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Platelet ice, the Southern Ocean's hidden ice: a review

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Abstract

Basal melt of ice shelves is not only an important part of Antarctica's ice sheet mass budget, but it is also the origin of platelet ice, one of the most distinctive types of sea ice. In many coastal Antarctic regions, ice crystals form and grow in supercooled plumes of Ice Shelf Water. They usually rise towards the surface, becoming trapped under an ice shelf as marine ice or forming a semi-consolidated layer, known as the sub-ice platelet layer, below an overlying sea ice cover. In the latter, sea ice growth consolidates loose crystals to form incorporated platelet ice. These phenomena have numerous and profound impacts on the physical properties, biological processes and biogeochemical cycles associated with Antarctic fast ice: platelet ice contributes to sea ice mass balance and may indicate the extent of ice-shelf basal melting. It can also host a highly productive and uniquely adapted ecosystem. This paper clarifies the terminology and reviews platelet ice formation, observational methods as well as the geographical and seasonal occurrence of this ice type. The physical properties and ecological implications are presented in a way understandable for physicists and biologists alike, thereby providing the background for much needed interdisciplinary research on this topic.

1. Introduction

This paper tells the story of a most interesting form of sea ice, which many people may never have heard of. Platelet ice, as introduced in a schematic diagram in Figure 1 and in a collection of photos in Figure 2, is a very peculiar and unusual type of sea ice, which is most commonly found along the coast of Antarctica (Langhorne and others, 2015). Its presence results from an interaction between the ocean, ice shelves (floating extensions of the continental ice sheet) and immobile, landfast sea ice attached to the latter (Fraser and others, 2012). Its appearance has fascinated researchers ever since its first documented observation in McMurdo Sound during the Discovery Expedition of 1904–1905 (Hodgson, 1907). In contrast to regular sea ice, which initially forms and grows at the ocean surface by heat conduction to the atmosphere (Stefan, 1891), platelet ice originates from supercooling of sea water deeper in the water column, inside the ice-shelf cavity. There, basal ablation of the ice shelf cools and freshens the surrounding ocean water, which then becomes more buoyant, and ascends towards the surface. The accompanying pressure relief can cause this water to have a potential temperature below the in situ freezing point, a condition which is called in situ supercooling (Foldvik and Kvinge, 1974).

The first study to hypothesise that platelet ice forms through heat transport into the ocean was performed by Wright and Priestley (1922). Reporting on observations made during the British Terra Nova Antarctic Expedition 1910–1913, they were also the first to see the potential significance of this phenomenon, stating that '[…] later in the winter the sea ice grows to its great thickness of 8 and 9 feet largely by the deposition of frazil crystals[1] from below'. Although a number of processes exist which may lead to supercooling conditions in polar oceans (Martin, 1981; Jeffries and others, 1995; Mager and others, 2013), only specific patterns of thermohaline convection beneath an ice shelf are able to generate and maintain supercooling of sufficient strength, spatial extent and permanency to lead to substantial platelet-ice formation (Foldvik and Kvinge, 1977, see Section 3 of this paper). Although the early insight by Wright and Priestley (1922) was accurate, they did not fully grasp the profound consequences this phenomenon has on the local cryosphere and biosphere. More than 100 years and many publications later, it is still incredibly difficult even for scientists from the relevant disciplines to fully appreciate, let alone understand, all the effects and implications that accompany platelet ice.

One of the main reasons is that, although researchers from diverse backgrounds have looked at this phenomenon from various angles, the limited number of interdisciplinary studies has led to a highly ambiguous terminology (see Section 2). As a result, a comprehensive picture of platelet-ice properties as well as its geographical distribution has not yet been established, and a solid understanding of its role in both the local and global contexts is lacking. This is a significant gap in our otherwise emerging understanding of ice–ocean interaction,

[1]See Table 1 for the definition of frazil.

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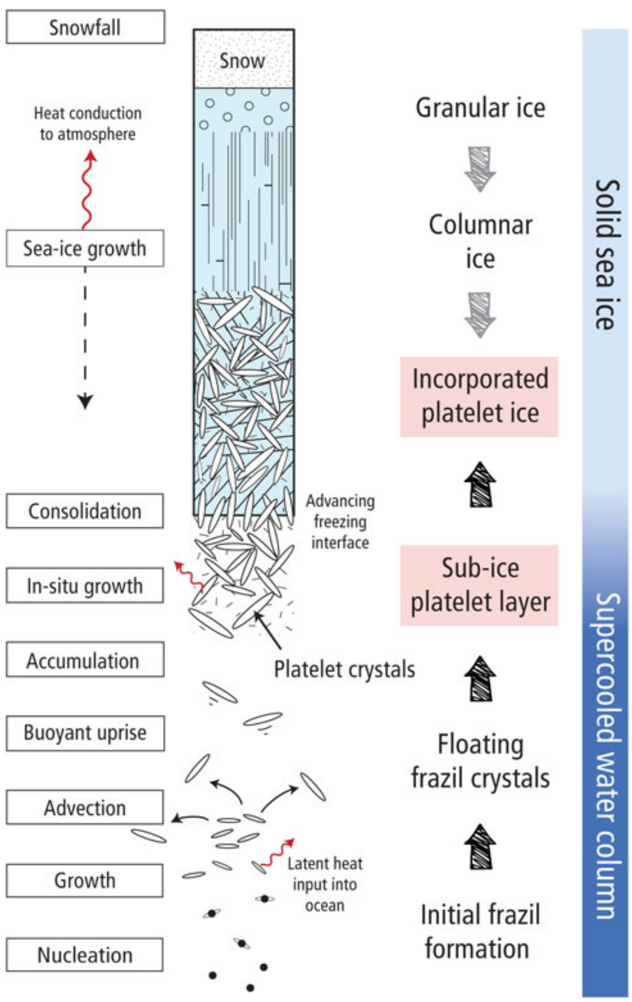

Fig. 1. Schematic illustration of an Antarctic sea-ice cover close to an ice shelf that was modified by platelet ice (not to scale). Initially, a granular ice cover forms from ice crystals at the sea surface, and grows to form columnar ice by heat transport to the atmosphere. At the same time, suspended frazil crystals also form in supercooled water at depth from a different process, which then are advected by currents, and eventually rise to the surface. The growing crystals accumulate into a porous network of disordered platelets, which constitute the sub-ice platelet layer. Throughout winter, the freezing interface advances into this layer, leading to a progressing consolidation and eventually forming incorporated platelet ice.

which this paper aims to fill. In the Conclusions (Section 9), we present a flow chart (Fig. 6) that attempts to illustrate all the involved processes, implications and interactions in one comprehensive figure, and that can be considered a graphical summary of this paper.

The term 'platelet ice' either refers to (1) loose accretions of individual ice crystals directly underneath drifting (Eicken and Lange, 1989) and landfast sea ice (e.g. Moretskii, 1965; Dayton and others, 1969; Cherepanov and Kozlovskiy, 1972; Gow and others, 1982; Arrigo and others, 1995; Robinson and others, 2014; Hoppmann and others, 2015b), or (2) the part of a solid sea-ice cover which has such crystals incorporated in its usually columnar fabric (e.g. Jeffries and Weeks, 1992; Jeffries and others, 1993; Gow and others, 1998; Tison and others, 1998). Refer to Section 2 for the exact definitions, and to Figure 2 for a collage of relevant images. Both forms come with its own specific consequences, which will all be described in the following. The occurrence of platelet ice in either its loose or consolidated form is limited to the Antarctic coast, in regions where cold-cavity ice shelves are present (Fig. 4, updated from Langhorne and others, 2015), and mostly associated with landfast sea ice. Although similar observations have sporadically been made in the Arctic (Jeffries and others, 1995; Kirillov and others, 2018), these were the result of different processes, such as refreezing melt ponds or the sudden release of snow meltwater.

Where present, platelet ice interacts with its surroundings in many ways (Fig. 6). Individual aspects of platelet ice and their impact on the local environment have been addressed in a number of studies from many different scientific disciplines, such as glaciology (e.g. Warren and others, 1993; Smith and others, 2001; Craven and others, 2009), oceanography (e.g. Leonard and others, 2011; Mahoney and others, 2011), geophysics (e.g. Hunkeler and others, 2016b), remote sensing (e.g. Price and others, 2014), numerical modelling (e.g. Dempsey and others, 2010; Wongpan and others, 2015), ecology (e.g. Arrigo and others, 1995; Günther and Dieckmann, 1999; Vacchi and others, 2012) and biogeochemistry (e.g. Günther and others, 1999b; Carnat and others, 2014), underlining its multi-faceted role. At the same time, the detection of its presence is very challenging due to its difficult-to-access location within or beneath a sea-ice cover. In particular, currently available observational techniques (Section 4) limit the determination of its extent, as well as its physical and biogeochemical properties.

The major aim of this review is to provide a comprehensive overview of the properties and implications of this extraordinary sea-ice type. In doing so, we try to consolidate our present understanding of this diverse topic in a way understandable for all relevant disciplines, hoping to facilitate and stimulate much needed multidisciplinary research.

Due to the challenges associated with the ambiguous terminology and the historical nature of some of the observations, a standard literature search did not yield a satisfactory overview. Instead, we scanned the reference lists of numerous papers from various disciplines, trying to identify as many relevant papers as possible. Although likely still not complete, one of the main outcomes of the current paper is the most comprehensive and extensive list of references dealing with the topic of platelet ice. In the following, we summarise what we consider the most relevant information from this collection.

We start with a clarification of the terminology (Section 2) which, on the initiative of the authors, will be included in the next update of the WMO Sea-Ice Nomenclature compiled by the JCOMM Expert Team on Sea Ice (2015). After reviewing in detail the formation process (Section 3), we introduce the most common observational and numerical techniques to investigate platelet ice (Section 4), before we build upon the work of Langhorne and others (2015) to give an overview of all published observations of platelet ice around Antarctica we are aware of to date (Section 5). After an extended discussion of the properties of platelet ice (Section 6), and how it interacts with its surroundings (Section 7), we speculate on the fate of platelet ice in a warming world (Section 8). We conclude this work with a synthesis of our findings, highlighting the major gaps and challenges that need to be addressed in the future (Section 9).

2. Terminology

The terminology related to ice formation and growth in supercooled water is extremely ambiguous, and to an extent, even chaotic. A lot of confusion arises from the fact that different disciplines use different terms for essentially the same type of ice, mainly as a result of their different methods and approaches. In addition to the use of entirely different terms such as 'underwater ice' (Moretskii, 1965; Cherepanov and Kozlovskiy, 1972, 1973; Kipfstuhl, 1991), there is particular inconsistency in the ways that the terms 'frazil ice', 'platelet ice', 'anchor ice' and even 'marine ice' are used in the literature, often interchangeably, as pointed out by Smith and others (1999) and Mager and others

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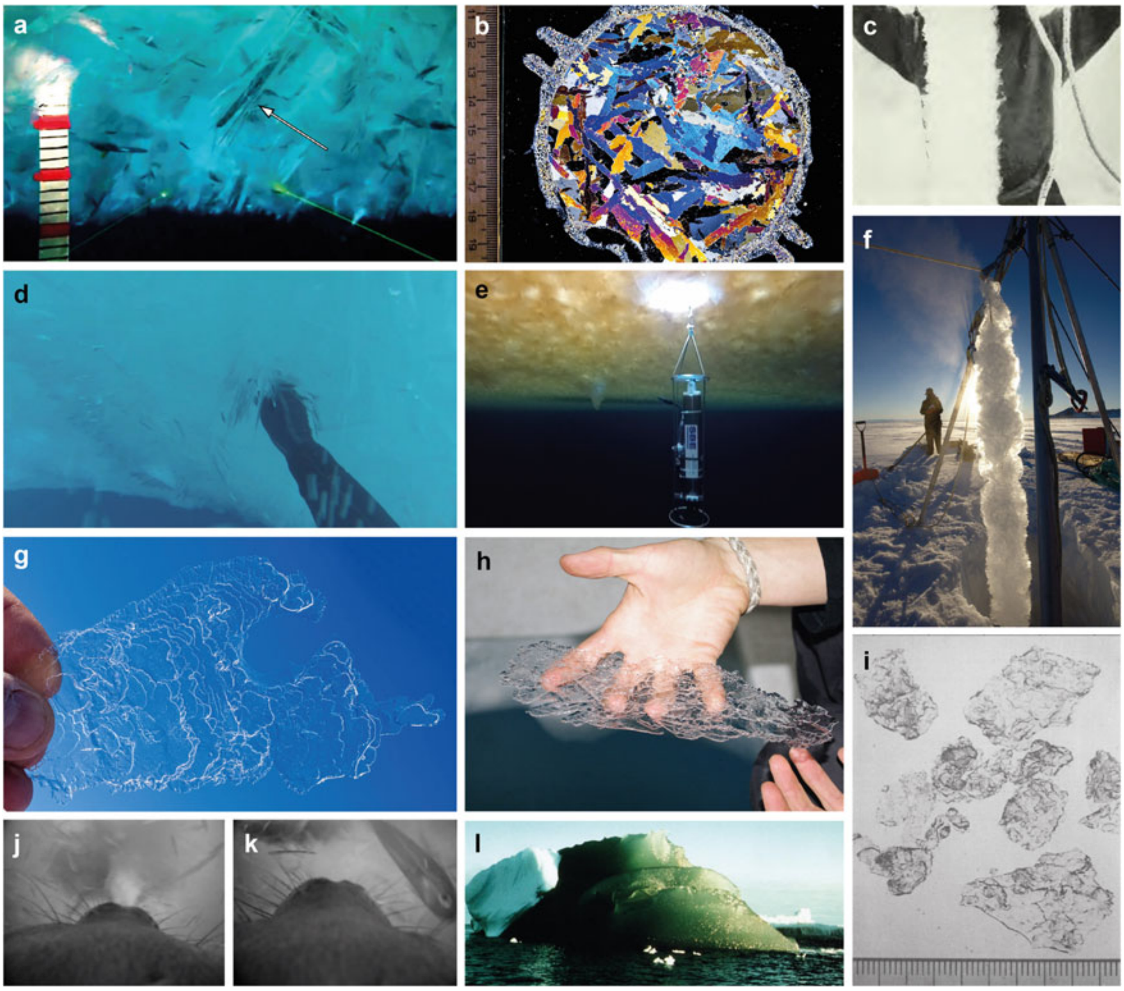

Fig. 2. Collage of platelet ice and associated ice types discussed in this paper: (a) view of sub-ice platelet layer (SIPL) by a camera with laser and ruler (Mahoney and others, 2011); (b) horizontal thin section showing incorporated platelet ice in Atka Bay; (c) the earliest published photo of ice on a rope (Wright and Priestley, 1922); (d) diver's hand reaching into SIPL in Atka Bay (Philipp Fischer, AWI); (e) oceanographic instrument lowered through SIPL in McMurdo Sound (2016 K066 team); (f) ice on rope in McMurdo Sound (Mahoney and others, 2011); (g, h) individual platelet crystals retrieved in Atka Bay (Mario Hoppmann) and McMurdo Sound (Craig Stevens, NIWA); (i) frazil crystals fished by net trawl in the Weddell Sea (Dieckmann and others, 1986); (j, k) fish escaping the SIPL after a seal blast (Davis and others, 1999); (l) green iceberg composed of marine ice (Kipfstuhl and others, 1992). The most extensive collection of video material so far can be found on the webpages and video channel of the McMurdo Oceanographic Observatory (MOO) that has been installed on the shallow seafloor in McMurdo Sound in late 2017 (Cziko, 2019).

(2013). To make it even more confusing, authors sometimes used different expressions for the same ice type in the same publication. As noted by Smith and others (1999), the term 'platelet ice' is often used at the same time to describe individual platelet crystals, their accumulations in layers and the structural component of solid sea ice modified by the incorporation of these crystals. Due to the profoundly different impacts and roles of these manifestations for the local systems it is urgently necessary to make a proper distinction.

To improve the communication and mutual understanding of the many involved disciplines, it is crucial to determine and adopt a unified nomenclature. Based on the most recently published literature (Mager and others, 2013; Langhorne and others, 2015; Smith and others, 2015; Hunkeler and others, 2016b), we recommend using the terms 'sub-ice platelet layer' for loose accretions of ice crystals under sea ice, 'incorporated platelet ice' for solid sea ice with platelet (ice) crystals incorporated in its fabric and use 'platelet ice' as a generic term only when a further specification is not deemed necessary. Small, individual ice crystals suspended in the water column continue to be referred to as 'frazil' in accordance with the existing definition from the JCOMM Expert Team on Sea Ice (2015), a term which has been used by the sea-ice community for decades. A future community discussion on possible changes to this rather general and ambiguous term would be useful. Instead, we suggest the term 'platelet crystals' for the individual crystals within either a sub-ice platelet layer or incorporated platelet ice (see Fig. 1 and Table 1).

As with every general definition, especially in the realm of sea ice, there are still some ambiguities and issues that remain unaccounted for: due to the lack of significant platelet-ice observations in the Arctic, we decided to introduce here a geographical limitation to the Antarctic. This may need to be revised in the future. Because of the impracticability of a distinction based on formation history, shape or size of individual crystals, another potential shortcoming is the lack of a distinction in the definition between frazil and a mobile sub-ice platelet layer. These shortcomings might (or should) change in the future. At this point however, we urge any authors to be particularly careful with these terms and stick to the proposed nomenclature especially for consistency reasons, until new knowledge has been obtained and any adjustment becomes necessary.

3. Platelet-ice formation in Antarctica

The usual process of sea-ice formation takes place at the ocean surface, when the colder atmosphere extracts heat from the

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Table 1. Definitions of the terminology used in this paper

Term	Definition	Additional information
Platelet ice	A type of sea ice that is formed in or modified by in situ supercooled Antarctic ISW. It can be further separated into a semi-consolidated form termed 'sub-ice platelet layer', and a consolidated form termed 'incorporated platelet ice'.	The term 'platelet ice' should be used to refer to both types, when a further distinction is not necessary.
Sub-ice platelet layer	A semi-consolidated, up to several metres thick layer of individual platelet (ice) crystals, which appear randomly oriented and reside at the underside of a solid sea-ice cover. The layer may be mobile or static.	See Figure 2a, d, e, j, k.
Incorporated platelet ice	Solid sea ice that results from a subsequent consolidation/freezing of the sub-ice platelet layer through thermal conduction to the atmosphere. Its texture is characterised by randomly oriented platelet crystals and it results in a much larger thickness of the local sea-ice cover.	See Figures 2b, 5.
Platelet crystals	The individual crystals within platelet ice.	See Figure 2g, h.
Frazil	Fine spicules or plates of ice, suspended in water.	Original definition from JCOMM Expert Team on Sea Ice (2015), Figure 2i.
Marine ice	Frozen sea water attached to the underside of ice shelves.	See Koch and others (2015), Figure 2l.
Anchor ice	Ice that is attached to, or anchored to, a substrate, e.g. the bed of a river or sea floor.	Adapted from JCOMM Expert Team on Sea Ice (2015). See Mager and others (2013).

On the authors' initiative, the definitions of 'platelet ice', 'sub-ice platelet layer', 'incorporated platelet ice' and 'platelet crystals' will be included in the updated version of the WMO Sea-Ice Nomenclature (JCOMM Expert Team on Sea Ice, 2015).

ocean surface (Stefan, 1891). In the polar oceans, sea ice may also form deeper in the water column, under conditions where the water becomes 'in situ supercooled', that is, colder than its freezing-point temperature (Martin, 1981; Daly, 1994; Mager and others, 2013). This process may occur in surface layers of leads and polynyas, at the interface between two fluid layers with different salinities, and, as reviewed in this paper, on a much larger scale in the water column adjacent to or below ice shelves (Martin, 1981). Approximately half of Antarctica's coastline is fringed by ice shelves (Fretwell and others, 2013). These are large, floating sheets of freshwater ice which extend hundreds of metres into the water column. Melting at the base of these ice shelves through contact with relatively warm water masses is a major contributor to Antarctica's ice-sheet mass budget (Pritchard and others, 2012; Depoorter and others, 2013; Rignot and others, 2013) and is a prerequisite for platelet-ice formation. In the following subsections, we will give a brief introduction to the physical processes involved in its formation. Additionally, a simplified scheme illustrating all the relevant components of this system, as well as their interlinkages, is presented in Fig. 3.

3.1 Melting or dissolving?

The ocean-driven, solid-to-liquid phase transition at the base of Antarctic ice shelves is dominated by either one of two different thermodynamic ablation processes: dissolving or melting (Woods, 1992). At ocean temperatures higher than the in situ seawater freezing temperature (∼−2.5°C at 800 m) and lower than the in situ freshwater ice melting point, ice is dissolved by the saline solute. The rate of ice loss is controlled by the supply of salt and heat to the ice–ocean interface, a process which is dominant at the deep grounding line of cold-cavity ice shelves. When the ocean is warmer than ∼−0.5°C at the surface (Wells and Worster, 2011), melting takes place; the ablation rate is controlled by heat transport to the ice–ocean interface only (e.g. at ice-shelf fronts in summer surface water). As the molecular diffusivity of salt is much smaller than the diffusivity of heat (mass diffusivity, $D \sim 5 \times 10^{-10}$ m^2 s^{-1}, while heat diffusivity, $\kappa \sim 10^{-7}$ m^2 s^{-1}), ablation by melting is of order $(\kappa/D)^{3/4} \sim 50$ times faster than by dissolving in environments of low turbulent kinetic energy (Woods, 1992; Kerr, 1994; Notz and others, 2003; Wells and Worster, 2011). However, throughout this paper we will omit the distinction between melting and dissolving. Instead, we use the terms 'melting' and 'ablation' interchangeably when referring to the phase change of ice to water.

3.2 How does Ice Shelf Water form?

Melting at the base of ice shelves can form Ice Shelf Water (ISW) (Jacobs and others, 1985), a water mass characterised by a potential temperature below the surface freezing point (called potential supercooling; Jacobs, 2004). ISW is part of a thermohaline convection mechanism under and in front of ice shelves (Foldvik and Kvinge, 1977; MacAyeal, 1984), that is also referred to as 'ice pump' (Section 3.5, Lewis and Perkin, 1986). Its presence is a necessary but not sufficient prerequisite for the formation of platelet ice (Mahoney and others, 2011).

3.3 How does High Salinity Shelf Water form?

Growing sea ice produces cold and saline surface water due to salt rejection during freezing. This process is enhanced in coastal polynyas, where an extensive air–water interface is maintained by seaward katabatic winds continuously driving the new sea ice offshore (Massom and others, 1998; Maqueda and others, 2004; Tamura and others, 2016). Polynyas are the main sources of such dense High Salinity Shelf Water (HSSW; Grumbine, 1991). Sufficient negative buoyancy by salt rejection at the ocean surface triggers deep convection that conveys HSSW to the ocean floor, where it either flows towards the continental shelf slope or into the cavities below ice shelves. Beneath many ice shelves, HSSW may penetrate as far as the grounding line several hundred metres below sea level (Nicholls and others, 2001). Since the convective and advective transfers are mainly adiabatic (without heat exchange), the potential temperature of HSSW remains close to the surface freezing point.

3.4 The three modes of ice-shelf melting

The freezing temperature of sea water decreases with increasing pressure and with increasing salinity (UNESCO, 1978; IOC and others, 2010). The HSSW temperature exceeds the in situ freezing point at depth by ∼1°C at 1300 m (Jacobs and others, 1992) and constitutes a heat source available for latent heat of melting. In places where local turbulence or molecular diffusion transports sufficient heat and salt to the ice–water interface, the ice shelf melts. Submarine melting of ice shelves can be grouped into three categories, or 'modes' (see Fig. 1 in Jacobs and others, 1992). The HSSW driven mechanism is termed Mode 1 ice-shelf melting, which dominates the deep basal melting near the grounding line (Jacobs and others, 1992). Mode 2 ice-shelf melting is associated with the inflow of relatively warm Circumpolar

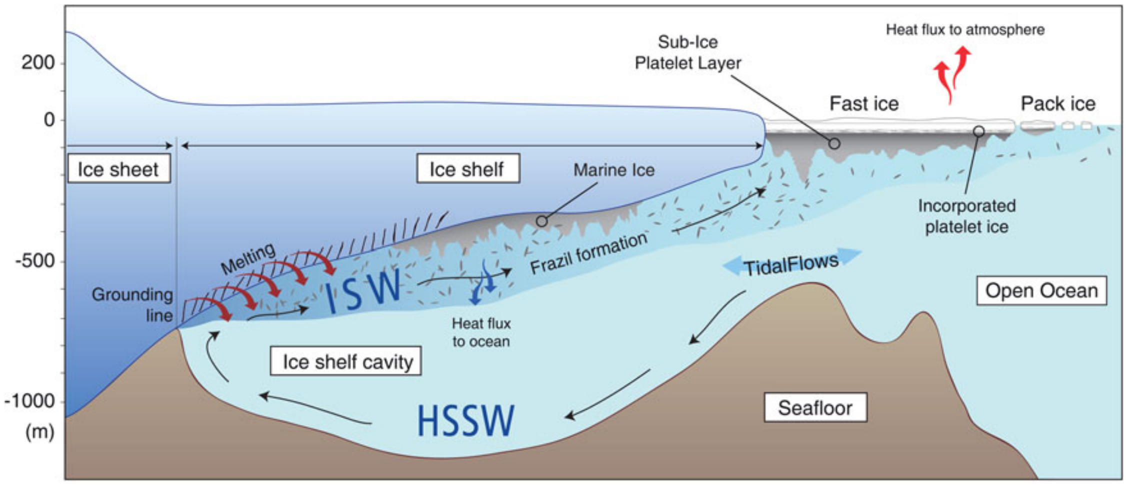

Fig. 3. Sketch of the ice pump process in an ice-shelf cavity. High Salinity Shelf Water (HSSW) enters the cavity and melts the base of the ice shelf. Basal melting leads to the formation of very cold, less saline Ice Shelf Water (ISW). The ISW rises, and the plume becomes in situ supercooled, as the freezing point depends on the pressure. Under these conditions, frazil crystals form in the water column. The crystals float upwards, where they may grow further. If they accumulate beneath the ice shelf, they are termed 'marine ice' (see Section 3.5), beneath the sea ice they are referred to as 'sub-ice platelet layer'. If they grow on parts of the shallow seafloor (not shown), they become 'anchor ice' (see Section 3.8). Graphic modified from Hughes (2013).

Deep Water (CDW; Jacobs and others, 1992). Mode 3 ice-shelf melting is associated with Summer Surface Water near the ice-shelf front (Jacobs and others, 1992) which may be transported under the ice shelf by tidal pumping (e.g. Makinson and Nicholls, 1999; Joughin and Padman, 2003; Malyarenko and others, 2019). Only Modes 1 and 3 ice-shelf melting are thought to lead to ISW formation and are thereby important for platelet-ice formation. This is because the CDW associated with Mode 2 melting is well above the surface freezing-point temperature (Jacobs and others, 1992).

3.5 ISW plumes and marine ice

As detailed above, basal melting can lead to ISW formation, characterised by cooling and freshening of the ambient water. As the water density at temperatures close to the freezing point mainly depends on salinity (UNESCO, 1981), freshening increases buoyancy, and the ISW plume rises along the basal slope of the ice shelf towards its front. The subsequent pressure release during the adiabatic ascent to shallower depths, together with the initial melt-induced freshening, raises the in situ freezing point of the plume. Therefore, when sufficient ascent and/or freshening occurs, the plume's freezing point can exceed its actual temperature, a condition termed in situ supercooling (Foldvik and Kvinge, 1974, 1977; Jacobs and others, 1985).

Thermodynamic re-adjustment leads to the release of latent heat by the generation of individual ice crystals in the plume (Jenkins and Bombosch, 1995; Smedsrud and Jenkins, 2004). However, the conditions under which nucleation occurs and frazil crystals are initially formed are still unclear. The growing ice crystals mixed with the sea water further increase the plume's buoyancy. This accelerates the ascent of water parcels along the ice slope, speeding up the pressure release (Jordan and others, 2015) and enhancing small-scale turbulent and diffusive processes. Theoretical considerations suggest a range of conceivable plume behaviours depending on the sensitive balance between crystal nucleation and precipitation, which itself is a function of growth rate (Rees Jones and Wells, 2018, 2015):

(1) Under conditions of near neutral crystal suspension and low growth rates, ascending water parcels sustain the increased buoyancy and may exit the cavity at shallower depths.
(2) Plumes under conditions where precipitation dominates experience an increase in bulk density. Arriving at the state of neutral buoyancy inevitably suppresses the generation of supercooling and associated frazil formation. Plumes could detach from the ice base and leave the cavity at depth, as observed near the front of the Ross Ice Shelf (Jacobs and others, 1979, 1985; Jacobs and Giulivi, 1999).
(3) At faster growth rates, precipitation is more likely and crystals accumulate at the base of ice shelves (Rees Jones and Wells, 2018) as evident in observations (e.g. Fricker and others, 2001; Craven and others, 2009; Kulessa and others, 2014; Koch and others, 2015).

Such marine ice layers have been observed beneath several Antarctic ice shelves (e.g. Gow and Epstein, 1972; Morgan, 1972; Zotikov and others, 1980; Oerter and others, 1992; Eicken and others, 1994; Tison and others, 1998; Craven and others, 2009), and contribute to the stability of ice shelves by counteracting basal melting and closing basal crevasses, thus retarding calving events (Kulessa and others, 2014). The overall process of ice-shelf melt and marine ice formation was termed 'ice pump' by Lewis and Perkin (1986), which in general terms describes a heat engine melting ice at some depth in the ocean and depositing it at a shallower location (Robin, 1979; Lewis and Perkin, 1983). Substantial evidence has been found that compacted marine ice is also the origin of occasionally observed green icebergs around Antarctica (Dieckmann and others, 1987; Kipfstuhl and others, 1992, Fig. 2l), whose green colour is attributed to marine-derived organic matter included in the ice (Warren and others, 1993), or, according to a more recent study, to iron-oxide minerals (Warren and others, 2019).

3.6 Frazil crystals outside of the cavity

Generally, an ISW plume will continue to rise until it either loses its characteristic properties through mixing with other water masses, reaches a depth of neutral buoyancy or arrives at the ocean surface in front of an ice shelf. Clouds of frazil crystals suspended in supercooled ISW plumes at depth near ice-shelf cavities have been detected by acoustic methods (Penrose and others, 1994) and retrieved by net hauls (Dieckmann and others, 1986). The dependence of frazil concentration on supercooling is

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well known (Tsang and Hanley, 1985), while the properties of frazil crystals and its occurrence are extensively reviewed in Daly (1984, 1994). However, the only published studies we are aware of that successfully measured the size distribution, shape and concentration of frazil crystals were conducted in fresh water, primarily in rivers (e.g. Ghobrial and others, 2013; Marko and others, 2015; McFarlane and others, 2017) or in the lab (e.g. Marko and Topham, 2015).

3.7 Supercooling, platelet ice and sea ice

Frazil crystals that are advected out of ice-shelf cavities may eventually rise to the surface by their own individual buoyancy if they are not melted by overlying warmer water masses. Depending on where frazil crystals aggregate and grow, they interact differently with their surroundings, and have therefore been given distinct names. When accumulating underneath a solid sea-ice cover, crystals may form a semi-consolidated sub-ice platelet layer (Dayton and others, 1969; Gow and others, 1982; Crocker and Wadhams, 1989; Gough and others, 2012b). If an in situ supercooled plume of ISW reaches the ocean surface (Hughes and others, 2014), crystals in such accumulations grow further (Leonard and others, 2006, 2011; Dempsey and others, 2010; Smith and others, 2012). Atmosphere driven heat extraction through the solid sea ice above freezes the water in the interstices between the individual crystals, leading to a downward progressing consolidation in the upper portions of the platelet layer, and ultimately to the platelets being incorporated into the growing sea-ice fabric (Dayton and others, 1969; Jeffries and others, 1993; Gow and others, 1998; Smith and others, 2001). This layer is called ‘incorporated platelet ice’ (Smith and others, 2001) and has a distinct sea-ice crystal structure (e.g. Serikov, 1963; Eicken and Lange, 1989; Jeffries and others, 1993; Tison and others, 1998), which reflects the properties of the surface ocean during freezing (Gough and others, 2012b; Langhorne and others, 2015). The presence and persistence of a sub-ice platelet layer depends on the ratio between the flux of platelet crystals from below, and the growth rate of the overlying sea ice (Dempsey and others, 2010; Mahoney and others, 2011; Gough and others, 2012b). Sea ice, mechanically strengthened by layers of incorporated platelet ice, can buttress and stabilise isolated ice tongues against neighbouring coastlines, and thus allow ice shelves to form outside of embayments (see Section 7; Hulbe and others, 2005; Massom and others, 2010).

3.8 Anchor ice

Another sibling of platelet ice is anchor ice. It describes ice crystals covering the seafloor (Dayton and others, 1969; Mager and others, 2013). The continued presence of supercooled water allows these initial ice crystals to grow rapidly (Osterkamp and Gosink, 1984) and form delicate, leaf-like ice structures that clump together (Kempema and others, 1993). This results in a patchy covering of ice that provides a lair for some benthic species, though it is also a potentially fatal environment for shallow water benthic communities (Dayton and others, 1969; Dayton, 1989; Denny and others, 2011). These ice clusters can grow large enough to become buoyant and detach from the sea floor, lifting any adhered sediment, flora, fauna or scientific equipment into the overlying ice (Dayton and others, 1969; Hunt and others, 2003). See Mager and others (2013) for a review of anchor ice. Related to this effect and to platelet-ice formation, any ropes or instrumentation immersed into in situ supercooled water can also have ice form on them (Figs 2c and f), leading to measurement errors or instrument failures (Robinson and others, 2020).

4. Observational and numerical techniques

One of the main reasons why knowledge of platelet ice is so sparse is the challenge of obtaining in situ observations. The first obstacle to overcome is gaining access to coastal Antarctic sea ice, which is usually only possible from the few land-based stations close to the coast. In summertime, when icebreakers are able to get near the shoreline to supply Antarctic stations, the fast ice has usually either broken up, or the sub-ice platelet layers beneath it have already melted due to warm water inflow. Even after the coastal fast ice has been accessed, the presence of platelet ice is generally not immediately evident. Although there are a number of general approaches to determine regular sea-ice thickness (Haas and Druckenmiller, 2009), there are fewer direct and indirect techniques of obtaining in situ and remote observations of sub-ice platelet layers, and only one technique to determine the fraction of incorporated platelet ice. In the following, we divide these field techniques into ice-based, ocean-based and remote-sensing methods, based on where they are applied. We do not cover specific laboratory-based experimental investigations of platelet ice, as there have been very few of these due to the challenges of duplicating such a complex system in a laboratory (see e.g. Smith and others, 2002). We also give a short overview of numerical techniques related to platelet-ice formation.

4.1 Ice-based measurements

Ice-based measurements have been used since the turn of the 20th century. They allow in situ observations and their relatively low operation costs (compared to techniques relying on aircraft or vessels) make them popular to this day. Most methods do however suffer from low spatio-temporal resolution, and all rely on ice conditions that are safe for on ice travel. Thus, observations of platelet ice during initial freeze-up or during spring time melt are rare and observations are often restricted to fast ice.

4.1.1 Drilling, thickness tapes and hot wires

The most direct and straightforward way to measure the thickness of sea ice in general, and the sub-ice platelet layer in particular, is by drilling holes into the sea ice. Sea ice can be drilled and cored with fairly simple and lightweight hand-powered equipment. A description of standard drilling equipment and field handling is found in Rand and Mellor (1985) and Haas and Druckenmiller (2009), while a detailed guide to thickness measurements using tapes and hot wires is given in Mahoney and Gearheard (2008). After a hole has been drilled through the ice, a thickness tape with a heavy metal bar (needed to penetrate the sub-ice platelet layer, if present) is lowered through the hole. Upon leaving the drillhole, the bar is pulled to the horizontal and catches at the bottom of the ice when the tape is pulled upwards (Mahoney and Gearheard, 2008; Haas and Druckenmiller, 2009). To measure the thickness of the sub-ice platelet layer, the point where the first resistance to pulling is felt is noted as the lower boundary. The bar is then pulled upwards through the loose platelet crystals until it reaches the lower boundary of the consolidated ice, which is the upper boundary of the sub-ice platelet layer (Gough and others, 2012b). Since the point at which resistance is first felt is somewhat subjective, this method can be ‘calibrated’ against camera footage if available, to get a better feeling for accuracy and precision (Gough and others, 2012b). The measurement is complicated by the rather undefined platelet layer bottom, to the point where just individual crystals are suspended in the water. To measure sea-ice thickness over a longer period of time without the need to drill and re-drill access holes, the hot wire method can be used (Untersteiner, 1961; Mahoney and others, 2009). A weighted wire is lowered through an access hole and allowed to freeze in. A ground wire is allowed to freeze in a second hole close by. Both wires extend into the ocean. By applying an electrical current to the wires, they heat up and melt the surrounding ice. The weighted wire can then be pulled upwards until the weight catches at the underside of the ice. The amount of wire pulled up is measured, and the sea ice and sub-ice platelet layer thickness thus determined, before lowering the weight back to its original position. Problems with these methods include the weight getting stuck in the platelet layer when lowering the tape or wire back through the hole, and platelet ice forming on the suspended wire (Gough and others, 2012b). The latter impacts the measured sub-ice platelet layer thickness, but not the measured thickness of the consolidated ice (Gough and others, 2012b). Both thickness measurements with a thickness tape and with the hot wire method have the advantage of being inexpensive and easy to perform, allowing them to be used by non-experts (Mahoney and Gearheard, 2008; Mahoney and others, 2009). However, both methods are time-consuming and not suitable for obtaining measurements at a high spatio-temporal resolution.

4.1.2 Thermistor chains

Thermistor chains are strings of temperature sensors which are lowered through an access hole in the ice and allowed to freeze in. They provide time series measurements of the temperature within the ice and of the water column beneath it, which can be used to calculate conductive heat fluxes and thermal conductivity (Trodahl and others, 2000). The resulting energy budgets can be used to determine the amount of freezing due to heat loss to the atmosphere or to the ocean (Trodahl and others, 2000; Smith and others, 2012). Additionally, they can be used to infer the thickness evolution of the sea ice by examining when successive thermistors freeze in (Smith and others, 2012; Hoppmann and others, 2015a). Different designs exist, with thermistors either housed in a metal tube filled with oil (Trodahl and others, 2000; Smith and others, 2012), mounted on a PVC rod (Perovich and Elder, 2001; Richter-Menge and others, 2006) or mounted on a polycarbonate support (Pringle and others, 2007; Gough and others, 2012b). Newer designs feature digital temperature chips linked by flexible printed circuit boards, allowing probes up to 10 m length to be built (Zuo and others, 2018). A modified form of a thermistor chain was designed by Jackson and others (2013), which is cheaper than standard ice mass-balance buoys (Richter-Menge and others, 2006) since it does not depend on acoustic instruments to detect interfaces. Instead, resistors in the chain can be heated and the air, snow, consolidated ice, sub-ice platelet layer and ocean can be distinguished by differences in their thermal conductivity (Jackson and others, 2013). Hoppmann and others (2015a) also used this feature to calculate the basal energy budget and infer the ice volume fraction in the sub-ice platelet layer.

The sea-ice thickness that can be monitored is limited by the length of the chain, which is typically between 2 and 5 m (Smith and others, 2012; Hoppmann and others, 2015a; Zuo and others, 2018). Longer chains experience stronger shear strain from currents under the ice and are thus more prone to instrument failure. It is not clear if the ice forming in the drillhole surrounding the thermistor chain has different properties from the ambient ice and how this may affect temperature and heat conduction measurements (Trodahl and others, 2000). Furthermore, the thermistor probe itself acts as a heat conductor (Trodahl and others, 2000). The part of the hole which lies above sea level (the ice freeboard) usually does not refreeze, which needs to be taken into account. In addition, uncertainties in the measurements of platelet-layer thickness may result from ice forming on the chain. Thermistor chains offer a depth resolution dependent on the spacing of the thermistors and a quasi-continuous temporal resolution of sea-ice temperature and thickness. Due to the high temporal resolution, relatively low cost of operation and ease of deployment, thermistor chains have been a standard monitoring instrument for many years and continue to be so to this day, providing valuable long-term time series.

4.1.3 Coring and thin sectioning for incorporated platelet ice

The only reliable method currently available to measure the fraction of the incorporated platelet ice in the ice cover is to take a sea-ice core. The stratigraphy of that core can be analysed from thick and thin sections (Eicken and Lange, 1989; Jeffries and Weeks, 1992; Jeffries and others, 1993; Tison and others, 1998). The drilling action and subsequent removal of the core from the hole may dislodge an unknown amount of unconsolidated platelets from the bottom of the core, making any thickness measurement of the sub-ice platelet layer a minimum estimate. Thin sections of sea-ice cores can be routinely taken to investigate sea-ice crystal structure by determining *c*-axis orientation of the individual crystals (Fig. 5). The distribution of the *c*-axis orientation differs significantly between columnar and incorporated platelet ice. Standard procedures for both field and lab-based analysis of *c*-axis distribution are described in Langway (1959).

There are some automated methods for analysing thin sections using fabric analysers and dedicated software packages (e.g. Eicken, 1993; Wang and Azuma, 1999; Wilson and Sim, 2002; Wilson and Peternell, 2011). Other methods of analysing crystal orientation in ice include X-ray diffraction (e.g. Owston, 1958; Wenk, 2000; Miyamoto and others, 2005, 2011), with application to incorporated platelet ice in Obbard and others (2016), and electron backscatter diffraction (EBSD; e.g. Iliescu and others, 2004; Prior and others, 2015; Wongpan and others, 2018c). The method suffers from the same spatio-temporal limitations as the other methods dependent on drilling, and further requires either a cold-lab close to the study site or temperature controlled shipment to a lab equipped with the necessary instruments, some of which are expensive.

4.1.4 Ground-based EM

Electromagnetic (EM) induction utilises the difference in electrical properties, particularly conductivity, between sea ice (Morey and others, 1984) and ocean water to calculate sea-ice thickness using a single layer model (e.g. Haas and others, 1997). The sub-ice platelet layer under sea ice has a mean volumetric salinity between that of sea ice and ocean water, acting as a second layer in the system. The return signal is difficult to interpret as the salinities, and thus the electromagnetic properties, of columnar ice and the sub-ice platelet layer do not differ as strongly as columnar ice from sea water.

Generally, single-frequency EM techniques either overestimate the thickness of the consolidated sea ice (Rack and others, 2013) or underestimate the total sea-ice thickness (consolidated and sub-ice platelet layer, Hunkeler and others, 2015). An approach using an inverse model and assuming three homogeneous layers (columnar ice, the sub-ice platelet layer and sea water) to interpret the response from a multi-frequency EM instrument is described in Hunkeler and others (2015, 2016b). The resulting sub-ice platelet layer thickness depends on the ice volume fraction, the grain shape and the pore geometry in the layer, all of which are poorly constrained (Hunkeler and others, 2015). A three layer model has also been applied in the case of a single-frequency device by optimising a forward model of the in-phase and quadrature components of the signal (Brett and others, 2020). The thickness of the sub-ice platelet layer is the principal output, subject to the uncertainty in ice volume fraction. In theory, snow cover on the ice needs to be regarded as a fourth layer, though to our knowledge no studies exist using four layer models.

Ground-based EM induction systems can be stationary, for example in ice mass-balance stations, or towed. The former gives higher temporal resolution, the latter higher spatial resolution. Stationary EM stations can produce errors by disturbing the snow drift at the measurement site (personal communication from G. Leonard, 2019). All EM systems have a lower accuracy in shallow ocean environments (Haas, 2006) and trade-offs must be made between resolution, penetration depth and signal-to-noise ratio (Haas, 2006). It has to be kept in mind that EM systems do not produce point measurements but average over a footprint, the size of which depends on frequency, EM configuration and distance to the air–ice and ice–ocean interface (Reid and others, 2006; Pfaffling and others, 2007). A great advantage of EM induction sounding is that it is a non-invasive method of measuring sea-ice thickness.

4.1.5 Oxygen isotopes ($\delta^{18}O$)

The isotopic composition of sea ice depends mainly on two factors: on the isotopic composition of the water from which it is formed, and on the growth rate of the ice (Souchez and others, 1987, 1988; Eicken, 1998). Sea ice is enriched in $\delta^{18}O$ compared to the water it forms from and depleted in salt. This effect weakens with increasing sea-ice growth rate. No agreed protocol exists for the preparation of sea-ice samples for the analysis of stable isotopes oxygen-18 and deuterium (Smith and others, 2012). To obtain a depth profile of isotope measurements, sea-ice cores are sliced horizontally, with each resulting sample stored in an airtight container and allowed to melt at room temperature. The resulting meltwater is poured into glass bottles and sealed for air-tightness. The liquid samples are then transported to a lab for isotope measurements. Full details of the procedure are given in Smith and others (2012). Samples can be analysed with dual-inlet, continuous flow or cavity ring-down laser mass spectrometers, but these systems differ in precision to each other with the dual-inlet giving a higher precision than the continuous flow mass spectrometers (Toyota and others, 2013). Isotope measurements on platelet crystals from the sub-ice platelet layer pose particular issues because of the likelihood that a thin film of sea water freezing on each platelet-ice crystal will alter the results of the value attributed to the single crystal. Although attempts have been made to examine the differences between methods for preparing bulk and single platelet crystals for isotope analysis (personal communication from Natalie Robinson, by email, 2010), to our knowledge nothing has been published on these methods so far.

The relationship between freezing rate, $\delta^{18}O$ and bulk salinity (Tison and others, 1998) was used to model growth rates as a function of sea-ice $\delta^{18}O$ values relative to the $\delta^{18}O$ value of the sea water from which it formed (Eicken, 1998). Several modifications of this model exist, attempting to account for glacial meltwater in ISW, the high growth rate of platelet ice compared to columnar ice (Smith and others, 2012) and the possible regime shift in fractionation between low and high growth rates (Toyota and others, 2013).

4.2 Ocean-based measurements

4.2.1 Water sampling

The space between the individual crystals within the porous sub-ice platelet layer is filled with sea water, usually referred to as pore water or interstitial water. Although a myriad of methods exist to obtain samples for the biogeochemical studies of sea ice (Miller and others, 2015), obtaining water samples from the interstices between the platelet crystals is not easily possible, especially not without significantly disturbing the system. A potential solution was presented by Dieckmann and others (1992), who developed a promising device for high-resolution under-ice sampling that can be lowered through a core hole in the ice to sample the unconsolidated platelet layer. It is essentially an array of small tubes guided through a plastic pipe that can be inserted into the platelet layer to simultaneously obtain samples of interstitial water at different depths. It was successfully utilised by Arrigo and others (1995) and Robinson and others (1998) to study the biogeochemistry and photophysiology of the platelet-ice community (Miller and others, 2015). Despite its simple and low-cost design, this technique has however not been utilised widely.

4.2.2 Acoustics

Acoustic Doppler Current Profilers (ADCPs) are a standard oceanographic instrument to measure ocean velocities. They also record backscatter intensity, which is related to the size and concentration of scatterers in the water column, though it is difficult to distinguish between the two (and impossible for single-frequency instruments; Gartner, 2004). The measured backscatter intensity is related to particle concentration and size by using empirically derived regression models (e.g. Ghobrial and others, 2012) or theoretical backscatter models. These depend on particle size, shape and material properties and the accuracy of the sonar, all of which may not be well constrained (Ghobrial and others, 2013). The same principles and caveats apply to ice-profiling sonars (IPSs), which can be used to monitor sea-ice draft and frazil ice in the water column (Ito and others, 2015). As far as we are aware, Ito and others (2015), who observed supercooling and increased backscatter in an Arctic polynya, remains the only study to have linked IPS backscatter to frazil ice presence in the ocean. The same principle, linking backscatter occurring simultaneously with supercooling and platelet-ice formation to the presence of frazil in the water column, was used by Leonard and others (2006) to interpret ADCP data. However, both with IPSs and ADCPs, care must be taken not to interpret vertical migration of zooplankton or tidal advection of particulate matter as changes in the supercooling and frazil ice regime (Leonard and others, 2006). Furthermore, difficulties arise due to backscatter from particles other than frazil ice (Marko and others, 2015) and ice build-up on the instruments (e.g. Leonard and others, 2006).

There have been efforts to measure particle concentration and size distribution of suspended frazil in the laboratory (Ghobrial and others, 2012; Marko and Topham, 2015) and in rivers (e.g. Morse and Richard, 2009; Ghobrial and others, 2013; Marko and others, 2015) using single-, two- and multi-frequency backscatter, respectively, but to our knowledge no such measurements have been published for sea water. The exception is the study of Purdie (2012), in which the authors were able to calculate estimates of particle mass and concentration from single-frequency backscatter, but not size.

Although the spatial resolution of IPS and ADCP measurements is low, they can offer very high temporal resolution. The length of the record depends on the deployment technique. Instruments moored to the sea ice or deployed through an access hole (e.g. Leonard and others, 2006; Mahoney and others, 2011; Stevens and others, 2014) can only be deployed and recovered from sea ice that is sufficiently stable, whereas floating buoys and instruments moored on the sea bed (e.g. Ito and others, 2015) can be deployed from a vessel, during low or absent sea-ice cover, thereby giving information during freeze-up and melt. Bottom-mounted ADCPs and IPSs can monitor the water column below and the underside of drifting ice (Eulerian view), whereas instruments moored to the sea ice will move with the ice (Lagrangian view). IPSs and ADCPs are both expensive and the analysis of the data complicated. At present, the most reliable ice information from both instruments is total sea-ice draft (including the sub-ice platelet layer) and the presence of frazil in the water column. A recent approach to map sea-ice draft and roughness at high resolutions used a phase measuring bathymetric sonar mounted on an autonomous underwater vehicle (AUV) (1 m and 5 cm respectively; Lucieer and others, 2016). The sea-ice roughness was successfully related to sub-ice platelet layer presence. This method is able to retrieve information on the underside of the sea ice over large areas, though the deployment of AUVs is costly (see Section 4.2.4 on more information on AUVs) and the processing of bathymetric sonar data is complicated.

4.2.3 Cameras

Independent of the particular method that is used to detect or measure the properties of sub-ice platelet layers, it is always useful to also co-deploy underwater cameras to gain a visual impression of the subject in focus (see e.g. Fig. 2a). From simple waterproof action cameras to pipe- or sewage cameras to complex, high-tech camera systems, any camera can give additional value to other measurements. Camera systems can be used to position instruments relative to the bottom of the sub-ice platelet layer (Smith and others, 2001). Leonard and others (2006) and Smith and others (2012) used still images from a video camera, positioned such that it viewed a platelet crystal at the bottom of the sub-ice platelet layer in front of a ruler, to measure growth rates of that crystal. Cameras can also be used to estimate frazil crystal size (Gough and others, 2012b), and their temporal occurrence (Hoppmann and others, 2015b). By using cross-polarised filters, frazil crystal size distributions and the fraction of disk shaped crystals can be measured (McFarlane and others, 2017), though no such measurements exist for marine settings.

As far as we are aware, no dedicated studies exist which employ cameras mounted on marine mammals to map sub-ice platelet layer presence, although the sub-ice platelet layer can occasionally be seen in video footage from such mammals (Davis and others, 1999; Figs 2j and k). Studies employing cameras mounted on AUVs or remotely operated vehicles (ROVs) would be more useful, and are described below.

Ice algae concentrations can be studied using camera systems operating in the visible or hyperspectral range (Cimoli and others, 2017) as well as by measuring the irradiance under sea ice (Fritsen and others, 2011; Wongpan and others, 2018b). Positioning instruments such as cameras in supercooled water incurs the risk of ice build-up on the instrument (as seen in Figs 2c and f) and as with all drillhole-based measurements, spatio-temporal resolution is low. Additionally, cameras cannot measure sub-ice platelet layer thickness, unless they are combined with some sort of measurement stick or ruler (see Fig. 2a). The advantage of cameras is that they can examine the sub-ice platelet layer, and especially individual crystals, virtually undisturbed. In late 2017, the McMurdo Oceanographic Observatory (MOO) was installed 21 m below the sea ice of McMurdo Sound, consisting of a live-streaming HD video camera that can point and zoom in all directions. Including cameras operated by divers, this project has created a wealth of underwater footage and currently represents (to our knowledge) the most extensive collection of openly accessible material (Cziko, 2019).

4.2.4 Robotic vehicles

Robotic vehicles such as ROVs and AUVs have a higher spatial and temporal range than sampling for sub-ice platelets by drilling or using divers. However, none of these vehicles can detect incorporated platelet-ice or sub-ice platelet layer thickness, but platelet layer presence and floating frazil crystals may be detected using upward looking camera systems (Spears and others, 2016) or sonars (Lucieer and others, 2016). On-board acoustic sensors, such as ADCPs, could be used to detect frazil in the water column. Furthermore, supercooling can be investigated using an on-board CTD system (Nelson and others, 2017), though not all currently integrated CTD systems have a high enough resolution to do this reliably.

There exists a wide variety of robotic vehicles that have been successfully deployed in ice-covered environments (see e.g. Spears and others, 2016, for an overview of some of these systems). Gliders are AUVs that vary their buoyancy to produce forward propulsion and can travel under sea ice (Asper and others, 2011). However, without access to the surface, the glider position can only be estimated. This means that, although gliders can detect potential or in situ supercooling in the water column under sea ice or ice shelves, this information cannot be linked to a precise enough location (Nelson and others, 2017). Different methods to improve under-ice navigation exist (Leonard and Bahr, 2016) and are included in some systems (Webster and others, 2014), but the only deployments to date beneath ice shelves using navigation are beneath the Dotson Ice Shelf where there was little-to-no in situ supercooling observed (personal communication from Pierre Dutrieux by email, 2019). ROVs rely on a tether for communication and power supply and are thus limited in range compared to AUVs.

A problem common to all vehicles is the high risk of loss should ice form on or in the instrument itself, as well as a large number of other causes (e.g. Strutt, 2006). Vehicles relying on buoyancy for forward or vertical propulsion may become trapped by strong currents or vertical stratification (Asper and others, 2011; Nelson and others, 2017). A number of ROVs exist that can be deployed through drillholes in the ice, such as Icefin (Spears and others, 2016; Meister and others, 2018), SCINI (Cazenave and others, 2011), Deep-SCINI (Burnett and others, 2015) and a customised Ocean Modules M500 ROV (Katlein and others, 2019). Larger AUVs and ROVs require significant logistical effort for deployment and recovery, often ship based, especially when relying on moored acoustic sources for navigation, making under ice missions rare and expensive.

4.2.5 SCUBA divers

Due to its presence mainly at the underside of coastal Antarctic sea ice, the only means to perform in situ controlled and targeted sampling of sub-ice platelet layers is by SCUBA-diving missions based from Antarctic stations. This is especially true for biological sampling. However, because of the challenging logistics and the dangers for human life that come with diving in ice-covered seas, there are only a few studies so far that have collected data using SCUBA divers. These have been performed on a regular basis in the shallow areas of McMurdo Sound, but were mostly focused on the benthic realm. The earliest work involving extensive diving in supercooled waters is the one of Dayton and others (1969), who showed that anchor ice frozen to the seabed is of 'considerable biological significance' because it can lift benthic organisms from the seafloor into the sub-ice platelet layer. They also observed instantaneous ice crystal formation in the water while diving. Later studies include for example the ones of Dayton (1989) and Denny and others (2011) at McMurdo and Galea and others (2016) in Atka Bay (Fig. 2d). More recently, the MOO has been installed and was continuously maintained by divers (Cziko, 2019). Many of the health risks associated with diving under Antarctic ice can be mitigated by using ROVs, however this is equally challenging from a logistical perspective.

4.3 Airborne remote sensing

Airborne remote sensing forms the link between in situ observations and satellite remote sensing and is crucial for verifying satellite mission data. Currently only one method of airborne observations of platelet ice exists, which is EM by plane or helicopter (Rack and others, 2013). Airborne EM functions in the same way as ground-based EM systems described above, but has a much higher spatial coverage and higher operating costs. A sub-ice platelet layer has been observed in EM thickness estimates below the sea ice in front of the McMurdo Ice Shelf and is in evidence beneath the ice shelf to a thickness of 55 m: the maximum ice-shelf thickness detectable by the airborne EM (induction sounding) instrument (Rack and others, 2013). The larger footprint of the measurement means that small-scale features cannot be resolved. In addition to the much wider spatial coverage, an advantage over ground-based EM is that airborne EM does not require a minimum sea-ice thickness to operate safely, allowing measurements during freeze in and melt/break-up. This method has great potential to fill the current observational gaps especially in remote regions far from coastal research stations, but much more development work with respect to suitable inversion algorithms is necessary.

4.4 Satellite remote sensing

Satellite altimetry measures the elevation of the snow or ice upper boundary above mean sea level. This measurement may then be converted to sea-ice thickness using estimates of snow depth and density, and sea-ice density (e.g. Kurtz and Markus, 2012). Global Navigation Satellite System (GNSS) surface elevation data have been used to assess the influence that the presence of a sub-ice platelet layer has on estimates of sea-ice thickness, with overestimates in consolidated sea-ice thickness of up to 19% close to an ice-shelf edge (Price and others, 2014). Indeed there is strong evidence of the influence on ICESat laser altimeter data of a sub-ice platelet layer beneath multi-year sea ice in McMurdo Sound between 2003 and 2009 (Price and others, 2013). If developed and used in conjunction with other tools, satellite altimetry has the potential to provide an Antarctic-wide view of the pervasiveness of platelet ice.

4.5 Frazil ice numerical models

Frazil ice formation in the water column influences the buoyancy of the surrounding water parcel (e.g. Jordan and others, 2015) and thus its dynamics as well as potentially influencing sea ice by accumulating as platelet ice. However, the processes involved in frazil ice formation are not well understood and its transport in supercooled plumes is difficult to observe. In addition, the range of scales on which these processes occur, from the molecular scale nucleation to ISW plumes extending hundreds of kilometres, naturally excludes them from being explicitly simulated in the same model for computational reasons. Frazil ice and plume models aim to bridge this gap by providing much needed insights into large scale effects of these small-scale physical processes. Their results can be used to parameterise frazil ice processes in large scale numerical models such as coupled ice-shelf–ocean, Earth system or climate models. Early theoretical work on frazil ice dynamics was undertaken by Daly (1984). There are many numerical models dealing with the representation of frazil generated by supercooled water resulting from heat loss to the atmosphere, e.g. in polynyas, but this section will focus on models dealing with frazil precipitating from ISW. Models focus on the propagation of (frazil-laden) ISW plumes and the effects on marine-ice thickness and sea-ice thickness (e.g. Jenkins and Bombosch, 1995; Smedsrud and Jenkins, 2004; Holland and Feltham, 2005) and have been steadily improved since then (e.g. Hughes and others, 2014; Jordan and others, 2015; Cheng and others, 2019). The newest frazil ice models more closely investigate the formation of the individual crystals (e.g. Rees Jones and Wells, 2018) based on theoretical investigations of nucleation (Rees Jones and Wells, 2015). Unfortunately, the lack of quantitative observations of frazil ice properties (e.g. frazil crystal size distributions and concentrations, and basal drag parameterisations) and the knowledge gaps in crucial physical processes such as nucleation mean that verification of model findings is difficult to impossible.

4.6 Platelet-ice numerical models

Since platelet ice is difficult and costly to measure on large scales, as seen above, many groups have worked on numerical models describing platelet ice (e.g. Ohashi and others, 2004; Ohashi and Kawano, 2007; Dempsey, 2008; Kawano and Ohashi, 2008; Dempsey and others, 2010; Wongpan and others, 2015; Buffo and others, 2018). Since the exclusion of platelet-ice effects from sea-ice models leads to large errors in areas affected by platelet-ice accretion (Buffo and others, 2018), these efforts are not only of relevance to the platelet-ice community, but also to the wider Antarctic sea ice and climate modelling community. Currently, the most comprehensive 3-D model of platelet-ice accretion is the one by Wongpan and others (2015), which is however limited to modelling small 10 cm^3 volumes at the ice–water interface, due to high computational costs. The most comprehensive 1-D model, capable of re-creating ice core characteristics (columnar to incorporated platelet-ice transition, thickness and growth duration) by forcing with realistic ocean and atmosphere parameters, was created by Buffo and others (2018). In the presence of platelet ice, the authors intend the model to calculate sea-ice properties accurately from environmental parameters. However, to date, this has only been tested against the single set of observations used to configure the model.

4.7 Ocean–ice shelf numerical models

In addition to the challenges in modelling ISW plumes, frazil formation and platelet-crystal accretion described above, accurately simulating the precursor processes of platelet-ice formation and incorporation is difficult. On the one hand, these processes affect the large scale circulation via the generation and advection of ISW and supercooled ocean water. On the other hand, they depend on molecule- to centimetre scale processes, such as ice-shelf melting, ocean turbulence and double diffusion. The evolution of the ocean boundary layer beneath the ice shelf–ocean interface is not well captured in current ocean and ice-shelf models. Sub-ice-shelf ocean observations are critically needed to constrain this component in model solutions and improve the underlying algorithms.

In the past decade, many numerical ocean model frameworks have adopted combined algorithmic and parameterised representations of thermodynamic ice–ocean interaction (e.g. MITgcm, Losch, 2008; FESOM, Timmermann and others, 2012; Fluidity, Kimura and others, 2013; ROMS, Robertson, 2013; NEMO, Mathiot and others, 2017; MOM6, Adcroft and others, 2019). However, a detailed digest of the many caveats in modelling ice-shelf cavities is beyond the scope of this study. A comprehensive overview on the evolution in theoretical concepts and numerical technologies of ice-shelf ocean simulation, including the main contemporary challenges, is given in Williams and others (1998) and Dinniman and others (2016). To date, there have been very few measurements of salinity, temperature, currents or anything else beneath ice shelves with which ocean–ice shelf numerical models can be tested.

5. Geographical occurrence and seasonality

We will now give an overview of the published observations of platelet ice in the Southern Ocean, building on the map produced by Langhorne and others (2015). An updated and expanded

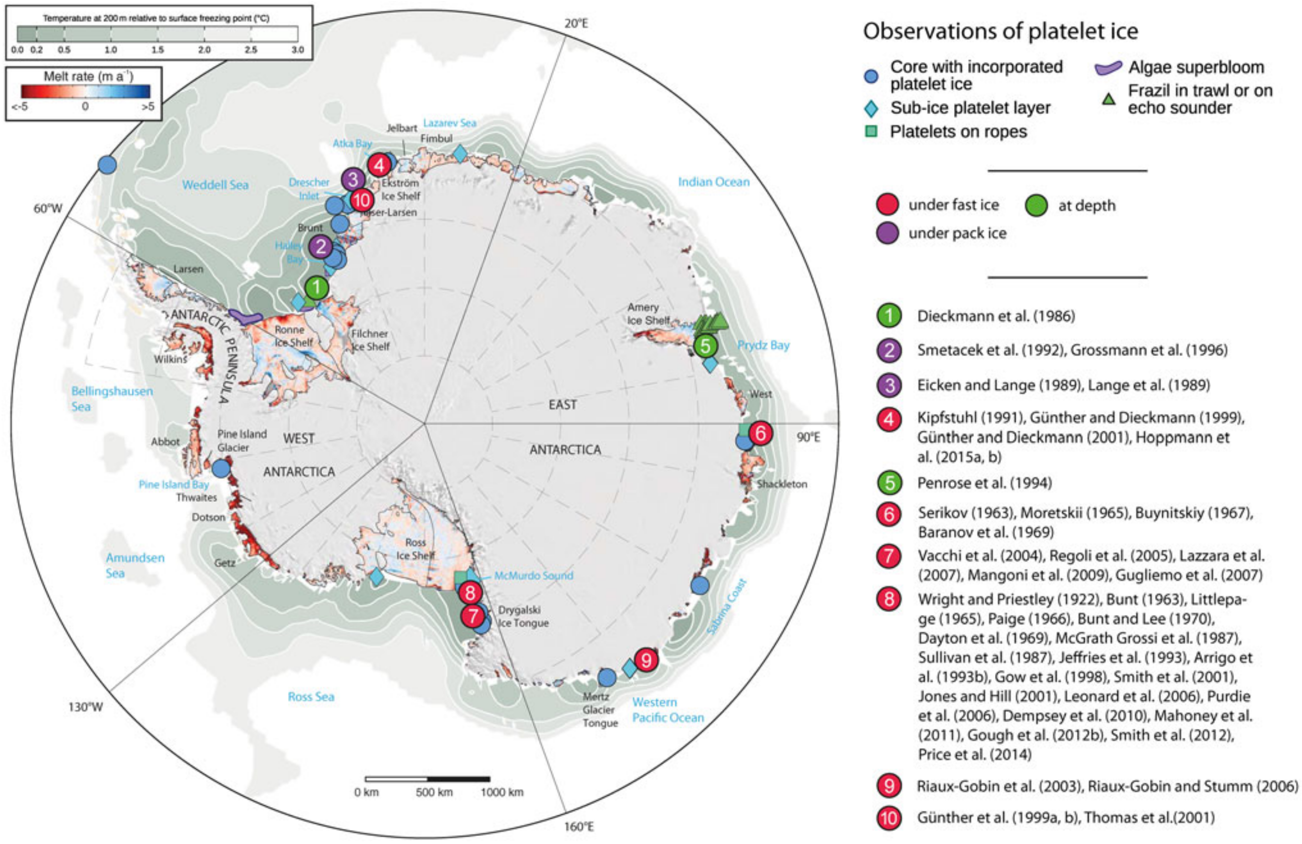

Fig. 4. Observations of platelet ice around Antarctica following Langhorne and others (2015), and background of potential ocean temperature at 200 m relative to surface freezing point. Ice shelves and their basal mass budgets, colour coded from <-5 m a^{-1} (melting) to >+5 m a^{-1} (freezing), and 2009 Moderate Resolution Imaging Spectroradiometer (MODIS) mosaic of Antarctica from Rignot and others (2013).

version of this map is shown in Figure 4. Again we neglect the Arctic, since our definition of platelet ice applies to the Antarctic only. We will discuss possible causes for the presence or absence of platelet ice in different regions and link this to larger scale processes around Antarctica.

5.1 Weddell Sea and Filchner–Ronne Ice Shelf

Sub-ice platelet layers and associated incorporated platelet ice in sea-ice cores have mainly been observed close to the ice-shelf edge or coastal polynyas (Eicken and Lange, 1989; Lange and others, 1989; Smetacek and others, 1992). However, Dai and others (2010) found platelet ice in drifting pack ice at the northwestern rim of the Weddell Sea Gyre, far from the influence of ice shelves. The Weddell Sea Gyre (Deacon, 1979; Fahrbach and others, 1994) may have carried the ice floe from its point of formation to the position it was observed. In front of the Filchner–Ronne Ice Shelf, ice crystals with diameters between 10 and 25 mm have been captured by trawl nets at depths of 250 m (Dieckmann and others, 1986).

5.2 Southeastern Weddell Sea

In Atka Bay close to the Ekström Ice Shelf, incorporated platelet ice has been observed in all fast-ice cores that have been published so far (e.g. Kipfstuhl, 1991; Günther and Dieckmann, 1999, 2001; Hoppmann and others, 2015a, 2015b; Arndt and others, 2020). The contribution of platelet ice to sea-ice thickness is sometimes so high that cores may not contain any columnar ice (Hoppmann and others, 2015a, 2015b; Arndt and others, 2020), although this mainly depends on the timing of initial sea-ice formation. At the end of a typical sea-ice growth season, the sub-ice platelet layer is on average 4 m thick, with up to 10 m observed locally (Hoppmann and others, 2015a, 2015b; Hunkeler and others, 2016b; Arndt and others, 2020). Hoppmann and others (2015b) found evidence of episodic bursts of floating frazil crystals in the water column that are most likely tidal-induced, and resulting from a plume of supercooled ISW emerging from the Ekström Ice Shelf cavity (Smith and others, 2020). Comparable sub-ice platelet layer thicknesses (3–7 m) were observed 10–15 km from the coast in Drescher Inlet (e.g. Eicken and Lange, 1989; Günther and others, 1999b). This layer was found to thin offshore and eastwards to ~0.5 m 35 km offshore of Halley Bay. Incorporated platelet ice was found to make up 11% of the total sea-ice thickness in the area with some cores consisting of 50% incorporated platelet ice (Eicken and Lange, 1989). The sub-ice platelet layer was observed using cameras mounted on an ROV (Marschall, 1988) which suggested that the platelets were mainly advected from deeper in the water column but also grew in situ (Eicken and Lange, 1989).

5.3 East Antarctica

At the Amery Ice Shelf, Penrose and others (1994) recovered frazil crystals from depths of 150 m using trawl nets. Along the East Antarctic coast, platelet ice is intensively formed at the Antarctic shore off Mirny Station and is responsible for the anomalously rapid growth of the fast ice there and its friable structure (Serikov, 1963; Moretskii, 1965). These authors also concluded that Antarctic platelet ice is formed by supercooling of sea water by ice shelves and icebergs. To our knowledge, there are no other studies that found individual icebergs to be a

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significant source for platelet-ice formation, although this may locally be the case under favourable conditions similar to those described in Section 3. The platelet ice off Mirny station attaches to the underside of the fast ice there and, after break-up, is carried by currents out to a distance of more than 40 km from the shore (Moretskii, 1965). The great thickness of the fast ice at Mertz Glacier has been hypothesised to be caused, at least in part, by platelet-ice accretion, though no direct evidence for this exists (Massom and others, 2010). Platelet ice has been found close to Dumont D'Urville Station (Delille and others, 2007), which may have been formed from ISW advected from Mertz Glacier (Williams and Bindoff, 2003).

5.4 Ross Sea and McMurdo Sound

Observations of platelet ice in McMurdo Sound, eastern Ross Sea, were compiled by Langhorne and others (2015). The first ever observations of platelet ice were made in McMurdo Sound (Hodgson, 1907) and it remains the region with the longest time series and the largest number of observations, mainly under fast ice (Langhorne and others, 2015). Observations include: sub-ice platelet layers (e.g. Bunt, 1963; Gow and others, 1982; SooHoo and others, 1987; Crocker, 1988; Rivkin and others, 1989; Smith and others, 2001; Ryan and others, 2006; Hughes and others, 2014; Price and others, 2014; Brett and others, 2020); incorporated platelet ice (e.g. Gow and others, 1998; Smith and others, 1999, 2001; Jones and Hill, 2001; Dempsey and others, 2010; Smith and others, 2012; de Jong and others, 2013); the presence of frazil crystals in the water column (e.g. Leonard and others, 2006; Gough and others, 2010, 2012b); anchor ice (e.g. Dayton and others, 1969; Mager and others, 2013, and references therein) and ice on ropes (e.g. Hodgson, 1907; Wright and Priestley, 1922; Dayton and others, 1969; Barry, 1988; Leonard and others, 2006; Gough and others, 2010; Mahoney and others, 2011). Due to the local ocean circulation (e.g. Leonard and others, 2006; Mahoney and others, 2011; Robinson and others, 2014), in the western McMurdo Sound platelet ice occurs earlier in the season, and makes up a greater percentage of the sea-ice thickness compared to the eastern McMurdo Sound, where it is sometimes absent (Dempsey and others, 2010; Hughes and others, 2014). In areas with strong tidal currents the sub-ice platelet layer has been observed to be separated from the overlying sea ice, and moving independently of the stationary fast ice (Robinson and others, 2017). The long time series of platelet-ice observations in McMurdo Sound (over 100 years) does not show any trends in the surface ocean temperatures or the thickness of the platelet ice (Langhorne and others, 2015).

5.5 West Antarctica

No platelet ice has been observed in the Amundsen and Bellingshausen Seas, except for the observation of platelet ice in Pine Island Bay in the winter of 1991/92 by Veazey and others (1994). That was the first study of sea ice in the region and the temperature profiles from the area, the first taken in 1994 (Jacobs and others, 1996, 2011), suggest that Veazey and others (1994) may have observed one of the last occurrences of in situ supercooled water outflow from Pine Island Glacier. This hypothesis remains speculative however, since the beginning of the oceanographic and glaciological observational record at Pine Island Bay possibly coincides with the beginning, or at least acceleration, of the dramatic melt-induced thinning (Wingham and others, 2009) of the glacier due to ocean forcing and associated changes in cavity geometry (Jenkins and others, 2010; Jacobs and others, 2011). The warming and shoaling of CDW in the Amundsen and Bellingshausen Seas (Schmidtko and others, 2014), which in 1994 was already present at the Pine Island Glacier calving front and was significantly warmer than the freezing point (Jenkins and others, 1997), make the presence of ISW and platelet ice highly unlikely in present-day conditions.

5.6 Discussion of observations

To understand the distribution of platelet-ice occurrence described above, we will take a closer look at the precursor of platelet-ice formation, the formation of ISW through ice-shelf melting. The presence of ISW is a necessary, though not sufficient precursor for platelet-ice formation (Mahoney and others, 2011). The occurrence of supercooling strongly depends on the mode of melting (see Section 3.4). In the Ross and Weddell Seas, the shelf waters are cold (e.g. Nicholls and others, 2009; Orsi and Wiederwohl, 2009) and platelet ice has been observed there (Langhorne and others, 2015). In contrast, for the Amundsen and Bellingshausen Seas (e.g. Jacobs and others, 1996, 2011) and along the Sabrina Coast (Silvano and others, 2017), the continental shelf is flooded by warm CDW and there are no recent observations of platelet ice (Langhorne and others, 2015). Even in close proximity to ice-shelf cavities cold enough to produce ISW, platelet ice may be absent for all or part of the year. This can be due to (a) ISW emerging at depth; (b) ISW mixing with warmer surface water masses before exiting the cavity (Jacobs and others, 1992; Hattermann and others, 2012); (c) in situ supercooling in the ISW plume being relieved through latent heat release from marine or anchor ice formation at depth (Sections 3.5 and 3.8) or (d) the presence of a polynya with intense brine rejection, as hypothesised by Langhorne and others (2015). The absence of platelet-ice observations in front of parts of the Filchner–Ronne (Nicholls and others, 2009; Hattermann and others, 2012), the Amery (Shi and others, 2010; Zheng and others, 2011) and the Ross Ice Shelves (Jacobs and others, 1985; Jeffries and Adolphs, 1997; Nelson and others, 2017) is likely attributed to (a). In cases (a), (b) and (c), ISW may be in situ supercooled at some depth and frazil ice can form. However, stratification may prevent the frazil from rising to the surface and reaching the sea ice by causing the crystals to melt in the overlying warmer waters. For example, ISW has been observed at depth in front of the Ross Ice Shelf (e.g. Jacobs and others, 1985; Nelson and others, 2017), but Jeffries and Adolphs (1997) did not observe any platelet ice there. In the hypothesised case (d), frazil crystals suspended at depth in the in situ supercooled ISW plume may be melted by the heat source of pressurised HSSW once deep convection sets in. Furthermore, crystals that have risen to the ocean surface may be indistinguishable from the frazil or granular ice formed during intense atmospheric cooling and polynya sea-ice production, as suggested by Langhorne and others (2015).

5.7 Seasonality of formation

The seasonality of platelet-ice formation is likely to be different for each location and may indeed vary from year to year depending on factors such as icebergs influencing fast-ice persistence and ocean circulation (Brunt and others, 2006; Dinniman and others, 2007; Remy and others, 2008; Robinson and others, 2010; Mahoney and others, 2011). Platelet-ice formation from July to September was recorded in several locations in the Mirny area (Buynitskiy, 1967), and has also been seasonally observed in other regions (Wright and Priestley, 1922; Dayton and others, 1969; Crocker and Wadhams, 1989; Günther and Dieckmann, 1999), suggesting that the water only becomes supercooled during

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this period or after sea ice has begun to form. However, there are substantial deviations from these dates in other regions. The mode of melting below the Amery Ice Shelf is known to be seasonal, with Mode 1 dominating melting and Mode 2 contributing in winter (Herraiz-Borreguero and others, 2015). ISW has been found at mid-depth year round and marine ice formation is highest during winter (Herraiz-Borreguero and others, 2013). In Atka Bay, Hoppmann and others (2015a, 2015b) found a thickening sub-ice platelet-ice layer throughout winter with a decline in thickness starting in December with the arrival of warm surface waters. In McMurdo Sound, the onset of near surface supercooling conditions was observed as early as March, with platelet ice appearing as early as April (Leonard and others, 2006) in a year when the local oceanography was heavily influenced by a grounded iceberg in the Ross Sea (Brunt and others, 2006; Dinniman and others, 2007; Remy and others, 2008; Robinson and others, 2010; Mahoney and others, 2011; Robinson and Williams, 2012). Other researchers found ISW arrived as late as mid-July and platelet ice began to form in early August (Mahoney and others, 2011; Gough and others, 2012b). The onset of supercooling conditions in McMurdo Sound is influenced by the location in the Sound, with an outflow of ISW likely present throughout the sea-ice growth season in western McMurdo Sound, as evident in oceanographic observations (e.g. Robinson and others, 2014) and the high contribution of platelet ice in sea-ice cores (e.g. Barry, 1988; Dempsey and others, 2010, recorded an absence of columnar ice from sea-ice cores taken in western McMurdo Sound). In the eastern McMurdo Sound, a summertime inflow of warmer surface waters prevents the appearance of surface supercooling at the start of the sea-ice growth season (Barry, 1988; Barry and Dayton, 1988; Robinson and others, 2014). This warm inflow subsides during winter as the ISW plume exiting in western McMurdo Sound spreads eastwards (Barry and others, 1990; Leonard and others, 2006; Mahoney and others, 2011; Robinson and others, 2014) resulting in an onset of platelet-ice occurrence deeper in the core (later in the growth season) for cores taken successively further eastwards (e.g. Hughes and others, 2014).

The picture of platelet-ice presence painted above should be viewed with some caution. Both the geographical and temporal occurrence suffer from significant sampling bias, with a higher density of observations close to research stations and during conditions with well-established fast ice. In addition to this, the picture is most likely incomplete, with many incidental observations of platelet ice never published. To expand the base of observations beyond platelet-ice observations published in the literature, it would be essential to undertake a search of expedition reports and other such sources. However, this was far beyond the scope of this review.

6. Physical properties

Incorporated platelet ice differs from columnar sea ice in the orientation of the individual ice crystals making up the sea-ice fabric. In columnar ice, the crystals are aligned, whereas in incorporated platelet ice, the crystals are randomly oriented (Fig. 5). Since the sub-ice platelet layer is a loose accretion of solid ice platelets surrounded and permeated by sea water, the physical property in which the sub-ice platelet layer differs most from consolidated sea ice (columnar and incorporated platelet ice) is the ice-volume fraction, also sometimes termed solid volume fraction. Most other differences in properties result from the difference in ice-volume fraction. In the following, we will examine some of the physical properties of platelet ice more closely.

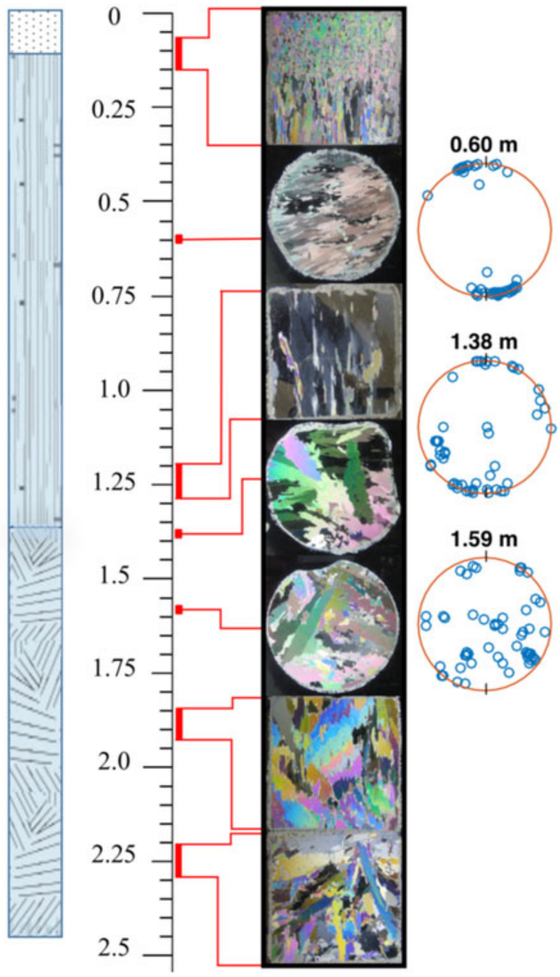

Fig. 5. Selected thin sections along a sea-ice core from McMurdo Sound, Antarctica, viewed under cross-polarised light, showing granular, columnar and incorporated platelet ice. Depth from sea-ice surface in metres. Crystallographic *c*-axes orientations have been displayed for three horizontal sections at 0.60, 1.38 and 1.56 m. The blue dots correspond to the orientation of the *c*-axes when projected on to an upper hemisphere Schmidt net, a standard method of visualising *c*-axes orientation (Langway, 1959). Horizontal *c*-axes will plot along the perimeter of the circle whereas vertical *c*-axes will lie in the centre. Vertical thin sections are shown for 0.06–1.15, 1.20–1.29, 1.84–1.93 and 2.20–2.29 m.

6.1 Size of individual platelets

Platelet crystals attached to a slab of sea ice removed from McMurdo Sound in 1999 were reported by Smith and others (2001) to be ~2 mm thick and up to 200 mm in diameter. Systematic measurements of the size distribution of individual platelet crystals were published by Stevens and others (2019), where over 100 individual platelet crystals were measured. The crystals were predominantly within the 50–100 mm diameter class, with some up to ~200 mm in diameter. Thicknesses ranged from ~0.5 to 4 mm.

6.2 Ice-volume fraction

The correct interpretation of signals from radar and EM induction measurements of sea ice are dependent on a knowledge of the electrical properties of sea ice. They are discussed in Morey and others (1984) and a field approach using a multi-frequency EM instrument is described in Hunkeler and others (2015, 2016b). The electrical conductivity of the sub-ice platelet layer can be used to calculate its porosity ϕ, and subsequently its ice-volume fraction $\beta = 1 - \phi$, via a modified Archie's law (Archie,

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Table 2. Estimates for the ice-volume fraction β within the sub-ice platelet layer

Location	β	Method	Source
Atka Bay	0.29–0.43	Multi-frequency EM induction sounding	Hunkeler and others (2016a)
	0.2–0.36	Inversion of multi-frequency EM data	Hunkeler and others (2016b)
	0.18	Energy balance from sea-ice temperature profiles	Hoppmann and others (2015a)
	0.18	Fit of modelled ice growth to observations	Hoppmann and others (2015a)
	0.25	Fit of modelled ice growth to observations	Hoppmann and others (2015b)
	0.36–0.54	Volume measurements in a bucket sample retrieved from a crack	Günther and Dieckmann (1999)
	0.2	Fit of modelled ice growth to observations	Kipfstuhl (1991)
McMurdo Sound	0.16	Archimedes' Law	Price and others (2014)
	0.25	Energy balance from sea-ice temperature profiles	Gough and others (2012b)
	0.35	Energy balance from sea-ice temperature profiles	Purdie and others (2006)
	0.33	Estimate from sea-ice temperature profiles	Trodahl and others (2000)
	>0.50	Estimate from horizontal thin sections	Jeffries and others (1993)
	0.50	Estimate from core holes	Crocker and Wadhams (1989)
	0.20	Estimate from core holes	Bunt and Lee (1970)
Model	0.22	3-D geometric model	Wongpan and others (2015)

Table modified from Gough and others (2012b) and Hoppmann and others (2015b).

1942; Hunkeler and others, 2016b) given by $\phi = \left(\sigma_{\mathrm{p}}/\sigma_{\mathrm{b}}\right)^{1/m}$ The ice-volume fraction β thereby depends on a knowledge of the brine conductivity, σ_{b}, the conductivity of the sub-ice platelet layer, σ_{p} and an empirical cementation factor, m. The latter in turn depends on the pore geometry and connectivity, and on the shape of the platelet crystals. All these factors are not well constrained for the sub-ice platelet layer (Hunkeler and others, 2016b). A range of other techniques have also been used to try to measure or estimate the ice-volume fraction in the sub-ice platelet layer. Thus it is not surprising that estimates of the ice-volume fraction, collected in Table 2, range from 0.16 (Price and others, 2014) to >0.50 (Jeffries and others, 1993), where the former used Archimedes' Law and the latter examined horizontal thin sections of incorporated platelet ice and determined what proportion of the ice was platelet crystals when frozen in.

6.3 Platelet crystal growth rates

Through video camera still analysis, Smith and others (2012) reported that individual crystals in the sub-ice platelet layer grew in episodic bursts with growth rates of the order of 10^{-6} m s^{-1} during these bursts. Incorporated platelet ice was reported by Smith and others (2012) to have growth rates of the order of 10^{-7} m s^{-1}, an order of magnitude slower than the individual platelet crystals. Leonard and others (2006) reported maximum growth rates for individual platelet crystals in the sub-ice platelet layer that were close to the minimum crystal growth rate observed by Smith and others (2012).

6.4 Basal topography and ocean dynamics in the boundary layer

The presence of sub-ice platelet layers forms an enhanced basal topography and increases the drag at the underside of sea ice (McPhee and others, 2016; Robinson and others, 2017) to 6–30 times the value for sea ice unaffected by platelet ice (Robinson and others, 2017). The growth of platelet ice is hypothesised to itself be limited by turbulent heat transfer, a quantity dependent on drag. Robinson and others (2017) described the effect of platelet-ice roughness-induced mixing on limiting (in a stratified ocean with warmer water underlying a supercooled plume) or increasing (in a homogeneous ocean or thick supercooled plume) platelet-ice growth. This also applies to vertical convection due to the latent heat and salt fluxes associated with platelet-ice growth (Robinson and others, 2014). From heat flux calculations, Smith and others (2001) inferred a kinematic eddy viscosity for a sub-ice platelet layer to be $\epsilon = 2 \times 10^{-5}$ m^2 s^{-1}. Stevens and others (2009) measured average turbulent energy dissipation rates beneath McMurdo Sound fast ice, where platelet ice is commonly present, to be 3×10^{-8} m^2 s^{-3}.

6.5 Crystal c-axis distribution

c-axis distribution measured from thin sections of ice cores reveal differences between columnar ice and incorporated platelet ice (Weeks and Ackley, 1982; Gough and others, 2012b; Fig. 5). In columnar ice, *c*-axes are preferentially oriented in the horizontal, forming a girdle structure when plotting their orientation (e.g. Weeks and Ackley, 1982; Gough and others, 2010, 2012b). In cases where the columnar ice grows in the presence of a current of constant direction, the horizontal *c*-axes cluster in the direction of the current (Langhorne and Robinson, 1986; Gough and others, 2010). Incorporated platelet ice shows random *c*-axis orientations, with some even aligned in the vertical (e.g. Gough and others, 2012b). The orientation of platelet crystals is thought to be dependent on the rotation of the crystal as it settles at the underside of the ice (Dempsey and others, 2010; Wongpan and others, 2015, 2018c). Wongpan and others (2018c) were able to measure the crystallographic *a*-axis orientations and showed that these too show differences between columnar ice and platelet ice.

6.6 Salinity, permeability and brine volume

Through analysis of multiple sea-ice cores taken at one site, Gough and others (2012a) showed that the salinity of incorporated platelet ice is slightly higher than the salinity of columnar ice, after growth rates were taken into account. This is a subtle effect that is not clearly obvious in the C-shaped salinity profiles from single cores (Smith and others, 2012). Wongpan and others (2018a) showed that this is the result of the arithmetic mean permeability for columnar and incorporated platelet ice being indistinguishable beneath thick Antarctic landfast sea ice, implying that porosity is more important than crystal geometry. It should be noted that Wongpan and others (2018a) were only able to probe incorporated platelet ice which has a porosity similar to columnar sea ice. Less is known of the sub-ice platelet layer which has been measured to be isothermal. If it is assumed that the system is in thermal equilibrium, then the salinity gradient in the brine in the interstitial space of the sub-ice platelet layer must also be minimal. Diffusive transport is unlikely to dominate in such a system. At the time of writing, the permeability-porosity relationship and fluid transport in the sub-ice platelet layer are poorly understood.

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6.7 Mechanical properties

Many authors (e.g. Weeks, 2010) have shown that all mechanical properties of sea ice are strongly dependent on the porosity, and platelet ice is no exception. Thus the mechanical properties of incorporated platelet ice would be expected to be very similar to the properties of columnar sea ice. Measurements of flexural strength and the fatigue properties of the first-year landfast sea ice of McMurdo Sound were made throughout the 1990s by subjecting in situ cantilever beams to repeated bending with zero mean stress (e.g. Haskell and others, 1996; Langhorne and others, 1998; Langhorne and Haskell, 1999). These beams were comprised mainly of columnar ice, but included between 10 and 35% incorporated platelet ice (Langhorne and others, 2015). The crystallographic structure was shown to exert much less influence on the mechanical properties of the beams than salinity, temperature or brine volume (e.g. Langhorne and Haskell, 2004). In contrast, in marine ice with low bulk salinities, the anisotropy in crystal fabric controls the rheological behaviour when samples are subject to unconfined uniaxial compression (Dierckx and others, 2014). Indeed, recently formed marine ice appears to behave as natural isotropic ice, provided the higher temperature of marine ice is taken into account (Dierckx and Tison, 2013). To our knowledge, no data on mechanical properties of the high porosity sub-ice platelet layer have been published.

6.8 Oxygen isotopes ($\delta^{18}O$)

There are two main controls on the δ^{18}O values of sea ice: (i) the growth rate of the sea ice (higher growth rates lead to lower sea-ice δ^{18}O values); and (ii) the δ^{18}O values of the water which the ice formed from (lower parent water values lead to lower sea-ice δ^{18}O values). As noted above, individual platelet crystals grow in episodic bursts at rates that are an order of magnitude faster than columnar ice. It would therefore be expected that δ^{18}O values for crystals from the sub-ice platelet layer and for incorporated platelet ice would be lower than for columnar ice; however, this is not the case. Smith and others (2015) reported that there was no discernible difference between the isotopic composition of columnar ice and incorporated platelet ice. Reliable δ^{18}O measurements for platelet crystals from the sub-ice platelet layer have not been published. Smith and others (2001) reported measurements from such crystals, but noted the possible contamination from the presence of sea water. Attempts to minimise this contamination have been made but not yet published (personal communication from Natalie Robinson). Smith and others (2015) reported a range of derived effective fractionation coefficients (the ratio of the isotopic composition of the sea water to that of the sea ice) to be +1.84‰ to +2.21‰ for McMurdo Sound sea ice in 2009.

7. Significance and impact

7.1 Contribution to sea-ice thickness and volume

Sea-ice thickness in front of an ice shelf is influenced by the stabilisation of the upper water column by glacial meltwater. Using an ocean model with ice-shelf cavity thermodynamics, Hellmer (2004) predicted that sea ice is up to 0.2 m thicker for this reason. The overall thickening effect of glacial meltwater emerging from the ice-shelf cavity on sea ice is likely to be higher than 0.2 m since the model of Hellmer (2004) does not take into account supercooling, the formation of frazil ice, or platelet ice. Since approximately half of Antarctica's coastline is fringed by ice shelves (Fretwell and others, 2013), this potentially affects large areas of the Southern Ocean. In the Ross Sea, Jeffries and others (1993) determined that incorporated platelet ice constituted over half of the thickness of fast ice in some locations in McMurdo Sound. In late winter, in first-year sea ice close to the ice shelf, at least 0.25 m of the 2 m thick cover forms due to heat loss to the ocean (Purdie and others, 2006; Gough and others, 2012b). Similarly, multi-year fast ice attached to the Mertz Glacier tongue was estimated to be between 10 and 55 m thick, and frazil accumulation must have contributed to its thickness (Massom and others, 2010).

The percentage contribution of platelets to the total volume of sea ice has been estimated for various regions in Antarctica. Kipfstuhl (1991) determined that fast ice in Atka Bay contained up to 50% incorporated platelet ice, while Günther and Dieckmann (1999) found up to 60% of the fast ice to consist of incorporated platelet ice in the same area. Jeffries and others (1993) and Smith and others (2001) showed that platelet ice can add up to more than 40% of the total sea-ice mass in McMurdo Sound. Eicken and Lange (1989) found their cores from the coastal zones of the southeastern Weddell Sea to contain 11% of incorporated platelet ice, while Lange (1988) and Lange and others (1989) estimate that between 20 and 30% of sea ice in coastal regions is comprised of platelet ice. The spatial variability of the contribution of platelet ice to sea ice was studied by Barry (1988), Smith and others (2001) and Dempsey and others (2010) based on ice-core analyses. The thickness of sub-ice platelet layers, when present, have been reported to range from consisting of ranging from individual crystals attached to the ice bottom (Mahoney and others, 2011) to 8 m or thicker (Hughes and others, 2014; Price and others, 2014; Hoppmann and others, 2015a). In some locations on the eastern side of McMurdo Sound, incorporated platelet ice has been observed in the lower parts of cores only (e.g. Smith and others, 2001; the lower 690 mm in a core with a total length of 2150 mm), with some locations not having any incorporated platelet ice present at certain times (e.g. Cape Evans in Smith and others, 2001). In contrast, Hoppmann and others (2015a) and Hughes and others (2014) took sea-ice cores in Atka Bay and western McMurdo Sound, respectively, which consisted of incorporated platelet ice throughout, i.e. these cores did not contain any pure columnar ice.

7.2 Further effects on sea ice

Sea ice is a critical part of Earth's climate system through its high albedo (especially when snow covered), thermal insulation properties, and through its role in deep water formation. It is generally agreed that the growth of a sub-ice platelet layer causes sea ice to be thicker than it would be with heat loss to the atmosphere only (e.g. Smith and others, 2012; Hoppmann and others, 2015b, Section 7.1). The presence of platelet ice will therefore alter the thermal insulation properties of sea ice and its longevity, with flow-on effects to climate. The overall impact of ice-shelf basal melt on sea-ice formation, and hence on climate, is not well understood. The contribution of ice-shelf melting as a factor in the unexplained discrepancy between global climate models and satellite-derived sea-ice extent around Antarctica has been explored using different climate models, but is controversial (Bintanja and others, 2013, 2015; Swart and Fyfe, 2013; Holland and others, 2014; Pauling and others, 2016, 2017; Bronselaer and others, 2018). As explained in Section 4.7, no ice-shelf–ocean (and thus climate) models currently include the effect of platelet-ice formation on sea-ice extent and thickness, so these papers have only taken into account the direct effects of the freshwater input (e.g. stratification, and sometimes also cooling). As shown earlier in this paper, manifestations of ice shelf–ocean interaction and associated phenomena have been observed in many locations around Antarctica (Fig. 4). Although aspects of these interactions have been investigated in detail for example

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in McMurdo Sound (Ross Sea) and Atka Bay (Weddell Sea), little is known about the overall role of platelet ice for coastal sea ice in Antarctica. This lack of regional information is a barrier for investigating the effects of platelet ice on sea ice and the climate system.

Although it is relatively simple to accurately predict the growth of undeformed Arctic sea ice by thermodynamic modelling, a thermodynamic model which accurately predicts ice growth in the Arctic will not do the same in the Antarctic when platelet ice is present due to the negative ocean heat flux associated with the presence of platelet ice (Langhorne and others, 2015). This phenomenon has encumbered efforts to predict growth rates of fast ice in Antarctica ever since Crocker and Wadhams (1989), as detailed in Smith and others (2015).

7.3 Effects on ice-shelf buttressing

As noted in previous sections, incorporated platelet ice results in thicker sea ice and therefore must contribute considerably to the overall stability of the fast ice around Antarctica and to its prolonged existence, especially in bays and inlets. The stability of the fast ice, with its estimated area of between 5.5×10^5 and 8×10^5 km^2 (Kozlovsky and others, 1977, as cited in Fedotov and others, 1998) also plays an important role in the stability of ice shelves, for example by protecting the calving front from ocean swell (Massom and others, 2018) or through buttressing (MacAyeal and Holdsworth, 1986). Consequently, the melting of ice shelves resulting in platelet-ice formation forming thicker and more stable fast ice may indirectly lead to ice shelves that are more stable due to protective, more stable fast ice in front of them. However, further research is needed to investigate these connections. The climate effects of platelet ice are therefore complex, involving a series of feedbacks.

The stability of fast ice and ice shelves not only has consequences for the global climate system, but also for the ecology of the coastal regions, as explained in Section 7.5.

7.4 An indicator for ice-shelf processes

More recently, Hoppmann and others (2015b) and in much more detail, Langhorne and others (2015), hypothesised that the presence and evolution of platelet ice and its physical properties as a signature of supercooling could be an indicator for the state of an ice shelf with respect to processes in the ice-shelf cavity. Smith and others (2015) suggested using δ^{18}O samples from sea ice as evidence for ice-shelf melt processes, but noted the challenges of doing this. This is a particular useful and intriguing idea, especially since the sampling beneath Antarctic ice shelves is a huge logistical and financial challenge. Although the exact connection between those two cryospheric elements is not clear, it is certain that the properties of sea ice (or more accurately, fast ice) close to an ice shelf should be an important element in the monitoring of the latter.

7.5 Significance for ecosystems and ecology

The first studies of the biology associated with sub-ice platelet layers date back to the 1960s in McMurdo Sound (Bunt, 1963; Bunt and Wood, 1963; Bunt and Lee, 1970). These first explorations described the dense microbial assemblages associated with platelet layers (e.g. Palmisano and Sullivan, 1985; Dieckmann and others, 1992; Arrigo and others, 1993b; Ackley and Sullivan, 1994; Arrigo and Thomas, 2004). The high concentration of biological matter in sub-ice platelet layers is usually immediately evident by the reddish-brown colour of the interstitial waters, and has significant implications for the entire coastal Antarctic food web.

7.5.1 Phytoplankton and bacteria

The colonisation of the sub-ice platelet layer by microalgae and other small planktonic organisms probably commences concurrently with its formation (Günther and Dieckmann, 1999). Whether the platelet crystals themselves are instrumental in scavenging the organisms from the water column is still not clear, albeit very likely (Garrison and Sullivan, 1983, 1988; Dieckmann and others, 1986; Walker and Marchant, 1989). Other evidence of particle inclusions is known from marine ice (Kipfstuhl and others, 1992; Goodwin, 1993; Warren and others, 1993; Eicken and others, 1994; Craven and others, 2009), where resuspended sediment particles may be incorporated in a similar manner. The organisms either dwell while suspended within the interstitial water between the platelets, or grow attached to platelet crystals themselves (Smetacek and others, 1992). Late summer sub-ice platelet layers seem to constitute a protected refugium for ice-associated algae and bacteria during a phase of intense pack-ice melting.

The timing of a phytoplankton bloom is strongly affected by light conditions, primarily controlled by the properties of the overlying snow cover (McGrath Grossi and others, 1987; Palmisano and others, 1985; Wongpan and others, 2018b). The spectral irradiance regime is generally the main limitation for growth of bottom-ice and under-ice microalgae (Palmisano and Sullivan, 1985; Palmisano and others, 1985, 1987; Cota and Smith, 1991), and light levels in the sub-ice platelet layer are lower than in the congelation ice above (Bunt, 2013b). The role of light in controlling algal growth and production in sub-ice platelet layers has been studied intensively, and there is evidence of extreme shade adaptation in sub-ice platelet layer associated algae (Palmisano and Sullivan, 1985; Palmisano and others, 1987; Arrigo and others, 1991, 1993b; Robinson and others, 1995; Lizotte and Sullivan, 1991; Guglielmo and others, 2000; Lazzara and others, 2007; Mangoni and others, 2008). However, other factors seem to compensate the light limitation, strongly favouring algal growth in this habitat: stable temperatures near the freezing point of sea water, stable salinity, a continuous supply of nutrients, ample opportunity for colonisation as well as protection from large grazers such as krill (Thomas and Dieckmann, 2002a).

Algal communities particularly thrive in layers that are hydraulically connected to the water column, supplying nutrients and providing seed populations of microalgae (Arrigo, 2016; Meiners and others, 2018; van Leeuwe and others, 2018). Being the most porous of all sea-ice habitats, sub-ice platelet layers provide a large surface area and at the same time enable free nutrient exchange with the underlying sea water (Arrigo and Thomas, 2004; Bunt, 2013a).

The productivity and biomass accumulation in sub-ice platelet layers often exceeds the high concentrations measured in the lower few centimetres of congelation ice (Bunt and Lee, 1970; Kottmeier and others, 1987; McGrath Grossi and others, 1987; Smetacek and others, 1992; Arrigo and others, 1993a; Arrigo and others, 1993b, 1995; Günther and Dieckmann, 1999; Lazzara and others, 2007; Meiners and others, 2012). Seasonal peaks in chlorophyll-*a* (Chl-*a*) concentrations in Antarctic and Arctic sea-ice types are up to 5400 and 800 mg Chl-*a* m^{-3}, respectively (Meiners and others, 2012; Arrigo, 2016). Reported peak accumulation in sub-ice platelet layer habitats are >6000 mg Chl-*a* m^{-3}, higher than any other sea-ice habitat either in the Arctic or the Antarctic (Arrigo and others, 2010). In a recent comprehensive synopsis of Chl-*a* standing stocks in Antarctic landfast ice, Meiners and others (2018) described how sites with platelet ice have the greatest concentration of sea-ice algal biomass in these highly productive regions.

Grossmann and others (1996) showed that substantial heterotrophic potential can be established within this special habitat.

Nutrient profiles and small-scale distribution of algal and bacterial cells suggest a close coupling between these two groups of organisms, thus implying the establishment of a community structure. In areas of greatest biomass accumulation, the platelet layers are also good examples of where the 'chemostatic' ice algal production can take place (Thomas and others, 1998): the high biomass production in highly porous systems and in the absence of grazers is supported by rapid turnover of inorganic nutrients. This is fuelled by high concentrations of organic matter which results in high-bacterial nitrogen, phosphorus and silicate regeneration in an elevated pH medium (Thomas and Dieckmann, 2002b; Ichinomiya and others, 2008).

A consequence of these sites of intensive biological activity is that there is considerable flux of material out of the platelet layers to the underlying waters and sediments. This has been measured by the deployment of small sediment traps under platelet layers and much of the material falling out is made up of ice diatoms, sometimes contained within faecal pellets produced by protists and small metazoans (Günther and others, 1999a, 1999b; Riaux-Gobin and others, 2000, 2005; Thomas and others, 2001; Ichinomiya and others, 2008).

7.5.2 Grazers in platelet ice

Thomas and Dieckmann (2002b) describe the debate about the absence of grazers leading to the establishment of high algal standing stocks in platelet layers (e.g. Smetacek and others, 1992). In contrast, other studies have recorded high numbers of protozoan and metazoan grazers in platelet layers (Arrigo and others, 1995; Archer and others, 1996; Grossmann and others, 1996; Günther and others, 1999a, 1999b). As with the bottom sea-ice communities, the sub-ice platelet layer communities provide an important nutritional resource for invertebrates such as juvenile krill (Marschall, 1988; Frazer, 1996; Quetin and others, 2013), amphipods (Rakusa-Suszczewski, 1972) and other zooplankton. Much of their production is exported to deeper layers by means of rapidly sinking faecal pellets of copepods and krill (Gonzales, 1992; Daly, 2013; Schnack-Schiel and others, 2013).

7.5.3 Fish

The notothenioid Antarctic silverfish (*Pleuragramma antarcticum*) has a pivotal importance in Southern Ocean ecosystems. In the adult stage, this fish is widely distributed and abundant in shelf waters around the continent, and represents a major contribution to the diet of most Antarctic vertebrates such as whales, seals, penguins, flying birds and benthic fish, especially in the Ross Sea (La Mesa and others, 2004). They also constitute the major link between lower (invertebrates) and higher (birds and mammals) levels of the food web. The sub-ice platelet layer has been found to play a crucial role in the early stages of the life cycle of this species (Vacchi and others, 2004), providing an important food source, but also a favourable environment, protected from predation (Gutt, 2002). These fish use antioxidants as adaptive responses to extreme environmental conditions and to the rapid changes of pro-oxidant pressure associated with the sub-ice platelet layer (Regoli and others, 2005). It is one of the major aims of the MOO (Cziko, 2019) to support studies on the freezing-avoidance abilities of Antarctic notothenioid fishes.

7.5.4 Mammals and birds

The exact roles and implications of platelet ice for higher trophic levels are still unclear. There are, to our knowledge, no studies that explicitly investigate the importance of the platelet-ice realm for seals or penguins. However, fast ice extent, stability and timing of break-up is a critical factor for Emperor Penguin adult survival in winter (Barbraud and Weimerskirch, 2001; Jenouvrier and others, 2005), breeding success (e.g. Massom and others, 2009; Trathan and others, 2011) and moult (Croxall and others, 2002). Furthermore, Emperor penguins mainly feed on Antarctic krill *Euphausia superba* and Antarctic silverfish *Pleuragramma antarcticum*. The prey composition suggests that these penguins perform shallow dives to explore the underside of sea ice where this food is foraged (Klages, 1989). Since fish and other small animals that mammals and birds rely on as a food source thrive in sub-ice platelet layers for the above reasons, one can hypothesise that this is why the mammals and birds tend to live close to these regions. This is especially true for the summer, during which melting platelet ice releases masses of algae and other organic particles into surface layers, creating locally attractive feeding spots. This results in an intensive foraging in zooplankton, krill and fish which aggregate under the melting sea ice, and which in turn attracts the seals (Plötz and others, 2001). Since the additional thickness provided by incorporated platelet ice contributes to the stability of coastal fast-ice regimes, and also because there is an increased supply of food due to the presence of a sub-ice platelet layer, it is likely that these conditions favour the breeding of Emperor penguins at those sites.

One particularly interesting adaptation of seals to sub-ice platelet layers was found by Davis and others (1999). Using a seal-borne camera, they showed how a seal was blowing bubbles to flush a fish (*Pagothenia borchgrevinki*) out of the platelet layer (see Figs 2j and k). They also saw how seals, in addition to biting exposed fish tails and flushing the fish out, may even pursue the fish into the sub-ice platelet layer.

8. Outlook

How will the properties of platelet ice change in a future higher greenhouse gas world? The overly-simplistic conceptual model 'warmer ocean leads to more basal melting leads to more platelet ice' is likely not applicable in such a complex system. ISW is a necessary but not sufficient precursor for platelet-ice formation. Furthermore, ISW presence and circulation in a future Southern Ocean is likely to be different in the Ross Sea, Weddell Sea and other regions where platelet ice is presently observed. HSSW formation in polynyas is the most important precursor for ISW formation in cold cavity ice shelves where Mode 1 melting dominates (Jacobs and others, 1992). Spatial and temporal changes to katabatic winds, and therefore changes to HSSW production in polynyas, would thus lead to changes in Mode 1 generated ISW and platelet-ice formation.

Stronger wind events in a future climate could on the one hand enhance sea-ice formation in polynyas and lead to greater HSSW production, and thus accelerate the circulation in the cavity. Subsequent heat advected to the cavity would cause stronger Mode 1 melting at the deep ice-shelf base, and eventually increase ISW and platelet-ice formation. Although this argument holds true for polynyas linked to katabatic winds which will retain subfreezing temperatures (but may vary in occurrence frequency and event duration) even with a warming climate, overall expected warmer Antarctic winters allowing less sea-ice production could potentially cause the opposite. Less HSSW production will slow down the cavity circulation and the associated heat influx, thus reducing Mode 1 ISW production (Nicholls, 1997). Although speculative, less and slower outflow of ISW could potentially generate a thicker layer of supercooled water, and, by maintaining the heat sink for longer, give frazil crystals more time to form. Thus, less HSSW production could actually contribute to frazil ice generation, even if the frazil crystals might never make it to the front. Instead, they are deposited at the ice-shelf base as marine ice.

On the other hand, stronger wind events (especially when paired with a reduced sea-ice cover) cause stronger lateral mixing in the upper ocean, thus eroding horizontal density gradients

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which drive the ocean circulation over the continental shelf (Jendersie and others, 2018). Even with potentially warmer and more accessible CDW, a slowed circulation between ice shelves and the deep Southern Ocean would transport less oceanic heat sourced from CDW towards the ice-shelf cavity, possibly reducing Mode 2 melting (Jendersie and others, 2018).

An observed increase in wind speeds over the ACC over the past five decades (Marshall, 2003) might be linked to the poleward shift of southern hemisphere Westerlies caused by global warming (Russell and others, 2006). The resulting increased overturning transport within the ACC through enhanced eddy activity (Hallberg and Gnanadesikan, 2006; Meredith and Hogg, 2006; Hogg and others, 2008; Meredith and others, 2012) has possibly made CDW more available to some parts of the Antarctic continental shelf already (Thoma and others, 2008; Dinniman and others, 2012; Gille and others, 2016).

Its wind-related shallower residence may contribute to the growing CDW-sourced heat exposure and melting of ice shelves along the West Antarctic Peninsula seen today (Rignot, 2008; Jenkins and others, 2010; Dinniman and others, 2011, 2012). Timmermann and Hellmer (2013) predict that increased CDW transport to the grounding line of the Filchner–Ronne Ice Shelf will lead to four to six times higher basal mass loss by the next century, potentially making the occurrence of platelet ice less likely. For the Ross Sea on the other hand, simulations suggest a reduction in on-shelf transport of CDW over the next 100 years (Smith and others, 2014), thus decreasing potential Mode 2 melting. Therefore, the modification of the Ross Ice Shelf from a cold-cavity to a warm-cavity ice shelf is unlikely over the next 100 years. Platelet-ice formation is therefore still likely to occur in this region, which includes the McMurdo Ice Shelf, on that timescale.

Other conceivable climate change related impacts on future Modes 1 and 3 melting and subsequent platelet-ice formation are the observed freshening in the Ross Sea (Jacobs and others, 2002; Assmann and Timmermann, 2005; Jacobs and Giulivi, 2010), and a possible strengthening of the stratification of the upper water column through a fresher and warmer summer surface mixed layer. Lower salinity HSSW may decrease the deep basal melting under ice shelves (Hellmer and Jacobs, 1995) thus slowing the local thermohaline overturning circulation. A prolonged surface freshwater layer may prevent ISW from rising to shallower depths and reaching in situ supercooling state. Conversely, fresher surface water with a higher freezing temperature facilitates earlier sea-ice formation, HSSW production and deep convection, which in turn decreases the stratification.

Clearly, with the multitude of mutually compensating processes mentioned here, more research is needed to detail and quantify the complex interaction between the various mechanisms involved, which govern the formation and melting of sea ice and platelet ice, heat advection into ice-shelf cavities, and the evolution of CDW access to ice shelves under global warming conditions.

9. Conclusions

First, our literature study shows that there seems to be a substantial body of research available that is associated with platelet ice in one way or another, certainly more than one would see at the first glance when, for example, conducting a keyword search on the common scientific portals. The knowledge is, however, extremely scattered, partly because the terminology has never been clearly defined. This paper tries to change that, by making authors of future studies aware of the issue and proposing terminology which should be used in the most consistent way possible, and that terminology is being adopted by the next update of JCOMM Expert Team on Sea Ice (2015).

Second, we conclude that the formation and presence of platelet ice, especially in its semi-consolidated form (sub-ice platelet layer), plays an exceptionally important role in a number of regions of coastal Antarctica that are associated with cold ice-shelf cavities. In an attempt to illustrate the far-reaching impacts for those regions, we compiled a scheme that summarises all the different aspects which have been touched upon in this paper (Fig. 6).

Third, most of the current knowledge and understanding of the processes related to platelet ice stems from observations in key areas like the Ross and eastern Weddell Seas, owing to only a small number of dedicated research programmes. Of the existing fast-ice and platelet-ice datasets, McMurdo Sound clearly stands out with its more than 100 year history of observations (Langhorne and others, 2015). In a few other regions, monitoring programmes have been established more recently, such as in Atka Bay (Arndt and others, 2020), and near Rektangelbukta (personal communication from Gerland and others, 2019).

Ocean–ice shelf interaction has become an important topic in polar research in recent years, and many initiatives were founded for this purpose or have already incorporated relevant elements into their research programmes (e.g. the Forum for Research into Ice Shelf Processes FRISP; the Southern Ocean Observing System SOOS, Rintoul and others, 2011; Observing and Understanding the Ocean below Antarctic Sea Ice and Ice Shelves OASIIS, Rintoul and others, 2014; the Antarctic Fast Ice Network, Heil and others, 2011; the Ross Ice Shelf Programme (Antarctica New Zealand) and many more). More engagement from these networks is however necessary to better guide and coordinate the international efforts with regards to fast ice and platelet ice. This could be done by providing best practice and standard operating procedures to help establish more monitoring sites at wintering stations, as well as to collect and maintain a database of all the scattered published and particularly the unpublished observations.

Fourth, only integrated, multidisciplinary research programmes are able to advance our knowledge of the many platelet-ice processes and their complicated linkages beyond the properties of the physical system. Therefore, we recommend that any new research project on the platelet-ice system be designed on a multidisciplinary basis, even though this can be challenging. Such a project needs to include process studies and long-term monitoring alike.

Fifth, to achieve a more complete and comprehensive picture of its physical properties, distribution, seasonal evolution and the associated biological processes and biogeochemical cycles, the observational techniques related to platelet ice have to be improved. There is some hope that recently developed technologies such as electronmagnetic sensing methods and improved thermistor chains, as well as the application of research platforms such as aircraft, ROVs and AUVs will be able to provide this. There is still a long way to go until we are able to study platelet ice with a much more integrated approach, in much greater detail and on much larger scales than currently feasible. Another gap is the lack of interaction between the observational and numerical studies, which currently do not provide enough feedback between each other. As pointed out in our third conclusion above, although there are initiatives and networks that are gathering observations on platelet-ice processes, there is not an over-arching coordination of efforts with regards to procedures, winter data gathering or data management. This lack of communication hinders analysis and comparison of data, especially unpublished or hard-to-find historical data. Long-term monitoring is difficult to obtain support for in most national Antarctic programmes,

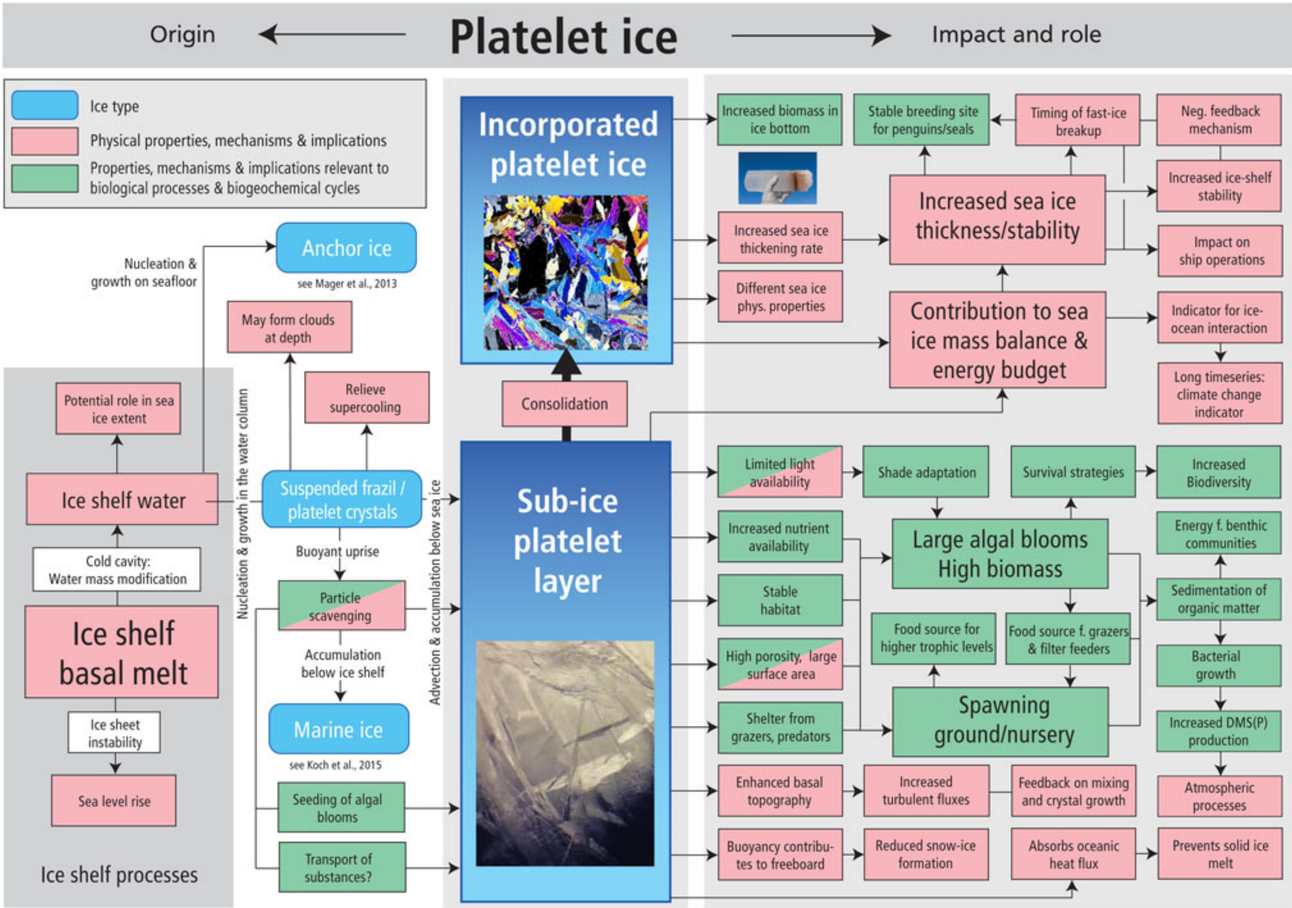

Fig. 6. Overview of origin (left) and implications (right) of platelet ice. Several aspects related to the role of incorporated platelet ice on the right also apply more generally to fast ice itself (see also Fraser and others, 2012), with the presence of platelet ice further enhancing these effects.

yet is critical for evaluating changes in systems such as ocean–ice-shelf systems. Very few research groups or projects related to platelet ice include observationalists, process modellers and larger-scale (e.g. climate and ocean–ice shelf–sea ice) modellers. These kinds of close collaborations need to be resourced at an appropriate level of time, money and logistics to be able to ensure the following occur: ground-truthing models against observations; having enough observations to constrain models; and knowing whether or not the models are missing components/physics that have been observed in the field. Modellers, for example, would like to know how common platelet ice is and how much of an effect it will have on climate-scale results. Observationalists, on the other hand, would like to know where ocean–ice shelf–sea ice models predict platelet ice will occur and therefore where observations should be carried out to test these predictions. A significant gap also exists with regards to ecological modelling of the platelet layer system, which has so far not extended beyond the skeletal layer at the sea ice underside (Arrigo and others, 1993a).

Sixth, it is extremely difficult to make accurate general statements about the implications of climate change on platelet-ice processes that are more than just speculation or educated guesses. Although so far no significant changes in the occurrence and seasonality of platelet ice have been observed, at least in the Ross and Eastern Weddell Seas (Langhorne and others, 2015; Arndt and others, 2020, respectively), that might not be the case in so far unmonitored locations. It is therefore crucially important that we tackle these issues sooner rather than later, before the significant changes related to the changing climate, as currently observed in West Antarctica and several of the East Antarctic glaciers, spread further.

Finally, we can safely say that the realms of sub-ice platelet layers are one of the least explored and at the same time highly productive ecosystems on our planet, inhabited by a multitude of yet undiscovered (micro-) organisms. We urgently need to improve our understanding of these systems and the complex inter-linkages with their environment to better advise stakeholders and decision makers how to preserve them.

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References

Ackley SF and Sullivan CW (1994) Physical controls on the development and characteristics of Antarctic sea ice biological communities — a review and synthesis. *Deep Sea Research Part I: Oceanographic Research Papers* **41**(10), 1583–1604. doi: 10.1016/0967-0637(94)90062-0.

Adcroft A and 28 others (2019) The GFDL Global Ocean and Sea Ice Model OM4.0: Model Description and Simulation Features. *Journal of Advances in Modeling Earth Systems* **11**, 3167–3211. doi: 10.1029/2019ms001726.

Archer SD, Leakey RJG, Burkill PH, Sleigh MA and Appleby CJ (1996) Microbial ecology of sea ice at a coastal Antarctic site: community composition, biomass and temporal change. *Marine Ecology Progress Series* **135** (1–3), 179–195. doi: 10.3354/Meps135179.

Archie GE (1942) The electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of the AIME* **146**(1), 54–62. doi: 10.2118/942054-g.

Arndt S, Hoppmann M, Schmithüsen H, Fraser AD and Nicolaus M (2020) Seasonal and interannual variability of landfast sea ice in Atka Bay, Weddell Sea, Antarctica. *The Cryosphere* **2020**. doi: 10.5194/tc-2019-293.

Arrigo KR and 5 others (1995) High-resolution study of the platelet ice ecosystem in McMurdo Sound, Antarctica – biomass, nutrient, and production profiles within a dense microalgal bloom. *Marine Ecology Progress Series* **127**(1-3), 255–268. doi: 10.3354/meps127255.

Arrigo KR (2016) Sea ice as a habitat for primary producers. In Thomas, DN ed. *Sea Ice*, chapter 14, Chichester, UK and Hoboken, NJ: John Wiley & Sons, Ltd, pp. 352–369. doi: 10.1002/9781118778371.ch14.

Arrigo K, Dieckmann G, Gosselin M and Sullivan CLB (1991) Studies on nutrient status in sea ice and underlying platelet layer of McMurdo Sound. *Antarctic Journal of the U.S.* **25**, 185–188.

Arrigo KR, Kremer JK and Sullivan CW (1993a) A simulated Antarctic fast ice ecosystem. *Journal of Geophysical Research: Oceans* **98**(C4), 6929–6946. doi: 10.1029/93jc00141.

Arrigo KR, Mock T and Lizotte MP (2010) Primary Producers and Sea Ice. In Thomas DN and Dieckmann GS eds. *Sea Ice*, chapter 8, Chichester, UK and Hoboken, NJ: John Wiley & Sons, Ltd, pp. 283–325. doi: 10.1002/9781444317145.ch8.

Arrigo KR, Robinson DH and Sullivan CW (1993b) A high-resolution study of the platelet ice ecosystem in McMurdo Sound, Antarctica: photosynthetic and biooptical characteristics of a dense microalgal bloom. *Marine Ecology Progress Series* **98**(1–2), 173–185.

Arrigo KR and Thomas DN (2004) Large scale importance of sea ice biology in the Southern Ocean. *Antarctic Science* **16**(4), 471–486. doi: 10.1017/s0954102004002263.

Asper V and 6 others (2011) Using gliders to study a phytoplankton bloom in the Ross Sea, Antarctica. In *OCEANS 2011*, 1–7, IEEE. doi: 10.23919/oceans.2011.6107082.

Assmann KM and Timmermann R (2005) Variability of dense water formation in the Ross Sea. *Ocean Dynamics* **55**(68). doi: 10.1007/s10236-004-0106-7.

Baranov GI, Nazintsev YL and Cherepanov NV (1969) Formation conditions and certain properties of Antarctic sea ice (according to observations of 1963). In *Collected Papers of Soviet Antarctic Expeditions*, Volume 38, translated from Russian by Israel Program for Scientific Translations, Jerusalem, 1969.

Barbraud C and Weimerskirch H (2001) Emperor penguins and climate change. *Nature* **411**(6834), 183–186. doi: 10.1038/35075554.

Barry JP (1988) Hydrographic patterns in McMurdo Sound, Antarctica and their relationship to local benthic communities. *Polar Biology* **8**(5), 377–391. doi: 10.1007/bf00442029.

Barry JP and Dayton PK (1988) Current patterns in McMurdo Sound, Antarctica and their relationship to local biotic communities. *Polar Biology* **8**(5), 367–376. doi: 10.1007/bf00442028.

Barry JP, Dayton PK, Dunbar R and Leventer-Reed AR (1990) Winter oceanographic observations in McMurdo Sound. *Antarctic Journal of the United States* **25**(5), 106–107.

Bintanja R, van Oldenborgh GJ, Drijfhout SS, Wouters B and Katsman CA (2013) Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature Geoscience* **6**(5), 376–379. doi: 10.1038/ngeo1767.

Bintanja R, van Oldenborgh GJ and Katsman CA (2015) The effect of increased fresh water from Antarctic ice shelves on future trends in Antarctic sea ice. *Annals of Glaciology* **56**(69), 120–126. doi: 10.3189/2015AoG69A001.

Brett GM and 5 others (2020) Variability in the distribution of fast ice and the sub-ice platelet layer near McMurdo ice shelf. *Journal of Geophysical Research: Oceans* **125**(3). doi: 10.1029/2019jc015678.

Bronselaer B and 7 others (2018) Change in future climate due to Antarctic meltwater. *Nature* **564**(7734), 53–58. doi: 10.1038/s41586-018-0712-z.

Brunt KM, Sergienko O and MacAyeal DR (2006) Observations of unusual fast-ice conditions in the southwest Ross Sea, Antarctica: preliminary analysis of iceberg and storminess effects. *Annals of Glaciology* **44**, 183–187. doi: 10.3189/172756406781811754.

Buffo JJ, Schmidt BE and Huber C (2018) Multiphase reactive transport and platelet ice accretion in the sea ice of McMurdo Sound, Antarctica. *Journal of Geophysical Research: Oceans* **123**(1), 324–345. doi: 10.1002/2017jc013345.

Bunt JS (1963) Microbiology of Antarctic sea-ice: diatoms of Antarctic sea-ice as agents of primary production. *Nature* **199**(4900), 1255–1257. doi: 10.1038/1991255a0.

Bunt JS (2013a) Primary productivity under sea ice in Antarctic waters: 1. Concentrations and photosynthetic activities of microalgae in the waters of McMurdo Sound, Antarctica. In *Biology of the Antarctic Seas*. Washington, D.C.: American Geophysical Union, pp. 13–26. doi: 10.1029/ar001p0013.

Bunt JS (2013b) Primary productivity under sea ice in Antarctic waters: 2. Influence of light and other factors on photosynthetic activities of Antarctic marine microalgae. In *Biology of the Antarctic Seas*. Washington, D.C.: American Geophysical Union, pp. 27–31. doi: 10.1029/AR001p0027.

Bunt JS and Lee CC (1970) Seasonal primary production in Antarctic sea ice at McMurdo Sound in 1967. *Journal of Marine Research* **28**(3), 304–320.

Bunt JS and Wood EJF (1963) Microbiology of Antarctic Sea-ice: Microalgae and Antarctic Sea-ice. *Nature* **199**, 1254–1257. doi: 10.1038/1991254a0.

Burnett J, Rack F, Zook B and Schmidt B (2015) Development of a borehole deployable remotely operated vehicle for investigation of sub-ice aquatic environments. In *OCEANS'15 MTS/IEEE Washington*, 1–7, IEEE. doi: 10.23919/oceans.2015.7404429.

Buynitskiy VK (1967) Structure, principal properties and strength of Antarctic sea ice. *Soviet Antarctic Expedition Information Bulletin, English Translation* **65**, 504–510.

Carnat G and 9 others (2014) Physical and biological controls on DMS,P dynamics in ice shelf-influenced fast ice during a winter-spring and a spring-summer transitions. *Journal of Geophysical Research: Oceans* **119** (5), 2882–2905. doi: 10.1002/2013jc009381.

Cazenave F, Zook R, Carroll D, Flagg M and Kim S (2011) Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica. *Journal of Ocean Technology* **6**(3), 39–58.

Cheng C and 5 others (2019) Responses of sub-ice platelet layer thickening rate and frazil-ice concentration to variations in ice-shelf water supercooling in McMurdo Sound, Antarctica. *The Cryosphere* **13**(1), 265–280. doi: 10.5194/tc-13-265-2019.

Cherepanov NV and Kozlovskiy AM (1972) Underwater ice in the coastal waters of Antarctica. *Soviet Antarctic Information Bulletin, English Translation* **86**, 335–338.

Cherepanov NV and Kozlovskiy AM (1973) Autumn formation of underwater ice in the Lazarev ice shelf area. *Soviet Antarctic Expedition Information Bulletin* **8**(8), 438–440.

Cimoli E, Meiners KM, Lund-Hansen LC and Lucieer V (2017) Spatial variability in sea-ice algal biomass: an under-ice remote sensing perspective. *Advances in Polar Science* **28**(4), 268–296. doi: 10.13679/j.advps.2017.4.00268.

Cota GF and Smith REH (1991) Ecology of bottom ice algae: III. Comparative physiology. *Journal of Marine Systems* **2**(3), 297–315. doi: 10.1016/0924-7963(91)90038-v.

Craven M, Allison I, Fricker HA and Warner R (2009) Properties of a marine ice layer under the Amery Ice Shelf, East Antarctica. *Journal of Glaciology* **55**(192), 717–728. doi: 10.3189/002214309789470941.

Crocker G (1988) *Physical Processes in Antarctic Landfast Sea Ice*. PhD thesis (University of Cambridge, Cambridge, UK)

Crocker GB and Wadhams P (1989) Modeling Antarctic fast-ice growth. *Journal of Glaciology* **35**(119), 3–8. doi: 10.3189/002214389793701590.

Croxall JP, Trathan PN and Murphy EJ (2002) Environmental change and Antarctic seabird populations. *Science* **297**(5586), 1510–1514. doi: 10.1126/science.1071987.

Cziko P (2019) The McMurdo Oceanographic Observatory. Available at https://moo-antarctica.net/, last checked 2020-07-24.

Dai FF and 5 others (2010) Physical structure and vertical distribution of chlorophyll a in winter sea ice from the northwestern Weddell Sea, Antarctica. *Acta Oceanologica Sinica* **29**(3), 97–105. doi: 10.1007/s13131-010-0041-z.

Daly SF (1984) Frazil Ice Dynamics, 84-1. US Cold Regions Research and Engineering Laboratory, Hanover, NH, USA.

Daly S (1994) *International Association for Hydraulic Research Working Group on Thermal Regimes: Report on Frazil ice*, Volume **96-23**. Virginia: US Army Cold Regions Research and Research Laboratory.

Daly KL (2013) Physioecology of Juvenile Antarctic Krill (*Euphausia superba*) during spring in ice-covered seas. In Lizotte, MP and Arrigo, KR *Antarctic Sea Ice: Biological Processes, Interactions and Variability*. Washington, D.C.: American Geophysical Union, pp. 183–198.

Davis RW and 7 others (1999) Hunting behavior of a marine mammal beneath the Antarctic fast ice. *Science* **283**(5404), 993–996. doi: 10.1126/science.283.5404.993.

Dayton PK (1989) Interdecadal variation in an Antarctic sponge and its predators from oceanographic climate shifts. *Science* **245**, 1484–1486. doi: 10.1126/science.245.4925.1484.

Dayton PK, Robilliard GA and Devries AL (1969) Anchor ice formation in McMurdo Sound, Antarctica, and its biological effects. *Science* **163**(3864), 273–274. doi: 10.1126/science.163.3864.273.

Deacon GER (1979) The Weddell Gyre. *Deep Sea Research, Part A. Oceanographic Research Papers* **26**(9), 981–995. doi: 10.1016/0198-0149(79)90044-x.

de Jong J and 6 others (2013) Iron in land-fast sea ice of McMurdo Sound derived from sediment resuspension and wind-blown dust attributes to primary productivity in the Ross Sea, Antarctica. *Marine Chemistry* **157**, 24–40. doi: 10.1016/j.marchem.2013.07.001.

Delille B, Jourdain B, Borges AV, Tison JL and Delille D (2007) Biogas (CO_2, O_2, dimethylsulfide) dynamics in spring Antarctic fast ice. *Limnology and Oceanography* **52**(4), 1367–1379. doi: 10.4319/lo.2007.52.4.1367.

Dempsey DE (2008) *Observation and modeling of platelet ice in McMurdo Sound, Antarctica* (Unpublished MSc thesis). University of Otago, Dunedin, New Zealand.

Dempsey DE and 5 others (2010) Observation and modeling of platelet ice fabric in McMurdo Sound, Antarctica. Journal of Geophysical Research: Oceans 115(C1). doi: 10.1029/2008jc005264.

Denny M and 6 others (2011) Anchor ice and benthic disturbance in shallow Antarctic waters: interspecific variation in initiation and propagation of ice crystals. *The Biological Bulletin* **221**(2), 155–163. doi: 10.1086/bblv221n2p155.

Depoorter MA and 6 others (2013) Calving fluxes and basal melt rates of Antarctic ice shelves. *Nature* **502**(7469), 89–92. doi: 10.1038/nature12567.

Dieckmann GS, Arrigo K and Sullivan CW (1992) A high-resolution sampler for nutrient and chlorophyll-a profiles of the sea ice platelet layer and underlying water column below fast ice in polar oceans – preliminary results. *Marine Ecology Progress Series* **80**(2–3), 291–300. doi: 10.3354/meps080291.

Dieckmann G, Hemleben C and Spindler M (1987) Biogenic and mineral inclusions in a green iceberg from the Weddell Sea, Antarctica. *Polar Biology* **7**(1), 31–33. doi: 10.1007/BF00286821.

Dieckmann G, Rohardt G, Hellmer H and Kipfstuhl J (1986) The occurrence of ice platelets at 250 m depths near the Filchner Ice Shelf and its significance for sea ice biology. *Deep Sea Research, Part A. Oceanographic Research Papers* **33**(2), 141–148. doi: 10.1016/0198-0149(86)90114-7.

Dierckx M, Peternell M, Schroeder C and Tison JL (2014) Influence of pre-existing microstructure on mechanical properties of marine ice during compression experiments. *Journal of Glaciology* **60**(221), 576–586. doi: 10.3189/2014JoG13J154.

Dierckx M and Tison JL (2013) Marine ice deformation experiments: an empirical validation of creep parameters. *Geophysical Research Letters* **40**(1), 134–138. doi: 10.1029/2012GL054197.

Dinniman MS and 5 others (2016) Modeling ice shelf/ocean interaction in Antarctica: a review. *Oceanography* **29**(4), 144–153. doi: 10.5670/oceanog.2016.106.

Dinniman MS, Klinck JM and Hofmann EE (2012) Sensitivity of Circumpolar Deep Water transport and ice shelf basal melt along the West Antarctic Peninsula to changes in the winds. *Journal of Climate* **25**(14), 4799–4816. doi: 10.1175/JCLI-D-11-00307.1.

Dinniman MS, Klinck JM and Smith WO (2007) Influence of sea ice cover and icebergs on circulation and water mass formation in a numerical circulation model of the Ross Sea, Antarctica. *Journal of Geophysical Research: Oceans* **112**(C11). doi: 10.1029/2006jc004036.

Dinniman MS, Klinck JM and Smith WO (2011) A model study of Circumpolar Deep Water on the West Antarctic Peninsula and Ross Sea continental shelves. *Deep Sea Research, Part II: Topical Studies in Oceanography* **58**(13-16), 1508–1523. doi: 10.1016/j.dsr2.2010.11.013.

Eicken H (1993) Automated image analysis of ice thin sections – instrumentation, methods and extraction of stereological and textural parameters. *Journal of Glaciology* **39**(132), 341–352. doi: 10.3189/s0022143000016002.

Eicken H (1998) Deriving modes and rates of ice growth in the Weddell Sea from microstructural, salinity and stable-isotope data. In Jeffries MO ed. *Antarctic Sea ice: Physical Processes, Interactions and Variability*, volume **74** Washington, D.C.: American Geophysical Union, pp. 89–122. doi: 10.1029/ar074p0089.

Eicken H and Lange MA (1989) Development and properties of sea ice in the coastal regime of the Southeastern Weddell Sea. *Journal of Geophysical Research: Oceans* **94**(C6), 8193–8206. doi: 10.1029/Jc094ic06p08193.

Eicken H, Oerter H, Miller H, Graf W and Kipfstuhl J (1994) Textural characteristics and impurity content of meteoric and marine ice in the Ronne Ice Shelf, Antarctica. *Journal of Glaciology* **40**(135), 386–398. doi: 10.3189/s0022143000007474.

Fahrbach E, Rohardt G, Schröder M and Strass V (1994) Transport and structure of the Weddell Gyre. *Annales Geophysicae*, Vol. 12, 840–855. doi: 10.1007/s00585-994-0840-7.

Fedotov VI, Cherepanov NV and Tyshko KP (1998) Some features of the growth, structure and metamorphism of East Antarctic landfast ice. In Jeffries MO (ed.), *Antarctic Sea Ice: Physical Processes, Interactions and Variability, Volume 74 of Antarctic Research Series*, Washington, D.C.: American Geophysical Union, pp. 141–160. doi: 10.1029/AR074p0343.

Foldvik A and Kvinge T (1974) Conditional instability of seawater at the freezing point. *Deep Sea Research and Oceanographic Abstracts* **21**(3), 169–174. doi: 10.1016/0011-7471(74)90056-4.

Foldvik A and Kvinge T (1977) Thermohaline convection in the vicinity of an ice shelf. In Dunbar MJ (ed.), *Polar Oceans, Proceedings of the Polar Oceans Conference Held at McGill University*, Montreal, May, 1974, Calgary, Alberta: Arctic Institute of North America, pp. 247–255.

Fraser AD, Massom RA, Michael KJ, Galton-Fenzi BK and Lieser JL (2012) East Antarctic landfast sea ice distribution and variability, 2000–08. *Journal of Climate* **25**(4), 1137–1156. doi: 10.1175/jcli-d-10-05032.1.

Frazer TK (1996) Stable isotope composition ($\delta^{13}C$ and $\delta^{15}N$) of larval krill, *Euphausia superba*, and two of its potential food sources in winter. *Journal of Plankton Research* **18**(8), 1413–1426. doi: 10.1093/plankt/18.8.1413.

Fretwell P and 59 others (2013) Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere* **7**(1), 375–393. doi: 10.5194/tc-7-375-2013.

Fricker HA, Popov S, Allison I and Young N (2001) Distribution of marine ice beneath the Amery Ice shelf. *Geophysical Research Letters* **28**(11), 2241–2244. doi: 10.1029/2000gl012461.

Fritsen CH, Wirthlin ED, Momberg DK, Lewis MJ and Ackley SF (2011) Bio-optical properties of Antarctic pack ice in the early austral spring. *Deep Sea Research Part II: Topical Studies in Oceanography* **58**(9-10), 1052–1061. doi: 10.1016/j.dsr2.2010.10.028.

Galea HR and 5 others (2016) *Glaciambulata neumayeri* gen. et sp. nov., a new Antarctic trachymedusa (Cnidaria: Hydrozoa), with a revision of the family Ptychogastriidae. *European Journal of Taxonomy* **252**, 1–30. doi: 10.5852/ejt.2016.252.

Garrison DL, Ackley SF and Buck KR (1983) A physical mechanism for establishing algal populations in frazil ice. *Nature* **306**(5941), 363–365. doi: 10.1038/306363a0.

Garrison DL, Close AR and Reimnitz E (1988) Algae concentrated by frazil ice: evidence from laboratory experiments and field measurements. *Antarctic Science* **1**(4), 313–316. doi: 10.1017/s0954102089000477.

Gartner JW (2004) Estimating suspended solids concentrations from backscatter intensity measured by acoustic Doppler current profiler in San Francisco Bay, California. *Marine Geology* **211**(3–4), 169–187. doi: 10.1016/j.margeo.2004.07.001.

Ghobrial TR, Loewen MR and Hicks F (2012) Laboratory calibration of upward looking sonars for measuring suspended frazil ice concentration. *Cold Regions Science and Technology* **70**, 19–31. doi: 10.1016/j.coldregions.2011.08.010.

Ghobrial TR, Loewen MR and Hicks FE (2013) Characterizing suspended frazil ice in rivers using upward looking sonars. *Cold Regions Science and Technology* **86**, 113–126. doi: 10.1016/j.coldregions.2012.10.002.

Gille ST, McKee DC and Martinson DG (2016) Temporal changes in the Antarctic circumpolar current: implications for the Antarctic continental shelves. *Oceanography* **29**(4), 96–105. doi: 10.5670/oceanog.2016.102.

Gonzales HE (1992) Distribution and abundance of minipellets around the Antarctic Peninsula. Implications for protistan feeding behaviour. *Marine Ecology Progress Series* **90**, 223–236.

Goodwin ID (1993) Basal ice accretion and debris entrainment within the coastal ice margin, Law dome, Antarctica. *Journal of Glaciology* **39**(131), 157–166. doi: 10.1017/s002214300001580x.

Gough A and 6 others (2010) Supercooling and seeding: oceanographic disruption of preferred crystal orientation in sea ice growing near ice shelves. In Proceedings of the 20th IAHR International Symposium on Ice, 14-17 June 2010, Lahti, Finland. International Association of Hydraulic Engineering and Research, Lahti.

Gough AJ and 5 others (2012b) Signatures of supercooling: McMurdo Sound platelet ice. *Journal of Glaciology* **58**(207), 38–50. doi: 10.3189/2012jog10j218.

Gough AJ, Mahoney AR, Langhorne PJ, Williams MJM and Haskell TG (2012a) Sea ice salinity and structure: a winter time series of salinity and its distribution. *Journal of Geophysical Research* **117**(C3). doi: 10.1029/2011jc007527.

Gow AJ, Ackley SF, Govoni JW and Weeks WF (1998) Physical and structural properties of land-fast sea ice in McMurdo Sound, Antarctica. In *Antarctic Sea Ice: Physical Processes, Interactions and Variability*. Washington, D.C.: American Geophysical Union, pp. 355–374. doi: 10.1029/AR074p0355.

Gow AJ, Ackley SF, Weeks WF and Govoni JW (1982) Physical and structural characteristics of Antarctic sea ice. *Annals of Glaciology* **3**, 113–117. doi: 10.3189/s0260305500002627.

Gow AJ and Epstein SS (1972) On the use of stable isotopes to trace the origins of ice in a floating ice tongue. *Journal of Geophysical Research* **77**(33), 6552–6557. doi: 10.1029/jc077i033p06552.

Grossmann S, Lochte K and Scharek R (1996) Algal and bacterial processes in platelet ice during late austral summer. *Polar Biology* **16**(8), 623–633. doi: 10.1007/bf02329060.

Grumbine RW (1991) A model of the formation of high-salinity shelf water on polar continental shelves. *Journal of Geophysical Research: Oceans* **96** (C12), 22049–22062. doi: 10.1029/91JC00531.

Guglielmo L and 8 others (2000) Structural and functional properties of sympagic communities in the annual sea ice at Terra Nova Bay (Ross Sea, Antarctica). *Polar Biology* **23**(2), 137–146. doi: 10.1007/s003000050019.

Guglielmo L, Zagami G, Saggiomo V, Catalano G and Granata A (2007) Copepods in spring annual sea ice at Terra Nova Bay (Ross Sea, Antarctica). *Polar Biology* **30**(6), 747–758. doi: 10.1007/s00300-006-0234-2.

Günther S and Dieckmann GS (1999) Seasonal development of algal biomass in snow-covered fast ice and the underlying platelet layer in the Weddell Sea, Antarctica. *Antarctic Science* **11**(3), 305–315. doi: 10.1017/s0954102099000395.

Günther S and Dieckmann GS (2001) Vertical zonation and community transition of sea-ice diatoms in fast ice and platelet layer, Weddell Sea, Antarctica. *Annals of Glaciology* **33**, 287–296. doi: 10.3189/172756401781818590.

Günther S, George KH and Gleitz M (1999a) High sympagic metazoan abundance in platelet layers at Drescher Inlet, Weddell Sea, Antarctica. *Polar Biology* **22**(2), 82–89. doi: 10.1007/s003000050393.

Günther S, Gleitz M and Dieckmann GS (1999b) Biogeochemistry of Antarctic sea ice: a case study on platelet ice layers at Drescher Inlet, Weddell Sea. *Marine Ecology Progress Series* **177**, 1–13. doi: 10.3354/meps177001.

Gutt J (2002) The Antarctic ice shelf: an extreme habitat for notothenioid fish. *Polar Biology* **25**(4), 320–322. doi: 10.1007/s00300-001-0352-9.

Haas C (2006) Airborne electromagnetic sea ice thickness sounding in shallow, brackish water environments of the Caspian and Baltic Seas. In *25th International Conference on Offshore Mechanics and Arctic Engineering*, 717–722, American Society of Mechanical Engineers, ASME. doi: 10.1115/omae2006-92369.

Haas C and Druckenmiller M (2009) Ice thickness and roughness measurements. In Eicken H (ed.), *Field Techniques for Sea Ice Research*, chapter 3.2, Fairbanks: University of Alaska Press, pp. 49–116.

Haas C, Gerland S, Eicken H and Miller H (1997) Comparison of sea-ice thickness measurements under summer and winter conditions in the Arctic using a small electromagnetic induction device. *Geophysics* **62**(3), 749–757. doi: 10.1190/1.1444184.

Hallberg R and Gnanadesikan A (2006) The role of eddies in determining the structure and response of the wind-driven southern hemisphere overturning: results from the Modeling Eddies in the Southern Ocean (MESO) project. *Journal of Physical Oceanography* **36**(12), 2232–2252. doi: 10.1175/JPO2980.1.

Haskell TG, Robinson WH and Langhorne PJ (1996) Preliminary results from fatigue tests on in situ sea ice beams. *Cold Regions Science and Technology* **24**(2), 167–176. doi: 10.1016/0165-232x(95)00015-4.

Hattermann T, Nøst OA, Lilly JM and Smedsrud LH (2012) Two years of oceanic observations below the Fimbul Ice Shelf, Antarctica. *Geophysical Research Letters* **39**(12). doi: 10.1029/2012gl051012.

Heil P, Gerland S and Granskog MA (2011) An Antarctic monitoring initiative for fast ice and comparison with the Arctic. *The Cryosphere Discussions* **5**(5), 2437–2463. doi: 10.5194/tcd-5-2437-2011.

Hellmer HH (2004) Impact of Antarctic ice shelf basal melting on sea ice and deep ocean properties. *Geophysical Research Letters* **31**(L10307). doi: 10.1029/2004GL019506.

Hellmer HH and Jacobs SS (1995) Seasonal circulation under the eastern Ross Ice Shelf, Antarctica. *Journal of Geophysical Research: Oceans* **100**(C6), 10873–10885. doi: 10.1029/95jc00753.

Herraiz-Borreguero L and 5 others (2015) Circulation of modified Circumpolar Deep Water and basal melt beneath the Amery Ice Shelf, east Antarctica. *Journal of Geophysical Research: Oceans* **120**(4), 3098–3112. doi: 10.1002/2015jc010697.

Herraiz-Borreguero L, Allison I, Craven M, Nicholls KW and Rosenberg MA (2013) Ice shelf/ocean interactions under the Amery Ice Shelf: seasonal variability and its effect on marine ice formation. *Journal of Geophysical Research: Oceans* **118**(12), 7117–7131. doi: 10.1002/2013jc009158.

Hodgson TV (1907) On collecting in Antarctic seas, British National Antarctic Expedition, 1901–1904. In *Zoology and Botany*, Volume **3**, London, UK: Trustees of the British Museum, pp. 1–10.

Hogg AM, Meredith M, Blundell JR and Wilson C (2008) Eddy heat flux in the Southern Ocean: response to variable wind forcing. *Journal of Climate* **21**(4), 608–620. doi: 10.1175/2007JCLI1925.1.

Holland PR and 5 others (2014) Modeled trends in Antarctic sea ice thickness. *Journal of Climate* **27**(10), 3784–3801. doi: 10.1175/Jcli-D-13-00301.1.

Holland PR and Feltham DL (2005) Frazil dynamics and precipitation in a water column with depth-dependent supercooling. *Journal of Fluid Mechanics* **530**, 101–124. doi: 10.1017/s002211200400285x.

Hoppmann M and 7 others (2015a) Seasonal evolution of an ice-shelf influenced fast-ice regime, derived from an autonomous thermistor chain. *Journal of Geophysical Research: Oceans* **120**(3), 1703–1724. doi: 10.1002/2014JC010327.

Hoppmann M and 11 others (2015b) Ice platelets below Weddell Sea land-fast sea ice. *Annals of Glaciology* **56**(69), 175–190. doi: 10.3189/2015AoG69A678.

Hughes K (2013) *Propagation of an Ice Shelf Water Plume beneath Sea Ice in McMurdo Sound, Antarctica* (Unpublished MSc thesis) University of Otago.

Hughes KG, Langhorne PJ, Leonard GH and Stevens CL (2014) Extension of an Ice Shelf Water plume model beneath sea ice with application in McMurdo Sound, Antarctica. *Journal of Geophysical Research: Oceans* **119**(12), 8662–8687. doi: 10.1002/2013jc009411.

Hulbe CL, Johnston R, Joughin I and Scambos T (2005) Marine ice modification of fringing ice shelf flow. *Arctic, Antarctic, and Alpine Research* **37** (3), 323–330. doi: 10.1657/1523-0430(2005)037.

Hunkeler PA and 8 others (2016a) Improved 1D inversions for sea ice thickness and conductivity from electromagnetic induction data: inclusion of nonlinearities caused by passive bucking. *Geophysics* **81**(1), WA45–WA58. doi: 10.1190/geo2015-0130.1.

Hunkeler PA, Hendricks S, Hoppmann M, Paul S and Gerdes R (2015) Towards an estimation of sub-sea-ice platelet-layer volume with multi-frequency electromagnetic induction sounding. *Annals of Glaciology* **56** (69), 137–146. doi: 10.3189/2015AoG69A705.

Hunkeler PA, Hoppmann M, Hendricks S, Kalscheuer T and Gerdes R (2016b) A glimpse beneath Antarctic sea ice: platelet layer volume from multifrequency electromagnetic induction sounding. *Geophysical Research Letters* **43**(1), 222–231. doi: 10.1002/2015GL065074.

Hunt BM, Hoefling K and Cheng CHC (2003) Annual warming episodes in seawater temperatures in McMurdo Sound in relationship to endogenous ice in notothenioid fish. *Antarctic Science* **15**(3), 333–338. doi: 10.1017/S0954102003001342.

Ichinomiya M and 5 others (2008) Temporal variations in the abundance and sinking flux of diatoms under fast ice in summer near Syowa Station, East Antarctica. *Polar Science* **2**(1), 33–40. doi: 10.1016/j.polar.2008.01.001.

Iliescu D, Baker I and Chang H (2004) Determining the orientations of ice crystals using electron backscatter patterns. *Microscopy Research and Technique* **63**(4), 183–187. doi: 10.1002/jemt.20029.

IOC and others (2010) The international thermodynamic equation of seawater – 2010: Calculation and use of thermodynamic properties. *Intergovernmental Oceanographic Commission, Manuals and Guides No. 56* (http://hdl.handle.net/11329/286).

Ito M and 7 others (2015) Observations of supercooled water and frazil ice formation in an Arctic coastal polynya from moorings and satellite imagery. *Annals of Glaciology* **56**(69), 307–314. doi: 10.3189/2015aog69a839.

Jackson K and 6 others (2013) A novel and low-cost sea ice mass balance buoy. *Journal of Atmospheric and Oceanic Technology* **30**(11), 2676–2688. doi: 10.1175/jtech-d-13-00058.1.

Jacobs SS (2004) Bottom water production and its links with the thermohaline circulation. *Antarctic Science* **16**(4), 427–437. doi: 10.1017/s095410200400224x.

Jacobs SS, Fairbanks RG and Horibe YG (1985) Origin and evolution of water masses near the Antarctic continental margin: evidence from $H_2^{18}O/H_2^{16}O$ ratios in seawater. In Jacobs, SS *Oceanology of the Antarctic Continental Shelf, Volume 43 of Antarctic Research Series*. Washington, D.C.: American Geophysical Union, pp. 59–85. doi: 10.1029/AR043p0059.

Jacobs SS and Giulivi CF (1999) Thermohaline data and ocean circulation on the Ross Sea continental shelf. In Spezie G and Manzella GMR eds. *Oceanography of the Ross Sea Antarctica*. Milano, Italia: Springer Milan, pp. 3–16.

Jacobs SS and Giulivi CF (2010) Large multidecadal salinity trends near the Pacific–Antarctic continental margin. *Journal of Climate* **23**(17), 4508–4524. doi: 10.1175/2010jcli3284.1.

Jacobs SS, Giulivi CF and Mele PA (2002) Freshening of the Ross Sea during the late 20th century. *Science* **297**(5580), 386–389. doi: 10.1126/science.1069574.

Jacobs SS, Gordon AL and Ardai JL (1979) Circulation and melting beneath the Ross Ice Shelf. *Science* **203**(4379), 439 doi: 10.1126/science.203.4379.439.

Jacobs SS, Hellmer H, Doake CSM, Jenkins A and Frolich R (1992) Melting of ice shelves and the mass balance of Antarctica. *Journal of Glaciology* **38** (130), 375–387. doi: 10.3189/s0022143000002252.

Jacobs SS, Hellmer HH and Jenkins A (1996) Antarctic ice sheet melting in the Southeast Pacific. *Geophysical Research Letters* **23**(9), 957–960. doi: 10.1029/96gl00723.

Jacobs SS, Jenkins A, Giulivi CF and Dutrieux P (2011) Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. *Nature Geoscience* **4**(8), 519–523. doi: 10.1038/ngeo1188.

JCOMM Expert Team on Sea Ice (2015) WMO Sea-Ice Nomenclature I-III. Report No. 259. World Meteorological Organization. http://www.jcomm.info/index.php? option=com_oe&task=viewDocumentRecord&docID=14598.

Jeffries MO and 5 others (1995) Evidence for platelet ice accretion in Arctic sea ice development. *Journal of Geophysical Research: Oceans* **100**(C6), 10905–10914. doi: 10.1029/95jc00804.

Jeffries MO and Adolphs U (1997) Early winter ice and snow thickness distribution, ice structure and development of the western Ross Sea pack ice between the ice edge and the Ross Ice Shelf. *Antarctic Science* **9**(2), 188–200. doi: 10.1017/s0954102097000242.

Jeffries MO and Weeks WF (1992) Structural characteristics and development of sea ice in the western Ross Sea. *Antarctic Science* **5**(1), 63–75. doi: 10.1017/s0954102093000094.

Jeffries MO, Weeks WF, Shaw R and Morris K (1993) Structural characteristics of congelation and platelet ice and their role in the development of Antarctic land-fast sea-ice. *Journal of Glaciology* **39**(132), 223–238. doi: 10.3189/s0022143000015884.

Jendersie S, Williams MJM, Langhorne PJ and Robertson R (2018) The density-driven winter intensification of the Ross Sea circulation. *Journal of Geophysical Research: Oceans* **123**(11), 7702–7724. doi: 10.1029/2018JC013965.

Jenkins A and 6 others (2010) Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat. *Nature Geoscience* **3**(7), 468–472. doi: 10.1038/ngeo890.

Jenkins A and Bombosch A (1995) Modeling the effects of frazil ice crystals on the dynamics and thermodynamics of Ice Shelf Water plumes. *Journal of Geophysical Research: Oceans* **100**(C4), 6967–6981. doi: 10.1029/94jc03227.

Jenkins A, Vaughan DG, Jacobs SS, Hellmer HH and Keys JR (1997) Glaciological and oceanographic evidence of high melt rates beneath Pine Island Glacier, West Antarctica. *Journal of Glaciology* **43**(143), 114–121. doi: 10.3189/s0022143000002872.

Jenouvrier S, Barbraud C and Weimerskirch H (2005) Long-term contrasted responses to climate of two Antarctic seabird species. *Ecology* **86**(11), 2889–2903. doi: 10.1890/05-0514.

Jones SJ and Hill BT (2001) Structure of sea ice in McMurdo Sound, Antarctica. *Annals of Glaciology* **33**, 5–12. doi: 10.3189/172756401781818347.

Jordan JR, Kimura S, Holland PR, Jenkins A and Piggott MD (2015) On the conditional frazil ice instability in seawater. *Journal of Physical Oceanography* **45**(4), 1121–1138. doi: 10.1175/jpo-d-14-0159.1.

Joughin I and Padman L (2003) Melting and freezing beneath Filchner–Ronne Ice Shelf, Antarctica. *Geophysical Research Letters* **30**(9). doi: 10.1029/2003GL016941.

Katlein C, Arndt S, Belter HJ, Castellani G and Nicolaus M (2019) Seasonal evolution of light transmission distributions through Arctic sea ice. *Journal of Geophysical Research: Oceans* **124**(8), 5418–5435. doi: 10.1029/2018jc014833.

Kawano Y and Ohashi T (2008) Effect of salinity diffusion and heat flux on the growth of sea ice microstructure. In *23rd Northern International Symposium*, Volume 23, 1–6, The Okhotsk Sea & Cold Ocean Research Association, Hokkaido, Japan. doi: http://id.nii.ac.jp/1450/00007336/.

Kempema EW, Reimnitz E, Clayton JR and Payne JR (1993) Interactions of frazil and anchor ice with sedimentary particles in a flume. *Cold Regions Science and Technology* **21**(2), 137–149. doi: 10.1016/0165-232x(93)90003-q.

Kerr RC (1994) Melting driven by vigorous compositional convection. *Journal of Fluid Mechanics* **280**, 255–285. doi: 10.1017/s0022112094002922.

Kimura S, Candy AS, Holland PR, Piggott MD and Jenkins A (2013) Adaptation of an unstructured-mesh, finite-element ocean model to the simulation of ocean circulation beneath ice shelves. *Ocean Modelling* **67**, 39–51. doi: 10.1016/j.ocemod.2013.03.004.

Kipfstuhl J (1991) Zur Entstehung von Unterwassereis und das Wachstum und die Energiebilanz des Meereises in der Atka Bucht, Antarktis. *Berichte zur Polar- und Meeresforschung* **85**, 1–88.

Kipfstuhl J, Dieckmann GS, Oerter H, Hellmer H and Graf W (1992) The origin of green icebergs in Antarctica. *Journal of Geophysical Research: Oceans* **97**(C12), 20319–20324. doi: 10.1029/92jc01754.

Kirillov S and 8 others (2018) The inferred formation of a subice platelet layer below the multiyear landfast sea ice in the Wandel Sea (NE Greenland) induced by meltwater drainage. *Journal of Geophysical Research: Oceans* **123**(5), 3489–3506. doi: 10.1029/2017jc013672.

Klages N (1989) Food and feeding ecology of emperor penguins in the eastern Weddell Sea. *Polar Biology* **9**(6), 385–390. doi: 10.1007/BF00442529.

Koch I, Fitzsimons S, Samyn D and Tison JL (2015) Marine ice recycling at the southern McMurdo Ice shelf, Antarctica. *Journal of Glaciology* **61**(228), 689–701. doi: 10.3189/2015JoG14J095.

Kottmeier ST, Grossi SM and Sullivan CW (1987) Sea ice microbial communities. VIII. Bacterial production in annual sea ice of McMurdo Sound, Antarctica. *Marine Ecology Progress Series* **35**, 175–186. doi: 10.3354/meps035175.

Kozlovsky A, Nazintsev YL, Fedotov VI and Cherepanov NV (1977) Fast ice of the Eastern Antarctic. *Proceedings of the Soviet Antarctic Expedition* (in Russian) **63**, 1–129.

Kulessa B, Jansen D, Luckman AJ, King EC and Sammonds PR (2014) Marine ice regulates the future stability of a large Antarctic ice shelf. *Nature Communications* **5(3707)**. doi: 10.1038/ncomms4707.

Kurtz NT and Markus T (2012) Satellite observations of Antarctic sea ice thickness and volume. *Journal of Geophysical Research: Oceans* **117**(C8), C08025. doi: 10.1029/2012JC008141.

La Mesa M, Eastman JT and Vacchi M (2004) The role of notothenioid fish in the food web of the Ross Sea shelf waters: a review. *Polar Biology* **27**(6), 321–338. doi: 10.1007/s00300-004-0599-z.

Lange MA (1988) Basic properties of Antarctic sea ice as revealed by textural analysis of ice cores. *Annals of Glaciology* **10**, 95–101. doi: 10.3189/s0260305500004249.

Lange MA, Ackley SF, Wadhams P, Dieckmann GS and Eicken H (1989) Development of sea ice in the Weddell Sea. *Annals of Glaciology* **12**, 92–96. doi: 10.3189/s0260305500007023.

Langhorne PJ and 12 others (2015) Observed platelet ice distributions in Antarctic sea ice: an index for ocean–ice shelf heat flux. *Geophysical Research Letters* **42**(13), 5442–5451. doi: 10.1002/2015gl064508.

Langhorne PJ and Haskell TG (1999) Sea ice fatigue. In Shen, HT (ed.), *Ice in surface waters: proceedings of the 14th international Symposium on Ice Potsdam, New York, USA, 27–31 July 1998*, A. A. Balkema, Rotterdam, Brookfield: IAHR, pp. 855–862, ISBN: 90 5410 971 8.

Langhorne PJ and Haskell TG (2004) The flexural strength of partially refrozen cracks in sea ice. In *The Fourteenth International Offshore and Polar Engineering Conference, Toulon, France*, International Society of Offshore and Polar Engineers (url: http://www2.physics.otago.ac.nz/research/ice/publications/Langhorne_ISOPE2004.pdf).

Langhorne PJ and Robinson WH (1986) Alignment of crystals in sea ice due to fluid motion. *Cold Regions Science and Technology* **12**(2), 197–214. doi: 10.1016/0165-232x(86)90033-9.

Langhorne PJ, Squire VA, Fox C and Haskell TG (1998) Break-up of sea ice by ocean waves. *Annals of Glaciology* **27**, 438–442. doi: 10.3189/s0260305500017869.

Langway CC (1959) Ice fabrics and the universal stage. Technical report, US Army Corps of Engineers, Snow Ice and Permafrost Research Establishment.

Lazzara L, Nardello I, Ermanni C, Mangoni O and Saggiomo V (2007) Light environment and seasonal dynamics of microalgae in the annual sea ice at Terra Nova Bay, Ross Sea, Antarctica. *Antarctic Science* **19**(1), 83–92. doi: 10.1017/S0954102007000119.

Leonard GH and 5 others (2006) Observations of platelet ice growth and oceanographic conditions during the winter of 2003 in McMurdo Sound, Antarctica. *Journal of Geophysical Research: Oceans* **111**(C4). doi: 10.1029/2005jc002952.

Leonard GH and 7 others (2011) Evolution of supercooling under coastal Antarctic sea ice during winter. *Antarctic Science* **23**(4), 399–409. doi: 10.1017/S0954102011000265.

Leonard JJ and Bahr A (2016) Autonomous underwater vehicle navigation. In Dhanak MR and Xiros NI eds. *Springer Handbook of Ocean Engineering*, Cham, Switzerland: Springer International Publishing, pp. 341–358. doi: 10.1007/978-3-319-16649-0_14.

Lewis EL and Perkin RG (1983) Supercooling and energy exchange near the Arctic ocean surface. *Journal of Geophysical Research: Oceans* **88**(C12), 7681–7685. doi: 10.1029/JC088iC12p07681.

Lewis EL and Perkin RG (1986) Ice pumps and their rates. *Journal of Geophysical Research* **91**(C10), 11756–11762. doi: 10.1029/jc091ic10p11756.

Littlepage JL (1965) Oceanographic investigations in McMurdo Sound, Antarctica. In Llano, GA *Biology of the Antarctic Seas II, Volume 5 of Antarctic Research Series*. Washington, D.C.: American Geophysical Union, pp. 1–37. doi: 10.1029/AR005p0001.

Lizotte MP and Sullivan CW (1991) Photosynthesis-irradiance relationships in microalgae associated with Antarctic pack ice – evidence for in situ activity. *Marine Ecology Progress Series* **71**(2), 175–184. doi: 10.3354/meps071175.

Losch M (2008) Modeling ice shelf cavities in a z coordinate ocean general circulation model. *Journal of Geophysical Research: Oceans* **113**(C8). doi: 10.1029/2007jc004368.

Lucieer V, Nau A, Forrest A and Hawes I (2016) Fine-scale sea ice structure characterized using underwater acoustic methods. *Remote Sensing* **8**(10), 821. doi: 10.3390/rs8100821.

MacAyeal DR (1984) Thermohaline circulation below the Ross Ice Shelf: a consequence of tidally induced vertical mixing and basal melting. *Journal of Geophysical Research: Oceans* **89**(C1), 597–606. doi: 10.1029/jc089ic01p00597.

MacAyeal DR and Holdsworth G (1986) An investigation of low-stress ice rheology on the ward-hunt ice shelf. *Journal of Geophysical Research: Solid Earth* **91**(B6), 6347–6358. doi: 10.1029/JB091iB06p06347.

Mager SM, Smith IJ, Kempema EW, Thomson BJ and Leonard GH (2013) Anchor ice in polar oceans. *Progress in Physical Geography* **37**(4), 468–483, ISSN 0309-1333. doi: 10.1177/0309133313479815.

Mahoney AR and 6 others (2011) The seasonal appearance of Ice Shelf Water in coastal Antarctica and its effect on sea ice growth. *Journal of Geophysical Research: Oceans* **116**(C11), ISSN 0148-0227. doi: 10.1029/2011jc007060.

Mahoney A and Gearheard S (2008) Handbook for community based sea ice monitoring. NSIDC Special Report 14. Boulder, Colorado: National Snow and Ice Data Center (https://nsidc.org/sites/nsidc.org/files/files/nsidc_special_report_14.pdf).

Mahoney A, Gearheard S, Oshima T and Qillaq T (2009) Sea ice thickness measurements from a community-based observing network. *Bulletin of the American Meteorological Society* **90**(3), 370–377. doi: 10.1175/2008bams2696.1.

Makinson K and Nicholls KW (1999) Modeling tidal currents beneath Filchner–Ronne Ice Shelf and on the adjacent continental shelf: their effect on mixing and transport. *Journal of Geophysical Research: Oceans* **104**(C6), 13449–13465. doi: 10.1029/1999JC900008.

Malyarenko A, Robinson NJ, Williams MJM and Langhorne PJ (2019) A wedge mechanism for summer surface water inflow into the Ross Ice Shelf cavity. *Journal of Geophysical Research: Oceans* **124**(2), 1196–1214. doi: 10.1029/2018jc014594.

Mangoni O and 5 others (2008) The role of platelet ice microalgae in seeding phytoplankton blooms in Terra Nova Bay (Ross Sea, Antarctica): a mesocosm experiment. *Polar Biology* **32**(3), 311–323. doi: 10.1007/s00300-008-0507-z.

Maqueda M, Willmott AJ and Biggs NRT (2004) Polynya dynamics: a review of observations and modeling. *Reviews of Geophysics* **42**(1). doi: 10.1029/2002rg000116.

Marko JR, Jasek M and Topham DR (2015) Multifrequency analyses of 2011–2012 Peace River SWIPS frazil backscattering data. *Cold Regions Science and Technology* **110**, 102–119. doi: 10.1016/j.coldregions.2014.11.006.

Marko JR and Topham DR (2015) Laboratory measurements of acoustic backscattering from polystyrene pseudo-ice particles as a basis for quantitative characterization of frazil ice. *Cold Regions Science and Technology* **112**, 66–86. doi: 10.1016/j.coldregions.2015.01.003.

Marschall HP (1988) The overwintering strategy of Antarctic krill under the pack-ice of the Weddell Sea. *Polar Biology* **9**(2), 129–135. doi: 10.1007/Bf00442041.

Marshall GJ (2003) Trends in the Southern Annular mode from observations and reanalyses. *Journal of Climate* **16**(24), 4134–4143. doi: 10.1175/1520-0442(2003)016<4134:titsam>2.0.co;2.

Martin S (1981) Frazil ice in rivers and oceans. *Annual Review of Fluid Mechanics* **13**, 379–397. doi: 10.1146/annurev.fl.13.010181.002115.

Massom RA and 6 others (2009) Fast ice distribution in Adélie Land, East Antarctica: interannual variability and implications for emperor penguins

Aptenodytes forsteri. *Marine Ecology Progress Series* **374**, 243–257. doi: 10.3354/meps07734.

Massom RA and 7 others (2010) Examining the interaction between multi-year landfast sea ice and the Mertz Glacier Tongue, East Antarctica: another factor in ice sheet stability? *Journal of Geophysical Research* **115**(C12), C12027. doi: 10.1029/2009jc006083.

Massom RA and 5 others (2018) Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell. *Nature* **558**(7710), 383–389. doi: 10.1038/s41586-018-0212-1.

Massom RA, Harris PT, Michael KJ and Potter MJ (1998) The distribution and formative processes of latent-heat polynyas in East Antarctica. *Annals of Glaciology* **27**, 420–426. doi: 10.3189/1998AoG27-1-420-426.

Mathiot P, Jenkins A, Harris C and Madec G (2017) Explicit and parametrised representation of under ice shelf seas in the z* coordinate ocean model NEMO 3.6. *Geoscientific Model Development* **10**(7), 2849–2874. doi: 10.5194/gmd-10-2849-2017.

McFarlane V, Loewen M and Hicks F (2017) Measurements of the size distribution of frazil ice particles in three Alberta rivers. *Cold Regions Science and Technology* **142**, 100–117. doi: 10.1016/j.coldregions.2017.08.001.

McGrath Grossi S, Kottmeier ST, Moe RL, Taylor GT and Sullivan CW (1987) Sea ice microbial communities – VI – growth and primary production in bottom ice under graded snow cover. *Marine Ecology Progress Series* **35**, 153–164.

McPhee MG, Stevens CL, Smith IJ and Robinson NJ (2016) Turbulent heat transfer as a control of platelet ice growth in supercooled under-ice ocean boundary layers. *Ocean Science* **12**(2), 507–515. doi: 10.5194/os-12-507-2016.

Meiners KM and 14 others (2012) Chlorophyll a in Antarctic sea ice from historical ice core data. *Geophysical Research Letters* **39**(21), L21602. doi: 10.1029/2012gl053478.

Meiners KM and 25 others (2018) Chlorophyll-a in Antarctic landfast sea ice: a first synthesis of historical ice core data. *Journal of Geophysical Research: Oceans* **123**(11), 8444–8459. doi: 10.1029/2018JC014245.

Meister M and 9 others (2018) Icefin: Redesign and 2017 Antarctic Field Deployment. In *Proceedings of OCEANS 2018, MTS/IEEE, Charleston*, 1–5, IEEE. doi: 10.1109/OCEANS.2018.8604725.

Meredith MP and Hogg AM (2006) Circumpolar response of Southern Ocean eddy activity to a change in the Southern Annular Mode. *Geophysical Research Letters* **33**(16), L16608. doi: 10.1029/2006GL026499.

Meredith MP, Naveira Garabato AC, Hogg AM and Farneti R (2012) Sensitivity of the overturning circulation in the Southern Ocean to decadal changes in wind forcing. *Journal of Climate* **25**(1), 99–110. doi: 10.1175/2011JCLI4204.1.

Miller LA and 22 others (2015) Methods for biogeochemical studies of sea ice: the state of the art, caveats, and recommendations. *Elementa-Science of the Anthropocene* **3**, 1–53. doi: 10.12952/journal.elementa.000038.

Miyamoto A and 5 others (2005) Ice fabric evolution process understood from anisotropic distribution of *a*-axis orientation on the GRIP (Greenland) ice core. *Annals of Glaciology* **42**, 47–52. doi: 10.3189/172756405781812501.

Miyamoto A, Weikusat I and Hondoh T (2011) Complete determination of ice crystal orientation using Laue X-ray diffraction method. *Journal of Glaciology* **57**(201), 103–110. doi: 10.3189/002214311795306754.

Moretskii VN (1965) Underwater sea ice (in Russian). *Problemy Arktiki i Antarktiki* **19**, 32–38.

Morey RM, Kovacs A and Cox GFN (1984) Electromagnetic properties of sea ice. *Cold Regions Science and Technology* **9**(1), 53–75. doi: 10.21236/ada140330.

Morgan VI (1972) Oxygen isotope evidence for bottom freezing on the Amery Ice Shelf. *Nature* **238**(5364), 393–394. doi: 10.1038/238393a0.

Morse B and Richard M (2009) A field study of suspended frazil ice particles. *Cold Regions Science and Technology* **55**(1), 86–102. doi: 10.1016/j.coldregions.2008.03.004.

Nelson MJS and 5 others (2017) Measurements of Ice Shelf Water beneath the front of the Ross Ice Shelf using gliders. *Annals of Glaciology* **58**(74), 41–50. doi: 10.1017/aog.2017.34.

Nicholls KW (1997) Predicted reduction in basal melt rates of an Antarctic ice shelf in a warmer climate. *Nature* **388**(6641), 460–462. doi: 10.1038/41302.

Nicholls KW, Osterhus S, Makinson K, Gammelsrod T and Fahrbach E (2009) Ice-ocean processes over the continental shelf of the Southern Weddell Sea, Antarctica: a review. *Reviews of Geophysics* **47**(3), RG3003 doi: 10.1029/2007rg000250.

Nicholls KW, Østerhus S, Makinson K and Johnson MR (2001) Oceanographic conditions south of Berkner Island, beneath Filchner–Ronne Ice Shelf, Antarctica. *Journal of Geophysical Research: Oceans*, **106** (C6), 11481–11492. doi: 10.1029/2000jc000350.

Notz D and 5 others (2003) Impact of underwater-ice evolution on Arctic summer sea ice. *Journal of Geophysical Research: Oceans* **108**(C7) doi: 10.1029/2001jc001173.

Obbard RW and 6 others (2016) Synchrotron X-ray fluorescence spectroscopy of salts in natural sea ice. *Earth and Space Science* **3**(11), 463–479. doi: 10.1002/2016EA000172.

Oerter H and 6 others (1992) Evidence for basal marine ice in the Filchner–Ronne ice shelf. *Nature* **358**(6385), 399–401. doi: 10.1038/358399a0.

Ohashi T and Kawano Y (2007) Numerical simulation of salinity diffusion and growth instability in the microstructure evolution of sea ice. In *Proceedings of the 22nd International Symposium on Okhotsk Sea & Sea Ice*, 11–16, Mombetsu, Hokkaido, Japan.

Ohashi T, Sasaki M and Yoshimura K (2004) A numerical simulation of the development of ice-microstructures. In *Proceedings of the 19th International Symposium on Okhotsk Sea & Sea Ice*, 180–185, Mombetsu, Hokkaido, Japan.

Orsi AH and Wiederwohl CL (2009) A recount of Ross Sea waters. *Deep Sea Research Part II: Topical Studies in Oceanography* **56**(13-14), 778–795. doi: 10.1016/j.dsr2.2008.10.033.

Osterkamp JP and Gosink TE (1984) Observations and analysis of sediment laden sea ice. In Barnes PW, Schell DW and Reimnitz E (eds), *The Alaska Beaufort Sea: Ecosystem and Environment*, San Francisco, CA: Academic Press, pp. 73–94. doi: 10.1016/b978-0-12-079030-2.50010-1.

Owston PG (1958) The structure of ice-I, as determined by X-ray and neutron diffraction analysis. *Advances in Physics* **7**(26), 171–188. doi: 10.1080/00018735800101207.

Paige RA (1966) *Crystallographic studies of sea ice in McMurdo Sound, Antarctica*. Naval Facilities Engineering Command, U.S. Naval Civil Engineering Laboratory, Port Hueneme, CA. doi: 10.5962/bhl.title.47716.

Palmisano AC, Beeler SooHoo J and Sullivan CW (1987) Effects of four environmental variables on photosynthesis-irradiance relationships in Antarctic sea-ice microalgae. *Marine Biology* **94**(2), 299–306. doi: 10.1007/bf00392944.

Palmisano AC, SooHoo JB and Sullivan CW (1985) Photosynthesis–irradiance relationships in sea ice microalgae from McMurdo Sound, Antarctica. *Journal of Phycology* **21**(3), 341–346. doi: 10.1111/j.0022-3646.1985.00341.x.

Palmisano AC and Sullivan CW (1985) Physiological response of micro-algae in the ice-platelet layer to low-light conditions. In Siegfried WR, Condy PR and Laws RM eds. *Antarctic Nutrient Cycles and Food Webs*, Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 84–88. doi: 10.1007/978-3-642-82275-9_12.

Pauling AG, Bitz CM, Smith IJ and Langhorne PJ (2016) The response of the Southern Ocean and Antarctic sea ice to freshwater from ice shelves in an earth system model. *Journal of Climate* **29**(5), 1655–1672. doi: 10.1175/JCLI-D-15-0501.1.

Pauling AG, Smith IJ, Langhorne PJ and Bitz CM (2017) Time-dependent freshwater input from ice shelves: impacts on Antarctic sea ice and the Southern Ocean in an earth system model. *Geophysical Research Letters* **44**(20), 10454–10461. doi: 10.1002/2017gl075017.

Penrose JD, Conde M and Pauly TJ (1994) Acoustic detection of ice crystals in Antarctic waters. *Journal of Geophysical Research: Oceans* **99**(C6), 12573–12580. doi: 10.1029/93jc03507.

Perovich DK and Elder BC (2001) Temporal evolution of Arctic sea-ice temperature. *Annals of Glaciology* **33**, 207–211. doi: 10.3189/172756401781818158.

Pfaffling A, Haas C and Reid JE (2007) Direct helicopter EM–sea-ice thickness inversion assessed with synthetic and field data. *Geophysics* **72**(4), F127–F137. doi: 10.1190/1.2732551.

Plötz J, Bornemann H, Knust R, Schröder A and Bester M (2001) Foraging behaviour of Weddell seals, and its ecological implications. *Polar Biology* **24** (12), 901–909. doi: 10.1007/s003000100297.

Price D and 5 others (2014) The sub-ice platelet layer and its influence on freeboard to thickness conversion of Antarctic sea ice. *The Cryosphere* **8** (3), 1031–1039. doi: 10.5194/tc-8-1031-2014.

Price D, Rack W, Haas C, Langhorne PJ and Marsh O (2013) Sea ice freeboard in McMurdo Sound, Antarctica, derived by surface-validated ICESat laser altimeter data. *Journal of Geophysical Research: Oceans* **118**(7), 3634–3650. doi: 10.1002/Jgrc.20266.

Pringle DJ, Eicken H, Trodahl HJ and Backstrom LGE (2007) Thermal conductivity of landfast Antarctic and Arctic sea ice. *Journal of Geophysical Research: Oceans* **112**(C4). doi: 10.1029/2006jc003641.

Prior DJ and 15 others (2015) Making EBSD on water ice routine. *Journal of Microscopy* **259**(3), 237–256. doi: 10.1111/jmi.12258.

Pritchard HD and 5 others (2012) Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature* **484**(7395), 502–505. doi: 10.1038/nature10968.

Purdie C (2012) *Winter Sea Ice Growth in McMurdo Sound, Antarctica* (Unpublished PhD thesis). University of Otago.

Purdie C, Langhorne P, Leonard G and Haskell T (2006) Growth of first-year landfast Antarctic sea ice determined from winter temperature measurements. *Annals of Glaciology* **44**, 170–176. doi: 10.3189/172756406781811853.

Quetin LB, Ross RM, Frazer TK and Haberman KL (2013) Factors affecting distribution and abundance of zooplankton, with an emphasis on Antarctic krill, *Euphausia superba*. In *Foundations for Ecological Research West of the Antarctic Peninsula*. Washington, D.C.: American Geophysical Union, pp. 357–371. doi: 10.1029/AR070p0357.

Rack W, Haas C and Langhorne PJ (2013) Airborne thickness and freeboard measurements over the McMurdo Ice Shelf, Antarctica, and implications for ice density. *Journal of Geophysical Research: Oceans* **118**(11), 5899–5907. doi: 10.1002/2013JC009084.

Rakusa-Suszczewski S (1972) The biology of *Paramoera walkeri* Stebbing (Amphipoda) and the Antarctica sub-fast ice community. *Polish Archives Hydrobiology* **19**, 11–36.

Rand J and Mellor M (1985) *Ice-coring augers for shallow depth sampling*, 85-21. US Cold Regions Research and Engineering Laboratory, Hanover, NH, USA.

Rees Jones DW and Wells AJ (2015) Solidification of a disk-shaped crystal from a weakly supercooled binary melt. *Physical Review E* **92**(2), 022406. doi: 10.1103/physreve.92.022406.

Rees Jones DW and Wells AJ (2018) Frazil-ice growth rate and dynamics in mixed layers and sub-ice-shelf plumes. *The Cryosphere* **12**(1), 25–38. doi: 10.5194/tc-12-25-2018.

Regoli F, Nigro M, Benedetti M, Fattorini D and Gorbi S (2005) Antioxidant efficiency in early life stages of the Antarctic silverfish, *Pleuragramma antarcticum*: responsiveness to pro-oxidant conditions of platelet ice and chemical exposure. *Aquatic Toxicology* **75**(1), 43–52. doi: 10.1016/j.aquatox.2005.07.003.

Reid JE, Pfaffling A and Vrbancich J (2006) Airborne electromagnetic footprints in 1D earths. *Geophysics* **71**(2), G63–G72. doi: 10.1190/1.2187756.

Remy JP, Becquevort S, Haskell TG and Tison JL (2008) Impact of the B-15 iceberg 'stranding event' on the physical and biological properties of sea ice in McMurdo Sound, Ross Sea, Antarctica. *Antarctic Science* **20**(06), 593 doi: 10.1017/s0954102008001284.

Riaux-Gobin C and 5 others (2005) Land-fast ice off Adélie Land (Antarctica): short-term variations in nutrients and chlorophyll just before ice break-up. *Journal of Marine Systems* **55**(3), 235–248. doi: 10.1016/j.jmarsys.2004.08.003.

Riaux-Gobin C, Tréguer P, Poulin M and Vétion G (2000) Nutrients, algal biomass and communities in land-fast ice and seawater off Adélie Land (Antarctica). *Antarctic Science* **12**(02), 160–171. doi: 10.1017/s0954102000000213.

Richter-Menge JA and 5 others (2006) Ice mass-balance buoys: a tool for measuring and attributing changes in the thickness of the Arctic sea-ice cover. *Annals of Glaciology* **44**, 205–210. doi: 10.3189/172756406781811727.

Rignot E (2008) Changes in West Antarctic ice stream dynamics observed with ALOS PALSAR data. *Geophysical Research Letters* **35**(12). doi: 10.1029/2008gl033365.

Rignot E, Jacobs S, Mouginot J and Scheuchl B (2013) Ice-shelf melting around Antarctica. *Science* **341**(6143), 266–270. doi: 10.1126/science.1235798.

Rintoul SR and 8 others (2011) The Southern Ocean Observing System: Initial Science and Implementation Strategy. Technical report, Scientific Committee on Antarctic Research and Scientific Committee on Oceanic Research (https://www.scar.org/library/scar-publications/occasionalpublications/3502-soos-strategy/).

Rintoul S and 39 others (2014) Seeing below the ice: a strategy for observing the ocean beneath Antarctic sea ice and ice shelves. In *SOOS workshop report*. Southern Ocean Observing System.

Rivkin RB, Putt M, Alexander SP, Meritt D and Gaudet L (1989) Biomass and production in polar planktonic and sea ice microbial communities – a comparative-study. *Marine Biology* **101**(2), 273–283. doi: 10.1007/Bf00391467.

Robin, G. de Q. (1979) Formation, flow, and desintegration of ice shelves. *Journal of Glaciology* **24**(90), 259–271. doi: 10.3189/s0022143000014787.

Robertson R (2013) Tidally induced increases in melting of Amundsen Sea ice shelves. *Journal of Geophysical Research: Oceans* **118**(6), 3138–3145. doi: 10.1002/jgrc.20236.

Robinson DH, Arrigo KR, Iturriaga R and Sullivan CW (1995) Microalgal light-harvesting in extreme low-light environments in McMurdo Sound, Antarctica. *Journal of Phycology* **31**(4), 508–520. doi: 10.1111/j.1529-8817.1995.tb02544.x.

Robinson DH, Arrigo KR, Kolber Z, Gosselin M and Sullivan CW (1998) Photophysiological evidence of nutrient limitation of platelet ice algae in McMurdo Sound, Antarctica. *Journal of Phycology* **34**(5), 788–797. doi: 10.1046/j.1529-8817.1998.340788.x.

Robinson NJ, Grant BS, Stevens CL, Stewart CL and Williams MJM (2020) Oceanographic observations in supercooled water: protocols for mitigation of measurement errors in profiling and moored sampling. *Cold Regions Science and Technology* **170**(102954). doi: 10.1016/j.coldregions.2019.102954.

Robinson NJ, Stevens CL and McPhee MG (2017) Observations of amplified roughness from crystal accretion in the sub-ice ocean boundary layer. *Geophysical Research Letters* **44**(4), 1814–1822. doi: 10.1002/2016gl071491.

Robinson NJ and Williams MJM (2012) Iceberg-induced changes to polynya operation and regional oceanography in the southern Ross Sea, Antarctica, from in situ observations. *Antarctic Science* **24**(5), 514–526. doi: 10.1017/s0954102012000296.

Robinson NJ, Williams MJM, Barrett PJ and Pyne AR (2010) Observations of flow and ice–ocean interaction beneath the McMurdo Ice Shelf, Antarctica. *Journal of Geophysical Research: Oceans* **115**(C3). doi: 10.1029/2008jc005255.

Robinson NJ, Williams MJM, Stevens CL, Langhorne PJ and Haskell TG (2014) Evolution of a supercooled Ice Shelf Water plume with an actively growing subice platelet matrix. *Journal of Geophysical Research: Oceans* **119**(6), 3425–3446. doi: 10.1002/2013JC009399.

Russell JL, Dixon KW, Gnanadesikan A, Stouffer RJ and Toggweiler JR (2006) The southern hemisphere Westerlies in a warming world: propping open the door to the deep ocean. *Journal of Climate* **19**(24), 6382–6390. doi: 10.1175/JCLI3984.1.

Ryan KG and 7 others (2006) Comparison of the microalgal community within fast ice at two sites along the Ross Sea coast, Antarctica. *Antarctic Science* **18**(04), 583–594. doi: 10.1017/S0954102006000629.

Schmidtko S, Heywood KJ, Thompson AF and Aoki S (2014) Multidecadal warming of Antarctic waters. *Science* **346**(6214), 1227–1231. doi: 10.1126/science.1256117.

Schnack-Schiel SB, Thomas DB, Dahms HUB, Hass CB and Mizdalski EB (2013) Copepods in Antarctic Sea Ice. In *Antarctic Sea Ice: Biological Processes, Interactions and Variability*. Washington, D.C.: American Geophysical Union, pp. 173–182.

Serikov MI (1963) Struktura morskogo antarkticheskogo l'da (Structure of Antarctic sea ice). *Soviet Antarctic Expedition Information Bulletin* **39**, 13–14.

Shi JX, Cheng YY, Jiao YT and Hou JQ (2010) Supercooled water in austral summer in Prydz Bay, Antarctica. *Chinese Journal of Oceanology and Limnology* **29**(2), 427–437. doi: 10.1007/s00343-010-0011-5.

Silvano A, Rintoul SR, Peña-Molino B and Williams GD (2017) Distribution of water masses and meltwater on the continental shelf near the Totten and Moscow University ice shelves. *Journal of Geophysical Research: Oceans* **122**(3), 2050–2068. doi: 10.1002/2016jc012115.

Smedsrud LH and Jenkins A (2004) Frazil ice formation in an Ice Shelf Water plume. *Journal of Geophysical Research: Oceans* **109**(C3). doi: 10.1029/2003jc001851.

Smetacek V and 6 others (1992) Early spring phytoplankton blooms in ice platelet layers of the southern Weddell Sea, Antarctica. *Deep Sea Research, Part A. Oceanographic Research Papers* **39**(2), 153–168. doi: 10.1016/0198-0149(92)90102-Y.

Smith IJ and 5 others (2001) Platelet ice and the land-fast sea ice of McMurdo Sound, Antarctica. *Annals of Glaciology* **33**, 21–27. doi: 10.3189/172756401781818365.

Smith IJ and 7 others (2015) First-year land-fast Antarctic sea ice as an archive of ice shelf meltwater fluxes. *Cold Regions Science and Technology* **113**, 63–70. doi: 10.1016/j.coldregions.2015.01.007.

Smith EC and 15 others (2020) Detailed seismic bathymetry beneath Ekström Ice Shelf, Antarctica: implications for glacial history and ice–ocean interaction. *Geophysical Research Letters* **47**(10). doi: 10.1029/2019gl086187.

Smith WO, Dinniman MS, Hofmann EE and Klinck JM (2014) The effects of changing winds and temperatures on the oceanography of the Ross Sea in the 21st century. *Geophysical Research Letters* **41**(5), 1624–1631. doi: 10.1002/2014GL059311.

Smith IJ, Gow AJ and Langhorne PJ (2002) Laboratory investigations into platelet ice crystal formation. In *Ice in the Environment: Proceedings of the 16th IAHR International Symposium on Ice*, Volume 3, 171–177, IAHR.

Smith IJ, Langhorne PJ, Frew RD, Vennell R and Haskell TG (2012) Sea ice growth rates near ice shelves. *Cold Regions Science and Technology* **83–84**, 57–70. doi: 10.1016/j.coldregions.2012.06.005.

Smith IJ, Langhorne PJ, Trodahl HJ, Haskell TG and Cole DM (1999) Platelet ice – The McMurdo Sound debate. In *Ice in Surface Waters. Proceedings of the International Association for Hydraulic Research 14th International Symposium on Ice*, 829–834, IAHR, A. A. Balkema, Rotterdam.

SooHoo JB and 5 others (1987) Spectral light absorption and quantum yield of photosynthesis in sea ice microalgae and a bloom of *Phaeocystis pouchetii* from McMurdo Sound, Antarctica. *Marine Ecology Progress Series* **39**, 175–189. doi: 10.3354/meps039175.

Souchez R, Tison JL and Jouzel J (1987) Freezing rate determination by the isotopic composition of the ice. *Geophysical Research Letters* **14**(6), 599–602. doi: 10.1029/gl014i006p00599.

Souchez R, Tison JL and Jouzel J (1988) Deuterium concentration and growth rate of Antarctic first-year sea ice. *Geophysical Research Letters* **15** (12), 1385–1388. doi: 10.1029/gl015i012p01385.

Spears A and 7 others (2016) Under ice in Antarctica: the Icefin unmanned underwater vehicle development and deployment. *IEEE Robotics & Automation Magazine* **23**(4), 30–41. doi: 10.1109/mra.2016.2578858.

Stefan J (1891) Ueber die Theorie der Eisbildung, insbesondere über die Eisbildung im Polarmeere. *Annalen der Physik* **278**(2), 269–286. doi: 10.1002/andp.18912780206.

Stevens CL and 5 others (2014) The influence of an Antarctic glacier tongue on near-field ocean circulation and mixing. *Journal of Geophysical Research: Oceans* **119**(4), 2344–2362. doi: 10.1002/2013jc009070.

Stevens C, O'Connor G and Robinson N (2019) The connections between art and science in Antarctica: Activating Science*Art. Polar Record **55**(4), 289–296. doi: 10.1017/S0032247419000093.

Stevens CL, Robinson NJ, Williams MJM and Haskell TG (2009) Observations of turbulence beneath sea ice in southern McMurdo Sound, Antarctica. *Ocean Science* **5**(2), 435–445. doi: 10.5194/osd-6-1407-2009.

Strutt JE (2006) Report of the inquiry into the loss of Autosub2 under the Fimbulisen. National Oceanography Centre Southampton Research and Consultancy Report 12, Southampton, UK. National Oceanography Centre Southampton, pp. 39 (https://eprints.soton.ac.uk/41098/).

Swart NC and Fyfe JC (2013) The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends. *Geophysical Research Letters* **40** (16), 4328–4332. doi: 10.1002/grl.50820.

Tamura T, Ohshima KI, Fraser AD and Williams GD (2016) Sea ice production variability in Antarctic coastal polynyas. *Journal of Geophysical Research: Oceans* **121**(5), 2967–2979. doi: 10.1002/2015JC011537.

Thoma M, Jenkins A, Holland DM and Jacobs SS (2008) Modelling Circumpolar Deep Water intrusions on the Amundsen Sea continental shelf, Antarctica. *Geophysical Research Letters* **35**(18), L18602. doi: 10.1029/2008GL034939.

Thomas D and 7 others (1998) Biological soup within decaying summer sea ice in the Amundsen sea, Antarctica. In Lizotte M and Arrigo K (eds), *Antarctic Sea Ice Biological Processes, Interactions and Variability, Volume 73 of Antarctic Research Series*, Washington, D.C.: American Geophysical Union, 161–171.

Thomas DN and 5 others (2001) Biogeochemistry of platelet ice: its influence on particle flux under fast ice in the Weddell Sea, Antarctica. *Polar Biology* **24**(7), 486–496. doi: 10.1007/s003000100243.

Thomas DN and Dieckmann GS (2002a) Antarctic sea ice – a habitat for extremophiles. *Science* **295**(5555), 641–644. doi: 10.1126/science.1063391.

Thomas DN and Dieckmann GS (2002b) Biogeochemistry of Antarctic sea ice. *Oceanography and Marine Biology: An Annual Review* **40**, 143–169.

Timmermann R and Hellmer H (2013) Southern Ocean warming and increased ice shelf basal melting in the twenty-first and twenty-second centuries based on coupled ice–ocean finite-element modelling. *Ocean Dynamics* **63**(9-10), 1011–1026. doi: 10.1007/s10236-013-0642-0.

Timmermann R, Wang Q and Hellmer HH (2012) Ice-shelf basal melting in a global finite-element sea-ice/ice-shelf/ocean model. *Annals of Glaciology* **53**(60), 303–314. doi: 10.3189/2012aog60a156.

Tison JL and 5 others (1998) Linking landfast sea ice variability to marine ice accretion at Hells Gate Ice Shelf, Ross Sea. In *Antarctic Sea Ice: Physical Processes, Interactions and Variability*. Washington, D.C.: American Geophysical Union, pp. 375–407, doi: 10.1029/AR074p0375.

Toyota T and 7 others (2013) Oxygen isotope fractionation during the freezing of sea water. *Journal of Glaciology* **59**(216), 697–710. doi: 10.3189/2013jog12j163.

Trathan PN, Fretwell PT and Stonehouse B (2011) First recorded loss of an emperor penguin colony in the recent period of Antarctic regional warming: implications for other colonies. *PLoS ONE* **6**(2), e14738–e14738. doi: 10.1371/journal.pone.0014738.

Trodahl HJ and 6 others (2000) Heat transport in McMurdo Sound first-year fast ice. *Journal of Geophysical Research: Oceans* **105**(C5), 11347–11358. doi: 10.1029/1999jc000003.

Tsang G and Hanley TO (1985) Frazil formation in water of different salinities and supercoolings. *Journal of Glaciology* **31**(108), 74–85. doi: 10.3189/S0022143000006298.

UNESCO (1978) Freezing point temperature of seawater, Eighth report of the Joint Panel on Oceanographic Tables and Standards, Woods Hole, March 1977. *UNESCO Technical Papers in Marine Science* 28.

UNESCO (1981) Background paper and supporting data on the International Equation of State of Seawater. *UNESCO Technical Papers in Marine Science* 38.

Untersteiner N (1961) On the mass and heat budget of Arctic sea ice. *Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie A* **12**(2), 151–182. doi: 10.1007/bf02247491.

Vacchi M and 6 others (2012) A nursery area for the Antarctic silverfish *Pleuragramma antarcticum* at Terra Nova Bay (Ross Sea): first estimate of distribution and abundance of eggs and larvae under the seasonal sea-ice. *Polar Biology* **35**(10), 1573–1585. doi: 10.1007/s00300-012-1199-y.

Vacchi M, La Mesa M, Dalu M and Macdonald J (2004) Early life stages in the life cycle of Antarctic silverfish, *Pleuragramma antarcticum* in Terra Nova Bay, Ross Sea. *Antarctic Science* **16**(3), 299–305. doi: 10.1017/s0954102004002135.

van Leeuwe M and 9 others (2018) Microalgal community structure and primary production in Arctic and Antarctic sea ice: a synthesis. *Elementa: Science of the Anthropocene* **6**(4), 1–25. doi: 10.1525/elementa.267.

Veazey AL, Jeffries MO and Morris K (1994) Small-scale variability of physical properties and structural characteristics of Antarctic fast ice. *Annals of Glaciology* **20**, 61–66. doi: 10.3189/172756494794586925.

Walker TD and Marchant HJ (1989) The seasonal occurrence of chroococcoid cyanobacteria at an Antarctic coastal site. *Polar Biology* **9**(3), 193–196. doi: 10.1007/Bf00297175

Wang Y and Azuma N (1999) A new automatic ice-fabric analyzer which uses image-analysis techniques. *Annals of Glaciology* **29**, 155–162. doi: 10.3189/172756499781821021.

Warren SG and 5 others (1993) Green icebergs formed by freezing of organic-rich seawater to the base of Antarctic ice shelves. *Journal of Geophysical Research: Oceans* **98**(C4), 6921–6928. doi: 10.1029/92jc02751.

Warren SG, Roesler CS, Brandt RE and Curran M (2019) Green icebergs revisited. *Journal of Geophysical Research: Oceans* **124**(2), 925–938. doi: 10.1029/2018jc014479.

Webster SE, Lee CM and Gobat JI (2014) Preliminary results in under-ice acoustic navigation for Seagliders in Davis Strait. In *Oceans-St. John's, 2014*, 1–5, IEEE, IEEE. doi: 10.1109/oceans.2014.7003070.

Weeks WF (2010) *On Sea Ice*. Fairbanks, AK: University of Alaska Press.

Weeks W and Ackley S (1982) The growth, structure, and properties of sea ice. In Untersteiner N (ed.) *The Geophysics of Sea Ice*. NATO ASI Series (Series B: Physics) Volume **82-1,** New York, NY: Springer, Boston, MA, pp. 9–164. doi: 10.1007/978-1-4899-5352-0_2.

Wells AJ and Worster MG (2011) Melting and dissolving of a vertical solid surface with laminar compositional convection. *Journal of Fluid Mechanics* **687**, 118–140. doi: 10.1017/jfm.2011.322.

Wenk HR (2000) 4: Pole figure measurements with diffraction techniques. In Kocks UF, Tomé CN, Wenk HR and Beaudoin AJ eds. *Texture and Anisotropy: Preferred Orientations in Polycrystals and Their Effect on Materials Properties*. Cambridge, UK: Cambridge University Press, pp. 126–177.

Williams GD and Bindoff NL (2003) Wintertime oceanography of the Adélie Depression. *Deep Sea Research, Part II: Topical Studies in Oceanography* **50** (8-9), 1373–1392. doi: 10.1016/s0967-0645(03)00074-2.

Williams MJM, Jenkins A and Determann J (1998) Physical controls on ocean circulation beneath ice shelves revealed by numerical models. In Jacobs S and Weiss R eds. *Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin*, Washington, D.C.: American Geophysical Union, pp. 285–299. doi: 10.1029/AR075p0285.

Wilson CJL and Peternell M (2011) Evaluating ice fabrics using fabric analyser techniques in Sørsdal Glacier, East Antarctica. *Journal of Glaciology* **57**(205), 881–894. doi: 10.3189/002214311798043744.

Wilson CJL and Sim HM (2002) The localization of strain and *c*-axis evolution in anisotropic ice. *Journal of Glaciology* **48**(163), 601–610. doi: 10.3189/172756502781831034.

Wingham DJ, Wallis DW and Shepherd A (2009) Spatial and temporal evolution of Pine Island Glacier thinning, 1995–2006. *Geophysical Research Letters* **36**(17). doi: 10.1029/2009gl039126.

Wongpan P and 8 others (2018b) Estimation of Antarctic land-fast sea ice algal biomass and snow thickness from under-ice radiance spectra in two contrasting areas. *Journal of Geophysical Research: Oceans* **123**(3), 1907–1923. doi: 10.1002/2017jc013711.

Wongpan P, Hughes KG, Langhorne PJ and Smith IJ (2018a) Brine convection, temperature fluctuations, and permeability in winter Antarctic land-fast sea ice. *Journal of Geophysical Research: Oceans* **123**(1), 216–230. doi: 10.1002/2017jc012999.

Wongpan P, Langhorne PJ, Dempsey DE, Hahn-Woernle L and Sun Z (2015) Simulation of the crystal growth of platelet sea ice with diffusive heat and mass transfer. *Annals of Glaciology* **56**(69), 127–136. doi: 10.3189/2015aog69a777.

Wongpan P, Prior DJ, Langhorne PJ, Lilly K and Smith IJ (2018c) Using electron backscatter diffraction to measure full crystallographic orientation in Antarctic land-fast sea ice. *Journal of Glaciology* **64**(247), 771–780. doi: 10.1017/jog.2018.67.

Woods AW (1992) Melting and dissolving. *Journal of Fluid Mechanics* **239**, 429–448. doi: 10.1017/S0022112092004476.

Wright CS and Priestley RE (1922) *Glaciology – British (Terra Nova) Antarctic Expedition 1910–1913*. London, UK: Harrison and Sons.

Zheng S, Shi J, Jiao Y and Ge R (2011) Spatial distribution of Ice Shelf Water in front of the Amery Ice Shelf, Antarctica in summer. *Chinese Journal of Oceanology and Limnology* **29**(6), 1325. doi: 10.1007/s00343-011-0318-x.

Zotikov IA, Zagardnov VS and Raikovsky JV (1980) Core drilling through the Ross Ice Shelf (Antarctica) confirmed basal freezing. *Science* **207** (4438), 1463–1465. doi: 10.1126/science.207.4438.1463.

Zuo G, Dou Y and Lei R (2018) Discrimination algorithm and procedure of snow depth and sea ice thickness determination using measurements of the vertical ice temperature profile by the ice-tethered buoys. *Sensors* **18**(12), E4162. doi: 10.3390/s18124162.