Article:
Shepherd, A, Fricker, HA and Farrell, SL (2018) Trends and connections across the Antarctic cryosphere. Nature, 558 (7709). pp. 223-232. ISSN 0028-0836

https://doi.org/10.1038/s41586-018-0171-6

Trends and connections across the Antarctic cryosphere

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Abstract

After a century of polar exploration, recent satellite observations have painted an altogether new picture of how Antarctica is changing.

Satellite observations have transformed our understanding of the Antarctic cryosphere. The continent holds the vast majority of Earth's freshwater, and blankets huge swathes of the Southern Hemisphere in ice. Reductions in the thickness and extent of floating ice shelves have disturbed inland ice, triggering retreat, acceleration, and drawdown of marine terminating glaciers. The waxing and waning of Antarctic sea ice is one of Earth's greatest seasonal habitat changes, and although its

extent has increased modestly since the 1970s, variability is high, and there is evidence of longer-term decline.

Introduction

At the height of austral winter, Antarctica and the surrounding ocean are covered in a 31.6 million km^2 cap of ice (Fig. 1). Of this, ~18.5 million km^2 is formed as sea ice when the ocean freezes [1], 11.9 million km^2 is a near-permanent ice sheet resting on land or the sea floor [2], and 1.6 million km^2 is contained within long-lived ice shelves that are the floating extensions of the continental ice [3]. All of Antarctica's ice is mobile, driven by gravity and, where it is afloat, by the atmosphere and the ocean (Fig. 1). Each element plays a unique role in the climate system, for example the grounded ice is Earth's primary freshwater reservoir [4], the ice shelves are a major source of ocean fresh water [5], and the sea ice is an important factor in the planetary albedo [6].

The greatest fluctuation in the extent of ice cover in the Southern Hemisphere is due to the seasonal cycle of sea ice formation which is less than a metre thick on average [7], and reduces to one sixth of its peak area in summer [8]. The decadal trend in Antarctic sea ice extent has, nevertheless, been modest [9], and the most striking contemporary changes have occurred in other elements of the regional cryosphere. For example, the grounded ice sheet is estimated to have lost 2720 ± 1390 Gt of its mass between 1992 and 2017 [10], and its peripheral ice shelves are thinning in numerous sectors [3,11-13] and collapsing [14,15] at the Antarctic Peninsula. These trends reflect global and regional environmental forcing and are related through a variety of processes, each of which is now better understood thanks to the array of satellite observations that have been acquired over recent decades.

Here, we analyse the satellite record to examine continental and regional scale trends in the Antarctic cryosphere, including fluctuations in the extent, thickness, and movement of sea ice, ice shelves, and the grounded ice sheet. We show that spaceborne measurements have allowed key events in Earth's recent climate history to be charted in remarkable detail - including the collapse of ice shelves at the Antarctic Peninsula and the drawdown of glacier ice from West Antarctica - and have illuminated the key processes that are driving contemporary change.

Grounded ice

Fluctuations in the mass of the Antarctic ice sheet arise due to differences between the net snow accumulation and ice discharge. In recent decades, a variety of techniques have been developed to measure changes in the speed, elevation, and weight of the grounded ice. Airborne radar measurements show that the Antarctic ice sheet is up to 4897 m thick, and has the potential to raise global sea level by 58 metres were it to be rapidly discharged [4]. It overlies terrain of variable geology and relief, and this has influenced both its formation and its contemporary dynamics. The continental-scale pattern of ice flow was first inferred from cartographic [16] and, more recently, satellite altimeter [17] records of the ice sheet surface elevation. On this basis, it has been determined that most of Antarctica's ice is routed into the Southern Ocean through around 30 glaciers and ice streams (Fig. 1), each draining a substantial inland catchment [2].

Grounded Ice Imbalance

The stability of Antarctica's ice can be assessed by tracking the movement of its principal glaciers and ice streams. Although few in number, this task is nevertheless beyond the scope of ground surveys because they are vast. The first remote measurements of ice motion were made possible by repeat satellite optical imagery [18] and, subsequently, by synthetic aperture radar interferometry [19]. Thanks to step increases in the quantity of satellite image acquisitions over time, systematic surveys of ice flow across and around the continent have now been completed [20], revealing anomalous behaviour in much of Marie Byrd Land [21,22] and also at isolated sites at the Siple Coast [23], at the Antarctic Peninsula [24-26], and in East Antarctica [27,28]. In most of these places, the pace of ice flow has increased during the satellite era, and, when considered as a whole, the rate of ice discharge from Antarctica exceeds inland snow accumulation [29].

In addition to changes in ice discharge, fluctuations in ice sheet mass can be detected through satellite measurements of their volume [30-32] and gravitational attraction [33,34]. Although all three methods lead to similar results at the continental scale, each approach has its merits, and they are now viewed as being complementary. To date, there have been over 150 individual assessments of ice loss from Antarctica based on these approaches [35] and, when collated [10,36], these studies show that the continent has contributed 7.6 ± 3.9 mm to global sea levels since 1992. Almost half (3.0 ± 0.6 mm) of this loss occurred during the last 5 years [10]. While the rate of ice loss from the entire Antarctic ice sheet has changed little during the satellite record, the speedup of glaciers in the Amundsen Sea sector has led to accelerated losses from this region [37,38].

Satellite radar altimetry is an especially powerful tool for ice sheet glaciology, because the technique can be used to resolve the detailed pattern of imbalance across individual glacier catchments (e.g. [39]), around the much of the continent, with monthly sampling, and over multi-decadal periods (Fig. 2). This allows signals of short-term variability to be separated from longer-term trends. Although most of Antarctica has remained stable over the past 25 years, there are clear patterns of imbalance in many coastal sectors - for example thickening of the Kamb Ice Stream and thinning of glaciers flowing into the Amundsen Sea and at the Antarctic Peninsula. These changes reflect imbalance between ice flow and snow accumulation within the surrounding catchments. While the pace of ice flow at the Kamb Ice Stream is unusually low [40] and has not altered in recent decades, analysis of ice penetrating radar measurements [41] shows that it stagnated over a century ago. Elsewhere, inland glacier thinning is almost exclusively coincident with contemporaneous ice speedup [21,42,43], indicating that it is dynamic in nature, and with perturbations at their marine termini [44], indicating that it has resulted from ocean forcing.

Active subglacial Lakes

A surprising application of satellite observations has been monitoring the movement of water beneath the Antarctic Ice Sheet. Over three hundred subglacial lakes - bodies of liquid water at the ice sheet base - have been discovered in Antarctica (Fig. 1) using ice penetrating radar [45], and these were at first considered to be isolated and stable reservoirs. However, localised and episodic rises and falls of the ice sheet surface were then spotted in satellite interferometric [46] and altimetric records [47,48], suggesting otherwise. These fluctuations, amounting to 1 to 10 m height-changes over sub-decadal timescales, are interpreted to be the surface expressions of water transferring between active subglacial lake networks. More than a hundred active lakes have now been identified using this approach [49], and monitoring of their evolution has led to improved understanding of how Antarctic subglacial water systems evolve, and the consequences of this variability [50]. At the Whillans, Mercer, and Recovery ice streams, the Crane and Byrd Glaciers, and in eastern Wilkes Land, for example, more than a decade of satellite measurements have been acquired [51]. Thanks to these data, we now know that in addition to periodically flushing subglacial cavities, the presence of [52] and fluctuations in [27] subglacial lake water can lubricate ice flow in parts of the continent.

Ice Shelves

When Antarctic glacier ice reaches the ocean it often remains intact, forming floating ice shelves in sheltered embayments. Altogether there are more than 300 Antarctic ice shelves, fringing three quarters of the continent and extending the grounded ice area by some 13 % [4]. Their average thicknesses range from 300 m to 2500 m [53], and peak at the grounding line where they are fed by inland glaciers. Ice shelves can provide mechanical support for the grounded ice sheet upstream, through contact with confining side walls or sea mounts [54]. Downstream, they thin as the ice spreads, and they gain and lose additional mass primarily through snow accumulation, iceberg calving, and basal ice melting. Basal melting is driven by several processes [5] including the formation of high-salinity water during winter sea ice growth, tidal mixing of seasonally warm water, and the intrusion of warm ocean currents into sub-shelf cavities. Meteorological and oceanographic conditions can also lead to surface melting and basal ice freezing. In some cases, it can take more than a thousand years for ice to travel through Antarctic ice shelves from the grounding line to the calving front [55], and geological records show that they have been a persistent element of the climate system throughout the Holocene period (e.g. [56]). Their dependence on a wide range of factors makes ice shelves a sensitive indicator of environmental change [57].

Ice Shelf Imbalance

Trends in ice shelf area, thickness, and flow can be detected using a wide range of satellite sensors, and a host of other properties can be inferred from these measurements. Ice shelf area can be measured using optical and radar satellite imagery, and this has been used, for example, to chart long-term changes in their extent [14]. A series of satellite radar and laser altimeter missions have provided near-continuous observations of ice shelf surface elevation for several decades, and these have formed the basis of ice shelf thickness [58] and thickness change [3,11,59] estimates on the assumption that the ice is buoyant within the surrounding ocean. These estimates require careful treatment of fluctuations in ocean tide [13] and of changes in the firn column thickness [60]. When combined, measurements of ice shelf area and thickness change allow their volume and mass trends to be derived. Ice shelf flow can be monitored with repeat pass satellite optical [61] and radar [62] imagery and, if contemporaneous changes in both the flow and thickness of ice shelves are available, the rate of steady state [63] and net [12,64,65] basal ice melting can be determined.

Analysis of ice-shelf surface elevation measurements derived from multi-mission satellite altimetry (Fig. 2) has allowed their decadal mass change and principal environmental forcing mechanisms to be identified [3,11,59,66]. While the major Ross, Filchner-Ronne, and Amery ice shelves have remained stable since the 1990s, many ice shelves in West Antarctica have experienced long-term thinning during the same period. In the locations where retreat or thinning have occurred, the grounded ice inland has also been destabilised. The dominant control on this pattern is believed to be the presence (or absence) of warm ocean currents offshore [59]. Altogether, the volume of Antarctic ice shelves has declined through net overall thinning (166 ± 48 km^3 yr^{-1} between 1994 and 2012; [11]) and through progressive calving-front retreat of those at the Antarctic Peninsula (210 ± 27 km^3 yr^{-1} between 1994 and 2008; [3]). Combined, these losses amount to less than 1 % of their volume. However, the highest ice shelf thinning rates have occurred in the Amundsen and Bellingshausen Seas [12], where five have lost between 10 to 18 % of their thickness [11] due to ocean-driven melting at their bases [67]. The effects of the wider El Niño-Southern Oscillation have also been detected alongside these longer-term trends [66].

Ice shelf collapse

Ice shelves at the Antarctic Peninsula (Fig. 3) are especially vulnerable, because they are situated at the most northerly latitude on the continent, where temperatures are relatively high and summertime melting is common. In recent decades, a number of these ice shelves have disintegrated in part or entirely [14]. Notable examples include the substantial (>70 %) retreat of the Larsen B [15,68]) and Wilkins [69] ice shelves, and the effective collapse (>90 %) of the Prince Gustav Channel [70], Larsen-A [71], and Wordie [72] ice shelves. Since the 1950s, the combined area of Antarctic ice shelves lost through retreat and collapse has been 33,917 km^2 [14,73], or 22 % of their original extent. Analysis of the geological record [56,74] has confirmed that the collapse events are unique during the Holocene period.

The retreat and collapse of Antarctic Peninsula ice shelves has occurred in tandem with a rapid regional atmospheric warming happening at several times the global trend [57]. These events have been linked; warmer air temperatures lead to intensified surface melting [75] which is believed to cause hydraulic fracture of surface crevasses followed by ice shelf collapse [76]. Several Antarctic Peninsula ice shelves have also thinned in the decades leading up to their collapse [11,13,59], primarily through ocean driven melting at their base. This thinning may contribute to instability by weakening ice shelf lateral margins prior to fracture [77], and by enhancing rates of iceberg calving [78]. The relationship is, however, not universal; for example, although the Wilkins ice shelf collapsed in 2009, it did not thin in the preceding five years [79]. Indeed, recent satellite altimetry [80] shows that the surface elevation of Larsen C increased in the preceding decade, in response to cooler and not warmer summertime temperatures. And allthough the observational evidence suggests that stability of Antarctic ice shelves depends on both their thickness, geographical location or setting, the extent to which those that are partially or wholly intact will continue to resist collapse remains uncertain.

The collapse of ice shelves does not contribute directly to sea level rise, because they are afloat. However, there is an indirect effect: observations show that the grounded tributaries to the Larsen A [81] and B [15,68] ice shelves did speed in response to the removal of the floating ice, which is presumed to have offered resistance. To date, ice shelf retreat and collapse has been restricted to those situated at the Antarctic Peninsula, in relatively warm climates, and has not threatened those farther South which fringe the East and West Antarctic Ice Sheets. The largest recorded reduction in ice shelf area at the Antarctic Peninsula to date was the calving of the 11,095 km^2 A-68 tabular iceberg (Fig. 3) from the Larsen-C in 2016 [73]. However, this berg represented just 7 % of the ice shelf area, and was similar in size to one (A-20) that broke free in 1986 [82]. It is, therefore, not without precedent - even during the relatively short satellite era - and there is as yet no evidence that either breakaway disturbed the remaining ice shelf, or was anything other than routine iceberg production.

Buttressing of Grounded Ice

The term “buttressing” is used to describe the resistive forces imparted to a grounded ice sheet by its peripheral ice shelves. In its absence, rates of ice sheet discharge increase non-linearly with ice thickness, making the grounding lines of marine-based ice sheets difficult to stabilise because their bedrock tends to deepen inland [83]. Floating ice shelves can, however, exert drag as they flow over and around seamounts (pinning points) or as a result of their lateral confinement, and the extent to which this drag can mitigate unstable retreat has long been the subject of glaciological debate (e.g.

[54]). In recent years, the rapid response of Antarctic glaciers to the collapse and thinning of ice shelves at their termini has led to a reassessment of their resistive properties. At the Antarctic Peninsula, for example, glaciers flowing into the former Larsen-A, Larsen-B, and Wordie ice shelves have surged [24,68,84] after their collapse [14], as too have ice streams flowing into the Amundsen and Bellingshausen Seas [21,43] in the wake of ice shelf thinning [3,12,79] and grounding line retreat [85,86]. While the former events have been attributed to the destabilising effect of increased melting at the surface of ice shelves, following regional atmospheric warming [15,68], the latter are now firmly linked to enhanced ocean-driven melting at their base, due to the intrusion of warm circumpolar deep water into the cavities beneath them [67,87].

Although the reservoir of grounded ice at the Antarctic Peninsula is relatively modest [13], destabilisation of Amundsen Sea sector glaciers is a matter of considerable concern, because the pace of ice drawdown during the satellite era has been swift [88], and because they contain enough ice to raise global sea levels by more than a metre [4]. Over the past two decades, for example, surface lowering has spread inland across the drainage basins of the Pine Island and Thwaites Glaciers at speeds of between 5 and 15 km yr^{-1}, and the majority of their catchments are now in a state of dynamical imbalance (thinning due to accelerated flow). This rapid spreading is a consequence of several connected processes [89] (Box 1); ice shelf thinning leads to initial reductions in sidewall and basal traction at glacier termini, which then causes increased strain rates (flow) within the glacier ice upstream, followed by further grounding line retreat due to the associated ice thinning – especially in marine-based sectors of the continent. Glacier speedup may also lead to further reductions in sidewall traction through rifting and fracture, and grounding line retreat can expose more ice to the ocean melting responsible for the initial imbalance.

Glaciers flowing into the Amundsen Sea sector of West Antarctica are particularly susceptible to climate forcing, due to their geometrical configuration and the absence of any significant ice shelf barrier [90], and today the pace of ice sheet retreat along parts of this coastline dwarfs that during the

Holocene period. The region's ice shelves have thinned by 3 to 6 m/yr [11,12], and its glacier grounding lines have retreated by 10 to 35 km since 1992 [85,86] – 20 to 30 times the rate since the last glacial maximum according to analysis of the marine geological record [91]. In response to these perturbations, the grounded glaciers inland have sped up [21,43] and thinned [32,37] at accelerating rates. For example, since the early 1990s, rates of ice flow at the Pine Island Glacier terminus have increased by ~1.5 km/yr [43] and rates of ice thinning have risen to over 5 m/yr [88], and the sector overall contributed 4.5 mm to global sea level rise between 1992 and 2013 [38].

The forcing for these events is now widely regarded to lie in the surrounding ocean, because ice drawdown has originated at and evolved from the terminus of neighbouring but distinct ice flow units [42], and because warm [67] and warming [44] water is present within the cavities beneath their peripheral ice shelves. According to numerical simulations, the Pine Island and Thwaites Glaciers [92,93] may contribute a further ~4 mm to global sea levels over the 21st century in response to continued forcing, and it has been concluded [94] that the region is now undergoing marine ice sheet instability, with no geometrical obstacles to prevent irreversible decline. However, satellite observations have revealed that retreat of the Pine Island Glacier halted around 2011 [95,96], and that ice thinning inland abated in the following years [88]. This suggests that the situation is more complicated than a consideration of the glacier geometry alone, and may involve changes in the degree of ocean forcing, as has occurred in the recent past [87,97].

Sea ice

Antarctic sea ice forms as the Southern Ocean surface freezes, and interacts with the neighbouring ice shelves and grounded ice in many ways (e.g. Box 1). Satellite observations (e.g. Fig. 1) have allowed us to map its extent [8,98], thickness [99,100] and drift [101,102], providing insight into the role it plays in climate [6] and how it impacts on ecosystems [103]. In winter, Antarctic sea ice extends from an inner zone of consolidated pack ice surrounding the continent, to the marginal ice zone near to the powerful Antarctic Circumpolar Current, where floes are less concentrated (Fig.1 and Fig. 4). In summer, the sea ice pack retreats to isolated pockets fringing the continent. As it forms, Antarctic sea ice produces high-salinity shelf water when brine is rejected, which then sinks to the seabed. This water drives buoyant plumes within the cavities beneath floating ice shelves, which melt glacier ice at the grounding line, before returning to the open ocean along their base. Antarctic sea ice is also characterized by local polynyas – persistent gaps in the ice cover (e.g. Fig. 4) that are sustained by upwelling warm water, winds, tides, and ocean currents. These polynyas are a source of bottom water (dense water occupying depths typically below 4000 m), and provide a link between the ocean and atmosphere that affects weather and wildlife [103]. Land-fast sea ice can also act to stabilise ice shelves and glacier tongues [104], and to suppress [105] or – upon its breakup - enable [106] iceberg calving.

Sea ice extent and drift

Fluctuations in the area of Antarctic sea ice have been routinely charted since the late 1970s using passive microwave satellite imagery [8]. Annually, its average extent ranges from 3.1 x 10^6 km^2 in February to 18.5 x 10^6 km^2 in September [1] (e.g. Fig. 1). In contrast to the Arctic, where the area of sea ice has declined progressively [1], there has been a small, positive increase (1.6 $\pm$ 0.4 % per decade between 1979-2016) in the hemispheric sea ice extent of the Southern Ocean [9]. This trend runs counter to the projections of most climate models [107], and has occurred alongside a slow warming (0.02 ^{o}C per decade since the 1950s) of the Southern Ocean [108]. Despite the trend, there is some evidence of longer-term decline; reanalysis of early satellite records [109,110] and historical whale catch positions [111] suggest there may have been more ice cover in the 1960s and early 1970s than there is today. In recent years, however, extreme changes have occurred - the extent of Antarctic sea ice reached record maxima in three successive winters (2012, 2013, and 2014; [112]), followed by a record summertime minimum in March 2017 [113,114].

Changes in both atmospheric and oceanic forcing affect the extent of Antarctic sea ice [115,116], and although total hemispheric extent has shown little overall change, there have been considerable regional variations [117,118]. While the Weddell Sea, Indian Ocean and Western Pacific Ocean have all seen modest trends (1.7 ± 0.8 %, 1.7 ± 0.99 % and 1.8 ± 1.2 % decade^{-1}, respectively) in sea ice extent during the satellite era (1979-2016), there have been more substantial trends (3.3 ± 0.9 % and -2.9 ± 1.4 % decade^{-1}, respectively) in the Ross Sea and Amundsen and Bellingshausen Seas [9]. The periods during which the Western Ross and Bellingshausen Seas are ice free in summer have also changed, decreasing and increasing by two and three months, respectively, between 1979 and 2011 [118]. Seasonal and decadal trends in the Weddell and Ross Seas (positive) and the Amundsen-Bellingshausen Sea and Western Pacific Oceans (negative) reflect the influence of atmospheric forcing [119]. Although these fluctuations in sea ice extent are strongly correlated with the dominant modes of Southern Hemisphere climate variability [117,119], other factors are involved [120]. A range of mechanisms have been explored, including changes in oceanic variability [121], atmospheric circulation [122,123], stratospheric ozone depletion [124], meridional wind forcing [102], and freshwater input from ice-shelf melt [125,126].

Understanding the role sea ice plays in the Antarctic climate system also requires a consideration of its dynamics [127]. In the Southern Ocean, sea ice drifts northwards and diverges under the influence of winds and ocean currents (Fig. 1), and the fraction of open water is higher than in the Arctic [128]. Satellite observations have illuminated both local-scale [129,130] and hemisphere-wide [101,102,131] Antarctic sea ice dynamics. Strong, circumpolar, westerly winds drive sea ice eastwards in the outer zonal band, while a nearly-continuous westward circumpolar flow exists along the coastal boundary [101]. Persistent atmospheric lows centered at the boundaries of major ocean basins are the dominant drivers of sea ice motion, and these sustain large-scale gyres in the Weddell and Ross Seas [132]. The speed of sea ice drift in the eastern Weddell and Ross Seas has increased, in contrast to the western Weddell Sea where it has decreased [102,132], though these signals are still small compared to the interannual variability [101]. The general northward trajectory of the Antarctic sea ice pack also impacts on its age and thickness; rarely does it survive for more than two years, and the average thickness of floes (typically in the range 0.6 to 1.2 m) and pressure ridges are smaller than in the Arctic Ocean [7]. Locally, katabatic winds, tides, and ocean currents sustain coastal polynyas through sea ice drift around the continent (e.g. Fig. 4), providing a link between the sea ice pack and the ice sheet through their initiation of plumes beneath floating ice shelves [133].

Summary and Outlook

In just three decades, satellites have transformed our appreciation of the extent and pace of change in the Antarctic cryosphere. Despite being remote, fluctuations in its ice cover have a global impact. The continent holds Earth's primary freshwater reservoir [4] and, together with its surrounding ice shelves [3] and sea ice [1], blankets 6 % of the planet in ice during austral winter. Although persistent ice shelves have fringed Antarctica for thousands of years [56], there is now widespread evidence of changes in their extent [14] and thickness [3,11]. Altogether, their volume has decreased by more than 300 km^3 yr^{-1} since 1994 [3,11], notably due to collapse and calving at the Antarctic Peninsula and rapid thinning of those in the Amundsen and Bellingshausen Seas. These events have triggered retreat [85,86] and acceleration [21,43] of marine terminating glaciers and ice streams around the continent, leading to the drawdown of ice from their inland catchments [39,42]. Since 1992, the grounded ice sheet has lost 1350 ± 1010 Gt of ice, causing a net 3.8 ± 2.8 mm contribution to global sea level rise [36]. The waxing and waning of Antarctic sea ice influences the planetary albedo, oceanic circulation, marine productivity, and ecosystems [6,103]. Although its extent has increased by 1.6 ± 0.4 % per decade since 1979 [9], there are significant regional variations [9,117,118], and there is evidence from historical records [109-111] of a longer-term decline. These discoveries, and many more, have transformed our understanding of the state of Antarctic ice.

Even though considerable progress has been made during the satellite era, key questions remain unanswered. For example, the detailed pattern of glacier change at the Antarctic Peninsula is not well known, because the rugged terrain poses a challenge for traditional remote sensing methods. Though modest, the mass balance of the East Antarctic Ice Sheet nevertheless remains uncertain, because its detection is complicated by uncertainties in rates of snowfall and glacial isostatic adjustment. And the evolution and impacts of abrupt subglacial lake drainage events is poorly defined, because frequent measurements of ice elevation and flow changes are often lacking at the local scale. But understanding the thickness of sea ice across the Southern Hemisphere and the nature of ice shelf collapse and retreat are pressing concerns. While the range of parameters that can now be measured on grounded ice and on ice shelves may be considered comprehensive, available satellite observations are insufficient to fully understand the nature and evolution of the processes that are driving contemporary imbalance. Although the satellite altimeter record has been used to resolve Southern Ocean dynamics, determining sea ice thickness - a key measure of its volume and longevity - from measurements of its freeboard (the portion protruding above the ocean surface) are hampered by poor knowledge of snow loading and its impact on the satellite retrieval.

In the case of Antarctic sea ice, uncertainties in the degree of radar penetration into the snowpack [134,135] has so far limited the use of the 25-year radar altimeter record for measuring its thickness. Some advances have been made using laser altimetry [99,100], which scatters from the surface of the overlying snow, but continental-scale trends in Antarctic sea ice thickness and volume nevertheless remain elusive due to the paucity of in situ measurements. One way to tackle this problem is to exploit the relationship between the amount and roughness of snow on sea ice and its total thickness [136], an approach that may be realised with the launch of ICESat-2 which has a laser capable of detecting surface roughness and thickness [137,138]. Another possibility is to combine freeboard measurements retrieved from different scattering horizons to estimate the snow load directly, for example using observations acquired by the CryoSat-2 Ku-band and ALtiKa Ka-band radar altimeters

[139,140], and, in the future, ICESat-2. New techniques are also emerging to map the extent, type, age, drift, and roughness of sea ice with fine resolution using synthetic aperture radar imagery.

Over land ice, the record of ice sheet motion data is too sparse to determine whether changes in flow have occurred on sub-annual timescales across much of the continent. For example, the record of ice sheet motion data is too sparse to determine whether changes in flow have occurred on sub-annual timescales across much of the continent. On this point, the outlook is promising thanks to the systematic acquisition plans of the Sentinel-1 synthetic aperture radar and Landsat-8 optical imager missions. A key unanswered science question is how long it will take for the ice shelves that are currently thinning to reach a point whereby they are no longer providing effective buttressing for the grounded ice inland. To address this, observations are required with sufficient frequency to track the events themselves which, in the case of ice shelf collapses, have taken place over months or even days [14]. Although it is possible to monitor grounding line migration with high precision using synthetic aperture radar interferometry [85,86], the revisit period of satellite missions is currently too long for the technique to be effective over rapidly deforming ice, and so other methods - such as repeat satellite altimetry [141] - will need to be exploited to track this precursor to ice sheet dynamical imbalance.

The past decade has been a golden era for satellite glaciology, with a host of different sensors in orbit, simultaneously. However, measuring ice loss from Antarctica at the continental scale is today heavily reliant upon a single ageing mission - CryoSat-2 - which, at 8 years old, is now more than double its planned lifetime, and the continuity of passive microwave observations of sea ice concentration and extent remains uncertain. Given the societal importance of changes in ice cover and global sea level, this situation carries considerable risk, and the next generation of satellite sensors are eagerly awaited.

Acknowledgements

This work was supported by the UK Natural Environment Research Council's Centre for Polar Observation and Modelling (cpom300001) and the European Space Agency's Climate Change Initiative. AS was supported by a Royal Society Wolfson Research Merit award. SLF was supported under NASA grant 80NSSC17K0006 and NOAA grant NA14NES4320003. We thank T. Slater, A. Ridout, and L. Gilbert for their help in preparing Fig. 1 and Fig. 2, and K. Duncan for help in preparing Fig. 4.

Competing Interests

The authors declare no competing interests.

Figures and tables

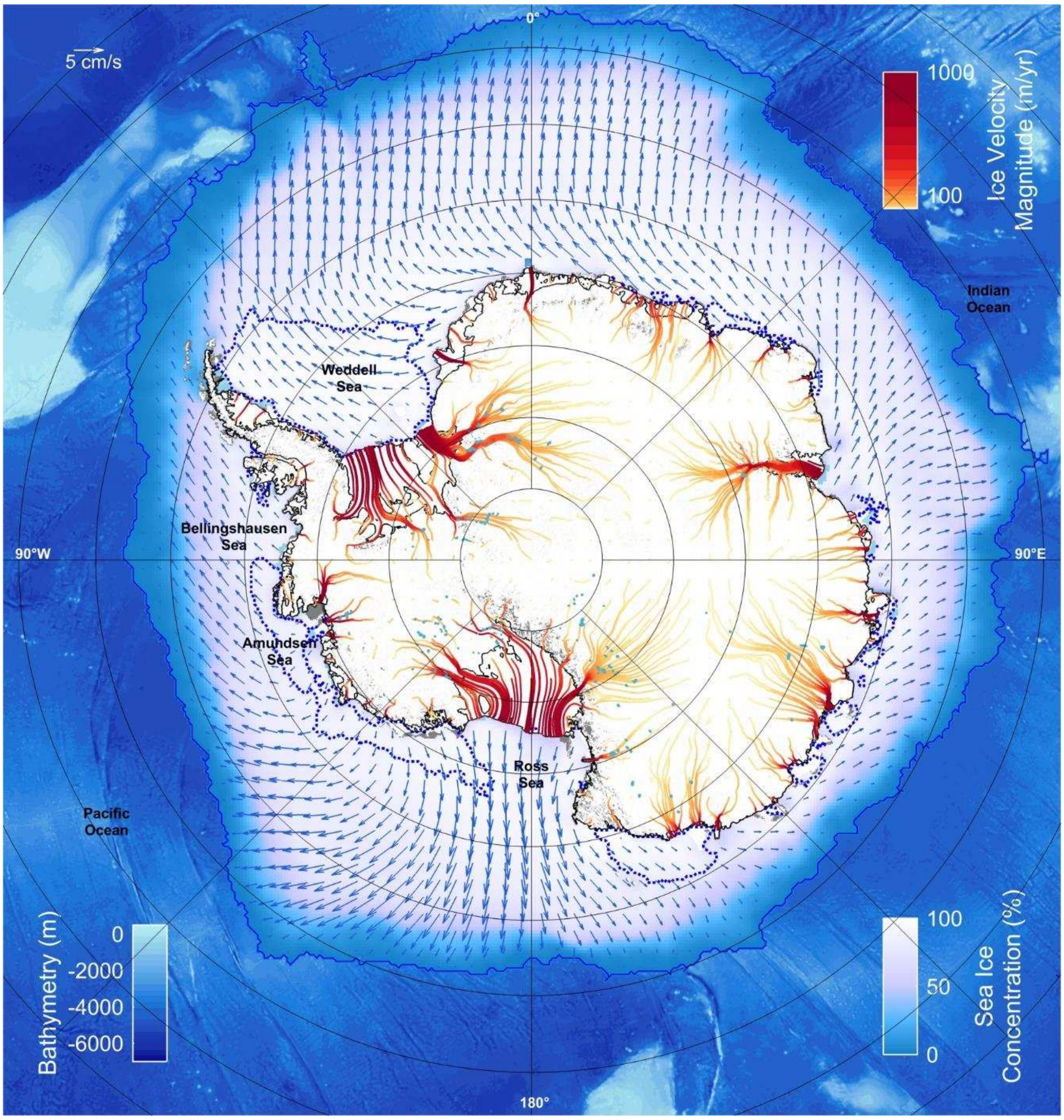

Figure 1. Average annual motion of the Antarctic ice sheet and ice shelves, and of the surrounding sea ice in winter. The ice sheet is drained by around 30 principle flow units and the sea ice transport is generally northwards, with gyres in the Ross and Weddell Seas. Grounded ice and ice

shelf motion are derived from multiple satellite interferometric synthetic-aperture radar data acquired between 2007 and 2009 [20]. Ice sheet motion flowlines are superimposed on the MODIS mosaic of Antarctica [142]. Sea ice motion is the mean of daily gridded Polar Pathfinder radiometry obtained during peak winter (September) of each year in the period 1990 to 2016 [143]. Sea ice motion vectors are superimposed on a map of mean sea ice concentration derived from passive microwave brightness temperatures in September between 1990 to 2016 [144]. Also shown (blue dashed boundaries) are the average minimum extent of sea ice recorded between 1990 to 2016 [144], the grounded ice sheet and the floating ice shelves (black boundaries), and the bathymetry of the surrounding ocean [145]. Active subglacial lakes (light blue) were mapped using satellite radar and laser altimetry [51].

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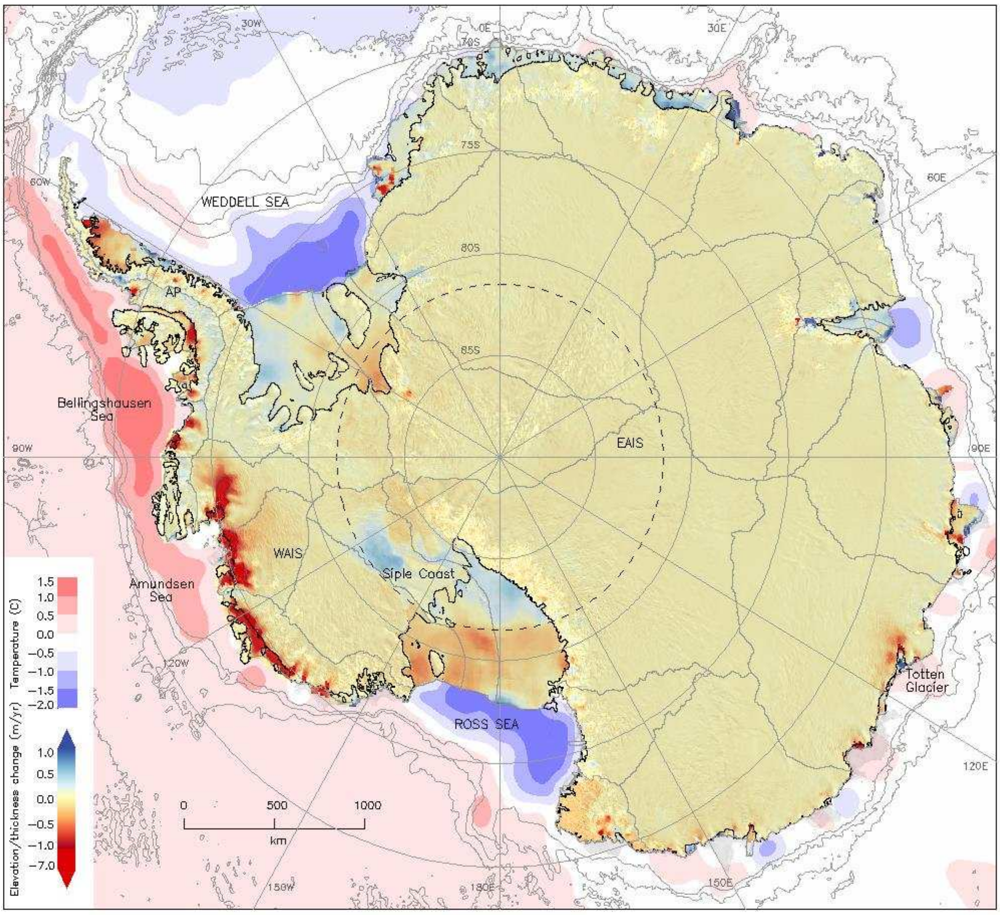


Figure 2. Average trend in the elevation and thickness of Antarctic grounded ice and ice shelves, respectively, determined between 1992 and 2017 North of 81.5°S (dashed grey circle), and between 2010 and 2017 elsewhere. Also shown is the depth of [146] and estimated ocean temperature at [147] the sea floor around the continent. Changes in grounded ice and ice shelf thickness were estimated using repeat satellite altimetry following the methods of [36], [148], and [3]. Thickness trends are superimposed on an optical image mosaic of the floating and grounded ice [142], and is divided (grey lines) into the principle ice drainage catchments [2]. Since 1992, the grounded ice sheet and its peripheral ice shelves have thinned in locations adjacent to warm ocean currents. Although the East Antarctic ice sheet is mostly stable, there have been marked

changes in West Antarctica, including accelerated thinning of glaciers draining the Amundsen Sea sector and constant thickening in southerly catchments of the Siple Coast. While the former is a response to ocean-driven melting of ice shelves at glacier termini [12], the latter is associated with stagnation of ice flow due to a loss of basal lubrication [149]. At the Antarctic Peninsula, ice shelf collapse (Cook and Vaughan, 2010) has triggered inland glacier acceleration [25,68] and thinning [15].

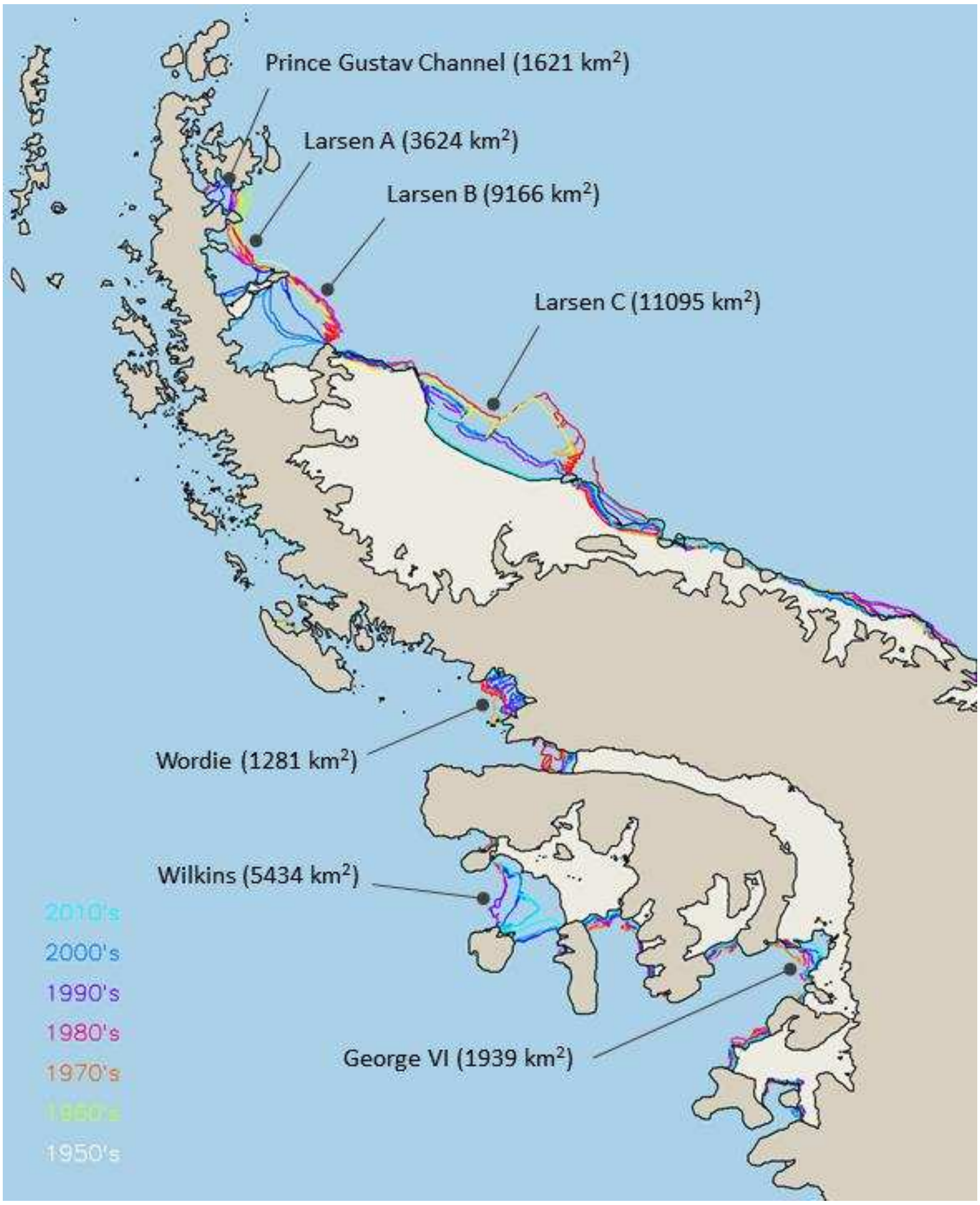


Figure 3. Temporal changes in the location of ice shelf barriers at the Antarctic Peninsula (coloured lines) as determined from satellite imagery since the 1950s, and their net reduction in area over the same period (numbers in brackets) [14,73]. The reduction in area at Larsen-C includes the recent calving of the A-68 tabular iceberg. In the 1950s, the total area of Antarctic Peninsula ice shelves was estimated to be 152,246 km^2. Since then, an area of 33,917 km^2 has been lost during episodic calving events.

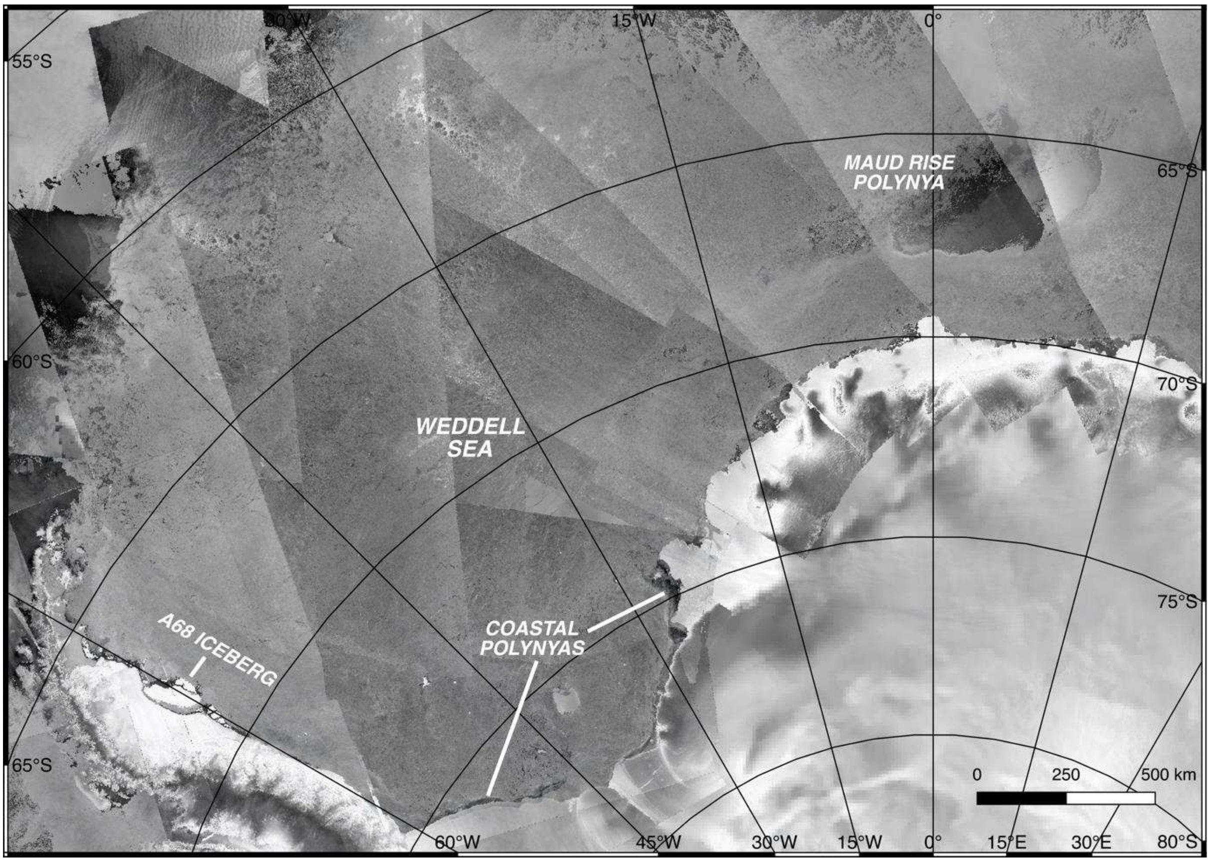


Figure 4. Sea ice in the Weddell Sea in early November 2017, based on a composite of Sentinel-1

synthetic aperture radar imagery, MODIS optical satellite imagery, and ASCAT scatterometer data. The satellite data were acquired during Austral winter when the ice cover is close to its maximum extent, stretching beyond the tip of the Antarctic Peninsula into Drake Passage. The composite reveals details of the diffuse ice cover in the marginal ice zone along the boundary with the open ocean, and the more compact, consolidated ice cover farther south. A large, ~35,000 km^2 ice-free area is visible near Maud Rise (66S, 5E); this polynya is formed by thermally-driven convection in the water column, due to the interaction of ocean currents and sea floor topography. Coastal polynyas are visible along the edges of the Filchner-Ronne, Brunt and Stancombe-Willis Ice Shelves, where openings in the ice cover are driven by katabatic wind, tides, and ocean currents. New sea ice, which rejects brine during formation, is continually produced in these polynyas, making polynyas a source of dense, high salinity deep water which plays an important role in the global thermohaline circulation. Also visible is the large, tabular A68 iceberg (located ~68S, 60.5W) which calved from Larsen C Ice Shelf on 12 July 2017, and is now adrift in the western Weddell Sea.

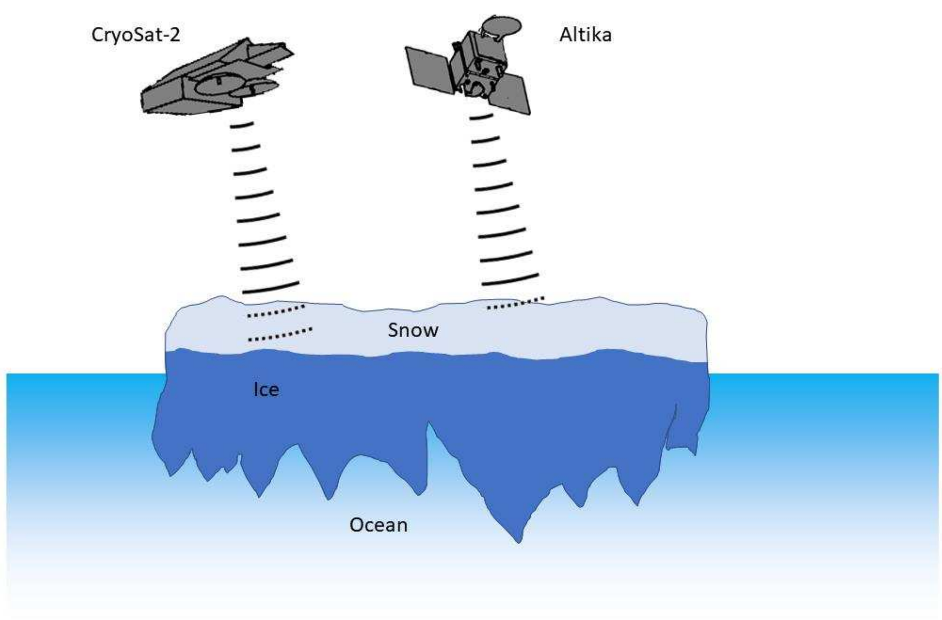
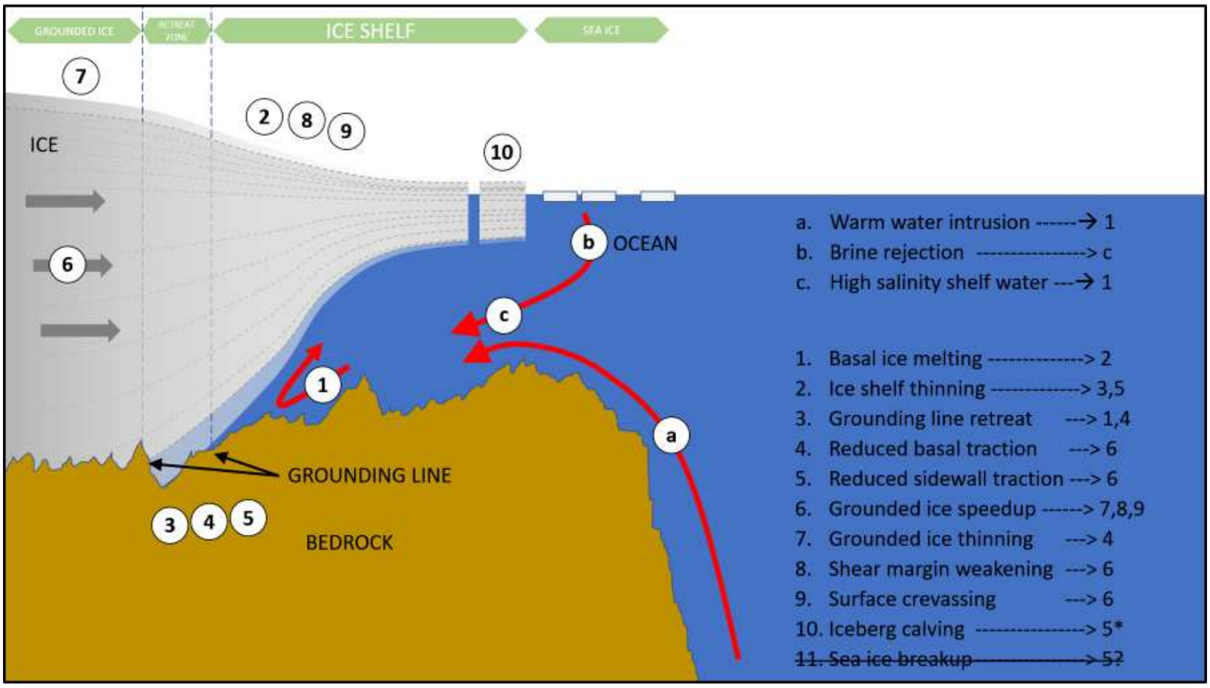


Figure 5. Schematic of a sea ice floe as observed by CryoSat-2 and AltiKa. Floe thicknesses are typically derived from measurements of their freeboard (the portion protruding above the ocean surface), an estimate of the snow loading, and the principal of buoyancy [99]. CryoSat-2 and AltiKa operate at different radar frequencies, and their echoes scatter from locations near to the lower and upper boundaries of the snow layer, respectively [139,140]. Measurements acquired at both frequencies could provide a direct measurement of the snow loading, improving the certainty of sea ice floe thickness estimates.

Box 1



Box 1. Ice shelf buttressing processes (points 1-10) associated with external forcing (points a-c), and their connectivity. Ice shelves are floating sheets of ice that form as glaciers spread out into the ocean, typically within confined embayments. They are permanently attached to the grounded ice sheet resting on land, and accumulate snow at their surface and, occasionally, frozen ocean water at their base. If warm water enters the ocean cavity beneath an ice shelf (a) it can drive increased basal

ice melting (1) and ice shelf thinning (2), which in turn leads to retreat of the grounding line (3) – the junction between grounded and floating ice on the seafloor. Ice shelf thinning reduces sidewall (lateral) traction (4) and grounding line retreat reduces basal traction (5). Both processes lead to speedup of the grounded ice (6), which causes grounded ice thinning (7). Glacier speedup can also lead to weakening of lateral shear margins (8) and increased crevassing (9). Iceberg calving (10) can also lead to reduced sidewall traction. Sea ice (frozen sea water) can play a role, through brine rejection (b) which drives the production of warm high salinity shelf water (c), and by effectively reducing traction on ice-shelf breakup (1).

References

1 Parkinson, C. L. Global sea ice coverage from satellite data: Annual cycle and 35-yr trends. Journal of Climate 27, 9377-9382, doi:10.1175/JCLI-D-14-00605.1 (2014). **This paper is a recent assessment of multi-decadal trends in global sea ice extent as derived from satellite passive microwave radiometer data, confirming that the losses in ice extent in the Arctic Ocean far exceed gains in the Southern Ocean.**

2 Zwally, H. J., Giovinetto, M. B., Beckley, M. A. & Saba, J. L. (GSFC Cryospheric Sciences Laboratory, 2012).

3 Shepherd, A. et al. Recent loss of floating ice and the consequent sea level contribution. Geophysical Research Letters 37, doi:10.1029/2010GL042496 (2010).

4 Fretwell, P. et al. Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica. Cryosphere 7, 375-393, doi:10.5194/tc-7-375-2013 (2013). **This paper presents models of the Antarctic ice sheet and ice shelf thickness, determined from a compilation of airborne and satellite remote sensing, that are widely-used across the glaciological community and beyond.**

5 Jacobs, S. S., Helmer, H. H., Doake, C. S. M., Jenkins, A. & Frolich, R. M. Melting of ice shelves and the mass balance of Antarctica. Journal of Glaciology 38, 375-387, doi:10.1017/S0022143000002252 (1992).

6 Massom, R. A. & Stammerjohn, S. E. Antarctic sea ice change and variability - Physical and ecological implications. Polar Science 4, 149-186, doi:10.1016/j.polar.2010.05.001 (2010).

7 Worby, A. P. et al. Thickness distribution of Antarctic sea ice. Journal of Geophysical Research: Oceans 113, doi:10.1029/2007JC004254 (2008).

8 Zwally, H. J., Parkinson, C. L. & Comiso, J. C. Variability of Antarctic sea ice and changes in carbon dioxide. Science 220, 1005-1012 (1983). **As an early application of satellite radar imagery for tracking trends in the extent of sea ice in the Southern hemisphere, this paper is a seminal study.**

9 De Santis, A., Maier, E., Gomez, R. & Gonzalez, I. Antarctica, 1979–2016 sea ice extent: total versus regional trends, anomalies, and correlation with climatological variables. International Journal of Remote Sensing 38, 7566-7584, doi:10.1080/01431161.2017.1363440 (2017).

10 The IMBIE Team, Mass balance of the Antarctic ice sheet from 1992 to 2017. Nature (In press). **This large collaborative work presents an updated comparison and synthesis of many individual estimates of Antarctic ice sheet mass balance derived from satellite observations to deliver a single result for use by the wider scientific community.**

11 Paolo, F. S., Fricker, H. A. & Padman, L. Volume loss from Antarctic ice shelves is accelerating. Science 348, 327-331, doi:10.1126/science.aaa0940 (2015). **A multi-mission record (1994 to 2012) of ice-shelf surface height from satellite radar altimetry showed accelerated loss of volume of Antarctica's ice shelves, with early increases in East Antarctica, likely due to accumulation, and substantial losses in West Antarctica, where some ice shelves thinned by up to 18% in the 18 years.**

12 Shepherd, A., Wingham, D. & Rignot, E. Warm ocean is eroding West Antarctic Ice Sheet. Geophysical Research Letters 31, 1-4, doi:10.1029/2004GL021106 (2004).

13 Shepherd, A., Wingham, D., Payne, T. & Skvarca, P. Larsen Ice Shelf Has Progressively Thinned. Science 302, 856-859, doi:10.1126/science.1089768 (2003). **This paper describes the first application of satellite measurements for detecting trends in the thickness of Antarctic ice shelves, providing direct observations of contemporary imbalance and evidence that ocean-driven melting is a destabilising force.**

14 Cook, A. J. & Vaughan, D. G. Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. Cryosphere 4, 77-98, doi:10.5194/tc-4-77-2010 (2010).

15 Scambos, T. A., Bohlander, J. A., Shuman, C. A. & Skvarca, P. Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. Geophysical Research Letters 31, L18402 18401-18404, doi:10.1029/2004GL020670 (2004).

16 Drewry, D. J. Antarctica: glaciological and geophysical folio. Antarctica: glaciological and geophysical folio. (1982).

17 Bamber, J. L., Vaughan, D. G. & Joughin, I. Widespread complex flow in the interior of the antarctic ice sheet. Science 287, 1248-1250, doi:10.1126/science.287.5456.1248 (2000). **This study was the first to apply the balance-velocity technique to map the continental pattern of ice flow, revealing the intricate nature of the ice sheet glaciers.**

18 Scambos, T. A., Dutkiewicz, M. J., Wilson, J. C. & Bindschadler, R. A. Application of image cross-correlation to the measurement of glacier velocity using satellite image data. Remote Sensing of Environment 42, 177-186, doi:10.1016/0034-4257(92)90101-O (1992).

19 Goldstein, R. M., Engelhardt, H., Kamb, B. & Frolich, R. M. Satellite radar interferometry for monitoring ice sheet motion: Application to an Antarctic ice stream. Science 262, 1525-1530 (1993).

This ground-breaking study was the first to explain how the innovative technique of satellite radar interferometry could be applied to glaciology, introducing methods for tracking glacier topography and motion, and the location of ice stream grounding lines.

20 Rignot, E., Mouginot, J. & Scheuchl, B. Ice flow of the antarctic ice sheet. Science 333, 1427-1430, doi:10.1126/science.1208336 (2011).

21 Joughin, I., Rignot, E., Rosanova, C. E., Lucchitta, B. K. & Bohlander, J. Timing of recent accelerations of Pine Island Glacier, Antarctica. Geophysical Research Letters 30, 39-31 (2003).

22 Rignot, E. Evidence for rapid retreat and mass loss of Thwaites Glacier, West Antarctica. Journal of Glaciology 47, 213-222, doi:10.3189/172756501781832340 (2001).

23 Joughin, I., Tulaczyk, S., Bindschadler, R. & Price, S. F. Changes in west Antarctic ice stream velocities: Observation and analysis. Journal of Geophysical Research: Solid Earth 107, EPM 3-1 - 3-22 (2002).

24 Rignot, E. et al. Recent ice loss from the Fleming and other glaciers, Wordie Bay, West Antarctic Peninsula. Geophysical Research Letters 32, 1-4, doi:10.1029/2004GL021947 (2005).

25 Rott, H., Müller, F., Nagler, T. & Floricioiu, D. The imbalance of glaciers after disintegration of Larsen-B ice shelf, Antarctic Peninsula. Cryosphere 5, 125-134, doi:10.5194/tc-5-125-2011 (2011).

26 Hogg, A. E. et al. Increased ice flow in Western Palmer Land linked to ocean melting. Geophysical Research Letters 44, 4159-4167, doi:10.1002/2016GL072110 (2017).

27 Stearns, L. A., Smith, B. E. & Hamilton, G. S. Increased flow speed on a large east antarctic outlet glacier caused by subglacial floods. Nature Geoscience 1, 827-831, doi:10.1038/ngeo356 (2008).

28 Li, X., Rignot, E., Morlighem, M., Mouginot, J. & Scheuchl, B. Grounding line retreat of Totten Glacier, East Antarctica, 1996 to 2013. Geophysical Research Letters 42, 8049-8056, doi:10.1002/2015GL065701 (2015).

29 Rignot, E. et al. Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. Nature Geoscience 1, 106-110, doi:10.1038/ngeo102 (2008).

30 Zwally, H. J., Brenner, A. C., Major, J. A., Bindschadler, R. A. & Marsh, J. G. Growth of Greenland ice sheet: Measurement. Science 246, 1587-1589 (1989).

31 Wingham, D. J., Ridout, A. J., Scharroo, R., Arthern, R. J. & Shum, C. K. Antarctic elevation change from 1992 to 1996. Science 282, 456-458, doi:10.1126/science.282.5388.456 (1998).

32 Pritchard, H. D., Arthern, R. J., Vaughan, D. G. & Edwards, L. A. Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. Nature 461, 971-975, doi:10.1038/nature08471 (2009).

33 Velicogna, I. & Wahr, J. Measurements of time-variable gravity show mass loss in Antarctica. Science 311, 1754-1756, doi:10.1126/science.1123785 (2006).

34 Luthcke, S. B. et al. Antarctica, Greenland and Gulf of Alaska land-ice evolution from an iterated GRACE global mascon solution. Journal of Glaciology 59, 613-631, doi:10.3189/2013JoG12J147 (2013).

35 Briggs, K. et al. Charting ice-sheet contributions to global sea-level rise. Eos, Transactions American Geophysical Union 97 (2016).

36 Shepherd, A. et al. A reconciled estimate of ice-sheet mass balance. Science 338, 1183-1189, doi:10.1126/science.1228102 (2012).

37 Wingham, D. J., Wallis, D. W. & Shepherd, A. Spatial and temporal evolution of Pine Island Glacier thinning, 1995-2006. Geophysical Research Letters 36, doi:10.1029/2009GL039126 (2009).

38 Sutterley, T. C. et al. Mass loss of the Amundsen Sea Embayment of West Antarctica from four independent techniques. Geophysical Research Letters 41, 8421-8428, doi:10.1002/2014GL061940 (2014).

39 Shepherd, A., Wingham, D. J., Mansley, J. A. D. & Corr, H. F. J. Inland thinning of Pine Island Glacier, West Antarctica. Science 291, 862-864, doi:10.1126/science.291.5505.862 (2001).

40 Whillans, I. M., Bolzan, J. & Shabtaie, S. Velocity of ice streams B and C, Antarctica. Journal of Geophysical Research 92, 8895-8902 (1987).

41 Retzlaff, R. & Bentley, C. R. Timing of stagnation of ice stream C, West Antarctica, from short- pulse radar studies of buried surface crevasses. Journal of Glaciology 39, 553-561, doi:10.1017/S0022143000016440 (1993).

42 Shepherd, A., Wingham, D. J. & Mansley, J. A. D. Inland thinning of the Amundsen Sea sector, West Antarctica. Geophysical Research Letters 29, 2-1 (2002).

43 Mouginot, J., Rignot, E. & Scheuchl, B. Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013. Geophysical Research Letters 41, 1576-1584, doi:10.1002/2013GL059069 (2014).

44 Jacobs, S. S., Jenkins, A., Giulivi, C. F. & Dutrieux, P. Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. Nature Geoscience 4, 519-523, doi:10.1038/ngeo1188 (2011).

45 Siegert, M. J., Carter, S., Tabacco, I., Popov, S. & Blankenship, D. D. A revised inventory of Antarctic subglacial lakes. Antarctic Science 17, 453-460, doi:10.1017/S0954102005002889 (2005).

46 Gray, L. et al. Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry. Geophysical Research Letters 32, 1-4, doi:10.1029/2004GL021387 (2005). **This study was the first to detect the surface expression of water transport beneath the Antarctic ice sheet, a new approach for studying the hydrology of the continents subglacial lakes.**

47 Wingham, D. J., Siegert, M. J., Shepherd, A. & Muir, A. S. Rapid discharge connects Antarctic subglacial lakes. Nature 440, 1033-1036, doi:10.1038/nature04660 (2006).

48 Fricker, H. A., Scambos, T., Bindschadler, R. & Padman, L. An active subglacial water system in West Antarctica mapped from space. Science 315, 1544-1548, doi:10.1126/science.1136897 (2007).

49 Smith, B. E., Helen, A. F., Ian, R. J. & Tulaczyk, S. An inventory of active subglacial lakes in Antarctica detected by ICESat (2003-2008. Journal of Glaciology 55, 573-595, doi:10.3189/002214309789470879 (2009).

50 Bell, R. E. The role of subglacial water in ice-sheet mass balance. Nature Geoscience 1, 297-304, doi:10.1038/ngeo186 (2008).

51 Siegfried, M. R. & Fricker, H. Thirteen years of subglacial lake activity in Antarctica from multi-mission satellite altimetry. Annals of Glaciology, 1-14 (2018).

52 Bell, R. E., Studinger, M., Shuman, C. A., Fahnestock, M. A. & Joughin, I. Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams. Nature 445, 904-907, doi:10.1038/nature05554 (2007).

53 Schaffer, J. et al. A global, high-resolution data set of ice sheet topography, cavity geometry, and ocean bathymetry. Earth System Science Data 8, 543-557, doi:10.5194/essd-8-543-2016 (2016).

54 Weertman, J. Stability of the junction of an ice sheet and an ice shelf. Journal of Glaciology 13, 3-11 (1974).

55 Fahnestock, M. A., Scambos, T. A., Bindschadler, R. A. & Kvaran, G. A millennium of variable ice flow recorded by the ross ice shelf, Antarctica. Journal of Glaciology 46, 652-664, doi:10.3189/172756500781832693 (2000).

56 Domack, E. et al. Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch. Nature 436, 681-685, doi:10.1038/nature03908 (2005).

57 Vaughan, D. G. et al. Recent rapid regional climate warming on the Antarctic Peninsula. Climatic Change 60, 243-274, doi:10.1023/A:1026021217991 (2003).

58 Griggs, J. A. & Bamber, J. L. Antarctic ice-shelf thickness from satellite radar altimetry. Journal of Glaciology 57, 485-498, doi:10.3189/002214311796905659 (2011).

59 Pritchard, H. D. et al. Antarctic ice-sheet loss driven by basal melting of ice shelves. Nature 484, 502-505, doi:10.1038/nature10968 (2012).

60 Helsen, M. M. et al. Elevation changes in antarctica mainly determined by accumulation variability. Science 320, 1626-1629, doi:10.1126/science.1153894 (2008).

61 Rosanova, C. E., Lucchitta, B. K. & Ferrigno, J. G. Velocities of Thwaites Glacier and smaller glaciers along the Marie Byrd Land coast, West Antarctica. Annals of Glaciology 27, 47-53 (1998).

62 Rack, W., Doake, C. S. M., Rott, H., Siegel, A. & Skvarca, P. Interferometric analysis of the deformation pattern of the northern Larsen Ice Shelf, Antarctic Peninsula, compared to field measurement and numerical modeling. Annals of Glaciology 31, 205-208 (2000).

63 Rignot, E. & Jacobs, S. S. Rapid bottom melting widespread near antarctic ice sheet grounding lines. Science 296, 2020-2023, doi:10.1126/science.1070942 (2002). **In reporting satellite**

derived estimates of ice shelf basal melting, this study was among the first to assess ice-ocean interactions and to highlight regional variations in ocean forcing.

64 Rignot, E., Jacobs, S., Mouginot, J. & Scheuchl, B. Ice-shelf melting around antarctica. Science 341, 266-270, doi:10.1126/science.1235798 (2013).

65 Depoorter, M. A. et al. Calving fluxes and basal melt rates of Antarctic ice shelves. Nature 502, 89-92, doi:10.1038/nature12567 (2013).

66 Paolo, F. S. et al. Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern Oscillation. Nature Geoscience 11, 121-126, doi:10.1038/s41561-017-0033-0 (2018).

67 Jacobs, S. S., Hellmer, H. H. & Jenkins, A. Antarctic Ice Sheet melting in the southeast Pacific. Geophysical Research Letters 23, 957-960, doi:10.1029/96GL00723 (1996).

68 Rignot, E. et al. Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. Geophysical Research Letters 31, L18401 18401-18404, doi:10.1029/2004GL020697 (2004).

69 Humbert, A. & Braun, M. The Wilkins Ice Shelf, Antarctica: Break-up along failure zones. Journal of Glaciology 54, 943-944, doi:10.3189/002214308787780012 (2008).

70 Cooper, A. P. R. Historical observations of Prince Gustav ice shelf. Polar Record 33, 285-294 (1997).

71 Skvarca, P. Fast recession of the northern Larsen Ice Shelf monitored by space images. Annals of Glaciology 17, 317-321 (1993).

72 Doake, C. S. M. & Vaughan, D. G. Rapid disintegration of the Wordie Ice Shelf in response to atmospheric warming. Nature 350, 328-330 (1991).

73 Hogg, A. E. & Gudmundsson, G. H. Commentary: Impacts of the Larsen-C Ice Shelf calving event. Nature Climate Change 7, 540-542, doi:10.1038/nclimate3359 (2017).

74 Pudsey, C. J. & Evans, J. First survey of Antarctic sub-ice shelf sediments reveals mid-Holocene ice shelf retreat. Geology 29, 787-790, doi:10.1130/0091-7613(2001)029<0787:FSOASI>2.0.CO;2 (2002).

75 van den Broeke, M. Strong surface melting preceded collapse of Antarctic Peninsula ice shelf. Geophysical Research Letters 32, 1-4, doi:10.1029/2005GL023247 (2005).

76 Scambos, T., Hulbe, C. & Fahnestock, M. A. Climate-induced ice shelf disintegration in the Antarctic Peninsula. Antarctic Research Series 76, 335-347 (2003).

77 Vieli, A., Payne, A. J., Shepherd, A. & Du, Z. Causes of pre-collapse changes of the Larsen B ice shelf: Numerical modelling and assimilation of satellite observations. Earth and Planetary Science Letters 259, 297-306, doi:10.1016/j.epsl.2007.04.050 (2007).

78 Liu, Y. et al. Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves. Proceedings of the National Academy of Sciences of the United States of America 112, 3263-3268, doi:10.1073/pnas.1415137112 (2015).

79 Fricker, H. A. & Padman, L. Thirty years of elevation change on Antarctic Peninsula ice shelves from multimission satellite radar altimetry. Journal of Geophysical Research: Oceans 117, doi:10.1029/2011JC007126 (2012).

80 Adusumilli, S. et al. Variable basal melt rates of Antarctic Peninsula ice shelves, 1994-2016. Geophysical Research Letters In press (2018).

81 Royston, S. & Gudmundsson, G. H. Changes in ice-shelf buttressing following the collapse of Larsen A Ice Shelf, Antarctica, and the resulting impact on tributaries. Journal of Glaciology 62, 905-911, doi:10.1017/jog.2016.77 (2016).

82 Phillips, H. A. & Laxon, S. W. Tracking of antarctic tabular icebergs using passive microwave radiometry. International Journal of Remote Sensing 16, 399-405, doi:10.1080/01431169508954407 (1995). **By tracking a large tabular iceberg that calved from Larsen C Ice Shelf with passive microwave imagery, this paper demonstrated how satellite imagery can be used to detect the calving of large, tabular icebergs from Antarctica, and to chart their motion as they drift around the continent.**

83 Schoof, C. Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. Journal of Geophysical Research: Earth Surface 112, doi:10.1029/2006JF000664 (2007).

84 De Angelis, H. & Skvarca, P. Glacier surge after ice shelf collapse. Science 299, 1560-1562, doi:10.1126/science.1077987 (2003). **Although qualitative in nature, this paper was the first to confirm that the disintegration of the Larsen ice shelf triggered increase flow of the grounded ice upstream, by tracking glacial geomorphological features in airborne and satellite imagery.**

85 Rignot, E. J. Fast recession of a West Antarctic glacier. Science 281, 549-551, doi:10.1126/science.281.5376.549 (1998). **As the first study to discover unstable retreat of a West Antarctic glacier in satellite data, this is a landmark paper in glaciology that has triggered widespread scientific interest in the Amundsen Sea sector.**

86 Park, J. W. et al. Sustained retreat of the Pine Island Glacier. Geophysical Research Letters 40, 2137-2142, doi:10.1002/grl.50379 (2013).

87 Thoma, M., Jenkins, A., Holland, D. & Jacobs, S. Modelling Circumpolar Deep Water intrusions on the Amundsen Sea continental shelf, Antarctica. Geophysical Research Letters 35, doi:10.1029/2008GL034939 (2008).

88 Konrad, H. et al. Uneven onset and pace of ice-dynamical imbalance in the Amundsen Sea Embayment, West Antarctica. Geophysical Research Letters 44, 910-918, doi:10.1002/2016GL070733 (2017).

89 Joughin, I., Alley, R. B. & Holland, D. M. Ice-sheet response to oceanic forcing. Science 338, 1172-1176, doi:10.1126/science.1226481 (2012). **This review provides a great introduction to ice-ocean interactions, and how satellite observations have informed our understanding of key processes.**

90 Mercer, J. H. West Antarctic ice sheet and CO2 greenhouse effect: A threat of disaster. Nature 271, 321-325, doi:10.1038/271321a0 (1978).

91 Anderson, J. B., Shipp, S. S., Lowe, A. L., Wellner, J. S. & Mosola, A. B. The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: A review. Quaternary Science Reviews 21, 49-70, doi:10.1016/S0277-3791(01)00083-X (2002).

92 Joughin, I., Smith, B. E. & Holland, D. M. Sensitivity of 21st century sea level to ocean-induced thinning of Pine Island Glacier, Antarctica. Geophysical Research Letters 37, doi:10.1029/2010GL044819 (2010).

93 Joughin, I., Smith, B. E. & Medley, B. Marine ice sheet collapse potentially under way for the thwaites glacier basin, West Antarctica. Science 344, 735-738, doi:10.1126/science.1249055 (2014).

94 Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H. & Scheuchl, B. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophysical Research Letters 41, 3502-3509, doi:10.1002/2014GL060140 (2014).

95 Milillo, P. et al. On the Short-term Grounding Zone Dynamics of Pine Island Glacier, West Antarctica, Observed With COSMO-SkyMed Interferometric Data. Geophysical Research Letters 44, 10,436-410,444, doi:10.1002/2017GL074320 (2017).

96 Konrad, H. et al. Net retreat of Antarctic glacier grounding lines. Nature Geoscience In press (2018).

97 Dutrieux, P. et al. Strong sensitivity of pine Island ice-shelf melting to climatic variability. Science 343, 174-178, doi:10.1126/science.1244341 (2014).

98 Gloersen, P. et al. Satellite passive microwave observations and analysis of Arctic and Antarctic sea ice, 1978-1987. Annals of Glaciology 17, 149-154 (1993).

99 Zwally, H. J., Yi, D., Kwok, R. & Zhao, Y. ICESat measurements of sea ice freeboard and estimates of sea ice thickness in the Weddell Sea. Journal of Geophysical Research: Oceans 113, doi:10.1029/2007JC004284 (2008). **This study was the first to attempt an extensive assessment of Antarctic sea ice thickness based on satellite altimeter measurements of floe freeboard.**

100 Kurtz, N. T. & Markus, T. Satellite observations of Antarctic sea ice thickness and volume. Journal of Geophysical Research: Oceans 117, doi:10.1029/2012JC008141 (2012).

101 Heil, P., Fowler, C. W. & Lake, S. E. Antarctic sea-ice velocity as derived from SSM/I imagery. Annals of Glaciology 44, 361-366, doi:10.3189/172756406781811682 (2006).

102 Holland, P. R. & Kwok, R. Wind-driven trends in Antarctic sea-ice drift. Nature Geoscience 5, 872-875, doi:10.1038/ngeo1627 (2012).

103 Brierley, A. S. & Thomas, D. N. in Advances in Marine Biology Vol. 43 171-276 (Academic Press, 2002).

104 Massom, R. A. et al. 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: Oceans 115, doi:10.1029/2009JC006083 (2010).

105 Robel, A. A. Thinning sea ice weakens buttressing force of iceberg mélange and promotes calving. Nature Communications 8, doi:10.1038/ncomms14596 (2017).

106 Miles, B. W. J., Stokes, C. R. & Jamieson, S. S. R. Simultaneous disintegration of outlet glaciers in Porpoise Bay (Wilkes Land), East Antarctica, driven by sea ice break-up. Cryosphere 11, 427-442, doi:10.5194/tc-11-427-2017 (2017).

107 Turner, J., Hosking, J. S., Bracegirdle, T. J., Marshall, G. J. & Phillips, T. Recent changes in Antarctic Sea Ice. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 373, doi:10.1098/rsta.2014.0163 (2015).

108 Armour, K. C. & Bitz, C. M. in US Clivar Variations Vol. 13 12-19 (2015).

109 Meier, W., Gallaher, D. & Campbell, G. G. New estimates of Arctic and Antarctic sea ice extent during September 1964 from recovered Nimbus I satellite imagery. The Cryosphere 7, 699-705 (2013).

110 Gallaher, D. W., Campbell, G. G. & Meier, W. N. Anomalous variability in Antarctic sea ice extents during the 1960s with the use of Nimbus data. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 7, 1116-1122, doi:10.1109/JSTARS.2013.2264391 (2014).

111 De La Mare, W. K. Changes in Antarctic sea-ice extent from direct historical observations and whaling records. Climatic Change 92, 461-493, doi:10.1007/s10584-008-9473-2 (2009).

112 Massonnet, F., Guemas, V., Fučkar, N. S. & Doblas-Reyes, F. J. The 2014 high record of antarctic sea ice extent. Bulletin of the American Meteorological Society 96, S163-S167, doi:10.1175/BAMS-D-15-00093.1 (2015).

113 Turner, J. et al. Unprecedented springtime retreat of Antarctic sea ice in 2016. Geophysical Research Letters 44, 6868-6875, doi:10.1002/2017GL073656 (2017).

114 Stuecker, M. F., Bitz, C. M. & Armour, K. C. Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring season. Geophysical Research Letters 44, 9008-9019, doi:10.1002/2017GL074691 (2017).

115 Zhang, J. Increasing antarctic sea ice under warming atmospheric and oceanic conditions. Journal of Climate 20, 2515-2529, doi:10.1175/JCLI4136.1 (2007).

116 Hobbs, W. R. et al. A review of recent changes in Southern Ocean sea ice, their drivers and forcings. Global and Planetary Change 143, 228-250, doi:10.1016/j.gloplacha.2016.06.008 (2016).

117 Kwok, R. & Comiso, J. C. Southern Ocean climate and sea ice anomalies associated with the Southern Oscillation. Journal of Climate 15, 487-501, doi:10.1175/1520-0442(2002)015<0487:SOCASI>2.0.CO;2 (2002).

118 Stammerjohn, S., Massom, R., Rind, D. & Martinson, D. Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. Geophysical Research Letters 39, doi:10.1029/2012GL050874 (2012).

119 Kwok, R., Comiso, J. C., Lee, T. & Holland, P. R. Linked trends in the South Pacific sea ice edge and Southern Oscillation Index. Geophysical Research Letters 43, 10,295-210,302, doi:10.1002/2016GL070655 (2016).

120 Turner, J. & Comiso, J. Solve Antarctica's sea-ice puzzle. Nature 547, 275-277, doi:10.1038/547275a (2017).

121 Gloersen, P. Modulation of hemispheric sea-ice cover by ENSO events. Nature 373, 503-506, doi:10.1038/373503a0 (1995).

122 Lefebvre, W., Goosse, H., Timmermann, R. & Fichefet, T. Influence of the Southern Annular Mode on the sea ice - Ocean system. Journal of Geophysical Research C: Oceans 109, 1-12, doi:10.1029/2004JC002403 (2004).

123 Holland, M. M., Landrum, L., Kostov, Y. & Marshall, J. Sensitivity of Antarctic sea ice to the Southern Annular Mode in coupled climate models. Climate Dynamics 49, 1813-1831, doi:10.1007/s00382-016-3424-9 (2017).

124 Turner, J. et al. Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophysical Research Letters 36, doi:10.1029/2009GL037524 (2009).

125 Bintanja, R., Van Oldenborgh, G. J., Drijfhout, S. S., Wouters, B. & Katsman, C. A. Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. Nature Geoscience 6, 376-379, doi:10.1038/ngeo1767 (2013).

126 Pauling, A. G., Smith, I. J., Langhorne, P. J. & Bitz, C. M. 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, 10,454-410,461, doi:10.1002/2017GL075017 (2017).

127 Perovich, D. K. & Richter-Menge, J. A. Loss of sea ice in the arctic. Annual Review of Marine Science 1, 417-441, doi:10.1146/annurev.marine.010908.163805 (2009).

128 Comiso, J. C. & Nishio, F. Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data. Journal of Geophysical Research: Oceans 113, doi:10.1029/2007JC004257 (2008).

129 Kwok, R. Ross sea ice motion, area flux, and deformation. Journal of Climate 18, 3759-3776, doi:10.1175/JCLI3507.1 (2005).

130 Hollands, T., Haid, V., Dierking, W., Timmermann, R. & Ebner, L. Sea ice motion and open water area at the Ronne Polynia, Antarctica: Synthetic aperture radar observations versus model results. Journal of Geophysical Research: Oceans 118, 1940-1954, doi:10.1002/jgrc.20158 (2013).

131 Emery, W. J., Fowler, C. W. & Maslanik, J. A. Satellite-derived maps of Arctic and Antarctic sea ice motion: 1988 to 1994. Geophysical Research Letters 24, 897-900, doi:10.1029/97GL00755 (1997). **This paper is an early application of repeat satellite imagery for track the motion on sea ice floes in the polar regions, demonstrating that the southern Hemisphere sea ice pack tends to drifts northwards under the influence of ocean currents and katabatic winds.**

132 Kwok, R., Pang, S. S. & Kacimi, S. Sea ice drift in the Southern Ocean: Regional patterns, variability, and trends. Elementa 5, doi:10.1525/elementa.226 (2017).

133 Alley, K. E., Scambos, T. A., Siegfried, M. R. & Fricker, H. A. Impacts of warm water on Antarctic ice shelf stability through basal channel formation. Nature Geoscience 9, 290-293, doi:10.1038/ngeo2675 (2016).

134 Giles, K. A., Laxon, S. W. & Worby, A. P. Antarctic sea ice elevation from satellite radar altimetry. Geophysical Research Letters 35, doi:10.1029/2007GL031572 (2008).

135 Willatt, R. C., Giles, K. A., Laxon, S. W., Stone-Drake, L. & Worby, A. P. Field investigations of Ku-band radar penetration into snow cover on antarctic sea ice. IEEE Transactions on Geoscience and Remote Sensing 48, 365-372, doi:10.1109/TGRS.2009.2028237 (2010).

136 Tin, T. & Jeffries, M. O. Sea-ice thickness and roughness in the Ross Sea, Antartica. Annals of Glaciology 33, 187-193 (2001).

137 Farrell, S. L. et al. Sea-ice freeboard retrieval using digital photon-counting laser altimetry. Annals of Glaciology 56, 167-174, doi:10.3189/2015AoG69A686 (2015).

138 Markus, T. et al. The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2): Science requirements, concept, and implementation. Remote Sensing of Environment 190, 260-273, doi:10.1016/j.rse.2016.12.029 (2017).

139 Armitage, T. W. K. & Ridout, A. L. Arctic sea ice freeboard from AltiKa and comparison with CryoSat-2 and Operation IceBridge. Geophysical Research Letters 42, 6724-6731, doi:10.1002/2015GL064823 (2015).

140 Guerreiro, K., Fleury, S., Zakharova, E., Rémy, F. & Kouraev, A. Potential for estimation of snow depth on Arctic sea ice from CryoSat-2 and SARAL/AltiKa missions. Remote Sensing of Environment 186, 339-349, doi:10.1016/j.rse.2016.07.013 (2016).

141 Fricker, H. A. & Padman, L. Ice shelf grounding zone structure from ICESat laser altimetry. Geophysical Research Letters 33, doi:10.1029/2006GL026907 (2006).

142 Haran, T., Bohlander, J., Scambos, T., Painter, T. & Fahnestock, M. A. (National Snow and Ice Data Center, Boulder, Colorado, USA, 2014).

143 Tschudi, M., Fowler, C. W., Maslanik, J. A., Stewart, J. S. & Meier, W. (NASA National Snow and Ice Data Center Distributed Active Archive Center, Boulder, Colorado, USA, 2016).

144 Fetterer, F., Knowles, K., Meier, W., Savoie, M. & Windnagel, A. K. (NSIDC: National Snow and Ice Data Center, Boulder, Colorado USA, 2017).

145 Ryan, W. B. F. et al. Global multi-resolution topography synthesis. Geochemistry, Geophysics, Geosystems 10, doi:10.1029/2008GC002332 (2009).

146 Timmermann, R. et al. in PANGEA (2010).

147 Locarnini, R. A. et al. (eds Ed. S. Levitus & NOAA Atlas NESDIS 68) (U.S. Government Printing Office, Washington D.C, 2010).

148 McMillan, M. et al. Increased ice losses from Antarctica detected by CryoSat-2. Geophysical Research Letters 41, 3899-3905, doi:10.1002/2014GL060111 (2014).

149 Anandakrishnan, S. & Alley, R. B. Stagnation of ice stream C, West Antarctica by water piracy. Geophysical Research Letters 24, 265-268, doi:10.1029/96GL04016 (1997).