Final report on the Newton Institute Programme

Mathematics of sea ice phenomena

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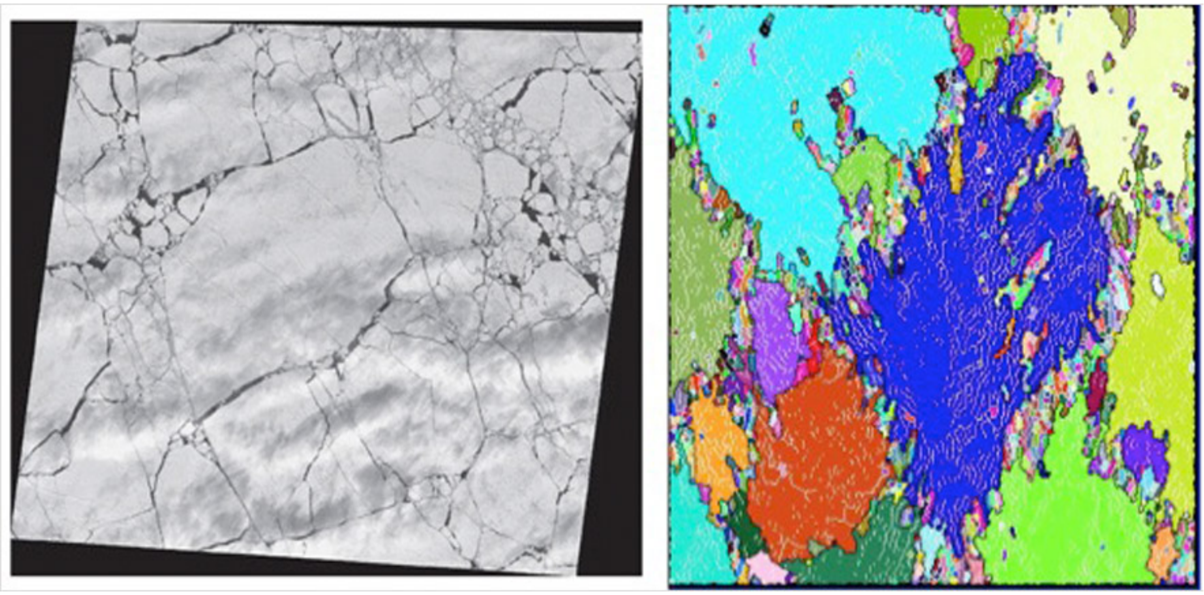

1. Brief background and historical information

Ice is one of the most common materials on Earth, yet it is very different from all other known materials. Depending on its morphology and microstructure, it may behave as an elastic, brittle, viscoelastic or even as a quasi-liquid material. Moreover, ice is present on the Earth in different forms, notably the fresh-water ice that occurs in the air, in ice caps, glaciers, icebergs, frozen rivers and lakes, and the many varieties of sea-ice that form in the polar and subpolar oceans. The sea-ice consists of solid fresh-water ice, liquid salty brine, gas inclusion and possibly some other components, which makes it difficult to describe.

Numerous existing mathematical models of sea-ice reflect some of its properties in particular situations. Nevertheless, there is in essence no unified general model of ice and it is not expected that a satisfactory parsimonious model could be found. Mathematical modelling of sea-ice and its behaviour in different situations is a challenging set of problems that spans several areas of mathematics and has massive implications in the Natural Sciences and Engineering. As a result, problems of ice and its interactions with solids and fluids have been studied seriously for more than a hundred years. Many observations have been well documented and many engineering models have been constructed, particularly for sea-ice and for ice in rivers. The background interest is huge in terms of the environment but alongside there is considerable industrial interest in translation opportunities as well. However, the theoretical aspects that should rightly undergird research on sea-ice are today much less developed than contemporary computational and experimental studies on sea-ice and its influences. As a result, there is a tendency to mimic sea-ice phenomena with empirical models that display similar behaviour but ignore the underlying mathematical and physical principles — a tactic that has invariably proved to be unwise in the past. This inadequacy in the body of theory and corresponding analysis is the main obstacle to progress towards meeting the needs of modern practice in this discipline, including advances in computations and in situ and laboratory experiments.

Ice is a crystalline particulate material in which fluid (liquid and gas) inclusions are often present that may coexist with a large temperature gradient, e.g. when floating. Its macroscopic behaviour in some situations cannot be understood without knowing its microstructure. From a mathematical viewpoint, multi-scale modelling of ice is required in many sea-ice-related problems, where asymptotic analysis is able to connect processes that occur at different scales. Homogenization techniques can help to derive the macroscopic characteristics of ice from information about its microstructure. Mixture theory leads to the mushy layer description of sea-ice as a porous ice matrix with brine inclusions, and perturbation and stability theory can be used to analyse morphological and convective instabilities within sea-ice, such as the formation of brine tubes. Variational formulations provide rigorous bounds on the fluid permeability tensor for sea-ice. Percolation theory is used to mathematically characterize evolution of the fluid pores and their connectedness. Complex analysis and functional analysis are helpful for remote sensing, for example when monitoring sea-ice thickness. Inverse methods provide information on the microstructure of ice from its macroscopic behaviour. It is also very challenging to apply these ideas to even larger scales, such as explaining how ice behaviour on the scale of individual ice floes can influence the regional disposition and evolution of the pack ice mélange. In a nutshell, the question is how to use information on a smaller scale to predict behaviour on a larger scale, and vice-versa.

Many problems of floating ice are coupled and these form such exciting research areas as ice-structure interaction (ISI) and ice-fluid interaction (IFI), especially for floating ice. In violent ISI, when sea-ice is crushed near the structure, it is observed that the ice is frequently 'pulverized' in the crushing zone. The magnitude of the forces involved in ISI can depend on aspects of how the broken ice is frozen together, which requires modelling of salt transport processes. In all forms of IFI there is a multi-parameter space with which to contend. Both ISI and IFI lie within the scope of the Sea Ice Programme.

Ice-related problems are usually presented and discussed at engineering conferences (OMAE, ISOPE, IAHR) or environmental ones (AGU, IGS) but with little scrutiny of the underlying mathematical and physical principles. More mathematical aspects of these problems receive much less, indeed minimal, attention and errors have been made in the past. The programme aimed at distinguishing the more mathematical aspects of ice-related problems, drawing mathematical and modelling talent together, and creating a network uniting all such problems and corresponding developments into one picture.

2. Programme Timeliness, Scope and Outline

The programme outlined the present state-of-the-art, identified the particular mathematical problems of sea-ice mechanics and thermodynamics of highest priority and suggested directions to attack these difficult problems. The programme was centered around four ice themes: Multi-scale modelling of ice characteristics and behaviour, Ice-fluid interaction, Ice-structure interaction, and Ice fracture and cracks. These four themes corresponded to four workshops within the programme.

Environmental aspects of ice-related problems were included when they related to sea-ice mechanics and thermodynamics. New ice-related problems were mainly inspired by recent researches on climate change and global models of ice effects on ocean-atmosphere interaction.

Workshop "Multi-scale modelling of ice characteristics and behaviour"

Sea ice processes across a wide range of length and time scales were addressed, with an emphasis on understanding emergent and scale–invariant phenomena. A fascinating feature of sea ice is that it displays rich structure and behaviour on scales ranging over 10 orders of magnitude: length scales from microns to hundreds of kilometres, and time scales from milliseconds to decades. This broad range of scales for sea ice structure and properties is relevant to biological, chemical, industrial, weather, as well as climate–related processes. It also leads to sea ice structure at certain scales being similar to other materials such as porous human bone and polycrystalline metals, which can be used to bring new techniques to studying sea ice, and vice versa. Mathematical methods that rigorously account for these smaller scale processes, and enable computation and analysis of their effective behaviour on larger scales relevant for coarse–grained climate models were presented and discussed.

The final day of this workshop was combined with the annual UK Sea ice meeting, which attracts observational scientists, particularly in remote sensing, climate model users and academics.

Many particular topics were discussed. Themes highlighted in the presentations and discussions were:

1. The needs of large-scale, typically climate but also environmental, numerical models of sea ice. In particular, the benefits of increased resolution and its limitations in continuum models, and of the need for parsimonious models of sub-grid processes (parameterisations) due to computational constraints.
2. Melt ponds: their impact on surface albedo but also properties of their spatial pattern and coverage derived from basic geometric and critical percolation considerations.
3. Sea ice thermodynamics (aside from melt ponds): brine drainage, frazil ice, and platelet ice.
4. Thickness distribution from satellite observations and field observations, robust properties of the thickness distribution and how they emerges from thickness redistribution in pressure ridging, including accounting for ridge porosity.
5. Sea ice rheology modelling and deformation characteristics at the Arctic ocean basin scale and how this is related to scale independent and dependent failure.
6. Floe size distribution: limitations in observations of small floe sizes and process models of its distribution including wave break up.
7. Application of ideas and analysis from idealised energy balance and single column models of ice and ocean to climate simulations, to gain insight and understanding of past and future climate evolution.

Each presentation was followed by lively discussion, continued in the packed poster sessions and social events.

Workshop "Ice-fluid interaction"

Modern mathematical models of ice include but are not restricted to ocean waves and swell propagating in ice fields and altering its morphology; linear and nonlinear hydroelastic waves, especially in the presence of floating ice; sea ice heterogeneity, e.g. electromagnetic, acoustic and ocean wave scattering; modelling the dynamics of fields of sea ice; ice growth and ablation, including phase transitions and sea ice as a mushy layer; the formation of sea ice morphology and melt ponds; sea ice constitutive equations and the relationship between internal ice forces and the deformation of ice covers; granular flow and discrete element models of sea ice; and other ice types, including glacial ice and river ice. Even the list above is already impressive, several important problems, which are still not well understood, were identified, such as icing of ships, energy loss mechanisms for waves in the marginal ice zone and some other.

The general theme of the workshop produced a stimulating week of diverse presentations given by participants from a wide variety of academic and technical backgrounds; primarily pure and applied mathematicians but also operational modellers, engineers, field and laboratory experimentalists, physical oceanographers, meteorologists and material scientists. Including those in the audience who didn't present, this often led to lots of challenging questions after presentations and plenty of discussion at coffee breaks and over lunch. Geophysical fluid dynamics involving sea ice is a very demanding research topic for a wealth of reasons, especially the temporal and spatial capriciousness of Nature, and plenty of conversations occurred that attempted to coalesce the mathematicians' ambition to create parsimonious models with the reality of multidimensional marine geophysics, i.e. to reduce massively complicated problems to their influential vital components. This is a difficult path to tread and, while the journey is not over, progress was definitely made in regard to stressing the significance of sensitivity studies in the creation of effective mathematical models and ensuring parameterizations were fit for purpose by making their physics as robust and as realistic as possible.

Experience and expertise was probably the broadest in span for this workshop amongst the four, covering everything from the purest rigorous mathematics often pertaining to Cosserat elasticity (coincidentally now called *micropolar* elasticity) to observational field experimentation and everything in between. While this undoubtedly presented challenges with respect to audience comprehension and commitment to engage in some cases where presentations were deemed less relevant, it also added colour to the interchanges and the event overall, e.g. a hypothetical conversation between Professors Plotnikov and Ackley would have been particularly enjoyable!

The workshop fell naturally into several general themes, as follows:

1. Wave ice interactions often involving modelling in ice fields made up of separate ice floes; presented by Meylan, Squire, Marchenko, Bennetts, Guyenne, (HH) Shen and Mosig.
2. Hydroelasticity, including the effect of moving loads on continuous sea ice and floating airports; with talks spanning the full spectrum from the most rigorous to the applied, given by Parau, Trichtchenko, Khabakhpasheva, Kalisch, Vanden-Broec, Il'ichev, Plotnikov, Groves, Smith.
3. Fluid dynamics; Haragus and Baldi.
4. Basin scale models in the context of sea ice, including earth system models; with talks given by Rynders, Hunke, Williams and Aksenov.
5. Other ice-fluid interactions including experimental aspects, comprising a rich miscellany of topic areas that often reminded the mathematicians present just how challenging the theme of the meeting, viz. Mathematics of Sea Ice Phenomena, really is. Here inspiring seminars were given by (HT) Shen on river ice, Grue, Langhorne, Folegot, Ackley, Malyarenko, Kämäräinen, Tiwari, Kadri and Gou.

The ground and mezzanine floors were hives of activity during and after presentations, which was a very satisfying outcome for the workshop organizers led by Professor Plotnikov.

Workshop "Ice-structure interaction"

Special attention during the programme was paid to industrial problems with sea ice. Interaction of ice with structures appears in numerous engineering applications including icing of structures (planes, turbines, cables, ships etc.), thermally induced loads on structures from ice and frozen soils, and mechanical loads on offshore and coastal structures due to the contact interaction. The physical mechanisms of ice-structure interactions are physically related to phase changes, ice micro-structure, the rheology and strength of ice, properties of contact interaction of ice with different materials, properties and behaviour of structures under the loading, and the driving forces applied to the ice when it interacts with structures. Understanding of the physical phenomena and proper formulation of mathematical models describing ice-structure interactions was shown to be necessary for adequate numerical simulations with useful input for industry.

The presentations in this workshop can be grouped as follows.

1. Eight presentations by Verlaan, Marchenko, Riska, Daley, Bridges, Sodhi, Onischenko, and Hopkins showed the present state-of-art and future of the mathematical modeling to predict ice loads on real structures and ships.

2. Four presentations by Metrikine, Tuhkuri, van Vliet, Miryaha were concerned with modeling of ice failure and ice interactions with model structures and concept development.

3. Mechanical properties and rheology of ice were discussed in presentations by Schulson, Cole and Kolari.

4. Icing of aircraft was covered by Smith, Tiwari and Hammond.

5. Interactions of waves in ice covered regions with model structures were subjects of talks by Korobkin, Maki, Herman, and Sturova.

6. Review of their studies were presented by Aksenov, Palmer, Eik and Taylor. Presentations by Schulson and Cole also included reviews but mostly focused on single topics (ice-ice friction and ice rheology in cyclic loading).

New unpublished scientific results were presented by Sodhi (influence of ice creep on synchronization of ice loads on a wide structure), Marchenko (influence of vertical migration of brine on the thermodynamic and stress state of confined ice inside a quay) and Korobkin (flexural-gravity wave interaction with vertical walls including account for double and triple roots of the dispersion equation). Palmer and Onishchenko presented useful information about official documents on design ice loads, and pointed out specific topics of ice research which require the expertise of specialists in probabilistic theory. Mathematical models of ice-induced vibrations were discussed in presentations of Metrikine and Sodhi. Kolari presented a numerical model and the results for ice failure under bi-axial loading using a damage mechanics approach which imitates the scenario of wind crack formation. DEM simulations presented by Tuhkuri were focused on the 2D modeling of ice rubble. Presentations on wave-ice interaction described new formulations and new methods within well-established models. All reviews were informative and delivered information about potential use of large-scale models of ice-ocean dynamics in engineering (Aksenov), the role of scale effects in ice-structure interaction (Palmer), Statoil activities in ice-infested waters (Eik) and investigations and observations of the ice mechanics group at the Memorial University of Newfoundland (Taylor). Several important topics were not covered in the workshop including ice actions on the seabed and on pipelines, iceberg management, the actions of frozen soils on structures in coastal zones, icing of ships and offshore structures, ice management and loads on floaters. On the other hand there was much promising interaction at the workshop between practitioners in ice loading on ships and structures, in ice-ice friction and ice failure, in mechanical and rheological properties, and in icing of aircraft: this concerned fundamental physical modelling as well as calculations and observations.

Workshop "Ice fracture and cracks"

The roles of fracture mechanics and damage mechanics in the breakup of ice shelves, river and sea ice breakup, ice-structure indentation, finite-element and discrete-element models, probabilistic models, crack nucleation, hydrofracture, refrozen leads, ice edge failure processes, brittle compressive failure, Coulombic faulting, and anisotropic sea ice dynamics were presented and explained by world-known specialists and their teams carefully guided by John Dempsey. The breakup of sea ice floes and aggregates of floes is the subject of intense study at present. The steady increase in the width of the marginal ice zone - apparently caused by global warming – is still unexplained by present wave-ice knowledge and represent an important challenge.

A number of the presenters are also preparing papers for the journal *Philosophical Transactions of the Royal Society, Series A,* and several others papers have been spawned by conversations that occurred at and around the workshops.

In addition to four workshops within the programme three satellite events were held through the Turing Gateway to Mathematics (TGM). The British Antarctic Survey hosted two of them.

Mathematics of Sea Ice Phenomena - British Antarctic Survey Day, 18/09/2017

The British Antarctic Survey (BAS) is a Centre of the UK Natural Environmental Research Council that delivers and enables world-leading interdisciplinary research in the Polar Regions with a strong focus on the Southern Ocean and Antarctica. Sea ice is an important part of the cryosphere in the Southern Ocean; both in its own right, and as it affects atmosphere-ocean exchanges and feedbacks, and global oceanic circulation. This knowledge exchange event was delivered by the TGM as part of the Isaac Newton Institute Research Programme on the Mathematics of Sea Ice Phenomena. BAS invited participants of the Isaac Newton Institute programme on Mathematics of Sea Ice Phenomena to attend a day of talks, posters, and discussions on topics relevant to sea ice in the Southern Ocean. The talks and posters were from BAS staff with broad ranging discussions sought between BAS and INI participants. Particular topics that were covered included diagnosis of, and the causes and mechanisms driving, trends and variability of sea ice, ranging from the deep past using ice core proxies, the current satellite era, and climate model projections of sea ice in the future.

Future Developments in Climate Sea Ice Modelling, 25/09/2017

Observations, theory and numerical modelling strongly indicate a substantial alteration of the Earth's climate with global average warming in the coming decades. Our understanding of current and future climate is substantially derived from climate models. This one-day event (held through TGM) specifically addressed climate model representation of sea ice and investigated fundamental and applied issues in mathematical modelling of sea ice. In particular, it sought to identify future priorities for development of climate sea-ice model. The following questions were discussed: What do climate models need sea ice for? What sea ice physics is missing from models? What modelling approaches can be used to address the complexity of sea ice and the needs of climate models? This workshop enabled the presentation and discussion of different views and modelling approaches, as well as issues relevant to adequate simulation of sea ice from the perspective of the mathematical modeller. It was of interest and relevance to those working on climate models, specifically for sea ice. In particular, a lively discussion panel, including stakeholder research group leaders, helped identify future priorities for climate sea ice model development.

Sea Ice - Structure Interaction, 13/11/2017

This one-day event (again held through TGM) was hosted by BAS just after the one-week workshop "Ice-Structure interaction". BAS invited participants of the programme and industrial partners to attend a day of talks and discussions on topics relevant to sea ice interaction with structures, such as ships and fixed platforms. Our current knowledge of sea ice mechanics stems largely from measurements performed in a multi-year ice setting, rather than the first-year, sea-ice dominated Arctic of recent years. Even less information is available regarding sea ice mechanics in the Antarctic. The remarkable reduction in Arctic sea ice extent and thickness we have witnessed over past decades influences many fundamental sea ice processes, including its dynamics, mechanics and thermodynamics. As a result, our current state of knowledge of these processes and the validity of many of the parameterisations presently embedded in models become questionable. The talks were from a broad range of experts, with the explicit aim to ensure open and free-flowing discussions between all participants. Particular topics covered included overview of sea ice changes in Arctic and Antarctic, advances in technology for ice mechanics, remote sensing for ship routing, ice forces on ship and structures, and the design and functionality of the polar research vessel RRS Sir David Attenborough currently under construction (completion due 2019). A panel discussion highlighted the interests and needs of the civil and naval engineering and insurance industries.

The participants of the programme had enough time to work together and discuss problems of mutual interest for further collaboration. Discussion sessions were organised to summarize the presentations and draw conclusions during each workshop. The early career researchers were encouraged to present their researches and speak in front of specialists and practitioners working on sea-ice. Special teaching events were held to introduce and explain complex mathematical techniques related to ice research. Industrial presentations were embedded in the programme, as well as in two satellite workshops run in cooperation with the British Antarctic Survey on ice-structure interaction and mathematics of sea-ice. The programme received generous support from the Office of Naval Research, and companies Total and Bureau Veritas.

3. Scientific Outcomes and Highlights

The programme demonstrated both the achievements in the ice-related research and some gaps still existing in our knowledge about ice and its behaviour.

While research on sea ice dynamics at large scales necessarily focuses on computational issues and software problems, many climate centres recognise the need to include more advanced representation of sea ice physics relevant to its observed reduction, such as ice breakup and surface albedo. Ice characteristics are modelled to explain the climate change (e.g., location of ice edge, ice concentration and ice thickness). Collaboration with research groups investigating ice properties in the field and on laboratory scales is weak. The gap between climate-oriented research and engineering research is too big. At the same time, there is a tendency to modify the large-scale models of sea ice dynamics for engineering purposes and shipping.

Large-scale rheology of ice in climate change models and small-scale ice rheology are not always related to each other. It results, in particular, in the absence of temperature dependence in yield criteria used in large scale models while this dependence is very important in the models used for the calculation of ice loads on structures. Ice stresses, drift velocities, and the boundaries between fast ice and drift ice are not still well represented in large-scale simulations. Large-scale thermodynamics is primarily concerned with ice surface albedo and melt pond effects. In large-scale models, the state variable describing ice is its thickness distribution but there are uncertainties in the appropriate characterisation of porosity and formation of ridges and interest in extending the state description to include floe sizes. It would be useful to estimate the impact of such an approach on the modelling of fresh water balance and atmosphere-ocean energy exchange in the Arctic. In conclusion, there is still a lack of reasonable understanding on how to combine small scale observations and modelling and large-scale observations and modelling to form a holistic understanding of sea ice.

Tidal effects are not included yet in large-scale models of sea ice dynamics. Analysis of ice trackers data shows that tide may have a significant influence on extreme velocities of ice drift, which is important for engineering applications. Tidal effects on ice drift cannot be ignored in some geographical regions, for example in the Barents Sea.

The impact of collision rheology of broken ice on wave damping could be overestimated in the current models. Numerous observations show that floe collisions are rare for waves propagating in marginal ice zones of open ocean. Viscoelastic properties of ice floes and wave scattering on them are not very important for wave damping when the diameters of ice floes are much smaller than wavelength. Energy dissipation in the boundary layers on the lower surfaces of the floes could be of main importance for wave damping in ice-covered areas of ocean. We still do not know with confidence mechanism(s) that remove(s) energy from waves in the presence of floating ice. Impact on ice or through/below ice is still waiting for its proper solution. Breaking ice by impact on it, from external pressure and waves, are challenging topics.

Ice-strength conception is still not well understood in the ice research community. The influence of sea ice salinity, temperature and strain rate on the ice failure should be investigated more deeply to describe ice failure under realistic loading conditions. In particular, it is known that the conditions of ductile-to-brittle transition of ice failure are different for ice in compression and in tension. This gap in our knowledge limits application of existing models with the limiting conditions not being clearly understood for some researchers. Effects of brine migrations through the ice are accounted for in large-scale models (mushy layer models) but not included in smaller scale models used for engineering purposes, while liquid brine content influences ice strength.

Some existing mathematical models of ice-structure and ice-ice interactions are not physically based. Such models mimic real processes with little reference to the physics they assume to represent. For example, the ranges of applicability of discrete-element models are usually not discussed. This results, for example, in ignoring fluid dynamical effects on submerged ice rubble and ignoring the influence of distances between submerged and/or floating ice blocks on their added masses. On the other hand, dedicated experiments are needed to confirm that existing theoretical models have physical meaning. If a phenomenon predicted theoretically has not yet been observed in field campaigns, this does not mean that the phenomenon does not exist. The topic of ice-induced vibration of structures languishes somewhat because the ice mechanics community seems only aware of a few older models that are based on dubious physics, rather than the advances that have been made recently. Unfortunately, new advances sometimes take a decade (or decades) to be recognized.

There is a serious lack of field studies regarding ice-structure interaction in general. Such studies are expensive, but not as expensive as the consequences (especially in the Arctic regions) if we do not conduct the studies. Ship transits through the Arctic are ramping up dramatically and plans for oil and gas development in Arctic regions will likely continue for some time. Furthermore there are major plans for deployment of offshore wind turbines in the Arctic and other cold regions around the world.

There is an old tendency to adopt continuum mechanics models originally formulated for some specific materials (e.g., steel) for the description of ice dynamics and ice-structure interaction. This approach is acceptable if ice rheology and very high homologous temperature of ice in natural conditions are taken into account. Some presentations during the programme ignored ice properties and accounted only for realistic geometry in numerical simulations. However, three-dimensional models with floating ice and non-linear hydrodynamics are still a challenge, even without complete account for ice rheology.

There is also a tendency to make existing models of ocean-ice-atmosphere interaction even more complex including more effects through extra terms and extra equations in the system to solve by computer. The idea is that “more adequate” and “more physical” models will better predict the interaction. Another way of doing research that involves making models simpler, including only the main effects and neglecting many others, concerning estimation of the likely significance of some sea-ice phenomena to the wider physical system in a simple way, was much less presented during the programme. Some presentations using large-scale models seemed to indicate that ice–atmosphere interactions were typically the most important; however, this conclusion could be difficult to extract clearly from piles of computation-related information.

Problems of sea ice are so complicated that observations and field measurements could be considered as quick approaches to solutions. Actually, they do not provide solutions and understanding but helpful hints for deeper studies. In general, as in any research, numerical, experimental, theoretical and field approaches to sea-ice related problems should be combined and used in balanced cooperation between each other to further improve our knowledge on sea ice. For global wave models, so far only pancake/grease ice fields can be considered to have a reasonable parameterization. Pack ice, and fragmented ice fields often encountered in the summer melt season, still do not have data to conduct such a study. We need to investigate how pancake ice forms in a wave field, and how to mathematically model this process, so that the extent, thickness, and pancake floe size can become standard output of ice dynamics models such as CICE.

Satisfactory understanding of ocean-ice-atmosphere interaction processes is still missing. We still need to understand multi-year sea ice before it is gone, the feedbacks that sea ice has on the ocean and on the atmosphere, as these are crucial for understanding the role of sea ice for the changing climate of our planet. Fundamental processes that determine the interior structure of sea ice and its interaction with atmosphere and ocean were discussed and new problems identified.

Collaborations

The programme participants reported their new contacts and collaborations in a survey at the end of the programme. The participants also listed papers they started with their new colleagues at the INI. Some examples of collaborations initiated or continued during the programme are:

Y. Aksenov, K. Maki and A. Korobkin: Large-scale ice models for ship navigation.

D. Bucur, B. Bogosel and E.I. Parau: two-dimensional, periodic, surface gravity waves with vorticity and on capillary-elastic waves with a dissipation energy term modeling a cracking behaviour.

D. Feltham, Y. Aksenov, P. Hwang: Floe size distribution characterisation and modelling in the marginal ice zone.

S. O'Farrell and L. Bennetts: ice-wave interaction and how we can bring that into the climate model space

A. Herman and N. Gray: (i) rheology of polydisperse granular materials, and (ii) segregation processes in polydisperse granular materials

A. Herman and S. Ackley: the role of ice-ocean-atmosphere interactions in the formation of frazil ice streaks in polynyas

H. Kalisch and E.I. Parau: fully-dispersive model equations for hydroelastic waves generated by moving loads

A. Korobkin, N. B. Disibüyük, S. Malenica and K. Maki: interaction of hydroelastic waves with structures

M. Meylan and Luke Bennetts: modelling wave-ice attenuation

M. Meylan and Dany Dumont: computation of wave attenuation in the marginal ice zone

E.I. Parau, O. Trichtchenko and J.-M. Vanden-Broeck: three-dimensional nonlinear hydroelastic waves

E. Rogers and M. Meylan: frequency distribution of wave dissipation by sea ice

D. Rees Jones, D. Flocco and C. Horvat: light field underneath sea ice, with special interest in the geometric controls on this field associated with the fraction of the surface of the ice that is covered by melt ponds, and the fractal dimension of this surface

A. Roberts with Chris Horvat: variational sea ice ridging

J. Toland, P. Plotnikov and A. Chambolle: nonlinear hydroelastic waves

Z. Wang and E.I. Parau: interaction of flexural-gravity waves under an ice cover with internal waves

How the programme advanced research in the field

Ice-related problems are usually presented and discussed at engineering conferences (OMAE, ISOPE, IAHR) or environmental ones (AGU, IGS) but with little scrutiny of the underlying mathematical and physical principles. Mathematical aspects of these problems receive much less attention. The aim of this programme was to distinguish the more mathematical aspects of ice-related problems, to draw mathematical and modelling talent together, and to create a network uniting all such problems and corresponding developments into one picture. The participants of the Programme presented their results in front of specialists from different fields and answered their questions. The expected outcomes have been attained: researchers from different fields of ice-related research became aware of the theoretical development and mathematical aspects in this field, the mathematical problems of sea-ice have been identified and information disseminated on the limitations and strengths of different methodologies.

What plans and direction have you identified for future investigations

The Sea-Ice Programme identified new problems and new perspectives on some old problems that require close attention and urgent solutions. Such problems can help to shape plans and directions of future ice-related investigations, and also form the basis of current and forthcoming research programmes and proposals. We suggest that future ice-related research stimulated by the SIP should be monitored by a steering committee composed of the organisers of the SIP, the chairs of its four workshops and ad hoc members using the network of the SIP. Progress will be reviewed at a two-week follow-up workshop with embedded Summer School in July 2019. This workshop will allow researchers from all around the globe and from any stage of their careers to catch up on up-to-date developments, capitalising on contemporary progress in ice problems. The workshop will consist of invited talks, discussion sessions and invited courses to update the participants on the progress in the ice-research fields triggered by the SIP. Topics for future research include but are not limited to: floe size distribution in climate sea ice modelling; large-scale ice models for offshore engineering and shipping; multi-scale ice modelling through several scales – keeping only the most important information from small-scale models; quantification of uncertainties in ice modelling; mechanisms of wave damping in the presence of broken floating ice; mathematically simple but still physically based ice models; ice-ship interaction with ice crushing, cracking and icing; three-dimensional models with floating ice and non-linear hydrodynamics; continuous parsimonious models of broken ice.

Publications

A special issue of the journal *Philosophical Transactions of the Royal Society, Series A,* on “Modelling of Sea-Ice” will be published in 2018 or 2019 with the following contributions:

John Dempsey, “Ice fracture and ice breakup”
Ian Eisenman, “Effects of Sea Ice Model Complexity”
Elizabeth Hunke, “Numerical Sea Ice Models”

Harry Heorton, Danny Feltham and Michel Tsamados, “Stress and deformation characteristics of sea ice in a high resolution, anisotropic sea ice model”

Ian Jordaan, “Localization of microstructural change in ice and associated softening during interaction with structures”
Alexander Korobkin, "Interaction of hydroelastic waves with structures"
Aleksey Marchenko, “Thermo-mechanical loads of sea ice on coastal structures: field observations and modeling”
Mike Meylan, “Waves in the Marginal Ice Zone”
Emilian Parau, "Three-dimensional hydroelastic waves and related flows "
Kaj Riska, “Line-like contact”
Jerome Weiss, “Sea ice rheology”Erland Schulson, "Friction and its role in ice-structure interactions"
Frank Smith, “Shear flow over flexible three-dimensional patches in surface”
Vernon Squire, "Contemporary theoretical and experimental advances in ocean wave / sea ice interactivity"
John Toland, Pavel Plotnikov, "Nonlinear hydroelastic waves. Geometric approach"
Jukka Tuhkuri and Arttu Polojarvi, “Discrete Element Simulation of Ice-Structure Interaction”

Other preprints submitted during the programme

M. Meylan and L. Bennetts have submitted a paper on the vibration of ice--shelves using methods developed to model sea ice.
O. Trichtchenko, P. Milewski , E.I. Parau, J.-M. Vanden-Broeck have submitted a paper on stability of periodic travelling flexural-gravity waves in two dimensions.

A number of ideas for grant proposals were discussed during the programme and will be submitted to EPSRC, ONR, The Royal Society of London, etc.

Media Streaming

Most of the SIP lectures were watched online more than 10 times with 33 lectures watched more than 20 times as of March 2018.

Below is a summary of the 10 most streamed videos associated with the SIP programme. With the exception of the third item (“Video interview with the programme Organisers”) these were all scheduled talks delivered as part of either the programme as a whole, or a specific workshop. All were and are hosted on **www.newton.ac.uk** and will remain free to view and access for the foreseeable future.

Media Item	Speaker	Views
Peridynamic Modelling of Ice Fracture	**Oterkus, E**	**67**
Filling the polar data gap with harmonic functions	**Strong, C**	**63**
Video interview with the programme Organisers		**54**
Mathematical Challenges in Modelling Wave Scattering in the Marginal Ice Zone	**Meylan, M**	**48**
Linking scales in the sea ice system	**Golden, K**	**33**
Modeling macro-porosity of ridged sea ice in basin-scale models	**Roberts, A**	**33**
Friction of Sea Ice	**Schulson, E**	**31**
A sea ice model with wave-ice interactions on a moving mesh	**Williams, T**	**30**
A different perspective on wave-ice interaction research	**Squire, V**	**27**
Small to big, quick to slow: The many scales of sea ice properties and processes	**Perovich, D**	**26**