Arctic Ice Cover, Ice Thickness and Tipping Points

Peter Wadhams

Published online: 19 January 2012

Abstract We summarize the latest results on the rapid changes that are occurring to Arctic sea ice thickness and extent, the reasons for them, and the methods being used to monitor the changing ice thickness. Arctic sea ice extent had been shrinking at a relatively modest rate of 3–4% per decade (annually averaged) but after 1996 this speeded up to 10% per decade and in summer 2007 there was a massive collapse of ice extent to a new record minimum of only 4.1 million km². Thickness has been falling at a more rapid rate (43% in the 25 years from the early 1970s to late 1990s) with a specially rapid loss of mass from pressure ridges. The summer 2007 event may have arisen from an interaction between the long-term retreat and more rapid thinning rates. We review thickness monitoring techniques that show the greatest promise on different spatial and temporal scales, and for different purposes. We show results from some recent work from submarines, and speculate that the trends towards retreat and thinning will inevitably lead to an eventual loss of all ice in summer, which can be described as a ‘tipping point’ in that the former situation, of an Arctic covered with mainly multi-year ice, cannot be retrieved.

Keywords Ice cover · Ice thickness · Multi-year ice · Ice loss

SEA ICE THINNING AND RETREAT

The present thinning and retreat of Arctic sea ice is one of the most serious geophysical consequences of global warming and is causing a major change to the face of our planet. A challenging characteristic of the behaviour is that both the rate of retreat (especially in summer) and the rate of thinning in all seasons have greatly exceeded the predictions of most models.

Although sea ice in the Arctic Ocean has been in slow retreat since the 1950s at a rate of 2.8–4.3% per decade (ACIA 2005) as measured from microwave satellites (Parkinson et al. 1999), the annual-averaged rate speeded up to 10.7% per decade from 1996 onwards (Comiso et al. 2008), whilst the summer extent has shrunk even faster. In September 2007 the area reached 4.1 million km², a record low (NSIDC 2007; Stroeve et al. 2007) and more than 1 million km² less than in the previous record year of 2005 (Stroeve et al. 2005). Although the area stabilized in 2008–2010 the continuing decline in multi-year (MY) ice fraction suggests that the total Arctic ice volume in late summer has continued to decrease, and indeed an accelerating decrease has been suggested in figures published using the PIOMAS model (Polar Science Center, Univ. Washington, personal commun., 2011). New model predictions, tuned to match these recent changes, predict disappearance of the summer sea ice within 20–30 years (Wang and Overland 2009).

At the same time, submarine sonar measurements have shown that the ice has been thinning much more rapidly, by some 43% in the 25 years between the early 1970s and late 1990s (Rothrock et al. 1999, 2003; Wadhams and Davis 2000, 2001; Yu et al. 2004; Kwok et al. 2009). The thinning rate implies that at some critical date the annual cycle of thickness will have a summer minimum at which a substantial fraction of the winter ice cover will disappear, with the thinner component (mainly undeformed first-year ice) melting completely. We may be already reaching this situation, since in the Beaufort Sea the measured summer bottom melt of a MY floe in 2007 was 2 m (Perovich et al. 2008) whilst the winter thickness achieved by first-year (FY) ice was only 1.6 m. This may be a special case of floes drifting into a previously warmed region, but the trend is clear: decreased winter growth and increased summer

melt leads to a decreased area at the end of summer, which itself offers a positive feedback through increased radiation absorption by the open water.

Figure 1 shows the ice cover on September 16 2007, with a huge area of open water extending northward from the Beaufort and Chukchi Seas, exposing the ocean there to the atmosphere for the first time since records began. The figure also shows the March 2007 track of HMS *Tireless*, which carried out a multibeam sonar survey of the ice underside, described later in this article.

Already we are seeing consequences from these changes. The new large area of open water warms up to 4–5°C during summer, which not only delays the onset of autumn freezing but also warms the seabed over the shelf areas, helping to melt offshore permafrost. One consequence of this melt is the release and decomposition of trapped methane hydrates, causing methane plumes which have global warming potential. Already such plumes have been directly observed in the East Siberian Sea (Shakhova et al. 2010) and off Svalbard, and the curve of global atmospheric methane content has undergone a (small) upward blip after being stable for some years. Molecule for molecule, methane is 23 times as potent as CO₂ as a greenhouse gas, and there have been warnings that a major methane outbreak may be imminent, with release from offshore permafrost melt being joined by releases from the

active layer under the tundra, which has grown thicker as the air temperature has warmed.

A further consequence is that the large area of open water in summer allows a wind fetch sufficient to create substantial wave energy input to the ice edge, which causes wave-induced ice break-up into floes so as to create a classic marginal ice zone (MIZ). Hitherto the MIZ structure has been considered as applying mainly to the Greenland Sea, Barents Sea, Bering Sea and Antarctic, with the Beaufort-Chukchi region facing only a narrow slot of open water. A Beaufort-Chukchi MIZ is a new situation which may also feature a positive feedback mechanism, because the fragmentation of the ice cover into wave-driven floes creates much new open water and a large floe perimeter for enhanced melt rates.

A challenging characteristic of the summer sea ice extent is that its decay has exceeded the predictions of models. The observed extent began to deviate from the ensemble mean of models used by Intergovernmental Panel on Climate Change (IPCC) in the 1970s and by the 1990s it was more than one standard deviation less than the mean (Fig. 2). The 2007 extent was less than the most extreme member of the ensemble. These results strongly suggest that existing climate models are inadequate in predicting Arctic sea ice extent and that some important physics is missing.

Our understanding of the processes governing these accelerating changes needs to be based on adequate measurements of ice thickness and extent throughout the year, particularly in the winter months preceding each summer's retreat. Satellites can track ice area, but ice *thickness* distribution can be most accurately measured by sonar from underneath the ice. This task has been carried out since 1958 by submarines of the US and British navies, with the most recent UK datasets being in 2004 and 2007 (Wadhams et al. 2011). Since the first UK voyage in 1971, scientific data gathering and analysis from UK submarines has been done by the author, who has sailed on many of the voyages himself. The first evidence of Arctic ice thinning, amounting to 15% up to 1987, was published by the author in 1990 (Wadhams 1990), whilst incorporation of more recent UK and US data has shown an enormous 43% decline in thickness from the 1970s to the late 1990s.

MECHANISMS FOR SEA ICE RETREAT

It is clear that a link exists between retreat and thinning, in that a thinner ice cover breaks up and opens up leads more readily in summer, leading to greater radiation absorption by the ocean, further enhancing the melt rate. In theory, thinning can come about by surface melt, due to warmer air temperatures (Comiso 2003); from an increase in the length

Fig. 1 Sea ice extent at the September 16 2007 absolute minimum, with the 2007 track of HMS “Tireless” shown (red line). Pink line shows median extent of ice cover for September of 1979–2000

Fig. 2 The September sea ice extent (red) compared with the predictions and hindcasts of an ensemble of models used by IPCC. Thick black line is median of model predictions; dotted black lines are one standard deviation away (modified from Stroeve et al. 2007)

of the melt season (Laxon et al. 2003); or from a change in the composition of the ice cover with less MY ice (Comiso 2002; Kwok et al. 2009), as well as from bottom melt, which itself could be caused by advection of warm water into the Arctic rather than local warming (Martinson and Steele 2001; Rothrock et al. 2003). However, the dependence on long-term thinning is supported by the summer 2007 field observations of Perovich et al. (2008) that ice in the Beaufort Sea showed no less than 2 m of bottom melt in places during the summer of 2007—far more than the expected thermodynamic summer melt of 0.5 m. A 2 m summer melt would cause the disappearance of all the undeformed FY ice in the Beaufort Sea, which in late winter 2007 had a mean thickness of only 1.6 m. Perovich explained that the ice became exceptionally open as summer approached, with a large network of leads absorbing solar radiation to heat up the near-surface water. This water, penetrating under the surrounding floes, caused bottom melt. The results of Rothrock et al. (1999) show that in many sectors of the Arctic the mean is itself only in the vicinity of 2 m, implying that a 2 m summer melt will remove much of the ice cover.

A clue to the missing physics that may be needed to explain thinning and retreat was the discovery from successive submarine cruises to the same part of the Arctic that the decline in thickness was most pronounced for pressure ridges. Whilst the mean draft showed a 43% drop between two cruises in 1976 and 1996, the occurrence of pressure ridges deeper than 9 m showed a much more dramatic drop of 73% (together with a decrease in their mean draft), implying a virtual absence of deep pressure ridges from the central Arctic (Wadhams and Davis 2000, 2001). The pressure ridge reduction suggests a change in ice dynamics as well as an enhanced melt rate for existing ridges. The loss has been demonstrated in a practical way by the fact that icebreakers now routinely transport tourists to the North Pole, which in the past was a dangerous and difficult procedure: the North Pole was not attained by ship until 1977.

The suggestion therefore is that, rather than uniform thinning taking place, there is a preferred loss of pressure ridge volume; they may be melting more rapidly than undeformed ice. Support for this idea comes from a set of submarine observations reported by Wadhams (1997a,b) in

which the development of a thickness probability density function (pdf) with downstream distance in the Trans Polar Drift Stream implied a melt rate that was proportional to ice thickness. Such a melt rate cannot be explained by thermodynamic considerations alone, even though thermodynamic theory implies that there is an equilibrium thickness of sea ice (about 2.9 m) and that ice, which is taken beyond this limit, i.e. by ridging, should slowly melt whilst ice that is thinner continues to grow. The first potentially feasible mechanism was put forward by Amundrud et al. (2006) which supposes that a ridge structure is porous and that the percolation of warmed sub-ice water, especially in summer, raises its internal temperature and causes it to preferentially melt or disintegrate. This implies that MY ridges, where the blocks are cemented together into a solid hummock, should be more resistant to percolation than FY ridges.

To test such theories, we must understand in detail how pressure ridges develop and how they interact with the ocean. The most recent submarine dataset collected in a transArctic experiment by HMS ‘Tireless’ in March 2007 (Wadhams 2008; Wadhams et al. 2011) allows such a study because the normal upward-looking echo sounder (ULES) was supplemented by a multibeam sonar which gives a full 3-D quantitative picture of the underside of the ice along a swath approximately 100 m wide (Fig. 3). This shows the true structure of ridges for which the ULES gives only a cross-section. We find from such data that MY ridges, although consolidated, possess many gaps due to cracks

and leads which opened across the icefield during the lifetime of the ridge, and these provide a mechanism for water percolation into the ridge, which allows MY ridges to melt by a similar mechanism to Amundrud et al. (2006).

It is therefore possible that bottom melt is an important factor in ice thinning. To understand the mechanism of ice retreat, a two-pronged experimental approach is therefore necessary: we must obtain large-scale data on $g(h)$, the probability density function of thickness, to map the continuing rate of loss and its geographical variation; and we must map in detail the way in which the topography of a deformed ice area evolves as a result of melt. For both these aims, the acquisition of under-ice sonar data is vital, especially 3-D multibeam data from Autonomous Underwater Vehicles (AUVs) and submarines under ice.

Interpretation of these data will yield the detailed physics of the ice melt process, which must then be incorporated into models to predict more adequately the future decay rate of the sea ice cover in the Arctic Basin and adjacent seas. Ice retreat has huge implications for global climate change: it is a source of ocean freshening from meltwater fluxes; the ice-albedo feedback mechanism involved may accelerate global warming; and it also participates in further feedbacks, e.g. by enhancing the melt rate of the terrestrial ice sheet on Greenland which will be surrounded by open water for more of the year, or by diminishing the convection rate in the Greenland Sea. Sea ice melt adds freshness to the ocean without raising sea levels, and this affects models which relate freshening to

Fig. 3 Structure of a MY pressure ridge, seen on multibeam sonar of HMS ‘Tireless’. Units for all axes are *m*

sea level rise by assuming glacier melt to be the cause (Munk 2003; Wadhams and Munk 2004). At some stage ice retreat will start in the Antarctic, and we need to know when and how fast this will happen in view of the different ridge composition and distribution there.

METHODS OF ICE THICKNESS MEASUREMENT

The fundamental parameter that we seek to measure is the ice thickness distribution and its variability over the Arctic Basin both in space and time. This is a real challenge to technology since no fully adequate and accessible method exists at present to achieve this aim. It is important to measure not just the mean thickness but also the entire probability density function $g(h)$ because:

- (i) $g(h)$ determines the ocean–atmosphere heat exchange, with thin ice dominating;
- (ii) together with the ice velocity, it gives mass flux;
- (iii) its downstream evolution, in the absence of deformation, gives the melt rate, i.e. the fresh water flux;
- (iv) the shape of $g(h)$ is a measure of the degree of deformation of the ice cover;
- (v) if MY fraction is also known, $g(h)$ can be used to give ice strength and other statistically definable mechanical properties of the ice cover;
- (vi) its variability is a test of model outputs;
- (vii) its long-term trend indicates the nature of the climate response.

In addition to $g(h)$ it is also valuable to have a measure of the ice bottom shape or roughness. This implies recording ice bottom surface profiles rather than simply sampling the draft at fixed time intervals as is done with moored sonar. The extra advantages of knowing ice surface shape are:

- (i) it is a determining factor for the aerodynamic and hydrodynamic drag coefficients;
- (ii) the deepest ridges are responsible for generating internal wave activity which may lead to a significant internal wave drag;
- (iii) seabed scour by the deepest ridges defines the limit of fast ice on shelves and the extent of the stamukhi zone (Reimnitz et al. 1994);
- (iv) ridges are an important component in the calculation of the force exerted by an ice field on offshore structures;
- (v) the scattering of underwater sound by ridges defines the range to which acoustic transmission can be accomplished in the Arctic, since upward refraction leads to repeated surface reflection;
- (vi) ridged ice provides a different habitat for sea ice biota from undeformed ice.

Methods of measuring ice thickness distribution in the Arctic can be divided into existing well-tried techniques and new methods.

ICE THICKNESS—CURRENT TECHNIQUES

Submarine sonar gives us the ability to obtain synoptic data on ice draft and under-ice topography in a rapid and accurate fashion, and most of our knowledge of the general distribution of $g(h)$ over the Arctic comes from such profiles. *Sidescan sonar* (Wadhams 1988; Sear and Wadhams 1992) or *multibeam sonar* (Wadhams 2008) can be added to give extra information about ice type and three-dimensional bottom topography. However, military submarines are not always available to obtain repeated profiles at a sufficient density to test for climate-related trends, nor are they necessarily able to profile over a desired systematic grid since ice profiling is an addendum to their operational task. Conversion of draft to ice thickness is a simple and accurate procedure, and in applications related to mass flux it is in fact useful to deal with draft as the relevant parameter, since this defines ice mass per unit surface area.

AUV sonar solves the problem of military data availability by placing the profiling sonar on an unmanned vehicle; this also enables the vehicle to work in shallow water and other unsafe situations. For short-range surveys the vehicle could be a cable-controlled Remotely Operated Vehicle (ROV), but for mesoscale and basin wide surveys it would have to be an AUV. The earliest AUV operation under ice was carried out by Francois (Francois and Nodland 1972) using an AUV in the Beaufort Sea; other early work is reviewed by Tonge (1992), whilst recent deployments are described by Brierley et al. (2002), Wadhams et al. (2004a, 2006) and Wadhams and Doble (2008). The latter experiments featured sidescan and multibeam sonar, of which the latter offers full 3-dimensional quantitative mapping capability of the ice underside, the best quality data yet obtained under Arctic sea ice.

Drifting sonar involves placing a local sonar system on a drifting buoy, and intensively studying the time-dependent development of ice and snow thickness of a single floe. By using upward sonar under the ice and a downward pinging sonar in air over the ice surface (together with thermistor chains) it is possible to separate the development of the upper and lower surfaces. Data are transmitted back by satellite.

Moored upward sonar solves the problem of systematic data collection by obtaining long-term information from a single point. It is invaluable for assessing the time variation of ice flux through critical regions such as Fram Strait. However, the ping rate is usually inadequate to resolve bottom topography, whilst the cost and difficulty of

deployment and recovery preclude its general use over the whole Arctic on some systematic measurement grid.

Airborne laser profilometry yields freeboard distribution which can be converted to draft distribution if the mean density of ice plus overlying snow is known (Wadhams et al. 1991). This varies with time and space over the Arctic, implying that seasonal and regional validation is needed before this otherwise rapid and efficient technique can be used for basinwide surveys. Recent developments include swath sounding lasers, which give a three dimensional image of the freeboard, making validation easier by facilitating matching with other types of profile.

Airborne electromagnetic techniques consist of generating and sensing eddy currents under ice by EM (10–50 kHz) induction from a coil towed behind a helicopter, with simultaneous laser to give range to the snow surface. The early development of the technique was reviewed by Rossiter and Holladay (1994), with recent results discussed by Haas et al. (2008). The wide footprint involves some loss of resolution of individual ridges and a need to fly very low. The first packaged system fixed wing aircraft use in the Arctic appears to be the system mounted in a Twin Otter by the Finnish Geological Survey (Hautaniemi et al. 1994). Recently, the Alfred Wegener Institute has been towing antennas behind a Basler BT-67 aircraft.

Drilling is the most accurate, but slowest, technique, the ultimate validation for all others. The use of a hot water drill increases the speed over that of a drill with a petrol-driven power head, and the replacement of the drill bit by a core barrel enables the ice to be directly sampled for salinity and other physical properties.

Radar altimetry involves the use of a radar beam from an aircraft or satellite; the time difference between the radar echo from the ice surface and from nearby thin ice or open water lying within the beam gives the freeboard. From this a conversion must be made to thickness from knowledge of the mean density of sea ice and the thickness and density of the overlying snow. Results from the Envisat altimeter have been used to estimate the variability of mean ice thickness over the Arctic up to 81.5°N (Laxon et al. 2003; Giles et al. 2008), whilst the ESA CryoSat-2 altimeter, launched in 2009, reaches almost to the Pole. The problem, as in laser profiling, is to use the correct conversion factor for the large multiplier needed to turn freeboard into thickness. An additional problem is that it is not clear where the reflection horizon lies; it is often assumed to be the snow-ice interface, but recent experimental research indicates that the horizon can lie within the snow layer, causing additional uncertainty.

Satellite laser altimetry operates in the same way as airborne laser altimetry. The first laser altimetry satellite was NASA's ICESat (Ice, Cloud and Land Elevation Satellite) (Kwok et al. 2004), which ceased operation in

2009 with a replacement planned in about 2015. The same problem of conversion from freeboard to thickness occurs as in airborne laser altimetry, but it is at least clear that the echo is coming from the top of the snow layer.

SUBMARINE MEASUREMENTS OF ICE THICKNESS 2007

The most recent large-scale measurements of the Arctic ice thickness distribution were carried out by the author in March 2007 using multi-beam and upward sonar systems mounted on HMS *Tireless*. Figure 1 shows the track of the submarine across the Arctic from Fram Strait to a final survey site under the APLIS-07 ice station in the Beaufort Sea; it can be seen that part of the track covers regions that subsequently became ice free during the extraordinary summer of 2007. The submarine was fitted with Kongsberg EM3002 multi-beam sonar. This was the first time that 3-D imaging of the under-ice surface has been obtained over long distances by a manned submarine, although in 2004 the author obtained such imagery from the Autosub AUV over shorter distances (Wadhams et al. 2006).

Figure 3 shows a typical section of multibeam sonar imagery, with a swath width of 100 m. Most of the track consisted of a single swath, but a mosaicking survey was carried out at about 85°N 65°W in a location where surface surveys were subsequently carried out as part of the EU DAMOCLES project. The structure, shape and topography of pressure ridges are clearly revealed, even though the speed and depth of the submarine meant that the resolution was not as good as has been obtained with an AUV close up to the ice (Wadhams et al. 2006; Wadhams and Doble 2008).

Figure 4 is a probability density function of ice draft from a 200 km section of track obtained using a narrow-beam upward-looking sonar. The location was the Beaufort Sea on the approach to the ice station, at a location which became ice-free in September 2007. It can be seen that the undeformed ice is mostly FY, with a modal draft of 1.35 m, corresponding to a thickness of about 1.51 m which corresponds well with the results of drilling FY ice and using an AUV under the ice at the camp. There is a further peak at a lesser draft of about 1 m, due to refrozen leads (again reproducing a typical thickness found by the AUV at the camp), and a gentle peak at about 2.8 m due to undeformed MY ice. The subsequent fall-off is the typical negative exponential relationship due to the contribution of pressure ridges to the pdf.

If we are to believe Perovich's (2008) idea about the cause of the 2007 summer retreat, then the weakened ice cover started to break up with the creation of an unusual number of leads early in the summer of 2007. These leads

Fig. 4 Probability density function of ice draft from southern Beaufort Sea, March 2007, from profiles carried out by HMS “Tireless”

absorbed radiation to warm up the water, producing bottom melt at a rate greater than earlier years. The 1 m and 1.35 m draft components would have melted away completely (Perovich (2008) detected 2 m of bottom melt in multiyear ice) whilst the remainder of the ice cover would have been pushed towards and into Fram Strait by the prevailing wind system of the summer (NSIDC 2007). Given the continued temperature rises due to global warming, it is likely that this process will be repeated and that the summer ice extent will continue to decline rapidly.

GLOBAL IMPLICATIONS

In considering the large-scale implications of Arctic ice melt, a central question is ‘how much does the enhanced sea ice melt affect the lower-latitude ocean circulation?’ From the Greenland and Labrador Seas the freshwater anomalies from ice melt propagate into the Nordic Seas, North Atlantic and further into the other parts of the global ocean either through advection or by means of the fast, topographically guided barotropic Rossby and Kelvin waves (e.g. Atkinson et al. 2009), changing the thermohaline structure. The freshwater storage surplus in the Arctic Ocean due to ice decline and discharge of this

anomaly into the global ocean need to be quantified. The estimated runoff gain is ca. $600 \text{ km}^3 \text{ yr}^{-1}$ over the last two decades, compatible to sea ice melt anomaly of $500\text{--}600 \text{ km}^3 \text{ yr}^{-1}$. The current change in the global ocean thermohaline structure is believed to be due to change in runoff, suggesting that the sea ice melt anomaly is still confined to the Arctic Ocean (Wadhams and Munk 2004). Eventually, the anomaly could make its way to the lower latitudes, impacting the sea level and Meridional Overturning Circulation (MOC).

FUTURE MEASUREMENT NEEDS

To improve the monitoring needs of the Arctic Ocean, two kinds of technology development are needed. One is to develop existing techniques further to give them the capability for routine basinwide use. The second is to develop and apply novel techniques that will permit the Arctic Basin to be surveyed rapidly and repeatedly. Examples of the first kind of development are:

- (i) To carry out a regional and seasonal survey of mean snow-ice column density over the Arctic to allow laser and radar altimetry to be used systematically. At present data on ice density are rather sparse

(Timco and Frederking 1996). This could be done in conjunction with airborne altimetry measurements, e.g. using the ASIRAS altimeter which resembles that of CryoSat, in order to achieve a full validation test, or by the use of buoys such as the high-resolution GPS buoys designed for the European Science Foundation's SATICE project.

- (ii) To carry out further basic research on the scales of variability, both horizontal and vertical, of such parameters as temperature, salinity and crystal fabric in first- and MY ice as well as densities as above; and also the scales of such larger-scale features as melt ponds, ridges and leads.
- (iii) To carry out further submarine surveys by manned submarine.
- (iv) To develop AUVs with basinwide capability, basically a problem of battery technology.

Examples of the second kind of development are:

- (i) Mounting sonar on a neutrally buoyant float, as already discussed.
- (ii) The use of acoustic techniques. It has been shown that travel time changes for an acoustic path are reduced by the presence of an ice cover, in most cases by an amount approximately proportional to the ice thickness (Guoliang and Wadhams 1989; Jin et al. 1993). In long-range acoustic propagation experiments this can be used to give a single mean value for ice thickness along a path.
- (iii) Increased efforts to obtain empirical correlations between ice thickness and the output of satellite sensors such as passive and active microwave or altimeter. Already a partial positive correlation between Synthetic Aperture Radar (SAR) backscatter and ice thickness has been demonstrated (Comiso et al. 1991; Wadhams and Comiso 1992; Massom et al. 1999). Further advance requires extensive validation studies. A different approach involves matching some informational property of the SAR image, e.g. connectedness of sectors of similar brightness, or distribution of brightness gradients, to g (h) in validated studies between SAR and submarines, in search of quantitative relationships of mathematic form. An example is the work of Kerman et al. (1999). For one specific ice type, pancake ice, it has been found that the thickness can be successfully inferred from the change in dispersion for ocean waves passing into the ice from the open sea, detected by the Fourier analysis of SAR subscenes (Wadhams et al. 2004b).
- (iv) Novel airborne electromagnetic techniques. An example is the use of the radar backscatter

co-polarisation ratio at a frequency of 1 Ghz (L-band) to obtain the thickness of thin ice.

- (v) Deriving ice thickness as a by-product of a proxy measurement. For instance, long distance swell propagation in ice is subject to dispersion which is a function of modal ice thickness (average thickness of undeformed ice). One can obtain the spectrum of flexure from an orthogonal pair of tiltmeters along a wave vector across the Arctic, and derive modal thickness from the arrival times of different frequencies. This has been successfully attempted during the EU FP6 DAMOCLES project (Wadhams and Doble 2009).

Until the advent of fully-validated polar orbiting altimetry satellites, the best way to achieve the reliable, synoptic and repeatable ice thickness measurements over the Arctic Basin is a combination of frequently repeated under-ice sonar profiles over a grid covering the Basin, accompanied by a programme of moored upward sonar measurements spanning key choke points for ice transport, i.e. Fram Strait, the Svalbard-Franz Josef Land gap and a small number of specimen points within the Trans Polar Drift Stream and Beaufort Gyre. Sonar moorings could well be combined with current meter moorings and sediment traps. The use of military submarines is necessary for these profiles, until or unless AUVs of sufficient range are developed. Valuable additional information can come from airborne laser surveys (again with validation needed) and airborne electromagnetic induction.

ARE WE AT A TIPPING POINT?

There are many possible definitions of a tipping point for an environmental parameter, but the one which I will adopt is that it occurs when a parameter which has been stressed beyond a certain level will not return to its original state when that stress is removed, but migrates to a new state. A parameter which has reached a tipping point is thus like a wire which has been stretched beyond its elastic limit, such that its further deformation is a creep process with a strain rate which does not allow the wire to return to its original length when the stress is removed. Has Arctic sea ice reached a tipping point? I believe that it has, and for the following reason.

We know that the area of MY ice in the Arctic during the winter is diminishing year on year (Kwok et al. 2004; Kwok 2007). This is partly an effect of the atmospheric pressure field, which now drives ice out of the Arctic Basin by direct paths from the formation regions, instead of allowing ice to make long-period rotations in a large

Beaufort Gyre. If this field continues to prevail, a greater area of sea ice will melt completely year on year, since FY ice grows more slowly than in the past, melts more rapidly and permits a greater area of warming water to be ice-free every year. Once the ice cover has completely gone in a given summer, the following winter's ice will be all FY, and will then melt again in the following summer. So there is no chance for a substantial MY ice cover to re-form. The tipping point, to be more exact, occurs when the summer melt rate versus winter growth rate becomes such that all FY ice melts during the summer. Then, no FY ice is promoted to MY ice in October, and the MY fraction in the Arctic cannot increase but must continue to decrease until there is none left. Then the Arctic, for ever afterwards, will have a seasonal ice cover.

Recently, much public attention was gained by a paper by Tietsche et al. (2011), which drew different conclusions, but in my view the arguments in this article are wholly misleading. The authors carried out the artificial procedure of removing the entire Arctic ice cover (in a model) and observed that within 2 years the ice cover recovered to its former level. This was repeated at 20 year intervals for an ice cover declining in area in response to the modelled amount of warming, and in each case the ice cover recovered to its former state. The authors concluded that, as their title suggested, ice retreat is reversible, and that all we have to do to regenerate the Arctic ice cover once it has retreated is to reduce carbon emissions such that the radiative forcing is no longer at work. This is an unjustifiable conclusion for two reasons. First, the act of total removal is an artificial change imposed on the ice cover without a credible forcing being involved, so naturally the ice will tend afterwards to revert to the status quo ante. Second, the conclusion that natural ice loss is reversible fails to take account of the well-known time lags involved in CO₂-induced radiative forcing, whereby a given quantity of CO₂ released in the atmosphere continues to have an impact upon the climate system for about 100 years. Even a precipitate reduction in CO₂ emission would not cause air temperatures, for instance, to drop for many years or even decades.

CONCLUSIONS

The sea ice cover in the Arctic Ocean is undergoing a transition from being a perennial (year-round) ice cover to a seasonal cover resembling the Antarctic, where most of the ice is FY and disappears in summer. The trend towards smaller areas in summer, which reached a temporary peak in 2007, will resume, and will lead to an ice-free summer Arctic in less than 30 years. The ice cover in the winter Arctic will be primarily FY, so that it will be passable by

polar icebreakers at any season, with a milder pressure ridging regime which has implications for the design of offshore structures such as drilling platforms. The open water in summer will not only allow unrestricted shipping, but will result in a warmer ocean regime leading to loss of methane from melting permafrost, itself accelerating global warming, as well as increased precipitation over the land masses surrounding the Arctic Ocean and an increased melt rate for terrestrial ice sheets such as that of Greenland. Within a decade we can expect summer ice to be largely confined to a redoubt north of the north coasts of Greenland and Ellesmere Island, the only location where substantial MY ice will be found.

The indications are that this is indeed a 'tipping point' for the ice cover, in that it will not return to a year-round cover but will change to a purely seasonal cover of FY ice, as currently found in the Antarctic.

Acknowledgements This is a contribution to the Arctic Tipping Points project (www.eu-atp.org) funded by FP7 of the European Union (contract #226248). The manuscript was improved by three anonymous reviewers.

REFERENCES

- ACIA. 2005. *Arctic climate impact assessment. Impacts of a warming Arctic*. Cambridge: Cambridge University Press.
- Amundrud, T.L., H., Melling, R.G. Ingram, and S.E. Allen. 2006. The effect of structural porosity on the ablation of sea ice ridges. *Journal of Geophysical Research* 111: C06004. doi:[10.1029/2005JC002895](https://doi.org/10.1029/2005JC002895).
- Atkinson, C.P., A.T. Wells, B. Shina, and V.O. Ivchenko. 2009. Rapid ocean wave teleconnections linking Antarctic salinity anomalies to the equatorial ocean-atmosphere system. *Geophysical Research Letters* 36: L08603. doi:[10.1029/2008GL036976](https://doi.org/10.1029/2008GL036976).
- Brierley, A.S., N.W. Millard, S.D. McPhail, P. Stevenson, M. Pebody, J. Perrett, M. Squires, and G. Griffiths. 2002. Antarctic krill under sea ice: Elevated abundance in a narrow band just south of ice edge. *Science* 295: 1890–1892.
- Comiso, J.C. 2002. A rapidly declining Arctic perennial ice cover. *Geophysical Research Letters* 29: 1956. doi:[10.1029/2002GL015650](https://doi.org/10.1029/2002GL015650).
- Comiso, J.C. 2003. Warming trends in the Arctic. *Journal of Climate* 16: 3498–3510.
- Comiso, J.C., C.L. Parkinson, R. Gersten, and L. Stock. 2008. Accelerated decline in the Arctic sea ice cover. *Geophysical Research Letters* 35: L01703. doi:[10.1029/2007GL031972](https://doi.org/10.1029/2007GL031972).
- Comiso, J.C., P. Wadhams, W.B. Krabill, R.N. Swift, J.P. Crawford, and W.B. Tucker. 1991. Top/bottom multisensor remote sensing of Arctic sea ice. *Journal of Geophysical Research* 96: 2693–2709.
- Francois, R.E., and W.K. Nodland 1972. Unmanned Arctic Research Submersible (UARS) system development and test report. Univ. Washington, Applied Physics Lab., Tech. Rept. APL-UW 7219.
- Giles, K.A., S.W. Laxon, and A.L. Ridout. 2008. Circumpolar thinning of Arctic sea ice following the 2007 record ice extent minimum. *Geophysical Research Letters* 35: L22502. doi:[10.1029/2008GL035710](https://doi.org/10.1029/2008GL035710).

- Guoliang, J., and P. Wadhams. 1989. Travel time changes in a tomography array caused by a sea ice cover. *Progress in Oceanography* 22: 249–275.
- Haas, C., A. Pfaffling, S. Hendricks, L. Rabenstein, J.-L. Etienne, and I. Rigor. 2008. Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat. *Geophysical Research Letters* 35: L17501. doi:[10.1029/2008GL034457](https://doi.org/10.1029/2008GL034457).
- Hautaniemi, H., M. Oksama, J. Multala, M. Leppäranta, K. Riska, and O. Salmela. 1994. Airborne electromagnetic mapping of ice thickness in the Baltic Sea. *Proceedings IAHR Symposium*, Trondheim, Norway.
- Jin, G., J.F. Lynch, R. Pawlowicz, and P. Wadhams. 1993. Effects of sea ice cover on acoustic ray travel times, with applications to the Greenland Sea Tomography Experiment. *Journal of the Acoustic Society of America* 94: 1044–1056.
- Kerman, B., P. Wadhams, and J. Comiso. 1999. Informational equivalence between synthetic aperture radar imagery and the thickness of Arctic pack ice. *Journal of Geophysical Research* 104: 29721–29731.
- Kwok, R. 2007. Near zero replenishment of the Arctic multiyear sea ice cover at the end of 2005 summer. *Geophysical Research Letters* 34: L05501. doi:[10.1029/2006GL028737](https://doi.org/10.1029/2006GL028737).
- Kwok, R., G.F. Cunningham, M. Wensnahan, I. Rigor, H.J. Zwally, and D. Yi. 2009. Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008. *Journal of Geophysical Research* 114: C07005. doi:[10.1029/2009JC005312](https://doi.org/10.1029/2009JC005312).
- Kwok, R., H.J. Zwally, and D. Yi. 2004. ICES at observations of Arctic sea ice: A first look. *Geophysical Research Letters* 31: L16401. doi:[10.1029/2004GL020309](https://doi.org/10.1029/2004GL020309).
- Laxon, S., N. Peacock, and D. Smith. 2003. High interannual variability of sea ice thickness in the Arctic region. *Nature* 425: 947–949.
- Martinson, D.G., and M. Steele. 2001. Future of the Arctic sea ice cover: Implications of an Antarctic analog. *Geophysical Research Letters* 28: 307–310.
- Massom, R.A., J.C. Comiso, A.P. Worby, V.I. Lytle, and L. Stock. 1999. Regional classes of sea ice cover in the East Antarctic pack ice from satellite and in situ data during the winter time period. *Remote Sensing Environment* 68: 61–76.
- Munk, W. 2003. Ocean freshening, sea level rising. *Science* 300: 2041–2043.
- NSIDC. 2007. from http://nsidc.org/news/press/2007_seaiceminimum/20070810_index.html.
- Parkinson, C.L., D.J. Cavalieri, P. Gloersen, H.J. Zwally, and J.C. Comiso. 1999. Arctic sea ice extents, areas, and trends, 1978–1996. *Journal of Geophysical Research* 104: 20837–20856.
- Perovich, D.K., J.A. Richter-Menge, K.F. Jones, and B. Light. 2008. Sunlight, water, ice: Extreme Arctic sea ice melt during the summer of 2007. *Geophysical Research Letters* 35: L11501. doi:[10.1029/2008GL034007](https://doi.org/10.1029/2008GL034007).
- Reimnitz, E., D. Dethleff, and D. Nürnberg. 1994. Contrasts in Arctic shelf sea-ice regimes and some implications: Beaufort Sea versus Laptev Sea. *Marine Geology* 119: 215–225.
- Rossiter, J.R., and J.S. Holladay. 1994. Ice-thickness measurement. In *Remote sensing of sea ice and icebergs*, ed. S. Haykin, E.O. Lewis, R.K. Raney, and J.R. Rossiter, 141–176. New York: Wiley.
- Rothrock, D.A., Y. Yu, and G.A. Maykut. 1999. Thinning of the Arctic sea-ice cover. *Geophysical Research Letters* 26: 3469–3472.
- Rothrock, D.A., J. Zhang, and Y. Yu. 2003. The arctic ice thickness anomaly of the 1990s: A consistent view from observations and models. *Journal of Geophysical Research* 108: 3083. doi:[10.1029/2001JC001208](https://doi.org/10.1029/2001JC001208).
- Sear, C.B., and P. Wadhams. 1992. Statistical properties of Arctic sea ice morphology derived from sidescan sonar images. *Progress in Oceanography* 29: 133–160.
- Shakhova, N., I. Semiletov, A. Salyuk, V. Yusupov, D. Kosmach, and Ö. Gustafsson. 2010. Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf. *Science* 327: 1246–1249.
- Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze. 2007. Arctic sea ice decline: Faster than forecast. *Geophysical Research Letters* 34: L09501. doi:[10.1029/2007GL029703](https://doi.org/10.1029/2007GL029703).
- Stroeve, J.C., M.C. Serreze, F. Fetterer, T. Arbetter, W. Meier, J. Maslanik, and K. Knowles. 2005. Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004. *Geophysical Research Letters* 32: L04501. doi:[10.1029/2004GL021810](https://doi.org/10.1029/2004GL021810).
- Tietsche, S., D. Notz, J.H. Jungclaus, and J. Marotzke. 2011. Recovery mechanisms of Arctic summer sea ice. *Geophysical Research Letters* 38: L02707. doi:[10.1029/2010GL045698](https://doi.org/10.1029/2010GL045698).
- Timco, G.W., and R.M.W. Frederking. 1996. A review of sea ice density. *Cold Regions Research and Technology* 24: 1–6.
- Tonge, E.M. 1992. An incremental approach to AUVs. *Proceedings Oceanology International '92*, Brighton, 10–13 March 1992. Spearhead Exhibitions 1.
- Wadhams, P. 1988. The underside of Arctic sea ice imaged by sidescan sonar. *Nature* 333: 161–164.
- Wadhams, P. 1990. Evidence for thinning of the Arctic ice cover north of Greenland. *Nature* 345: 795–797.
- Wadhams, P., and J.C. Comiso. 1992. The ice thickness distribution inferred using remote sensing techniques. In *Microwave remote sensing of sea ice*, ed. F. Carsey, Geophysical Monograph 68, American Geophysical Union, Washington, 375–383.
- Wadhams, P. 1997a. Ice thickness in the Arctic Ocean: The statistical reliability of experimental data. *Journal of Geophysical Research* 102: 27951–27959.
- Wadhams, P. 1997b. Variability of Arctic sea ice thickness—statistical significance and its relationship to heat flux. In *Operational oceanography, The challenge for European co-operation*, 368–384. Elsevier.
- Wadhams, P. 2008. Arctic sea ice changes under global warming. *Proceedings ICETECH 2008, International Conference on Performance of Ships and Structures in Ice*, Banff, July 20–23 2008. Society of Naval Architects and Marine Engineers, ISBN 978-0-9780896-1.
- Wadhams, P., N. Hughes, and J. Rodrigues. 2011. Arctic sea ice thickness characteristics in winter 2004 and 2007 from submarine sonar transects. *Journal of Geophysical Research* 116: C00E02. doi:[10.1029/2011JC006982](https://doi.org/10.1029/2011JC006982).
- Wadhams, P., and N.R. Davis. 2000. Further evidence of ice thinning in the Arctic Ocean. *Geophysical Research Letters* 27: 3973–3975.
- Wadhams, P., and N.R. Davis. 2001. Arctic sea-ice morphological characteristics in summer 1996. *Annales of Glaciology* 33: 165–170.
- Wadhams, P., and M. Doble. 2008. Digital terrain mapping of the underside of sea ice from a small AUV. *Geophysical Research Letters* 35: L01501. doi:[10.1029/2007GL031921](https://doi.org/10.1029/2007GL031921).
- Wadhams, P., and M.J. Doble. 2009. Sea ice thickness measurement using episodic infragravity waves from distant storms. *Cold Regions Science and Technology* 56: 98–101.
- Wadhams, P., and W. Munk. 2004. Ocean freshening, sea level rising, sea ice melting. *Geophysical Research Letters* 31: L11311. doi:[10.1029/2004GL020039](https://doi.org/10.1029/2004GL020039).
- Wadhams, P., F. Parmiggiani, G. de Carolis, D. Desiderio, and M.J. Doble. 2004a. SAR imaging of wave dispersion in Antarctic pancake ice and its use in measuring ice thickness. *Geophysical Research Letters* 31: L15305. doi:[10.1029/2004GL020340](https://doi.org/10.1029/2004GL020340).

- Wadhams, P., W.B. Tucker III, W. Krabill, R. Swift, J.C. Comiso, and N.R. Davis. 1991. Relationship between sea ice freeboard and draft in the Arctic Basin, and implications for ice thickness monitoring. *Journal of Geophysical Research* 97: 20325–20334.
- Wadhams, P., J.P. Wilkinson, and A. Kaletsky. 2004b. Sidescan sonar imagery of the winter marginal ice zone obtained from an AUV. *Journal of Atmospheric and Oceanic Technology* 21: 1462–1470.
- Wadhams, P., J.P. Wilkinson, and S.D. McPhail. 2006. A new view of the underside of Arctic sea ice. *Geophysical Research Letters* 33: L04501. doi:[10.1029/2005GL025131](https://doi.org/10.1029/2005GL025131).
- Wang, M., and J. Overland. 2009. A sea ice free summer Arctic within 30 years? *Geophysical Research Letters* 36: L07502. doi:[10.1029/2009GL037820](https://doi.org/10.1029/2009GL037820).
- Yu, Y., G.A. Maykut, and D.A. Rothrock. 2004. Changes in the thickness distribution of Arctic sea ice between 1958–1970 and

1993–1997. *Journal of Geophysical Research* 109: C08004. doi:[10.1029/2003JC001982](https://doi.org/10.1029/2003JC001982).

AUTHOR BIOGRAPHY

Peter Wadhams (✉) Peter Wadhams is Professor of Ocean Physics at the Department of Applied Mathematics and Theoretical Physics in the University of Cambridge and an associate professor at the Laboratoire d'Océanographie de Villefranche, Université Pierre et Marie Curie, France. He has led over 40 polar field expeditions and he is a member of the Scientific Committee of the European Environment Agency, Copenhagen.

Address: Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, University of Cambridge, Cambridge CB3 0WA, UK.

e-mail: p.wadhams@damtp.cam.ac.uk