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Temporal Changes in the Antarctic Circumpolar Current

IMPLICATIONS FOR THE ANTARCTIC CONTINENTAL SHELVES

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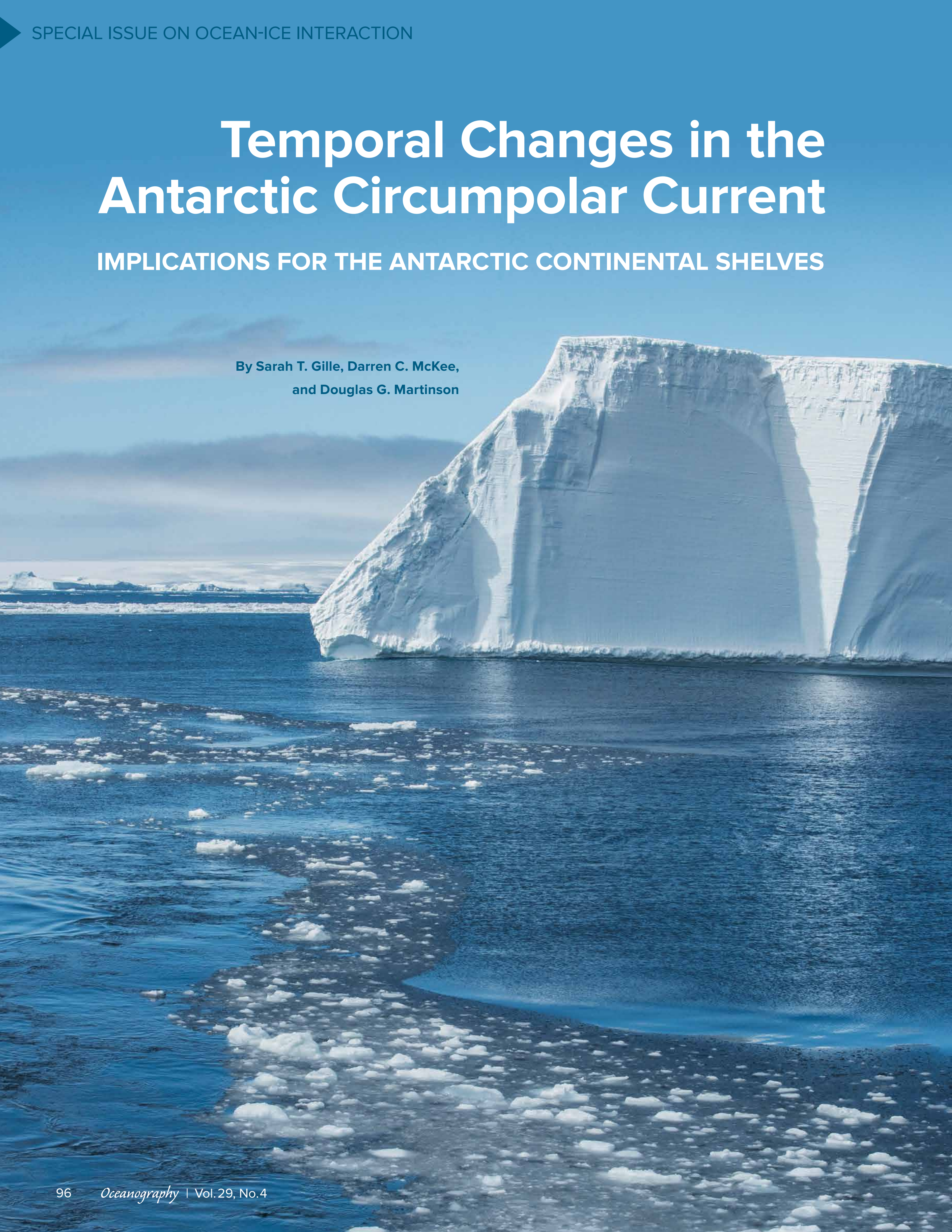

> "One of the major sources for climate change in the Southern Hemisphere comes from the middle atmosphere, approximately 10–50 km above Earth's surface."

ABSTRACT. Some of the most rapid melting of ice sheets and ice shelves around Antarctica has occurred where the Antarctic Circumpolar Current (ACC) is in close proximity to the Antarctic continent. Several mechanisms have been hypothesized by which warming trends in the ACC could lead to warmer temperatures on the Antarctic continental shelves and corresponding thinning of ice shelves. One possibility is that a southward shift in the dominant westerly winds has led to a southward shift in the ACC, bringing comparatively warm (1°C–3°C) Circumpolar Deep Water (CDW) in closer contact with Antarctica; however, satellite altimetry does not provide strong evidence for this option. A second possibility is that stronger winds have led to stronger poleward eddy heat transport, bringing more CDW southward. In addition, submarine canyons and winds are hypothesized to be critical for transporting CDW across the continental shelves. The specific mechanisms and the relative roles of westerly winds, easterly winds, and wind-stress curl remain areas of active research.

INTRODUCTION

The Antarctic Circumpolar Current (ACC) is the major current system of the Southern Ocean, transporting approximately 150×10^6 m^3 s^{-1} of water eastward around Antarctica (e.g., Ganachaud and Wunsch, 2000; Rintoul and Sokolov, 2001; Mazloff et al., 2010; Griesel et al., 2012). The ACC consists of multiple fronts, each corresponding to jet-like currents. From north to south, the fronts are referred to as the Subantarctic Front, the Polar Front, and the Southern ACC Front (Figure 1; Orsi et al., 1995), though each of them may have multiple quasi-stable manifestations (Sokolov and Rintoul, 2009a). The fronts, which are steered by bathymetry, are top-to-bottom features and serve as major water mass transitions, separating waters with substantially different densities and correspondingly different temperature and salinity properties. For example, in surface waters, the temperature difference between the north and south of the Polar Front is about 3°C–4°C (e.g., Dong et al., 2006).

Physical oceanographers often hypothesize that the ACC fronts isolate the Antarctic marginal seas from the mid-latitude gyres that transport heat poleward within the ocean. This occurs not only because of the water mass property contrasts across the fronts, but also because the fronts coincide with steeply tilted isopycnal surfaces that rise from 1,000 m to 2,000 m depth in mid-latitudes to outcrop at the surface within the ACC (Martinson, 2012). Water parcels preferentially mix along isopycnals rather than across them, bringing water from mid-depth into contact with the atmosphere but preventing it from reaching the Antarctic continental margins (e.g., Marshall and Speer, 2012).

While the tilted isopycnals of the ACC may help to confine warmer, less-dense water to the north of the ACC, they also serve as a conduit that connects atmospheric forcing to the ocean interior, allowing the Southern Ocean to change in response to a changing atmosphere. Profiling float observations collected since 2004 indicate that the Southern Hemisphere oceans, poleward of 20°S, show a more rapid increase in heat content than any other sector of the global ocean (Roemmich et al., 2015). Over multidecadal time periods, observations indicate that the Southern Ocean has experienced some of the most significant long-term warming in the global ocean (e.g., Gille, 2002, 2008; Böning et al 2008). This warming extends through the full water column: warming of bottom water in recent decades is more evident in the Southern Ocean than in bottom waters elsewhere in the world (Purkey and Johnson, 2010, 2013).

Because of the ACC's role as a barrier between the mid-latitudes and the Antarctic margin, we might expect that changes in the region of the ACC would have little impact on the Antarctic continental shelves. However, evidence suggests otherwise. Figure 2 shows regions of rapid ice mass loss from the continent (red dots) determined by Rignot et al. (2008) and the mean ACC position (shaded). The latitude of the ACC varies along its circumpolar path, and the latitude of the Antarctic continental margin also varies with longitude, meaning that the distance between the ACC and the continent can be thousands of kilometers or just a few hundreds of kilometers. Rapid ice melt is concentrated in the Amundsen and Bellingshausen Seas, just upstream of Drake Passage, and in the region south of Australia. Strikingly, these regions are also places where the ACC has its closest approach to the Antarctic continent.

The goal of this paper is to review the possible mechanisms by which changes in the ACC might influence water properties on the Antarctic continental shelves and correspondingly control ice melt. First, we review the oceanic processes that are hypothesized to contribute to glacial melt rates and also the role that changing atmospheric processes are thought to play in the forcing that drives the ACC. We then evaluate observed changes in the ACC and discuss whether they are consistent with observed forcing changes. We follow with an examination of the roles that wind and submarine canyons play in bringing water from the ACC onto the Antarctic continental shelf. The article concludes with a summary of the current understanding of ACC influences on Antarctic ice shelves.

BACKGROUND: LINKING THE ATMOSPHERE AND OCEAN TO THE CRYOSPHERE

Recent studies (e.g., Jacobs et al., 2011; Pritchard et al., 2012) emphasize the possibility that the ocean plays a critical role in determining how Antarctic continental ice sheets melt. These ice sheets are buttressed in part by the floating ice shelves that extend out over the ocean. Circumpolar Deep Water (CDW), which originates in the ACC (e.g., Orsi et al., 1995), has temperatures of 1°C–3°C (e.g., Santoso et al., 2006; Schmidtko et al., 2014) and has warmed along with the Southern Ocean as a whole. CDW can be transported onto the Antarctic continental shelf, and because it is dense relative to shelf waters, it can circulate through the cavities beneath the ice shelves. In addition, CDW is comparatively warm, which can lead to basal melting of the ice shelves and eventually ice shelf collapse. Ice sheet thinning or collapse can, in turn, lead to thinning of the continental ice sheets because their buttressing has been weakened or removed. Evidence from satellites and aircraft surveys indicates that the ice shelves have thinned in recent years (Rignot et al., 2013; Paolo et al., 2015), predominantly as a result of basal melting (Rignot et al., 2013; see Dinniman et al., 2016, in this issue, for a review basal melting mechanisms). Figure 2 shows that regions of significant ice shelf thinning largely coincide with regions of substantial ice loss from the Antarctic continent where the ACC is in close proximity to the continent. These observations indicate the possibility that the system could be highly sensitive to modifications in ocean circulation (e.g., Hellmer et al., 2012). Thus, a critical goal has been to understand the chain of climate-related events that allow CDW to enhance basal melting of ice shelves.

One of the major sources for climate change in the Southern Hemisphere comes from the middle atmosphere, approximately 10–50 km above Earth's surface. Anthropogenic emissions of chlorofluorocarbons during the twentieth century resulted in a stratospheric ozone hole over the South Pole, starting in the 1980s. The ozone hole resulted in exceptionally cold temperatures over the pole in spring and summer and correspondingly intensified temperature gradients between the pole and mid-latitudes, as well as a stronger polar vortex (e.g., Baldwin et al., 2003). These stratospheric effects can propagate downward

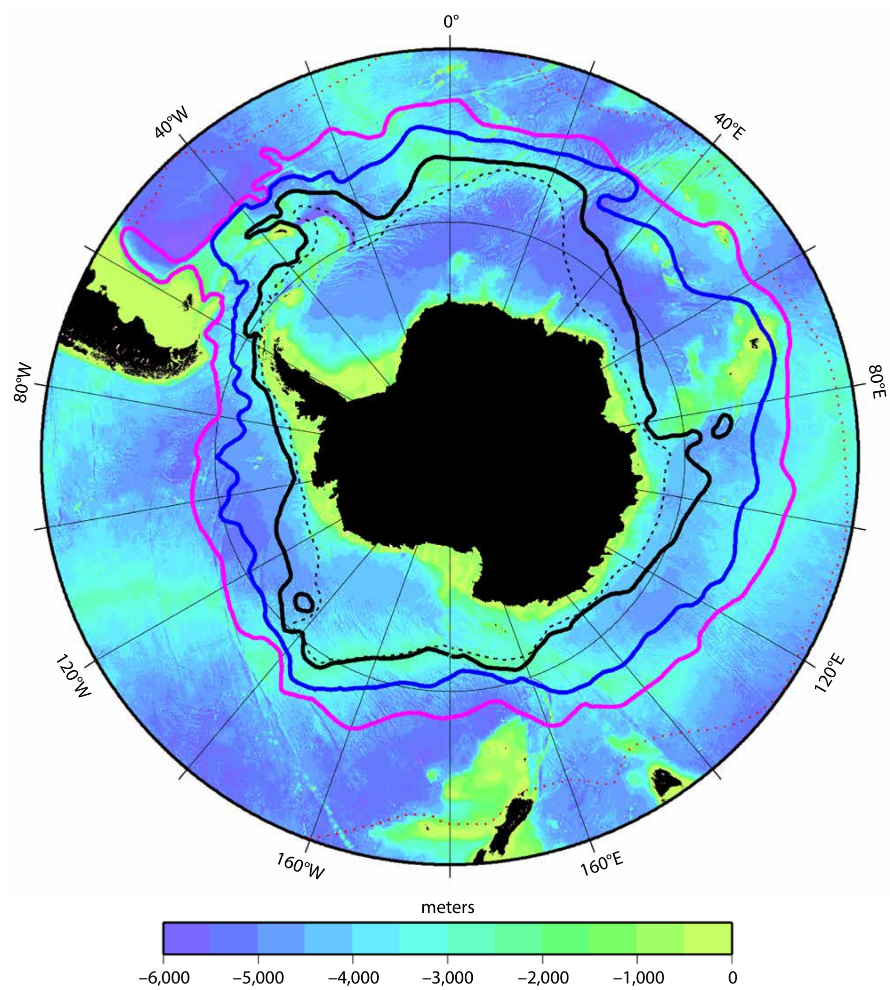

FIGURE 1. Major frontal features that define the Antarctic Circumpolar Current (ACC) superimposed over bathymetry: the Subantarctic Front (magenta), the Polar Front (dark blue), and the Southern ACC Front (black). The figure also shows the Subtropical Front (red dotted line) and the Continental Water Boundary (black dotted line). *Frontal positions from Orsi et al. (1995) and bathymetry by Smith and Sandwell (1997)*

through the troposphere (D. Thompson et al., 2005) and are associated with intensification of the leading order pattern of Southern Hemisphere atmospheric variability called the Southern Annular Mode (SAM; e.g., D. Thompson and Wallace, 2000), implying a strengthening and poleward shift of winds over the Southern Ocean (e.g., Cai, 2006; Fyfe and Saenko, 2006; Swart and Fyfe, 2012; Bracegirdle et al., 2013). Although the ozone hole is beginning to recover, greenhouse warming can also lead to intensification of the SAM, which could mean a persistent strong SAM in the future (e.g., Arblaster et al., 2011; Polvani et al., 2011; Gillett et al., 2013). Several recent studies point out the pitfalls in using the SAM as a simple index for Southern Hemisphere variability: changes in jet strength and position both influence the SAM index, and as a result, the SAM is an unreliable proxy for any one parameter of the wind (Swart et al., 2015; Solomon and Polvani, 2016).

While there may be doubts about the fidelity of the SAM as a proxy for all aspects of the changing wind, the impact of changing winds on the ocean also remains a source of speculation. If ozone depletion and greenhouse warming result in long-term changes in tropospheric winds, then a natural question is whether the ACC has changed in direct response to wind changes. A southward displacement of the wind jets might be expected to result in a southward displacement of the jets that comprise the ACC, as suggested by the third Coupled Model Intercomparison Project (CMIP3; e.g., Fyfe and Saenko, 2006), though not by CMIP5 (e.g., Meijers et al., 2012). In addition, stronger winds might imply a spin up of more eddy kinetic energy (e.g., Meredith and Hogg, 2006). Either of these processes could lead to greater southward transport of CDW and facilitate basal melting of the Antarctic ice shelves. In the next section, we review research efforts to evaluate both southward displacement of the ACC and changes in eddy transport.

ACC RESPONSE TO CHANGING WINDS

Has the ACC Shifted Southward?

Data from a three-year record of sea surface temperature (Dong et al., 2006) and from 36 years of in situ observations in Drake Passage, including historical archives extending back to 1969 and expendable bathythermograph (XBT) data collected since 1996 (Sprintall, 2008), suggest the possibility of wind-induced poleward migration of the ACC, but a more complete assessment requires a broader range of observational data. The most complete full Southern Ocean data available to map changes in the ACC come from satellite altimetry. High-quality repeat altimetry started with the launch of ERS-1 in 1991 and TOPEX/Poseidon in 1992, and these data now offer a nearly 25-year record of sea surface height. The largest contributor to sea surface height comes from Earth's gravity field, the geoid, which is essentially time invariant. Geoid-related sea surface height undulations are of O(100 m) and are associated with seafloor topography and inhomogeneity of Earth's interior; they are not related to ocean circulation. Dynamic topography represents the sea surface height that would be observed if only geostrophic ocean currents influenced sea surface height, and it is roughly two orders of magnitude smaller than the geoid, with variations across the ACC of O(1 m). Geostrophic velocities across a given line vary in proportion to the first-derivative of dynamic topography computed along the line. Thus, a geostrophic jet that has a Gaussian velocity structure in the cross-jet direction will have a corresponding dynamic topography in the form of an

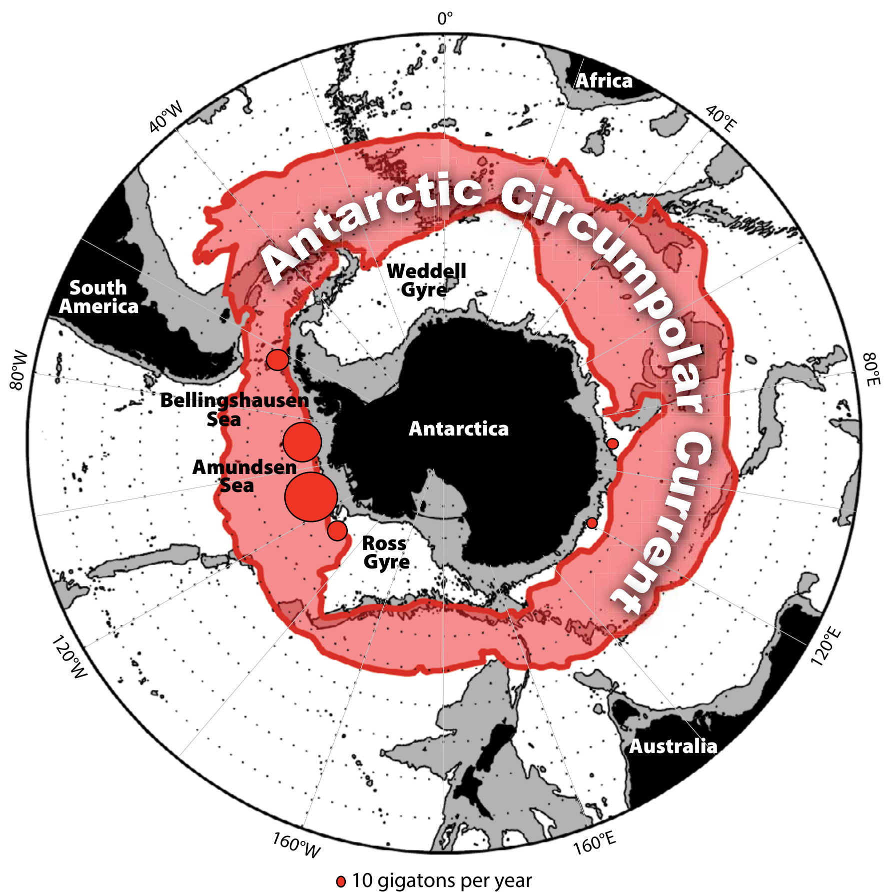

FIGURE 2. Mean position of the ACC frontal features (pink, bounded by red lines at northern and southernmost streamlines that pass through Drake Passage). Red circles indicate regions of significant ice mass loss from the Antarctic continent, as found by Rignot et al. (2008). The northern latitude boundary is 30°S, and latitudes are marked with dotted lines at 5° increments. Gray shading indicates bathymetry shallower than 3,000 m, and black indicates land.

error function, determined by integrating geostrophic velocity in the cross-jet direction (e.g., Kelly and Gille, 1990; Gille, 1994). Because mean dynamic topography is not measured directly, it must be inferred from other sources (e.g., see Griesel et al., 2012).

Studies of the time-varying position and strength of the ACC have explored a number of possible strategies for identifying ACC frontal positions. Recent work has typically obtained a best estimate of time-varying dynamic topography by adding the time-varying component of sea surface height (as measured by altimetry) to a best estimate of mean dynamic ocean topography derived from a combination of satellite gravity data (from the GRACE and GOCE missions), in situ observations, and altimetry (e.g., Rio and Hernandez, 2004; Maximenko and Niiler, 2005; Rio et al., 2009; Pavlis et al., 2012).

Because the ACC jets are geostrophic, the jet cores are expected to align with strong gradients in sea surface height. Time-varying positions of strong gradients are hard to identify (e.g., Graham et al., 2012) because nearby eddies can make gradient positions ambiguous (e.g., Chapman, 2014). Sokolov and Rintoul (2009a) found that they could reasonably identify the ACC fronts using fixed sea surface height contours. Their results indicated a large-scale southward shift in the sea surface height contours that define each of the fronts of the ACC (Sokolov and Rintoul, 2009b), implying a 60–70 km southward shift over 15 years.

One of the challenges to using a fixed sea surface height contour as a proxy for ACC frontal position is that the latitude of the height contour varies not only with changes in the geostrophic current but also with large-scale changes in steric sea level associated with warming and cooling (or freshening and salinification) of the upper ocean, which expand and contract seawater. The annual cycle of heating and cooling of the ocean leads to an annual cycle in steric sea level, which Sokolov and Rintoul (2009b) removed by plotting only an annual average in the jet positions that they inferred from sea level. However, eliminating the effects of long-term warming of the ocean is more difficult.

Several strategies have been tested to identify ACC frontal positions from altimeter data, given the fact that changes in sea surface height might be more indicative of shifts in steric height rather than displacements in gradients associated with geostrophic currents. Gille (2014) noted that the multitude of quasi-stationary frontal positions identified by Sokolov and Rintoul (2009a) imply that transport could shift between fronts without the frontal positions actually moving. In order to avoid tracking changes in fronts that were no longer transporting much mass, Gille (2014) computed displacements of a transport-weighted index of mean ACC position. The results showed substantial spatial and temporal variability in the latitude of the ACC (see Figure 3) but no long-term trends and no statistically significant correlation with variations in the SAM. Although a longer record might reveal a sharper signal, these results suggested that the long-term warming of the ACC might not be associated with a long-term poleward shift of the ACC.

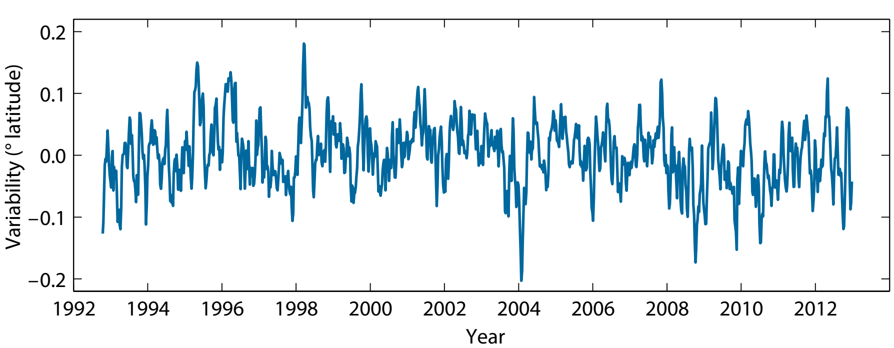

FIGURE 3. Time series of anomalies in the zonally averaged mean latitude of ACC transport (from Gille, 2014). Results indicate no long-term trend and no significant correlation between the ACC latitude and the Southern Annular Mode or the El Niño-Southern Oscillation indices (not shown).

Shao et al. (2015) implemented a slightly different approach, building on work of K. Thompson and Demirov (2006), who had shown that the skewness of the sea surface height probability density function changes sign at the latitude of major fronts. Shao et al. (2015) used this approach to identify the mean positions of the Subantarctic Front and the Polar Front in the ACC and to evaluate trends and sensitivity to SAM. Their results, like those of Gille (2014), indicated no evidence for a long-term trend in the positions of the ACC fronts and no correlation with the SAM.

While the altimeter analyses do not exclude the possibility that some segments of the ACC may have shifted in response to long-term changes in the wind, they provide little evidence for a large-scale poleward migration of the ACC. To explain the observed localized melting of Antarctic ice, a poleward shift might be required only in the ACC sectors that are already closest to the Antarctic continent (as illustrated in Figure 2), but the altimeter data also provide no convincing evidence for sector-wide poleward displacement of the ACC. These results thus imply that other mechanisms are likely to be more relevant for explaining how the ACC is changing on decadal time scales and what its implications are for heat transport into Antarctic marginal seas.

Do Stronger Winds Induce Stronger Eddies and More Poleward Heat Transport?

Although the ACC does not appear to have shifted southward in response to changing winds, we might hypothesize that it should nonetheless respond to stronger winds. Böning et al. (2008) noted that the warming and freshening of the Southern Ocean that they observed from historical data did not correspond to long-term shift in the slopes of isopycnals, implying no increase in transport. Eddy-resolving model results are consistent with this interpretation, indicating no acceleration of the mean ACC in response to stronger winds (e.g., Hogg et al., 2008; Munday et al., 2013). These results have been interpreted as evidence for eddy saturation: both altimeter data and eddy-resolving models indicate that stronger winds generate more eddies, albeit with a one- to three-year time lag (e.g., Meredith and Hogg, 2006; Hogg et al., 2015; Patara et al., 2016), and with regional variations and variations that depend on the relative phases of SAM and the El Niño-Southern Oscillation (e.g., Morrow et al., 2010). Thus, a long-term increase in wind strength would be expected to lead to a long-term increase in eddy kinetic energy in the Southern Ocean.

Occurrence of more eddies in the Southern Ocean implies more poleward heat transport. As Morrow et al. (2004) illustrate, most eddies in the ocean migrate meridionally and westward over their lifetimes, with warm-core (anticyclonic) eddies moving equatorward and cold-core (cyclonic) eddies moving poleward. In the Southern Ocean, eddies are advected eastward by the ACC instead of westward (e.g., Klocker and Marshall, 2014). As a result of the eastward motion, the meridional migration is also reversed (U. Zajaczkovski, Scripps Institution of Oceanography, *pers. comm*., 2016), and eddies are responsible for downgradient, poleward heat transport. Results from eddy-resolving models are generally consistent with observations, and models suggest that wind-induced eddies drive enhanced poleward heat transport across the ACC at mid-depth (e.g., Hallberg and Gnanadesikan, 2006; Screen et al., 2009; Abernathey et al., 2011; see Gent, 2016, and Meredith, 2016, for recent reviews.)

A warming Southern Ocean with stronger poleward eddy heat transport has the potential to deliver more and warmer CDW to the Antarctic marginal seas, particularly in regions where the ACC is in close proximity to the Antarctic continent. The next section examines mechanisms that are hypothesized to transport CDW across the Antarctic continental shelf and toward the margins of the Antarctic ice shelves.

HOW DO ACC WATERS INFLUENCE SUBGLACIAL CAVITIES?

While variability in the ice-free Southern Ocean can be studied from satellites, satellites do not illuminate the detailed mechanisms by which CDW from the ACC traverses the Antarctic continental shelf and eventually reaches the subglacial cavities below the Antarctic ice shelves (typically located 200–1,000 m below the ocean surface; e.g., Griggs and Bamber, 2011). In this issue, Jenkins et al. (2016) and Heywood et al. (2016) review the ice-ocean interactions that occur near the ice shelves, with a particular focus on the Amundsen Sea. Here, we more generally consider mechanisms that bring CDW onto the continental shelf.

By analyzing historic in situ observations of the deepest waters on the Antarctic continental shelf, Schmidtko et al. (2014) inferred decadal-scale warming and salinification in the Amundsen and Bellingshausen Seas, just upstream of Drake Passage. They found that warming was most pronounced in places where CDW was most able to shoal and intrude onto the Antarctic continental shelf. This shoaling and shoreward intrusion of CDW could be linked to changes in wind patterns: weaker easterly winds or stronger westerlies facilitate shoaling of CDW (e.g., Schmidtko et al., 2014; Dutrieux et al., 2014). In the GFDL-MOM025 model, a similar effect is achieved with poleward-shifting westerlies that limit the effects of easterlies (Spence et al., 2014). In the Amundsen and Bellingshausen Seas, these patterns have been linked to strengthening of the Amundsen Sea Low, which like the SAM, is linked to stratospheric ozone depletion (Turner et al., 2009, 2013). Cook et al. (2016) concluded that similar processes are at work along the western coast of the Antarctic Peninsula: shoaling of the pycnocline is associated with the arrival of warmer CDW and increased ice melt.

The processes associated with CDW exchanges across the Antarctic continental shelves have inherently small length scales that pose a challenge for observation and modeling. First, the large Coriolis parameter and weak stratification make the deformation radius very small (about 4–5 km; Martinson and McKee, 2012). Moreover, the submarine canyons that are believed to be major conduits for CDW delivery are themselves narrow and often poorly mapped. For these reasons, high-resolution numerical models have proved particularly valuable for identifying hypotheses needing further investigation and for informing observational sampling strategies.

The vertical structure, strength, and orientation of the shelf break current—which may be regionally and/or temporally coincident with the southern ACC Front—are believed to be important for determining where CDW is delivered to the shelves and how its delivery may vary temporally. The theory of canyon upwelling (e.g., Allen and Hickey, 2010) provides a dynamical framework by which a current flowing opposite the Kelvin wave direction (a current with the coast on its right in the Southern Hemisphere) interacts with a submarine canyon to yield an upwelling current into the downstream wall of the canyon and onto the shelf proper. In the Southern Ocean, this mechanism produces eastward-flowing currents with associated intruding flow along the eastern walls of canyons. These conditions are met along the West Antarctic Peninsula and Bellingshausen Sea, as well as in parts of the Amundsen Sea. Even in the western Amundsen Sea where surface currents are westward, an eastward undercurrent exists at canyon depths (Walker et al., 2013), which should permit the process.

In the Amundsen and Bellingshausen Seas and along the West Antarctic Peninsula, CDW delivery within canyons is both observed (Martinson and McKee, 2012; Assmann et al., 2013; Schofield et al., 2013; Wåhlin et al., 2013; Walker et al., 2013) and modeled (Thoma et al., 2008; Dinniman et al., 2011). Many studies implicate the westerlies in driving the exchange. Using an isopycnic-coordinate model, Thoma et al. (2008) found that enhanced westerlies led to more cross-shelf transport of CDW, but they were not able to deduce the underlying process. Dinniman et al. (2011) used a 4 km resolution model configuration of the Regional Ocean Modeling System (ROMS) to find that cross-canyon CDW-dye flux correlated with inner slope transport, which in turn correlated with along-slope wind fluctuations in the weather band. In a later study, Dinniman et al. (2012) found that enhanced westerlies led to more total cross-shelf transport of CDW. Interestingly, the greater transport of CDW was not associated with greater basal melting for the deeper ice shelves because the stronger winds additionally drove stronger cross-pycnocline mixing of CDW heat to the atmosphere. (Presently, cross-pycnocline mixing of heat is believed to be rather weak; Howard et al., 2004.) Wåhlin et al. (2013) and Assmann et al. (2013) also found eastward wind at the shelf break to be important in the exchange, observing depth-independent fluctuations at weather-band frequencies along the eastern wall of the canyon that correlated with the eastward wind. Carvajal et al. (2013) used the same mooring data as Wåhlin et al (2013) and found that including higher spatial resolution synthetic aperture radar winds improved the statistical correlation with the subsurface currents. They also suggested that sea ice cover may mitigate the ocean's ability to respond to events on time scales of a few days or less. In most of these studies, delivery was found to be, at least in part, episodic, and coherency of CDW transport with wind stress was found at various time scales.

In addition to the advective process, canyons may channel mesoscale CDW-core eddies toward the coast (Moffat et al., 2009). In an idealized numerical model study with a baroclinically unstable zonal current flowing along a continental slope cross-cut by a submarine trough, St-Laurent et al. (2013) found that canyons yield intrusions of CDW not only by the advective-driven canyon upwelling process but also by channeling CDW eddies into the canyon. They found that the dominance of one mechanism over the other is dependent on whether the jet was wide enough to straddle the canyon (yielding mean flow-topography interaction) or held offshore (yielding wave-topography interaction). It is not known how or if winds may alter the location of the shelf break current or by how much the current's location varies, though their model jet widths varied by 12 km. Mesoscale structure has also been observed on the continental shelf above the trough walls on the western Antarctic Peninsula. Boluses with length scale (8–10 km) and vertical structure consistent with a first-mode baroclinic instability of the shelf break current have been documented (recent work of author McKee and colleagues whose linear stability analysis suggests that, assuming stratification and shear do not change, these eddies should be common around the margins of Antarctica over a range of bottom slopes—they considered –0.15 through +0.15; for reference the West Antarctic Peninsula slope is about +0.12—and current orientations, zonal through meridional).

While canyons are clearly significant for fostering cross-shelf transport, they cannot provide the only means of exchange, because intrusions of CDW are also observed in both westward-flowing currents (e.g., Ross Sea) and in regions without canyons. In their 4 km resolution ROMS model study, Dinniman et al. (2011) found that intrusion sites are generally correlated with isobath curvature: at a sufficiently high Rossby number, in locations where isobaths curve into the shelf break current, the flow cannot adjust to the changing topography, and nonlinear momentum advection carries the current onto the shelf. As stated earlier, inner-slope transport of the shelf break current in their model was correlated with the along-slope wind, so changes in these winds might plausibly have associated changes in CDW transport.

Most of the mechanisms discussed implicate the westerly winds in governing cross-continental shelf transport of CDW, but there is not full consensus on this point. Using an idealized high-resolution (5 km) version of the MITgcm, Stewart and Thompson (2012) found that the magnitude of cross-shelf exchange depended more on the strength of easterly winds near the Antarctic continent than on westerly winds that occur further north. Similarly, Spence et al. (2014) found that a poleward shift in the wind jet resulted in reduced easterlies near the continent and reduced coastal downwelling, thus facilitating the poleward transport of CDW. Stewart and Thompson (2015) develop an eddy-resolving process model of the Antarctic Slope Front in which the shoreward transport of CDW is entirely eddy-driven. The easterly wind stress controls the pycnocline depth at the shelf break, which can prohibit eddy-driven exchange of CDW as deep isopycnals are cut off. In this model, even though the CDW exchange is not wind-driven, it is ultimately still sensitive to the wind. Rodriguez et al. (2016) used the 1/6° resolution Southern Ocean State Estimate (SOSE; Mazloff et al., 2010) to examine cross-shelf exchange. Because SOSE is an assimilating model, its estimates of the transport across the Antarctic continental shelf are constrained by open ocean observations, including satellite altimetry as well as conductivity-temperature-depth profiles collected by elephant seals and Argo floats, but in its current configuration, it does not fully resolve processes on the continental shelf or in subglacial cavities. In SOSE for the Amundsen Sea just west of Drake Passage, Rodriguez et al. (2016) showed that wind-stress curl, more than wind stress, governs variations in transport across the continental shelf into the Amundsen Sea.

Evaluating the relative roles of wind stress and wind-stress curl in driving the transport of CDW across the continental shelf and into the subglacial cavities requires further investigation to unravel the impact of model resolution, far-field open ocean conditions, canyons, and processes near (or under) the ice shelves, as well as the relative roles of wind stress and wind-stress curl. Additionally, the continuum of time scales involved (weather band through interannual) suggests that changes in both mean values and variances need to be considered.

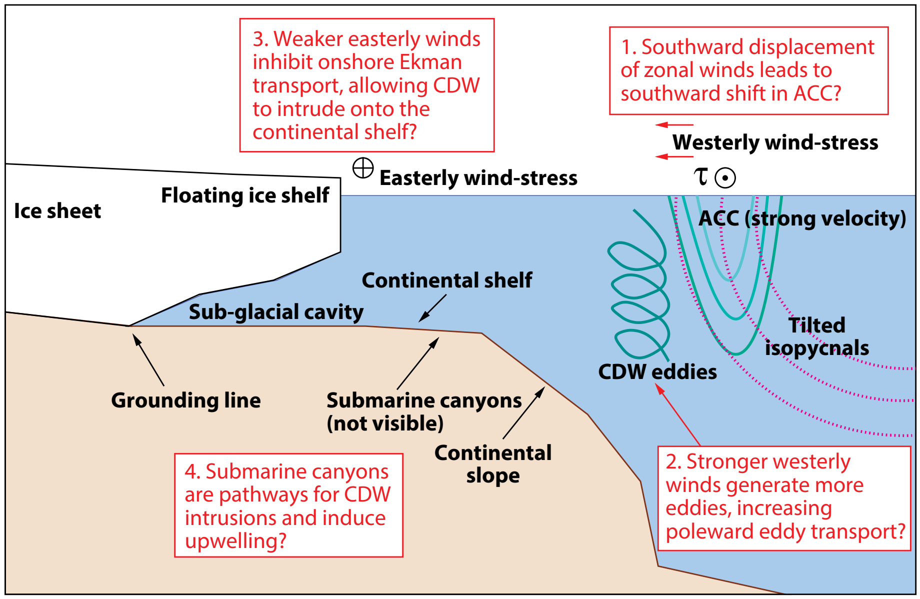

FIGURE 4. Schematic illustration of mechanisms hypothesized to govern transport of Circumpolar Deep Water (CDW) from the Antarctic Circumpolar Current (ACC) across the continental shelf to influence temperatures in subglacial cavities below the Antarctic ice shelves. Mechanism 1 (a southward displacement of the velocity jet structures and corresponding sloping isopycnals that define the ACC in response to a southward shift in winds) is not supported by decadal-scale altimeter observations. Mechanisms 2–4 all appear able to contribute to decadal-scale patterns in ACC-induced warming of the continental shelf.

SUMMARY AND CONCLUSIONS

The long-term warming of mid-depth waters in the ACC region (e.g., Gille, 2008; Böning et al., 2008) has been hypothesized to be associated with long-term changes in wind forcing. Figure 4 provides a schematic illustration of hypothesized mechanisms that govern transport of CDW onto the continental shelf. Available evidence suggests that the mean position of the ACC (box 1 in Figure 4) has not measurably changed in response to changes in either the strengths or positions of the westerly wind jets that drive the ocean (e.g., Gille, 2014; Shao et al., 2015). However, stronger winds have potentially led to strengthening of the eddy field in the Southern Ocean (box 2 in Figure 4; e.g., Hogg et al., 2015; Patara et al., 2016) and correspondingly to heightened poleward eddy heat transport across the ACC (e.g., Gent, 2016; Meredith, 2016).

Comparatively warm CDW from the ACC can traverse the Antarctic continental shelf to influence water at the margins of the Antarctic ice shelves and in the subglacial cavities below the ice shelves. There is evidence that water in the Antarctic margins has warmed in recent years (e.g., Schmidtko et al., 2014; Dutrieux et al., 2014). Winds have been implicated to explain the cross-shelf transport of CDW (box 3 in Figure 4), and submarine canyons are also thought to play a critical role (box 4 in Figure 4), but the specific mechanisms central to this exchange of water masses remain an area of investigation.

Priorities for the future include improving the observing system, particularly with an eye to evaluating the extent to which winds are actually changing and the mechanisms by which winds can drive CDW poleward across the Antarctic continental shelf. For example, a capability for expanded satellite scatterometer wind observation over the open ocean coupled with intensified mooring observations of cross-shelf exchange would be valuable for drawing connections between forcing and oceanic response. As higher-resolution measurement and modeling capabilities become more available, additional mechanisms may become evident that also contribute to cross-shelf transport of heat. Studies to date have largely focused on the role of mesoscale eddies, but emerging work suggests that tides and internal waves could account for a significant fraction of high-frequency, high-wavenumber variability in the Southern Ocean (e.g., Rocha et al., 2016) and thus could potentially modulate meridional transport mechanisms in ways that have not been explored with existing models.

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