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ON THE PROBLEM OF SEA ICE MECHANICS

Abstract

In the context of short-term sea ice forecasting, the model should capture as many of the synoptic features and as much of their variability, as possible. We are interested in the meso-scale properties and processes, i.e. thickness, consolidation, compactness, smoothness, accumulation of ridges, formation of leads and ice edge, drift and displacement, etc. Modelling and forecasting of synoptic ice formation are of interest to shipping as it affects route planning and the operation of icebreakers. With a view to conventional ice charting, the forecast problem might read: Given today's ice chart, what will tomorrow's ice chart look like?

The model has to return meso-scale features, while essential smaller-scale mechanisms have to be parameterised. The problem in a meso-scale model is to adequately take into account the governing fine-scale mechanisms.

Pack ice is a crushable fragmented aggregate, characterized by point-like contacts and stress trajectories. In compressible loading, even local traction forces, causing brittle failure, may be induced. The localization of stress and strain is a considerable complication! By way of localization, critical phenomena at singular points, affect the entire structure. Meaningful characteristics are integrity, state of damage (flaws, cracks), fragmentation and skeletal structure (fabric of fragments, strength of the structure).

Structural properties and their evolution during the material history could be represented by suitably chosen internal variables. To reflect the state of degradation, fragmentation, consolidation, etc., special concepts are required for the damage mechanics of fracturing pieces and fragmented aggregates. Using such a vehicle, the meso-scale mechanics of sea ice could be accommodated in a continuum mechanics model. More elements have been worked out in plasticity.

1. Problems of forecasting sea ice

To put it simply, the question is: *What will happen to the ice at sea?* The problem is anything but easy. Before taking any practical steps, the basic question of what sea ice actually is has to be addressed. *Sea ice exhibits considerable complexity. How can it be described?*

In this particular context of short-term sea ice forecasting, the model should capture as many of the synoptic features and as much of their variability, as possible. We are interested in meso-scale properties and processes, i.e. thickness, consolidation, compactness, smoothness, formation of leads and ice edge, drift and displacement, etc.

Any practical description of the *synoptic appearance* is highly idealised. Conventional ice charts nevertheless, provide a reasonable synoptic picture. On such charts, sea ice is represented as a composition of various types of ice whose main characteristics are **mean thickness, compactness,** and **structure** (rafted ice, hummocks/ridges, cracks, jammed brash barriers). Considerable abstraction is involved. Sea ice is, in some way, regarded as a substance that occurs in varying states and extends in a variety of shapes.

Despite all the idealisation, for practical purposes, the forecast problem could be put as follows: **Given today's ice chart, how will tomorrow's ice chart look like?**

2. Problems of modelling sea ice

At such an abstract level, it is evident that sea ice modelling suffers from some fundamental flaws. The model has to return meso-scale features while essential smaller-scale mechanisms have to be parameterised. A major problem is the fact that elementary processes can only be addressed in a very abstract way. Besides, *it is impossible to carry out a controlled experimental test.* For that reason, it is all the more important to establish a sound theoretical model basis. This is extremely difficult, however, because of the obvious complexity of sea ice.

Sea ice undergoes various changes due to both production/ablation and drift/deformation, which are referred to as thermodynamics and dynamics, respectively. The growth and melting of sea ice are associated with phase conversion of water to ice and vice versa, a relatively slow process of considerable thermal inertia. Thermodynamics is about cooling, heating and the budget of latent heat (of fusion). It is an essentially local process, controlled by vertical fluxes (of heat). By contrast, mechanics involve major horizontal interaction. Pushing and shoving ice floes can pass momentum across considerable distances. During a storm, ice conditions may change dramatically. The most salient variations are due to displacement and deformation. Therefore, the major concern in short-term forecasting, is dynamics.

The ice field is actuated according to the balance (imbalance) of forces. Dynamics is about horizontal motion. As for thermodynamics, external forcing is mainly provided by vertical fluxes. Ice drift is forced by drag stresses - vertical flux of horizontal momentum - primarily wind, secondly water.

The total balance of forces includes external forces and internal forces. The latter are a matter of material response, concerning the way in which loads are supported by the material structure. Although at the scale that is relevant to us, the details of floe shape and arrangement, show random characteristics, it is evident that the mechanical behaviour of sea ice is governed by its fragmentary structure and brittleness. Fragmented pack ice is capable of withstanding some compression but is unable to support tension. Basic compressive processes are rafting and ridging. Ridges are also formed in shearing motion. As a significant complication, response properties depend on the integrity and type of loading.

In a meso-scale model, the problem is to adequately consider the governing fine-scale mechanisms that are relevant and required. Although the modelling scale used is larger than the ice fragments, it is important to build characteristic material properties (integrity, granularity, fragmentary structure) into the model.

Meso-scale ice mechanics models seem to be rarely discussed. As a rule, sea ice studies either address small-scale (engineering) mechanics or climate issues. There are problems with ice load on (offshore) structures, resistance to vessel motion, etc. for which discrete elements and fracture mechanics are suitable. In climate models, where short-term variations and meso-scale features are of minor importance, sea ice is modelled as a non-Newtonian (viscous) fluid, irrespective of granularity and brittleness. Such a crude parameterisation appears to work for basin-scale circulation (gyres) of ice, e.g. in the Arctic, the Weddell Sea and in the area around Antarctica. The meso-scale problem ranges between engineering and climate modelling. Modelling and forecasting of ice formation is of interest to shipping as it affects route planning and icebreaker operation.

In a general circulation model, with momentum balance as a general framework, the ice is treated as a continuum substance. The core of the ice mechanics model is a description of its constitutive behaviour. As a mechanical response to deformation, internal stresses act as horizontal fluxes of momentum. The continuum concept should be practical as far as damage, granularity, compactness, etc. can be regarded as continuously distributed parameters. Meso-scale phenomena of interest are, e.g., the formation of leads, accumulation of ridges, and arching. If the ice pack is regarded as an aggregate of solid blocks, fracture mechanics and comminution act as sub-scale processes for which some parameterisation could be found. The model should capture those features which are left after a meso-scale filter has been applied to its complex interactions (a similar closure problem is encountered in turbulence modelling).

In a different interpretation, the model to be developed, represents a fictitious substance exhibiting properties similar to those of real ice. A surrogate mechanism should mimic what is perceived as the typical meso-scale performance of real ice. The key issue, for a model of this type, is a suitable idealisation. An adequate characterisation depends on appropriately chosen state properties. First of all, a consistent set of relevant properties must be determined. It is highly likely that the characteristics, commonly displayed on ice charts, are inadequate for the description of mechanical response. Thus, a closure problem exists even from the phenomenological point of view.

3. Mechanics of sea ice

Sea ice is **brittle** and its main failure mode is **fracture**. The principal mechanisms are **buckling, creep, cracking, flaking or spalling, and crushing** (In flaking, plane horizontal cracks are bent upwards and downwards, creating fragments that break away). Deformation leads to rupture. Ice is broken into pieces. Ultimately the resisting mechanism is a matter of fine-scale properties. A characteristic quantity is fracture toughness.

Pack ice is a **crushable fragmented aggregate**. Stress devolves to some pattern of intergranular forces. The network of floes and contacts forms a skeleton. The distribution of stress is highly irregular. There are **point-like contacts** and **stress trajectories**. In compressible loading, even **local traction forces** can be induced. Brittle failure (in cleavage mode) is caused at crack tips. **Localization of stress and strain** is a great complication! By way of localization, **critical phenomena at singular points affect the entire structure**. This is a difficult problem.

In spite of localization, the sea ice cover constitutes a whole. Deformation of the ice field results from the displacement of floes (interaction among individual ice floes). Like other granular materials, fragmented ice is subject to frictional shear deformation.

Mechanical energy input, that cannot be absorbed by a stress increase, is dissipated in the form of damage and fracture, i.e. irreversible changes in the material structure. The energy driving a crack, is produced by the release of elastic energy. Damage and fracture act as relaxation mechanisms. Sea ice is a **progressively degrading solid**. Fragmentation, frictional shear and ridging are all associated with major consumption of mechanical energy. Such dissipation certainly is a stabilising feature but rather difficult to model. The ice is additionally damaged by thermal stress and icebreaker operation. Under freezing conditions, fractures and flaws may also disappear as new ice forms, mending cracks, flaws and leads.

4. Characteristics of structure and response

As a result of loading and deformation, the material structure (flaws, cracks, leads, ridges) is highly irregular. Suitable characteristics are **integrity, state of damage (flaws, cracks), fragmentation and skeletal structure (fabric of fragments, strength of the structure)**.

As long as the deformation is elastic, it is *reversible*. As soon as damage, fracture, rafting, ridging or crushing are involved, the deformation is *irreversible*. In reversible deformation the expended energy is retrievable. However, ice is rather inflexible and, consequently, its energy storing capacity is limited. In practice, most of the expended energy is dissipated, i.e. it is irretrievable. Irreversible deformation occurs in *individual fragments* (damage and fracture), as well as in the *entire structure* (fabric). Modelling of the disintegration and re-fitting of fragments, is extremely difficult. In cyclic deformation it is impossible to exactly restore the structure. To make the pieces fit again, work has to be done in re-compression. Close packing of fragments always requires crushing. A restoration of the ensemble shape requires input of work. **Irreversible changes are dissipative.**

There are many different forms of ice (intact, damaged, fragmented). The complexity of phenomena (over a spectrum of scales) and the need for suitable abstraction, constitutes a truly difficult problem. We are dealing with **mechanics of continuum, damage (flaws), fracture and contact**. How can these characteristics be integrated into a practical model of meso-scale response? This is a challenging problem, and it is no surprise that **a readily available constitutive model for the mechanics of sea ice on a synoptic scale does not exist**. What should be done?

5. Strategies, concepts and elements of a sea ice model

One could proceed along any or some, of the following lines of development.

- Construct a *phenomenological model* which qualitatively captures characteristic features at a medium level of sophistication and optimise tuning parameters.
- It is supposed that **the basic mechanism is both material-independent and scale-independent**. Consider comparable materials and processes, to make use of relevant concepts. What are the most suitable proxi-materials?
- Most (advanced) constitutive models have been worked out in continuum mechanics. Apart from metals, much study has been devoted to **soil, concrete** and **rock**. Can such models be applied to sea ice?

Relevant *phenomenological characteristics* might be integrity, fragmentation, compactness, consolidation, hardening, damage, hysteresis and stress relaxation.

Does fragmented sea ice, as a granular material, behave like soil? Common granular materials consist of particles of comparable size. What about typical length scales of fragmentation and structure, self-similarity and scaling laws? Fractal crushing and formation of fractality is addressed in **clastic mechanics**.

Degradation of strength is addressed in **damage mechanics** but standard damage mechanics applies to continuous materials. Yet pack ice consists of brittle fragments. Can damage mechanics be applied to fracturing pieces and fragmented aggregates? Sea ice undergoes cracking, fragmentation and disintegration, even crack healing. Both coastal fast ice and pack ice should be accommodated in one model. What to do about contact mechanics and fractality?

Regarding a continuum mechanics model, the question is: what would an **equivalent homogeneous continuum** look like? Continuum mechanics material modelling is well developed, and many specific, continuously deforming, materials have been addressed. Related topics are generalised thermodynamics (thermodynamics of irreversible processes, thermomechanics) and material science. Hysteresis (plasticity) and rate dependence of response (viscosity), lead to **viscoplasticity**, the most comprehensive concept. Related frameworks are **hypoplasticity** and **endochronic plasticity**.

Loading, unloading and reloading, also affect the structural properties of the material, which in turn determine its response. The material has a memory. Its behaviour is history-dependent. The loading history could be captured in terms of **internal variables** which stand for changing properties of **material structure** (structure, degradation, hardening, etc.) and **response**. Internal variables indicate the state of **irreversible changes**. Thus, irreversible changes in material characteristics are modelled by the evolution of suitably defined internal variables.

Candidates for internal parameters might be:

- length scales, scaling properties
- degree of fragmentation, fractal dimension
- variance of internal structure, degree of disorder
- pre-consolidation pressure, degree of pre-compaction

Structural parameters that can be identified on satellite images are particularly convenient.