# Sea Ice Science

*Tokoloho Rampai*

## Provocation 1: Research in/and the Antarctic

The Antarctic sea ice plays an important role in global climate and ocean systems; therefore, Antarctic sea ice is an important aspect regulating the response to and being impacted by anthropogenic climate change (Light et al., 2003). The structural properties of sea ice affect optical properties, the biology within the ice, the mechanical properties, exchanges between the atmosphere and the ocean, amongst other factors. The formation of sea ice affects other environmental systems and thermohaline circulation. Thus, studying the growth dynamics of sea ice and the resulting structure is of great importance.

Vast areas of silent, floating ice on frigid and uninviting seas, the polar regions have always been the subject of fascination and curiosity. The hostile climate has discouraged habitation and exploration of these regions, especially in the Southern Hemisphere, where the latitudes have become known by their tempestuous conditions, the roaring forties, furious fifties and screaming sixties (National Ocean and Atmospheric Administration [NOAA], 2017).

As exploration and knowledge of these regions has developed, scientists have come to realise the importance of sea ice.

The ice provides a barrier between the atmosphere above and the ocean below, affecting local and global climate, ocean mixed layer structure, and ocean heat flux (Brandon, Cottier and Nilsen, 2010; Morrison and Smith, 1981; Maykut and McPhee, 1995). The sea ice also provides a habitat for microorganisms that live within the brine channels present in the ice. Brines allow the microorganisms to access the light filtering in from above, while the nutrients they require are provided in concentrated doses from the ocean as the ice forms and rejects all impurities (Arrigo, Mock and Lizotte, 2010).

Considering the substantial role that sea ice plays in local and global climates, and its effect on radiative, heat and salt fluxes within the ocean, it is paramount that sea ice properties are studied and recorded. This is of special significance considering the impact of global warming upon the sea ice and the feedback that ice has on the climate system.

Original and independent sea ice research in South Africa started only recently (2017) thanks to a collaboration between oceanographers and chemical engineers at UCT. The first projects demonstrated the initial capability of carrying out research in Antarctic sea ice and were mostly focused on capacity building and community engagement for knowledge sharing.

*For more see:* Hall, B., Johnson, S., Thomas, M., and Rampai, T. "Review of the Design Considerations for the Laboratory Growth of Sea Ice", *Journal of Glaciology* 69, no. 276 (2023): 953–965. doi:10.1017/jog.2022.115

## Provocation 2: Sea ice properties

Sea ice properties are also important for the environmental characterisation associated with shipping, offshore construction activities and tourism, which are increasing in the polar regions.

The safety and economic success of these endeavours depend on a comprehensive understanding of sea ice and its effect on these activities (Timco and Weeks, 2010). The polar regions are fragile environments, and the efforts to preserve them are continuing, especially in Antarctica, which is protected under the Antarctic Treaty of 1959, prohibiting commercial activities in the region and preserving it for scientific research (Secretariat of the Antarctic Treaty, 2011).

Timco and Weeks (2010) provide a comprehensive and thorough review of the engineering properties of sea ice, including mechanical properties such as tensile, uni-axial compression and multi-axial compression strength, elastic modulus and Poisson's ratio. It is important to note that all of the reviewed studies focus on Arctic ice and this study mostly spans from the 1960s to the mid-1980s. The mechanical properties of ice vary greatly, since they are a function of many factors including, but not limited to ice temperature, salinity and gas content, crystal size and orientation, load direction and strain rate (Schwarz and Weeks, 1977). In addition, the behaviour of ice shifts between inelastic and elastic, with viscoplastic behaviour also shown (Mellor, 1983). Therefore, there is a need for a compound model to describe the mechanical behaviour of sea ice, that aims to incorporate its different behaviour in different regions. These models can either be elastic-plastic or viscous-plastic (Feltham, 2008).

As input to these models, and for calibration purposes, the mechanical properties of ice need to be assessed under a variety of conditions and in laboratory experiments. The mechanical properties of interest and their current knowledge status are reviewed below. Elastic Modulus, or Young's Modulus, is the ratio of stress to strain during the elastic behaviour regime. Given a stress-strain curve, this can be obtained by computing the slope during the elastic behaviour; however, this is too impractical since it requires strain measurements from within the sample itself, not through the platens. The initial tangent modulus is constant for such a small region that it is difficult to obtain (Mellor, 1983).

*For more see:* Johnson, S., Audh, R.R., de Jager, W., et al. "Physical and morphological properties of first-year Antarctic sea ice in the spring marginal ice zone of the Atlantic-Indian sector". *Journal of Glaciology* 69, no. 277 (2023): 1351–1364. doi:10.1017/jog.2023.21

## Provocation 3: Sea ice dynamics

Changes in salinity and temperature exert a fundamental control on sea ice physical, chemical and biological properties (Vancoppenolle et al., 2019). It is essential to have a deep understanding of desalination processes in sea ice, especially in the context of climate change, during which a substantial reduction in the sea ice extent is expected in both hemispheres (Comiso et al., 2017; Parkinson, 2019).

Previous observations have proposed that desalination of sea ice takes place through a variety of mechanisms during its growth and decay: for example, salt segregation at the growing ice-ocean interface, brine diffusion, brine expulsion, gravity drainage and flushing (Weeks and Ackley, 1986; Notz and Worster, 2009; and references therein). In growing sea ice, gravity drainage and salt segregation are thought to dominate desalination processes; the relative proportion of which remains hotly debated, as illustrated by the contrasting views in the conclusions of Notz and Worster (2009) and Middleton et al. (2016).

Gravity drainage refers to the draining of brines out of sea ice by convection caused by a hydrostatically unstable brine density profile. Brine density is primarily a function of brine salinity. Any temperature gradient in sea ice is accompanied by a salinity gradient in the interstitial brine to maintain phase equilibrium (Vancoppenolle et al., 2009). In growing sea ice, temperature decreases upward and, therefore, brine salinity increases upward: a configuration that is hydrostatically unstable. Depending on the permeability of the sea ice, this configuration may lead to convective overturning of brine and the replacement of some of the brine with the underlying seawater. The salinity difference between the brine

leaving sea ice and the brine entering sea ice is the cause for the net desalination by gravity drainage (Eide and Martin, 1979; Notz and Worster, 2009).

Observations in both field and controlled-lab experiments have highlighted the key role of brine channels as a major path for brine rejection in growing sea ice (Wakatsuchi and Kawamura, 1987; Eide and Martin, 1975; Cole and Shapiro, 1998; Cottier et al., 1999; Middleton et al., 2016). However, there are still unknowns regarding the nature of brine overturning (i.e., on-off behaviour, onset development, etc.) and its relationship to internal ice microstructures (i.e., meandering of brine channels, roles played by ice crystal lamellae, etc.).

Salt segregation at the growing ice-ocean interface refers to a process by which most of the salts are rejected from the newly growing pure ice crystals and become concentrated at the interfacial boundary layer between the ice and the ocean (Weeks and Ackley, 1986). By itself, the morphology of the ice-ocean interface (i.e., 'the skeletal layer') requires that this process occurs. The segregation of salt at the interfacial boundary layer leads to a diffusion of salt away from this interface. In parallel, the freezing point decreases with increasing salinity, as an increase in salt concentration goes along with a drop in temperature. Different rates between the transport of heat and salt diffusion leads to the development of a constitutionally super-cooled layer at the growing interface (Weeks and Ackley, 1986; Petrich and Eicken, 2016).

Any small perturbation from the planar growing interface, protruding in the constitutionally super-cooled layer, has a growth advantage and explains the lamellar structure of the interface: consisting of sub-millimetre-thick blades of ice separated by narrow films of brine. The presence of this interfacial boundary layer is required to explain many of the chemical fractionation processes that are observed in growing sea ice, such as the fractionation of gases (Tison et al., 2002). This statement relies on Tison et al.'s (2002) observations of the continuous bulk salinity field across the ice-ocean interface with no immediate segregation of salt at the advancing front. The observation of continuous interfacial

convection by Middleton et al. (2016), independent of the location of brine channels, contradicts this statement. However, except for Middleton et al. (2016), these imaging methods suffer from the important drawback that internal structures in the ice can only be investigated after growth in 'post-mortem' investigation.

*For more see:* Moos, S., Rampai, T., Vichi, M., Tison, J. L., De Witt, A., and Fripiat, F. "Investigating the dynamics and exchanges across the ice-ocean interface in artificial sea ice". South African National Antarctic Programme, 2024.

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