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# Southern Ocean Warming

By Jean-Baptiste Sallée



**ABSTRACT.** The Southern Ocean plays a fundamental role in global climate. With no continental barriers, it distributes climate signals among the Pacific, Atlantic, and Indian Oceans through its fast-flowing, energetic, and deep-reaching dominant current, the Antarctic Circumpolar Current. The unusual dynamics of this current, in conjunction with energetic atmospheric and ice conditions, make the Southern Ocean a key region for connecting the surface ocean with the world ocean's deep seas. Recent examinations of global ocean temperature show that the Southern Ocean plays a major role in global ocean heat uptake and storage. Since 2006, an estimated 60%–90% of global ocean heat content change associated with global warming is based in the Southern Ocean. But the warming of its water masses is inhomogeneous. While the upper 1,000 m of the Southern Ocean within and north of the Antarctic Circumpolar Current are warming rapidly, at a rate of 0.1°–0.2°C per decade, the surface subpolar seas south of this region are not warming or are slightly cooling. However, subpolar abyssal waters are warming at a substantial rate of ~0.05°C per decade due to the formation of bottom waters on the Antarctic continental shelves. Although the processes at play in this warming and their regional distribution are beginning to become clear, the specific mechanisms associated with wind change, eddy activity, and ocean-ice interaction remain areas of active research, and substantial challenges persist to representing them accurately in climate models.

## INTRODUCTION

The climate of planet Earth is largely governed by the world ocean, one of the central regulators of global climate through its continuous radiative, mechanical, and gaseous exchanges with the atmosphere.

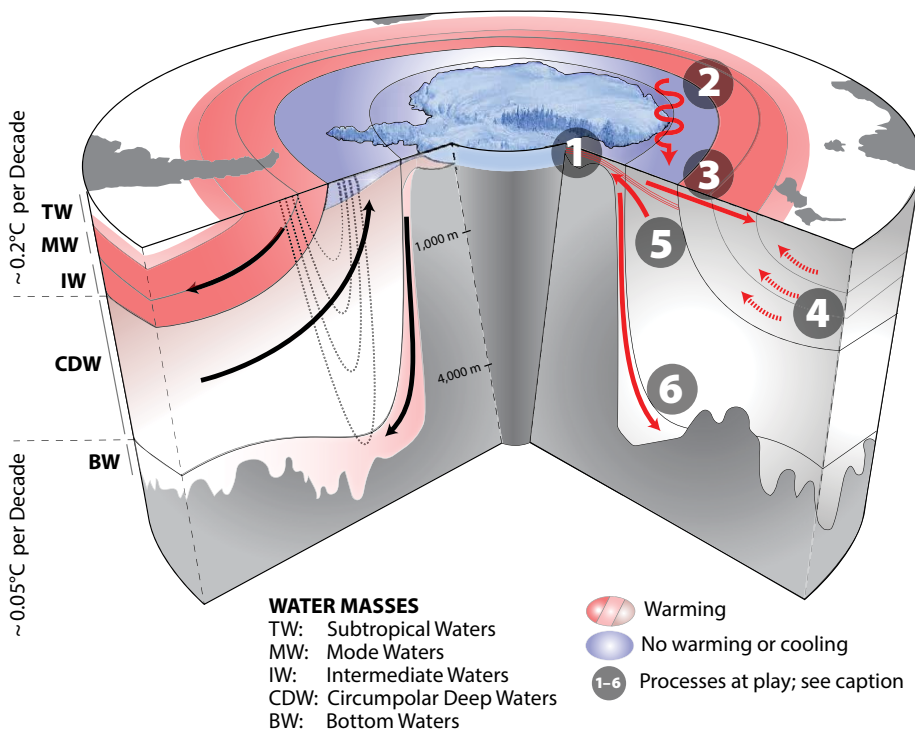
**FACING PAGE.** RRS *James Clark Ross* during Water-mass transformation and Pathways In The Weddell Sea (WAPITI) cruise JR16004 in the southern Weddell Sea. Photo credit: Yves David

The ocean tends to moderate climate changes by absorbing large proportions of heat and carbon that are associated with current climate change. It is estimated that the ocean has absorbed 93% of the excess energy in the climate system arising from global warming (referred to as “excess heat”; Rhein et al., 2013).

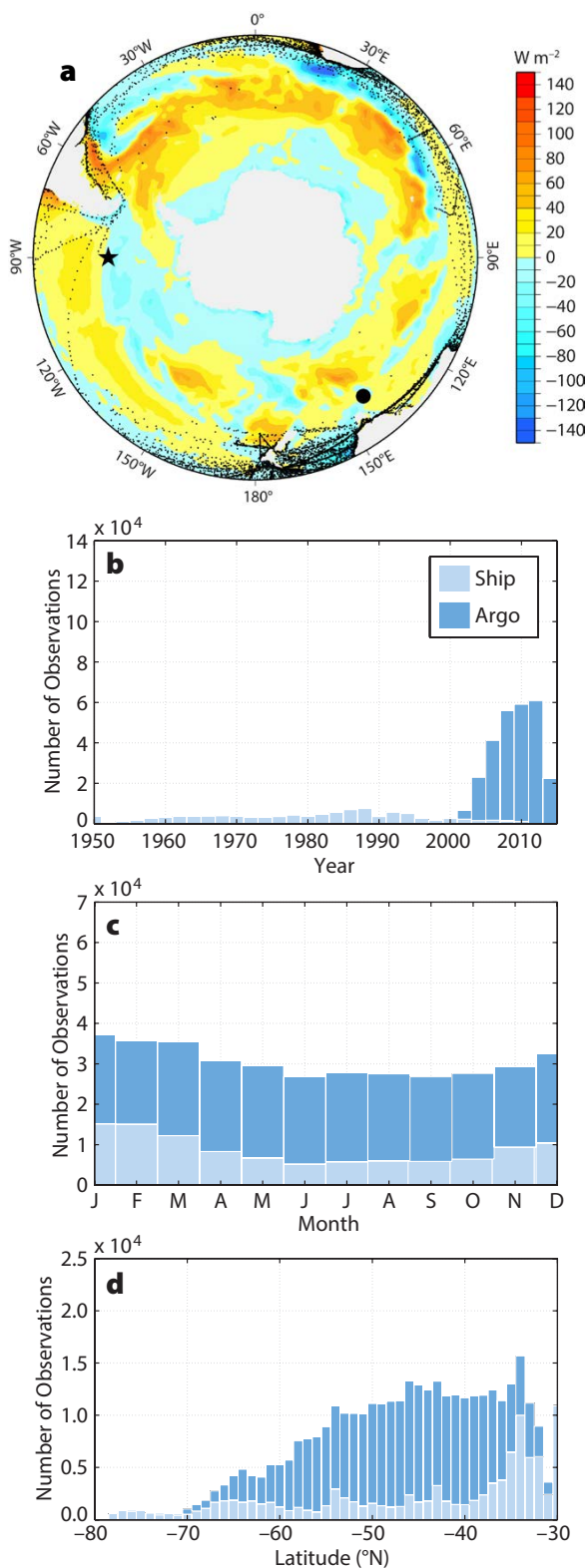
The Southern Ocean is of major importance in this absorption of excess

heat because of its unique circulation pattern. The Southern Ocean provides the principal connections among the world's major ocean basins and between the deeper and upper layers of the global ocean circulation (the global overturning circulation; see Figure 1). Cold water that sinks at high latitudes upwells along surfaces of constant density that connect the deep ocean to the sea surface in the Southern Ocean, where water masses can interact with the atmosphere, exchanging heat and gases before being sent back to the ocean depths for decades to millennia (e.g., Marshall and Speer, 2012).

In addition to its key role in regulating Earth's excess heat, the Southern Ocean plays an important role in ventilating the world's deep ocean and setting its characteristics. A vast majority of the world ocean acquires its physical and biogeochemical characteristics in the Southern Ocean, with more than half of the world ocean volume having last had contact with the atmosphere in the Southern Ocean surface layer (DeVries and Primeau, 2011). Any change in the Southern Ocean can therefore have massive global ocean and climate consequences. In addition, its ability to buffer



**FIGURE 1.** Schematic showing temperature trends in different layers of the Southern Ocean. The layers are defined as 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. The red arrows and associated numbers represent processes at play in the warming of the Southern Ocean and are discussed in the text: ① increased surface stratification and shallowing of CDW layer, ② increased heat uptake in the subpolar basins, ③ increased northward heat transport associated with increased subpolar heat uptake, ④ reduced eddy-mediated southward heat transport across the Antarctic Circumpolar Current, ⑤ intrusion of CDW onto the continental shelves, and ⑥ warming of the bottom water ventilating the abyssal ocean.



**FIGURE 2.** (a) Time-averaged net air-sea heat flux from the European Centre for Medium Range Weather Forecasts Reanalysis Interim for 2008–2010. The colored fields are measured in watts per square meter ( $\text{W m}^{-2}$ ). Blue indicates ocean heat loss to the atmosphere. Star and circle symbols show surface flux moorings. Dots show available winter ship observations over all July months within an example five-year period (2000–2004) with sufficient information to estimate the latent heat flux. *Reproduced with permission from Gille et al. (2016)* (b–d) Number of hydrographic profile observations available in the Southern Ocean (south of  $30^{\circ}\text{S}$ ) from ship-based and Argo instruments (b) per year, (c) per month, and (d) per  $1^{\circ}$  latitude band.

terrestrial climate change influences the entire Southern Ocean climate and ecosystem via acidification of its water masses (Feely et al., 2009), deep-reaching warming and freshening (Purkey and Johnson, 2013), melting of floating glaciers (Schmidtko et al., 2014), spatial reorganization of sea ice (Vaughan et al., 2013), and possible changes in populations of krill and predators (Atkinson et al., 2004).

### OBSERVING THE SOUTHERN OCEAN

Despite its pivotal role in climate, the Southern Ocean has remained poorly observed for many decades, and it remains undersampled compared to other ocean basins. The paucity of ocean observations is primarily due to the difficulty of accessing these regions and the immensity of this ocean basin. The presence of sea ice in a large part of the domain makes ship-based observation complex and expensive and hinders satellite-based observation of the ocean surface as well as satellite communication with autonomous platforms (in addition to sea ice, cold temperature is also an issue for retrieving surface salinity estimates from satellite measurements). Two quantities are of utmost relevance for monitoring and understanding ocean warming. First is the amount of heat entering the ocean surface from the atmosphere, the net air-ice-sea heat flux, and second is the heat stored and transported by ocean water masses.

Air-ice-sea exchanges of heat are not well documented because fluxes are sparsely sampled (see Figure 2a). The sparseness of conventional observations and the issues in calibrating remotely sensed observations causes the availability and accuracy of air-sea heat flux estimates to be especially poor in this region (Josey et al., 1999; Taylor, 2000; Dong et al., 2007; Gulev et al., 2007; Bourassa et al., 2013; Cerovečki, et al., 2011). The mean climatological state of air-sea heat fluxes in the Southern Ocean is very uncertain, and long-term trends are therefore far from resolved.

Instead, oceanographers have focused on the storage of heat observed from conventional ocean temperature measurements, which were initiated as early as the 1950s at accuracies allowing detection of multidecadal trends (Domingues et al., 2008; Palmer and Brohan, 2011). It remains, however, a real challenge to estimate average changes in ocean temperature, both because ocean temperature varies on multiple timescales, ranging from seasonal to centennial, and because of sampling bias. Two main ways to measure temperature are used in studies looking for long-term trends: top-to-bottom temperature measurements taken from sensors lowered from a ship and autonomous profiling floats that drift with ocean currents and adjust their buoyancy in order to measure vertical profiles of temperature in the upper 2,000 m of the water column. In addition, free-falling bathythermograph probes launched from ships are also used, but their measurements are limited to the upper 700 m, and often do not measure salinity, which limits their utility for associating warming with specific water masses. Because of the harsh climate conditions in winter and the difficulties in accessing the remote southern seas, ship-based sampling is seasonally biased, with most observations concentrated during the summer months (November to March) and toward the coastlines of America, Africa, Australia, and New Zealand, in the latitude band  $30^{\circ}$ – $40^{\circ}\text{S}$  (Figure 2c,d). In contrast, autonomous profiling floats have no seasonal biases, but their observations are limited to the upper 2,000 m of the water column, and their time series began only in

2002 in the Southern Ocean (Figure 2b,c). Although autonomous float observations cover the middles of the ocean basins, equally sampling all latitude bands north of  $\sim 50^{\circ}\text{S}$ , their sampling diminishes south of the Antarctic Circumpolar Current, where sea ice cover is a challenge for their survival and for data recovery (Figure 2d). In addition to these conventional measurements, the upper ocean (upper 500 m) under sea ice has been heavily sampled over the last decade with animal-borne sensors (Treasure et al., 2017), but the accuracy of such observations limits their usefulness in studies seeking to detect subtle long-term change.

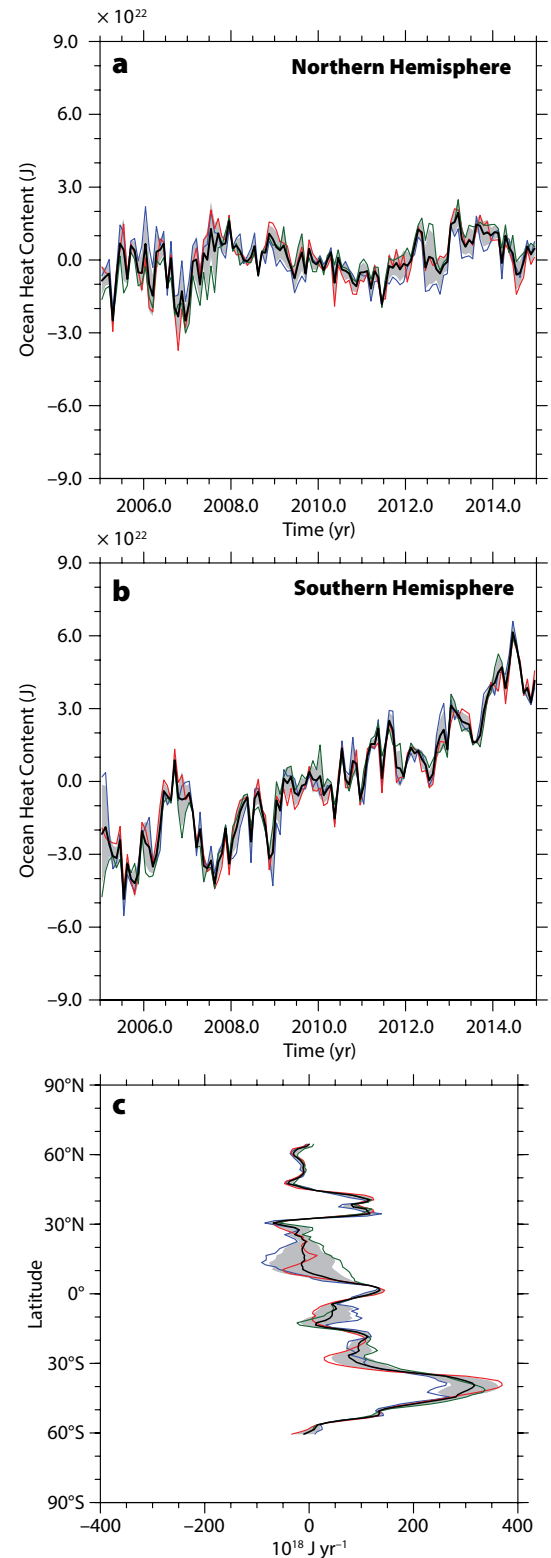
### SOUTHERN OCEAN HEAT CONTENT

Ship-based observations, floats, and bathythermographs have been used to measure the total heat content change of the ocean in the upper 700 m, 1,000 m, or 2,000 m (Trenberth et al., 2009) to better understand the total Earth energy imbalance caused by global warming. The increasing greenhouse gases in the atmosphere create an energy imbalance at the top of Earth's atmosphere: there is more energy coming into the system than energy radiated out, because greenhouse gases trap heat in the atmosphere, which creates warming (IPCC, 2007; Trenberth et al., 2009). This imbalance in Earth's energy budget is one of the best metrics for determining the rate of current global warming (von Schuckmann et al., 2016). Determining Earth's energy imbalance is therefore one important research subject. The excess energy associated with current global warming is mostly stored in the ocean: more than 93% of Earth's net energy imbalance over 1971–2010 is stored in the ocean (Rhein et al., 2013), and interannual to decadal variability is strongly correlated with ocean heat content variations (Allan et al., 2014; Smith et al., 2015). The Southern Ocean is central to our understanding of the world ocean's long-term trend in heat content (Figure 3).

Though it represents only 30% of the world ocean's surface, it is estimated that since 1970, the Southern Ocean has accounted for 30%–50% of the change in 0–700 m ocean heat content (Smith and Murphy, 2007; Domingues et al., 2008; Ishii and Kimoto, 2009; Levitus et al., 2012). However, recent work suggests that the overall heat uptake in these estimates may be biased low as a result of the sparse Southern Hemisphere observations available in early records, so that the Southern Ocean would instead more likely represent 60% of the global ocean heat content trend since 1970 (Durack et al., 2014). In the most recent period, which is better observed by autonomous profiling floats, the Southern Ocean contribution to the change in global 0–2,000 m heat content has climbed to 67% to 98% for the period 2006–2013 (Figure 3), with a clear peak in the latitude band of the Antarctic Circumpolar Current or north of it ( $30^{\circ}$ – $50^{\circ}\text{S}$ ; Figure 3c; Roemmich et al., 2015; Llovel and Terray, 2016). This net Southern Ocean excess heat content is stored in different regions and layers of the basin, as documented by investigating temperature trends within the water column.

### OBSERVED TEMPERATURE TRENDS

Comparing temperature measurements obtained at the end of the twentieth century or early in the twenty-first century with temperature records of previous decades is unambiguous: the Southern Ocean within and north of the Antarctic Circumpolar Current has warmed at all depths



**FIGURE 3.** (a–b) Ocean heat content change above 2,000 m depth with respect to the temperature climatology for (a) the Northern Hemisphere, and (b) the Southern Hemisphere. (c) Zonally integrated ocean heat content ( $10^{18} \text{ J yr}^{-1}$ ). Curves show estimates based on different observation-based products from different institutions: Scripps Institution of Oceanography (blue curves), International Pacific Research Center (red curves), and Japan Agency for Marine-Earth Science and Technology (green curves). The mean estimates are shown as black curves. The gray envelope denotes one standard deviation around the mean. Adapted from Llovel and Terray (2016)

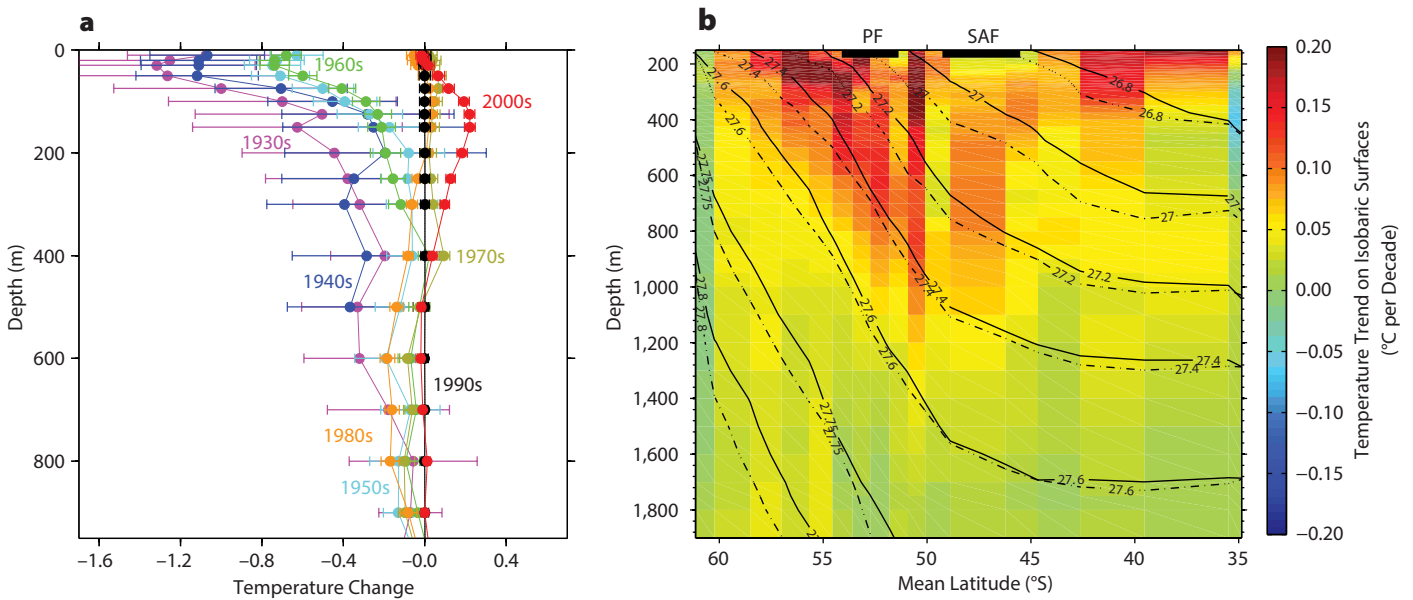
in the upper 2,000 m at a more rapid rate than the globally averaged ocean warming (Figure 4a,b; Gille, 2008; Böning et al., 2008; Giglio and Johnson, 2017). This long-term trend agrees with warming observed during the last decade, when profiling floats greatly improved spatial sampling (e.g., Giglio and Johnson, 2017). The water masses north and within the Antarctic Circumpolar Current have warmed at a rate of 0.1°–0.2°C per decade in the upper 1 km (Figures 1 and 4).

In stark contrast with the rapid warming observed within and north of the Antarctic Circumpolar Current, the surface ocean poleward of the Antarctic Circumpolar Current has warmed very slowly or has possibly even cooled slightly (Figure 1; Armour et al., 2016). The weak warming of the southernmost

surface region of the Southern Ocean is consistent with the observed and concomitant increase of Antarctic sea ice area (Vaughan et al., 2013). South of the Antarctic Circumpolar Current, the paucity of observations under the surface layer discourages any comment on long-term change, but there is some suggestion that heat might have accumulated right below the surface layer (Lecomte et al., 2017). Close to the Antarctic continent, over the continental shelf and slope, there are indications that the old and relatively warm waters (CDW; see Figure 1) have slightly warmed over the past decades, associated with a shoaling of the upper layer, which allowed CDW greater access to continental shelves (Schmidtke et al., 2014). This CDW warming and increased access to the continental shelf

has very important consequences for basal melt of the ice shelves that flank the Antarctic continent.

While most of the warming of the world ocean has occurred in the upper 2,000 m, the significance of the amount of heat stored in the deep ocean has become increasingly clear (Purkey and Johnson 2010; Mauritzen et al., 2012). Approximately 19% of excess heat associated with contemporary global warming has gone into the deep ocean below 2,000 m, and a large part of it has entered the ocean through abyssal waters that sink in the Southern Ocean (Rhein et al., 2013). Observations of the deep ocean remain scarce and are largely limited to quasi-decadal repeats of a few hydrographic sections across each deep basin (Figure 4c; Purkey and Johnson, 2010).



**FIGURE 4.** (a) Profiles of temperature differences between 1990s temperature profiles and hydrographic data sorted by decade. Differences are computed as 1990s reference temperatures minus historic temperature profiles sorted by decade. Results are presented here for summer data (November through March), averaged first by latitude band. See reference for details of the method. *Reproduced with permission from Gille (2008)* (b) Mean decadal potential temperature trends averaged on isobaric surfaces. Black contours illustrate the migration of isopycnal surfaces during the past four decades: continuous (dashed) curves represent potential densities obtained by subtracting (adding) the linear trends over two decades from (to) the climatological values. See reference for details of the method. *Reproduced with permission from Böning et al. (2008)* (c) Mean warming rates (°C per decade) below 4,000 m (color bar) estimated for deep ocean basins (thin black outlines), centered on 1992–2005. The positions of repeat oceanographic transects from which these warming rates are estimated (thick black lines) are also shown. *Adapted from Rhein et al., (2013); data from Purkey and Johnson (2010)*

Linear trends of deep ocean change, constructed from repeat sections between 1992 and 2005, reveal that most of the abyssal ocean is warming, with strongest warming close to Antarctica (Figures 1 and 4c; Purkey and Johnson, 2010; Rhein et al., 2013; Talley et al., 2016). The abyssal waters are also contracting in volume and freshening (Purkey and Johnson, 2012, 2013; Shimada et al., 2012; Jullion et al., 2013; van Wijk and Rintoul, 2014). The observed bottom water changes reflect the responses of bottom water source regions to changes in surface climate, to ocean-ice shelf interaction, and to downstream propagation of the signals by wave and advective processes (Jacobs and Giulivi, 2010; Masuda et al., 2010; Johnson et al., 2014; van Wijk and Rintoul, 2014).

### SOUTHERN OCEAN WARMING IN GLOBAL CLIMATE MODELS

The observed heat uptake and associated warming of the Southern Ocean plays a key role in climate and can feed back into the Earth system by affecting ecosystems, the biogeochemical environment, and heat and carbon cycles. It is crucial to correctly represent the observed changes in numerical models if we are to model and predict future climate. Since 1995, the climate community has regularly organized Coupled Model Intercomparison Project (CMIP) activities, in which virtually the entire international climate numerical modeling community simulates atmosphere-ocean climate under “realistic” scenarios for both past and present climate forcing. In phase 5 of the Coupled Model Intercomparison Project (CMIP5), simulated Southern Ocean trends in global ocean heat storage agree with observation-based estimates within uncertainties, with a total heat uptake of  $23 \pm 9 \times 10^{22}$  J south of 30°S over 1870–1995 (Frölicher et al., 2015). In the models, the upwelling of mid-depth waters to the Southern Ocean surface south of the Antarctic Circumpolar Current stabilized

ocean surface temperatures to levels close to pre-industrial levels over the historical period, which allowed the ocean to take up a large amount of the atmosphere’s excess heat (Frölicher et al., 2015). In simulations, the Southern Ocean accounts for as much as  $75 \pm 22\%$  of the global ocean heat uptake over the historical period.

However, the variability of this Southern Ocean heat uptake across models is large, with the standard deviation of the multimodel mean heat uptake over the Southern Ocean being  $\pm 40\%$  of the mean (Frölicher et al., 2015). The excess heat taken up by the ocean is then vigorously transported northward by the large-scale circulation and redistributed over different basins and ocean layers.

At the end of the CMIP5 historical period (2005), the CMIP5 model ensemble shows that different models store heat differently over the Southern Ocean water column. Comparing ocean layers across models is not an easy task, as each model has slightly different water-mass characteristics and depths. Using an automatic classification of the main Southern Ocean water masses can help overcome this problem for an intermodel comparison (Sallée et al., 2013; Meijers et al., 2014). The shallow ventilated layers (TW, MW, IW; see Figures 1 and 5) are simulated with large temperature differences and are consistently too warm compared to climatological mean observations

(Figure 5; Sallée et al., 2013). This probably reflects the fact that climate models do not accurately represent the complex processes that export heat within the global ocean system after having taken it up, and consequently, they accumulate too much heat in the shallow ventilated layers of the Southern Ocean. Mid-depth

“ The complexity of Southern Ocean circulation and the intricate feedback associated with warming an ocean that significantly impacts sea ice and ice sheet stability make it one of the most difficult ocean basins to represent in global climate models. ”

waters (CDW; see Figure 1) have significantly smaller biases in temperature, although they still tend to be too warm (1.9°C relative to observational estimates of 1.3°C; Figure 5), reflecting the fact that these water masses are less sensitive to biases in heat transport over the 135 years of the historical period, because their last contact with the atmosphere took place more than 135 years ago. The multimodel mean of bottom water temperature appears consistent with the observation-based estimate, but individual models show a very large spread, reflecting issues in accurately modeling the formation and transport of this water mass (Heuzé et al., 2013).

Under future climate change with moderate (Representative Concentration Pathway<sup>1</sup> 4.5; RCP4.5) or business-as-usual (Representative Concentration Pathway<sup>1</sup> 8.5; RCP8.5) greenhouse gas emissions, the suite of CMIP5 climate models shows there is a very consistent warming of the entire water column by the end of the century, concentrated largely in the subtropical, mode, and

<sup>1</sup> [http://sedac.ipcc-data.org/ddc/ar5\\_scenario\\_process/RCPs.html](http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html)



intermediate waters (Figure 4; Sallée et al., 2013). Under moderate emission pathways (RCP 4.5), the warming of the water column is estimated to range between 1°C and 1.3°C, and is 30%–60% stronger under business-as-usual emission pathways (RCP 8.5). Warming of the mid-depth waters that tend to upwell in the Southern Ocean is moderate compared to other layers of the water column, reflecting the distance from their formation site in the North Atlantic, so surface warming at their formation site does not have time to propagate to the Southern Ocean by the end of the twenty-first century. It is therefore expected that the continuous upwelling of this water mass will moderate the warming of the Southern Ocean surface south of the Antarctic

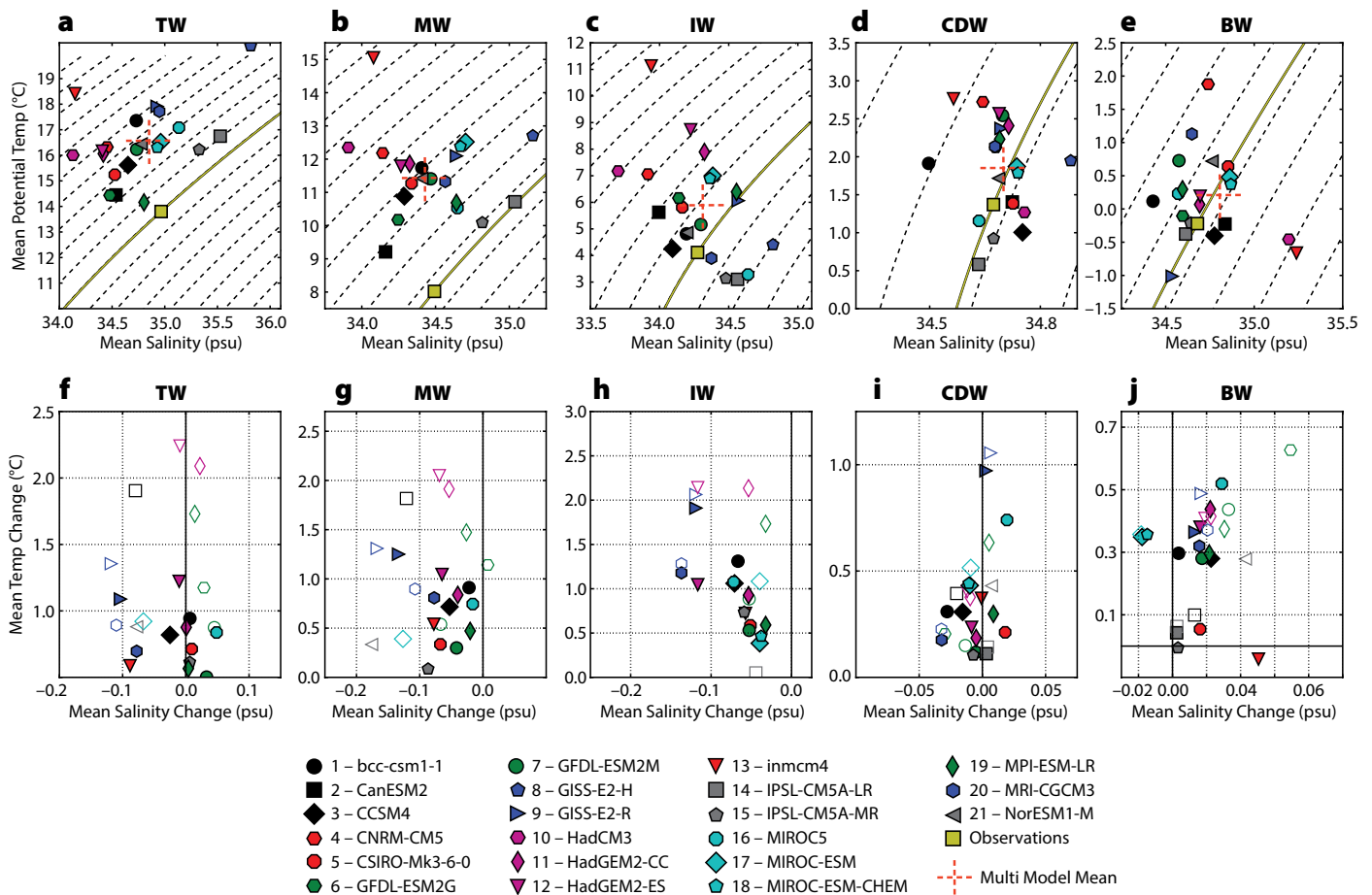
Circumpolar Current, helping to take up more heat from the atmosphere, at least until the end of the twenty-first century.

The Southern Ocean south of 30°S therefore accounts for a very large proportion of the global excess heat uptake in the CMIP5 model suite (Frölicher et al., 2015), which appears consistent with observations (e.g., Roemmich et al., 2015; Llovel and Terray, 2016). However, the large intermodel variability of the uptake and warming of Southern Ocean water-mass layers, although reduced compared to earlier-generation climate models, also indicates that the exact processes governing the magnitude and regional distribution of heat uptake and storage remain poorly understood. Better understanding of Southern Ocean processes that matter

for heat uptake and storage are urgently needed to reduce the greatest sources of uncertainties in predictions of ocean heat storage, and therefore in climate.

### MECHANISMS AT PLAY

The depth-integrated warming of the upper 2,000 m of the water column is greatest in the core of the Antarctic Circumpolar Current, and could be consistent with a long-term poleward shift (Böning et al., 2008; Gille, 2008). However, the possible poleward shift of the Antarctic Circumpolar Current has been under debate over the last few years (Sokolov and Rintoul, 2007, 2009; Sallée et al., 2008; Graham et al., 2012; Gille, 2014; Chapman, 2017), and most recent studies agree on the stability of



**FIGURE 5.** Southern Ocean temperature-salinity characteristics and future changes. The panels in the upper row (a–e) show the mean temperature–salinity of each water mass for the period 1970–2000 with superimposed 0.2 kg m<sup>-3</sup> density contours. The bottom panels (f–j) show the mean end of century changes in the temperature and salinity characteristics (2070–2100 minus 1970–2000). The filled symbols represent changes associated with emission scenario RCP4.5, and the unfilled symbols represent changes associated with emission scenario RCP8.5. Each column is associated with one water mass: from left to right, Subtropical Water (TW), Mode Water (MW), Intermediate Water (IW), Circumpolar Deep Water (CDW), and Bottom Water (BW); also see Figure 1. Potential density is referenced to the surface except when associated to bottom water where it is referenced to 4,000 m. Adapted from Sallée et al. (2013)

its meridional position (Graham et al., 2012; Gille, 2014; Chapman, 2017). The warming of the water masses north of and within the Antarctic Circumpolar Current must therefore reflect increased heat uptake at the Southern Ocean surface and/or a change of heat transport by the large-scale meridional circulation. Both of these hypotheses have been put forward in recent studies (e.g., Frölicher et al., 2015; Armour et al., 2016; Morrison et al., 2016).

One hypothesis is that heat uptake has increased over the last few decades south of the Antarctic Circumpolar Current due to a decoupling of oceanic and atmospheric warming (Armour et al., 2016): surface air temperatures have warmed, while surface ocean temperatures have been constant or have slightly cooled. The stability of subpolar surface ocean temperature might therefore be key to global ocean heat uptake. The stability of subpolar ocean temperature has been explained by at least two mechanisms that might be at play in parallel in different parts of the ocean, or that might be associated with different timescales (Ferreira et al., 2015; Kostov et al., 2017): (1) increased near-surface stratification, and (2) mean meridional overturning circulation continuously feeding the surface waters with old mid-depth waters (CDW; see Figure 1) that have been isolated from atmospheric warming (Frölicher et al., 2015; Armour et al., 2016; Morrison et al., 2016).

Near-surface stratification has increased due to a decrease in surface salinity south of the Antarctic Circumpolar Current at the circumpolar scale (de Lavergne et al., 2014; Lecomte et al., 2017), associated with ice shelf melt and/or a sea ice regime change that releases freshwater in the surface layer (Jacobs, 2006; Haumann et al., 2016). Increased near-surface stratification (process [1] in Figure 1) reduces intrusion of the relatively warm CDW into the surface layer. Surface water conditions are therefore associated with a cooling of the surface layer, and a circumpolar-scale increase in

sea ice extent (Cavalieri and Parkinson, 2008; Comiso, 2010; Vaughan et al., 2013). In addition, the reduced entrainment and mixing of surface waters with underlying warmer waters causes heat to accumulate beneath the surface layer (Schmidtke et al., 2014; Lecomte et al., 2017). Near the continental slope and shelf, observations also suggest that the surface layer shoals, allowing the relatively warm CDW to reach the continental shelves (Schmidtke et al., 2014; process [5] in Figure 1). However, the processes that allow CDW to cross the continental slope current and reach the continental shelves are still unclear (e.g., Gille et al., 2016).

While the warming of the Antarctic continental shelves has important consequences for increasing Antarctic ice shelf melt via feedback to ocean near-surface stratification and ocean heat uptake, it also means that the precursors of Antarctic Bottom Waters, which mostly form on the Antarctic continental shelves, warm and freshen before being entrained into the deep ocean (process [6] in Figure 1).

The overall increased heat taken up in the surface layer south of the Antarctic Circumpolar Current is then vigorously transported northward by the wind-induced Ekman transport (Frölicher et al., 2015; Armour et al., 2016; Morrison et al., 2016; process [3] in Figure 1). Excess heat eventually accumulates within and north of the ACC in the surface layer and in the relatively shallow layers (upper 1,000 m) that are ventilated within the Antarctic Circumpolar Current (mode and intermediate waters; see Figure 1; Cai et al. 2010; Bryan et al., 2014; Marshall and Zanna, 2014; Exarchou et al., 2015; Frölicher et al., 2015; Kuhlbrodt et al., 2015; Morrison et al., 2016). In addition, eddy processes within and north of the Antarctic Circumpolar Current result in southward along-isopycnal heat transport across the Antarctic Circumpolar Current in the mean climatological circulation state (Gregory, 2000; Wolfe et al., 2008). With increased surface warming, the along-isopycnal temperature gradient

decreases, which reduces the efficiency of the southward eddy-mediated transport of heat, resulting in heat accumulating north of the Antarctic Circumpolar Current (process [4] in Figure 1; Gregory, 2000; Dalan et al., 2005; Morrison and Hogg, 2013; Morrison et al., 2016). While surface warming might not be strong enough yet to efficiently impact southward eddy-mediated transport of heat, this decreased eddy heat transport could become an important mechanism in future warming (Morrison et al., 2016).

All of the processes described here to explain the importance of the Southern Ocean for heat uptake and storage are associated with a change in heat transport, but not with a change in the circulation itself. Potential circulation changes might also impact Southern Ocean heat uptake and storage. Several studies have discussed the possibility of an acceleration of the upper meridional overturning circulation in response to westerly wind intensification in the Southern Hemisphere, which is associated with the observed long-term trend of the dominant Southern Hemisphere climate mode known as the Southern Annular Mode (SAM; Marshall, 2003). The trend in the SAM has been shown to be a response to the ozone hole (Thompson et al., 2011), and is predicted to continue in the future in response to greenhouse gas forcing (Bracegirdle, et al., 2013). Intensification of the westerly wind can lead to an increase in the volume of mid-depth waters (CDW) upwelled south of the Antarctic Circumpolar Current, and an increased volume of water subducted north of the Antarctic Circumpolar Current (MW and IW; Le Quéré et al., 2009; Waugh et al., 2013; Landschützer et al., 2015; DeVries et al., 2017). Although such circulation changes are still under debate, if present, they would further increase Southern Ocean heat uptake in the subpolar basins, northward transport of heat north of the Antarctic Circumpolar Current, and accumulation of heat in the upper ventilated layers (mode and intermediate waters; see Figure 1).

## SUMMARY AND CONCLUSION

The Southern Ocean is a central component of the global ocean heat uptake, of Earth's energy imbalance, and of global warming. Its complex circulation, which connects all ocean density layers to the sea surface, makes it a unique place on Earth to facilitate the transfer of heat from the atmosphere to great depths, where the heat is stored for decades to millennia. However, warming of the Southern Ocean is not homogeneous. In particular, the surface of the ocean in the subpolar regions is not warming and is not predicted to warm at a pace similar to other regions in the coming century. The subpolar regions therefore constitute a very large excess heat sink due to the decoupling of atmospheric warming from stable or slower warming of the subpolar surface ocean. This largely explains why Southern Ocean heat uptake is estimated to account for more than 70% of the global ocean's heat uptake. This large amount of heat is then stored in different areas of the Southern Ocean, as well as being exported to other ocean basins. In the Southern Ocean, the ventilated layers of the upper 1 km accumulate large amounts of heat within and north of the Antarctic Circumpolar Current. But the abysses are also warming, due to the formation of bottom water around the Antarctic continent.

The warming of the Southern Ocean has important climate consequences due to its central influence on the Southern Hemisphere ice reservoir. Near-surface Southern Ocean heat content is key in limiting the seasonal development of sea ice (Martinson, 1990), and warming can therefore feed back into the global climate by limiting Earth's albedo. In addition, ocean warming accelerates melt of Antarctic ice shelves (Schmidt et al., 2014), threatening the stability of the Antarctic ice sheet (Paolo et al., 2015), with global implications in terms of sea level rise (Hellmer et al., 2012). Melt of the ice sheet also means that freshwater input onto the ocean surface is increased, which stabilizes the ocean

surface and can feed back on heat uptake (Lecomte et al., 2017).

The complexity of Southern Ocean circulation and the intricate feedback associated with warming an ocean that significantly impacts sea ice and ice sheet stability make it one of the most difficult ocean basins to represent in global climate models. While these models generally agree that the Southern Ocean has a pivotal role in historical and future heat uptake, there is a wide disparity among models in their predictions of this ocean's heat uptake and storage. In particular, the subpolar seas and the abyssal waters are not correctly represented in these models, because their processes are not well understood and observed. While there is relatively good observational sampling in the upper 2,000 m of the Southern Ocean outside the sea ice region, a sustained observing system in the sea ice sector and in the deep seas below 2,000 m, which are efficiently ventilated in the Southern Ocean, is urgently required to detect and interpret change. Because of the short and incomplete nature of existing time series, the causes and consequences of observed changes are difficult to assess. The current development of a Deep Argo network (Jayne et al., 2017), as well as the current efforts to observe the under-ice ocean with Argo probes and animal-borne sensors (Klatt et al., 2007; Wong and Riser, 2011; Treasure et al., 2017) offer a bright future and will push the limits of the current observing system. ©

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