WAVE-ICE INTERACTION: A WARNING SIGN FOR GLOBAL CLIMATE CHANGE

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There is already clear evidence of anthropogenic climate change occurring on the planet including the rise in global temperatures, ocean warming and increasing sea levels. However, wave-ice interaction is an aspect often dismissed. The hastening decline in Arctic sea ice and the prediction that it will cease to exist by 2050 given current carbon dioxide emissions [1], prompts further research into and raises awareness of the importance of wave-ice interaction and its relationship with global climate patterns [2]. Although diminishing Arctic sea ice is a perturbing concept concerning the survival of wildlife in the region, such adjustments to the marginal ice zone (MIZ), which is the transition between sea ice and deep-water open ocean, create more economic opportunities in the region including new shipping routes and further oil and gas exploration [3]. An understanding of wave-ice interaction and wave attenuation models is necessary for accurate local and global climate predictions. An oversight of this could result in potential danger for such exploration and investigation in the region.

The region in which the most prominent wave-ice interaction occurs is the MIZ. In this region sea ice is broken into ice floes, free floating pieces of ice. These ice floes can fracture or deform due to ocean waves interacting with them. Concomitantly, the existence of the ice floes also affects the propagation of waves. However, depending on the size and properties of the ice floe, the propagation of waves will vary. Mathematical models have been developed to further quantify the interaction between ocean waves and sea ice.

Waves propagating in ice are fundamentally observed to decrease in amplitude [2], more specifically an exponential decay with distance. This occurs due to two processes: scattering and dissipation. Scattering redistributes energy within a system. Whereas dissipation removes energy, thus it is transferred to various other parts of the atmosphere. A vast number of wave attenuation models have been established in the field of geophysical research based on the properties of ice floes. Three of the most well-developed wave attenuation models will be explored in this article, one encompassing the elastic properties of certain ice floes in the MIZ, another exploring the relationship between the viscosity of ice with wave propagation, and the last model incorporating a combination of the previous two.

SEA ICE FORMATION IN MIZ: HOW WAVES AFFECT SEA ICE

The key to understanding the significance of wave-ice interaction, its influence on global climate and the complexities of the wave attenuation models begins with the formation of sea ice. Sea ice consists of frozen sea water often broken into floes floating on the surface of the ocean [4]; these ice floes range in size from 10m to 5km wide [4]. The formation begins at temperatures low enough for the ocean to freeze, with the absence of sunlight [5]. The exact freezing point of the ocean depends of the salinity of the water in the region, with the freezing point and salinity sharing an inversely proportional relationship [4]. The first stage of the process produces frazil ice which is a collection of millimetre-sized crystals [6], as seen in Fig. 1a. In calm ocean conditions, such crystals then coalesce to form a thin layer of grease ice on the water surface, such as Fig. 1b. However, stronger waves interacting with frazil ice cause the crystals to be forced together and merge into pancake ice floes, displayed in Fig. 1c. During pancake ice formation, the frazil slush oscillates and amalgamates to form the circular ice floes [6]. Over a period of time, small pancake ice floes freeze together creating larger ice floes.

(a)
(b)
(c)


Figure 1. (a) frazil ice [7] (b) grease ice [8] (c) pancake ice [9]

The formation of sea ice is affected by several different factors, for example solar radiation, air currents and waves. Conversely to how the lack of solar radiation during winter months encourages the formation of frazil ice, the presence of solar radiation in summer months raises temperatures triggering the melting of sea ice. Yet the melting of sea ice is also dependent on the reflectivity of the surface, known as its albedo [1]. During winter months the high surface albedo leads to 80% of the solar radiation being reflected back into the atmosphere [10]. Whereas during summer months, ice begins to melt from the rise in temperature. Thus, ocean is revealed rather than being covered by sea ice, leading to a reduced albedo. The dark waters absorb a greater amount of solar radiation instigating a further melting of sea ice [5].

With regard to air currents, forceful winds formed by storms are an important driving factor for the behaviour of sea ice. Penetrating winds apply a drag force to sea ice, thereby increasing ice drift [11]. Both elastic and inelastic collisions can occur between pancake ice floes, forming larger ice floes with varying properties. Pressure ridges are created as a result of the stress established between two conjoined ice floes, represented in Fig. 2, making larger floes more prone to being affected by the drag force again [12].

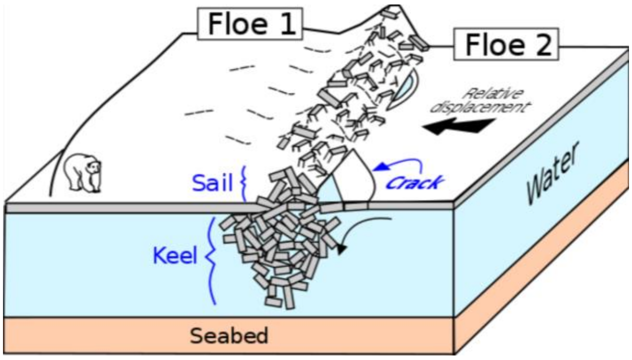

Figure 2. Interaction between two ice floes moving towards each other forming a pressure ridge consisting of sea ice fragments [13].

Winds also generate waves at the surface of the ocean, which affect sea ice composition. Similarly to the effect of wind on sea ice, waves can promote the merging of ice floes by exerting a drag force [11]. However, waves are predominantly responsible for the breakup of sea ice. Wave propagation in larger sheets or ice floes in the MIZ can cause them to break up into smaller floes. Yet the breakup of sea ice has different consequences depending on the season. In the winter, the exposure of ocean results in the formation of more sea ice because it creates further surfaces over which frazil ice can be produced. In the summer, the opposite effect occurs. Here, more openings of surface water lower the overall albedo, thus prompting more melting of ice [14].

Both of the seasonal effects can be considered localised effects of waves on ice. The large-scale effect of waves on ice encompasses the entire floe size distribution. Qualitatively, the floe size distribution is number of ice floes defined by their size in a particular region of the MIZ. A mathematical representation of this would be a distribution $f(r)$; $f(r)dr$ is the proportion of the ocean surface where ice floes, between size r and $r + dr$, can be seen on floating on top [1]. All of the small-scale effects including the formation and break up of sea ice change the floe size distribution. Furthermore, the seasonal effects are related to the height of waves and wind strength. Stronger winds induce larger waves which cause a greater amount of ice floes to break up, implying either more ice coverage or melting depending on the season [15].

PROPERTIES OF ICE FLOES

Ice exists in crystalline or non-crystalline forms. To date, research has recognised 16 different types of ice formed due to fluctuating conditions such as temperature and pressure [16]. Non-crystalline forms of ice, known as amorphous, are less likely to be found on Earth due to extreme conditions in which they are formed and lack the long-term order of a crystalline solid. The structure of crystalline ice depends on the arrangement of oxygen atoms relative to the water molecules. Concerning the mechanics of sea ice, the relevant crystalline structure is hexagonal ice and is formed at $0\ ^{\circ}C$ [16]. This hexagonal structure is explicitly shown in Fig. 3, with the oxygen atoms forming hexagonal rings from two planes.

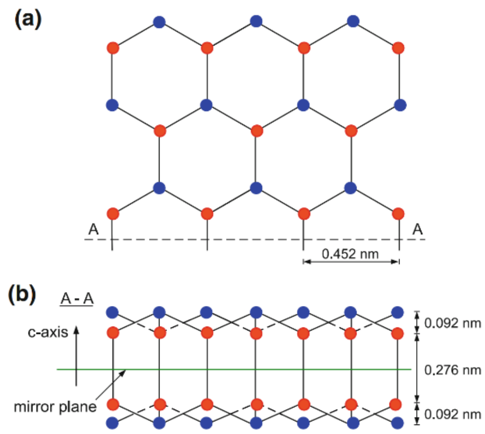

Figure 3. (a) Hexagonal oxygen rings forming crystalline structure with red and blue dots representing oxygen atoms in upper and lower planes from a projection on the plane parallel to the crystal. (b) Projection parallel to the c-axis, an axis which runs along the length of a crystal [16].

When under the influence of stress and strain from waves, the internal properties of ice can change. For example, the original elasticity transforms. Polycrystalline, meaning made of many crystals, ice undergoes a process of elastic and creep deformation followed by cracking when subjected to constant stress. Creep is a time-dependent deformation under applied mechanical stress which can lead to permanent deformation for a material [17]. There are three stages in the deformation of ice represented by Fig. 4. Firstly, for polycrystalline hexagonal ice, strain increases with stress, but at a decelerating rate. This stage of the progression known as primary creep is an elastic process. Secondary creep is a phase where strain continues to increase constantly with time but the elements of elastic deformation transform to inelastic deformation making it an irreversible process. In the final stage, tertiary creep, the rate of strain accelerates. Here further inelastic deformation occurs and the internal configuration of the atoms is altered, thus changing the elasticity of the ice floe. For large stresses applied by a wave, tertiary creep is also the part of the process where a fracture may form in the ice [16,17].

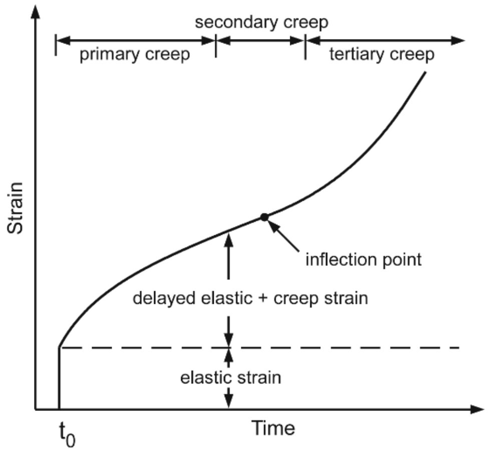

Figure 4. Strain in polycrystalline ice as a function of time under constant stress [16].

Sheets of ice at the shore are often surrounded by pancake ice floes. The pancake ice floes are formed from the cracking of a thin ice sheet. The sheet and larger ice floes are bent by wave induced stress, demonstrating the elastic properties and behaviour of ice [18], before breaking. Ice floes and sheets can display completely elastic behaviour at the beginning of the primary creep process and this is classically described using Hooke's Law [16].

Viscosity describes the resistance to flow for a substance and a viscous material should undergo constant structural change when subjected to stress [19]. The viscosity of ice varies depending on its type and has a greater influence on wave-ice interaction for frazil ice and ice floes which have a length smaller than the wavelength of waves propagating through them [20].

The properties of elasticity and viscosity are not only of interest because they can change under the influence of stress exerted by a wave; but also, since these properties determine how a wave will attenuate in ice.

WAVE ATTENUATION MODELS: HOW ICE AFFECTS WAVES

Having considered the effect of waves on the formation and destruction of sea ice, it is important to consider that the interaction is mutual. Therefore, ice floes trigger the attenuation of waves. Wave attenuation can occur in the form of dissipation or scattering of energy [18]. The most significant models demonstrating such distributions of energy are the elastic plate model and the viscosity-based model, respectively regarding the scattering and dissipation of energy.

From wave attenuation measurements made over 40 years ago it was shown that waves attenuate exponentially as a function of wave period and the attenuation occurs at a decreasing rate [18]. In more recent experiments measuring wave attenuation, difficulties were encountered such as the necessity to take measurements in multiple locations within the MIZ. Yet analogous mathematical relationships have been identified for energy and amplitude attenuation,

$$E(x,\omega) = E_0(\omega)e^{-\alpha x} \quad (1)$$
$$A(x,\omega) = A_0(\omega)e^{-k_i x} \quad (2)$$

where E_0 and A_0 are incident wave energy and amplitude, x is the distance travelled by the wave in the ice, α is the attenuation rate and k_i is the imaginary component of the wave number in the MIZ [18].

The two paradigms of wave attenuation due to scattering or dissipation depend on properties of the ice floe including its length, thickness, elasticity and viscosity. When wavelengths are similar to or shorter than floe lengths, the scattering mechanism used in the elastic plate model is more applicable. For wavelengths longer than the length of the ice floe, this model is invalid and energy scattering will be predicted as negligible, resulting in the dissipation of energy instead [18]. The dissipation of energy in ice floes is represented well by viscosity-based models of attenuation [21].

A. ELASTIC PLATE MODEL

Elastic plate models of attenuation consider the elastic properties of ice floes when waves propagate through them and only consider attenuation of energy by scattering. Therefore, each individual floe is represented as a thin elastic plate based on Euler-Bernoulli beam theory which provides a relationship between applied load and deflection of the material [22].

A noteworthy wave attenuation model proposed by Kohout and Meylan presents the decay of ocean waves through a two-dimensional elastic plate. The only parameters required for this model are length, mass and elastic stiffness of the ice floe [23]. There are four main features of the model apart from the expected exponential decay relationship. Firstly, the model is completely coherent, which indicates that the superposition of waves propagating through an ice floe will always be observed [23]. Secondly, the scattering of energy is independent of ice floe length for wavelengths longer than the floe length because in this case the floe will bend elastically when interacting with a wave. The bending causes reflections at the edges of the ice floe and the wave propagates around it without any attenuation occurring. Thirdly, wave energy decreases exponentially with the number of floes, shown by the relationship,

$$E \; \alpha \; e^{-\alpha\Lambda}, \tag{3}$$

where α is the attenuation coefficient and Λ is the number of ice floes in the marginal ice floe. Lastly, stronger wave attenuation occurs for thicker ice floes and waves of a shorter time period [23].

B. VISCOSITY-BASED MODEL

Viscosity-based attenuation models assume attenuation by dissipation [18]. The models consist of a two-layer system in which the ice is considered a thin, very viscous sheet and water is a significantly less viscous layer underneath [24].

Research conducted by De Carolis and Desiderio has produced a viscosity-based attenuation model suitably matched to observations. Equation 4 proposes a relationship between decay rate and wave number in ice,

$$\kappa = k + iq \tag{4}$$

where κ is the wave number in ice, k is the wave number in water and q is the decay rate with distance of the propagating wave [24]. This relationship implies that the wave number in ice is linked to the decay rate, which is a function of the viscosities of ice and water. Data collected and the model propose greater attenuation for a higher ice viscosity and shorter wave periods [24].

C. VISCOELASTIC MODEL

Viscoelastic models for wave attenuation are examples of effective medium models in which composite materials are described [1]. As opposed to the other models, they consider the effects of both viscosity and elasticity. For the case of sea ice and water, the layer of ice is modelled as viscoelastic, whereas the water underneath is considered as having a negligible viscosity.

The most prominent viscoelastic model is that proposed by Wang and Shen. The model captures elasticity in the top layer of the ice-water system and assumes that the MIZ only consists of grease ice or pancake ice floes [20]. The dispersion relation, linking wavenumber and frequency, defined in the model is

$$\sigma^2 = Q_c gk tanh(kH) \tag{5}$$

where σ is angular frequency, Q_c is a factor which modifies the open water dispersion relation for ice, g is gravitational acceleration, k is the wave number in water and H is the height of the wave. This factor takes into account elastic properties, viscosity and the densities of ice and water [20].

THE IMPORTANCE OF WAVE-ICE INTERACTION

The wave attenuation models, and the destructive consequences of waves on ice may seem trivial in the context of global climate. Yet these small interactions are very relevant in the governing of gas, moisture and heat exchanges between the ocean and atmosphere [25].

The Earth's atmosphere constitutes of mainly nitrogen, oxygen and argon. The remaining atmospheric gases are often greenhouse gases such as carbon dioxide, methane and water vapour. The MIZ is a carbon sink as it absorbs carbon dioxide from the atmosphere, but the amount of absorption depends greatly on wave-ice interactions and wind speed. A greater wind speed increases the gas exchange velocity; thus, the ocean absorbs more carbon dioxide. Additionally, gas exchange in the MIZ is proportional to the ratio of open water to ice [26, 27]. This is one way in which wave-ice interactions, that result in the fragmentation of ice floes, can affect the climate system. Although the ocean acting as a carbon sink is a vital way of removing excess carbon dioxide from the atmosphere, a larger absorption of anthropogenic gases could increase the acidity of the water, destroying wildlife and plants which previously absorbed carbon dioxide [27].

With regard to wave-ice interactions and heat transfer, the ocean does not store heat but helps to distribute it around the globe. The majority of solar radiation is absorbed by the ocean and the ice albedo feedback mechanism determines the difference in absorption between summer and winter months [5]. Higher temperatures cause the melting of sea ice and evaporation of water, which increases humidity in the surroundings. This results in the formation of rain clouds and storms, which are then carried by winds towards land.

The bipartisan relationship between wave-ice interactions and storms is particularly interesting as extreme weather conditions induce larger waves [15]. However, larger waves have different implications on sea ice. The decay of larger waves has been observed to be linear rather than exponential, and the fractures caused in ice floes propagate deeper into the floe diameter [15]. The fractured ice is then more easily broken through the propagation of smaller waves as well. This increased uncovering of ocean further augments heat and gas exchange.

Whilst prior discussion explores the importance of wave-ice interaction on a global scale, wave attenuation models are also necessary for local predictions. For ice concentrations above 30%, current wave and climate models predict no wave energy [28], rather than gradual attenuation. These inaccurate models make it more difficult for safe shipping passages to be discovered as wave height predictions do not capture the attenuation of waves correctly. Therefore, the additional insight of wave-ice interaction is essential not only for the improvement of climate and wave propagation forecasting, but is also vital for further research and exploration to continue occurring in MIZ regions.

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