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Advancing the understanding of variations of Arctic sea ice optical and thermal behaviors through an international research and mobility project

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Abstract In recent decades, significant changes of Arctic sea ice have taken place. These changes are expected to influence the surface energy balance of the ice-covered Arctic Ocean. To quantify this energy balance and to increase our understanding of mechanisms leading to observed changes in the Arctic sea ice, the project "Advancing Modelling and Observing solar Radiation of Arctic sea ice—understanding changes and processes (AMORA)" was initiated and conducted from 2009 to 2013. AMORA was funded and organized under a frame of Norway-China bilateral collaboration program with partners from Finland, Germany, and the USA. The primary goal of the project was achieved by developing an autonomous spectral radiation buoy, deploying it on drifting sea ice close to the North Pole, and receiving a high-resolution time series of spectral radiation over and under sea ice from spring (before melt onset) to autumn (after freeze-up) 2012. Beyond this, *in-situ* sea ice data were collected during several field campaigns and simulations of snow and sea ice thermodynamics were performed. More autonomous measurements are available through deployments of sea ice mass balance buoys. These new observational data along with numerical model studies are helping us to better understand the key thermodynamic processes of Arctic sea ice and changes in polar climate. A strong scientific, but also cultural exchange between Norway, China, and the partners from the USA and Europe initiated new collaborations in Arctic reseach.

Keywords **Arctic, sea ice, snow, solar radiation, ice-albedo feedback, international collaboration**

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1 Introduction

Sea ice plays a key role in the global climate system. In recent decades, the Arctic sea ice has been undergoing dramatic changes[1-2], latest in 2012 with a new Arctic sea ice extent minimum record: rapid retreat in ice extent[3], rapid decrease in ice thickness[4-6], and a rapid reduction in old ice with a shift to more seasonal sea ice[7-8]. The decline in Arctic sea ice reduces the surface albedo and modifies the surface energy balance[9-12]. It has a leading role in the recent Arctic temperature amplification[13-14], shifts the balance between primary production by ice algae and phytoplankton[15], and

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affects the ice-associated marine mammals in the Arctic[16]. There are likely a number of mechanisms induced that may have contributed to the observed changes in the Arctic sea ice, but their relative importance is so far unclear. It was attributed to, for example, a recent change in the linkage between the North Atlantic Oscillation and Arctic sea ice export through Fram Strait, to changes in the surface winds from the Arctic Oscillation[17-18], to abnormal Arctic cyclones[19], to the warm Pacific inflow[20], to the sea ice dynamic and thermodynamic effects[8,21]; and to the ice/ocean-albedo feedback[22-23]. As a result, this accelerates melting of summer sea ice[24-25]. A numerical modelling study indicated that a time dependent surface albedo parameterization is critical for the seasonal evolution of snow and sea ice thickness[26]. The modelling errors in the onset of sea ice melt, snow and sea ice mass balance, and the annual equilibrium sea ice thickness are caused by inaccuracy of albedo[27]. In order to address the knowledge gaps, and to initate and strengthen international collaboration on the complex aspects of sea ice in the climate system, we initated a project that especially focused on the surface energy balance in the Arctic Basin.

2 Aim and concept of AMORA

The main goal of the project "Advancing Modelling and Observing solar Radiation of Arctic sea ice—understanding changes and processes (AMORA)" was to increase the understanding of the surface energy balance and the radiative transfer in snow and sea ice in the Arctic Ocean. The project was organized within the Norwegian-Chinese bilateral collaboration program for advance in climate research of the Research Council of Norway and lasted from 2009 to 2013. In addition, active partners from Finland, Germany, and the USA were involved (Figure 1d). AMORA was funded by the Research Council of Norway and by in kind contributions of the project partner institutes. Beside the scientific objectives, networking between the project partners, particularly between Norway and China, were established through joint field campaigns, project workshops and researcher visits. This allowed for knowledge exchange about key processes in polar climate, especially sea ice feedbacks, generated education support for young scientists and students, and resulted in outreach towards the public in all participating countries.

To achieve the primary objective, AMORA had three main tasks: (1) developing a Spectral Radiation Buoy (SRB), an autonomous system continuously measuring solar radiation over (incident and reflected) and under (transmitted) sea ice following the concept of a setup developed for the International Polar Year 2007-2009[28], and deploying such buoy(s) together with ice mass balance buoys (IMBs), (2) performing manned *in-situ* observations of physical properties of snow and sea ice in different regions of the Arctic, and (3) improving parameterizations of feedback mechanisms in the numerical sea ice and snow model HIGHTSI (high-resolution thermodynamic snow/ice model)[26] and use it for numerical studies related to buoy and *in-situ* data from manned observations to understand sea ice sensitivity to key feedbacks.

AMORA was organized into four work packages (WPs), covering different observational and modelling aspects to study key feedback processes of Arctic sea ice and snow. One key element of WP1 was the development of the SRB, to enable autonomous measurements of radiation transfer through sea ice in the high Arctic. Besides this development, also a suite of other *in-situ* observations of optical and other physical properties of snow and sea ice were performed during different field experiments or ship-borne expeditions (Figure 1). Measurements of sea ice mass balance complemented to the optical measurements, partly through thermistor-string IMBs and IMBs based on sonic height measurements[29]. High-resolution numerical simulations and model improvements on snow and ice physics were performed in WP2 with the thermodynamic snow/ice model HIGHTSI, developed in late 1990s[30]. Focus of this work was the seasonal evolution of snow and sea ice mass balance, applied and compared to different field observations. WP3 dealt with manned *in-situ* measurements and process studies. Different data sets on physical properties of snow and sea ice were collected to support the modelling work in WP2 and the development of SRB in WP1. These included *in-situ* sea ice data acquisition in Svalbard fjords, the Chukchi Sea, the Beaufort Sea, the Central Arctic, and Fram Strait/Greenland Sea (Figure 1). WP4 comprised all activities of dissemination and knowledge transfer. It included coordination for common fieldwork with shared infrastructure and equipment, workshops and meetings, presentations at conferences and symposia, and guest stays and young scientist training. The kick-off workshop of AMORA was held in late 2009 in Shanghai, China. The second and third project annual meetings, combined with topical seminars/workshops, were held in Tromsø (Norway, fall 2010) and Dalian (China, fall 2011). The last project seminar/workshop was held in Helsinki (Finland, fall 2012).

3 Methods and results

The SRB was successfully developed by the project scientists and engineers, in collaboration with Satlantic Inc. (Halifax, Canada)[31]. Three spectral radiometers (Satlantic HYPEROCR) are the main sensor elements of the SRB, two of them in air with one looking-upward and the other looking-downward to measure incident and reflected irradiance above the ice, and one looking-upward under the ice to measure transmitted irradiance. The under-ice sensor was additionally equipped with a bio-shutter, for preventing bio-fouling on the sensor. In addition to the spectral radiometers, the SRB consisted of a data processing and storage unit (Satlantic STOR-X), an Iridium modem for satellite communication, and a battery unit for power-supply. The Iridium transfer and a bioshutter to avoid biofouling on

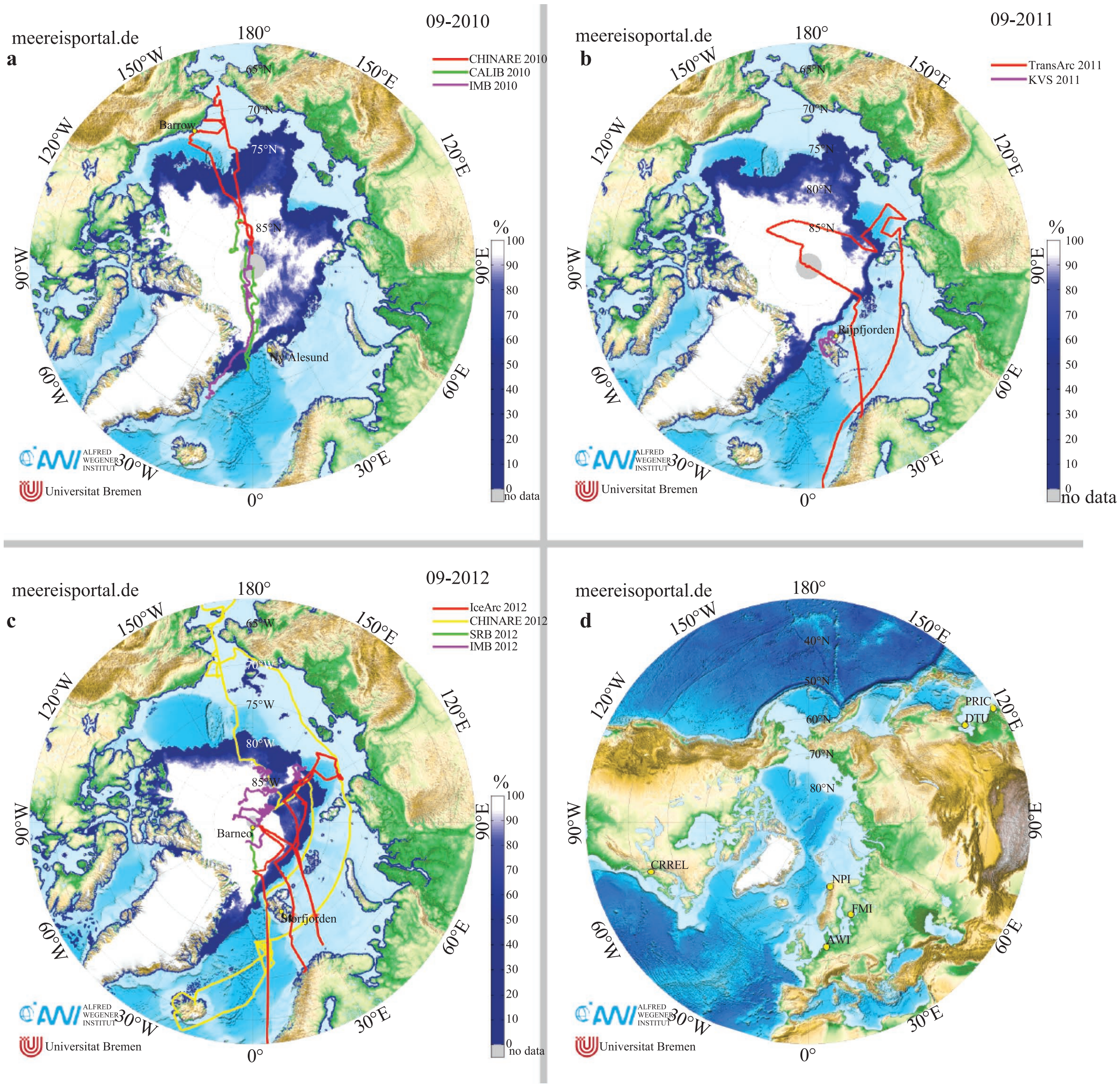

Figure 1 **a-c**, Maps of all field experiments and expeditions, as well as buoy drift tracks. Background data give the mean ice concentration in September of the respective years. Buoy types and expedition abbreviations as listed in the legends are explained in the main text. **d**, Map of all project partner's main locations

the under-ice radiometer were the major advances compared to earlier radiation setups[28,32]. The first deployment was, after a test in Tromsø, planned to be deployed for a limited time on land-fast sea ice in Rijpfjorden, Svalbard, in May 2011 (Figure 1b). During the attempt to deploy the buoy, the hull of the buoy broke while transporting it with a helicopter. Thus, the buoy could not be installed, and was instead brought back to the Norwegian Polar Institute (NPI) in Tromsø. After modifying the buoy construction from a one-piece hull to a modular setup, similar to the stations described by Nicolaus et al.[28], the buoy was successfully deployed on drifting sea ice in the central Arctic Basin near the North Pole in April 2012 from the temporary Russian ice camp Barneo (Figures 1c and 2)[31]. The modular setup could be completely dissembled and packed in boxes. The under-ice sensor was installed on a foldable arm, reaching about 1.5 m to the side of the deployment hole. An IMB was co-located with the SRB in order to provide additional information on sea ice and snow properties during the drift. More drifting platforms were installed in the vicinity of the SRB by different groups, including two web cameras (University of Washington, USA), giving valuable information on the surface conditions at the ice floe. Other data from the platforms installed at Barneo by other groups, addressing oceanography, atmosphere and ice measurements, can be also combined with the rad iation data during the pre- and post- processing. The SRB worked until 4 October 2012 when most part of the SRB could be recovered in Fram Strait during an operation of the Norwegian R/V *Lance*. The co-located IMB was not recovered and continued to work until 24 October 2012.

The drift track of the SRB is shown in Figure 1c. Through all these installations, a continuous data set of spectral radiation fluxes, surface albedo, and light transmittance was obtained covering the entire summer season, including pre-melt conditions, through melt onset, snow melt and pond formation and autumn freeze-up (Figure 3). Results of the SRB drift are summarized and discussed in detail by Wang et al.[31].

As a consequence of the successful retrieval of most components of the SRB in late 2012, the SRB could be re-deployed again in April 2013 (Figure 2b). This time the SRB was modified to include a GPS to obtain accurate positions from the unit. Similar to the previous year it was deployed from the next Barneo ice camp close to the North Pole and drifted towards Fram Strait (Figure 1). Again, an IMB was co-located to the SRB. In addition, a newly developed snow-depth buoy was installed next to the SRB to extend the autonomous data set in order to get an improved description of the snow cover, currently seen as the most important factor for radiation transfer through sea ice. Unfortunately, this buoy stopped transmission for unknown reasons after only a few weeks of operation. The main differences between 2012 and

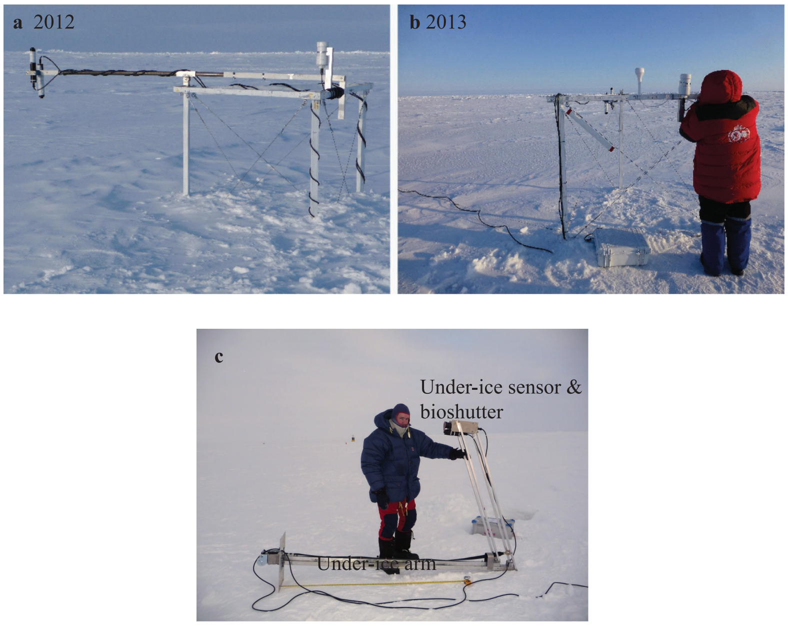

Figure 2 Spectral Radiation Buoy, as deployed in April 2012 (**a**) and in April 2013 (**b**) at the Barneo ice camps. The spectral radiometers are the cylinders on the left in (**a**) and in the background in (**b**). In 2012, all power supply and batteries are buried in the snow. In 2013, they were mounted on the frame. The under-ice arm of the SRB before final installation is given in (**c**).

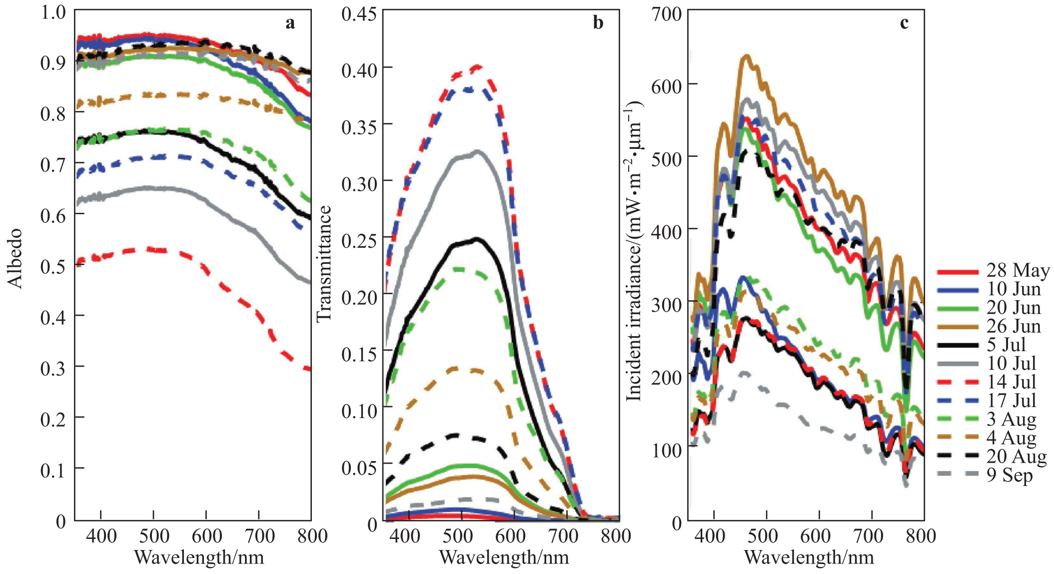

Figure 3 Evolution of spectral albedo (**a**), transmittance (**b**), and incident irradiance (**c**) from 28 May to 9 September 2012. The detail information is in Reference [31].

2013 were the initial snow and sea ice conditions with thinner snow and sea ice in April 2013: Sea ice thickness was 1.26 m, snow depth was 0.04 m, and freeboard was 0.10 m.

In addition to the IMB co-located with the SRB, a total of 10 other IMBs have been deployed as part of AMORA, 3 sonic rangefinder IMBs (IMB-S) and 7 thermistor chain IMBs (IMB-T). One IMB-S deployed in the land-fast ice region of Rijpfjorden, Svalbard, in 2011 by NPI. It worked for more than two months during April-June 2011, and then was successfully retrieved in late June 2011 and the data analysis is given in Figure 4[33]. The second IMB-S was deployed in the central Arctic during the CHINARE-2010 cruise with R/V *XUE LONG* by scientists from the Polar Research Institute of China (PRIC)[34]. It operated from mid August 2010 until mid July 2011, drifted through Fram Strait into the Greenland Sea. The third IMB-S was deployed by Alfred-Wegener-Institut (AWI) in the Arctic Basin during the expedition ARK-XXVI/3 (TransArc) of the German icebreaker R/V *Polarstern* in September 2011. After drifting for 63 d, it stopped sending signals. Two IMB-T were deployed during ARK-XXVI/3 (TransArc) covering sea ice conditions over several months. During CHINARE-2012, the PRIC deployed five IMB-T in the Eurasian section of the Central Arctic. Within these five buoys, two collected valid data of snow-ice temperature profile only for one month, one collected data for about 6 months, and two collected valid data for up to one year. All these high resolution measurements of vertical temperature profiles are under processing to retrieve the *in-situ* snow and ice thickness. Furthermore, three GPS buoys (CALIB) were deployed in the Central Arctic in the CHINARE-2010 (Figure 1a). All buoys drifted from the Central Arctic Ocean to the Eurasian Basin, with two continuing on through the Fram Strait as driven by the Transpolar Drift. All these data are received and analyzed in combination with additional observations, available through buoy deployments of other groups, to study seasonality of sea ice mass balance in different regions of the Arctic Ocean. They feed also into the International Arctic Buoy Programme (IABP, http://iabp.apl.washington.edu/).

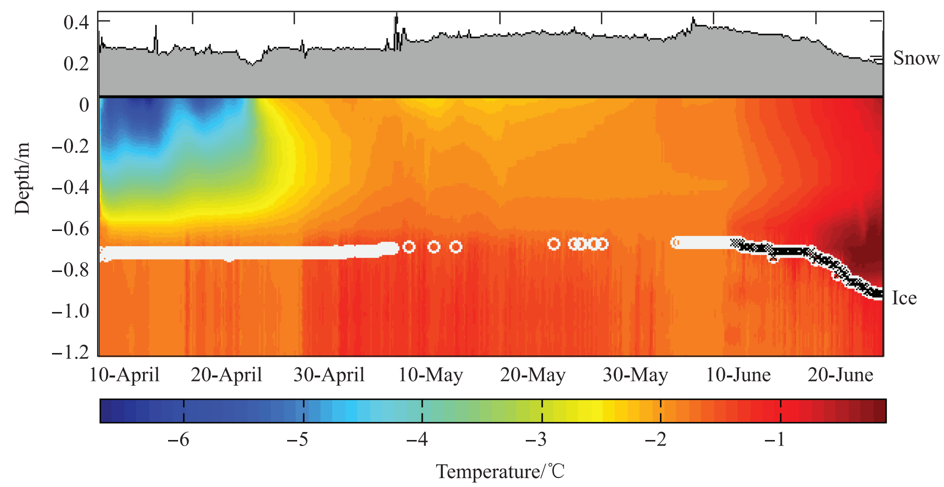

Figure 4 IMB-derived snow (grey shading) and ice (white circles) thickness, and ice/under-ice water temperature (colored shading). The zero line is the snow/ice interface (at the start of the deployment and assuming no change in the ice/snow interface). The erroneous ice thickness after 11 June is highlighted with black crosses, which is due to reflections from a layer deeper than the underside of the ice during the melting phase. This can be explained as a reflection of the sonar pulses from an interface between a freshwater layer under the ice and more saline water below, or as a false-bottom formation. More details see Reference [33].

Beyond the autonomous data, *in-situ* measurements of physical properties of snow and sea ice were a key element of AMORA. Hence, *in-situ* data have been collected in various regions in the Arctic via several international cruises and field campaigns in different Arctic regions (Figure 1). Most prominent was the work on sea ice stations during the R/V *XUE LONG* cruises CHINARE 2010 and 2012, the Norwegian cruises north of Svalbard on R/V *Lance* and KV *Svalbard* in 2011, and the German R/V *Polarstern* cruises ARK-XXVI/3 (TransArc 2011) and ARK-XXVII/3 (IceArc 2012). These measurements comprised sea ice thickness by electromagnetic methods and manual drillings[33-34], sea ice temperature, salinity, density, and texture[35], routine ice observations from the vessels bridges, optical observations above and under sea ice[12,36-37], snow depth and physical properties of ice cores, and melt ponds morphology investigated from different platforms[35]. However, not all measurements have been performed during all campaigns. Currently all data are compiled in order to synthesize for consistent analyses. Many of these observations are also (or mainly) supported by other research projects, but AMORA was an important contributor and initiator, especially to and for the international collaboration between the groups. It is also most remarkable that two CHINARE expeditions contributed to the project, with CHINARE 2012 having a strong focus on sea ice conditions along the Northeast Passage. Additional optical measurements have been performed in Barrow, Alaska, between March and June

2010 (Figure 1). Measurements of the spatial variability and temporal evolution of light transmission through land-fast sea ice have contributed to the project. The results highlight the significance of snow-melt onset for under-ice irradiance and demonstrate that the seasonal evolution of transmittance far exceeds spatial variability[38].

The HIGHTSI model has been developed further, and used the observation data from several large international research cruises (Tara 2007/08, CHINARE 2010, CHINARE 2012) to investigate the mass and energy balance in snow and ice. These observations cover different regions of the Arctic Ocean. In order to validate the model physics, field data obtained from Arctic fjords and lakes were also utilized. These studies are important since the weather stations are usually placed in the vicinity of field experiment sites, so as to provide more accurate inputs for numerical modelling, and to search the sensitivity of atmospheric models towards lake and sea ice albedo, the spatial and temporal variation of snow properties, the snow and ice mass balance, and the snow to ice transformation.

One of the HIGHTSI model updates considers the large spatial inhomogeneity of the ice conditions in the Arctic, and their impact on the improvement of snow thermal properties. This spatial inhomogeneity has a major impact on the spatially averaged heat conductivity, especially when snow depth is less than 0.4 m[39]. In this case, thermal properties of bare ice are very similar a unit area, and bare ice is likely presented in the vicinity because of wind redistribution of the snow cover. Therefore, the effective snow heat conductivity needs to be a mixture of heat conductivity of snow and ice within that unit area[40]. The new parameterization considers thin snow and the effective heat conductivity of a unit area could be as high as the value of bare ice heat conductivity. Hence, the ice may still continue to grow and will prevent too low sea ice thickness due to the too strong insulation effect of snow, particularly early in the season.

Cheng et al. carried out snow and ice thermodynamic modelling experiments in the Arctic Ocean[26]. However, the validation of modelled snow-ice and superimposed ice is insufficient due to limited available observations. Semmler et al. and Yang et al. applied HIGHTSI to calculate the snow-ice and superimposed ice formation in two different Arctic lakes[40-41]. The snow-ice and superimposed ice formation in an Arctic fjord was investigated and the reason why ice bottom growth cannot explain the total ice thickness was found. By taking into account snow to ice transformation, the model results showed great improvement compared with observations. According to the energy balance on snow/ice surface, surface temperature is a result of radiative fluxes, turbulent heat and thermal conductive flux of the snow/ice layer. In cold conditions, HIGHTSI modelling indicated that surface temperature showed a strong dependency on the thickness of thin ice (0.5 m), supporting the feasibility of thermal remote sensing and showing that sea ice affects atmospheric processes, too. During warm conditions, however, the surface temperature and ice thickness dependency is much weakened mostly due to the impact of solar radiation[42].

Both, the observational and modelling work, have strongly benefited from an extensive exchange program and the close collaboration between the different project partners. The key elements of the personnel and cultural exchange were visiting scientist program, such as research scientists from Dalian University of Technology (DUT) and PRIC, China, visiting NPI and FMI for several months. All field measurements strongly benefited from the common joint use and exchange of instrumentation, research facilities, including freezer laboratory, and logistics. Some measurements could not have been performed without this exchange program. The HIGHTSI model has also been applied for knowledge dissemination purpose during AMORA.

In order to contribute to the Arctic-wide objectives of the project, the Chinese partners extended their Arctic sea ice research regionally, also including the Fram Strait region and methodically, including new research objectives, such as sea ice surface features[43-45], physical characteristics[46], ice thermal behaviors[47-48]. Furthermore, ice studies in Bohai Sea and Tibet were included to develop advanced technology for future Arctic studies[49-50].

Complementing the scientific studies, public and general outreach activities were essential project aims. All partners contributed to present AMORA progress and polar science magazines, newspapers, and online platforms. The comprehensive exchange and workshops resulted in a strong knowledge transfer between the European/USA partners and China, also including open student courses (Figure 5a), field work exchange (Figure 5b) and workshops (Figure 5c). The education of undergraduate and graduate students was performed as part of the project (e.g. a work on sea ice thermal diffusivity studies[51-52] was completed in 2014[53]).

Sea ice mass balance data were made publicly available

Figure 5 Photographs of M. Nicolaus lecturing for students at Dalian University of Technology, China (**a**), field work with KV Svalbard north of Svalbard in 2011 (**b**), and the project workshop in Tromsø in 2011, showing the AMORA project team (**c**) (photo: A. K. Balto, NPI).

through the integration of the IMBs deployed during AMORA into the CRREL online database. (http://www.crrel.usace.army.mil/sid/IMB/). Along-track ice observations from the two *Polarstern* cruises are published through the online data repository Pangaea under doi:10.1594/PANGAEA.803312 and doi:10.1594/PANGAEA.803221. The data from CHINARE cruise and according buoys are available at http://www.chinare.org.cn/index/.

4 Future work and perspectives

The inclusion of site photograph series during the 2012 SRB drift that were performed by two The North Pole Experimental Observatory (NPEO) webcams, showed once more the great value of such photographs[24]. Therefore it would be most useful to add such systems to SRB measurements in future; however, this technology is not commercially available these days. Nevertheless, this shows the value of modular systems of IMBs, SRBs, photo buoys, snow depth buoys, weather stations, and oceanographic instrumentation for combined studies. The experiences with such complex systems also indicates that modular solutions of independent buoys, deployed as an autonomous observatory are likely more beneficial than single, but very complex and expensive units.

Another conclusion from the SRB development and data is that this kind of data is highly useful and urgently needed to further improve our understanding of the surface energy budget of the Arctic Ocean. But in order to obtain these data in large quantities for more areal and seasonal coverage, combination of few such autonomous SRB-like systems with a larger number of more simple and cheaper setups could be a way to go in future. However, also for cheaper units, the (partly very high) costs for deployment, data transmission, and engineering have still to be taken in account. In addition, more routines in data analyses have to be developed.

The large observational data sets need to be analyzed in more detail and to be connected to additional data sets from other buoys (e.g. IMBs deployed in other projects in similar regions). In addition, if re-analyses data in this project, especially the physical (primarily optical) properties of snow and sea ice, are associated with satellite observations data, more new findings would be generated.

Future scientific cooperation in the field of sea ice physics between Europe, North America and China will certainly benefit from the established cooperation in AMORA. Based on scientific exchanges and collaboration between institutes and individual scientists, it will be much more efficient to work on joint proposals and to develop common ideas and research strategies. Such follow-up cooperation will also benefit from the current support on political levels to increase international cooperation on climate (including the polar regions) research. Examples are the Fram Centre-funded “International workshop on Norway-China research collaboration in sea ice, snow and climate” held in Tromsø, Norway, in January 2013 or the “Sino-German symposium on ice-covered aquatic systems in the changing climate” in Taiyuan, China, in April 2014. Several internet news were published summarizing some of the findings from AMORA around end of 2014. The details can be found from http://www.fondriest.com/news/buoy-delivers-rare-real-time-albedo-data-arctic-ice-floe.htm, http://www.sciencedaily.com/releases/2014/11/141113085150.htm and http://www.forskningsradet.no/servlet/Satellite?c= Nyhet & pagename=klimaforsk%2FHovedsidemal&cid=1254001699348.

5 Conclusions

The AMORA project, through a Norway-China bilateral project, brought together an international team to investigate the role of solar radiation in the observed changes in the Arctic sea ice cover. Through monitoring sea ice conditions and radiation processes in the drift sea ice region and land-fast ice region in the Arctic, we are improving the understanding of the surface energy balance of the ice-covered Arctic Ocean, and mechanisms leading to observed changes in the Arctic. Through this project, we have also significantly improved the scientific collaboration between Norwegian and Chinese sea ice scientists, and provided a good base for more Norwegian-Chinese and other international collaborations in the future.

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