Backwell, 664 pp., 2017.

Spreen, G., Kwok, R., and Menemenlis, D.: Trends in Arctic sea ice drift and role of wind forcing: 1992–2009, Geophys. Res. Lett., 38, L19501, https://doi.org/10.1029/2011GL048970, 2011.

Starkov, A. N., Landberg, L., Bezroukikh, P. P., and Borisenko, M. M.: Russian Wind Atlas. Russian-Danish Institute for Energy Efficiency, Moscow, Risø National Laboratory, Roskilde, 551 pp., ISBN 5-7542-0067-6, 2000.

Sumata, H., Kauker, F., Karcher, M., Rabe, B., Timmermans, M.-L., Behrendt, A., Gerdes, R., Schauer, U., Shimada, K., Cho, K.-H., and Kikuchi, T.: Decorrelation scales for Arctic Ocean hydrography – Part I: Amerasian Basin, Ocean Sci., 14, 161–185, https://doi.org/10.5194/os-14-161-2018, 2018.

Tammelin, B., Vihma, T., Atlaskin, E., Badger, J., Fortelius, C., Gregow, H., Horttanainen, M., Hyvönen, R., Kilpinen, J., Latikka, J., Ljungberg, K., Mortensen, N. G., Niemelä, S., Ruosteenoja, K., Salonen, K., Suomi, I., and Venäläinen, A.: Production of the Finnish Wind Atlas, Wind Energy, 16, 19–35, https://doi.org/10.1002/we.517, 2013.

Tetzlaff, A., Kaleschke, L., Lüpkes, C., Ament, F., and Vihma, T.: The impact of heterogeneous surface temperatures on the 2-m air temperature over the Arctic Ocean under clear skies in spring, The Cryosphere, 7, 153–166, https://doi.org/10.5194/tc-7-153-2013, 2013.

Timmermans, M.-L., Cole, S. T., and Toole, J. M.: Horizontal density structure and restratification in the Arctic Ocean surface layer, J. Phys. Oceanogr., 42, 659–668, 2012.

Tisler, P., Vihma, T., Müller, G., and Brümmer, B.: Modelling of warm-air advection over Arctic sea ice, Tellus A, 60, 775–788, 2008.

Tjernström, M. and Graversen, R. G.: The vertical structure of the lower Arctic troposphere analysed from observations and the ERA-40 reanalysis, Q. J. Roy. Meteor. Soc., 135, 431–443, https://doi.org/10.1002/qj.380, 2009.

Tjernström, M., Birch, C. E., Brooks, I. M., Shupe, M. D., Persson, P. O. G., Sedlar, J., Mauritsen, T., Leck, C., Paatero, J., Szczodrak, M., and Wheeler, C. R.: Meteorological conditions in the central Arctic summer during the Arctic Summer Cloud Ocean Study (ASCOS), Atmos. Chem. Phys., 12, 6863–6889, https://doi.org/10.5194/acp-12-6863-2012, 2012.

Tjernström, M., Leck, C., Birch, C. E., Bottenheim, J. W., Brooks, B. J., Brooks, I. M., Bäcklin, L., Chang, R. Y.-W., de Leeuw, G., Di Liberto, L., de la Rosa, S., Granath, E., Graus, M., Hansel, A., Heintzenberg, J., Held, A., Hind, A., Johnston, P., Knulst, J., Martin, M., Matrai, P. A., Mauritsen, T., Müller, M., Norris, S. J., Orellana, M. V., Orsini, D. A., Paatero, J., Persson, P. O. G., Gao, Q., Rauschenberg, C., Ristovski, Z., Sedlar, J., Shupe, M. D., Sierau, B., Sirevaag, A., Sjogren, S., Stetzer, O., Swietlicki, E., Szczodrak, M., Vaattovaara, P., Wahlberg, N., Westberg, M., and Wheeler, C. R.: The Arctic Summer Cloud Ocean Study (ASCOS): overview and experimental design, Atmos. Chem. Phys., 14, 2823–2869, https://doi.org/10.5194/acp-14-2823-2014, 2014.

Toole, J. M., Krishfield, R. A., Timmermans, M.-L., and Proshutinsky, A.: The Ice-Tethered Profiler: Argo of the Arctic, Oceanography, 24, 126–135, https://doi.org/10.5670/oceanog.2011.64, 2011.

Tschudi, M. A., Curry, J. A., and Maslanik, J. A.: Airborne observations of summertime surface features and their effect on surface albedo during FIRE/SHEBA, J. Geophys. Res., 106, 15335–15344, 2001.

Tsui, S., Wong, E., Chi, L., and Tiejun, W.: One Belt, One Road, 68, 36–45, https://doi.org/10.14452/MR-068-08-2017-01_4, 2017.

Tubi, A. and Dayan, U.: The Siberian High: teleconnections, extremes and association with the Icelandic Low, Int. J. Climatol., 33, 1357–1366, https://doi.org/10.1002/joc.3517, 2013.

Uotila, P., Karpechko, A., and Vihma, T.: Links between the Arctic sea ice and extreme summer precipitation in China: An alternative view, Adv. Polar Sci., 25, 222–233, https://doi.org/10.13679/j.advps.2014.4.00222, 2014.

Uotila, P., Goosse, H., Haines, K., Chevallier, M., Barthélemy, A., Bricaud, C., Carton, J., Fučkar, N., Garric, G., Iovino, D., Kauker, F., Korhonen, M., Lien, V. S., Marnela, M., Massonnet, F., Mignac, D., Peterson, K. A., Sadikni, R., Shi, L., Tietsche, S., Toyoda, T., Xie, J., and Zhang, Z.: An assessemnt of ten ocean reanalyses in the polar regions, Clim. Dynam., https://doi.org/10.1007/s00382-018-4242-z, 2018.

Uttal, T., Curry, J. A., McPhee, M. G., Perovich, D. K., Moritz, R. E., Maslanik, J. A., Guest, P. S., Stern, H. L., Moore, J. A., Turenne, R., Heiberg, A., Serreze, M. C., Wylie, D. P., Persson, O. G., Paulson, C. A., Halle, C., Morison, J. H., Wheeler, P. A., Makshtas, A., Welch, H., Shupe, M. D., Intrieri, J. M., Stamnes, K., Lindsey, R. W., Pinkel, R., Pegau, W. S., Stanton, T. P., and Grenfeld, T. C.: Surface heat budget of the Arctic Ocean, B. Am. Meteorol. Soc., 83, 255–275, 2002.

Uttal, T., Starkweather, S., Drummond, J., Vihma, T., Cox, C. J., Dlugokencky, E., Ogren, J., McArthur, B., Schmeisser, L., Walden, V., Laurila, T., Darby, L., Makshtas, A. P., Intrieri, J., Burkhart, J., Haiden, T., Goodison, B., Maturilli, M., Shupe, M., de Boer, G., Stone, R., Saha, A., Grachev, A., Bruhwiler, L., Persson, O., Lesins, G., Crepinsek, S., Long, C., Sharma, S., Massling, A., Turner, D. D., Stanitski, D., Asmi, E., Aurela, M., Skov, H., Eleftheriadis, K., Virkkula, A., Platt, A., Forland, E., Verlinde, J., Yoshihiroo, I., Nielsen, I. E., Bergin, M., Candlish, L., Zimov, N., Zimov, S., O'Neil, N., Fogal, P., Kivi, R., Konopleva, E., Kustov, V., Vasel, B., Viisanen, Y., and Ivakhov, V.: International Arctic Systems for Observing the Atmosphere (IASOA): An International Polar Year Legacy Consortium, B. Am. Meteorol. Soc., 97, 103–1056, https://doi.org/10.1175/BAMS-D-14-00145.1, 2016.

Vihma, T.: Weather extremes linked to interaction of the Arctic and mid-latitudes, in: Climate Extremes: Mechanisms and Potential Prediction, edited by: Wang, S.-Y., Geophys. Monogr. Ser., American Geophysical Union, 226, 39–49, 2017.

Vihma, T., Jaagus, J., Jakobson, E., and Palo, T.: Meteorological conditions in the Arctic Ocean in spring and summer 2007 as recorded on the drifting ice station Tara, Geophys. Res. Lett., 35, L18706, https://doi.org/10.1029/2008GL034681, 2008.

Vihma, T., Tisler, P., and Uotila, P.: Atmospheric forcing on the drift of Arctic sea ice in 1989–2009, Geophys. Res. Lett., 39, L02501, https://doi.org/10.1029/2011GL050118, 2012.

Vihma, T., Pirazzini, R., Fer, I., Renfrew, I. A., Sedlar, J., Tjernström, M., Lüpkes, C., Nygård, T., Notz, D., Weiss, J., Marsan, D., Cheng, B., Birnbaum, G., Gerland, S., Chechin, D., and Gascard, J. C.: Advances in understanding and parameterization of small-scale physical processes in the marine Arctic climate system: a review, Atmos. Chem. Phys., 14, 9403–9450, https://doi.org/10.5194/acp-14-9403-2014, 2014.

Vihma, T., Screen, J., Tjernström, M., Newton, B., Zhang, X., Popova, V., Deser, C., Holland, M., and Prowse, T.: The atmospheric role in the Arctic water cycle: A review on processes, past

and future changes, and their impacts, J. Geophys. Res.-Biogeo., 121, 586–620, https://doi.org/10.1002/2015JG003132, 2016.

Vlasova, T. and Petrov, A.: Migration and Socio-Economic Well-Being in the Russia North: Interrelations, Regional Differentiation, Recent Trends, and emerging Issues, in: Migration in the Circumpolar North, edited by: Huskey, L. and Southcott, C., CCI Press/University of the Arctic, 163–192, 2010.

von Schuckmann, K. and the CMEMS OSR task team: The Copernicus Marine Environment Monitoring Service Ocean State Report, J. Oper. Oceanogr., 9, 235–320, https://doi.org/10.1080/1755876X.2016.1273446, 2016.

Weiss, J., Schulson, E. M., and Stern, H. L.: Sea ice rheology from in situ, satellite and laboratory observations: Fracture and friction, Earth Planet. Sc. Lett., 255, 1–8, 2007.

Wicks, A. J. and Atkinson, D. E.: Identification and classification of storm surge events at Red Dog Dock, Alaska, 2004–2014, Nat. Hazards, 86, 877–900, https://doi.org/10.1007/s11069-016-2722-1, 2017.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L-B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., Gonzalez-Beltran, A., Gray, A. J. G., Groth, P., Goble, C., Grethe, J. S., Heringa, J., Hoen, P. A. C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., and Mons, B.: The FAIR Guiding Principles for scientific data management and stewardship, Sci. Data, 3, 160018, https://doi.org/10.1038/sdata.2016.18, 2016.

WMO: WWRP Polar Prediction Project Implementation Plan, WWRP/PPP No. 2 – 2013, World Meteorological Organization, Geneve, Switzerland, 72 pp., 2013.

Worcester, P. F., Cornuelle, B. D., and Dzieciuch, M. A.: Canada Basin Acoustic Propagation Experiment (CANAPE), Scripps Institution of Oceanography, available at: https://scripps.ucsd.edu/research/proposals/canada-basin-acoustic-propagation-experiment-canape, last access: 26 January 2019, 2015.

Zhang, X., Walsh, J. E., Zhang, J., Bhatt, U. S., and Ikeda, M.: Climatology and interannual variability of Arctic cyclone activity: 1948–2002, J. Climate, 17, 2300–2317, https://doi.org/10.1175/1520-0442(2004)017<2300:CAIVOA>2.0.CO;2, 2004.

Zhang, Z., Uotila, P., Stössel, A., Vihma, T., Liu, H., and Zhong, Y.: Seasonal southern hemisphere multi-variable reflection of the southern annular mode in atmosphere and ocean reanalyses, Clim. Dynam., 50, 1451–1470, https://doi.org/10.1007/s00382-017-3698-6, 2017.