https://doi.org/10.5194/tc-2020-362
Preprint. Discussion started: 6 January 2021

The Cryosphere Discussions

Brief communication: Grease Ice in the Antarctic Marginal Ice Zone

Felix Paul[1], Tommy Mielke[1], Carina Nisters[2], Jörg Schröder[2], Tokoloho Rampai[3], Sebastian Skatulla[4], Riesna Audh[5], Ehlke Hepworth[5], Marcello Vichi[5], Doru C. Lupascu[1]

[1] Institute for Materials Science and Center for Nanointegration Duisburg-Essen (CENIDE), University of Duisburg-Essen, Germany
[2] Institute of Mechanics, University of Duisburg-Essen, Germany
[3] Department of Chemical Engineering, University of Cape Town, South Africa
[4] Department of Civil Engineering, University of Cape Town, South Africa
[5] Marine Research Institute, University of Cape Town, South Africa

Correspondence to: Doru C. Lupascu (doru.lupascu@uni-due.de)

Abstract. Frazil ice, consisting of loose disc-shaped ice crystals, is the very first ice that forms in the annual cycle in the marginal ice zone (MIZ) of the Antarctic. A sufficient number of frazil ice crystals forms the surface "grease ice" layer taking a fundamental role in the freezing processes in the MIZ. As soon as the ocean waves are sufficiently damped, a closed ice cover can form. In this brief communication we investigate the rheological properties of frazil ice, which has a crucial influence on the growth of sea ice in the MIZ. Grease ice shows shear thinning flow behavior.

1 Introduction

The growth and melting of sea ice in the Antarctic polar region represents one of the largest seasonal changes on earth (Doble, 2003). These seasonal variations are of greatest importance for the bio-habitat of Antarctica as well as for the global climate. Yet, the seasonal and long-term variability of sea ice extent in the marginal ice zone (MIZ) of the Antarctic is poorly understood and not captured by current climate models (Turner et al., 2013). Frazil ice, which consists of loose disc-shaped ice crystals formed in turbulent and supercooled water, plays a key role in this freezing process in the MIZ of the Antarctic. The MIZ is the transition zone between open water and consolidated ice, where the sea ice concentration is between 15 % and 80 %. When a sufficiently large quantity of frazil ice is present, it clusters to form agglomerations of ice, which later form into pancake ice. These pancakes grow and a frazil/ pancake mixture develops, where the frazil ice acts like a binder between the pancakes (Squire, 2011). Large incident ocean waves lead to fracture, overtopping and rafting of pancakes in the high wave energy regime closer to the open water edge of the MIZ. As soon as the waves are sufficiently attenuated by this frazil/pancake layer, a consolidated ice cover can form. This process is denoted as the pancake ice cycle (Lange et al., 1989).

Frazil ice crystals are simple in their shape, appearing as thin, circular, disc-shaped crystals due to the higher growth rate within the basal plane of hexagonal crystal lattice of ice. The crystals tend to have a diameter between 0.01 mm to 5 mm and their thickness varies between 1 µm to 100 µm. Frazil ice crystals can only develop under turbulent and supercooled conditions (McFarlane et al., 2015). Turbulence, induced by wind and wave energy, is necessary for the nucleation of crystals from the supercooled water, as well as for the ongoing frazil ice production (Maksym et al., 2012). Stronger turbulence leads to a higher

https://doi.org/10.5194/tc-2020-362
Preprint. Discussion started: 6 January 2021

particle collision rate and, therefore, to faster frazil production. During freezing, salt ions are hardly incorporated into the ice lattice and, therefore, get rejected from the ice into the water (Eicken, 2003). When the frazil ice concentration increases, it appears as a milky grey layer at the surface. This layer is called grease ice and consists of water and frazil ice crystals (De Santi and Olla, 2017).

This study investigates the properties of grease ice, encompassing salinity, temperature and its rheological properties. The latter are essential for numerical simulations of sea ice dynamics in the Antarctic MIZ. The temporal and spatial evolution of sea ice and coupled wave attenuation is influenced by damping effects due to interstitial frazil ice and the complex pancake ice floe collision dynamics including dissipative effects, such as friction, ridging and rafting, as well as eddy viscosity in the turbulent boundary layer (Sutherland et al., 2019). The hydrodynamics of interstitial grease ice and its interaction with pancake ice floes in terms of form drag are key aspects in wave energy dissipation. Therefore, a sufficiently precise description of the rheological properties of grease ice is essential.

In literature, no in-situ measured rheological properties of grease ice or frazil ice can be found, only measurements in wave tanks have been recorded (Newyear, 1999; Rabault et al., 2019; Wang and Shen, 2010; Zhao and Shen, 2015). The viscosity of the sea ice layer has also been derived on the basis of SAR images in the Antarctic (Wadhams et al., 2006) and a combination of buoy and SAR measurements in the Arctic (Rogers et al., 2016). Our study specifically focuses on in-situ data collected during the SCALE (http://scale.org.za) Winter Cruise in July 2019 to the MIZ of the Antarctic. The results are compared to literature values.

2 Materials and Methods

The experiments were conducted on the South African research vessel SA Agulhas II during the SCALE Winter Cruise 2019. Grease ice was collected at three stations, termed MIZ1s on the 26th of July, MIZ2 on the 27th of July and MIZ1n on the 28th of July. The frazil ice sample was lifted out of the water with a custom-built frazil ice sampler (Figure 1 (III)). The viscosity of the specimen was measured with an eBTV-Rheometer (Schleibinger Testing Systems, Buchbach, Germany).

https://doi.org/10.5194/tc-2020-362
Preprint. Discussion started: 6 January 2021

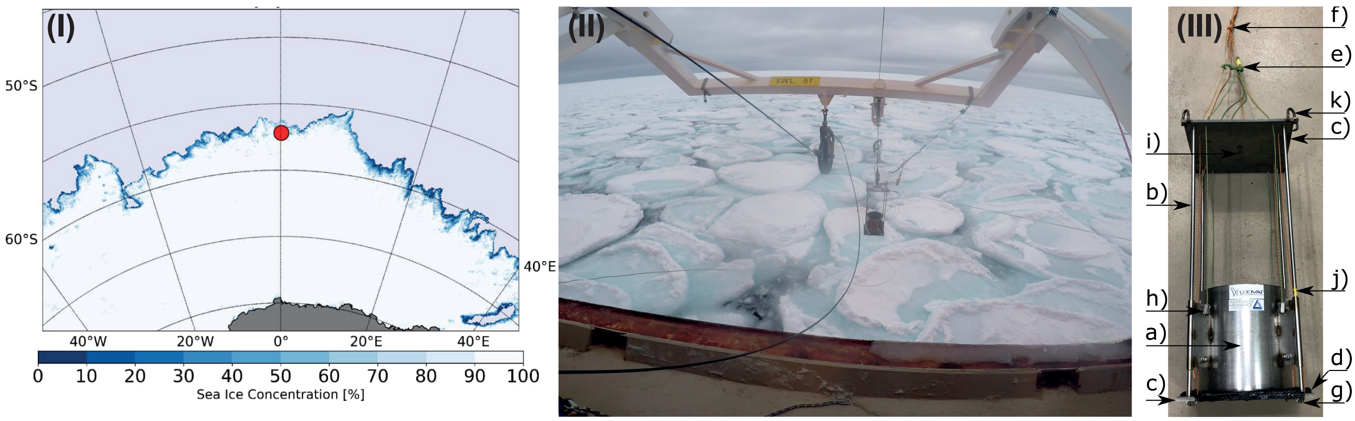

Figure 1 ***(I) The map shows the see ice condition on the 2019-07-28, the red dot on the map shows the positions of the vessel. ASI Algorithm AMSR-E sea ice concentration were obtained for 2019-07-28 from the Integrated Climate Date Center (ICDC, icdc.cen.uni-hamburg.de/), University of Hamburg, Hamburg, Germany.*** (Kaleschke et al., 2001; Spreen et al., 2008) ***(II) A picture of the actual sea conditions is displayed. (III) A sketch of the frazil ice sampler to receive an undisturbed sample consisting of: (a) metal cylinder, b) four steel bars, c) two metal plates, d) foam mat, e) rope to open the sampler, f) rope to close the sampler, g) loop for rope, h) bolts to fasten rope, i) hook, j) yellow mark, k) hooks).***

The frazil ice sampler (Figure 1 (III)) is designed similar to a Niskin bottle. It allows to retrieve an undisturbed grease ice specimen. The sampler consists of a metal cylinder, which is moveable along four steel bars between two fixed metal plates. The metal cylinder acts as the wall of a bucket. A foam mat attached to the bottom metal plate acts as a seal when the cylinder is placed on top of it, forming a water-tight bucket preventing water from draining out. Before lowering the frazil sampler into the water, the cylinder is pulled up to the top plate via the green ropes shown in Figure 1 (III) f) where it is held before sampling. Once the sampler is lowered into the grease ice layer with the yellow mark touching the ocean (Figure 1 (III) j)), it is moved horizontally with the help of guidance lines to a position where the grease ice is undisturbed. Then the cylinder is carefully lowered to the bottom plate and shut by pulling the red ropes see Figure 1 (III) f). It is then lifted on board, yielding an undisturbed grease ice sample.

On deck the temperature of the grease ice sample is instantly measured. Subsequently, the viscosity is tested in the very same sampling bucket using a vane rheometer. The vane has a radius of $R_V = 51.5$ mm and a height of $H = 103$ mm. The viscosity test lasts 60 s linearly ramping up from an initial rotation speed of $\omega = 1\frac{rev}{min}$ up to $\omega = 10\frac{rev}{min}$. The collected data allow to determine the shear stress τ (Equation 1), shear rate $\dot{\gamma}$ (Equation 2) and viscosity η (Equation 3) of every sample based on the measured resistance torque M:

$$\tau = \frac{M}{2\pi R_V^3}\left(\frac{H}{R_V} + \frac{2}{3}\right)^{-1} \qquad 1$$

$$\dot{\gamma} = \frac{4\pi R_S^2}{\left(R_S{}^2 - R_V{}^2\right)}\omega \qquad 2$$

$$\eta = \frac{\tau}{\dot{\gamma}} \qquad 3$$

Here R_S denotes the metal cylinder diameter. Immediately after the viscosity measurement, the grease ice is separated into its two components frazil ice and salt water for further testing of the individual constituents.

3 Results

During the cruise, twelve grease ice samples were collected. The volumes of the grease ice samples varied between 11.2 dm^3 and 16 dm^3. The highest frazil ice weight percentage in the sample is calculated for MIZ2 at 22:10 h with 40 % frazil, the lowest at MIZ2 21:35 h with 16 % frazil. The large variation of the frazil ice concentrations at MIZ2 shows that the frazil ice is not equally distributed between the pancakes reflecting continuous spatial and temporal changes.
While the frazil ice concentration varies, the sample temperature is constant over all stations with - 1.90 °C and is practically not affected by the outside temperature, which varied between - 4.4 °C and - 18.9 °C. Wind speeds at the three stations range between Beaufort scale 2 to 4 and indicate that the remaining incident wave energy additionally sustained by the wind forcing introduces enough turbulence in the water for continued frazil ice production. This corresponds to the findings of Smedsrud (Smedsrud, 2011) in the Arctic region that a wind speed of 10 m/s is sufficient to form a 30 cm grease ice layer.
The salinity for the salt water drained from the grease ice sample only varies between 31 PSU and 36 PSU and a majority of the samples exhibiting 34 PSU, whereas the spread of the salinity value in frazil ice is between 8 PSU and 28 PSU. The salinity of frazil ice is less than that of water, as the salt is rejected from the ice during the freezing process and is, therefore, not incorporated into the ice crystal lattice. Nevertheless, the salt water salinity is nearly constant over all stations and is independent of the frazil salinity. It is inferred, that the water salinity is thus constant due to the dilution of the water, enhancing diffusion of salt with the ocean underneath.

https://doi.org/10.5194/tc-2020-362
Preprint. Discussion started: 6 January 2021

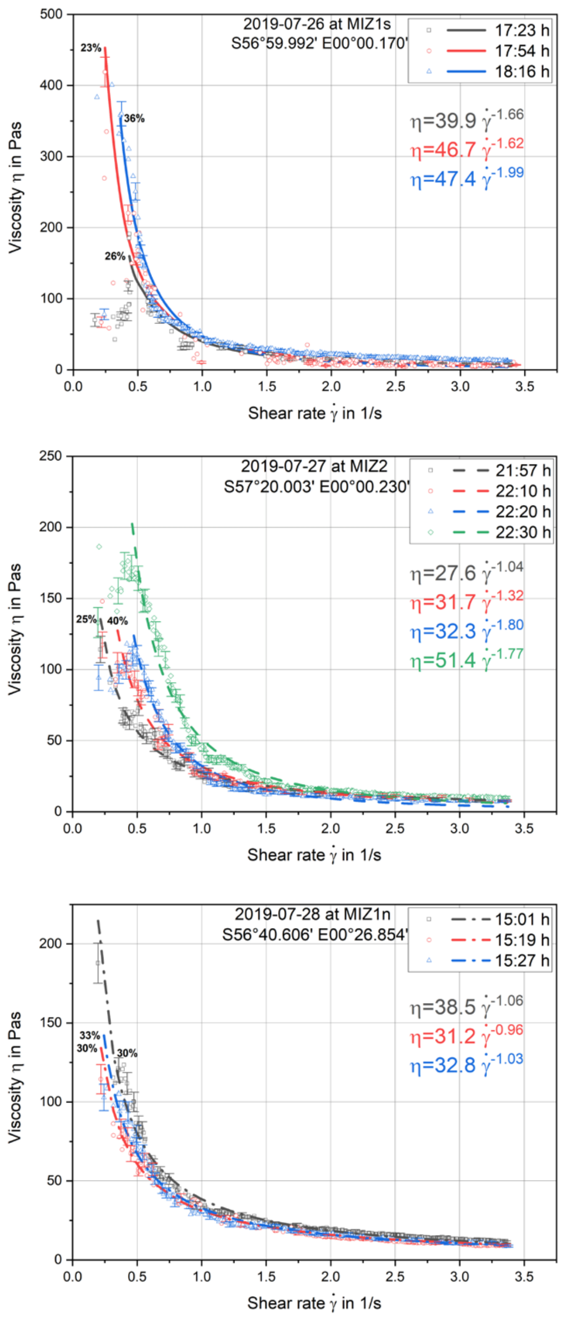

Figure 2 Viscosity at MIZ1s, MIZ2 and MIZ1n. The data set label equals the sampling time. The percentage of frazil ice in weight percent in the samples are given. The displayed error bars are valid for all data points in its vicinity.

https://doi.org/10.5194/tc-2020-362
Preprint. Discussion started: 6 January 2021

Figure 2 shows the viscosity of the three grease ice samples at MIZ1s, MIZ2 and MIZ1n. The curves are fitted with the Herschel-Bulkley model. The model can be simplified to the Ostwald de Waele model, with the flow coefficient k and the flow index n, following Equation 4.

$$\eta = k\dot{\gamma}^{n-1} \qquad 4$$

All curves in *Figure 2* show shear thinning behavior of the sample with $n < 1$. Calculated from the rotation velocity of the tests, 1/6th rotation of the vane (≙ 60°) is done after $6.66\ s$, i.e. at a shear rate of $0.67\frac{1}{s}$. The rotation by 1/6th of a full turn is important, because at this time all vanes are one position further than the starting position. After all bonds in the sample are broken, which is assumed to be the case after 1/6th rotation of the vane, the ice crystals rearrange and orientate themselves like other dispersions (Mezger, 2009). It is assumed that, after reorientation, mostly water is shearing in the gap between the rotating cylinder and the outer grease ice layer. This can also explain, why all graphs independent of the frazil ice concentration descend towards zero for higher shear rates. The highest viscosity at MIZ1s is shown in the curve for 18:16 h, this sample also had the highest percentage of frazil ice. The fitting curve at MIZ1s for 17:54 h lies above the fitting curve for 17:23 h, even though the percentage of frazil ice is lower for sample 17:54 h. This could imply that a higher frazil ice concentration leads to a slightly lower viscosity. This trend cannot be confirmed by the measurements at MIZ2 (*Figure 2*). The curve from 22:10 h with 40 % frazil ice overlaps with the curve of 21:57 h with 25 % frazil ice. The measurement from 17:23 h shows an increase in viscosity until the maximum at 121 Pas is reached. This can be explained by a short period of shear thickening, where the frazil ice particles friction against each other, which leads to a higher viscosity, before the shear thinning behavior sets in (Macosko, 1994). The samples from station MIZ1n show the same behavior as the samples from MIZ1s (*Figure 2*). The percentage of frazil ice in the sample is very similar for all three samples and, therefore, the viscosity values barely differ.

3 Discussion

Previous publications calculated the viscosity of grease ice or the viscosity of a frazil and pancake ice system by measuring wave propagation through laboratory tanks, by SAR images on a large scale in the Antarctic and a combination of buoy and SAR in the Arctic combining different scales. Newyear and Martin obtained a viscosity between 15 ± 0.3 Pas to 30 ± 0.6 Pas (Newyear, 1999), Wadhams et al. obtained a viscosity of 50 ± 1 Pas (Wadhams et al., 2006), Wang and Shen calculated a viscosity between 20 ± 0.4 Pas to 60 ± 1.2 Pas (Wang and Shen, 2010) and Zhao and Shen calculated the viscosity to be 14 ± 0.3 Pas (Zhao and Shen, 2015).

The viscosity calculated by Zhao and Shen (Zhao and Shen, 2015) is at the lower end of the range obtained in our measurements. This viscosity was measured at MIZ1s for shear rates greater than $2.00\frac{1}{s}$, at MIZ2 for shear rates greater than $1.40\frac{1}{s}$ and at MIZ1n for shear rates greater than $2.20\frac{1}{s}$. Therefore, data from the Winter Cruise agree with the findings by Zhao

https://doi.org/10.5194/tc-2020-362
Preprint. Discussion started: 6 January 2021

and Shen on the low viscosity end of our data (Zhao and Shen, 2015). The viscosity values obtained by Wang and Shen (Wang and Shen, 2010), Newyear and Martin (Newyear, 1999), Wadhams et al. (Wadhams et al., 2006) fit well with the data from our experiments. All stations showed viscosity values in this range between shear rates from $1.00\frac{1}{s}$ to $2.50\frac{1}{s}$. On the other hand, the data presented in this study suggest, that higher viscosities of up to 150 to 300 Pas can be reached when the shear rate, respectively the ocean, is calm.

In order to be able to judge whether the measurements with the rheometer and measurements in a wave tank on artificial sea ice can be compared, the differences between the methods must be highlighted. When measuring the viscosity with a rheometer, an initially undisturbed sample is analyzed by rotating the vane in the sample and recording the torque. The viscosity can then be calculated from the torque using proven formulas from other fields. During the rotation of the vane the internal structure of the frazil ice is rearranged. In contrast, for measurements in the wave tank the ice is assumed to be a layer on the water in which the internal structure is undisturbed. The measurement with a rheometer, therefore, also detects structural changes within the sample. A further advantage of measuring with a rheometer is that samples can be specifically selected. With the frazil ice sampler it was possible to collect samples between the pancakes and measure them afterwards. An eye was also kept on the correct scale of the measurement geometry and the frazil sampler. A smaller measuring device could have been blocked by ice chunks in the sample, larger measurements or other measuring methods always measure the influence of the pancakes on the viscosity. Despite the differences described, the measured viscosities are in the same range of values for the rheometer and measurements in wave tanks.

Shear thinning behavior obtained in the field mean that under light swell the sea ice acts more like consolidated or pack ice, comparable to a film on the water even though pancakes still drift freely in the ocean. Whereas under stormy conditions, the frazil ice between the pancakes is less viscous, allowing the pancakes to drift independently. It is also assumed, that the low viscosity under high shear rates supports the air-water interaction during storms enhancing the formation of new frazil ice.

4 Conclusion

This paper gives a brief overview on the importance of frazil and grease ice for the growth of Antarctic sea ice which plays a key role in global warming. In situ measurements for temperature, salinity and viscosity were conducted during the Winter Cruise 2019 and constitute the first data set on grease ice from the Antarctic MIZ ever taken in situ. Results are shown for three stations and twelve samples. Shear rate-dependent viscosity graphs were fitted. All samples show shear thinning behavior. The values from the Winter Cruise are compared to literature values, which were measured indirectly from wave propagation characteristics in laboratory showing good agreement. The shear thinning behavior observed in our experiments illustrates that viscosity values vary greatly between different weather conditions in the Antarctic making further frazil formation an easy scenario for highly perturbed surface waters while the global pancake field dynamics are dominated by lower shear rates exhibiting much higher viscosity values overall. Our dataset enables future modelling approaches to rely on a real data set of the grease ice viscosity from the Antarctic MIZ showing that two fundamentally different viscosity regimes must be considered in models. It may furthermore help to understand the sea ice growth dynamics in detail. This will improve the reliability of modelling and the understanding of the dynamics of the Antarctic MIZ on the small scale, as well as its implications on the larger scale dynamics and the annual freezing-thawing cycle in this remote part of the earth.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author on request.

Acknowledgements

The SCALE cruises are funded by the South African National Research Foundation (NRF) through the South African National Antarctic Programme (SANAP), with contributions from the Department of Science and Innovation and the Department of Environmental Affairs.

Author contribution

F. Paul and R. Audh carried out the experiments. F. Paul wrote the manuscript with support from D. C. Lupascu and E. Hepworth. T. Mielke designed the frazil sampler. J. Schröder and C. Nisters helped during the cruise and supervise the project. D. C. Lupascu, S. Skatulla, M. Vichi and T. Rampai conceived the original ideas. M. Vichi provided the opportunity for the cruise. D. C. Lupascu supervised the project.

References

Doble, M. J.: Pancake ice formation in the Weddell Sea, J. Geophys. Res., 108(C7), doi:10.1029/2002jc001373, 2003.

Eicken, H.: From the Microscopic, to the Macroscopic, to the Regional Scale: Growth, Microstructure and Properties of Sea Ice, in Sea Ice, pp. 22–81, Blackwell Science Ltd, Oxford, UK., 2003.

Kaleschke, L., Lüpkes, C., Vihma, T., Haarpaintner, J., Bochert, A., Hartmann, J. and Heygster, G.: SSM/I Sea Ice Remote Sensing for Mesoscale Ocean-Atmosphere Interaction Analysis, Can. J. Remote Sens., 27(5), 526–537, doi:10.1080/07038992.2001.10854892, 2001.

Lange, M. A., Ackley, S. F., Wadhams, P., Dieckmann, G. S. and Eicken, H.: Development of Sea Ice in the Weddell Sea, Ann. Glaciol., 12, 92–96, doi:10.1017/S0260305500007023, 1989.

Macosko, C. W.: Rheology: Principles, Measurements and Applications., 1994.

Maksym, T., Stammerjohn, S. E., Ackley, S. and Massom, R.: Antarctic sea ice- A polar opposite?, Oceanography, 25(3), 140–151, doi:10.5670/oceanog.2012.88, 2012.

McFarlane, V., Loewen, M. and Hicks, F.: Measurements of the evolution of frazil ice particle size distributions, Cold Reg. Sci. Technol., 120, 45–55, doi:10.1016/j.coldregions.2015.09.001, 2015.

Mezger, T.: Fittung functions for flow and viscosity curves, in The Rheology Handbook, pp. 59–64., 2009.

Newyear, K.: Comparison of laboratory data with a viscous two-layer model of wave propagation in grease ice, , 104, 7837–7840, 1999.

Rabault, J., Sutherland, G., Jensen, A., Christensen, K. H. and Marchenko, A.: Experiments on wave propagation in grease ice: Combined wave gauges and particle image velocimetry measurements, J. Fluid Mech., 864, 876–898, doi:10.1017/jfm.2019.16, 2019.

Rogers, W. E., Thomson, J., Shen, H. H., Doble, M. J., Wadhams, P. and Cheng, S.: Dissipation of wind waves by pancake and frazil ice in the autumn Beaufort Sea, J. Geophys. Res. Ocean., 121(11), 7991–8007, doi:10.1002/2016JC012251, 2016.

De Santi, F. and Olla, P.: Limit regimes of ice formation in turbulent supercooled water, Phys. Rev. E, 96(4), 1–11, doi:10.1103/PhysRevE.96.043106, 2017.

Smedsrud, L. H.: Grease-ice thickness parameterization, Ann. Glaciol., 52(57 PART 1), 77–82, doi:10.3189/172756411795931840, 2011.

Spreen, G., Kaleschke, L. and Heygster, G.: Sea ice remote sensing using AMSR-E 89-GHz channels, J. Geophys. Res., 113(C2), C02S03, doi:10.1029/2005JC003384, 2008.

Squire, V. A.: Past, present and impendent hydroelastic challenges in the polar and subpolar seas, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., 369(1947), 2813–2831, doi:10.1098/rsta.2011.0093, 2011.

Sutherland, G., Rabault, J., Christensen, K. H. and Jensen, A.: A two layer model for wave dissipation in sea ice, Appl. Ocean Res., 88(May), 111–118, doi:10.1016/j.apor.2019.03.023, 2019.

Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J. and Scott Hosking, J.: An initial assessment of antarctic sea ice extent in the CMIP5 models, J. Clim., 26(5), 1473–1484, doi:10.1175/JCLI-D-12-00068.1, 2013.

Wadhams, P., Parmiggiani, F. and De Carolis, G.: Wave dispersion by antarctic pancake ice from SAR images: A method for measuring ICE thickness, Eur. Sp. Agency, (Special Publ. ESA SP, (613), 2006.

Wang, R. and Shen, H. H.: Experimental study on surface wave propagating through a grease-pancake ice mixture, Cold Reg. Sci. Technol., 61(2–3), 90–96, doi:10.1016/j.coldregions.2010.01.011, 2010.

Zhao, X. and Shen, H. H.: Wave propagation in frazil/pancake, pancake, and fragmented ice covers, Cold Reg. Sci. Technol., 113, 71–80, doi:10.1016/j.coldregions.2015.02.007, 2015.