4

SOUTHERN OCEAN CIRCULATION

Global Drivers and Ongoing Changes

*Jean-Baptiste Sallée, Adele K. Morrison,
Kaitlin Naughten, and Andrew F. Thompson*

4.1 Introduction

Nearly one-third of the planet's oceanic surface is located in the Southern Ocean encircling the Antarctic continent south of 30°S (Figure 0.1). This immense oceanic expanse is unique in many ways and exerts a significant influence on global ocean circulation and the planet's climate. The Southern Ocean is subject to the planet's most intense winds and hosts the most energetic current on Earth, the Antarctic Circumpolar Current (ACC). During winter, a large part of its surface is covered by sea ice, providing a refuge for unique fauna and supporting biodiversity. The Southern Ocean is in contact with the vast Antarctic glaciers that flow onto its surface for hundreds or thousands of kilometres. This unique and hostile climatic environment influences the structure of a global ocean circulation that connects all ocean depths from the surface to the abyss and links the Pacific, Atlantic, and Indian ocean basins. The circulation in the Southern Ocean plays a crucial role in heat and carbon exchange between the atmosphere and the ocean, as well as redistributing worldwide a large amount of vital life-supporting tracers, such as nutrients and oxygen.

The horizontal circulation of the Southern Ocean is dominated by the strong ACC, which flows uninterrupted from west to east in the mid-latitudes (Figure 4.1). South of the ACC, two main subpolar cyclonic gyres create a buffer between the ACC and the Antarctic continental margin in the Ross and Weddell Seas (Figure 4.1). The circulation along the fringe of the Antarctic continental shelf is dominated by the Antarctic Slope Current (ASC), generally flowing from east to west, along much of the Antarctic continental slope. The horizontal circulation is closely coupled to a vertical overturning circulation, associated with the formation and consumption of various water masses, creating a three-dimensional circulation

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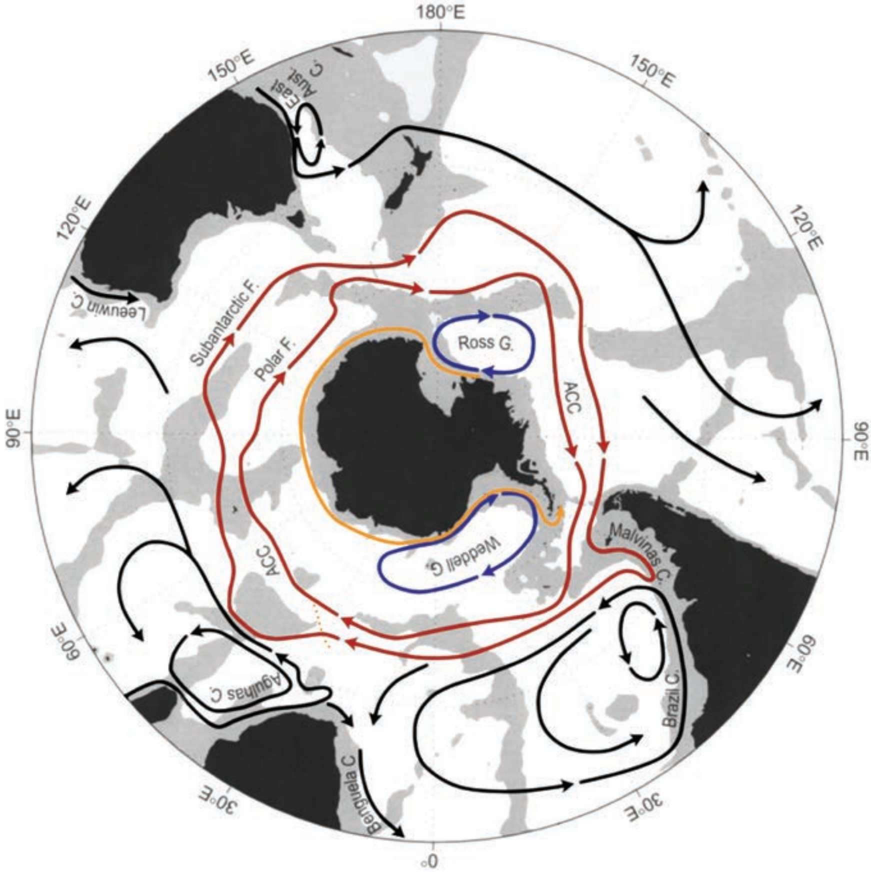

FIGURE 4.1 Schematic map of major currents in the southern hemisphere oceans south of 20°S. Depths shallower than 3500 m are shaded in gray. The two major cores of the Antarctic Circumpolar Current are shown in red, the Subantarctic Front and Polar Front. The two main subpolar gyres, the Ross and Weddell Gyres, are shown in blue. The Antarctic Slope Current is shown in orange. Abbreviations used are F for front, C for Current and G for gyre. Adapted from Rintoul et al. (2001).

system (Figure 4.2). Water masses are parcels of water of common origin with distinct temperature, salinity, and density ranges (Figure 4.2a), which can become "transformed" into different classes, through processes such as surface forcing, interaction with sea ice and ice shelves, or interior mixing. This water mass transformation is at the heart of the Southern Ocean's overturning circulation, a double-cell structure which replenishes, or transfers, surface-sourced tracers into the ocean interior (DeVries et al., 2011; Marshall & Speer, 2012; Sallée et al., 2010). This transfer is known as ventilation.

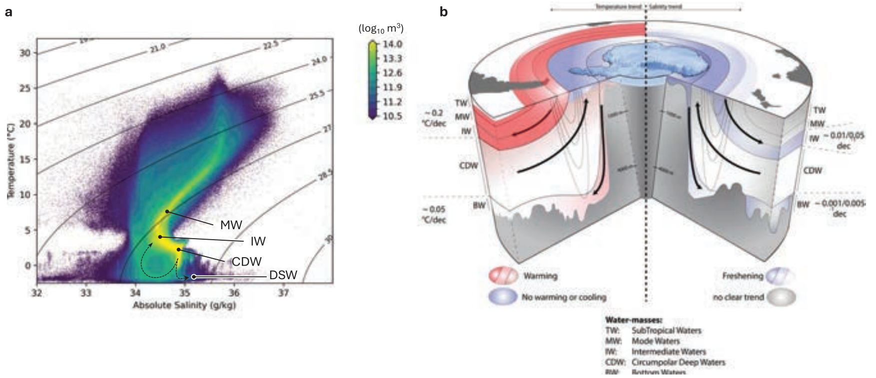

FIGURE 4.2 (a) Southern Ocean (<30°S) upper ocean (<2000 m) temperature/salinity volumetric water mass census (in units of m³, plotted as log volume of each 0.01 °C by 0.01 g/kg temperature/salinity bin) estimated from the IAP (Institute of Atmospheric Physics, Chinese Academy of Sciences) reconstruction from years 2000 to 2022 (Cheng et al., 2017). Selected water masses are labelled: mode waters (MW), intermediate water (IW), Circumpolar Deep Water (CDW) and Dense Shelf Waters (DSW). The black dashed arrow shows the main surface closing of the overturning circulation, connecting the upwelled CDW with the IW and MW through a "cold water transit", as well as connecting the upwelled CDW with DSW. (b) Schematic showing temperature and salinity trends in different layers of the Southern Ocean. The layers are defined as the main water masses of the Southern Ocean: subtropical water (TW), mode water (MW), intermediate water (IW), Circumpolar Deep Water (CDW) and bottom water (BW). Black arrows show the main overturning pathways in the basin, and the dashed black contours show a vertical slice of the deep-reaching Antarctic Circumpolar Current circulating clockwise around the Antarctic continent. Adapted from Sallée (2018).

Observed changes in Southern Ocean water masses and associated changes in Southern Ocean circulation have the potential for widespread climate implications within this century, making them highly relevant to politics and society. Due to its vertical circulation pattern and because a large range of densities rise up towards and outcrop at its surface, the Southern Ocean is disproportionately effective at absorbing and sequestering anthropogenic heat (Frölicher et al., 2015; Zanna et al., 2019). The surface temperature of the Southern Ocean, which is influenced by the delicate balance of overturning strength, upper ocean stratification, and sea ice cover, plays a significant role in cloud feedback and has been identified as a key regulator of global temperature (Kang et al., 2023). In fact, it is one of the primary factors determining the timing at which the global warming threshold of 2°C will be reached for a given emission scenario (Shin et al., 2023).

Changes in the strength of the upper overturning cell circulation can impact the ocean's capacity to absorb excess heat and carbon resulting from human activities and distort the global redistribution of nutrient fluxes (Sarmiento et al., 2004). A reduction in the strength of the lower overturning cell can delay the exceedance of global atmospheric warming targets, 1.5°C or 2°C, by more than a decade (Bronselaer et al., 2018). Decreases in the abyssal overturning can also disrupt global precipitation patterns by enhancing drying in the Southern Hemisphere, increasing precipitation in the Northern Hemisphere (Bronselaer et al., 2018), and reducing the efficiency of the global ocean carbon sink (Liu et al., 2023). The warming and potential change in the circulation of the subpolar Circumpolar Deep Water (CDW) due to increased upper ocean stratification can intensify the basal melt of Antarctic ice shelves, thereby destabilising them and leading to significant global sea level rise (Li et al., 2023; Silvano et al., 2018).

In this chapter, we review some recent advances in our understanding of the processes that drive and change the circulation and water masses of the Southern Ocean. In Section 4.2, we begin by providing a detailed account of the circulation and its drivers, including the dynamics of the circulation and the formation and transformation of associated water masses. Moving on to Section 4.3, we describe the observed changes and projected future changes, and their drivers. Finally, we conclude the chapter in Section 4.4.

4.2 Southern Ocean Circulation: Three-Dimensional Structure and Drivers

4.2.1 ACC and the Upper Cell of the Overturning Circulation

The ACC connects the Atlantic, Pacific, and Indian basins, thus enabling a truly global circulation (Figure 4.1). The eastward flow of the ACC is divided into a series of narrow jets that are among the strongest currents in the ocean and also give rise to coherent ocean vortices, or eddies, that are responsible for intense mixing in regions where ACC jets interact with major bathymetric features of the seafloor (Thompson & Sallee, 2012). Because of these processes, the ACC not only connects different ocean basins but also effectively blends waters from these disparate regions and contributes to setting global distributions of heat, nutrients, and dissolved gas concentrations.

The circulation of the ACC derives its energy from both mechanical and thermodynamical sources, or from surface wind and buoyancy forcing, respectively. The ACC largely coincides with the latitudes of the Southern Hemisphere westerlies. As the westerlies are aligned with the eastward flow of the ACC, they provide a source of kinetic energy to the surface ocean. The winds also generate a near-surface, frictionally balanced equatorward transport, known as Ekman transport, that is linearly proportional to the magnitude of the surface wind stress, creating upward pumping south of the ACC and downward pumping north of the ACC. This pattern of “upwelling” and “downwelling” on the flanks of the ACC has important consequences for the stratification within the ACC by tilting density surfaces away from horizontal, rising towards the surface as they stretch from north to south across the ACC (Marshall & Speer, 2012). This tilting is also a source of potential energy in the system, which is readily converted to kinetic energy through a hydrodynamic instability known as baroclinic instability. Baroclinic instability fuels the formation of mesoscale eddies that support the intense mixing of the Southern Ocean. Modelling studies have also shown that the total surface buoyancy forcing can also influence the strength of the ACC by modifying the upper ocean density distribution (Shi et al., 2020).

In addition to the flow of waters around Antarctica, the ACC also supports a secondary, overturning circulation that is roughly ten times weaker than the eastward flow of the ACC (in terms of volume transport) but is critical for the transfer of heat, carbon, and nutrients northward and southward across the ACC (Figure 4.2). The tilted density surfaces within the ACC provide a pathway for deep ocean waters to rise up towards the surface while remaining roughly along the same density surfaces (Marshall & Speer, 2012). Similarly, waters at the surface can be subducted along density surfaces flowing into lower latitudes at intermediate depths (Morrison et al., 2022; Sallée et al., 2010). Thus, the ACC’s density structure and overturning circulation influence how waters fill the deep ocean (Purkey et al. 2018), how nutrients are delivered to low latitudes (Sarmiento et al., 2004), how heat is delivered to the Antarctic ice shelves (Tamsitt et al., 2017), and how older water masses are brought back to the surface and exchange dissolved gasses with the atmosphere (Morrison et al., 2022).

In a two-dimensional, depth-latitude framework, the Southern Ocean overturning is dominated by “upper” and “lower” cells, while in reality, it has a complex three-dimensional structure (Tamsitt et al. 2017) (Figure 4.2). Both the upper and the lower cells of the overturning circulation are fed by warm and salty CDW, which upwells within and south of the ACC (Figure 4.2b). The north-south flow of CDW across the ACC is enabled by eddy motions, which are strongly enhanced downstream of major topographic features (Thompson & Sallee, 2012; Yung et al., 2022). The heavier version of CDW originates from North Atlantic Deep Water, whereas the lighter version of CDW originates from transformed Antarctic Bottom Water (AABW) (Talley, 2013). As CDW reaches the surface, some of it freshens by mixing with sea ice meltwater and precipitation (Pellichero et al., 2018). It flows northward and is transformed into mode water and then intermediate water, which subducts below warmer subtropical water to form the upper cell of the overturning circulation. The transformation of CDW into intermediate water (IW) starts with a transformation into near-surface winter water (WW) via wintertime mixing, and the WW is then warmed to form intermediate water through summertime surface heat fluxes (Figure 4.2a) (Evans et al., 2018). In contrast, another portion of upwelling CDW flows southward to reach the Antarctic continental shelf, where strong sea ice formation causes it to become colder and saltier (Figure 4.2). The result is AABW, the densest class of seawater, which cascades down the continental slope to the bottom of the Southern Ocean to form the lower cell of the overturning circulation. AABW is carried northward along the seafloor into the rest of the world's ocean basins (Purkey et al., 2018; Solodoch et al., 2022).

The sloping density layers that outcrop at the surface in the Southern Ocean provide a connection for atmospheric-sourced tracers, such as oxygen and anthropogenic carbon to penetrate relatively freely into the deeper ocean. A range of processes contribute to ventilation in the Southern Ocean, including convection and turbulence in the upper ocean, large-scale circulation features, such as the overturning and subtropical gyres, and eddy stirring (also known as mixing). The energetic mesoscale eddies of the Southern Ocean stir tracers along density layers, resulting in the downward movement of surface-sourced tracers. This eddy stirring ventilates all depth layers of the Southern Ocean, even transporting tracers downward along upwelling density layers against the opposing upward advection of the overturning circulation (Naveira Garabato et al., 2017). However, the vast majority of the anthropogenic heat and carbon absorbed into the Southern Ocean is advected northward in the thin upper Ekman layer and subducted across the base of the mixed layer on the northern edge of the ACC, filling the mode and intermediate water layers (Armour et al., 2016). Subduction in mode and intermediate layers occurs in a handful of localised hot spots set by the interactions of the meandering ACC with the underlying bathymetry (Sallée et al., 2010). Recent work has highlighted that submesoscale dynamics may also contribute substantially to Southern Ocean ventilation through enhanced deep-reaching vertical velocities and the outcropping of deep-density layers associated with filamentary structures (Bachman & Klocker, 2020; Dove et al., 2021; Siegelman et al., 2020).

4.2.2 ASC, Ice-Shelf Interactions, and the Lower Cell Overturning

Waters that flow across the ACC and continue poleward participate in an intricate circulation system at the Antarctic margins. Above the Antarctic continental slope, relatively warm CDW—a few degrees above the freezing temperature—rises up toward the continental shelf (Figure 4.3). Here, a combination of the shallow shelf bathymetry, surface wind forcing, and water properties of the continental shelf contribute to the formation of the Antarctic Slope Front (ASF; Figure 4.3a). The ASF acts as a key dynamical gateway for the delivery of heat to the ice shelves and the grounding zones of the Antarctic Ice Sheet (AIS), a process that influences global sea level (Fox-Kemper et al., 2021; Thompson et al., 2018). The formation of the ASF has traditionally been attributed to the surface wind forcing (Gill & Niiler, 1973). Around much of Antarctica, the continental shelf break is collocated with a band of easterly (westward) winds that push surface waters onshore in the Ekman layer, establishing a sea surface height gradient that supports a geostrophically-balanced westward flow, the ASC. Similar to the ACC, regions of Ekman convergence and divergence can vertically displace density surfaces that modify the frontal structure of the ASF (Figure 4.3b–d). This has two important implications. First, the density structure determines which water masses have access to the continental shelf. In much of East Antarctica, the density classes that host relatively warm CDW intersect, or incrop, on the continental slope; here, shelf waters are colder, consistent with weaker basal melting of East Antarctic ice shelves (Figure 4.3a). This behaviour is in contrast to West Antarctica, where CDW density classes can flow onto the shelf unimpeded (Figure 4.3a). Second, lateral density gradients at the shelf break lead to vertically-sheared flow in thermal wind balance and can give rise to an "Undercurrent" that flows eastward. In the Amundsen Sea, the strength of the Undercurrent has been tied to the heat content on the continental shelf (Dotto et al., 2020; Wåhlin et al., 2013) as well as ice shelf melt rates on longer time scales (Silvano et al. 2022). Recent studies have also suggested that there is the potential for feedback between coastal processes, e.g. sea ice formation and ice shelf melt, and the ASF through the delivery of modified waters back to the shelf break (Si et al., 2024; Thompson et al., 2020).

Spatial variations in the structure of the ASF are also influenced by the Southern Ocean's subpolar gyres, most notably the Ross and Weddell gyres (Gordon et al., 1981). These features play an important role in both buffering the continental shelf from the ACC's warmer waters but also transporting lighter waters towards the coast and dense waters back to lower latitudes, largely around the gyre periphery. In this way, the subpolar gyres also participate in setting the three-dimensional structure of the Southern Ocean overturning circulation (MacGilchrist et al., 2019; Wilson et al., 2022). Although the subpolar gyres are among the larger circulation features in the Southern Ocean, their size and sea ice cover make them among the more sparsely observed regions and their impact on heat transport and ice shelf melt in a changing climate remains an active area of research (Gómez-Valdivia et al., 2023; Prend et al. 2024). However, recent advances in the processing of satellite altimetry observations now allow their strength, area, and dynamics to be observed from space. These altimetry measurements have led to major progress in our understanding of the subpolar gyres, including their seasonal cycle, drivers, and the associated mesoscale activity (Armitage et al., 2018; Auger et al., 2022, 2023; Dotto et al., 2018).

Over the continental shelf, local water mass characteristics and associated circulation regimes set the rate of ice-shelf melt rates in ice-shelf cavities, the regions of ocean water covered by floating ice shelves. Within these ice-shelf cavities, the ocean transfers heat to the ice shelf, melting ice and increasing the buoyancy of the ocean, which flows back towards the shelf break in lighter density classes. Spatial variations in water masses and in the melting and freezing rates in ice shelf cavities give rise to different conditions around the Antarctic coastline. The continental shelf seas can be broadly categorised into three regimes: fresh shelves, warm shelves, and dense shelves (Moorman et al., 2020; Thompson et al., 2018) (Figure 4.3). These regimes are described, in turn, below.

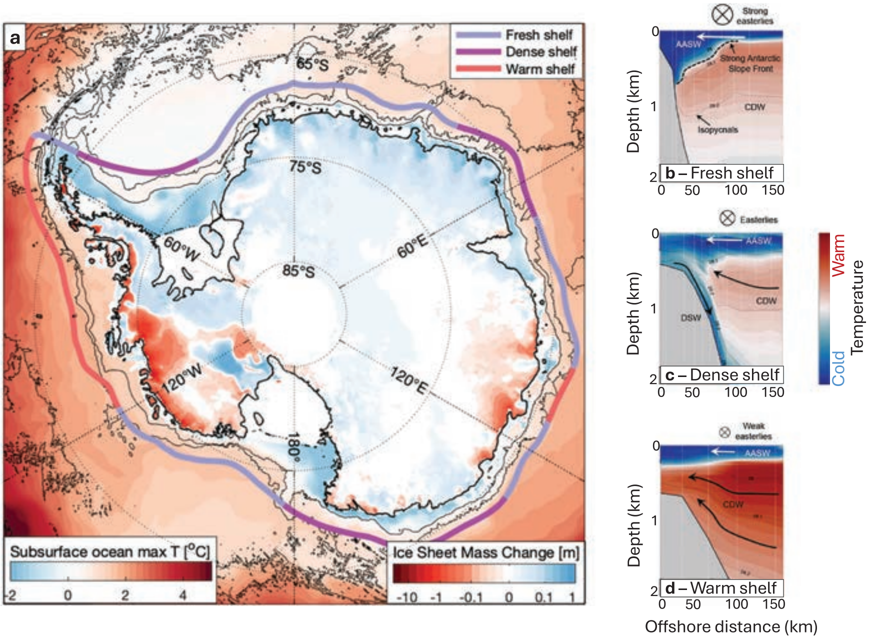

FIGURE 4.3 (a) Oceanic colours show the 2005–2010 mean subsurface ocean potential temperature maximum from the Southern Ocean State Estimate (Mazloff et al., 2010). Black lines indicate isobaths from ETOPO2v2, contoured every 2000 m from the 1000-m isobath; thick black line is the Antarctic continental coast. The thick coloured line parallel to the coast differentiates the three main oceanic shelf regimes (fresh shelf, dense shelf, warm shelf). Continental colours represent ice sheet elevation change (2003–2019), corrected for firn air content to reflect mass change (Smith et al., 2020). (b, c, d) Schematic latitude-depth transects indicating typical winds, subsurface ocean circulation, temperature and density structure in a (b) fresh shelf, (c) dense shelf, and (d) warm shelf regime. Colours represent temperature and black contours isopycnals of neutral density, with the bold black dashed line in (b) indicating the sharp density gradient across the Antarctic Slope Front. Cross-slope circulation is shown schematically with black and white arrows, and wind direction and strength by arrow tails going into the page. Water masses shown include Antarctic Surface Water (AASW), Circumpolar Deep Water (CDW), and Dense Shelf Water (DSW, also referred to as High Salinity Shelf Water in some sectors). Adapted from Stokes et al. (2022)

Fresh shelves. Fresh shelves include the eastern Weddell Sea, the eastern Antarctic Peninsula, and much of East Antarctica (Figure 4.3b). Here, sea ice formation is relatively weak, as is the transport of water onto the shelf from the deep ocean. There is generally minimal presence of either CDW or very dense water masses, and instead, the water column is filled with WW, a cold and relatively fresh water mass near the surface freezing point (−1.9°C).

Warm shelves. Warm continental shelves include the Amundsen and Bellingshausen Seas of West Antarctica, as well as isolated regions of East Antarctica, such as the region surrounding the Totten Ice Shelf (Figure 4.3c). Here, warm and salty CDW flows directly from the subsurface Southern Ocean onto the continental shelf. In some regions, e.g. the West Antarctic Peninsula and Bellingshausen Sea, the CDW is transported onto the continental shelf essentially unmodified, with a temperature of around 1°C (Schulze Chretien et al., 2021). In other regions, slightly cooler modified Circumpolar Deep Water (mCDW) results from mixing with other water masses as they are transported onto the continental shelf. However, even mCDW is warm enough to support substantial ice shelf melting, and warm shelf regions have the highest ice shelf basal melt rates in Antarctica (Adusumilli et al., 2020). Depending on its buoyancy, the admixture of meltwater with ambient ocean then travels westward either within the Antarctic Coastal Current or in the ASC, freshening the regions downstream (Jacobs et al., 2022). Sea ice formation is relatively weak on the warm shelves but causes some water mass transformation during the winter months. As sea ice is formed, the upper layers of the ocean are mixed, and lose their heat to the atmosphere and form WW, which can modulate ice shelf melt rates at interannual timescale (Jenkins et al., 2018; Holland et al., 2022).

Dense shelves. Dense shelves include the Ross Sea, the southwestern Weddell Sea (surrounding the Filchner-Ronne Ice Shelf), Adélie Land, and Cape Darnley near Prydz Bay. These regions are associated with extreme heat loss to the atmosphere, intense CO_2 exchange with the atmosphere, and dense water formation in coastal polynyas, which are regions of open ocean surrounded by sea ice that form due to persistent winds blowing off the ice sheet known as katabatic winds (Williams et al., 2007). Sustained heat loss and associated sea ice formation in the polynyas, lead to the formation of High Salinity Shelf Water (HSSW) that mixes throughout the entire water column, becoming "reset" to the surface freezing point. There is large transport of mCDW onto dense continental shelves from offshore, but its heat is almost entirely lost to the atmosphere by mixing associated with sea ice formation by the time it reaches the ice shelves (Morrison et al., 2020). Instead, ice shelf melting in dense shelf regions may be driven by HSSW (Nicholls et al., 2009). Even though HSSW is at the surface freezing point, it is still warm enough to melt ice shelves at depth, where the freezing point of seawater is lower due to increased pressure. The resulting ice shelf meltwater is supercooled relative to the surface, forming a water mass known as Ice Shelf Water (ISW). Because of their high density, both HSSW and ISW are commonly referred to as Dense Shelf Water, a precursor of AABW.

AABW is the coldest and densest type of water found in the global ocean and is characterized by temperatures below 0°C and neutral densities greater than 28.27 kg/m^3 (Orsi et al., 1999). AABW is formed from Dense Shelf Water, which flows down the continental slope and mixes with surrounding water masses, and ultimately spreads along the ocean bottom. The properties and formation rates of AABW may also be influenced by offshore, open-ocean polynyas, such as those observed in the Weddell Sea during the 1970s, causing convection to depths of up to 3,000 m (Gordon, 1978). However, the primary source region for AABW is the Antarctic continental shelf. AABW originates in localized areas around the Antarctic continent, sinking into the deep ocean and following isobaths on the lower continental slope until redirected northward along deep western boundary currents. AABW is guided topographically through the Southern Ocean, and travels northward in the global ocean abyss along deep western boundary currents, recirculating into the interior of these basins (Orsi et al., 1999). AABW sourced from the Weddell Sea and Prydz Bay are blended and exported together, mainly to the Atlantic and Indian Oceans, while AABW sourced from Adelie Land and the Ross Sea are blended together and exported mainly to the Pacific Ocean (Solodoch et al., 2022). Along this northward trajectory, AABW encounters sills and narrow passages, leading to further modification of its properties through mixing, resulting in increased buoyancy and warmer temperatures (de Lavergne et al., 2016). AABW covers close to 80% of the global seafloor (Purkey et al., 2018). As AABW fills the deep ocean from below, it determines the abyssal ocean stratification, i.e. the change in density with depth, which in turn, regulates the timescale over which heat and carbon can be sequestered in the deep ocean.

4.3 Observed Changes and Outlook in the Future of the Southern Ocean

4.3.1 Large-Scale Warming and Freshening Trends in the Southern Ocean Depths

The Southern Ocean is a major sink of excess heat associated with climate change. Estimates from an observation-based reconstruction suggest that over 1871–2017, the Southern Ocean has accounted for 67% of the global ocean uptake of excess heat (Zanna et al., 2019), and climate models broadly agree with an estimate of ~75% over 1870–1995. This heat is then distributed globally through the overturning circulation (Figure 4.4). The storage of heat that remains in the Southern Ocean south of 30°S in the upper 2000 m is estimated from historical temperature observations to account for 35–43% of the global ocean heat gain since 1970 (Meredith et al., 2019). This proportion has increased in the past two decades (2005–2017) to 45–62% (Meredith et al., 2019).

A large part of this excess heat resides north of and within the ACC (Figure 4.4a), in the mode and intermediate waters layers, which have warmed at a pace of about 0.2°C per decade since 1970 (Figure 4.2b) (Auger et al., 2021; Sallée, 2018). South of Tasmania, a warming of 0.29±0.09°C per decade in these water masses has been estimated from repeated observations; this rate is 2.40 times larger than the typical interannual variability (Auger et al., 2021). The warming is also associated with a freshening of about 0.01–0.05 g/kg per decade (Figure 4.2b) (De Lavergne et al., 2014; Durack & Wijffels, 2010; Fox-Kemper et al., 2021). Freshening and

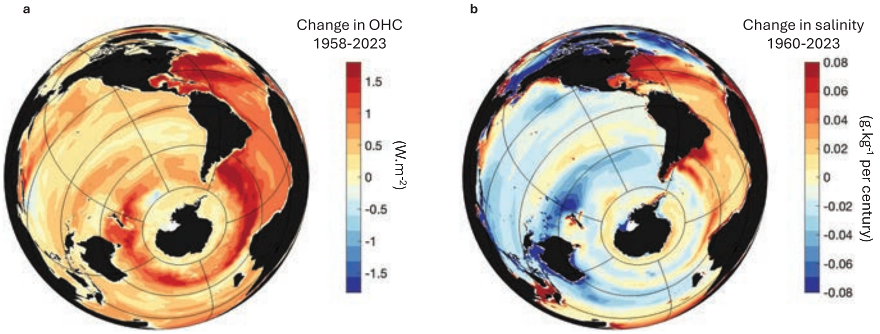

FIGURE 4.4 (a) Ocean heat content (OHC) change from 1958 to 2023 as estimated from a linear trend computed from the IAP reconstruction. (b) Linear trend of ocean salinity averaged over the top 2000 m computed from the IAP reconstruction from years 1960 to 2023 (Cheng et al., 2017, 2020).

warming in these water masses are expected to continue in the future at a rate depending on our future emissions (Silvy et al., 2020, 2022). Changes in mode and intermediate water properties primarily result from changing air-sea-ice fluxes in the subpolar Southern Ocean and within the ACC, and the associated surface hydrographic anomalies are passively subducted north of the ACC with the overturning circulation (Silvy et al., 2022). Decadal-scale variability in the circulation can temporarily accelerate or decelerate these hydrographic changes and thus impact the interpretation of Southern Ocean heat uptake.

In the subpolar Southern Ocean, south of the ACC, the surface layer has slightly cooled and freshened in the past decades (Zhang et al., 2021) (Figure 4.2b, 4.4). The freshening has stratified the upper ocean (Sallée et al., 2021), isolating the relatively warm subsurface water from the cold surface layer and creating favourable conditions for the growth of sea-ice cover. The observed regime changes in sea-ice observed since 2016 is likely to be affecting the long-term trend in surface ocean temperature in the subpolar ocean, with some suggestion of a large surface warming since then (Purich & Doddridge, 2023). The freshwater content change of the subpolar surface ocean is controlled by a combination of changes in the sea-ice growth/melt (Haumann et al., 2016), in ice shelf melt (Jacobs, 2006), and in the atmospheric hydrological cycle (Akhoudas et al., 2023).

Deeper in the water column, the upper part of the CDW layer shows subtle warming, right below the surface layer (Auger et al., 2021; Lecomte et al., 2017; Schmidtko et al., 2014). A repeated expendable bathythermograph (XBT) section of 25 years between Tasmania and Antarctica permitted an estimate of this warming of 0.06±0.02°C per decade, which is 2–4 times greater than the typical interannual variability (Auger et al., 2021). In another study, the warming of this water mass was estimated to be 0.8–2.0°C in 2010–2018 compared to 1930–1990 in the sector 80–160°E (Herraiz-Borreguero & Naveira Garabato, 2022). In addition to the warming of CDW, the depth of the temperature maximum has shoaled at a significant rate that may facilitate the access of warm waters to the Antarctic continental shelf (Auger et al., 2021; Schmidtko et al., 2014).

The abyssal Southern Ocean has also experienced change in the past decades, with a reported AABW volume reduction, warming, and freshening (Purkey & Johnson, 2013; Silvano et al., 2023). These signals appear in all basins of the Southern Ocean (Silvano et al., 2023): the Weddell Sea, East Antarctica, and the Ross Sea, and some of these trends might have regionally accelerated (Purkey et al., 2019). The cause of these changes remains, however, uncertain, with possible drivers including a slowdown in dense water formation (Gunn et al., 2023b; Zhou et al., 2023).

4.3.2 Changes in the Circulation: ACC, Upper Cell, Lower Cell

In contrast to the widespread evidence for warming and freshening trends in the Southern Ocean, observational evidence for circulation changes is scarce, due to the difficulty of measuring circulation directly and the challenge of disentangling trends from variability. Whether or not the ACC has shifted or strengthened over recent decades is still under debate. Some studies have reported a southward shift in the position of ACC fronts (Kim & Orsi, 2014; Sokolov & Rintoul, 2009). However, the detected shift has been shown to be sensitive to the method used to identify frontal locations, and no coherent trend in the position of the ACC is detected when a more accurate definition of fronts is used (Chapman et al., 2020). This absence of frontal movement is consistent with work showing that the path of the ACC is strongly constrained by the underlying bathymetric features (Graham et al., 2012). A regional shift of ACC fronts in regions less constrained by bathymetry, e.g. west of the Kerguelen Plateau, might however be possible according to observed and projected changes (Azarian et al., 2024).

Recently, an acceleration of the eastward flow on the northern edge of the ACC was reported from Argo and satellite observations (Shi et al., 2021). This increase is consistent with modelling work showing that increased buoyancy forcing can drive an acceleration of the ACC (Hogg, 2010; Shi et al., 2020). However, it remains unclear whether the observed acceleration represents a strengthening of the ACC itself or rather a southward shift of the subtropical gyres. This possible sensitivity to buoyancy fluxes is in contrast with the now well documented insensitivity of the ACC zonal transport to changes in the zonal wind stress, a phenomenon referred to as “eddy saturation” (Morrison et al., 2013; Munday et al., 2013).

Observational evidence is limited for long-term trends in the strength of the upper overturning circulation in the Southern Ocean due to the lack of direct circulation measurements and the difficulty of observing such a spatially distributed flow. Indirect reconstructions using an inverse model indicate large decadal variability of up to 50% from one decade to the next (DeVries et al., 2017). Such large variability may obscure any longer-term trends in the upwelling. Observations of chlorofluorocarbons and other tracers of ventilation allow us to compute age changes in different water masses and are suggestive of an enhanced overturning circulation (Ting & Holzer, 2017; Waugh et al., 2013). However, such results need to be interpreted with caution, as there are also other mechanisms that may drive ventilation change, such as eddy stirring, submesoscale activity, subtropical gyre circulations, and upper ocean mixing.

Recent observational evidence indicates that the lower overturning cell transport is weakening. In the Australian Antarctic Basin, AABW transport fed from the Ross Sea and Adelie Land sources has declined by ~30% over the period 1994–2017, driven by meltwater-driven freshening of the source waters (Gunn et al., 2023). In the Weddell Sea, the bottom water volume has reduced by 30% from 1992 to 2020, indicative of a reduced dense water formation rate that would be consistent with an observed wind-driven decline in sea ice formation (Zhou et al., 2023). The decreased northward transport of bottom waters in turn is likely to be driving the observed contraction of the densest waters in the abyssal ocean (Purkey & Johnson, 2012). Similar to the upper overturning, direct observations of the lower overturning cell away from the Antarctic margins are limited.

4.3.3 Continental Shelf and Ice-Shelf Interactions

Ice shelf basal melt is ocean-driven and is the main cause of mass loss from the AIS, which contributes to global sea level rise (Shepherd et al., 2018). Long-term monitoring of ice shelf basal melting across Antarctica began with the advent of satellite missions in the 1990s. A clear increase in basal melting has been observed along the warm continental shelves of West Antarctica, including the Amundsen and Bellingshausen seas (Adusumilli et al., 2020; Paolo et al., 2015), although there is substantial interannual and decadal variability.

Retreat of the West Antarctic Ice Sheet (WAIS) was likely triggered in the 1940s, as determined by analysis of sediment cores from the Amundsen Sea (Smith et al., 2017). This timing corresponds to a strong El Nino event, which is thought to create warm oceanic conditions on the Amundsen Sea causing increased basal melt rates. Smith et al. (2017) hypothesised that if the conditions in the Amundsen Sea were unusually warm in the past, this might have initiated the present thinning of ice.

Model simulations suggest that the Amundsen Sea warmed in response to changes in wind patterns over the 20th century (Gómez-Valdivia et al., 2023; Naughten et al., 2022). Ocean warming would explain why the WAIS failed to recover from a natural climate anomaly, and why increased basal melting continues to the present day (Holland et al., 2022). However, observations of water mass properties on the continental shelf are sparse in both space and time (Schmidtko et al., 2014). The short record of in situ measurements in the Amundsen Sea, combined with large decadal variability, means that significant long-term trends in ocean temperature have not been established in observations.

Ice shelf melting in West Antarctica is determined by the heat content of the CDW layer reaching the continental shelf, which itself can be modulated by the strength of the Amundsen Undercurrent (Naughten et al., 2023). The Undercurrent flows from west to east along the continental slope and transports warm CDW onto the shelf. Variations in the strength of the Undercurrent have been linked to decadal variability in observed melt rates (Jenkins et al., 2016). The first future projections with specialised Amundsen Sea models suggest that ocean warming and increased ice shelf melting will continue over the 21st century, even if global average temperatures stabilise (Jourdain et al., 2022; Naughten et al., 2023), and the continental shelf ocean warming has been attributed to a long-term strengthening of the Undercurrent (Naughten et al., 2022, 2023).

Changes have also been observed in the dense continental shelves, especially in the Ross Sea. A significant freshening trend has been observed in the Ross Sea, where in situ measurements now span six decades (Jacobs et al., 2022). The Ross Sea is directly downstream of the Amundsen Sea so that its freshening has been attributed to the retreat of the WAIS. Freshening of the dense shelves may have the potential to flip these regions to a warm regime (Hellmer et al., 2017; Naughten et al., 2021; Siahaan et al., 2022). HSSW forms a density barrier, which prevents offshore mCDW from reaching the ice shelves. A freshening of the HSSW water mass would weaken the density barrier and could allow warm water to flow directly into the ice-shelf cavities. A larger number of climate projections have focused on the Filchner-Ronne Ice Shelf (FRIS) in the Weddell Sea, showing a potential to abruptly transition to a warm regime (Hazel & Stewart, 2020; Hellmer et al., 2012). Such a transition would dramatically increase FRIS melt rates and potentially cause significant sea level rise. However, it is not clear how easily such a transition could occur, and it may only occur under extreme climate change scenarios, with more moderate forcing causing a slight decrease in basal melting (Naughten et al., 2021; Nicholls, 1997).

4.4 Conclusion

The Southern Ocean stands as a pivotal component of the global climate system, regulating heat, carbon, and nutrient fluxes on a global scale. As we conclude this chapter, it becomes evident that our understanding of its intricate circulation and associated transport processes has advanced significantly in recent years. However, profound uncertainties persist, posing challenges to predicting its future evolution and the consequent impacts on global climate.

Throughout this chapter, we have explored the multifaceted nature of the Southern Ocean circulation, emphasising its three-dimensional structure and the interconnectedness of its water masses. From the powerful ACC to the overturning circulation connecting the surface and the deep ocean, each component plays a vital role in shaping not only regional but also global oceanic and climatic patterns. The frontal structures of the ACC, which arise from a complex interplay between surface wind stress and bathymetry interactions, are a key regulator of the meridional water mass transport. Directly south of the ACC, the subpolar gyres, such as the Ross and Weddell gyres, tend to buffer the continental shelf from the warm CDW. The subpolar gyres influence extends beyond this buffering role, as they participate in setting the three-dimensional structure of the Southern Ocean overturning circulation.

The interaction between warm CDW and the Antarctic continental shelf, moderated by the ASF, determines the ocean heat transfer to the ice shelves and grounding zones of the AIS. The formation of the ASF acts as a dynamic gateway for the delivery of heat and largely determines which water masses have access to the shelf. The presence of lateral density gradients at the shelf break gives rise to vertically-sheared flow, which contributes to the formation of an “Undercurrent” in the West Antarctic region, with implications for heat content and ice shelf melt rates in this region. The combination of these ocean currents and associated water mass transports ultimately determine the distinct characteristics on the Antarctic continental shelf, which can be broadly classified in three main regimes: warm shelf, fresh shelf, and dense shelf.

The water masses of the Southern Ocean have experienced rapid changes in recent decades. The observed large-scale warming and freshening trends result from an intricate interplay between changing air-sea-ice fluxes and the redistribution of heat and freshwater within the ocean. These trends, characterized by increasing heat storage and stratification, have significant implications for regional and global climate dynamics, in particular through the modulation of the sea ice cover and upper ocean temperatures.

Climate projections suggest a future trajectory of the Southern Ocean that includes continued warming, freshening, and changes in circulation patterns. However, significant uncertainties persist, particularly regarding the response of ice shelves and ice-ocean interactions to ongoing climate change. Addressing these uncertainties will require concerted observational and modelling efforts, as well as interdisciplinary collaborations to better understand and anticipate the complex dynamics of the Southern Ocean in a changing climate.

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