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Annual Review of Marine Science Arctic and Antarctic Sea Ice Change: Contrasts, Commonalities, and Causes

Ted Maksym

Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA; email: tmaksym@whoi.edu

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Keywords

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Abstract

Arctic sea ice has declined precipitously in both extent and thickness over the past four decades; by contrast, Antarctic sea ice has shown little overall change, but this masks large regional variability. Climate models have not captured these changes. But these differences do not represent a paradox. The processes governing, and impacts of, natural variability and human-induced changes differ markedly at the poles largely because of the ways in which differences in geography control the properties of and interactions among the atmosphere, ice, and ocean. The impact of natural variability on the ice cover is large at both poles, so modeled ice trends are not entirely inconsistent with contributions from both natural variability and anthropogenic forcing. Despite this concurrence, the coupling of natural climate variability, climate feedbacks, and sea ice is not well understood, and significant biases remain in model representations of the ice cover and the processes that drive it.

1. INTRODUCTION

Ice extent: The area of the ocean surface that contains sea ice exceeding some threshold fractional coverage (usually 15%)

GCM: global climate model

The area of the Northern Hemisphere covered by sea ice has declined dramatically since the 1990s (Meier et al. 2014). The decline is particularly evident in summer; in 2007, the summer minimum ice extent dropped to 40% below its long-term mean (Comiso et al. 2008), an anomaly that was almost twice the previous record, from 2005. This record was again surpassed in 2012 (Parkinson & Comiso 2013). At the time, global climate models (GCMs) did not capture the observed declines, even prior to 2007 (Stroeve et al. 2007), which drove suggestions that Arctic sea ice might be nearing a tipping point, beyond which irreversible changes in ice extent changes would lead rapidly to an ice-free Arctic in summer (e.g., Lenton et al. 2008). Simple projections of trends suggested that an essentially ice-free Arctic could be imminent (Maslowski et al. 2012). But despite such concerns, Arctic summer ice cover has not declined further (Swart 2015).

These recent Arctic changes stood in stark contrast to those in the Antarctic, where the ice cover overall has increased modestly in extent over the past several decades (e.g., Comiso et al. 2017) and reached successive record-high maximum extents from 2012 to 2014 (Reid & Massom 2015)—a contrast that has been called an Antarctic paradox (Simmonds 2015). While the increase is small relative to the decrease in the Arctic, GCMs again failed to accurately capture the observed behavior, instead suggesting that modest declines due to global warming should have begun (Maksym et al. 2012, Turner et al. 2013).

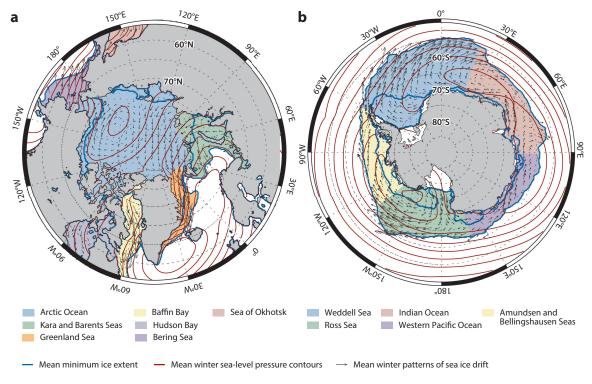
Several reviews of changes in both Arctic sea ice (Meier 2017, Meier et al. 2014, Stroeve et al. 2012b) and Antarctic sea ice (Hobbs et al. 2016, Stammerjohn & Maksym 2017) have been recently published. In this review, I focus on the contrasts and commonalities between the Arctic and Antarctic trends and variability and how specific characteristics of the sea ice cover and its environment can explain these changes.

2. A CONTRAST IN GEOGRAPHY

The defining difference that governs the contrasting behavior of sea ice at the poles is geography. With the exception of some of the peripheral seas, the Arctic ice cover is constrained by land. This restricts the motion of sea ice in the Arctic basin, with the only significant export of ice going into the North Atlantic (primarily through the narrow Fram Strait between Svalbard and Greenland). While sea ice in the peripheral seas mostly melts completely each summer, most of the ice cover survives the summer melt in the high Arctic. In the Antarctic, the ice grows unbounded by land at its northern edge in winter and retreats close to the coast in summer, resulting in twice the seasonal cycle of growth and retreat in ice extent compared with the Arctic. The maximum northward extent of ice is limited principally by the Antarctic Circumpolar Current (Martinson 2012). The Antarctic ice edge is constantly buffeted by some of the highest winds and waves on Earth; the frequent passage of cyclones affects ice variability (Uotila et al. 2011), and the waves break up the ice hundreds of kilometers inside the ice edge (Kohout et al. 2014).

2.1. The Atmosphere

Sea ice drift in the Arctic is dominated by two connected features of the atmospheric circulation. A persistent high pressure over the western Arctic Ocean—the Beaufort High (Serreze & Barrett 2011)—drives an anticyclonic sea ice circulation (see **Figure 1**). Coupled with the trough of low pressure that extends from the eastern Arctic to the Icelandic Low in the North Atlantic, the Beaufort High also helps drive the Transpolar Drift Stream, which transports ice from the Russian Arctic toward Greenland and Fram Strait. This circulation favors thick ice that can persist



Geographic setting of (*a*) Arctic and (*b*) Antarctic sea ice. The average maximum sea ice extents for 1979–2016 (March in the Arctic, September in the Antarctic) are indicated by the colored ocean areas. The blue lines indicate the mean minimum ice extents (September in the Arctic, February in the Antarctic). The black arrows indicate the mean winter patterns of sea ice drift, and the red lines show the mean winter sea-level pressure contours (2-hPa intervals) (January–March in the Arctic, July–September in the Antarctic). Different colors indicate different traditional regions or sectors chosen to examine trends and variability (Cavalieri & Parkinson 2008, Parkinson & Cavalieri 2008). Sea ice drift patterns are driven largely by climatological highs and low pressures, which drive prevailing winds. Much of the variability in the ice cover is then driven by atmospheric variability.

for many years in the North American Arctic (Stroeve et al. 2012b) and determines the quantity of ice that is removed from the Arctic through Fram Strait. Variability in this circulation is then a primary driver of the amount of thick ice in the Arctic (Maslanik et al. 2011, Rigor et al. 2002).

The Antarctic atmospheric circulation is dominated by the Antarctic Circumpolar Trough—a nearly annular low-pressure field from the coast to north of the ice edge that results from the frequent passage of low-pressure systems (**Figure 1**). This trough drives strong, circumpolar westerly winds and a generally eastward ice drift at the ice edge, and weaker easterly winds and a slower westward ice drift along the coast. The westerly winds impart a northerly Ekman drift to the ice at the ice edge, so that the northward seasonal expansion of the ice is driven both by ice drift and ice formation and by a generally divergent ice cover. Variations in this mean westerly flow broadly define the Southern Annular Mode (SAM), which is the major mode of atmospheric variability in the Antarctic. The most prominent deviation from zonal flow is associated with the Amundsen Sea Low (ASL), a climatological low pressure centered between 110°W and 150°W and between 60°S and 70°S. The ASL, itself a consequence of the interaction of the westerly winds with the Antarctic (Raphael et al. 2016).

SAM: Southern Annular Mode ASL: Amundsen Sea Low

Multiyear ice:

ice that has survived through one or more summers

Deformation:

the process of ice thickening through rafting and ridging as ice floes collide due to winds and currents Lastly, the surface drivers of ice growth and melt differ (see **Figure 2**). In summer, Arctic sea ice is marked by widespread surface melt and the development of a patchwork of surface melt ponds. These ponds lower the albedo (reflectivity) of the summer ice cover, allowing greater absorption of solar radiation, which accelerates summer melt (Perovich & Polashenski 2012, Perovich et al. 2002). Melt ponds are more extensive on seasonal ice, exacerbating sea ice loss as the Arctic perennial ice declines (Perovich & Polashenski 2012). Melt ponds are almost nonexistent in the Antarctic. Instead, greater snowfall rates in the Antarctic and thinner ice promote seawater flooding of the snow cover, which refreezes, thickening the ice cover from above (Maksym & Markus 2008). This process may help stabilize the ice cover in a warmer, wetter climate (Fichefet & Maqueda 1999).

2.2. The Ocean

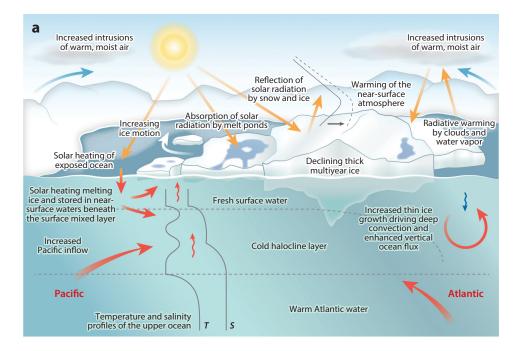
When seawater freezes, it rejects most of the salt from the growing sea ice and forces it into the underlying ocean. The dense brine thus formed sinks through the ocean surface mixed layer, and this convection entrains denser waters from below. In the Arctic, the fresh, buoyant surface waters are insulated from warmer Atlantic water that enters through Fram Strait by a layer of cold, salty water known as the cold halocline layer (Steele & Boyd 1998), which acts as a barrier to upward mixing of the warmer water beneath. This barrier limits vertical ocean heat flux to the ice to only 1–3 W m⁻² in the high Arctic in winter (Carmack et al. 2015), which is the primary reason that multiyear ice is able to grow to several meters thick. Only a few watts per square meter of increased vertical heat flux from the ocean to the ice would be enough to entirely remove the Arctic multiyear ice cover (Maykut & Untersteiner 1971).

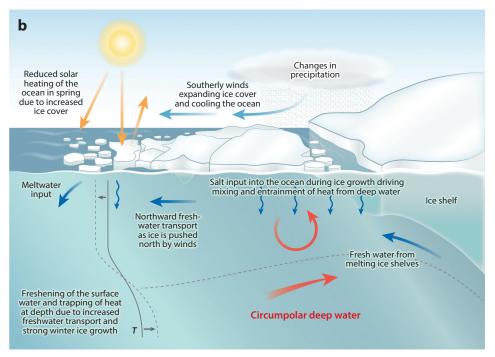
In the Antarctic, by contrast, the upper ocean is weakly stratified, and therefore heat is readily ventilated to the surface, with typical winter ocean heat fluxes of 25-35 W m⁻² (Martinson & Iannuzzi 1998), which limits the thickness of undeformed seasonal ice (flat, level ice that thickened through vertical downward freezing) to only approximately 50 cm. Widespread deformation increases this thickness to a mean of 70–90 cm (Worby et al. 2008). The entrainment of heat can be so strong that relatively thin ice can be actively melting from below, even in winter (e.g., Jeffries et al. 2001), and thicker ice occurs only through rafting and ridging or from surface flooding and refreezing rather than thickening through growth on the bottom. Thick ice does occur along the Antarctic coast and western Weddell Sea, where low vertical ocean heat fluxes, substantial deformation, and deep snow cover can lead to very thick ice (Williams et al. 2015), which may help it persist through summer in a warmer climate (e.g., Massom et al. 2006).

It is these characteristics of the atmospheric circulation, ocean properties, and sea ice that determine how the ice cover responds to both human-induced and natural variability and explain much of the contrast in sea ice trends between the poles. Section 5 explores this contrast, but first, Sections 3 and 4 summarize observed trends in the sea ice cover.

3. CHANGES IN ICE EXTENT AND SEASONALITY

The longest and most complete sea ice data set is the now almost 40-year record of global sea ice coverage from multichannel passive microwave radiometers that have flown on a series of satellites since late 1978. The data have different regional and seasonal biases depending on the algorithm used to process them (Ivanova et al. 2015), but trends in ice extent are consistent between algorithms. Here, I use the latest version of the Bootstrap data set (Comiso 2017), which has been updated to improve intersatellite calibration (Comiso et al. 2017). **Table 1** shows the trends in ice extent from 1979 to 2017 along with confidence intervals and trends as percentages of the 1979–1989 mean extents.





(Caption appears on following page)

Figure 2 (*Figure appears on preceding page*)

Schematic of key ice-ocean-atmosphere interactions and feedbacks contributing to sea ice changes. (a) The Arctic. Processes depicted include (i) ice-albedo feedback accelerating ice loss through enhanced heating of the open ocean and melt ponds driving ice melt, and heat storage in the upper ocean; (*ii*) enhanced near-surface heating due to radiative feedbacks; (iii) increased radiative heating from clouds and water vapor; (*iv*) increasing intrusion of clouds and water vapor into the Arctic; (v) increased ice motion; (vi) increased inflow of warm Pacific water; and (vii) deep convection in the Atlantic sector due to thin ice growth entraining heat from the warm Atlantic layer. (b) The Antarctic. The schematic illustrates processes that contribute to increasing sea ice (e.g., in the Ross Sea). Processes depicted include (i) increased wind-driven northward advection and growth of ice; (ii) reduced ice-albedo feedback (solar heating of the open ocean in spring and summer) due to a reduced open water season; (iii) transport of fresh water northward with drifting ice; (iv) possible impacts from increased precipitation thickening ice and freshening surface waters; (v) strong winter ice growth deepening the surface mixed layer and trapping heat at depth, combined with a freshening surface layer reducing upward heat flux; (vi) freshwater input from melting ice shelves; and (vii) upward entrainment of heat due to ice-growth-induced haline convection modulating ice growth. Where sea ice is decreasing, these processes would generally act in the opposite direction to that depicted. Antarctic changes are initiated primarily by changes in winds that are driven by changes in large-scale atmospheric circulation. Orange and red arrows indicate the flow of heat and warmer water, and blue arrows indicate the flow of water affecting surface freshwater balance (dark blue) or air (light blue).

The picture of Arctic change is clear. While there are some modest regional differences, there is a consistently strong decline in all regions, the only exception being the Bering Sea, where increased northwesterly winds and cooling associated with changes in the Pacific Decadal Oscillation favor more extensive ice (Frey et al. 2015). The Arctic trends are more strongly negative in summer,

Region	Annual	January–March	April–June	July-September	October-December
Northern Hemisphere	$-56.8 \pm 8.2 (-4.6\%)$	-43.9 ± 9.2 (-2.8%)	-41.5 ± 7.8 (-3.0%)	-83.8 ± 13.5 (-9.3%)	-58.1 ± 11.0 (-5.2%)
Seas of Okhotsk and Japan	-4.1 ± 2.8 (-9.2%)	-9.3 ± 5.2 (-7.9%)	-5.8 ± 4.9 (-12.5%)	NI	$-1.3 \pm 1.7 (-8.7\%)$
Bering Sea	$-0.6 \pm 2.2 (-1.8\%)$	$-0.2 \pm 3.7 (-0.3\%)$	$-0.5 \pm 4.1 (-1.2\%)$	NI	$-1.6 \pm 1.8 (-9.3\%)$
Hudson Bay	-3.8 ± 1.5 (-4.4%)	$-0.1 \pm 0.1 (0.1\%)$	-2.4 ± 1.0 (-2.0%)	$-6.2 \pm 2.2 (-19.0\%)$	-6.4 ± 2.9 (-9.8%)
Baffin Bay and Labrador Sea	-5.9 ± 5.3 (-6.9%)	-7.2 ± 9.4 (-5.2%)	-5.6 ± 6.1 (-4.9%)	-5.2 ± 2.1 (-18.8%)	-5.6 ± 2.7 (-8.9%)
Greenland Sea	$-6.8 \pm 2.7 (-8.8\%)$	$-10.3 \pm 3.5 (-10.4\%)$	$-5.8 \pm 2.4 (-6.5\%)$	-4.9 ± 2.7 (-9.8%)	-6.1 ± 2.8 (-8.9%)
Kara and Barents Seas	$-16.5 \pm 5.6 (-11.4\%)$	$-13.0 \pm 5.0 (-6.9\%)$	$-17.0 \pm 6.2 (-9.3\%)$	$-17.5 \pm 5.5 (-23.3\%)$	-18.6 ± 6.4 (-14.2%)
Arctic Ocean	$-18.0 \pm 3.9 (-2.4\%)$	$-0.5 \pm 0.4 (-0.1\%)$	$-3.0 \pm 1.1 (-0.4\%)$	$-50.1 \pm 11.5 (-7.0\%)$	-18.2 ± 4.5 (-2.4%)
Southern Hemisphere	11.2 ± 14.6 (1.0%)	6.6 ± 18.0 (1.6%)	18.0 ± 17.2 (1.8%)	12.0 ± 14.1 (0.7%)	8.2 ± 17.6 (0.6%)
Weddell Sea	5.0 ± 9.4 (1.2%)	14.5 ± 13.1 (10.3%)	10.9 ± 10.1 (3.0%)	$-2.6 \pm 10.6 (-0.4\%)$	$-3.0 \pm 10.8 (-0.5\%)$
Indian Ocean sector	2.3 ± 4.7 (1.2%)	1.2 ± 2.8 (3.6%)	3.7 ± 4.2 (2.7%)	2.8 ± 6.6 (0.9%)	1.4 ± 8.2 (0.5%)
Pacific Ocean sector	2.4 ± 3.5 (2.0%)	2.5 ± 2.9 (5.3%)	3.9 ± 3.8 (3.6%)	2.1 ± 5.6 (1.1%)	1.2 ± 5.0 (0.8%)
Ross Sea	6.4 ± 9.2 (2.4%)	0.8 ± 11.0 (0.8%)	8.3 ± 8.4 (3.1%)	7.0 ± 9.0 (1.8%)	9.4 ± 11.6 (2.9%)
Amundsen and Bellingshausen Seas	-4.8 ± 5.1 (-3.1%)	-12.4 ± 5.4 (-14.2%)	-8.8 ± 6.2 (-6.3%)	2.7 ± 7.3 (1.3%)	$-0.8 \pm 7.4 (-0.5\%)$
Global	-45.6 ± 18.8 (-1.9%)	-37.3 ± 23.2 (-1.9%)	-23.4 ± 20.9 (-1.0%)	$-72.0 \pm 17.6 (-2.7\%)$	-49.9 ± 20.6 (-1.9%)

Table 1 Sea ice extent trends for 1979–2017

Values are in thousands of square kilometers per year, with the percentage change per decade (relative to the 1979–1989 mean extents) given in parentheses. Gray shaded cells indicate significant e significant at a 95% level. Blue shaded cells indicate where significant trends existed for 1979–2015 but are no longer significant at the 95% level. The trend error bounds are the 95% confidence limits from a two-sided *t*-test. Confidence intervals in the trend are calculated from the seasonal means while accounting for autocorrelation in the time series (Santer et al. 2000). Data are from Comiso (2017). Abbreviation: NI, no ice present during season.

consistent with GCM predictions (Stroeve et al. 2012a). A clear consensus of an anthropogenic driver has emerged (Flato et al. 2013, Kay et al. 2011, Min et al. 2008, Notz & Marotzke 2012, Stroeve et al. 2012a).

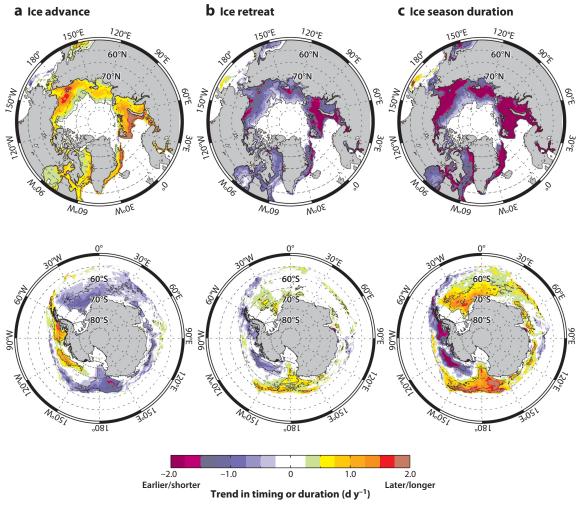
An important question is whether sea ice decline in the Arctic has accelerated in the wake of the dramatically low sea ice minimum in 2007 (Stroeve et al. 2012b) and indications that the ice cover might continue to decline faster than models predict (Stroeve et al. 2012a). Since 2007, September sea ice extent has fluctuated strongly but has shown no significant trend (Swart 2015). Such step changes in the ice cover are consistent with similar large declines seen in GCMs, known as rapid ice loss events. These events can occur when a weakened ice cover exacerbates the impact of large but potentially natural variations in the forcing (Holland 2013, Holland et al. 2006). Northern Hemisphere winter trends are consistent across the satellite period (Meier 2017; see also **Figure 6** in Section 6) and do not show statistically significant differences for different time periods. On the other hand, there has been a steepening of the trend in summer, with the rate of decline doubling since 2000 (from -55 to -115 km³ y⁻¹). Negative Arctic annual trends become significant by 1990.

By contrast, there has recently been a modest increasing trend in the Antarctic. These trends are similar to those reported by prior studies (Comiso & Nishio 2008), but as of 2017 are statistically significant (at the 95% level) Antarctic-wide only in autumn. Ice extent increases have been most prominent in the Ross Sea, with positive trends in all seasons except summer through 2015, but due to recent record ice extent minima, these trends are no longer statistically significant. Nevertheless, positive trends are generally strongest in autumn, where trends are significant at the 90% level in all regions. This recent variability is further discussed in Section 6. These findings agree with the results of Yuan et al. (2017), who, using a more sophisticated trend analysis accounting for persistence, suggested that significant positive trends are present only in the Ross Sea. Overall, Arctic change dwarfs Antarctic change, so that the global sea ice cover is strongly decreasing.

Negative trends in the Amundsen and Bellingshausen Seas have been noted for the past two decades, with a loss of most of the perennial ice (Jacobs & Comiso 1997). These negative trends are significant for summer and autumn, reflecting a lengthening of the summer season, but by winter, the ice has recovered. Due to recent years of heavier ice, the annual trend is no longer significant at the 95% level.

Despite much recent debate on the causes of the Antarctic increase (Hobbs et al. 2016), the trend is small and potentially short term (the circumpolar trends are statistically significant only since 2008, and as of 2017 may no longer be so), and it obscures the much larger regional variability. Antarctic trends depend strongly on the time period and season, with only the opposing trends in the Ross, Amundsen, and Bellingshausen Seas being relatively consistent over time. Thus, the story is one of variability and why that variability is centered in the Pacific sector of the Southern Ocean. Section 6 further discusses the significance of these trends in the context of historical and future change.

Since the extent of the sea ice cover varies by a factor of 3–5 throughout the year, an alternative and perhaps more intuitive way of understanding these changes is through the length of the ice-covered season (Stammerjohn et al. 2008, 2012). The date of ice advance is defined as the date at which the ice edge advances past a given location in autumn; conversely, the date of retreat can be defined as the date at which the ice disappears in the summer. The difference between these dates is the length of the ice-covered season. Where there is perennial ice, the ice-covered season is year-round. **Figure 3** shows the trends in ice advance, retreat, and ice-covered season. An advantage of these metrics is that trend maps are visually intuitive in terms of the impact of climate forcing in driving or responding to these changes. For instance, a longer summer season



Trends in (*a*) the timing of sea ice advance, (*b*) the timing of sea ice retreat, and (*c*) the length of the ice-covered season between 1979 and 2016. Figure adapted and updated from Stammerjohn et al. (2012).

is directly related to the ice-albedo feedback (see the sidebar titled Ice-Albedo Feedback) through the increased absorption of solar heating by the open ocean.

The picture of regional changes is clear. Across the Arctic, autumn ice advance is trending later and spring/summer retreat earlier in almost all regions, the only exception being the Bering Sea, where there has been very little change. The regions of greatest Arctic change are in the Beaufort, Chukchi, and eastern Siberian Seas in the Canada Basin and the Kara and Barents Seas in the east (Stammerjohn et al. 2012). Here, sea ice retreat is earlier by approximately 1.5–2 months and advance is later by 1–1.5 months, resulting in an ice season that is shorter by approximately 2–3.5 months since 1978. In the Antarctic, the trends are much more regionally variable, but the contrasting trends between the southern Amundsen and Bellingshausen Seas and the western Ross Sea are as large as those between the Antarctic and the Arctic. In the Amundsen and Bellingshausen Seas, ice retreat is approximately 1 month earlier and advance approximately 1–2 months later,

ICE-ALBEDO FEEDBACK

In the summer, enhanced sea ice loss is dominated by the ice–albedo feedback. Snow-covered sea ice reflects most of the incident solar radiation. As the ice melts, it reveals the dark ocean, which absorbs more solar radiation. The heat absorbed by the ocean melts more ice, which in turn promotes more solar heating of the ocean, thus creating a positive melting feedback (Perovich et al. 2011).

resulting in an ice season that is shorter by approximately 2–3 months. By contrast, the western Ross Sea has had opposing trends, with a later retreat of approximately 1 month and earlier advance of approximately 1–2 months (Stammerjohn & Maksym 2017). Note that, while trends in the Arctic are consistent over time, the impact of recent interannual variability is fairly large in the Antarctic. Since the study by Stammerjohn et al. (2012), a partial reversal of regional trends has shortened the sea ice season in the Amundsen Sea and western Ross Sea and increased it in the southern Bellingshausen Sea. The magnitude of the trends in ice season length vary over different timescales for different regions, with subdecadal variations in the Bellingshausen Sea and a more consistent trend in the Ross Sea (Simpkins et al. 2013).

4. CHANGES IN ICE THICKNESS AND DRIFT

The loss of Arctic ice thickness and volume is expected to outpace ice extent declines under global warming (Gregory et al. 2002). The only large-scale time series of ice thickness is from sonar measurements of ice draft from submarines that have traversed under the ice since 1958. The available data are sparse and cover only approximately 40% of the Arctic, but in the western and central Arctic, there was a 36% decline in ice thickness between the 1980s and 2000s (Rothrock et al. 2008).

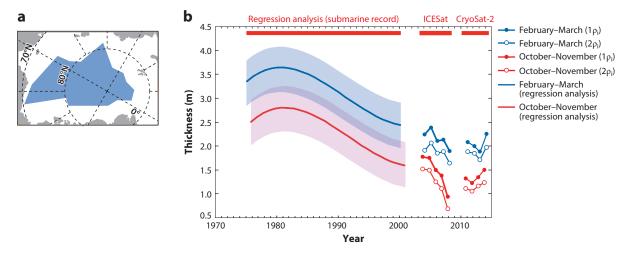
More recently, satellite altimeters on the Ice, Cloud, and Land Elevation Satellite (ICESat) and CryoSat-2 have provided estimates of ice thickness from 2003 to 2009 and from 2009 to the present, respectively. These data show an accelerating decline in ice thickness over the ICESat period coincident with the rapid loss of perennial ice leading up to and including 2007 (Kwok & Rothrock 2009, Kwok et al. 2009). Remarkably, multiyear ice declined by approximately 40% and thinned by approximately 0.6 m between 2005 and 2008 (Kwok et al. 2009). This loss then leveled off, with possibly some recovery after 2007 (Kwok & Cunningham 2015) (**Figure 4**), consistent with ice extent variability.

There are significant uncertainties in these satellite-based observations, as an independent estimate of snow depth is required to derive ice thickness (Kwok & Cunningham 2015), particularly over thinner first-year ice. Because interannual variations in first-year ice thickness are then difficult to detect (Kwok & Cunningham 2015, Tilling et al. 2015), the long-term observed changes in ice thickness are primarily (or perhaps entirely) due to changes in multiyear ice. Recently, however, anomalies in the thickness of thin ice have been detected due to reduced ice growth in the anomalously warm winter of 2015–2016 (Ricker et al. 2017).

Since Arctic ice thickness and volume changes are due mostly to changes in the amount of multiyear ice, the age of the ice provides a proxy for changes in ice thickness. Ice age has been monitored since 1983 by tracking ice parcels that survive the summer melt through each subsequent season that they survive (Maslanik et al. 2011). These data show a dramatic decline in the age of ice since 1984, with almost all of the older, thicker ice having vanished (**Figure 5**). The pace of loss of older ice is consistent with both the long-term decline in ice thickness from submarine

ICESat: Ice, Cloud, and Land Elevation Satellite

First-year ice: ice that has formed during the current winter season



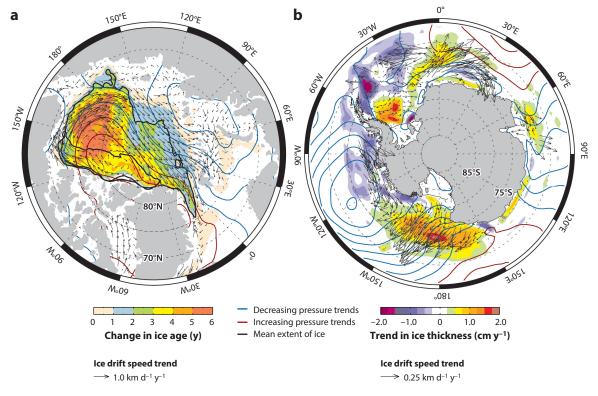
Comparison of historic submarine and modern satellite observations, showing dramatic declines in Arctic ice thickness since the 1980s. (*a*) The submarine data release area. (*b*) Average winter (February–March) and autumn (October–November) declines in ice thickness in the data release area, from a regression of submarine data and satellite [Ice, Cloud, and Land Elevation Satellite (ICESat) and CryoSat-2] estimates between 1980 and 2014. The shaded areas show residuals in the regression and quality of the submarine data. ICESat and CryoSat-2 thicknesses are shown using a single ice density ($1\rho_i$, *solid symbols*) and different ice densities for first-year and multiyear ice ($2\rho_i$, *open symbols*). Figure adapted from Kwok & Cunningham (2015).

data and the acceleration since the early 2000s, but the decline is most prominent for the oldest ice (five or more years old), which has almost completely disappeared (Maslanik et al. 2011).

Changes in ice extent and thickness (or age) are accompanied by changes in ice motion. These drift changes are not monotonic and have changed over the past four decades as atmospheric circulation has changed (Kwok et al. 2013). Ice drift speed has increased in the Arctic, primarily since 2001 (Kwok et al. 2013). These long- and short-term trends are not associated with linear trends in wind speed; rather, they appear to be due to the increased mobility of the ice associated with the thinning and weakening of the pack in both winter and summer (Kwok et al. 2013). Changes in the circulation are relatively weak in winter; in summer, there has been increased transport from the Canadian Arctic into the Beaufort and Chukchi Seas, a strengthening of the Transpolar Drift Stream, and an increased tendency for ice to be transported from the western to eastern Arctic in summer (Kwok et al. 2013) (**Figure 5**).

Ice thickness data in the Antarctic are too sparse (Worby et al. 2008) and the satellite altimetry record too short to detect any trends. However, several modeling efforts show broadly consistent trends (Holland et al. 2014, Massonnet et al. 2013, Zhang 2007). These models suggest that ice may have thickened in winter in the Ross Sea and the inner Weddell Sea and thinned in the Belling-shausen Sea (Figure 5). These results are also consistent with the trends in sea-level pressure, ice motion, and ice extent (Holland & Kwok 2012). Trends in atmospheric circulation and drift tend to push ice toward the thickening regions and away from regions where ice thickness, extent, and ice season length have decreased (Holland et al. 2014), which supports the notion that these trends in the ice cover are largely driven dynamically by wind-driven drift. Zhang (2014), however, attributed increases in ice thickness to increased deformation driven by intensifying winds.

Changes in the surface properties of Arctic sea ice have also accompanied the declines in its extent and thickness. The sea ice surface melt season (the period during which the snow and ice surface experiences melting conditions) lengthened by approximately five days per decade between



Changes in ice thickness and ice motion over time. (*a*) Decreases in Arctic sea ice age (a proxy for ice thickness) between the periods 2007–2016 and 1984–1993 (Tschudi et al. 2016b), overlaid with May–September ice motion trends (*arrows*) (Tschudi et al. 2016a) and trends in mean sea-level pressure from 1984 to 2016 (*contour lines*, at intervals of 2 hPa y^{-1}). Decreasing pressure trends are shown in blue, and positive pressure trends are shown in red. Thick black contours indicate the mean extent of ice that is three or more years old during the early and late period. (*b*) Modeled May–June Antarctic sea ice thickness trends (Massonnet et al. 2013), overlaid with changes in ice motion (*arrows*) (Kwok et al. 2016) and trends in sea-level pressure (*contour lines*, at intervals of 3 hPa y^{-1}) for 1990–2009. Old, thick Arctic ice has almost disappeared due to coupling between thermodynamic melting of the ice and increased ice advection out of the Arctic. Loss of multiyear ice is responsible for most of the decline in thickness. Antarctic ice thickness trends are uncertain, but model trends are consistent with observed changes in ice extent and driven largely by winds.

1979 and 2013, a change dominated by a delay in the timing of the onset of freezing conditions (Stroeve et al. 2014b). Webster et al. (2014) showed that the Arctic snow depth may also have thinned, which is correlated with a delayed onset of autumn ice advance. This lengthening of the melt season would tend to favor increased ice surface melt, but no clear trends from the limited in situ measurements of surface melt rate are apparent (Perovich & Richter-Menge 2015). No trends in melt onset (the initiation of surface melting conditions in summer) (Arndt et al. 2016) or snow depth (Maksym & Markus 2008) are apparent in the Antarctic.

5. DRIVERS OF CHANGE AND VARIABILITY

The picture of consistent decline in the Arctic and temporal and regional variability in the Antarctic raises the question of how much of these changes is due to expected response to global warming and how much is due to natural variability of the climate.

5.1. Atmospheric Drivers of Variability

The leading mode of atmospheric variability in the Arctic is the Arctic Oscillation, which describes variations in air pressure over the central Arctic associated with the Beaufort High (Thompson & Wallace 1998). In its positive phase, circulation is more cyclonic (counterclockwise), which tends to promote transport of older, thicker ice away from the Eurasian Arctic and out through Fram Strait, consequently increasing the production of younger, thinner ice (Rigor & Wallace 2004). A generally positive winter Arctic Oscillation in the 1980s to 1990s has been associated with a reduction in multiyear ice, but despite a shift to more neutral conditions in the mid-1990s, sea ice continued to decline.

The second leading mode of Arctic atmospheric variability, the Dipole Anomaly, is expressed as surface air pressure variability between the North American and Eurasian Arctic (Watanabe et al. 2006). It has different expressions in summer and winter, but in both seasons, its impact is to drive variations in meridional winds across the pole, and it therefore has a major impact on ice export via the Transpolar Drift Stream (Wang et al. 2009). Multiyear ice has continued to decline as the Dipole Anomaly favored increased export in the Transpolar Drift Stream through the 1990s and 2000s (Maslanik et al. 2011).

Note, however, that the strengthening of the Transpolar Drift Stream noted by Kwok et al. (2013) is not strongly driven by changes in winds; Kwok et al. (2013) found that, while ice export through Fram Strait has increased since 2001, the overall increase in export since 1982 is negligible due to a compensating decrease in ice concentration. By contrast, Smedsrud et al. (2017) used correlations of drift with geostrophic winds to suggest that export increased by 5.9% per decade from 1979 to 2014, with the greatest increases occurring in spring. The long-term trend is largely attributable not to the Arctic Oscillation but to surface pressure trends with a Dipole Anomaly–like pattern. Ogi et al. (2010) stressed the importance of both winter and summer wind anomalies in driving anomalies in summer sea ice extent.

The results described above paint a complex picture of the role of atmospheric variability in ice declines. The impact of the winter Arctic Oscillation on sea ice declines prior to the 1990s would plausibly have a greater impact when the multiyear ice fraction was high. A shift toward a circulation pattern favoring a strengthening of the Transpolar Drift Stream and increasing drift speed would enhance summer ice export. Strengthening of anticyclonic circulation in the Beaufort Gyre (**Figure 5**) increased the divergence of the pack, enhancing ice melt in summer (Kashiwase et al. 2017). Loss of multiyear ice is exacerbated by increased transport from north of the Canadian Archipelago into the Beaufort Sea, where it can melt more readily in summer.

These changes can reflect more than a dynamic sea ice response, as atmospheric circulation variability can also be accompanied by changes in transport of heat and moisture into the Arctic. A warmer, moister atmosphere increases downwelling long-wave radiative forcing and warms the surface. Several recent studies have shown an increasing frequency of warm air intrusions in the Arctic, which can explain a significant fraction of the surface winter warming and sea ice declines in the Eurasian Arctic (Gong et al. 2017, Park et al. 2015, Woods & Caballero 2016).

The proximate driver of sea ice variability in the Antarctic is winds (Holland & Kwok 2012, Kwok et al. 2016, Matear et al. 2015). Offshore winds can promote expansion either dynamically, by advecting sea ice northward, where this expansion may be reinforced by ocean feedbacks (see Section 5.2), or by cooling and freezing. Conversely, warmer onshore winds can push the ice edge back dynamically or through warming. In the Pacific sector, the relationship between winds and ice extent trends is clear, and appears to be largely dynamic in the Amundsen and Ross Seas but largely thermodynamically driven in the Bellingshausen Sea (Holland 2014, Matear et al. 2015).

Wind forcing may be sufficient to explain trends in all areas except the western Antarctic Peninsula regions, where warming has contributed to trends (Matear et al. 2015).

Variations in winds are associated with two major modes of climate variability: the SAM and the El Niño-Southern Oscillation (ENSO). There has been a long-term positive trend in the SAM associated with ozone depletion (Thompson et al. 2011), which is presumed to have intensified westerly winds. This positive trend in the SAM deepens the ASL, increasing warm, northerly winds over the Bellingshausen Sea and cold southerly winds over the Ross Sea. This deepening is most prominent in autumn and drives the pattern of sea ice drift shown in Figure 5. A similar pattern of sea-level pressure in the high-latitude southeast Pacific is exhibited by ENSO, which drives a dipole pattern of opposing sea ice anomalies in the Bellingshausen-Weddell and Amundsen-Ross Seas (Yuan 2004). Stammerjohn et al. (2008) showed that when the SAM is positive (and ASL generally deeper), the sea ice season is reduced in the eastern Bellingshausen Sea and longer in the western Ross Sea, consistent with the pattern shown by the trends shown in Figure 3. The SAM and ENSO can act in concert so that this pattern of variability is strongest when a positive SAM is coupled with a La Niña. The pattern reverses when a negative SAM is coupled with an El Niño. These links are complicated by the distinct regional and seasonal variability in the SAM, ENSO, and the ASL and their connections with sea ice variability (Hobbs et al. 2016). Climate modes with multidecadal variability and a tropical origin also affect sea ice variability, particularly in the Pacific sector (e.g., Li et al. 2014).

While these links are compelling, trends in ice extent are not so easily explained by simple trends in these climate modes. Simpkins et al. (2012) did not find any significant link between sea ice trends and the SAM or ENSO, although the connections were stronger in winter. Kohyama & Hartmann (2016) showed that removing the linear response to climate modes such as the SAM and ENSO can remove much of the sea ice extent trends in some sectors, including the Ross Sea. But because these modes act differently in different areas, it is difficult to explain sea ice trends solely with known modes of climate variability. Hobbs et al. (2016) showed clearly that while various modes of climate variability affect sea ice variability, they do not fully explain the trends, especially in the Ross Sea.

Meehl et al. (2016) suggested that recent trends in sea ice extent in the Ross Sea are driven by tropical Pacific variability acting through deepening of the ASL, and that trends in the SAM have not contributed. This might explain recent increases in the Ross Sea that have contributed to the recent emergence of a circumpolar positive trend but does not explain the much longer term trend in the Ross Sea (Simpkins et al. 2012) (also Section 6).

By contrast, Kwok et al. (2016) demonstrated that as much as two-thirds of the winter trend in ice edge position is explained by ENSO-driven trends in winds. This finding may be consistent with other studies, as the regional ice edge trends do not coincide with the broader regions of ice concentration or ice extent used in earlier studies.

5.2. The Changing Role of the Ocean

Arctic sea ice has historically been largely insulated from the impact of heat trapped beneath the surface ocean (Section 2.2). While the vertical heat flux to the ice has in the past been very low, allowing very thick, old ice to grow, changes in ocean circulation and upper-ocean properties may be changing this flux and contributing to the thinning of the ice cover. Most solar radiation absorbed by the ocean in summer is used immediately to melt ice, but some may be trapped beneath the surface as sea ice melt stratifies the upper ocean and inhibits mixing. This trapped heat is released later as winter cooling and brine released during freezing break down this stratification, and the heat mixes upward. As summer sea ice has declined in the Beaufort and Chukchi Seas,

ENSO: El Niño–Southern Oscillation the amount of heat stored below the mixed layer in summer has increased and likely slowed ice growth through the autumn and winter (Jackson et al. 2012).

There has been a long-term warming of the Atlantic water in the Arctic Ocean (Polyakov et al. 2012). While normally sea ice is insulated from this heat by the cold halocline layer, recent pulses of more weakly stratified Atlantic water have been observed in the Eurasian Basin of the eastern Arctic (Polyakov et al. 2017). As the ice cover here has retreated, a negative sea ice feedback can occur during autumn freeze-up. Increased ice production in autumn drives stronger haline convection that mixes up more heat from these pulses of warm water (Ivanov et al. 2016), inhibiting winter ice growth. Modeling results suggest that future rapid ice loss events may be associated with increased pulses of ocean heat transport into the Arctic driven by atmospheric circulation variability (Holland et al. 2006).

At the other side of the Arctic, enhanced inflow of warmer Pacific water through the Bering Strait in the 2000s (Woodgate 2018, Woodgate et al. 2012) has likely contributed to sea ice loss in the Canada Basin (e.g., Shimada et al. 2006). The drivers of this increased inflow include not only local wind-driven variability but also far-field forcing that may have been driven by increased anticyclonic circulation in a weaker, faster ice cover (Peralta-Ferriz & Woodgate 2017, Shimada et al. 2006).

Although the dominant role of the ocean in observed sea ice decline is carried out directly through the ice–albedo feedback, there is now emerging evidence that changes in the ocean—possibly driven partly by the thinning and increased seasonality of the ice—may be accelerating the sea ice decline. The role that such ice–ocean interactions will have in the future is critical to understanding future Arctic change. (For further discussion on the role of the ocean in the Arctic, see Carmack et al. 2015.)

Because of the weak stratification of the Southern Ocean and high ocean heat flux (Martinson & Iannuzzi 1998), most sea ice variability attributed to ocean changes is due to changes in upperocean stratification. These changes can occur through a variety of mechanisms that freshen the surface. Bintanja et al. (2013) suggested that increased ice shelf melt may have driven sea ice expansion, though the pattern of sea ice change is not consistent with the regions of greatest melt (Swart & Fyfe 2013). Observed freshening in the Ross Sea since 1958 is consistent with increased melt from ice shelves upstream in the Amundsen Sea but may also be linked to changes in the SAM (Jacobs & Giulivi 2010). Liu & Curry (2010) argued that increased precipitation in a warming climate could drive stratification-driven changes in sea ice extent. Surface stratification changes may also be achieved via increased northward transport of sea ice from where it forms in the south to where it melts to the north, creating a freshwater pump that favors ice expansion (Haumann et al. 2016). Similarly, a positive ice-growth feedback can occur if vigorous winter ice growth drives the brine released deep into the water column. Summer melt water is confined to a shallower layer, so if this saltier water is not reincorporated into the surface waters in subsequent winters with less vigorous growth, the surface will freshen, increasing stratification and reducing vertical ocean heat fluxes (Goosse & Zunz 2014). Lecomte et al. (2017) have suggested that this process may have contributed to increasing sea ice in the Ross Sea. Thus, ice-ocean interactions can provide a positive ice-growth feedback through either dynamics (increased northward advection of ice) or thermodynamics (increased winter ice growth). Zhang (2007) also suggested that a similar process could occur in a warming climate, with increased ice melt driving increasing stratification.

An ice–albedo feedback also drives Southern Ocean sea ice variability. Increased solar heating and warming of the upper ocean in response to sea ice decline has been suggested to drive further ice retreat in the Antarctic Peninsula region (Meredith & King 2005). Stammerjohn et al. (2012) showed that a later autumn ice advance was strongly correlated with a previous earlier spring and summer ice retreat, but a later autumn ice advance was not strongly correlated with a subsequent earlier spring and summer ice retreat. This finding suggests that enhanced solar heating of the ocean due to a reduced ice cover delayed subsequent freeze-up, which is supported by connections between autumn ice production and spring ice reductions (Holland 2014).

As in the Arctic, these ice–ocean feedbacks result partly from wind-driven circulation changes that can be displaced in time and space. Holland et al. (2017) showed that variability in zonal winds and ice advection in spring favors decreased open water in the Ross Sea, which reduces summer warming of the ocean and thus favors an earlier autumn ice advance. These effects can explain approximately 30% of the sea ice increase in the Ross Sea. Pope et al. (2017) showed that the impacts of ENSO forcing in the Ross Sea can produce anomalies that propagate temporally and spatially into the Bellingshausen Sea. These nonlocal and noncontemporaneous links between atmospheric forcing and sea ice may help explain why the observed sea ice trends cannot be fully explained by simple linkages to trends in major modes of climate variability.

5.3. Arctic Amplification and Anthropogenic Forcing

One of the most striking features of predicted warming due to increasing atmospheric CO_2 is the pronounced warming of the Arctic relative to the global average. Perhaps somewhat surprisingly, no enhanced warming is seen in the Southern Ocean. This Arctic amplification (see the sidebar titled Arctic Amplification) is both observed and a robust feature of current GCMs (Serreze & Barry 2011). The ice–albedo feedback clearly governs recent extreme summer sea ice retreat episodes (Perovich et al. 2008) and is often considered the major contributor to Arctic amplification (Screen & Simmonds 2010). But recent work suggests that other processes in winter may be as important in enhancing warming at the poles and sea ice decline. The most important are surface temperature feedbacks arise because colder Arctic surfaces are less efficient at shedding increased heat than surfaces at the warmer lower latitudes (Pithan & Mauritsen 2014). The stable stratification and strong surface inversion in the Arctic atmosphere traps most of the warming near the surface (Bintanja et al. 2011). Thus, sea ice changes that warm the near surface (e.g., Screen & Simmonds 2010) are coupled with this radiative feedback, which tends to reduce winter ice growth and further enhance warming.

Reduced sea ice also promotes increases in clouds and water vapor that increase the downward radiative heating of the surface (Francis & Hunter 2006), but this may be predominantly due not to a local feedback but rather to increasing transport of warm air from lower latitudes into the Arctic (Cao et al. 2017). Moreover, estimates of the relative roles of the magnitudes of these feedbacks vary considerably, and the magnitudes themselves vary considerably among models

ARCTIC AMPLIFICATION

A robust feature of climate models that is consistent with observations is enhanced warming of the Arctic relative to lower latitudes. This warming is most often associated with the ice–albedo feedback in autumn. As the ice cover retreats further in summer, this sea ice loss, subsequent release of heat to the atmosphere from the ocean during autumn freeze-up, and resultant thinner ice cover through the winter and spring warms the atmosphere near the ice surface (Screen & Simmonds 2010). Other important feedbacks that limit radiative cooling of the ice cover, such as increased humidity and cloud cover and a warming lower atmosphere, also contribute to Arctic amplification (for more details, see Serreze & Barry 2011). The term polar amplification has sometimes been used, but in both observations and modern climate models, there is little or no enhanced warming in the Southern Ocean, largely due to effects of ocean circulation and limited summer sea ice cover.

(Bintanja et al. 2011, Goosse et al. 2018, Pithan & Mauritsen 2014), so the impacts on Arctic and Antarctic warming and sea ice trends are uncertain.

The role of these feedbacks in the Antarctic has received less attention, but a recent review suggested that most of them are smaller in the Antarctic (Goosse et al. 2018). Because of the lack of melt ponds on Antarctic sea ice and the limited summer ice extent, the ice–albedo feedback may be somewhat weaker in the Antarctic. More importantly, the lack of strong inversions over Antarctic sea ice limits the surface radiative feedback.

Perhaps the most important factor governing the differing response in the Arctic and Antarctic is the role of ocean heat uptake and ocean circulation. It has long been assumed that the delayed Antarctic warming was due to the ability of the Southern Ocean to act as a sink for ocean heat. This assumption is true to a degree, but it relies on the stored heat being efficiently transported away to prevent sea ice loss and atmospheric warming. Armour et al. (2016) showed that wind-driven upwelling south of the Antarctic Circumpolar Current brings unmodified deep waters to the surface and drives equatorward transport of the warmed surface waters. This means that Antarctic warming will be paced by the rate at which these deeper waters can be warmed and transported from their source in the North Atlantic.

An important difference in the anthropogenic forcing in the Antarctic is the role of ozone depletion. The ozone hole acts to strengthen the SAM, cooling most of coastal Antarctica (Thompson & Solomon 2002). Turner et al. (2009) suggested that this effect would also deepen the ASL and drive sea ice increases. This response is modulated by the ocean, with the initial response of cooling and ice expansion eventually giving way to warming and sea ice decrease as the increased westerlies drive upwelling of warmer water (Ferreira et al. 2015). Thus, in the short term, anthropogenic warming may be countered by the lingering effects of ozone depletion.

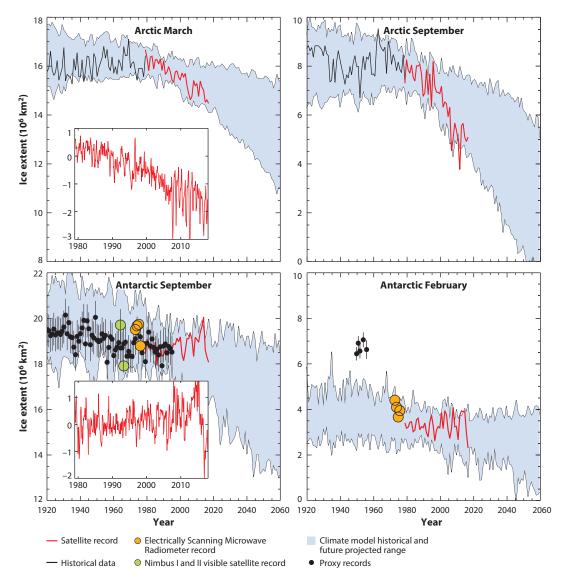
6. HISTORICAL VARIABILITY, TRENDS, AND PROJECTIONS

What are we to make of the observed trends and variability? We now have four decades of consistent observations of the Arctic and Antarctic ice cover, but evidence from models suggests that this time frame may not be long enough to discern a forced trend in Antarctic sea ice (Polvani & Smith 2013).

6.1. The Historical Perspective

Figure 6 places the 1979–2017 satellite observations in a longer-term context with a variety of historical records, along with a range of historical and projected sea ice extents from selected GCM runs from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5 (CMIP5) (Maksym et al. 2012). In the Arctic, Walsh et al. (2017) produced a reconstruction from a variety of ice charts and ship-based observations going back to 1850. Because these data are sparse, particularly prior to the 1950s, the accuracy of the observations for pan-Arctic reconstruction is uncertain, but it is clear that the current trends in ice extent are anomalous over the last century, particularly in summer. September trends are historically low from the 1990s onward, consistent with the emergence of human influence on the Arctic (Min et al. 2008).

In the Antarctic, observations are exceedingly sparse prior to the satellite record. There are some data from other satellites from the 1960s and early 1970s, but prior to the 1960s, various proxies must be used, including whaling records (de la Mare 2009) and glacial ice core proxies for ice extent (e.g., Abram et al. 2010; for a description of the proxy records used in **Figure 6**, see Hobbs et al. 2016). These data suggest that the recent increase in ice extent may be a reversal of



Comparison of modern observed and historical trends and variability of sea ice extent along with selected global climate model (GCM) historical and projected trends from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5 (CMIP5) (Maksym et al. 2012). The red lines show the 1979–2017 satellite record. For the Arctic, the black lines show historical reconstructions (Walsh et al. 2017). The Antarctic historical data are from the Electrically Scanning Microwave Radiometer satellite instrument (*orange circles*, from Cavalieri et al. 2003), Nimbus I and II visible satellite imagery (*green circles*, corrected to September based on the mean annual cycle, from Meier et al. 2013 and Gallaher et al. 2014), and various proxy records (*black dots*, compiled in Hobbs et al. 2016). The Antarctic proxy data are averaged over winter (August, September, and October) and summer (December, January, and February). The black bars show uncertainty in proxy and early Nimbus records; note that uncertainty in the Antarctic proxy records may be larger than indicated (particularly for summer). The blue shaded regions show the range of variability (± 1 standard deviation) from a suite of selected GCMs. The projections are based on Representative Concentration Pathway 8.5 (a high-emissions scenario) and have been bias corrected to match the satellite record for 1979–2002; note that this makes the match appear much better than it is, as many models have large mean biases (compare with Flato et al. 2013, figure 9.24). The two insets show satellite monthly ice extent anomalies for 1979–2017.

a previous decline, an idea that is supported by consistent multidecadal variations in sea ice, sea surface and air temperatures, and zonal winds (Fan et al. 2014). The shift in summer ice extent since the 1950s suggested by the whaling records may be spurious, as direct historical observations from the early 1900s indicate a more modest decline in extent of 14% (Edinburgh & Day 2016), which is within the satellite summer ice extent variability. Regionally, there is ice core proxy evidence for long-term positive trends since the mid-twentieth century in the Ross Sea (Thomas & Abram 2016) and eastern Antarctic (Curran et al. 2003) and for negative trends in the Bellingshausen Sea (Abram et al. 2010).

6.2. Natural and Forced Variability: Can Models Capture These Trends?

Either Arctic sea ice is less sensitive to global warming in models than it is in reality, or there is significant natural variability in sea ice extent that the models do not capture (Stroeve et al. 2012a). Overland & Wang (2013) have used the recent observed steep trends to extrapolate that an ice-free Arctic in summer is likely to occur much sooner (within a decade or two) than models project (Boe et al. 2009). But how much of the discrepancy between recent trends and models is due to inadequate representation of key processes, and how much is due to internal (i.e., natural) variability? Many studies have noted the internal variability in models, which is apparent from the variability seen between individual runs of the same model. For example, Kay et al. (2011) and Stroeve et al. (2012a) suggested that internal variability can explain as much as half of the observed decline, although actually attributing the observed variability to this natural variability is more challenging. The recent dramatic summer ice loss and pause since 2007 (see Figure 6) have since sharpened the question of the role of natural variability. Swart (2015) showed that, while Arctic ice extent has decreased faster than most models predict, both the rapid decline from 2001 to 2007 and the subsequent pause in sea ice decline fall within the envelope of individual model realizations (within both the range of different models and the range of an ensemble of runs from the same model), which suggests that simulated and observed Arctic sea ice trends are not inconsistent. Note, however, that while the decline from 2001 to 2007 could plausibly occur, the probability is quite low in the models (5% or less), so this result does not rule out the possibility that the models are indeed not sensitive enough to anthropogenic forcing.

But is modeled natural variability actually representative of true natural variability, and is natural variability indeed responsible for a significant portion of the observed trend and variability? Ding et al. (2017) showed that changes in atmospheric circulation over the Arctic are strong drivers of September near-surface warming and responsible for up to 60% of Arctic sea ice loss since 1979. They also showed that greenhouse gas forcing drives only a modest amount of the circulation change; hence, they suggested that approximately 40% of the September sea ice decline since 1979 is due to internal variability, which is consistent with prior but unattributed estimates (e.g., Kay et al. 2011, Stroeve et al. 2012a).

The mechanism here is interesting, as it is not low-level circulation driving changes in ice drift (as discussed in Sections 4 and 5) but rather upper-level circulation changes driving increases in near-surface warming, water vapor, and downwelling long-wave radiation, and hence providing thermodynamic forcing of the ice cover. As much as 50% of the circulation changes and warming in the same area is linked to a negative trend in the North Atlantic Oscillation (related to the Arctic Oscillation) that is driven by trends in tropical sea surface temperature. Here we see a commonality with the Antarctic, in that tropical forcing plausibly drives a significant amount of the natural sea ice variability, though causal links remain to be demonstrated.

If internal climate variability plays such a large role in recent Arctic sea ice trends, then this fact would have implications for our ability to predict the future sea ice state. Model variability

suggests that there is a two-decade uncertainty in any prediction of when a mostly ice-free Arctic might occur (Jahn et al. 2016).

The potential concurrence between models and observations does not on its own mean that models simulate the Arctic properly. There is a large intermodal spread in simulated Arctic sea ice extent (Massonnet et al. 2012) and significant model mean biases (Flato et al. 2013). Models also poorly represent the thickness and spatial distribution of sea ice (Stroeve et al. 2014a), largely because of their poor representation of the atmospheric circulation that drives sea ice motion and hence thickness distribution. This poor representation is generally due to a displaced Beaufort High and inability to capture the Transpolar Drift Stream (Kwok 2011), but even models that do simulate thickness distribution well do not necessarily capture these features (Stroeve et al. 2014a). Models also do not capture the observed acceleration of sea ice drift (Rampal et al. 2011). All of these issues raise concerns about the ability of climate models to realistically simulate Arctic sea ice decline.

The fact that internal variability is a significant contributor to sea ice decline does not diminish the central role of anthropogenic forcing in the disappearance of Arctic sea ice—there is widespread evidence for the role of greenhouse gases in this respect (Flato et al. 2013, Notz & Marotzke 2012). Min et al. (2008) showed that the human impact on Arctic sea ice emerged in the early 1990s. Historical evidence suggests that the decline of ice has been greater since the 1990s than at any time in the historical record (i.e., since the mid-nineteenth century) (**Figure 6**). Other paleoclimate evidence suggests that the current Arctic warming (Kaufman et al. 2009) and sea ice decline (Kinnard et al. 2011) may be greater than at any time in the past millennium. Notz & Stroeve (2016) showed that Arctic sea ice area is strongly correlated with cumulative anthropogenic CO_2 emissions and suggested that models underestimate the sea ice response to CO_2 emissions.

Climate models predict a much more muted response in the Antarctic (Figure 6), with an approximately 30% decline in ice extent by the end of the century (Arzel et al. 2006, Bracegirdle et al. 2008), which is consistent with the reduced warming in the Antarctic. Ice volume is projected to decrease at a similar rate to ice extent, in contrast to the rapid thinning predicted (and observed) in the Arctic (Arzel et al. 2006), which is expected because thicker ice thins more in response to a warming perturbation than thin ice (Bitz & Roe 2004).

The seasonal response in the Antarctic is notably the reverse of that in the Arctic. Models predict the greatest decline in winter and little to no decline in summer (**Figure 6**). These different declines may be due partly to the geographic constraints imposed by the Antarctic continent on the ice cover (Eisenman et al. 2011), but summer sea ice extent is poorly represented in most models (Turner et al. 2013).

Overall, models do not capture key features of the Antarctic ice cover. Large biases in ice extent occur in many models, and the interannual variability in models is much larger than the observed variability (Maksym et al. 2012, Zunz et al. 2013). Models also do not capture the observed increase in ice extent (Maksym et al. 2012, Turner et al. 2013, Zunz et al. 2013) (**Figure 6**). Several studies have, however, shown that the observed trends are within the range of natural variability in the models (Polvani & Smith 2013). However, the negative trend in sea ice extent in most models over the modern period is a continuation of a decline originating from the mid-nineteenth century (Turner et al. 2013) (**Figure 6**), suggesting that the models cannot adequately capture the processes driving sea ice extent over the past four decades. Notably, models do not adequately capture the ASL, a major driver of Antarctic sea ice variability (Hosking et al. 2013).

As shown by the discussion in Section 3, the real story of Antarctic change is not the small circumpolar trend but the much larger, contrasting regional trends. Examining regional trends, Hobbs et al. (2016) showed that the observed trends fall within the model spread, with the exception

of the western Ross Sea and the Bellingshausen Sea in summer and autumn—which, notably, are two of the regions of greatest change (**Figure 6**). Clearly, understanding the role of natural variability is key to improving model predictions of Antarctic sea ice.

6.3. Recent Variability: Is Further Change Imminent?

In the last few years, variability has increased in both hemispheres (insets in **Figure 6**). Extreme summer anomalies have occurred for several years in the Arctic, and extreme anomalies in winter temperatures that affected ice extent and thickness occurred during the winters of 2014–2015 and 2016–2017 due to increased intrusions of cyclones (Graham et al. 2017). These anomalies culminated in the extreme warm autumn and record-low winter ice extent anomalies in 2016 (Simpkins 2017), raising the question of whether human-induced change and reduced sea ice cover are now contributing to a greater frequency of warm, moist air intrusions that will accelerate the pace of Arctic change, particularly in winter.

In the Antarctic, recent variability has been even more dramatic. Three consecutive record highs in sea ice extent occurred from 2012 to 2014, but with different causes driving each (Reid & Massom 2015). These record highs were followed in 2016–2017 by a record-low anomaly in spring that rivaled those seen recently in the Arctic summer. As discussed in Section 2, these recent negative anomalies in ice extent have been so large that the previously reported increasing trends are mostly no longer statistically significant except in autumn. Stuecker et al. (2017) attributed this record low to two unusual events: a strong El Niño in summer that drove sea surface temperature anomalies, and a subsequent anomalously low SAM index that drove anomalous warming in November–December 2016. These recent events highlight the important role of both natural variability and climate feedbacks in driving future sea ice changes.

7. CONTRASTS AND COMMONALITIES

The changes in sea ice between the Arctic and Antarctic are a study in contrast: The Arctic has experienced dramatic and consistent losses of ice extent, thickness, and volume over the past several decades, while in the Antarctic the picture is one of regional and temporal variability. But this contrast can plausibly be attributed to an expected response due to both (*a*) the differing role of various processes that are ultimately controlled by contrasts in geography and (*b*) the differing role of key processes that drive an amplified response to anthropogenic forcing in the Arctic and a more muted response overall in the Antarctic. But despite a growing understanding of how both forced and natural variability is driving changes in both regions, current climate models cannot robustly capture these changes, limiting our ability to project future changes on decadal timescales.

Given the contrasting changes in sea ice in the north and south, are there connections and commonalities between the two? First, we have seen the important impact that modes of natural variability have on the ice cover at both poles. There is emerging evidence that ice extent in the Arctic, as has been well established for the Antarctic, is governed partially by natural variability that may originate from the tropics. Although this variability manifests differently at each pole due to differences in geography, evidence is emerging that wind-driven variability and ocean feedbacks such as the ice–albedo feedback act in concert to drive sea ice trends. Moreover, as the Arctic ice cover continues to shrink and thicker, multiyear ice continues to disappear, the Arctic is becoming more like the Antarctic. In 2012, for instance, the summer minimum extent in the Arctic matched that in the Antarctic for the first time. The thinner Arctic ice is more dynamic, with more fractures and changes in the role of deformation, increasing the fluxes of heat and moisture from the ocean. As open water fetch increases, the impact of waves and storms on the ice cover

will become more important, and changes in ocean heat (through both insolation and increased intrusion of subarctic waters into the Arctic Ocean) may enhance the ocean heat supplied to the base of the ice. Furthermore, increased poleward heat and moisture transport in the Arctic may strengthen linkages to lower-latitude modes of variability.

Despite an emerging understanding of the observed changes in the sea ice cover over the past four decades, it is clear that the response of the ice to both forced and natural variability is governed by complex interactions and feedbacks among the atmosphere, ocean, and ice. Our ability to predict future changes in sea ice rests on improved understanding of the role of these interactions and feedbacks, particularly the role of natural variability. Many of these processes, such as ice–ocean interactions and feedbacks, are poorly observed. Improved understanding will require a sustained network of both satellite and in situ observations of these interactions as the ice cover continues to change.

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The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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