The Antarctic Slope Current in a Changing Climate

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Abstract.

The Antarctic Slope Current (ASC) is a coherent circulation feature that rings the Antarctic continental shelf and regulates the flow of water towards the Antarctic coastline. The structure and variability of the ASC influences key processes near the Antarctic coastline that have global implications, such as the melting of Antarctic ice shelves and water mass formation that determines the strength of the global overturning circulation. Recent theoretical, modeling, and observational advances have revealed new dynamical properties of the ASC, making it timely to review. Earlier reviews of the ASC focused largely on local classifications of water properties of the ASC's primary front. Here, we instead provide a classification of the current's frontal structure based on the dynamical mechanisms that govern both the along-slope and cross-slope circulation; these two modes of circulation are strongly coupled, similar to the Antarctic Circumpolar Current. Highly variable motions, such as dense overflows, tides, and eddies are shown to be critical components of cross-slope and cross-shelf exchange, but understanding of how the distribution and intensity of these processes will evolve in a changing climate remains poor due to observational and modeling limitations. Results linking the ASC to larger modes of climate variability, such as El Niño, show that the ASC is an integral part of global climate. An improved dynamical understanding of the ASC is still needed to accurately model and predict future Antarctic sea ice extent, the stability of the Antarctic ice sheets, and the Southern Ocean's contribution to the global carbon cycle.

Keypoints:

- Dynamical properties of the Antarctic Slope Current (ASC) that impact heat transport are reviewed.
- A geographical classification of the ASC's frontal structure is presented.
- The potential for feedbacks between the ASC circulation and larger-scale climate is summarized.

1. Introduction

Ocean heat transport and other oceanic processes occurring along the Antarctic coastline are vital to Earth's climate. By influencing the oceanic flow towards the Antarctic continent, the Antarctic Slope Current (ASC), a coherent westward circulation and frontal feature that encircles the Antarctic continental shelf, is the linkage between these processes and the rest of the global ocean [*Jacobs*, 1991] (Fig. 1). The intensity and variability of the ASC controls the rate at which heat moves across the continental slope and on to the continental shelf. Eventually, the circulation over the continental shelf brings this warm water into contact with marine-terminating glaciers of the Antarctic Ice Sheet (AIS). The ASC is a unique feature that responds not only to local changes, for example the surface wind stress [*Gill*, 1973; *Stewart and Thompson*, 2015a], but also to larger-scale modes of climate variability, such as El Niño and the Southern Annular Mode [*Dutrieux et al.*, 2014; *Spence et al.*, 2014a; *Nakayama et al.*, 2018]. Shifts in the intensity or position of ASC fronts, or changes to the range of densities that occupy the continental shelf, will therefore exert a strong influence over the heat budget of the Antarctic margins.

Increases in the heat content of Antarctic shelf waters [*Schmidtko et al.*, 2014; *Heywood et al.*, 2014] have contributed to changes in the AIS, especially in West Antarctica. One of the most dramatic signals has been a large-scale thinning of floating Antarctic ice shelves over most of the West Antarctic Ice Sheet (WAIS) [*Cook and Vaughan*, 2010; *Paolo et al.*, 2015]. Most of the ice shelf thinning has been attributed to melting from below due to the circulation of warm ocean water coming into contact with the floating ice shelves [*Pritchard et al.*, 2012]. This thinning has been implicated in the observed retreat of the grounding line of certain WAIS glaciers [*Rignot et al.*, 2014] as well as the acceleration of ice sheet flow of WAIS glaciers [*Joughin et al.*, 2002]. Enhanced basal melt rates due to warm ocean waters have also been observed in regions of East Antarctica, for example at Totten Glacier [*Rintoul et al.*, 2016]. Melting by the ocean has contributed to an acceleration in the rate of ice loss of the WAIS; the rate of loss between 2012 and 2017, 159 ± 26 billion tonnes per year, was more than three times the rates estimated in 1990's [*IMBIE team*, 2018].

These changes motivate the need for continued observations and improved mechanistic understanding of physical processes that control the flow of heat across the ASC and towards the AIS. Quantifying how the ASC has changed over time, and how it might evolve in the future, is a challenging goal as waters responsible for the thinning of Antarctic ice shelves reside below the surface. This review seeks to provide an updated perspective on the spatial and temporal variability of the ASC and its place in the larger climate system; we also highlight key areas for future research.

1.1. ASC characteristics

The ASC is one of the ocean's most extensive and coherent current systems (Fig. 2), sustaining along-slope velocities of 10-30 cm s^{-1} over a span of 21,000 km on Antarctica's upper continental slope. Yet it remains remarkably understudied compared to other major oceanic circulation features, such as western boundary currents, or the Southern Ocean's Antarctic Circumpolar Current (ACC). The ASC is a complex, turbulent feature and similar to other major frontal currents, its effectiveness as a barrier to transport is variable in both space and time [see Fig. 1 and *Bower et al.*, 1985]. In some areas of the Antarctic continental shelf, a shallow current flows to the west, poleward of the continental shelf break. This feature, known as the Antarctic Coastal Current, often follows the edge of ice shelves, for example in the southern Weddell Sea [*Nicholls et al.*, 2009], or close to the coast, for example in the West Antarctic Peninsula (WAP) [*Moffat and Meredith*, 2018]. For succinctness, this review will focus only on the ASC.

Around Antarctica, the strongest gradients in water mass properties typically occur between shelf waters and the relatively warm and salty water that comprises Circumpolar Deep Water (CDW) [*Jacobs*, 1991; *Baines and Condie*, 1998; *Whitworth et al.*, 1998]; this gradient is the Antarctic Slope Front (ASF). In this article, we will at times refer to both the ASC and the ASF, however, in general, reference to the ASC implies the coupled circulation and frontal system. The properties of CDW are largely determined by processes occurring in ocean basins north of the Southern Ocean. The warm CDW then rises along density surfaces as it crosses the ACC and circulates through the sub-polar gyres of the Southern Ocean until it eventually sits at depths comparable to the sea floor of the continental shelf. The depth of the continental shelf is roughly 500 m around much of Antarctica, although deeper troughs play a key role in shelf-slope exchange. In addition to gradients in temperature and salinity, the ASF may also support cross-slope gradients in density. These gradients are physically realized as density surfaces that tilt away from horizontal. The geometry of these surfaces, or isopycnals, influences which density classes have access to, or "ventilate," the shelf, and which density classes intersect, or "incrop," on the seafloor [*Meredith et al.*, 2011; *Dutrieux et al.*, 2014] (§2). A density class refers to waters within a range of densities, which typically have similar thermodynamic/chemical properties and are subject to similar physical processes. Isopycnal tilting is typically largest at the shelf break, where it also has the capacity for rapid change [*Su et al.*, 2014].

Lateral density gradients are also associated with geostrophically-balanced, vertically-sheared along slope flows, such that the density field influences the vertical structure of the ASC's along-slope flow (§3). Finally, lateral density gradients may be a source of potential energy that impacts the generation and intensity of ocean eddies, which in turn influence the transport of heat, freshwater, and other tracers [*Moffat et al.*, 2009; *Nøst et al.*, 2011; *Stewart and Thompson*, 2016].

Poleward of the ASC, the continental shelf hosts unique water formation processes related to sea ice formation, extreme air-sea fluxes of heat and freshwater, and ocean interactions with floating ice shelves [*Orsi et al.*, 1999; *Nicholls et al.*, 2009]. Sustained formation of shelf waters requires both an export of newly formed water across the shelf break and the delivery of offshore water to replace it. This implies a circulation that traverses the continental slope and shelf break, encountering steep bathymetry and strong gradients in water properties [*Whitworth et al.*, 1998]. In certain locations, the ASC accommodates both on-shore and off-shore exchange, but elsewhere only one of these two exchanges may be active (Fig. 1). This implies equally important roles for the along-slope and cross-slope circulations of the ASC. The former contributes to the establishment of strong gradients at the shelf break and is key for delivering water to and from deep water formation sites on the shelf. The cross-slope circulation is associated with a volume transport that is roughly an order of magnitude smaller than the along-slope flow of the ASC, but it remains crucial for setting shelf properties [*Heywood et al.*, 2014]. Physical processes that enable this cross-slope exchange are a major focus of this review (§3).

The ASC is a changeable feature as it navigates the margins of Antarctica. Often, the ASC exhibits characteristics that are common to shelf-break currents found throughout the global ocean [*Allen*, 1980]. These slope currents typically arise from a surface wind stress aligned parallel to the coast and act as barriers to mixing between shelf and open-ocean waters. The formation of the ASC through this mechanism relies on physical processes localized at the shelf break, and was central to *Gill* [1973]'s early description of the ASF in the Weddell Sea (§2). Additionally, the ASC interfaces with the larger-scale circulation features of the Ross and Weddell Seas (Fig. 2). Here, cyclonic gyres arise from a combination of surface buoyancy forcing, a negative wind stress curl, and confinement by major bathymetric ridges and fracture zones to the north and by the Antarctic continent to the south [*Gordon et al.*, 1981]. Following Sverdrup dynamics that govern low-latitude subtropical gyres, the surface forcing is expected to give rise to a large-scale poleward transport that delivers water towards the continental slope [*Vallis*, 2006]. These waters are then entrained into the ASC, where they can be returned to the northern part of the gyre in narrow and frictionally-balanced boundary currents. Thus, the ASC may also exhibit characteristics similar to western boundary current systems, and it can be an important mediator of oceanic and atmospheric changes over much broader spatial scales [*Nakayama et al.*, 2018].

A comparison can also be drawn between the westward ASC and the eastward ACC. Over the past few decades, appreciation of the ACC's meridional eddy transport has grown because this circumpolar circulation feature cannot support a mean meridional flow in the upper ocean (*e.g.* above the sill depth of the ACC) [*Marshall and Speer*, 2012]. While the ASC is not a true circumpolar circulation feature—it is disrupted by the Antarctic Peninsula between the Pacific and Atlantic sectors of the Southern Ocean (Fig. 2)—it has been questioned whether large-scale pressure gradients along the path of the ASC can sustain the exchange of heat and other tracers across the shelf break [*Stewart and Thompson*, 2013]. Alternatively, the cross-slope transfer of mass and tracers may be accomplished through eddy transports [*Dinniman and Klinck*, 2004; *Nøst et al.*, 2011; *Stewart and Thompson*, 2013; *Thompson et al.*, 2014], which are described in detail below. Also similar to the ACC, the ASC's zonal and meridional circulations are coupled through a system of multiple coherent, but variable, along-slope jets (quasi-zonal jets in the case of the ACC) [*Stern and Nadeau*, 2015; *Stewart and Thompson*, 2016]. Longitudinal variations in bathymetry or in surface forcing, which are key to setting the dynamical structure of the ACC [*Rintoul*, 2018], can also give rise to spatial anomalies in the intensity of the eddy field and the effectiveness of cross-slope eddy exchange [*Stewart et al.*, 2018].

Finally, both observational and numerical studies have confirmed that the Antarctic margins support a vigorous eddy field that makes significant contributions to heat and volume transports [*Nøst et al.*, 2011; *St-Laurent et al.*, 2013; *Thompson et al.*, 2014; *Stewart and Thompson*, 2015a; *Stewart et al.*, 2018]. While "eddies" are often associated with mesoscale eddies, apparent as coherent vortices in satellite images or model output, an eddy flux can, in general, arise from correlations (between velocity and another property, such as temperature) across a range of temporal and spatial scales. In addition to the mesoscale, variability due to surface forcing, coastally-trapped waves and tides all contribute to velocity and transport variations that influence shelf-slope exchange. In §3 we on the processes that shape the distribution of eddy variability at the Antarctic margins as well as their impact on transport properties. In §4, we hope to motivate future work that improves our understanding of how this eddy transport may evolve in a changing climate.

1.2. Motivation

The ASC plays a critical, if under-appreciated, role in Earth's climate system. While the primary focus of this review is on ASC dynamics, we conclude, in §4.3, with a summary of the ASC's impact on the large-scale ocean circulation, on the stability of Antarctic ice sheets, and on the global carbon cycle. This section can be read independently of the more detailed, dynamical parts of this review.

Advances in describing the circulation at the Antarctic margins have been slow, in part because of challenges in acquiring observations in this harsh environment. Strong winds, sea ice and icebergs frequently prevent access, and most ship-based measurements occur by necessity at the height of summer. In many years and in many Antarctic shelf or slope regions, there are no measurements at all [*Schmidtko et al.*, 2014]. Furthermore, processes at the Antarctic continental slope are particularly challenging to observe. Moorings are difficult to place precisely on a steep slope. Their uppermost instruments have to lie below the likely keel depth of icebergs (often 400-500 m). The Rossby radius, which determines the mesoscale eddy scale, is only a few km on the Antarctic continental shelves, and submesoscale processes occur on an even smaller scale [*Heywood et al.*, 2014]. The ASC varies on time scales of hours (due to internal waves and tides) to years (due to atmospheric forcing variability and climate modes such as the Southern Annular Mode). Numerical modeling of the ASC and the Antarctic margins is also challenging [*Dinniman et al.*, 2016]. While regional or idealized models may have sufficient resolution to resolve important dynamical features, they are unable to incorporate larger-scale forcing. Climate models and forced ocean models have, until recently, been too coarse to represent the steep topography of the Antarctic slope, and therefore were unable to adequately represent the ASC. These models also struggle to represent ocean properties on the continental shelf [*Heuzé et al.*, 2013], and are unable to export dense water to the abyss.

Yet, a combination of intensive numerical modeling studies and new observations have led to progress in our mechanistic understanding of the ASC system. On the modeling side, the ability to carry out higher-resolution simulations, along with more realistic bathymetry, has increased appreciation of the important role of mesoscale variability over the Antarctic continental shelf and slope [*Dinniman et al.*, 2016]. Increased observational coverage of the ASC system, including novel observational techniques using autonomous vehicles and instrumented seals, have enhanced the spatial and temporal scales at which the ASC has been measured, helped to evaluate model results, and guided process-based studies. These new observations build upon, but greatly enhance, the concerted multinational effort expended in the Synoptic Antarctic Shelf Slope Interaction (SASSI) program as part of the International Polar Year in 2008-2011 [*Heywood et al.*, 2012].

We now proceed to a more in-depth review of the dynamical structure of the ASC. A descriptive overview of the ASF appears in §2, summarizing the key features that impact the circulation structure of the ASC. In §3, we summarize the current understanding of the ASC's dynamical properties. Throughout, a major goal is to better understand the ways by which the ASC may respond to modifications in surface forcing and other aspects of the ocean's circulation. We address the ASC's role in the climate in §4.

2. Structure and regional variations of the ASC

The ASC and ASF system is a coupled circulation and frontal feature whose structure and strength varies along its path. *Whitworth et al.* [1998] provided a comprehensive review of the ASF using a large amount of historical hydrographic data, focusing in particular on nine cross-slope transects that covered different regions of the Antarctic margins. This earlier review largely detailed water mass properties, and while we comment on some of these properties below, our goal is not to repeat this exercise. Instead, we introduce three different classifications of the ASC, illustrated in Fig 3, that help to identify the dynamical processes that influence both the ASC's local variability and its cross-slope transport. These classifications will serve as a framework for the discussion of dynamics in §3. Of course, over the past two decades, measurements have been acquired in new locations, and, in certain cases, at finer horizontal scales ($\sim$1 km). Where appropriate, we have used these new data (Fig. 4), and we reference the appropriate studies below. These ASC classifications are determined by hydrographic properties over the continental shelf and at the shelf break as described below. The three cases are: (i) Fresh Shelf, (ii) Dense Shelf, and (iii) Warm Shelf.

The ASC is typically tied to a strong, subsurface lateral gradient in temperature (warmer offshore), forming at or close to the shelf break. The temperature difference changes regionally around Antarctica, taking values between 1°C and 3°C (Fig. 3). Salinity gradients are also established between the relatively salty water in the CDW layer and the fresher water over the continental shelf. Lateral gradients in temperature (Θ) and salinity (S) can combine to produce lateral gradients in density as well. However, $\Theta - S$ gradients may also compensate, so that lateral density gradients are weak. These distinct situations are important because the turbulent transport of tracers, e.g. Θ and S, may arise from two separate processes. First, eddies may stir fluid along a density surface. If the density surface has a large-scale gradient in temperature (compensated by a salinity gradient), the stirring will tend to homogenize the temperature field, or equivalently, produce a down-gradient eddy heat flux [*Redi*, 1982]. Alternatively, lateral gradients in the thickness of a given density class may also be eroded by eddy fluxes. Correlations between fluctuations in velocity and layer thickness within a density class give rise to an eddy, or "bolus", velocity that will advect large-scale tracer distributions [*Gent and McWilliams*, 1990; *Young*, 2012], and is another source of eddy tracer fluxes.

Shelf water properties exert a strong influence over the strength and vertical structure of the ASF and the ASC. Surface temperatures and salinities are not typically a good indicator of the position of the ASF and are more likely to reflect local processes related to sea ice formation and melt or wind-driven upwelling. Warm subsurface waters reside in the CDW density layer that spans roughly $\gamma^n = 28.0 - 28.2$ kg m^{-3} (this range varies regionally, *e.g.* Fig. 3); here, γ^n is neutral density [*Jackett and McDougall*, 1997]. We use this density layer as the main diagnostic for classifying the ASC. The frontal structure of the ASC is strongest in the Fresh Shelf case; processes that establish this deep front (§2.1) also limit access of warm sub-surface waters onto the shelf. We define Fresh Shelf regions where neutral density layers $\gamma^n > 28.0$ kg m^{-3} do not extend on to the shelf. The Dense Shelf regime is associated with those regions where there is water denser than $\gamma^n = 28.0$ kg m^{-3} on the continental shelf, but the shelf stays relatively cold due to the presence of convection and dense water formation. In Warm Shelf regions, waters with densities greater than $\gamma^n = 28.0$ kg m^{-3} have access to the shelf, but in the absence of dense water formation, the shelf is warm. We take shelf waters that exceed 0.5°C, at any depth, as the defining criterion for Warm Shelf regions.

2.1. Fresh shelf

Over large parts of East Antarctica, as well as in the western Amundsen/eastern Ross Seas, persistent and strong easterly winds are located over the continental shelf (see §2.5). This gives rise to an onshore Ekman transport, a positive sea surface height (SSH) anomaly over the continental shelf, and a westward flowing ASC. Cold shelf waters, weak cross-slope exchange due to a strong ASC, and a converging surface Ekman transport that produces downwelling velocities, all combine to establish a strong front separating cold and fresh shelf water from warm and salty CDW offshore. In this Fresh Shelf regime, density surfaces are largely aligned with isotherms. Therefore, along-isopycnal gradients of temperature and salinity are weaker in these regions as compared to other ASC cases. On the other hand, the strong frontal structure can give rise to intense lateral density gradients near the shelf break (Fig. 3a,d).

Fresh Shelf fronts are characterized by density surfaces that tilt downward and poleward from the surface towards the continental slope [*Orsi and Whitworth*, 2005; *Chavanne et al.*, 2010; *Dong et al.*, 2016; *Peña-Molino et al.*, 2016]. This downward tilting of density surfaces also occurs in the Ross and Weddell Sea sectors due to the large-scale wind forcing. Here, a negative wind stress curl integrated over the subpolar gyre, produces a minimum in SSH at the gyre's center [*Armitage et al.*, 2018]. Interior density surfaces tend to compensate these SSH variations, which causes the pycnocline to tilt down toward the margins of the gyres [*Schmidtko et al.*, 2014]. In Fresh Shelf cases, the tilt of these density surfaces is sufficiently strong that they intersect, or "incrop," on the continental slope (Fig. 3d). This removes a pathway for the direct transport of warm waters onto the continental shelf within the CDW density class (Fig. 3a). Instead, water must move across density surfaces, which requires mixing that modifies the properties of the CDW. Alternatively, variability in the ASC may intermittently allow CDW layers to ventilate the shelf, even if the time-averaged structure of the CDW density class incrops on the seafloor. This intermittency may occur across a range of temporal scales, including periods as short as a tidal cycle, as discussed in §3.

The Fresh Shelf region is also associated with SSH gradients that increase towards the coast, resulting in westward near-surface flows. However, the shape of the interior density front gives rise to a vertically-sheared geostrophic flow that results in the ASC becoming weaker with depth and potentially reversing back to the east. This eastward undercurrent, located on the continental slope, was first revealed by a series of closely-spaced, ship-based measurements during WOCE in 1995 [*Heywood et al.*, 1998], and later studied in further hydrographic sections [*Chavanne et al.*, 2010]. The former survey also provided the first observed transit of glacial meltwater across the ASF, linked to the undercurrent (see also §2.4).

2.2. Dense shelf

Dense shelf water forms in localized sites around the Antarctic margins [*Baines and Condie*, 1998]: the western Ross Sea [*Gordon et al.*, 2004], the Weddell Sea [*Nicholls et al.*, 2009], the Adélie coast [*Rintoul*, 1985; *Williams et al.*, 2010], and Cape Darnley [*Ohshima et al.*, 2013]. Downstream of these formation regions (indicated by purple lines in Fig. 4c), dense shelf water (DSW) flows across the continental shelf break, which has a significant impact on the ASC and ASF. Most notably, these regions tend to be associated with a distinctive "V"-shaped frontal structure that accommodates both an on-shore transport of CDW and the export of DSW. The V-shaped front focuses cold and relatively fresh surface waters, such that, in these regions, a minimum in surface salinity can be a good indicator of the primary front of the ASC. The surface flow within the "V" also provides an efficient conduit for the export of icebergs from the western Weddell Sea [*Gladstone et al.*, 2001].

While the "V" has been discussed extensively in the literature, *e.g.* [*Gill*, 1973; *Whitworth et al.*, 1998; *Thompson and Heywood*, 2008], the implications of the front's lateral and vertical stratification on turbulent cross-shelf exchange have only been highlighted more recently. Similar to the Fresh Shelf case, warm CDW tilts down towards the seafloor over most of the continental slope. However, as the CDW approaches the shelf break in the Dense Shelf case, it shoals again (Fig. 3b,e). This shoaling at the shelf break enables fresher but colder and heavier DSW to be carried across the shelf break in a dense outflow layer [*Gill*, 1973; *Baines and Condie*, 1998; *Ou*, 2007]. In the interior of the water column, the V-shaped structure enables a relatively large range of densities to have access to the continental shelf without intersecting frictional layers at the ocean surface or at the seafloor over the continental slope. This access to the shelf is further linked to an extreme vertical thinning of the density classes hosting warm CDW. This establishes both strong lateral density and isopycnal potential vorticity gradients within this layer. It has been proposed that mesoscale turbulence will work to reduce these gradients, consistent with an on-shore eddy flux (or bolus transport) of heat [*Thompson et al.*, 2014], §3.3. Finally, near the seafloor, the export of dense water enhances the vertical stratification between exported DSW and overlying Deep Water (Weddell Sea Deep Water, WSDW, for example). This secondary deep pycnocline strongly influences the generation, intensity and structure of mesoscale turbulence over the continental slope [*Stewart and Thompson*, 2016].

The physical processes that occur at the base of the "V" are critical to water mass modification and to setting the properties of AABW. Here there is less consensus about the leading order dynamics. *Gill* [1973] emphasized diabatic processes that implied a mixing of offshore and shelf waters leading to a modified form of Deep Water forming in the Weddell Gyre (WSDW). A complementary view suggested that turbulent entrainment into deep outflows flowing down the slope sets the frontal structure at the shelf break [*Baines*, 2009]. Direct observations needed to quantify the rate of mixing at the shelf break in these regions, e.g. microstructure measurements, have been limited [*Hirano et al.*, 2015]; the weak vertical stratification makes other finescale methods, e.g. Thorpe scales [*Thorpe*, 1977], difficult to apply.

In these Dense Shelf cases, it was noted in early work that compensated temperature and salinity anomalies are commonly found at the ASF. This strong thermohaline interleaving led *Foster and Carmack* [1976] to suggest that double diffusion and salt-fingering could enhance mixing at the ASF. However, high resolution hydrographic sections [*Thompson and Heywood*, 2008] also suggest a strong role for these tracer anomalies arising from along-isopycnal stirring, consistent with increased evidence of an active mesoscale eddy field over the continental shelf and slope (see §3). Considering the strong temperature and salinity gradients along density surfaces around much of Antarctica, cabbeling may also be relevant for understanding the regional density structure [*Groeskamp et al.*, 2016], although this mechanism has received less attention at the shelf break.

2.3. Warm shelf

As discussed in §1.1, the ASC is not a circumpolar feature. The Antarctic Peninsula extends northward into latitudes that are occupied by the core of the ACC over most of the Southern Ocean. Thus, along the WAP the southernmost fronts of the ACC flow towards the continental slope and turn to the north and east, a direction that is in opposition to the ASC's westward flow elsewhere around Antarctica (Fig. 2). On the eastern side of the Antarctic Peninsula, the ASC is found throughout the Weddell Scotia Confluence (Fresh Shelf regime in Fig. 4), and a westward boundary current is found along the continental slope in the southern Scotia Sea [*Palmer et al.*, 2012; *Flexas et al.*, 2015]. However, the ASC is not obviously connected to the WAP through this route. Wave mechanisms that may allow for the propagation of signals around the Peninsula are discussed in §4. A strong westward-flowing ASC is weak or absent over most of the WAP and West Antarctica. Indeed, the strongest frontal currents along most of the WAP continental shelf are eastward, rather than westward. *Moffat and Meredith* [2018] provide a recent review of the unique cross-slope exchange processes occurring on the WAP.

In addition to the proximity of the ACC to the Antarctic margins, other properties of West Antarctica conspire to produce a weak frontal structure here. Coastal atmospheric wind patterns, most notably the Amundsen Sea Low and the Bellingshausen Sea Low, impart a weaker and more variable surface wind forcing, as compared to East Antarctica or the Weddell Sea [*Turner et al.*, 2013]. This removes a key mechanism for forming a persistent frontal jet at the shelf break. Furthermore, dense water formation does not occur on the shelf in West Antarctica, which removes another mechanism for generating strong density gradients at the shelf break. Finally, this region largely resides outside of the major gyres, where density surfaces tilt down towards the coast. Instead, along the WAP and Bellingshausen Sea, the mean depth of the subsurface temperature maximum associated with CDW shoals moving poleward from the open ocean to the continental shelf [*Schmidtko et al.*, 2014]. Moreover, *Schmidtko et al.* [2014] found that over the past two decades the depth of this warm layer off West Antarctica shoaled at a rate of several meters per year.

Thus along the WAP and parts of West Antarctica, warm CDW has nearly uninhibited access to the shelf [*Jenkins and Jacobs*, 2008]. These regions are characterized by the seafloor of the continental shelf being bathed in waters with temperatures exceeding 0°C (Fig. 4), 2–3 degrees warmer than the freezing temperature at the base of floating ice shelves. Warm Shelf regions are also the sites where Antarctic ice shelves are thinning rapidly [*Pritchard et al.*, 2012] (see §4). Despite warmer waters on the shelf, lateral gradients in both temperature and salinity are still enhanced at the shelf break, indicating that a key role remains for eddy variability on cross-slope exchange. Finally, the Warm Shelf case is of dynamical interest because over this region the eastward-moving flow along the WAP transitions to a westward-moving flow associated with the southern boundary of the Ross Gyre (Fig. 2). The location, variability and physical processes associated with the initiation of the westward flow, traditionally linked to the ASC, in the Bellingshausen and Amundsen sector remains an open question, and may be influenced by non-local processes that determine the spatial extent of the Ross Gyre and the intensity of its southern boundary [*Armitage et al.*, 2018; *Dotto et al.*, 2018; *Nakayama et al.*, 2018].

2.4. Jet structure

While the primary along-slope flow of the ASC tends to reside near the shelf break, there is now substantial modeling and observational evidence that the ASC system is composed of multiple, unsteady jets, separated by a distance as small as a few tens of kilometers, that drift coherently across the continental slope [*Stern and Nadeau*, 2015; *Peña-Molino et al.*, 2016; *Azaneu et al.*, 2017]. This jet spacing was found in numerical experiments by *Stern and Nadeau* [2015], who simulated the flow of an eastward zonal current over a continental slope with the shelf to the south, a configuration consistent with the WAP. In these simulations, the main jet drifted off-shore and was periodically replaced by a new feature at the shelf break. *Stewart and Thompson* [2016], using a configuration consistent with the northwestern Weddell Sea, further showed that drifting jets significantly modulated the distribution of eddy momentum and buoyancy fluxes over the continental shelf on the timescale of months. *Peña-Molino et al.* [2016] used a long time series from a mooring array in East Antarctica (113°E) and inferred a persistent drift of coherent jets across the continental slope. This jet drift was found to impact the meridional extent of the ASC system as well as the zonal transport carried by the ASC (see also §4.1)

The main velocity cores, or jets, of the ASC tend to have an equivalent barotropic structure: there is some vertical variation in the intensity of the flow, but the jets remain unidirectional. However, this velocity structure is not representative of the continental slope as a whole. *Thompson and Heywood* [2008] collected a high-resolution velocity section, referenced to lowered ADCP data, in the northwestern Weddell Sea and found that immediately offshore of the primary shelf break front a second narrow frontal region exhibited a strong baroclinic character with a southward flow (opposite to the ASC) in the upper part of the water column and a northward near the bottom. An eastward undercurrent is also a feature that is commonly observed in Fresh Shelf regions around Antarctica [*Heywood et al.*, 1998; *Chavanne et al.*, 2010]. The undercurrent is believed to play an important role in bringing warm water onto the continental shelf, largely through up-slope bottom Ekman transport, particularly in the Amundsen Sea sector [*Walker et al.*, 2013]. Further studies of this feature, absent in models, are vital, particularly for its potential impact on heat and freshwater fluxes.

2.5. External forcing of the ASC

Regional variations in the structure of the ASC arise from a combination of surface forcing, e.g. fluxes of momentum and buoyancy, and local environmental characteristics. *Stewart and Thompson* [2015a] showed that a large part of the longitudinal variations in the structure of the ASF can be attributed to the strength of the along-slope component of the surface wind stress. The zonal winds around Antarctica are predominantly easterly (Fig. 5b) with a tendency for the wind stress curl to induce downwelling velocities (Ekman pumping) over the continental slope. The mean wind speed, at the Antarctic margins, along most of East Antarctica is nearly 10 m s^{-1}, while over West Antarctica the wind speed is weaker and more variable; this is consistent with a stronger frontal structure occurring throughout East Antarctica. Shifts in the center of the Bellingshausen and Amundsen Sea low pressure systems can significantly change the surface forcing, including a reversal in its orientation. Note that the wind speed is plotted in Fig 5b, rather than the surface wind stress; the latter governs the magnitude and orientation of the surface Ekman transport. The wind speeds here are obtained from reanalysis products [*Dee et al.*, 2011], but the wind stress is a more complicated value to estimate because sea ice can modulate the transfer of momentum between the atmosphere and the surface ocean. For example, in regions, and seasons, in which the ASC lies beneath sea ice, the stress at the ocean surface may be reduced if the ice is drifting at speeds comparable to the ASC.

The influence of surface buoyancy fluxes on the structure of the ASF is less clear. Averaged over the Antarctic margins, freshwater fluxes have a larger impact on water transformation than heat fluxes [*Abernathey et al.*, 2016; *Pellichero et al.*, 2018] (Fig. 5d-f). Dense water formed over the continental shelf, and eventually exported as AABW, is largely related to sea ice formation and the associated brine rejection in coastal polynyas [*Tamura et al.*, 2008], located shoreward of the ASC (Fig. 5e). Most of the sea ice that is formed each year is advected by surface winds away from the coast [*Holland and Kwok*, 2012] and melts in regions (and into density classes) equatorward of the ASC [*Abernathey et al.*, 2016] (Fig. 5d). Thus net transformation at the ocean surface over the continental slope is weak. Water mass transformation occurring in overflows or due to bottom mixing are more important for setting the structure of the ASC (see §3.1).

Similar to the ACC, both the zonal and meridional circulations of the ASC facilitate the convergence of distinct water masses. Thus, non-local processes that set water mass properties may impact the ASC's frontal structure as these waters are transported to the upper continental shelf and shelf break. While the surface wind stress plays a leading order role in determining the strength of the ASC, dense water formation on the shelf will also intensify lateral buoyancy gradients across the shelf break by increasing the density contrast with offshore water masses. This mechanism may be sensitive to changes in either the location or rates of sea ice formation, since brine rejection tends to mix dense waters throughout the water column, increasing the density at depths comparable to the offshore CDW [*Goddard et al.*, 2017]. In regions where the shelf fills with dense water, further production is balanced by the export of this dense water and a compensating onshore flow of lighter density classes that shoals the stratification at the shelf break. Other non-local influences include large-scale atmospheric patterns that set the strength and structure of the polar gyres and can give rise to seasonal or inter-annual variability in the ASC [*Armitage et al.*, 2018].

In addition to direct forcing, advection, and mixing, the bathymetry of the Antarctic margins also has a strong impact on the structure of the ASC. Due to the effects of rotation and the relatively weak stratification of the Southern Ocean, conservation of potential vorticity (PV) [*Pedlosky*, 1987] constrains the ASC to approximately follow contours of f/h, where f is the local Coriolis frequency and h is the depth of the water column. Large excursions over the continental slope imply significant changes in h, or traversing a large PV gradient. The water column depth is a much stronger constraint here than it is for large-scale open ocean flows, which are influenced by the planetary PV gradient, or the change in f with latitude. In fact, around the Antarctic margins, the topographically-induced PV gradient is typically two to three orders of magnitude larger than the planetary PV gradient over the continental slope (Fig. 5a). Increasing slope steepness increases the topographic PV gradient and stabilizes the along-slope flow [*Blumsack and Gierasch*, 1972; *Isachsen*, 2011].

The depth of the continental shelf break, and especially troughs, can determine the range of density classes that ventilate the continental shelf. The depth of the shelf may also impact heat and freshwater budgets over the continental shelf [*Couto et al.*, 2017]. Troughs are known to be major sources of inflow to the continental shelf [*Moffat et al.*, 2009; *St-Laurent et al.*, 2013; *Zhang et al.*, 2016]. A deeper access to the shelf enables warm water to move onshore, although lateral pressure gradients supported by the walls of the trough may also sustain a mean geostrophic flow across the shelf break. Circulations within these troughs tend to be cyclonic; but inflows and outflows may occur at different depths or density classes [*Zhang et al.*, 2016].

2.6. Future challenges: Structure and variability of the ASC

Although measurements at the upper Antarctic continental slope remain sparse, especially during winter and over large regions of East Antarctica, a clearer picture of the spatial variability of the ASC has emerged over the past couple decades. Open challenges largely pertain to capturing or inferring temporal changes in the ASC's density structure, either through novel observation techniques, such as the deployment of long-term autonomous vehicles or the use of satellite data, or using non-local observations. The latter implies a need to mechanistically understand how the ASC responds to local and non-local climate changes. A few specific research directions are suggested here.

1. **Linking interior density changes to remotely-observed properties.** Estimates of remotely-sensed SSH at the Antarctic margins [*Rye et al.*, 2014; *Armitage et al.*, 2018; *Dotto et al.*, 2018] have provided the first circumpolar, mutli-year time series of variability over the continental slope and shelf. However, these products are relatively coarse in scale, and it remains unclear how variations in SSH impacts either sub-surface lateral gradients associated with the ASC or the deepening/shoaling of warm water at the shelf break. This interior adjustment is critical to the transport of CDW on to the the continental shelf.

2. **Zonal connectivity of the ASC.** Throughout this article we emphasize the tight link between meridional and zonal circulations of the ASC. Recent studies have suggested that localized changes in surface forcing can remotely influence the density structure of the ASC [*Spence et al.*, 2017]. The various means by which this information is communicated by and causes changes to the ASC requires further study. This topic covers both large-scale processes, for instance the propagation of signals around the Antarctic Peninsula, and smaller scale circulation features, such as how the structure of the ASC is communicated across major bathymetric troughs, e.g. the Filchner-Ronne and Belgica Troughs in the Weddell and Bellingshausen Seas.

3. **Capacity for abrupt changes in water properties on the continental shelf.** Currently, rapid ice shelf thinning is largely limited to West Antarctica where CDW floods the shelf. A strong ASC shields the continental shelf and floating ice shelves from warm water over much of East Antarctica. However, the potential for rapid changes to the density structure of the ASF, responding to either local or remote forcing, could cause more of the AIS to be vulnerable to instability. The size of the Filchner-Ronne ice shelf makes this region particularly critical to study [*Hellmer et al.*, 2012; *Golledge et al.*, 2017].

3. Dynamics and variability of the ASC

In §2 we provided a survey of the ASC's state around the continent. We now turn to the question of what controls the observed hydrographic structure, along-slope flow and cross-slope transport. Historically, attempts to answer this question have drawn on continental-scale patterns of wind and buoyancy forcing [*e.g. Deacon*, 1937; *Gill*, 1973; *Jacobs*, 1991; *Whitworth et al.*, 1998], but more recent studies consistently indicate a central role for variability [see *Klinck and Dinniman*, 2010]. In this regard our evolving understanding of the ASC's dynamics parallels that of the ACC, which also historically assigned the surface wind forcing as the primary mechanism setting the current's characteristics [*Munk and Palmén*, 1951; *Warren et al.*, 1996]. The role of variability in the ACC was latterly recognized as crucial [*e.g. Tréguier and McWilliams*, 1990; *Marshall and Radko*, 2003]. In this section we synthesize our current understanding of the ASC's characteristic variability. The challenges inherent in observing variable flows at the Antarctic margins have biased these advances toward results from model simulations, but they are increasingly supported by evidence from observational deployments.

The Antarctic continental slope strongly constrains exchanges between the shelf seas and the broader Southern Ocean. The rapid change in sea floor depth across the continental slope produces a barotropic PV gradient [see *Pedlosky*, 1987; *Vallis and Maltrud*, 1993, and Fig. 5a] that steers the geostrophic ASC along, rather than across, the continental slope [*e.g. Thompson and Heywood*, 2008; *Meijers et al.*, 2010; *Dong et al.*, 2016]. The resulting along-slope flows of the ASC provide a conduit between sectors of the Antarctic margins, for example by transporting freshwater anomalies from East Antarctica to the Weddell Sea [*Graham et al.*, 2013] and spreading glacial meltwater westward from the Amundsen and Bellingshausen Seas [*Nakayama et al.*, 2014b]. In contrast, exchanges of water masses across the ASC must be supported by mechanisms other than geostrophic mean flows. Fig. 6 illustrates the dynamic character of the ASC via a snapshot of potential temperature in the vicinity of the Antarctic Peninsula from a global high-resolution model simulation. This plot suggests a prominent role for small-scale variability in stirring tracers across the ASC and onto the continental shelf, particularly along the WAP and in the southwestern Weddell Sea.

Below we review three mechanisms that contribute to setting the structure of the ASC and facilitate exchanges across it: dense water overflows (§3.1), tidal flows (§3.2), and mesoscale eddies (§3.3). These contributions are illustrated schematically in Fig. 3, which we refer to throughout the following subsections. Though this represents only a subset of the processes contributing to ASC's variability, they are arguably the best understood processes at the time of writing. In §3.4 we discuss additional contributors to variability of the ASC as well as outstanding questions regarding the ASC's dynamics.

3.1. Overflows

The topographic constraint on cross-slope exchange has long been known to be overcome by overflows of DSW, the precursor to AABW [*Foster and Carmack*, 1976]. These overflows produce the "V"-shaped isopycnal structure [see §2.2, Fig. 3b,e and *Gill*, 1973; *Ou*, 2007] that characterizes the ASF in the vicinity of the four known major DSW formation sites [*Baines and Condie*, 1998]: the western Ross Sea [*Bergamasco et al.*, 2004; *Gordon et al.*, 2004], the Weddell [*Seabrooke et al.*, 1971; *Nicholls et al.*, 2009], the Adélie coast [*Rintoul*, 1985], and Cape Darnley [*Meijers et al.*, 2010; *Ohshima et al.*, 2013] (§2.2). The phenomenology and dynamics of Antarctic overflows have been reviewed extensively [*Baines and Condie*, 1998; *Legg et al.*, 2009; *Gordon et al.*, 2009b], so here we focus on their interaction with the ASC.

Close to the shelf break, DSW overflows can directly modify the overlying stratification associated with the ASF via (i) entrainment of ambient fluid into energetic DSW plumes and (ii) detrainment from the descending DSW gravity current [*Baines*, 2008]. The former mechanism appears to be active at the major DSW overflows in the Ross and Weddell Seas, and the resulting entrainment of CDW substantially modifies the properties and volume transports of the resulting bottom waters [*Gordon et al.*, 2004; *Foldvik et al.*, 2004; *Visbeck and Thurnherr*, 2009]. Plumes descending into weak ambient stratification may be expected to undergo vertical "splitting" and inject shelf waters into the mid-depths of the ASC, though this has not been directly observed around Antarctica [*Baines*, 2008; *Marques et al.*, 2017]. As it descends the slope the DSW adjusts geostrophically and drifts westward under the action of the Coriolis force, and has thus been observed at the base of the ASC many hundreds of kilometers west of identified overflow sites [*e.g. Baines and Condie*, 1998; *Thompson and Heywood*, 2008; *Gordon et al.*, 2015].

A series of authors [*Gill*, 1973; *Ou*, 2007; *Baines*, 2009] have argued from first principles that the circulation induced by the downslope flow and entrainment into the DSW plume plays a leading order role in shaping these portions of the ASC. However, the processes related to ASC itself also play an active role in mediating the export of DSW. *Kida* [2011] used idealized simulations to show that wind-induced strengthening of the ASF, *i.e.* deepening the offshore side of the "V"-shaped isopycnals, increases the export of DSW, and vice versa. *Stewart and Thompson* [2012, 2013] obtained a qualitatively similar result using a combination of residual-mean theory and three-dimensional eddy-resolving simulations, and demonstrated that DSW export was controlled by wind-driven Ekman transport. However, subsequent idealized simulations with finer resolution [*Stewart and Thompson*, 2015a, b] showed almost no sensitivity to the along-shelf winds because variations in the wind-driven export of DSW were compensated by an eddy-driven export, discussed further in §3.3. Finally, the ASC's narrow jets, particularly in regions where the current is bottom-intensified, can produce lateral variations in bottom Ekman transport.

This can then lead to Ekman convergence or divergence, which may influence exchange between the overflows and the interior [*Thompson et al.*, 2014; *Benthuysen et al.*, 2015].

3.2. Tides

The Antarctic shelves support relatively strong tidal ellipses and mixing, with average tidal velocities reaching $\mathcal{O}(1\,\mathrm{m\,s^{-1}})$ around localized stretches of the shelf break [*e.g. MacAyeal*, 1984; *Foldvik et al.*, 1990; *Robertson*, 2001; *Padman et al.*, 2018]. The rapid change in the amplitude of the tidal ellipses across the continental slope leads to wave-averaged, along-slope "Stokes' drift" and an opposing Eulerian-mean flow, the latter being required to conserve momentum [*Garreau and Maze*, 1992; *Chen and Beardsley*, 1995]. The "residual" of these velocities can reach $\mathcal{O}(10\,\mathrm{cm\,s^{-1}})$, and therefore can contribute substantially to the transport of the ASC [see Fig. 3a and *Foldvik et al.*, 1990; *Robertson*, 2001]. These tidally-induced along-slope flows may, in fact, play a central role in the formation and location of the ASC: *Whitworth and Orsi* [2006] observed the ASF migrating diurnally back and forth across the shelf break of the northwestern Ross Sea. *Flexas et al.* [2015] used idealized model simulations to demonstrate that tides alone can produce a realistic ASC in the northwestern Weddell Sea.

Whereas the Antarctic slope has long been known to support strong tidally-rectified flows [*Foldvik et al.*, 1990; *Robertson*, 2001], most studies demonstrating that these tidal fluctuations can substantially enhance cross-slope exchange have only materialized in the last decade. *Beckmann and Pereira* [2003] suggested that the strong tides of the central Ross and Weddell Seas should suppress cross-slope exchange, whereas the weaker tidal amplitudes in regions like the western Weddell should enhance it. In contrast, the AnSlope experiment [*Gordon et al.*, 2009b] revealed that DSW could be transported most of the way across the continental slope over a single tidal cycle, substantially enhancing its export rate [see Fig. 3b and *Whitworth and Orsi*, 2006]. This finding was corroborated by analytical theory and idealized numerical simulations, and regional simulations of tidally-enhanced DSW discharge [*Ou et al.*, 2009; *Guan et al.*, 2009; *Padman et al.*, 2009].

Tides also play a role in transporting and modifying CDW across the continental shelf and slope. For example, *Wang et al.* [2013] used a Ross Sea regional model to show that the export of DSW is partially counteracted by tidal shoreward transport of CDW, which mixes with and lightens the DSW, such that the DSW export is strongest at intermediate tidal amplitude. The tidal transfer of CDW may also impact shelf productivity by supplying iron to surface waters, though it appears that benthic sources are dominant in the Ross polynya [*Mack et al.*, 2017]. *Castagno et al.* [2017] measured modified CDW inflow in the western Ross Sea using moorings in 2004–2005 and 2013–2014, and inferred that its variability was primarily driven by tides (Fig 3b). *Stewart et al.* [2018] showed that tides make a leading-order contribution to the heat budget around almost the entire Antarctic margins, though the shoreward tidal heat transport is closely compensated by an offshore heat transport by mean flows. Tides also play a key role in transporting this heat across the continental shelf and into the cavities beneath Antarctica's floating ice shelves, as recently reviewed by *Padman et al.* [2018].

3.3. Eddies

In discussing "eddies" we will refer not only to coherent vortices, but to all transient features associated with quasi-two dimensional turbulent flows in the ASC. Such features might be characterized by length scales ranging from just a few kilometers on the continental shelf [*St-Laurent et al.*, 2013; *Gunn et al.*, 2018] to $\mathcal{O}(100\,\mathrm{km})$ in the open ocean, with time scales of a few days to several weeks, respectively [*McWilliams*, 2008]. Though stirring by mesoscale ocean turbulence is the most striking sign of oceanic variability in Fig. 6, the role of eddies in the ASC has largely only been explored in the past 10–15 years. This is due to logistical challenges associated with making *in situ* observations of the characteristic length and time scales of eddy variability, combined with the inability of current satellite altimetric measurements to resolve them [*Armitage et al.*, 2018]. Similarly, even regional model simulations have only relatively recently been able to resolve the first Rossby radius of deformation, $O(1-10)$ km, over the continental slope [*Klinck and Dinniman*, 2010], as is required to adequately simulate the statistics of baroclinic turbulence [*Hallberg*, 2013].

Eddies have long been understood to form in dense overflows over the Antarctic continental slope [*Baines and Condie*, 1998], as anticipated from a series of laboratory investigations of dense flows descending slopes [*e.g. Smith*, 1977; *Condie*, 1995]. In particular, *Lane-Serff and Baines* [1998] showed that in an experimental setup, a deep descending layer will break up into a series of domes and generate eddies in the overlying fluid. These findings have subsequently been confirmed in idealized eddy-resolving simulations of overflows, though modeling efforts are hindered by strong sensitivity to their numerical grid configurations, especially at the resolutions used in coupled climate models [*Legg et al.*, 2008]. Despite these challenges, regional simulations indicate that eddies should indeed be abundant in Antarctic DSW overflows, for example downstream of the Filchner overflow in the Weddell Sea [*Wang et al.*, 2009] and adjacent to Cape Darnley in East Antarctica [*Nakayama et al.*, 2014a]. In an idealized numerical model setup, *Stewart and Thompson* [2012, 2013] showed that eddies generally complement wind-driven coastal downwelling to export DSW from the Antarctic continental slope. *Stewart and Thompson* [2015a] further showed that as the winds and wind-driven DSW export weaken, the generation of eddies and eddy-driven DSW export intensify to compensate, leaving the overall DSW export relatively insensitive to the along-slope winds. Recent studies have also indicated a role for eddies in mediating DSW export to the wider Southern Ocean by mediating the stratification of the ASF around the Weddell Gyre and its response to variable wind forcing [*Su et al.*, 2014; *Dufour et al.*, 2017; *Daae et al.*, 2018].

Scientific focus on ASC eddies, and mesoscale variability in general, has intensified in recent decades largely due to their role in transporting heat across the Antarctic continental slope [*e.g.* Fig. 3(a–c) and *St-Laurent et al.*, 2013; *Stern and Nadeau*, 2015; *Goddard et al.*, 2017]. Initial modeling forays into this topic at relatively coarse resolution ($\sim$4 km horizontal grid spacing) detected CDW accessing the shelf via "inertial overshoots," in which the slope current approaches a trough in the continental slope and continues onto the shelf via inertia [see Fig. 3c and *Dinniman et al.*, 2003; *Dinniman and Klinck*, 2004; *Dinniman et al.*, 2011]. This approximate horizontal resolution appears to be a required minimum for simulating heat transport onto Antarctica's "warm" shelves [*Nakayama et al.*, 2014c]. Note that CDW accessing the shelf via this mechanism requires an adjacent shelf circulation to carry its heat anomalies further onshore, giving rise to strong spatial inhomogeniety in the cross-slope heat transport [*Klinck and Dinniman*, 2010]. A finer ($\mathcal{O}(1\,\mathrm{km})$) horizontal grid spacing is required to fully resolve the Rossby waves and coherent vortices that can carry CDW onto the shelf via troughs [*St-Laurent et al.*, 2013] or coastal embayments [*Zhang et al.*, 2011]. *Graham et al.* [2016] found that a similar increase in horizontal resolution resulted in transient amplifications of the heat flux into the Belgica and Marguerite Troughs of the WAP shelf by a factor of two or more. These model-based findings are corroborated by hydrographic measurements of structures resembling coherent eddies on the WAP shelf [*Moffat et al.*, 2009]. *Couto et al.* [2017] used data collected by a series of glider deployments to estimate that 20–53% of the heat flux onto the WAP shelf was carried by eddies entering Marguerite Trough. Based on seismic imaging calibrated against available hydrographic measurements, *Gunn et al.* [2018] identified a series of subsurface CDW-bearing "lenses", ranging from 0.75 to 11 km in horizontal scale and from 100 to 150 m in thickness, located off the WAP and believed to be a prominent source of warm shelf water.

CDW transport onto Antarctica's "cold" shelves must negotiate a sharp ASF and associated strong ASC that shield the continental shelf [see Fig. 3(d), §2.1 and *Goddard et al.*, 2017]. However, high-resolution model simulations indicate that CDW is still able to reach the shelf in such regions via bottom-trapped eddies that intrude beneath the ASF and onto the shelf, generated by instabilities of the ASC [see Fig. 3a and *Nøst et al.*, 2011; *Hattermann et al.*, 2014]. *Stewart et al.* [2018] concluded that this remained the dominant mechanism of cross-shelf/slope heat transport even in the presence of tides, whose large shoreward heat fluxes were compensated by offshore mean heat fluxes. An exception to this mechanism occurs where DSW descends the continental slope: the presence of DSW at the sea floor necessarily leads to an isopycnal connection between CDW offshore and the shelf waters, offering a pathway for eddies to stir heat shoreward along isopycnals [see Fig. 3c,f, §2.2 and *Stewart and Thompson*, 2015a, b]. Consistent with this, *Thompson et al.* [2014] found boluses of CDW intruding onto the continental shelf in the western Weddell Sea, and *Kohut et al.* [2013] observed small-scale ($\mathcal{O}$(30 km)) structures moving modified CDW onto the Ross Sea continental shelf. In an idealized eddy-resolving model setup, *Stewart and Thompson* [2016] showed that baroclinic instability of DSW descending the continental slope provides the source of momentum and energy required to produce a shoreward eddy-driven CDW transport, consistent with laboratory findings of overflows generating eddies in overlying fluid layers [*Lane-Serff and Baines*, 1998]. Consistent with this paradigm, *Azaneu et al.* [2017] diagnose substantial spatial variability of the ASC in the western Weddell Sea from a series of glider sections, calculating transports ranging from 0.2 Sv to 5.9 Sv (1 Sv = 1 Sverdrup = 10^6 m^3 s^{-1}) .

3.4. Future challenges: Emerging ASC dynamics and phenomena

In addition to the physical processes discussed in §§3.1–3.3, a range of other dynamics have been identified in the ASC that potentially influence its structure, transport, and cross-slope exchanges. For example, in addition to the tides, the continental shelf and slope support westward-propagating topographic Rossby waves [TRWs, *Thompson and Luyten*, 1976] and coastally-trapped waves [CTWs, *Huthnance et al.*, 1986]. TRWs may be energized by tidal excursions across the continental slope [*Middleton et al.*, 1987; *Foster et al.*, 1987] or generated alongside mesoscale eddies by dense overflows [*Lane-Serff and Baines*, 1998; *Marques et al.*, 2014]. TRWs may directly contribute to the steering of CDW onto warm continental shelves via troughs [*St-Laurent et al.*, 2013], but their importance relative to, *e.g.*, tides and coherent eddies [*Wang et al.*, 2013; *Couto et al.*, 2017], remains unknown. CTWs are generated by circum-Antarctic and remote atmospheric variability [*Kusahara and Ohshima*, 2014], and the former has recently been identified as a mechanism of rapidly generating heat content anomalies along the WAP [*Spence et al.*, 2017].

The surface mixed layer has long been known to play a key role in the dynamics of the ASC, *e.g.* by supporting shoreward Ekman transport of surface water (see Fig. 3), and more generally in water mass transformation around Antarctica [*e.g. Abernathey et al.*, 2016]. However, the ocean's bottom boundary layer (BBL) has recently drawn scientific focus due to its role in upwelling Antarctic-sourced dense waters [*Stewart*, 2017], and is emerging as a potentially important contributor to the dynamics of the Antarctic continental slope. For example, mixing in the BBL has been shown to facilitate the down-slope flow of DSW once it has transitioned from a plume [*Baines*, 2008] into a geostrophically adjusted, bottom-trapped flow [*Hirano et al.*, 2015]. Diapycnal mixing in the BBL is particularly elevated in locations that coincide with the critical latitude of the M2 tide, such as the continental slope of the southern Weddell Sea [*Daae et al.*, 2009; *Fer et al.*, 2016]. The implications of these locations of elevated mixing for water mass transformation remains to be explored. However the BBL has been directly implicated in the transformation of CDW to surface water masses at the tip of the Antarctic Peninsula [*Ruan et al.*, 2017]. Finally the development of "arrested" or "slippery" Ekman layers [*Garrett et al.*, 1993] in the BBL has been proposed as a mechanism of enhancing transport of CDW onto the Amundsen Sea shelf [*Wåhlin et al.*, 2012].

In addition to the various forms of intrinsic variability discussed so far, variability in the ASC is also imposed by the pronounced seasonal cycle in surface heat, freshwater and momentum input to the ocean (see §2.5). For example, *Mathiot et al.* [2011] analyzed the seasonal cycle of the ASC in a heirarchy of global model simulations, and found that the transport of the ASC exhibits a seasonal cycle of 6–8 Sv (depending on the product used to prescribe the atmospheric state), more than 50% of which was directly driven by the seasonal cycle in surface winds. However, the model grids used in this study were too coarse to represent most of the other types of variability discussed in this section [*e.g. Padman et al.*, 2009; *St-Laurent et al.*, 2013]. The seasonal cycle also projects onto exchanges across the ASC: for example, seasonal changes to shelf break wind forcing mediate DSW overflow transports in the Weddell Sea [*Wang et al.*, 2012], the Ross Sea [*Gordon et al.*, 2015], and the Adélie coast [*Fukamachi et al.*, 2000]. Relatively warm summer surface waters are advected shoreward in the eastern Weddell Sea via wind-driven Ekman transport, yielding an additional, seasonal mode of ice shelf melt in this sector [*Zhou et al.*, 2014]. Finally, CDW intrusions into troughs on the Amundsen Sea continental shelf are forced by seasonal shifts in the Amundsen Sea Low [*Thoma et al.*, 2008]. In addition to the seasonal cycle, local and remote modes of low-frequency climate variability also project onto the ASC [*e.g. Armitage et al.*, 2018]; this will be discussed further in §4.

Though efforts over the past two decades have unambiguously demonstrated the importance of variability in the ASC, our understanding of this topic continues to change rapidly. In many regards the dynamics of the ASC as a whole remains an emerging field of study, with many open questions of a fundamental nature. Below we outline a few of the major challenges that remain.

1. **Theoretical insight.** Above we have identified several key forms of ASC variability (see Fig. 3). Predictive theories for, *e.g.*, overflows [*e.g. Baines*, 2009], tides [*e.g. Chen and Beardsley*, 1995], and eddies [*e.g. Stern and Nadeau*, 2015] have been developed. However, these fundamental physical insights have yet to be synthesized to provide a comprehensive theory for the ASF's stratification, the ASC's transport and cross-slope exchanges, and

for their response to variations in surface wind and buoyancy forcing, tidal forcing, and shelf/open-ocean stratification. Such theories are essential to assessing comprehensive climate models' representations of the ASC's response to future climate shifts (see §4). Theoretical understanding is particularly lacking for mesoscale eddies, whose behavior differs qualitatively over continental slopes from the open ocean [*Isachsen*, 2011], though limited progress has been made via idealized modeling [*Stewart and Thompson*, 2016].

2. **Observational characterization.** As noted above, many of the recent insights into the ASC's dynamics and variability have been drawn from model-based studies. Observational deployments in specific locations around Antarctica have provided valuable insights into the dynamics of *e.g.* overflows [*Gordon et al.*, 2004; *Nicholls et al.*, 2009; *Ohshima et al.*, 2013], tides and tidal mixing [*Daae et al.*, 2009; *Fer et al.*, 2016; *Castagno et al.*, 2017] and eddy variability [*Moffat et al.*, 2009; *Couto et al.*, 2017; *Azaneu et al.*, 2017]. However, observational validation of many of the findings discussed above remains lacking. Such validation is particularly challenging for mesoscale eddies because they are not localized (like overflows) and are less straightforward to characterize via moored measurements than tidal flows. Observational insight into the ASC's dynamics may be gained from measuring systems with broad areal coverage, such as remotely-sensed sea surface elevation under sea ice [*Armitage et al.*, 2018], sea ice-capable Argo floats [see *e.g. Pellichero et al.*, 2017], and tagged seals [*e.g. Costa et al.*, 2008].

3. **Circumpolar perspectives.** Almost all of the studies discussed above focus on idealizations of the ASC or on specific sectors of the Antarctic margins, due to computational limitations on models and observational deployment constraints. Going forward, circumpolar observational and modeling perspectives that incorporate the forms of vari-

ability identified in Fig. 3 will be an essential complement to regionally-focused studies. Such perspectives are necessary to accurately represent connections between sectors of the Antarctic margins [*e.g. Graham et al.*, 2013; *Nakayama et al.*, 2014b; *Spence et al.*, 2017], to identify "hot spots" for exchanges of water masses across the continental slope, and to characterize fundamental circumpolar-scale features of the ASC, such as its thermodynamic, energy and momentum/vorticity budgets. Circumpolar perspectives are becoming more commonplace in modeling studies [*Schodlok et al.*, 2016; *Dinniman et al.*, 2016; *Goddard et al.*, 2017; *Stewart et al.*, 2018], and to a more limited extent in observational deployments, *e.g.* the synoptic Antarctic shelf-slope interactions (SASSI) project [*Heywood et al.*, 2012].

4. Climate of the Antarctic Slope Current

The previous sections focused on our understanding of the ASC's structure and dynamics. Here we address the interconnected processes by which the ASC influences and is influenced by global climate. Early studies identified the ASC's role in connecting the Antarctic coastal ocean with the Southern Ocean by acting as a dynamical barrier to transport across the continental slope [*e.g. Gill*, 1973; *Jacobs*, 1991]. Recently the ASC has become more recognized as an acute component of the global climate system that can alter the stability of Antarctic glaciers [*Rignot and Jacobs*, 2002; *Rignot et al.*, 2013], the global carbon cycle [*Heywood et al.*, 2014; *Mack et al.*, 2017], and the abyssal stratification throughout the global ocean [*Orsi et al.*, 2002; *Stewart and Hogg*, 2017]. Our understanding of the climate processes that influence the ASC has also expanded from local to global contexts with atmospheric tele-connections from the tropics [*Turner*, 2004; *Purich et al.*, 2016], anthropogenic gas emissions [*Thompson et al.*, 2011], and large-scale ocean variability [*Wang*, 2013; *Downes and Hogg*, 2013] among the many climate processes implicated in ASC variability. This section aims to synthesize the observed and projected 21st century changes in the ASC, the large-scale drivers of these changes, and the role the ASC plays in climate change.

4.1. ASC variability and trends

A suite of factors make identifying and attributing changes in the ASC a difficult task. The small spatial scales of ASC dynamics are in stark contrast to the enormous spatial extent of the Antarctic continental slope. Precise knowledge of ocean properties are needed to identify the temporal state of the ASC, while its sensitivity to a changing climate requires data spanning decades. Remote sensing efforts are limited by winter sea ice and regular thick cloud cover. In situ measurements are largely focused on measuring ASF properties on seasonal or shorter time scales in a few key locations, namely the Weddell, Ross, and Amundsen Seas [*e.g. Gordon et al.*, 2009a; *Wåhlin et al.*, 2012; *Graham et al.*, 2013; *Peña-Molino et al.*, 2016]. Meanwhile large regions of East Antarctic coastal waters have never been sampled [*Rintoul et al.*, 2016]. Consequently, climate studies are reliant on gross interpolations of observational data over large regions of the Antarctic continental shelf and slope [*Schmidtko et al.*, 2014]. The sparse observational data also leaves model simulations poorly constrained, and the small Rossby deformation radius makes it currently impossible for models to resolve ASC dynamics on climate-relevant time scales [*Stewart et al.*, 2018]. Despite the growing appreciation for the ASC's role in global climate, our understanding of ASC variability and how it responds to a changing climate is in its infancy.

Graham et al. [2013] and *Peña-Molino et al.* [2016] are useful case studies on the challenges of observing and attributing variability across the Antarctic continental slope. *Graham et al.* [2013] collected hydrographic data across the continental slope for one year in the southeastern Weddell Sea at ∼18°W from five moorings that spanned ∼50 km. They found sub-monthly fluctuations of temperature and salinity that often exceeded 1°C and 0.1 psu at ∼400-1000 m depth as the pycnocline vertically fluctuated over the steepest portion of the continental slope. *Graham et al.* [2013] attributed this high-frequency variability primarily to the local winds, while acknowledging that the influence of mesoscale eddies and coastally-trapped waves were difficult to identify from the mooring data. *Peña-Molino et al.* [2016] attempted to directly observe the vertical and horizontal structure of currents along the continental slope for long enough to estimate its time-mean transport and variability. Using 17 months of current data across the continental slope near 113°E, they found a highly variable flow, with transports ranging from 0 to -100 Sv (negative westward) over periods of 25-30 days. They estimated the time-mean transport to be -21.2 Sv and largely barotropic. *Peña-Molino et al.* [2016] found a distinct seasonal cycle in the current speeds over the upper continental slope that they attributed primarily to seasonal variability in the local winds. An analysis of sea level variability from satellite data found the barotropic speeds of the ASC to be up to twice as fast in the autumn compared with spring, with the monthly variability strongly influenced by the local wind field [*Armitage et al.*, 2018] .

Observational time series are generally too short to discern interannual variability of ASC properties, which complicates the analysis of longer-term trends. Despite these challenges, there is growing evidence of decadal trends in the water mass properties near the ASC from hydrographic cruise data. By combining seven hydrographic databases spanning 1975-2012, *Schmidtko et al.* [2014] present a circumpolar assessment of multi-decadal linear trends near the continental slope. They found Antarctic shelf bottom water warming trends of 0.1-0.3 °C decade^{-1} in portions of the Bellingshausen Sea and Amundsen Sea since the 1990s, and a weak cooling trend (0.05 °C decade^{-1}) in portions of the Ross Sea since the 1970s (Fig. 7a). They also found increasing Antarctic shelf bottom water salinity in portions of the Bellingshausen Sea and Amundsen Sea (0.01-0.04 g kg^{-1} decade^{-1}), and freshening in the Ross Sea (-0.027 g kg^{-1} decade^{-1}), Weddell Sea (-0.01 g kg^{-1} decade^{-1}) and Cosmonauts Sea (-0.05 g kg^{-1} decade^{-1}). *Schmidtko et al.* [2014] also evaluated CDW trends near the shelf break where the ocean depth exceeds 1500m, finding warming (∼0.1 °C decade^{-1}) and shoaling (-30 m decade^{-1}) of CDW around most of the continent with little evidence of salinity changes. Other more localized observational studies have found freshening trends in bottom waters north of the shelf break in the Ross Sea [*Jacobs and Giulivi*, 2010], and Australian Antarctic basin [*Aoki et al.*, 2005; *Rintoul*, 2007] since the mid-1990s.

The ocean component of most fully-coupled global climate models have a resolution that is too coarse (i.e. ∼1 °) to capture the fine-scale processes that influence Antarctic shelf/slope water masses (see §3), making them insufficient for interpreting ASC variability or the impacts of climate change in the region. In the majority of Coupled Model Intercomparison Project Phase 5 (CMIP5) models, AABW is unrealistically formed in massive regions of deep open-ocean convection, rather than as dense shelf water cascading down the continental slope [*Heuzé et al.*, 2013]. Consequently, significant biases in continental shelf and Southern Ocean water mass properties are found in CMIP5 models, and the biases appear to be random and without a consistent behavior between the models [*Heywood et al.*, 2014]. CMIP5 models are more capable of simulating the larger-scale dynamics important to Southern Ocean CDW transport, and they are more consistent in predicting a substantial warming of CDW with continued anthropogenic forcing (Fig. 7b) [*Sallée et al.*, 2013]. A few studies with finer resolution global ocean models have identified decadal trends and anthropogenic influences on Antarctic continental shelf/slope water masses. For example, using a fully coupled climate model with a 0.1° Mercator ocean grid, *Goddard et al.* [2017] found that a doubling of atmospheric CO_2 led to a 0.59°C temperature increase within the 100-1000 m depth range of Antarctic shelf waters. Using a 0.25° Mercator grid ocean sea-ice model, *Spence et al.* [2014a] suggest that recent trends in Southern Ocean winds may at least partially explain the observed warming of shelf waters in the WAP, Amundsen Sea and Bellingshausen Sea.

The most compelling evidence of decadal trends in the continental shelf/slope waters comes from satellite-derived observations of Antarctic glacial ice. The most important heat source for Antarctic ice shelf melting is the intrusion of the offshore CDW onto the Antarctic continental shelf and into the ice shelf cavities. West Antarctic ice mass loss has doubled from 2003-2014 with most dramatic changes coinciding with the ASBW warming trends of *Schmidtko et al.* [2014]: the Bellingshausen Sea, Amundsen Sea and the WAP (Fig. 7b). Totten Glacier in East Antarctica has thinned by $\sim$12 m at its grounding line in recent decades [*Li et al.*, 2015], and recent observations found a large pool of warm shelf water nearby [*Rintoul et al.*, 2016; *Nitsche et al.*, 2017].

4.2. Climate modes of variability and the ASC

Interpreting ASC variability on interannual and decadal time scales requires detailed understanding of the large-scale climate processes that can influence ASC dynamics; these may include: (i) atmospheric tele-connections from the tropics [*Turner*, 2004; *Purich et al.*, 2016]; (ii) variability in the Southern Ocean wind field [*Thompson and Wallace*, 2000]; (iii) glacial meltwater [*Rignot et al.*, 2013], and changing sea ice conditions [*Haumann et al.*, 2016]; (iv) the pathways of the ACC, the Weddell and Ross Gyres [*Wåhlin et al.*, 2012; *Wang*, 2013]; and (v) the transport and properties of the Southern Ocean overturning circulation [*Downes and Hogg*, 2013; *Meijers*, 2014]. Global warming is altering many of these processes, as well as the air-sea heat and moisture fluxes in the region. Our focus here is on two key large-scale climate modes of variability known to influence the Antarctic margins, the Southern Annular Mode (SAM) and the El Niño Southern Oscillation (ENSO). These climate modes influence polar regions largely through changes in atmospheric wind patterns that modify the surface stress of the polar gyres. However, other changes, for example due to surface buoyancy forcing, may modify gyre circulations and, non-locally, the ASC [*Behrens et al.*, 2016].

The SAM is the dominant mode of atmospheric variability in the southern hemisphere extratropics, accounting for ∼25% of the monthly sea level pressure variability [*Thompson and Wallace*, 2000; *Marshall*, 2003]. The spatial pattern of the SAM is characterized by near zonally-symmetric changes in the meridional pressure gradient between 40°S and 65°S (Fig. 7c). Positive SAM phases are associated with a strengthening and poleward shift of the Southern Ocean westerly winds, with the opposite occurring during negative phases. Zonal asymmetries in the SAM pattern occur in the Amundsen and Bellingshausen Seas.

Changes in SAM, as well as ENSO, have been linked to changes in gyre strength and ASC structure, for instance as seen from long-term mooring observations in the Weddell Sea [*Meijers et al.*, 2016], but observation the circumpolar response, especially under sea ice, was not possible until recently. Using new data processing techniques, *Armitage et al.* [2018] examined monthly sea level variability in the seasonally ice-covered regions from satellite data spanning 2011-2016. They found significant correlations with the SAM; as the westerlies contract poleward during positive SAM phases the equatorward surface Ekman transport is enhanced and the coastal sea level drops by ∼1-2 cm around much of the Antarctic coastline (Fig. 7c). The opposite effect, a near circumpolar coastal sea level rise, was found during negative phases of the SAM.

Significant decadal scale SAM trends have emerged from its interannual variability. The SAM was generally negative throughout 1970s and 1980s, and has been generally positive since then. The shift to a positive decadal SAM trend since the 1990s is attributed to both stratospheric ozone depletion and increased greenhouse gases [*Thompson et al.*, 2011]. This positive SAM trend is expected to persist through the 21st century with continued anthropogenic forcing (Fig. 7b) [*Zheng et al.*, 2013]. By changing the pattern and magnitude of wind stress and surface buoyancy fluxes, the SAM can influence large-scale features of the Southern Ocean such as the ACC, the mesoscale eddy field, sea level patterns, and the upwelling of CDW [*Sen Gupta and England*, 2006; *Sijp and England*, 2009; *Hogg et al.*, 2014; *Frankcombe et al.*, 2013]. Many observational studies have identified wind forcing as a key component of ASC dynamics, however the impacts of a long-term positive SAM trend on the Antarctic coastal winds and the ASC are uncertain. Modeling studies suggest that the position of currents near the coast and the upwelling of warm

CDW could shift southward with the SAM [*Downes and Hogg*, 2013; *Wang*, 2013; *Meijers*, 2014]. A drop in Antarctic coastal sea level associated with a positive SAM could also weaken the ASC and the coastal currents, allowing for more warm CDW to flow onshore by shoaling isopycnals on the continental slope [*Spence et al.*, 2014a]. Changes in coastal sea level initiated by wind perturbations can propagate around the Antarctic coastline via coastal waves, possibly leading to adjustments of the ASF and CDW intrusions in distant coastal locations [*Spence et al.*, 2017].

ENSO is the strongest driver of global climate variability on interannual to decadal timescales. Changes in tropical Pacific atmospheric convection patterns during ENSO events can often, but not always, establish a Rossby wave train of atmospheric geopotential height anomalies that modify the Amundsen Sea low atmospheric pressure system [*Turner*, 2004]. El Niño phases of ENSO can create an anticyclonic atmospheric pressure anomaly over the Amundsen and Bellingshausen Seas, leading to a reduction in cyclones and more south-westerly winds in the region. La Niña phases generally have the opposite effect by acting to strengthen the Amundsen Sea low pressure system. In a composite analysis of monthly sea level variability in ice-covered regions, *Armitage et al.* [2018] found a ∼1 cm sea level decrease (increase) in the Pacific sector of the Antarctic coastline during El Niño (La Niña) events (Fig. 7d), most likely due to a local surface Ekman layer response to the wind changes. During the strong El Niño event of 2015-2016, they found a sustained coastal sea level anomaly of -6 cm in the Pacific sector. Following the Ekman dynamics of *Spence et al.* [2014a], it is possible that the ASF weakens during such El Niño events and the coastal isopycnals shoal, allowing more inflow of CDW onto the shelf. Satellite altimetry has also found increased basal melting of ice shelves in the Antarctic

Pacific sector during intense El Niño events [*Paolo et al.*, 2018]. There is little consensus regarding how ENSO will respond to continued anthropogenic forcing [*Collins et al.*, 2010], but some models suggest that large El Niño events may become more frequent [*Cai et al.*, 2014].

4.3. ASC influences on global climate

By modulating the flow across the Antarctic continental slope, the ASC links processes occurring at the coast with the global ocean. Here we briefly review the importance of the ASC to global climate, focusing on its importance to the global ocean circulation, the basal melting of Antarctic glacial ice shelves, and the global carbon cycle.

Upper and lower limbs of the global meridional overturning circulation (MOC) support a volume transport of roughly 20 Sv [*Ganachaud and Wunsch*, 2000]. The ACC delivers water towards Antarctica along a spiraling pathway [*Tamsitt et al.*, 2017] that reaches the Antarctic continental slope along the WAP (Fig. 2). Some of this water is entrained into the ASC and is distributed around the Antarctic margins. The ASC sustains an along-slope transport of 10-30 Sv [*Fahrbach et al.*, 1992; *Peña-Molino et al.*, 2016], equivalent to the MOC, despite the ASC being initiated "from scratch" along the WAP (Fig. 2). Thus, the zonal redistribution of water by the ASC plays a key role in the MOC. The ASC's zonal flow is also an important conduit by which icebergs originating from Antarctic ice shelves are carried westwards. These icebergs may be important contributors to the ocean's surface freshwater flux far from calving sites [*Stern et al.*, 2016].

AABW accounts for $\sim$40% of the total ocean volume and fills the abyss of the Southern, Pacific, Atlantic and Indian Oceans [*Johnson*, 2008]. AABW is initially sourced from dense shelf water created by surface buoyancy fluxes in polynyas fringing the Antarctic coastline [*Gordon*, 2009]. As the dense shelf water overflows and mixes down the Antarctic continental slope it must transition through the ASC region. In doing so, the ASC constrains the stratification and circulation of abyssal water throughout the global ocean. The outflow of AABW from the Southern Ocean is compensated by a return flow of lighter waters from the subtropical basins. Together, this exchange of water forms the lower cell of the global meridional overturning circulation, which plays a crucial role in the ocean's storage of carbon, heat, freshwater and other geochemical tracers. Dense water export from the shelf also influences the lateral circulations of the ACC, the Weddell gyre and the Ross gyre via its impact on topographic form stress [*Spence et al.*, 2014b; *Stewart and Hogg*, 2017]. Consequently, any adjustment in the export of dense water across the ASC plays a vital role in global climate change. In recent decades AABW has both warmed and freshened [*Purkey and Johnson*, 2013]. The freshening has been primarily linked to increased input of Antarctic glacial meltwater [*Jullion et al.*, 2013], but there is little consensus on the causes of AABW warming. Climate modeling studies suggest a slowdown of AABW transport under continued anthropogenic forcing, but as noted in §4.1, these models do not realistically capture AABW formation processes [*Downes and Hogg*, 2013; *Meijers*, 2014].

Melting Antarctic ice sheets have contributed ∼28% to global sea level rise in recent decades [*Hock et al.*, 2009], and is the largest uncertainty in future projections of sea level rise [*Church et al.*, 2013]. The melt rate of Antarctica's marine-terminating ice sheets is, at present, controlled by the amount of heat delivered from the Southern Ocean to the Antarctic continental shelf margins [*Paolo et al.*, 2015]. Increased melt rates at the base of floating ice shelves, retreat of ice sheet grounding lines, and increased ice sheet discharge are all positively correlated with increasing ocean temperatures on the shelf (Fig. 7a) [*Pritchard et al.*, 2012; *Schmidtko et al.*, 2014; *Paolo et al.*, 2015]. There is a growing list of oceanographic processes identified as capable of changing the amount of warm CDW water brought onto the Antarctic continental shelf, including: (i) changing Southern Ocean westerly and polar easterly winds [*Spence et al.*, 2014a, 2017]; (ii) feedbacks between the glacial meltwater and the ocean circulation [*Donat-Magnin et al.*, 2017]; (iii) mesoscale turbulence [*Stewart et al.*, 2018]; (iv) tide-topography interactions [*Flexas et al.*, 2015]; and (v) ocean boundary layer processes [*Fer et al.*, 2016]. Understanding the circulation and cross-shelf exchange of CDW around the Antarctic coastline is central to understanding the increased Antarctic glacial melt rates.

The Southern Ocean accounts for approximately 50% of the ocean uptake of anthropogenic carbon and its primary productivity is limited by the availability of iron [*Buesseler and Boyd*, 2009; *Watson et al.*, 2014]. The sediments on the continental shelf are iron-rich and dissolved iron concentrations are highest in the shelf waters. Cross-shelf transport is likely the most significant source of iron for the Southern Ocean south of the Polar Front. Model simulations estimate 90% of the usable iron in the Southern Ocean comes from shelf sediments with icebergs providing most of the remaining 10% [*Heywood et al.*, 2014; *Wadley et al.*, 2014]. The ASC has been hypothesized as a key pathway for delivering iron to the Scotia Sea, one of the few regions of high chlorophyll concentrations in the Southern Ocean [*Thorpe et al.*, 2004; *Thompson and Youngs*, 2013]. Observational studies have also identified onshelf intrusions of nutrient-rich CDW, particularly in the WAP, as determining the phytoplankton assemblages on the shelf with diatom blooms dominating during intrusion events. Variability in the onshelf transport of CDW may alter the overall biological production on the continental shelf [*Prézelin et al.*, 2000; *Prezelin et al.*, 2004]. The efficiency of the biological pump in the Southern Ocean has been identified as a key component of glacial-interglacial swings in atmospheric CO_2 [*Sigman et al.*, 2010; *Menviel et al.*, 2018], suggesting that, through its influence on nutrient transport, the ASC could influence long-term climate variability.

4.4. Future challenges: ASC trends, long-term variability, and feedbacks

Understanding ASC variability on inter-annual and longer time-scales is vital to constraining projections of global sea level rise, and the ocean's uptake of anthropogenic heat and carbon. The coincidence of rapid increases in anthropogenic emissions with warming Antarctic shelf waters and with dramatic increases in glacial melt rates are cause for global alarm. It is now necessary to develop a deeper understanding of how the ASC responds to both anthropogenic and natural climate forcing. Some suggested avenues for future research are provided below.

1. **Internal decadal variability**. There are multiple lines of evidence pointing to decadal warming trends of Antarctic shelf bottom water in several Antarctic coastal regions. These ocean warming trends may at least be partially caused by anthropogenic forcing (see §4.1). However, the natural decadal variability of these water masses and the drivers of the internal variability are poorly understood. Constraining the inter-annual to decadal scale internal variability of the heat transport across the continental slope is crucial to identifying the extent to which the shelf water warming trends are driven by anthropogenic forcing and how much warming should be expected with further emissions.

2. **Changes in surface forcing.** Observational and modeling efforts continue to refine our understanding of the physical drivers of ASC dynamics at near steady state. A

natural evolution is to understand how the ASC and the physical process maintaining it will respond to a changing climate. For example, the coastal easterly winds and katabatics are fundamental to the ASC, but there is little understanding of how these winds respond to a warming climate (e.g. *Spence et al.* [2014a]). Climate models also have difficulty simulating surface buoyancy fluxes associated with atmospheric, sea ice and glacial melt processes near the ASC, leading to significant model biases and large uncertainties in climate projections (e.g. *Purich et al.* [2018]). Improved constraints on projected changes in ocean surface fluxes of momentum and buoyancy will also allow for better constraints on how ocean dynamic processes (i.e. eddy and tidal fluxes) near the Antarctic margin may change.

3. **Feedback mechanisms.** While there is growing appreciation for the importance of the ASC in climate change, perturbation feedbacks associated with ASC dynamics at this stage are often left to conjecture. Understanding if an initial perturbation will be amplified or weakened, and the physical processes behind this feedback, is fundamental to climate change projections. Interactions between a multitude of processes including dense shelf water formation, on-shelf transports of CDW, sea ice growth and melt, glacial ice cavity shapes, glacial ice freezing and melting are important avenues of research that will improve global climate projections [*e.g. Donat-Magnin et al.*, 2017; *Silvano et al.*, 2018].

5. Summary

The main goals of this review article were (i) to document recent advances in our understanding of the dynamical structure of the ASC (§§2-3); (ii) to highlight an increased appreciation of the ASC's impact on larger-scale climate (§4); and (iii) to identify priorities for further study of the ASC and its climate connections. The key points of goals (i) and (ii), taken together, demonstrate that significant challenges remain for predicting future changes to the ASC and the Antarctic margins. Observational studies and high-resolution modeling have revealed the ASC to be a narrow and variable circulation feature, where processes occurring over the time scales of weeks (mesoscale) to hours (tides) have a significant impact on heat and tracer fluxes [*Stewart et al.*, 2018]. At larger scales, coupled climate models have identified processes by which the ASC responds to remote changes [*Dutrieux et al.*, 2014; *Steig et al.*, 2012] or the ASC enables connections between different regions of the Antarctic margins [*Hughes et al.*, 1999; *Spence et al.*, 2017]. At present, modeling and observational capabilities are unable to capture feedbacks between these small-scale dynamics and the larger-scale forcing. Adequately representing these small-scale features in GCMs through physical parameterizations is one approach, but creatively coupling different model types and model domains may also provide additional insight [*Nakayama et al.*, 2018].

In §2 a geographic classification of the frontal structure at the upper continental shelf around Antarctica is provided, emphasizing processes that govern the along- and cross-slope circulation of the ASC. Abrupt transitions in this structure are observed to occur across bathymetric features associated with localized production of DSW, e.g. the southern Weddell Sea and Ross Seas (Fig. 4). Other transitions are less distinct, and, particularly in East Antarctica, high-resolution sections across the shelf break are sparse. In regions where DSW is found on the shelf, the on-shore transport of CDW is largely carried out by mesoscale eddies, and the heat flux is likely to be sensitive to subtle changes in the generation of mesoscale variability or changes to the density structure (and thickness gradients of the CDW density class) at the shelf break. These are processes that are difficult to capture in models with grid spacings larger than roughly 1 km [*St-Laurent et al.*, 2013]. Over Fresh Shelf regions, the accessibility to the shelf of CDW intrusions is the dominant constraint on on-shore heat transport. Modifications to the depth of CDW layers are changing with time [*Schmidtko et al.*, 2014], and are likely to depend on both localized and large-scale changes to atmospheric circulation patterns. The classification in Fig. 4 relies on observations collected over many decades, but the majority of these data sets represent a single snapshot of the frontal structure; the extent to which the density structure at the shelf break varies over seasonal or interannual time scales remains an open question. Our ability to predict abrupt changes in the frontal structure, and thus access of CDW to the continental shelf, is critical for future predictions of the stability of the AIS.

In §3 we reviewed the various forms of variability that manifest in the ASC. Almost all of the literature on this topic is drawn from the 2 to 3 decades since the last major reviews of the ASF [*Jacobs*, 1991; *Whitworth et al.*, 1998]. Thus the increasing recognition of the ASC as a dynamic feature (see *e.g.* Fig. 6) represents a major shift in the community's understanding of the ASC. In §3 we emphasized three specific phenomena — overflows, tides and eddies — because their roles in the ASC (summarized in Fig. 3(a–c)) have received substantially more attention in recent studies. However, the synthesis of current understanding presented in §3 and Fig. 3 has been drawn from an incomplete patchwork of regionally-specific observational and modeling studies, and is therefore likely still an incomplete characterization of the role of variability in the ASC. It is also increasingly clear that these modes of variability cannot be understood in isolation: for example, dense water overflows generate eddies in overlying fluid layers [*Lane-Serff and Baines*, 1998] and drive CDW onto the continental shelf [*Stewart and Thompson*, 2016], dense water overflows are enhanced by cross-slope tidal excursions [*Ou et al.*, 2009; *Padman et al.*, 2009], and tidal intensification of the the ASF [*Flexas et al.*, 2015] likely modifies its stability properties and thus propensity for eddy generation [*Isachsen*, 2011]. Further work is required to achieve a complete understanding of these interplays and their role in shaping the ASF, and of feedbacks between modes of ASC variability and continental-scale climate variability. Accurately quantifying the relative contributions of different types of ASC variability may require reanalysis products able to resolve features of just a few kilometers in scale around the entire Antarctic margins [*Stewart et al.*, 2018]; it will likely be decades before computational resources and sufficient measurements to produce such tools become available. In the interim, there remain many gaps in understanding to fill via a combination of observational deployments with high spatial and temporal resolution [*e.g. Azaneu et al.*, 2017; *Couto et al.*, 2017], process-oriented studies to disentangle different phenomena unambiguously [*e.g. Stewart and Thompson*, 2016; *Daae et al.*, 2017], and comprehensive forward modeling at circum-Antarctic scales [*e.g. Goddard et al.*, 2017; *Stewart et al.*, 2018].

In §4 we focused on the role the ASC plays in Earth's climate. We discussed the challenge of identifying ASC variability on climate relevant time-scales, the possible drivers of this variability, and how the ASC can impact global climate change. Observational studies find ASC properties to be highly variable with large seasonal and sub-monthly fluctuations [*Graham et al.*, 2013; *Peña-Molino et al.*, 2016]. Detecting and attributing a changing climate amidst this high frequency variability is difficult, but increasingly important. A significant decadal scale warming trend in Antarctic shelf bottom water to the west of the Antarctic Peninsula has recently been identified, and this trend is very likely the key driver of increased glacial melt rates in the region (Fig. 7a). The extent to which this shelf bottom water warming trend is caused by anthropogenic emissions and should be expected to continue, or is part of natural climate variability that should subside in coming years, is highly uncertain. Global climate models are not able to resolve the fine-scale processes important to ASC dynamics, but they do robustly project substantial warming of the CDW located further offshore with continued anthropogenic emissions (Fig. 7b). There are many large-scale climate processes capable of altering the ASC. We focused primarily on changes in the Antarctic coastal winds associated with SAM and ENSO. Both positive (negative) phases of the SAM and El Niño (La Niña) events can weaken (strengthen) the coastal easterly winds, leading to a drop (rise) in coastal sea level (Fig. 7c,d), a shoaling (deepening) of subsurface isopycnals and a weakening of the ASC that may allow for more onshore flowing of CDW [*Spence et al.*, 2014a; *Armitage et al.*, 2018; *Paolo et al.*, 2018]. By modulating the cross shelf transport of dense shelf water that fills the abyssal ocean, CDW that drives ice shelf melt rates, and nutrients vital to Southern Ocean productivity, the ASC plays a uniquely important role in determining Earth's climate. The response of the dynamic processes that sustain the ASC to anthropogenic emissions will have widespread consequences [*Rintoul*, 2018].

Observations will continue to be essential for constraining future changes to the ASC. There is a need to exploit opportunities provided by new technologies to make the necessary high-resolution, long-term ocean observations at the Antarctic shelf break and slope across wide regions of the Antarctic margins. The SASSI program for the International Polar Year was the first international effort to coordinate observations all around the

Antarctic continent across the continental shelf and slope (see Special Issue of Ocean Science). The primary tool was moorings, enabling observations in winter. However it is costly and technically challenging to maintain a moored array on the slope in the longer term. Moorings that send capsules to the surface to transmit their data via satellite, or moorings with acoustic transmission of data to surface "data bus" vehicles may be options for the future. Profiling floats (e.g. the Argo array) have made an enormous contribution to understanding the processes in the Southern Ocean. The ASC is more problematic, however, because it is narrow, shallow, and under sea ice for much of the year. Although profiling floats can be acoustically tracked under the ice, this technology will not in the foreseeable future be sufficiently widespread or accurate to locate floats within the ASC system. Floats and drifters are now being developed that will profile on the Antarctic continental shelf, and that will follow bathymetric contours as dense water spills off [*Schulze Chretien and Speer*, 2018]. These promise great insight into the dynamics and processes of the subsequent mixing and topographic steering. New methodologies such as using satellite altimetry to monitor the sea surface slope [*Armitage et al.*, 2018; *Dotto et al.*, 2018] may be more promising, but there remains a need to link these surface changes to the interior dynamics. We suggest that the Southern Ocean Observing System (SOOS; `soos.aq`) has shown that it can play a leading role in the implementation of an international observational network [*Meredith et al.*, 2013].

This review article is strongly motivated by the critical influence that the ASC exerts on the stability of the AIS. Melt rates at the Antarctic margins are expected to be sensitive to changes in the temperature of CDW, the rate at which CDW is delivered on to the continental shelf, and the thickness of the water column that CDW occupies over the continental shelf. This latter feature impacts whether warm water reaches the grounding zone in many ice shelf cavities. To date, most mechanistic theories for temporal changes in Antarctic melt rates have invoked changes in atmospheric circulation patterns, e.g. [*Spence et al.*, 2014a; *Paolo et al.*, 2018], even over glacial-interglacial time scales [*Hillenbrand et al.*, 2017]. These theories largely emphasize localized changes in the access of CDW to the continental shelf, and the associated modifications to the thickness of the CDW layer on the shelf [*Dutrieux et al.*, 2014]. However, Southern Ocean waters have warmed persistently and circumpolarly over the past half century [*Gille*, 2008; *Schmidtko et al.*, 2014], and on shore transport has been shown to be sensitive to changes in the density structure at the shelf break, which is likely to accompany a warming ocean [*Stewart and Thompson*, 2016]. The relative importance of these three contributions to the heat budget of the Antarctic margins, over various time scales, requires further exploration.

This article has attempted to strike a balance between providing a comprehensive summary of physical oceanographic advances in our understanding of the ASC, while seeking to describe these processes in a manner that is accessible to a broad audience. Our ability to assess the climate implications of an evolving ASC inherently requires interdisciplinary research. Improvements in dynamical models of the ASC should lead to improved boundary conditions for ice sheet models. These models then need to be tested against a range of measurements from *in situ* or under-ice platforms, satellites and even paleorecords to understand feedbacks between ice sheet dynamics and the circulation of the ASC. Efforts in the future to bridge these disciplinary boundaries will be particularly valuable.

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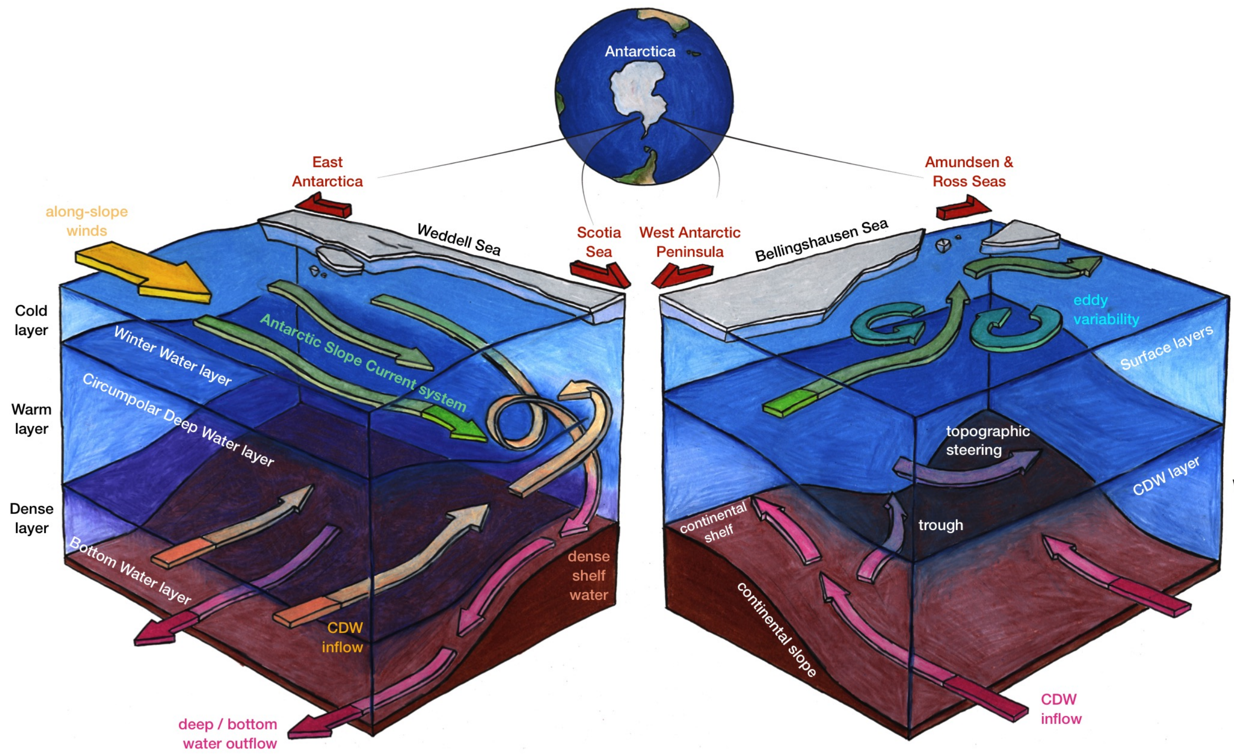

Figure 1. Sketch of the along- and cross-slope circulations associated with the Antarctic Slope Current (ASC) system. Schematics of the ASC on either side the Antarctic Peninsula illustrate regional differences in the ASC. The left-hand panel shows key processes that occur in the Weddell Sea. Here, dense water formation on the shelf is exported via bottom water outflows, enabling an onshore transport of warm Circumpolar Deep Water (CDW) that is isolated from frictional surface and bottom boundary layers. Over much of West Antarctica, for instance in the Bellingshausen Sea (right-hand panel), where bottom water formation is absent, CDW floods the upper continental slope and shelf. Strong along-slope winds in East Antarctica and the Weddell Sea maintain a strong shelf break front; surface winds are less uniform in West Antarctica. Topographic steering of the ASC at major bathymetric troughs is a prominent feature. Classifications of regional variations in the ASC is discussed in more detail in §2. Note that the vertical scale in this figure has been distorted to emphasize ocean processes and circulation.

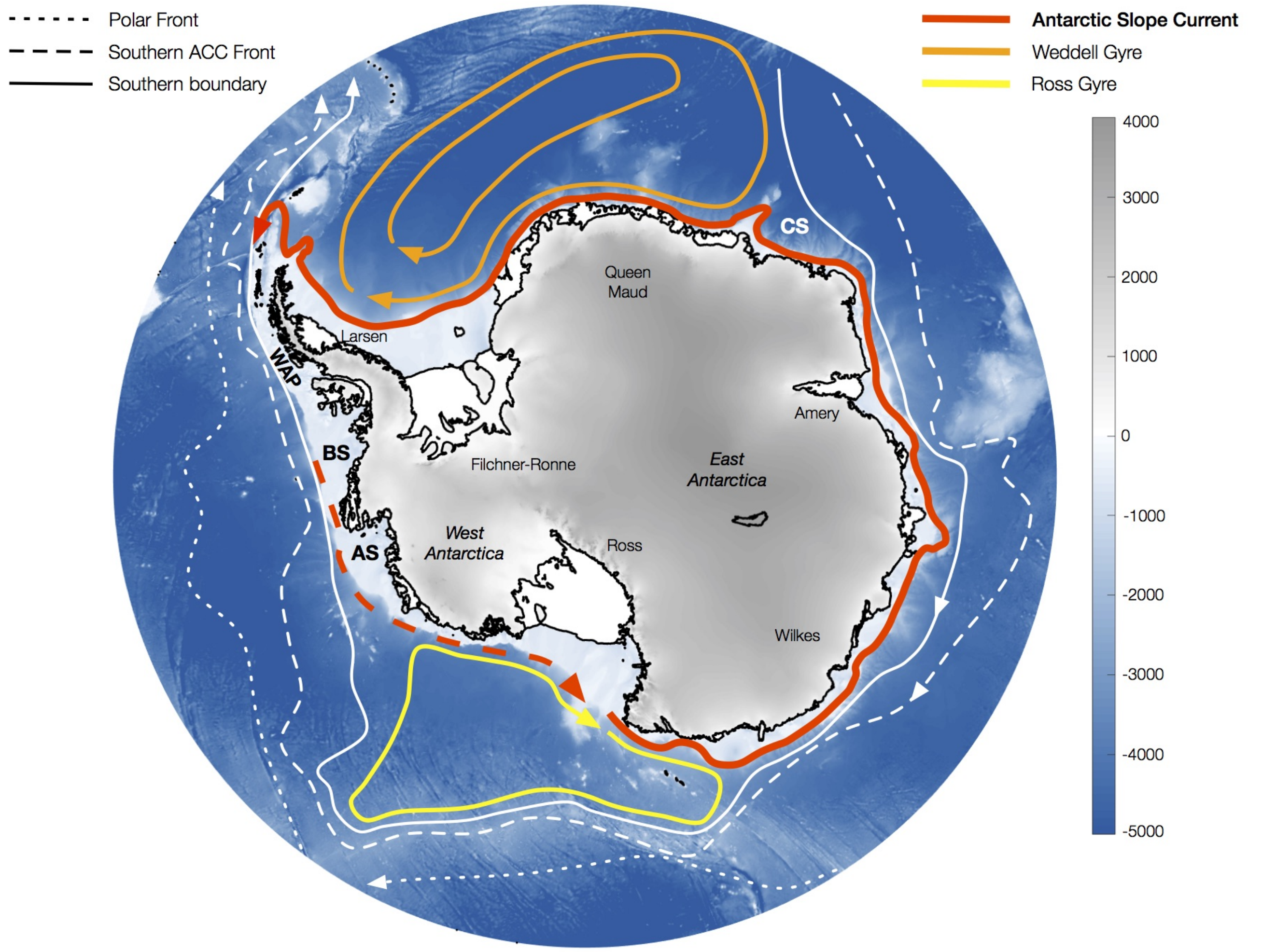

Figure 2. Schematic circulation of the Antarctic margins. The Antarctic Slope Current (ASC, red) is depicted as a near-circumpolar, anti-cyclonic (westward) feature appearing at the shelf break in East Antarctica and the Weddell Sea. Uncertainty regarding the initiation of the ASC is indicated by the dashed line in the Bellingshausen and Amundsen Seas (BS, AS) in West Antarctica, as well as the western Ross Sea. Along the West Antarctic Peninsula (WAP), a slope current flows eastward, along with the southern boundary of the Antarctic Circumpolar Current (ACC). Interactions with the Weddell (orange) and Ross (yellow) Gyres, as well as the southern fronts of the ACC (white) are highlighted by their proximity to the ASC in various locations around the Antarctic margins, (*e.g.* east of the Cosmonauts Sea, CS). The color gives the topography: depth for the open ocean and elevation for ice shelves and ice sheets [*Schaffer et al.*, 2016]. Positions of the ACC fronts are based on *Orsi et al.* [1995]; gyre circulations are based on *Armitage et al.* [2018]; the ASC is plotted along the 1000 m isobath.

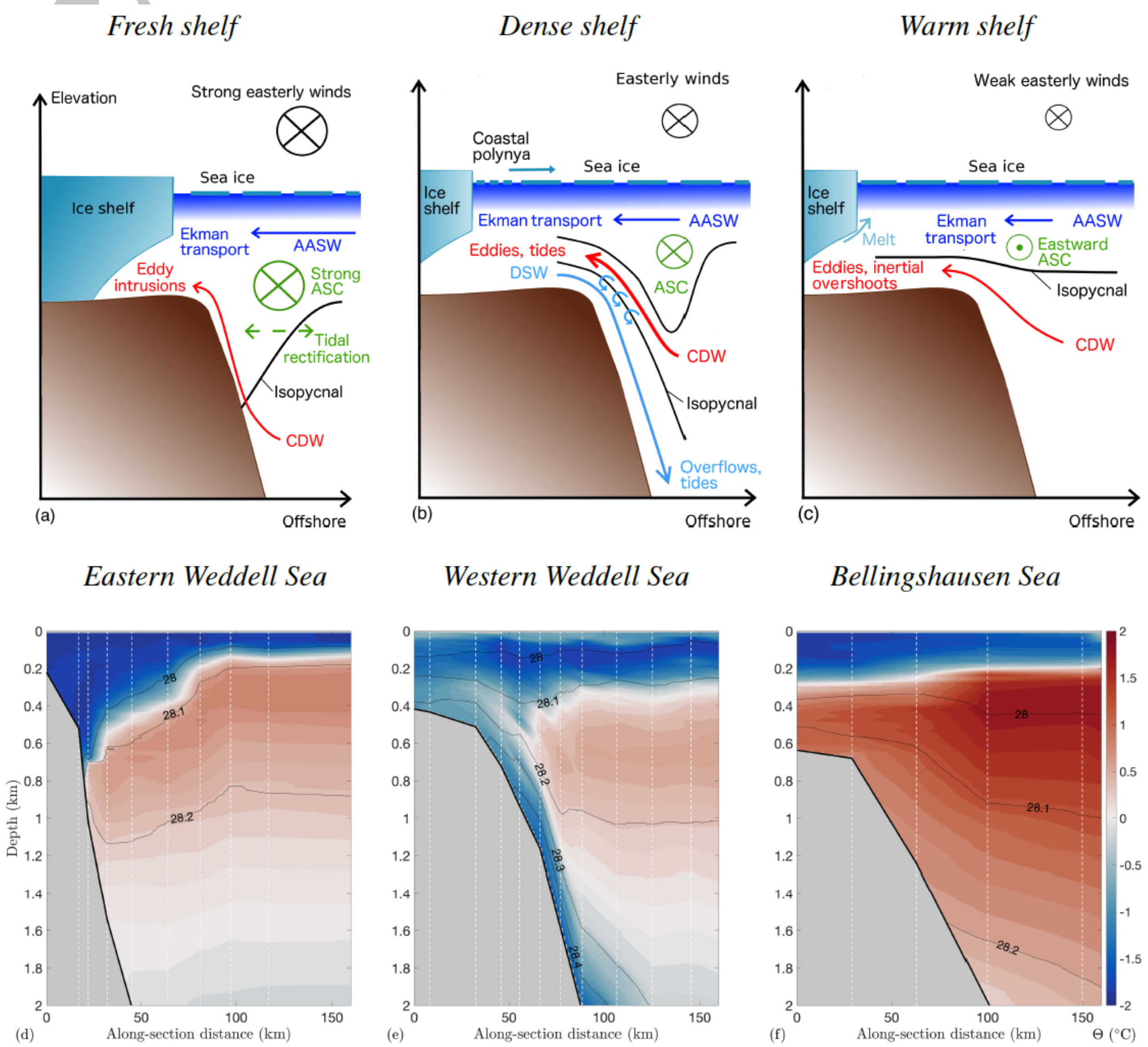

Figure 3. (a–c) Key water masses, along- and across-slope flows and supporting mechanisms in the (a) "Fresh shelf", (b) "Dense shelf", and (c) "Warm shelf" Antarctic Slope Current (ASC) regimes defined in this article. (d–f) Measurements of conservative temperature (colors) and neutral density (black contours) across the ASF in locations corresponding to each ASF regime: (d) the eastern Weddell Sea [*Heywood and King*, 2002], (e) the western Weddell Sea [*Thompson and Heywood*, 2008], and (f) the Bellingshausen Sea [*Orsi and Whitworth*, 2005]. Section locations are shown in Fig. 6, and white dashed lines indicate locations at which hydrographic casts were taken. The following water masses are identified: Antarctic Surface Water (AASW), Circumpolar Deep Water (CDW), Dense Shelf Water (DSW).

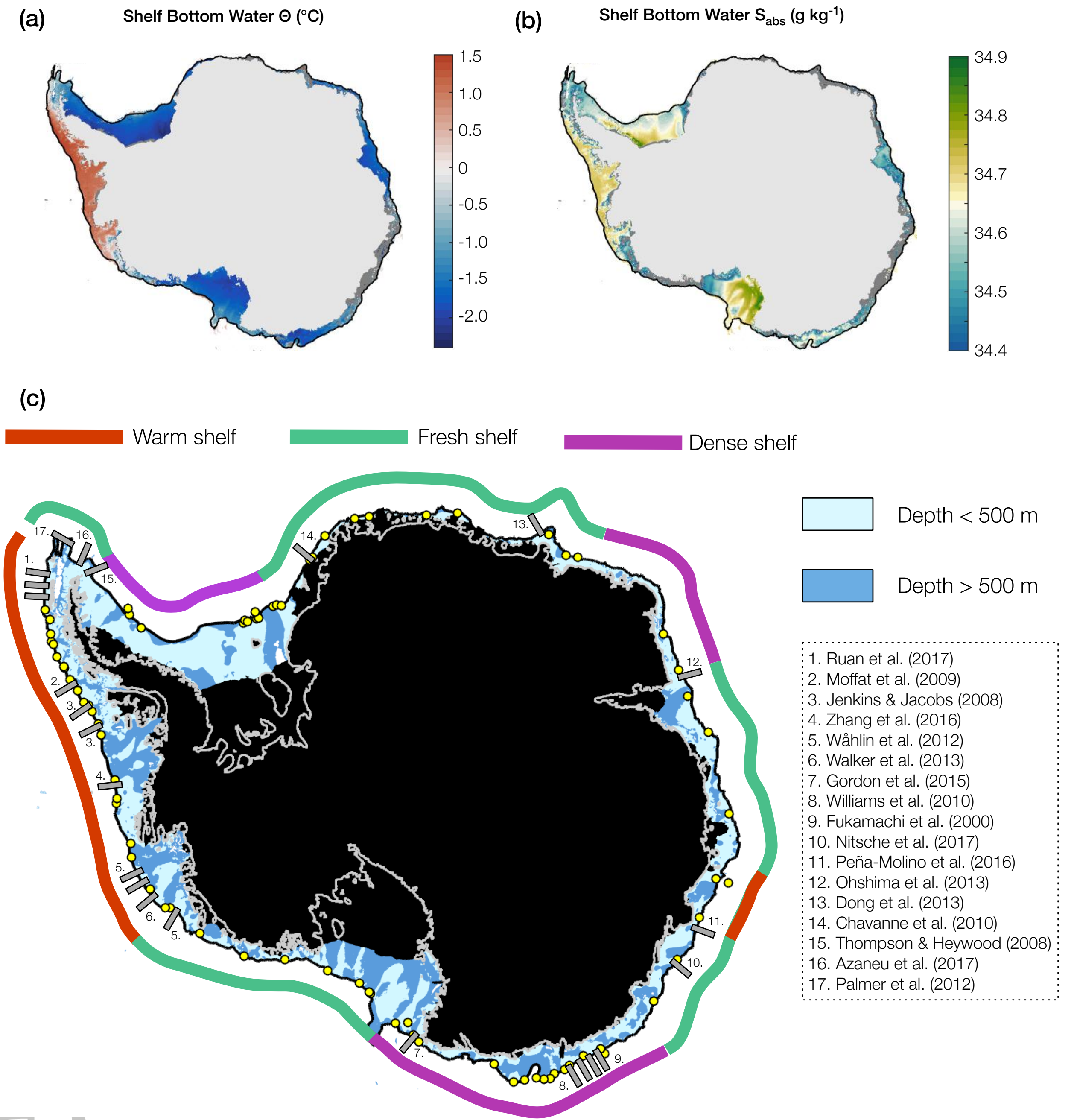

Figure 4. Classification of the Antarctic Slope Current system around Antarctica. (a) Conservative temperature and (b) absolute salinity of Antarctic Shelf Bottom Water (ASBW). (c) The colored bar shows the spatial distribution of the three ASC classifications depicted in Fig. 3: Warm Shelf, Fresh Shelf, Dense Shelf. The shelf break is indicated by the black contour marking the 1000 m isobath. The shading shows the bathymetry of the continental shelf. Yellow circles show the position of historical hydrographic measurements used to determine the presence of Dense Shelf Water from *Baines and Condie* [1998] and *Amblas and Dowdeswell* [2018]. Gray bars indicate the positions of recent hydrographic sections that were used in determining ASC classifications. References to descriptions of the hydrographic sections are provided in the dotted box.

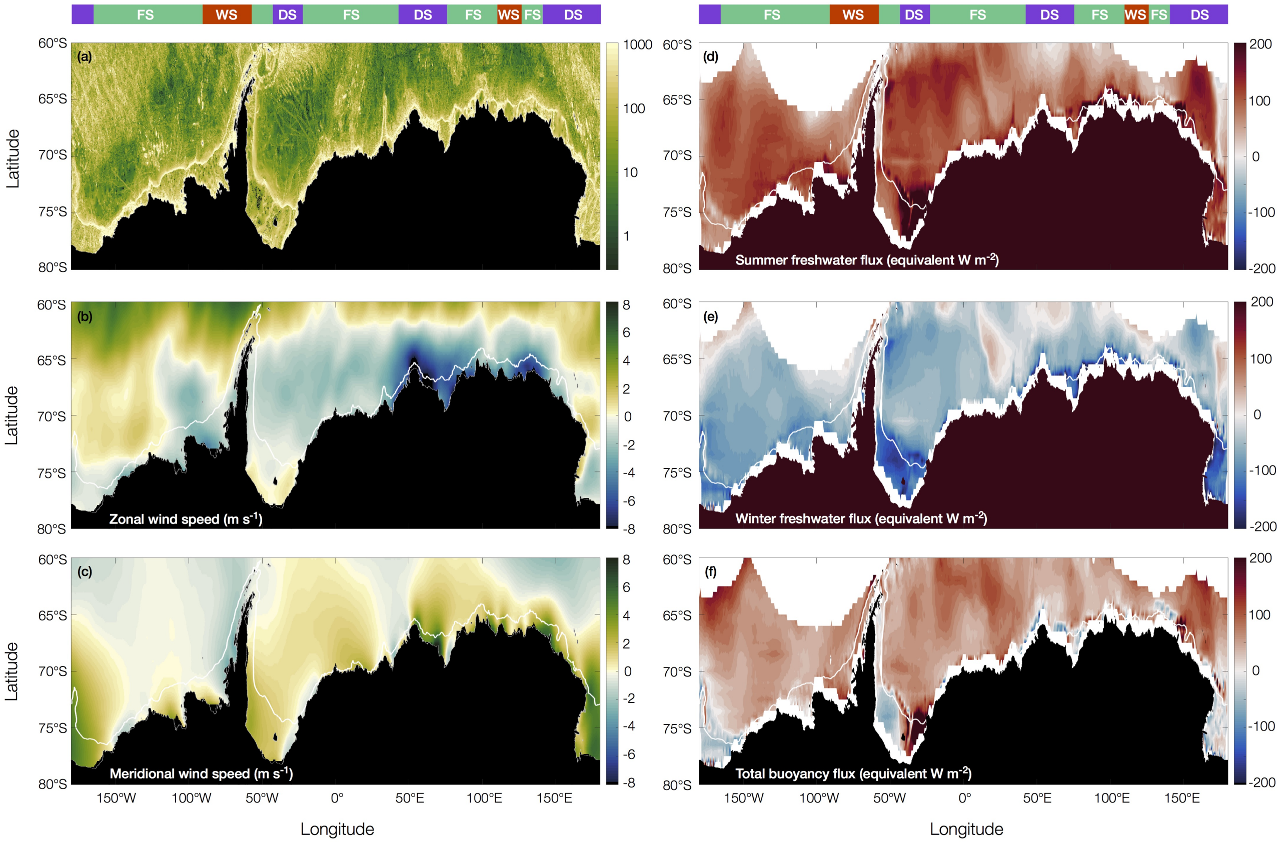

Figure 5. Surface forcing and environmental characteristics. (a) Relative strength of the topographic slope; the non-dimensional value, $(f\,|\nabla h|)\,/\,(\beta h)$, where h is the depth of the water column, f is the local Coriolis parameter, and β is the meridional gradient of f. This value compares the magnitude of the topographic potential vorticity gradient to the planetary potential vorticity gradient. Values greater than 1 indicate a dominance of the topographic PV gradient. (b) Zonal and (c) meridional wind speed (m s^{-1}) at 10 m above the surface from ERA-Interim reanalysis [*Dee et al.*, 2011]. (d) October-February and (e) March-September mean surface freshwater flux, given in equivalent units of heat flux (W m^{-2}). (f) Annual mean surface buoyancy flux (sum of heat and freshwater fluxes), given in equivalent units of heat flux (W m^{-2}). The net buoyancy flux is dominated by the freshwater component. Data shown in panels (d)-(f) are taken from and described in *Pellichero et al.* [2018]. The bars over the top panels show the ASC classifications as in Figs. 3 and 4.

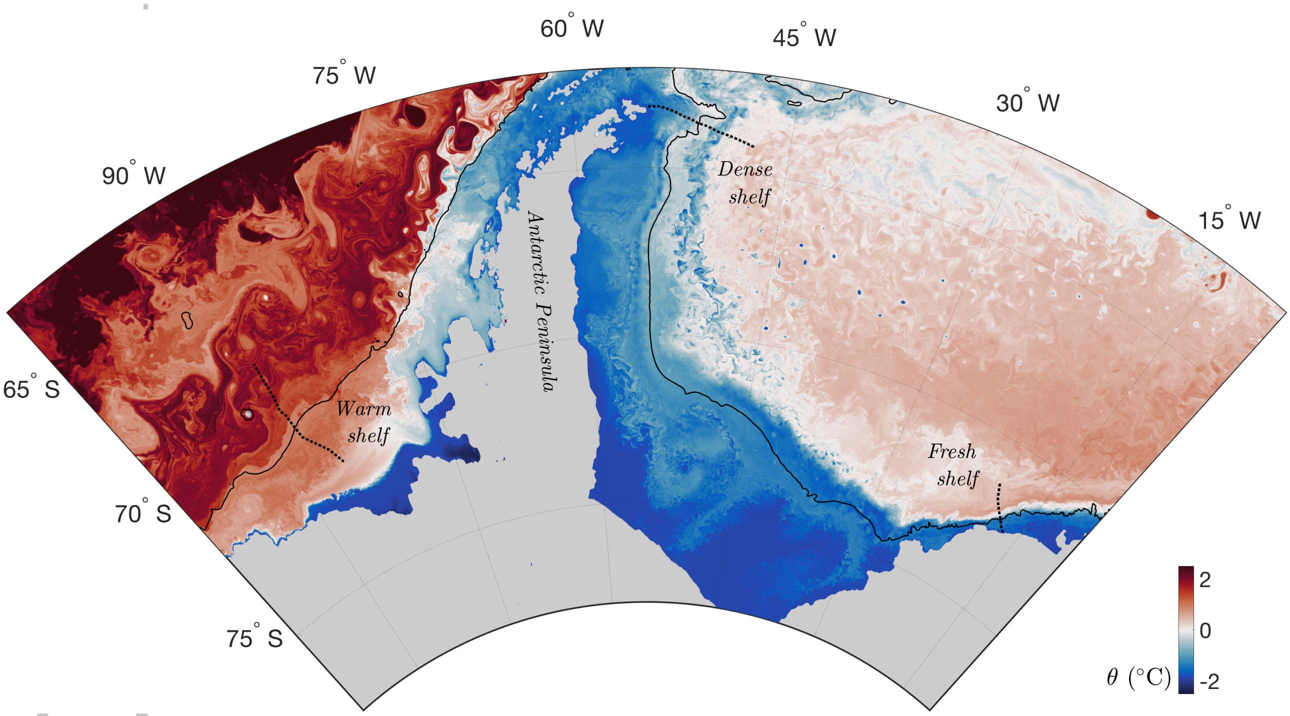

Figure 6. An illustration of the ASF's dynamic character, spanning the three major ASF regimes identified in this review (see §2 and §3), derived from a global ocean/sea ice simulation run at 1/48° horizontal resolution [*Stewart et al.*, 2018]. Colors indicate the potential temperature at a depth of 230 m, or at the ocean bed in regions shallower than 230 m, on simulation date October 9th, 2012. The black contour indicates the 2000 m isobath, which is approximately the center of the continental slope. Black dotted lines indicate the locations of the ship-based hydrographic sections shown in Fig. 3, with corresponding classifications of the ASF found at each site indicated by text labels.

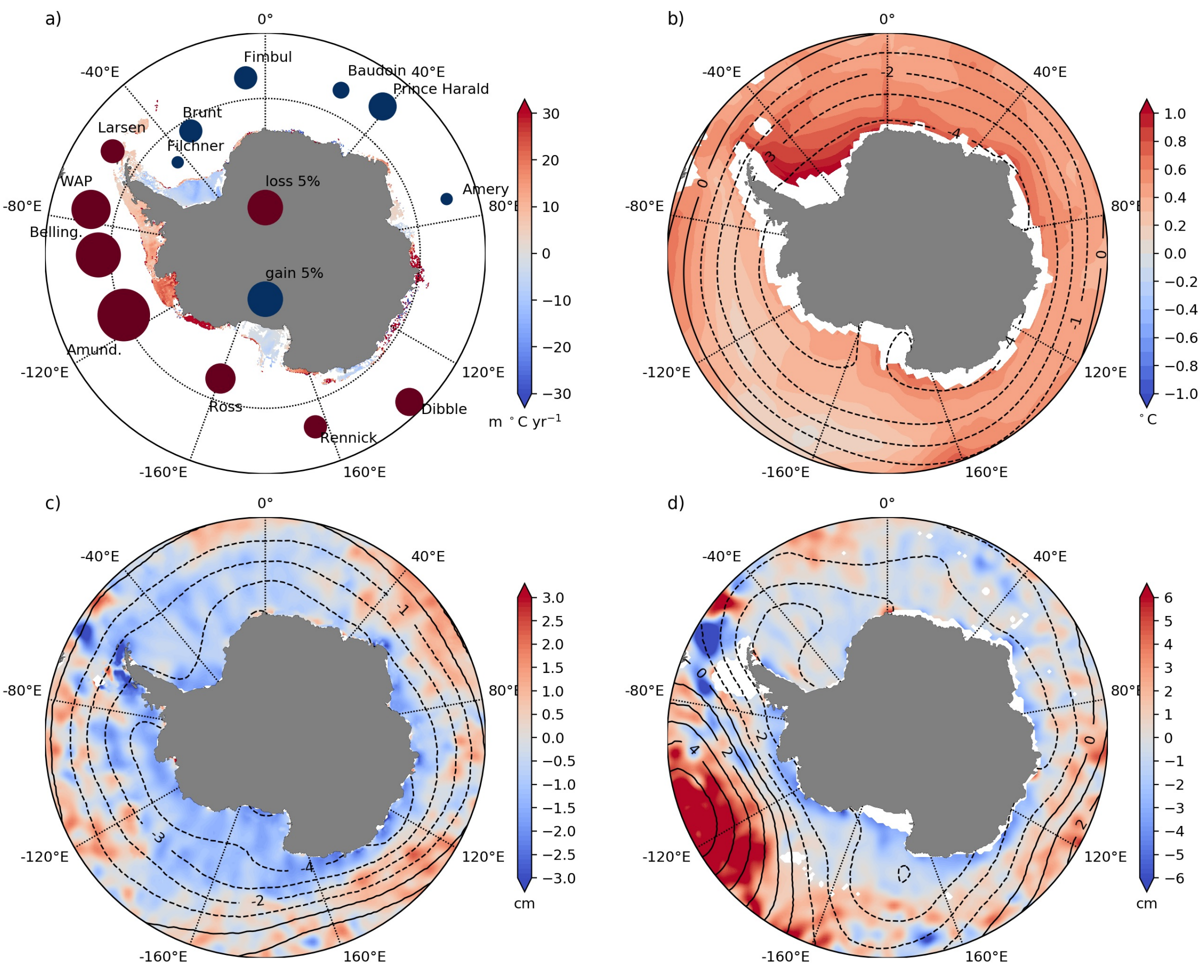

Figure 7. (a) Linear temperature trend (color, °C) significantly different from zero at the seabed for depths shallower than 1500 m for the period 1975 to 2012 reproduced with permission from *Schmidtko et al.* [2014]. Circles indicate the percentage of ice shelf thickness lost (red) or gained (blue) for the period 1994-2012 reproduced with permission from *Paolo et al.* [2015]. The ice shelves are text labeled: Larson is the average of the Larsen B, C, and D shelves; WAP (West Antarctic Peninsula) is the average of the Bach, Wilkins and George VI shelves; Bellingshausen is the average of the Abbot, Venable, and Stange shelves; Amundsen is the average of the Getz, Dotson, Crosson, Thwaites, and Pine Island shelves; and Ross is the average from the Ross-WAIS, Withrow, and Ross-EAIS shelves. (b) Year 2081-2100 minus 1981-2000 multi model mean temperature anomaly at 975 m (color, °C) and sea level pressure anomaly (black contours, 1 mb intervals, dashed negative) under the RCP8.5 emissions scenario for 21 CMIP5 models that have a positive SAM trend. (c) Sea level anomaly (colour, cm) and sea level pressure anomaly (black contours, 1 mb intervals, dashed negative) for positive SAM composites. (d) As in panel (c) but for positive El Niño composites.

Panels (c) and (d) are reproduced from *Armitage et al.* [2018].