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The rise of sea ice research collaboration between China and Finland

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Abstract Collaboration between China and Finland in marine sciences was commenced in winter 1988. The main topic was then short-term sea ice forecasting in the seasonal sea ice zone (SSIZ), particularly in the Bohai Sea in China and the Baltic Sea in Finland. The sea ice in SSIZ is thin and highly dynamic so that ice conditions may change rapidly. While the length scales of the Baltic Sea and the Bohai Sea are similar, the main difference between them is that the former is brackish and non-tidal while the latter is oceanic for the salinity and possesses a large tidal amplitude. The Bohai Sea is located at latitudes 37°N–41°N, and the Baltic Sea is located at latitudes 55°N–66°N. However, the same sea ice model is applicable for both. The main application field of sea ice forecasting was winter shipping in Finland and oil drilling in China. The collaboration was successful and in late 1990s the research was expanded to polar seas, lakes, and to climate change applications.

Keywords **sea ice, Baltic Sea, Bohai Sea, dynamics, thermodynamics, ice engineering**

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1 Introduction

Sea ice occurs in about 10% of the world ocean's surface, growing, melting, and drifting under the influence of solar, atmospheric, oceanic, and tidal forcing. Most of sea ice lies in the polar oceans above 60° latitude, but seasonally freezing smaller basins exist further south in the northern hemisphere, such as the Sea of Okhotsk, the Hudson Bay, the Baltic Sea, and the Bohai Sea (Figure 1). These sub-polar freezing seas form a part of the seasonal sea ice zone (SSIZ), where the annual ice season lasts a few months. The physics of sea ice bears many similarities in all freezing seas, and characteristic to the sub-polar freezing seas are the limited length scale (less than 500 km), thin ice (less than 1 m), absence of multi-year ice, and large interannual variability of ice seasons.

In marine basins, due to the large spatial scale solid sea ice lids are statically unstable, and, consequently, ice cover appears broken into fields of ice floes (e.g., Coon, 1980; Wadhams, 2000; Leppäranta, 2011). These fields undergo transport as well as opening and closing, which altogether create the exciting sea ice landscape as it appears to the human eye. For shipping, sea ice formation has introduced a barrier; in particular, the drift of ice with internal pressure and ridging has made the management of this barrier

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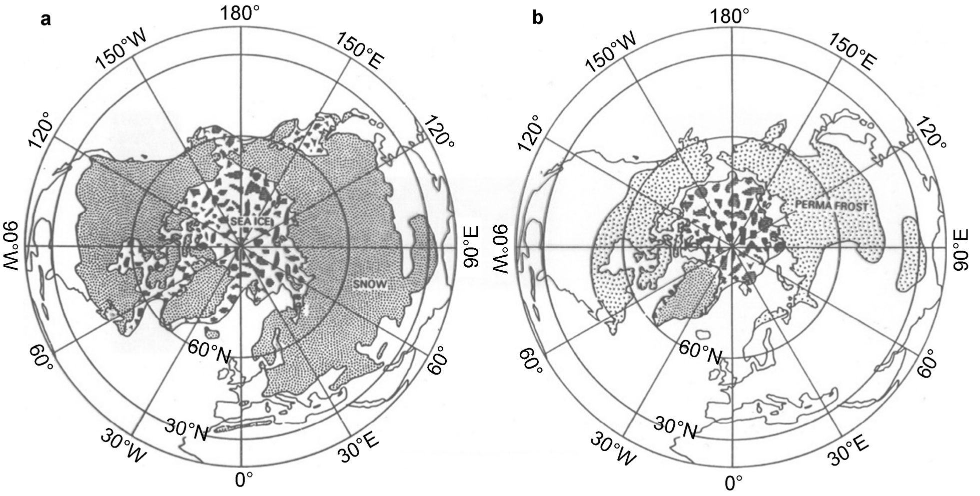

Winter northern hemisphere

Summer northern hemisphere

Figure 1 The cryosphere and the seasonal sea ice zone including the Bohai Sea and the Baltic Sea in winter (drawn based on Untersteiner, 1984).

difficult. Forces on oil and gas platforms by drifting ice cause the most difficult problems in terms of platform design and prediction of ice loads (Palmer and Croasdale, 2012). The transport and dispersion of pollutants in sea ice, and oil spills in ice-covered waters are important research topics for the protection of the cold ocean environment (e.g., Wadhams, 2000).

Sub-polar freezing seas reach to inhabited areas, where people have known sea ice phenomenon for a long time and adapted their life and traditions to a freezing sea (e.g., Palosuo, 1953; Leppäranta and Myrberg, 2009). Winter fishing and seal hunting could be based on sea ice, but shipping was stopped for the ice season until the introduction of steamboats. In recent decades, winter shipping and offshore engineering have largely grown in freezing seas that has demanded much basic and applied sea ice research. Numerical sea ice models were developed in the 1970s for sea ice forecasting in the Arctic Ocean (see, e.g., Hibler, 1979; Leppäranta, 2011). The models, applicable for subpolar seas as well, predict the evolution of ice concentration, thickness, and velocity.

In the 1980s when China was further developing science and technology collaboration, a natural field of mutual marine interest with Finland was ice engineering in ice-covered seas. In the Baltic Sea, with a fleet of 10 icebreakers Finland had kept the main harbors open all year since the year 1972, and by ice charting and forecasting the cost of using icebreakers could be reduced. In China, oil drilling had started in Bohai Sea in 1967 that needed ice charting and forecasting services as well, particularly forecasts of ice loads on the drilling platform. A delegation from Finland, organized by the Ministry of Trade and Industry of Finland, visited China in 1987, and cold ocean oceanography, particularly sea ice, was taken as the core line of future collaborative research (Professor Pentti Mälkki, oral communication). The overall goal was further development of sea ice charting and forecasting methods in the Baltic Sea and the Bohai Sea. In the following year, Professors Wu Huiding (National Marine Environmental Forecasting Centre, NMEFC in Beijing), and Wang Renshu (National Marine Environmental Monitoring Centre, NMEMC in Dalian) visited the Finnish Institute of Marine Research (FIMR) in February–April taking part in the work of the FIMR sea ice research team. Professor Wu worked on sea ice dynamics science and modeling, while Professor Wang worked on sea ice information systems and joined the ice service for operational ice charting in the Baltic Sea (Grönvall, 1988). In January 1989 Mr. Hannu Grönvall and Dr. Matti Leppäranta (FIMR) made a trip to China visiting the sea ice teams in Beijing, Tianjin, and Dalian.

After the mutual visits in 1988–1989, a memorandum was prepared for joint modelling and field research. Field campaigns were arranged in the Bohai Sea and Baltic Sea (Seinä et al., 1991), and an improved short-time (1 h–1 week) sea ice forecasting model was developed for both seas (Wu and Leppäranta, 1990). Exchange of scientists and students was started that has continued until present (2021). Beyond the year 2000, the collaboration was expanded to polar seas (Cheng et al., 2008; Wang, 2011), with the topic continued to focus on sea ice and also joint research was commenced on lake ice in Finland and China (Wang et al., 2005; Li et al., 2010, 2011). The climate change question and the Northern Sea Route became the leading themes in the joint polar research, while ecology and mechanics dominated as the background in lake research.

This paper gives a summary of the first 20 years of the sea ice science collaboration between China and Finland. In this period the program grew steadily from short-term sea ice forecasting to the polar sea ice cover and freezing lakes. The main partners were FIMR and the University of Helsinki (UH) in Finland and NRCMEF, NMEMC and Dalian University of Technology (DUT) in

China. Later on, the collaboration expanded to cover several institutions in China and Finland with the topics including polar meteorology, air quality, and environmental technology.

2 Ice conditions in the Baltic and Bohai Seas

2.1 Sub-polar freezing seas

In the northern hemisphere, many intracontinental and marginal seas freeze in winter south of the Arctic circle (Weeks, 2010). These subpolar seas are semi-enclosed and shallow or stratified in salinity that makes it possible for the sea surface layer to reach the freezing point temperature. The Baltic Sea and the Bohai Sea are both shallow and semi-enclosed, and the Baltic Sea is also stratified in salinity. The Baltic Sea is located in Northern Europe in the Eurasian boreal zone, while the Bohai Sea is located in northern coast of China in the far-east Asian monsoon climate zone. These basins are at the climatological sea ice edge, where climate variations show up drastically in the ice conditions.

On the coastal and archipelago areas sea ice appears as landfast ice and further out as drift ice (Wadhams, 2000). Landfast ice is a solid and smooth sheet of ice, and it stands immobile apart from the very early and late ice season. On average, the outer boundary of the landfast ice zone lies at 10 m isobath in the SSIZ (Leppäranta, 2011). Growth and melting of landfast ice follow the evolution of air temperature and solar radiation. The air–sea momentum transfer can be large for drift ice but is cut out in the landfast ice zone. A drift ice landscape consists of leads and ice floes with ridges, hummocks, and other morphological characteristics. Ice types have been defined originating from practical shipping activities in ice-covered waters (WMO, 1970). These ice types are based on the appearance of sea ice, i.e., on how the ice looks to an observer on a ship or in an aircraft. The formation mechanisms, aging, and deformation influence on the appearances of ice types, which therefore contain information of the ice thickness, seldom known from direct measurements.

In an ice-covered sea, the ice buffers the surface water temperature into the freezing point (Weeks, 2010). The presence of ice has a pronounced influence on the transfer of heat and sunlight into the water. Ice and snow have a high albedo, which lowers the penetration of solar radiation into the ice and water, and their cold surface lowers the long-wave radiation loss and the turbulent exchange of sensible and latent heat. Overall, an ice cover is a good thermal insulator. Because sea ice salinity is low, the surface layer of the sea receives a major freshwater flux when the ice melts that shows up in the salinity climatology. Atmospheric deposition accumulated in the ice layer will be released to sea water during the short melting phase.

A sea ice cover is a stiff, thin lid between the atmosphere and the sea (Hibler, 1979; Coon, 1980). The influence of the ice cover on the air–water momentum fluxes vary widely depending on the ice situation. Because of the surface roughness, in free drifting ice fields the sea may even receive more momentum from the wind than in open water conditions (McPhee, 2008). But much work needs to be done by the forcing against internal friction at onshore drift, and in such conditions the ice velocity and the momentum transfer to the water body beneath the ice are small. Forcing of sea ice against structures is studied in the field for mechanical properties of sea ice and in laboratory tank experiments (Palmer and Croasdale, 2012).

2.2 Baltic Sea

The Baltic Sea is located in the northern Europe between the latitudes 55°N and 66°N. The exchange of water with the North Atlantic Ocean is highly limited that is reflected in the low salinity of the Baltic Sea, only 1/5 of the oceanic level (Voipio, 1981). The key factor for the freezing of the Baltic Sea is the semi-enclosed state, shallow depth and halocline, and cold northern climate (Leppäranta and Myrberg, 2009). The basin does not receive much heat from the North Atlantic, and the regional climate forces the Baltic Sea to get annually an ice coverage by 12%–100% of the total area. The length of the ice season is 5–7 months. An example is shown in a satellite picture in Figure 2.

The sea ice cover has a very important role in the annual course of the basin and also in the human living conditions, particularly for the sea traffic. Back in the history in the era of sailboats the shipping of the whole Finland was cut off in the ice season, while presently icebreakers take care for a workable marine transportation system to all the main harbors.

In the fall, the Baltic Sea cools due to radiation and turbulent heat losses, and the surface layer temperature goes down at the rate of 3–4℃ per month. The ice season begins on average in the middle of November on the northern coast, and the freezing front then progresses southward (SMHI and FIMR, 1982). During the 20th century, the earliest, average, and latest freezing dates in the north were October 6th, November 10th and December 23rd, the range was thus as much as 2.5 months (Jevrejeva et al., 2004). In the central basins the freezing date is much delayed as compared with coastal sites. The northern basin, the Bay of Bothnia, freezes over on average in mid-January, and in normal winters the Sea of Bothnia, the Gulf of Finland, and the Gulf of Riga freeze one month later. In mild winters only the Bay of Bothnia and eastern part of the Gulf of Finland freeze over. In fall and winter there is a homogeneous upper layer, halocline at 40–80 m depth, and in the lower layer the stratification is continuous. Fall mixing of the cooling water mass reaches just the halocline that also helps the freezing of the sea.

The annual ice extent is at largest in mid-February–

Figure 2 The Baltic Sea ice cover on March 15, 2010 seen by Envisat satellite. © European Space Agency (ESA).

mid-March, and on average the maximum annual ice-covered area is 45% of the total area of the Baltic Sea (Omstedt and Nyberg, 1996; Leppäranta and Myrberg, 2009). In normal winters the ice edge crosses the sea at about 60°N latitude, further south ice occurs only in shallow coastal areas. The latest total freeze-over of the Baltic Sea dates to 1947. The maximum annual thickness of landfast ice is 50–110 cm (Seinä and Peltola, 1991). Landfast ice zone extends further offshore when the ice becomes thicker. In heavy storms, landfast ice rides or piles up onshore creating loads the coastal buildings and causes scouring of ice bottom and shore erosion (Leppäranta, 2013).

The onset of melting begins in the south in early March when in the north new ice still forms (SMHI and FIMR, 1982). Melting progresses in the central basins due to the absorption of solar radiation in leads and due to decrease of ice compactness, and somewhat later melting starts from the shoreline due to the shallow sea depth and the neighborhood of warm land. In the 20th century, the mean date of ice break-up was 21 May in the north, with the extremes of 16 April and 27 June (Jevrejeva et al., 2004). The length of the local melting season is 1–2 months and the average melting rate is therefore 1–2 cm per day. Melting is an accelerating process where the melt rate increases as the melting season progresses, and as the porosity of ice has reached around 50%, the ice breaks and thereafter the remnants melt fast. The outer fast ice boundary with large and grounded ridges is the last place where ice is seen at the end of the ice season.

The Baltic Sea has experienced a trend towards milder ice seasons in the last 50 years (Jevrejeva et al., 2004; Haapala et al., 2015). This has meant 5–10 d later freezing and earlier breakup in the northern part of the Baltic Sea. In the south, the change is not clear in the freezing and breakup dates, but the probability of freezing has become lower. The variability of the ice seasons is large dominated by the strength of the westerly winds from North Atlantic Ocean.

Real-time information of the ice conditions is available in ice charts published daily by the ice services in the Baltic Sea, in Finland by the Ice Service of the Finnish Meteorological Institute (FMI). These ice charts present the ice extent, ice fields, ice types, ice compactness, and ice thickness. Ice drift may change the ice conditions remarkably in a few days, and therefore it is essential to update the charts daily. The ice information is based on coastal stations, ship reports, and satellite imagery (mainly

NOAA, Terra/Aqua, Radarsat and Sentinel). Short-term ice forecasting was commenced in the operational Ice Service in Finland in the 1970s for winter shipping (Leppäranta, 1981; Leppäranta and Zhang, 1992a, 1992b, 1992c). The forecasting systems have been further revised, and the FMI Ice Service present system is based on real time ice information for the model initialization and the marine weather forecast. A local thermodynamic model was developed by Cheng (2002) also taken into the operational system.

2.3 Bohai Sea

The Bohai Sea and the northern Yellow Sea are located on the east side of the Chinese continent and span between 37ºN and 41ºN. The Bohai Sea is a semi-enclosed shallow sea that connects to the Yellow Sea through the Bohai Strait on the east. Its average depth is 18 m, and its surface area is about 77000 km^2. The salinity of the Bohai Sea is the lowest of the four seas of China because of the large amount of freshwater supply from river discharge and limited oceanic inflow. During the winter, the surface water salinity is 28–30 ppt.

The circulation in the Bohai Sea consists of the tail of the Yellow Sea warm current flowing into the Bohai Sea through the Bohai Strait and the coastal current with lower salinity. The circulation is stronger in winter than in summer. The Bohai Sea has its own unique amphidromic tidal system, including one diurnal and two semidiurnal constituents. The maximum mean tidal range along the coast is 2.7 m at the head of the Liaodong Gulf. The tidal current is predominantly semidiurnal, with a velocity range of 50–100 cm·s^{-1}.

The Bohai Sea and the northern Yellow Sea belong to a typical monsoon zone (Wu et al., 2000). In the winter, the prevailing wind direction is from the north, controlled by the Asian continental high pressure. A cold air mass often passes through the area, accompanied by abrupt air temperature drops and strong wind. The continental type of variation of air temperature is predominant, and the lowest temperature occurs in January, the mean is between –4℃ and –8℃ with a minimum of –25℃. The mean wind speed from December to March is 5–7 m·s^{-1}, with a maximum of 35–40 m·s^{-1}.

The Bohai Sea is the southernmost sea in the northern hemisphere that freezes each winter. Sea ice is an important marine environmental factor to be considered in the planning, design, and construction of offshore structures in the Bohai Sea and northern Yellow Sea. The sea ice is mostly distributed in the Liaodong Bay, in the northern Bohai Sea. The Bohai Sea ice has a large impact on coastal and near-shore oil-drilling operations. Figure 3 shows a map of the Bohai Sea, including locations of the oil platform JZ20 and coastal tidal stations. Severe ice seasons have occurred there in the last century, e.g., in 1936, 1947 and 1969, which was the most severe in the records. Then the entire Bohai Sea was covered by sea ice causing a collapse of an oil platform on 8 March 1969. Following this disaster, the research on safety and ice resistant pillars of the offshore platform started in China. Also, Finnish–Chinese collaboration was carried out on this topic. Ice tank modelling tests for the concept design of the JZ93 platform in the Bohai Sea were performed in the Ice Basin of the Helsinki University of Technology (now Aalto University) in the 1990s.

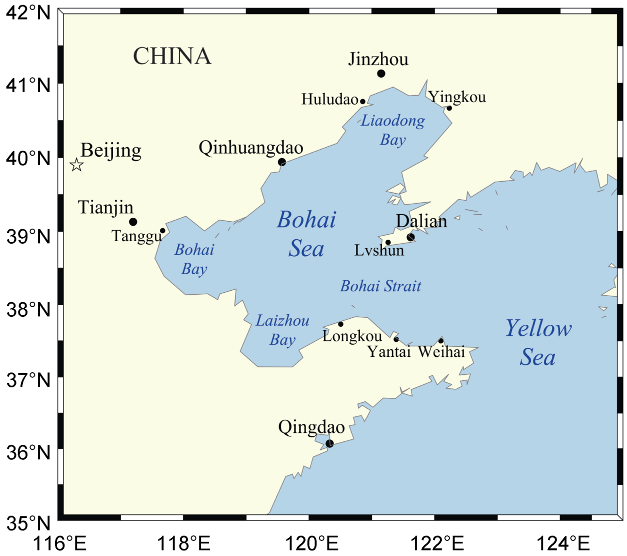

Figure 3 A map of the Bohai Sea.

The long-term Bohai Sea ice grade (severity) was highly correlated with the Arctic Oscillation (AO) between 1954/55–2001/02 (Gong et al., 2007). Between the 1950s and 1990s, the appearance of mild ice conditions increased gradually. The ice thickness has become thinner, the ice cover area has become smaller, and the length of ice season has become shorter. It has been suggested that the solar activity has a great influence on variations of the ice conditions of the Bohai Sea, also concerning extreme ice seasons (Zhang et al., 2007). A study by Tang et al. (2015) found that the Siberian high pressure is the most important and direct climate factor influencing the Bohai Sea ice.

3 Joint field investigations

3.1 Baltic Sea

An international BEPERS (Bothnian Experiment in Preparation for ERS-1) research program was carried out 1987–1992. Chinese scientists visiting Finland took part in the field work as a part of the Finnish team. The field work was performed in the Gulf of Bothnia, in the northern Baltic Sea (Askne et al., 1992; Figure 4). This experiment involved 61 scientists from Canada, China, Finland, Germany, Sweden, and the United States. The Finnish base was the research vessel *Aranda* moored to ice at the landfast ice boundary. The main aim was to investigate remote

Figure 4 Sea ice experiment BEPERS in the Baltic Sea in 1988. A Chinese team took part in this expedition.

sensing of sea ice by airborne SAR to prepare for ERS-1 satellite SAR coming in 1992, particularly for sea ice charting and sea ice forecasting (Leppäranta and Zhang, 1992b). Another collaborative field experiment was performed in 1997 on sea ice dynamics in the Baltic Sea to improve sea ice model parameterizations (Leppäranta et al., 2001). This work was a part of EU-funded Baltic Sea ice research.

3.2 Bohai Sea

Since the Bohai Sea ice disaster in 1969, the seasonal Bohai sea ice monitoring has been carried out nationally by the Chinese navy portal icebreakers *Haibing* 721 (1971–; in reserve) and *Haibing* 722 (1973–2013; decommissioned), and by small aircraft flights. Those activities performed visual sea ice reconnaissance and aerial photography (Anon., 1990). Visual sea ice monitoring has been done also onboard oil-platform (JZ20-2) located in the central Liaodong Bay (Figure 5). In addition to snow and ice thickness estimation, the type of sea ice and its dynamic features, such as ice drift, rafting and piling up around the platform were documented on a daily basis. A weather station installed on the platform measured the air temperature, wind, and moisture. A coastal radar was constructed at Bayuquan in 1987 in the northern Liaodong Bay to monitor the local sea ice conditions as part of the operational service of NMEMC (Dong, 1989).

Figure 5 JZ20-2 oil platform in Liaodong Bay (photograph supplied by Ji Shunying).

A joint Finnish-Chinese winter experiment was carried out on the landfast sea ice at Bayuquan in the north part of the Liaodong Bay between 25 January and 7 February 1991. Two Finnish scientists, Mr. Ari Seinä and Mr. Henry Söderman, joined a group of five scientists from NMEMC and took part in the campaign. Measurements of sea ice physical properties, the time evolution of the ice cover, and the weather conditions were carried out. A weather mast was deployed on the ice, and wind, temperature and relative humidity were measured at heights of 10 m, 4.5 m and 2 m (Figure 6). The near-surface incoming and reflected solar radiation was also measured. The ice temperatures at various depths were recorded by thermistor strings, ice thickness was observed manually each day, and the ice salinity was determined from ice core samples (Seinä et al., 1991). The currents below the ice layer were also measured. This was the first bilateral sea ice field campaign carried out by Finnish and Chinese scientists.

4 Sea ice modelling collaboration

4.1 Background

The original goal of the research collaboration was focused on short-term sea ice forecasting in the Baltic Sea and Bohai Sea for shipping and oil drilling platforms. This

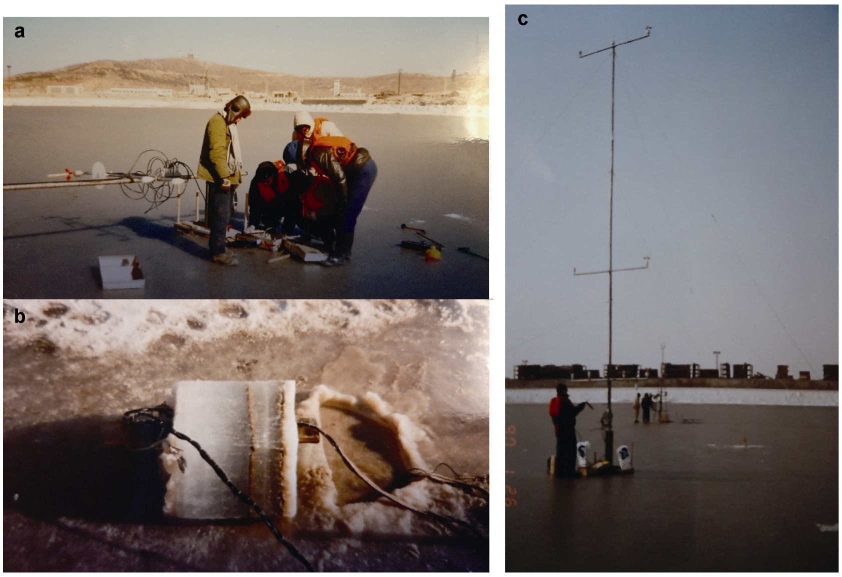

Figure 6 **a**, Installation of the 10 m weather mast; **b**, Recovering the thermistor string deployed in an ice block, the heavy sandy dust are visible on ice surface and within ice layer; **c**, The experiment site on landfast ice. Photographs by Li Zhijun and Ari Seinä.

necessitated the modelling of sea ice concentration, thickness, and velocity. Landfast ice is stable and smooth for most of the winter, supported by islands and grounded ice ridges on shoals, but over large basins, the wind fetch is long so that the resulting forcing breaks the ice cover, and creates drift ice. The drift of sea ice is a mesoscale or large-scale phenomenon, where the elements are ice floes, and the ice landscape consists of leads, fields of ice floes and deformed ice such as pressure ridges, rafted ice, and brash ice. In many places at the landfast ice boundary, heavy zones of ridged ice are found. Winds, currents, tides, sea-level variations, thermal cracking, etc. keep the drift ice in broken state allowing the dynamics to continue. The drift makes sea ice an active player in the atmosphere–ocean interaction.

Modelling of the evolution of an ice cover is a coupled dynamic–thermodynamic problem. The thermodynamic scale of seasonal sea ice, based on heat conduction, is less than 10 m, but the dynamics length scale, based on motion and deformation, is up to hundreds of kilometers or the size of the basins in the present cases. Sea ice grows and melts in the vertical direction, while the dynamics causes horizontal transport and deformation. The growth and melting of ice influence ice strength, and the transport and deformation influence the heat exchange between the ice and the atmosphere and between the ice and the ocean. Thus, thermodynamics and dynamics of sea ice constitute a coupled problem.

Basin-scale sea ice models consist of five elements:

(i) Ice state $J = J(J_1, J_2, \cdots)$;

(ii) Ice rheology $\sigma = \sigma(J, \varepsilon, \dot{\varepsilon})$;

(iii) Equation of motion $\rho\tilde{h}\dot{u} = \nabla \cdot \sigma + \sum_k F_k$;

(iv) Ice conservation law $j = \psi(J, u, \dot{\varepsilon}) + \Phi(\dot{h})$;

(v) Heat balance $\dot{h} = f\left(\sum_k Q_k\right)$.

where J is drift ice state, σ is ice stress, ε is strain, ρ is ice density, h is ice thickness, u is ice velocity, F_k is external forces on ice, Q_k is external heat fluxes, and Ψ and Φ represent formally the mechanical and thermal effects on the ice state. Ice models are forced by the solar radiation, atmospheric forcing, and ice–ocean interaction. The heat balance freezes and melts ice, while wind and ocean current influence on the ice drift. The salinity of ice is prescribed. The present sea ice models are essentially coupled ice–ocean models with exchange of heat, salts, and momentum internally and forced by atmospheric fluxes. Thermodynamics works on the elements i+iv+v while dynamics works on i+ii+iii+iv that illustrates a strong coupling.

In the 1990s, two Chinese PhD students, Cheng Bin and Zhang Zhanhai, visited, respectively, FIMR and the Department of Geophysics of the University of Helsinki for long-term numerical modelling research and finally defended their PhD theses in Helsinki. Zhang's (2000) thesis was on sea ice dynamics modelling and Cheng's (2002) thesis was on sea ice thermodynamics modelling. These works meant great progress to the ice forecasting systems in the Baltic and Bohai Seas.

4.2 Thermodynamic modelling

Thermodynamics plays a critical role on the seasonal cycle of sea ice. Thermodynamic modelling of sea ice is therefore a core research topic accompanying with dynamics modelling. A 1-D thermodynamic sea ice model was set up based on the joint Chinese–Finnish sea ice seminar in NMEFC in 1989. Later on, a review article on sea ice thermodynamics by Leppäranta (1993) was largely recognized as a roadmap on the joint sea ice thermodynamic modelling. Sea ice mass balance is based on the heat balance at the ice surface and bottom.

The ice temperature regime is provided by the heat conduction equation, which is solved by a numerical scheme (Cheng, 1996). When a snow cover is present, the temperature of snow needs to be solved as well. When there is a lot of snow on sea ice, the snow–ice interaction also transforms snow into snow-ice (Leppäranta, 1993). At the air–ice interface, the stability of the atmospheric surface boundary layer dominates the turbulent heat exchange between air and sea ice, and impurities of sea ice (salinity, gas bubbles) affect thermodynamic properties of sea ice. Taken all those effects into account, a 1-D thermodynamic model (HIGHTSI) was developed (Cheng and Launiainen, 1998; Launiainen and Cheng, 1998; Cheng, 2002; Cheng et al., 2003).

One breakthrough of HIGHTSI development was to calculate the refreezing of snow melt to form superimposed ice (Figure 7). This concept, largely used for modelling in glaciology, was first applied for sea ice modelling by Cheng et al. (2003). Together with the snow-ice formation process (Leppäranta, 1983), the modelling of seasonal cycle of snow to ice transformation was completed.

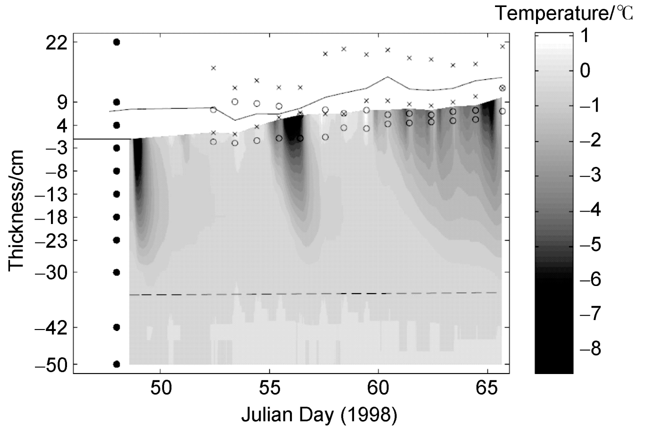

Figure 7 Snow, ice thickness, water level (relative to the snow/ice interface) and ice/water temperature field measurements in BASIS-98. The filled circles indicate the locations of the thermistors. The time series (×) and (o) give the maximum and minimum snow thicknesses and water level, respectively, observed along a 50-m long line. The solid line at the top is the average snow thickness, and the lowest dashed line is the ice bottom detected from the thermistor string between the initial deployment and final pick-up stage (Cheng et al., 2003) .

The validation of HIGHTSI was largely benefited from the Finnish–Chinese joint field program (Seinä et al., 1991). Once HIGHTSI was completed, it has been used extensively in various applications for seasonal ice-covered seas (e.g., Zhang et al., 2006; Mäkynen et al., 2007), boreal lakes (Yang et al., 2012, 2015) and polar oceans (Cheng et al., 2008; Karvonen et al., 2012) until present.

4.3 Modeling sea ice dynamics

A drift ice field is considered as a continuum, where the size of continuum particles is much larger than the floe size. Ice thickness is the most important ice property in drift ice geophysics. The strength of ice and ice volume are proportional to the thickness of ice. The ice thickness may vary largely. Even in a small area there may be ridges thicker than 10 m and thin new ice. Ice ridges are the most difficult obstacles in winter shipping, and they cause the largest forces against marine structures in first-year sea ice basins. The severe practical problem is that there is no good space borne or airborne remote sensing method for ice thickness mapping accurate enough for modeling work.

The joint Baltic–Bohai sea ice forecasting model was developed around 1990 (Wu and Leppäranta, 1990; Leppäranta and Zhang, 1992c). This was a viscous-plastic three-level model based on the status of Arctic models (Hibler, 1979; Coon, 1980) and the operational Baltic Sea ice model (Leppäranta, 1981). The revised model has been in use in the Ice Service in Finland with further developments. Similar model system has been set up in China.

In the Baltic Sea, the model was first used in an effort to utilize ERS-1 satellite SAR data in model calibration and validation (Leppäranta and Zhang, 1992b). In another model study to examine the role of ice cover in water level variations it was found that due to frictional losses in very close and compact ice water level variations are damped down by a factor of two (Zhang and Leppäranta, 1995). Due to internal friction, sea level tilt is much lower in ice season than in open water season (Figure 8).

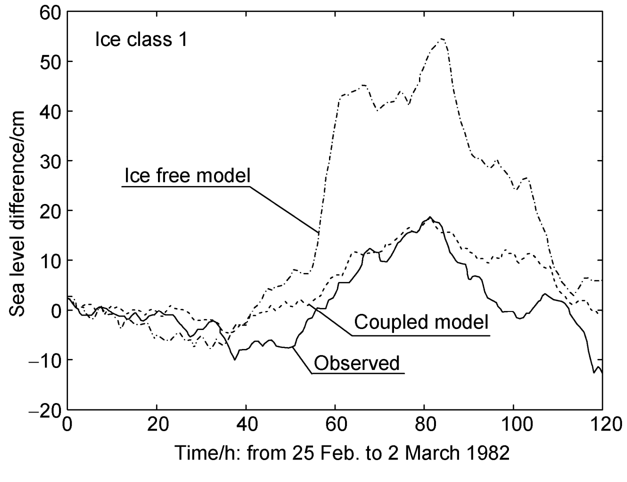

Figure 8 Sea level difference across the Bay of Bothnia as observed and in free drift (no internal friction in drift ice) and full models (Zhang and Leppäranta, 1995).

In 1990s, the joint ice model was used in both Finnish and Swedish ice service (Leppäranta and Zhang, 1992c; Haapala and Leppäranta, 1996; Omstedt and Nyberg, 1996). This model was largely based on sea ice dynamics work done by Wu and Leppäranta (1990), Haapala and Leppäranta (1996) and Zhang (2000). The Bohai Sea model has been under continuously development from a solely sea ice dynamic model to the dynamic-thermodynamic coupled model (Yang and Bai, 1991; Bai and Wu, 1998) and further upgraded to the ice-ocean tidal coupling model (Hai et al., 1998; Yu et al., 2011).

This model was further examined in detail for the dynamics in different basins of the Baltic Sea, particularly for scaling and the influence of coastal geometry and islands (Leppäranta and Wang, 2002; Wang et al., 2005; Wang, 2007). It has worked well down to a bay of 15 km size with thin ice moving under strong wind. The model also served as a tool in the development and testing an oil spill forecasting system in ice-covered seas (Wang et al., 2008). A major question in the scaling problem was to evaluate ice loads on ships and fixed structures (Figure 9) from basin scale sea ice dynamics (Kõuts et al., 2007).

Figure 9 Ice ride-up on shore in the Bohai Sea. The diameter of the cylinders is about 1 m. In the front sediment-enriched ice floes are seen. Photograph by Professor Li Zhijun.

The key areas of short-term modelling research are ice thickness distribution and its evolution and use of satellite SARs for ice kinematics. The scaling problem and in particular the downscaling of the stress from geophysical to local (engineering) scale is examined for combining scientific and engineering knowledge and developing ice load calculation and forecasting methods. The physics of drift ice is quite well represented in short-term ice forecasting models, in the sense that other questions are more critical for their further development.

5 Final remarks

The initiation of scientific and technology collaboration between China and Finland on sea ice research was a great success with mutual benefits. We believe that similarities of the research domains, seasonality of sea ice, and the demand of marine services are the external driving forces to bound connection between the two parties for sustainable and long-term collaboration. Another important factor to support the rise of sea ice research collaboration between China and Finland is the enthusiasm and unconditional pursuit of research by old and young generations of geophysicists in both countries. The modelling work has highly improved the operational sea ice forecasting products in the Baltic Sea Ice Service in Finland and in the Bohai Sea ice operational service since the early 1990s.

The Baltic Sea and the Bohai Sea have experienced trends towards milder ice seasons in the last 50 years (Jevrejeva et al., 2004; Zhang et al., 2007; Haapala et al., 2015; Yan et al., 2007). In neither basin, no extreme ice seasons with complete ice cover have occurred in this period. The variability of the ice seasons is large, in the Baltic Sea dominated by the strength of the westerly winds from North Atlantic Ocean and in the Bohai Sea the severity of ice seasons has been connected to Arctic Oscillation (Gong et al., 2007) and east Asian continental high pressure.

After the year 2010, the collaborative sea ice activities were expanded to polar seas and freezing lakes, and research topics have expanded to polar meteorology and climatology of the cryosphere (e.g., Li et al., 2011; Huang et al., 2012, Lei et al., 2012; Yang et al., 2012, 2015, 2016). The research mobility programs, and knowledge disseminations have been implemented and achieved in a much more frequent way. We have estimated that about 30 scholar and postgraduate students have been involved in the follow-up collaboration. We expect high-quality research collaboration with fruitful results to continue in future.

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