



# Defining Southern Ocean fronts and their influence on biological and physical processes in a changing climate

Christopher C. Chapman<sup>1</sup>✉, Mary-Anne Lea<sup>2</sup>, Amelie Meyer<sup>2,3</sup>, Jean-Baptiste Sallée<sup>4</sup> and Mark Hindell<sup>2</sup>

**The Southern Ocean is a critical component of the global climate system and an important ecoregion that contains a diverse range of interdependent flora and fauna. It also hosts numerous fronts: sharp boundaries between waters with different characteristics. As they strongly influence exchanges between the ocean, atmosphere and cryosphere, fronts are of fundamental importance to the climate system. However, rapid advances in physical oceanography over the past 20 years have challenged previous definitions of fronts and their response to anthropogenic climate change. Here we review the implications of this recent research for the study of climate, ecology and biology in the Southern Ocean. We include a frontal definition ‘user’s guide’ to clarify the current debate and aid in future research.**

The Southern Ocean, generally defined as the global ocean south of about 35° S that encircles the Antarctic continent, is a unique oceanographic environment due to the lack of continental barriers blocking its flow and the strong winds that blow over its surface<sup>1</sup>. At large scales, the Southern Ocean is characterized by both the intense eastward-flowing Antarctic Circumpolar Current (ACC), one of the most powerful current systems on Earth, and strongly tilted isopycnals (lines of constant density) that shallow to the south.

Observations of the Southern Ocean dating back to the *Discovery* expedition in the 1920s revealed that the transition from warmer subtropical waters to colder Antarctic waters does not occur smoothly but is concentrated into a series of sharp transition zones, aligned generally east–west, that have come to be called fronts<sup>2</sup>. Further observations revealed that salinity, oxygen, nutrients and various other tracers showed similar behaviour, and that between the fronts, water properties are relatively homogeneous. As such, fronts delimit the boundaries between different water-masses with distinct environmental characteristics<sup>3</sup>. These fronts also tend to coincide with the locations of narrow yet very intense currents known as ‘jets’<sup>4</sup> that dominate the ACC’s flow<sup>5</sup>. The Southern Ocean is divided by fronts into a number of distinct biophysical zones, and hence a number of distinct habitats, which in turn support distinct biota<sup>6,7</sup>. Numerous studies have shown that seabirds and marine mammals tend to congregate and forage in and around fronts<sup>7</sup>. As the Earth continues to warm because of anthropogenic climate change, it is vital that we understand how these fronts and jets will respond to changes in the global climate system, and what influence that might have on associated ecosystems<sup>8–10</sup>.

Because of its remoteness and harsh climate, undertaking field studies in the Southern Ocean is both difficult and expensive. As a result, the Southern Ocean is amongst the most data-sparse of all major ocean basins, which has hindered progress on key questions regarding its dynamics and ecological communities<sup>10</sup>. In recent

decades, however, a deluge of new data from satellites and Argo profiling floats, along with ever-increasing numerical modelling capabilities, has hugely changed our understanding of the Southern Ocean. Concurrently, advances in microelectronics have enabled researchers to track individual animals over time and relate their behaviour to environmental conditions<sup>11</sup>.

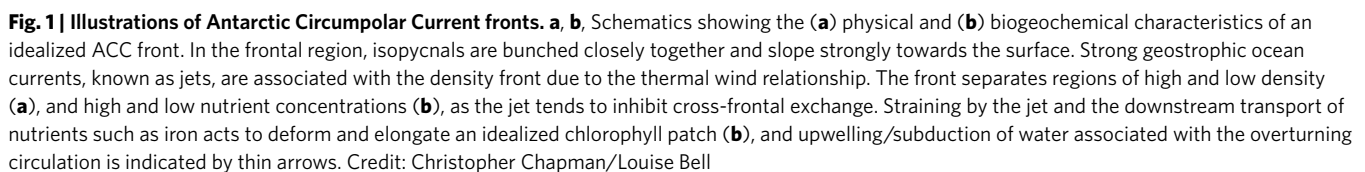
The unprecedented detail provided by these new data has caused the community to question longstanding and fundamental ideas about the nature of the ACC and its fronts. Seemingly simple questions such as “What is a front? How many fronts are there? Are ‘fronts’ and ‘jets’ the same thing? What role do fronts play in the Southern Ocean ecosystem?” have been revisited as new data and methodologies have become available<sup>12</sup>. A changing conceptual understanding of the ACC has occasionally resulted in surprising disagreements: studies using the same data but different methodologies have arrived at very different conclusions. The conflicting definitions of a front, the often technical nature of the debates, and the fact that the terms ‘front’ and ‘jet’ are often used interchangeably has resulted in a degree of confusion.

The purpose of this Review is to summarize our current understanding of Southern Ocean fronts and the potential impact of recent research in physical oceanography outside the domain. We will make clear the areas of consensus and those where substantial debate still remains. Our synthesis is aimed at the broader oceanographic community and marine biologists who may not have been aware of these recent advances or how to best exploit new data and techniques to answer outstanding questions. To this end, we include a Southern Ocean fronts ‘user’s guide’ to assist future research.

## Physical oceanography of the fronts

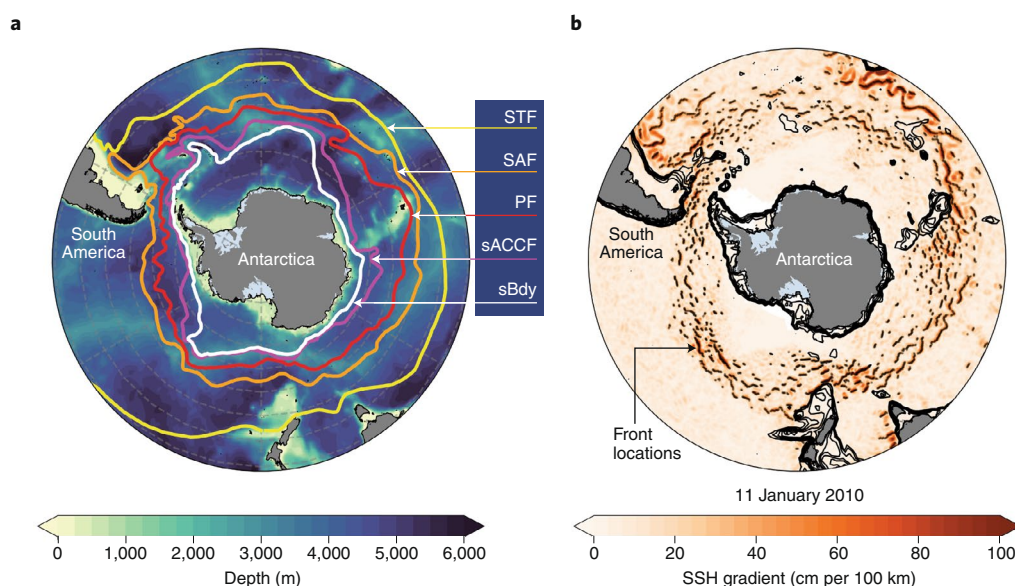
The existence of fronts in the Southern Ocean has important implications for both the physical oceanography of the region and the entire climate system. For example, enhanced density gradients near fronts support, via thermal wind, strong oceanic jets. Frontal jets are

<sup>1</sup>CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia. <sup>2</sup>Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia. <sup>3</sup>Australian Research Council Centre of Excellence for Climate Extremes, University of Tasmania, Hobart, Tasmania, Australia. <sup>4</sup>Sorbonne Université, CNRS, LOCEAN, Paris, France. ✉e-mail: [chris.chapman@csiro.au](mailto:chris.chapman@csiro.au)



Historically, fronts in the Southern Ocean have been defined as the boundary between two zones with distinct water-mass properties<sup>2</sup>. By compiling hydrographic data obtained from research cruises over many decades, researchers built what has become known as the

By necessity, the traditional view of ACC fronts was a time-averaged view: it took decades to assemble a database of hydrographic profiles capable of representing the broad-scale structure of the ACC. However, as fronts are sharp boundaries between two different water-masses, they manifest as strong horizontal gradients in



**Fig. 2 | The changing conception of the Antarctic Circumpolar Current and its fronts.** **a**, Smooth, continuous, circumpolar fronts determined by Orsi and collaborators<sup>3</sup> using historical hydrographic data and applying water-mass criteria (such as a particular temperature value at a certain depth) to define their locations. The named fronts are, north to south, the Subtropical Front (STF); the Subantarctic Front (SAF); the Polar Front (PF); the southern ACC Front (sACCF); and the Southern Boundary (sBdy) front. Colours show the ocean depth, illustrating the strong steering of the fronts by submarine bathymetric features. **b**, A daily snapshot (11 January 2010) of the gradient of SSH obtained from the gridded AVISO satellite altimetry product (colours). Broken black lines indicate the location of fronts or jets on this date determined by SSH gradient thresholding<sup>25</sup>. Solid contour lines are isobaths (contour interval of 1,000 m).

fields such as sea-surface temperature (SST) or sea-surface height (SSH) that can be observed by satellites. With the availability of high-resolution satellite data in the 1980s and 1990s, it became apparent that the Southern Ocean is more complex than the traditional view would suggest (Fig. 2b), and that the ACC is not composed of a distinct number of coherent, circumpolar fronts, but of an intricate web of thin filaments that can spontaneously form and disappear, split and merge, meander and drift, bearing little resemblance to the traditional view of the ACC. Crucially, there is no settled answer to how many ACC fronts exist, as the number of fronts varies both temporally and spatially<sup>23–25</sup>.

During the satellite era, it was established that fronts in the Southern Ocean arise primarily by complicated nonlinear interaction between the mean flow and turbulent eddies: in some regions of the ACC, mesoscale eddies accelerate jets and sharpen tracer gradients<sup>18,26</sup>. Jets also act to suppress mixing; regions with strong jets tend to have greatly reduced meridional (north–south) exchange of heat and other tracers<sup>13</sup>. Conversely, in regions with weaker jets, which typically occur downstream of large bathymetric features, the transport barrier effect is weaker, and elevated north–south exchanges are found in these ‘leaky’ jet regions<sup>13,14,27–30</sup>.

Reconciling the traditional view of the ACC from hydrography and the new dynamic view provided by high-resolution satellite observations has, despite intense research, eluded closure. Numerous studies have argued that the major hydrographic fronts are composed of numerous branches: distinct coherent frontal features that can occasionally merge together in certain regions<sup>5,24,31–34</sup>. However, more recent research has cast some doubt on this interpretation, with several studies showing that the frontal structure of the ACC rearranges itself several times around the circumpolar circuit<sup>23,25,35</sup>, manifesting as the splitting of a single front into numerous subfronts, rather than coherent meandering of the individual frontal branches as suggested by earlier studies<sup>12,24,33</sup>. Evidence so far does not suggest that any one front maintains a continuous structure over the entire ACC<sup>25,35,36</sup>.

### Practical definitions of fronts

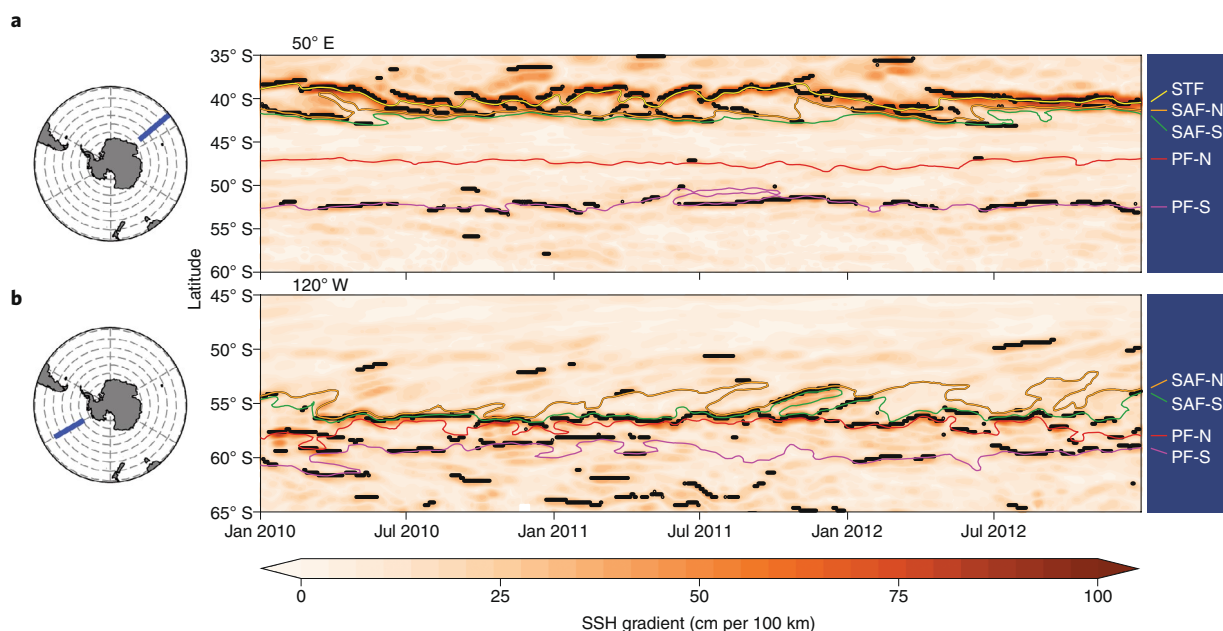
In his seminal review<sup>37</sup> of fluid dynamical jets, Rhines stated, “It is not easy to give a precise definition of a jet of fluid motion, but most of us know one when we see it.” This statement could also apply to Southern Ocean fronts: although the conceptual idea of a front as a water-mass boundary is universally accepted, there is no single, precise definition of a front. In practice, a wide variety of definitions are used<sup>12</sup>. Inconsistent frontal definitions and conflicting nomenclature have led to a great deal of confusion about what is, and what is not, a front<sup>38</sup>.

Early studies based on hydrographic data typically used water-mass criteria, such as a particular value of temperature, to define a front<sup>3,22</sup>. However, with the changing view of the ACC, these definitions have been reevaluated. Currently, frontal definitions fall into two broad classes<sup>12</sup>.

**Local definitions.** These use criteria found in the immediate neighbourhood of a geographical location to determine if a front is present. Gradient thresholding is probably the most commonly used local method: a front is detected should the gradient of some quantity (typically SST<sup>39–41</sup> or SSH<sup>12,25,26</sup>) exceed some pre-defined threshold. However, other local definitions exist, such as those based on statistical properties<sup>14,27,36,42</sup> or the dissimilarity of nearby hydrographic profiles<sup>43,44</sup>. Locally defined fronts are not necessarily continuous, and the number of fronts can vary in space and time.

**Global definitions.** These seek to identify some quantity, for example a particular value of temperature or SSH, that one can use to identify a front over some region, or even over the entire ACC<sup>5</sup>. Fronts defined using global definitions are generally continuous in space, and the number of fronts is chosen a priori<sup>24</sup>.

Typically, biologists define fronts based on SST criteria, whereas physical oceanographers generally use SSH. There is a subtle difference between these oceanographic variables: the SST seen by satellites is strictly the near-surface temperature, whereas the SSH



**Fig. 3 | A cautionary example of using sea-surface height to track fronts.** **a, b,** Colours show latitude–time (Hovmöller) diagrams of SSH gradient (obtained from the AVISO gridded satellite altimetry product) from 1 January 2010 to 31 December 2012 at locations in the **(a)** southwest Indian Ocean and **(b)** central-south Pacific Ocean. The thin solid lines are five contours of SSH, corresponding to values that best define (from north to south) the STF; the northern and southern branches of the Subantarctic Front (SAF-N and SAF-S); and northern and southern branches of the Polar Front (PF-N and PF-S), the values themselves are taken from the work of Chapman<sup>25</sup>. The black dots indicate the location of fronts determined from SSH gradient thresholding<sup>25</sup>. The SSH contours do not always follow the regions of high SSH gradient and occasionally identify fronts where gradients are weak. This example is inspired by the work of Graham and colleagues<sup>35</sup>.

is a function of both the temperature and salinity throughout the entire water column. As such, SST reflects surface ocean conditions, whereas SSH is influenced by both surface and subsurface processes.

That global frontal definitions resemble older water-mass definitions is no coincidence, as they arose from work seeking to resolve the discrepancy between the traditional and dynamic views of the ACC. These studies showed that regions of, for example, high SSH gradients were consistently associated with both hydrographic fronts and particular values of SSH itself<sup>21,5,31–34</sup>. By finding the SSH or SST value most closely associated with high gradients or water-mass criteria, one obtains a definition of a front that is both time variable, yet spatially continuous.

However, it has been shown that the value of temperature or SSH associated with a particular front may not perfectly align with high gradient regions over the entire region of interest, leading to the suggestion of the presence of a front where it may, in fact, be absent<sup>35</sup>. Additionally, the frontal structure is variable in both time and space, and a value of (for example) SSH representative of a front at one location or time may not be representative at another<sup>14,25,35,36</sup>. These phenomena are illustrated in Fig. 3, which shows a time-series of the gradient of satellite-derived SSH at two longitudes in the Southern Ocean, together with contours of SSH associated with five major ACC fronts. Although the SSH contours represent the mean positions of the fronts very well, the contours frequently drift off high-gradient regions, or persist during periods without high SSH gradients.

Both local and global definitions of fronts have advantages and disadvantages, and the choice of definition must be based on the nature of the scientific question being posed. Advice for choosing frontal definitions is presented in the ‘user guide’ below.

### Fronts, biogeochemistry and ecosystems

The unique oceanographic conditions of the Southern Ocean have profound implications for the ecology of the region and

biogeochemical cycles that influence the climate system. As a result of its steeply sloped isopycnals, it is in the Southern Ocean that nutrient- and CO<sub>2</sub>-rich deep water-masses (so called as they are found at a depth greater than 1 km throughout most of the global ocean) upwell to the ocean surface<sup>16</sup>. Once at the ocean surface, these formerly deep waters are able to exchange heat and CO<sub>2</sub> with the atmosphere<sup>45</sup>, and their nutrients may be consumed by biology confined to the euphotic zone<sup>7</sup>.

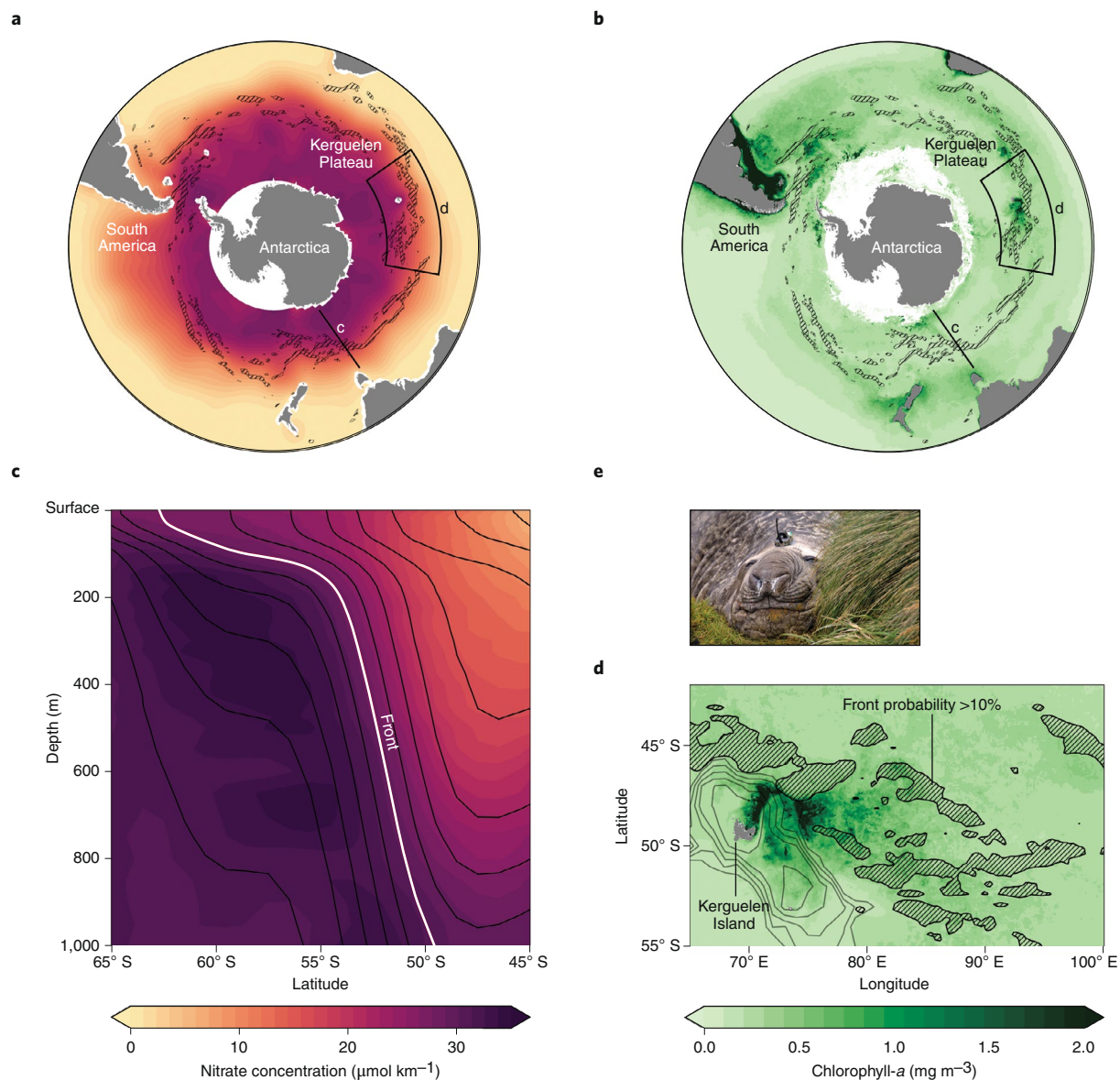
Southern Ocean fronts are thought to play a key role in the global distribution of important nutrients, such as nitrates, through two primary mechanisms<sup>46</sup>: (1) the fronts act as sites of enhanced vertical exchange between the deep and surface ocean; and (2) the ‘mixing barrier’ effect for frontal jets reduces the exchange of tracers across fronts.

Throughout most of the global ocean, less-dense, nutrient-poor water-masses are vertically stacked on top of dense, nutrient-rich water-masses. However, in the Southern Ocean, the intense upwelling (localized in frontal regions) results in vertical property gradients being tilted sideways and therefore becoming horizontal property gradients. The mixing barrier effect then inhibits the exchange of these upwelled waters with neighbouring nutrient-poor water-masses, forming biogeochemical fronts<sup>46,47</sup> (see Fig. 4a,c).

However, there is a paucity of high-resolution biogeochemical data in the Southern Ocean. The impact of the filamented, dynamic fronts (discussed in the ‘Physical oceanography’ section) on the nutrients and other tracers is therefore poorly understood. However, recent work has shown that the upwelling and subduction in the Southern Ocean is controlled by the complex interactions between the frontal jets, large bathymetric features and surface winds<sup>45,48,49</sup>. The upwelling of nutrients and subduction of CO<sub>2</sub> into the ocean interior is thus localized to regions where fronts interact with bathymetry<sup>49–51</sup>.

Similar frontal dynamics also influence the ecology of the Southern Ocean from the base to the top of the trophic chain.





**Fig. 4 | The influence of fronts on nutrients and phytoplankton blooms.** **a**, The springtime (September to December) mean concentrations of nitrates ( $\text{NO}_3^-$ ) from the World Ocean Atlas 2018 (WOA18)<sup>100</sup>. **b**, Chlorophyll-*a* concentration, a proxy for phytoplankton concentration, from MODIS ocean colour satellite system<sup>57</sup>. This is a time mean for 2003–2018 November. **c**, Depth/latitude transect between Tasmania and Antarctica (along 140°, shown as a thin black line in **a**) showing the spring mean WOA18 nitrate concentration from the surface to 1,000 m depth. The thin black lines are lines of constant surface referenced potential density ( $\sigma_\theta$ ), also from WOA18, and the white line shows the approximate location of the nitrate front. **d**, MODIS chlorophyll-*a* concentrations near Kerguelen Island, showing the extent of the seasonal bloom. Time mean for 2003–2018 November. Thin grey lines are bathymetric contours (contour interval 500 m). In **a**, **b** and **d**, hatching shows regions where the probability of encountering a front is greater than 10% (from ref. <sup>25</sup>). **e**, A Kerguelen southern elephant seal, equipped with a miniaturized temperature, salinity and depth sensor (the Sea Mammal Research Unit (SMRU) SRDL tag). Southern elephant seals are known to forage in the Kerguelen phytoplankton plume. Photo: Mark Hindell.

Although upwelling of deep waters supplies the Southern Ocean with large quantities of nitrates, phosphates and silicates, the region is a known ‘high-nutrient, low-chlorophyll’ zone because of iron limitation<sup>52,53</sup>. However, downstream of several islands scattered throughout the Southern Ocean, as well as near the South American continental shelf, phytoplankton concentrations can be relatively high<sup>52,54–56</sup>, as illustrated in Fig. 4b,c by satellite-derived chlorophyll-*a* concentrations<sup>57</sup>. Phytoplankton blooms are initiated in regions where frontal jets interact with bathymetry, bringing iron-rich sediments to the surface<sup>49,54</sup>. Jets then export these high iron concentrations downstream, which can extend phytoplankton blooms hundreds or even thousands of kilometres downstream of the iron

source regions<sup>56</sup>, as shown for the Kerguelen Plateau region in Fig. 4d. Zooplankton, such as krill, that graze on phytoplankton congregate in these productive regions, and are, in turn, targeted by many larger Antarctic predators, including fish, squid, seabirds and mammals<sup>58–60</sup> (Fig. 4e).

At the fronts themselves, the dynamic nature of the oceanography may result in increased biomass and biodiversity as the interfrontal communities interact<sup>58</sup>. This increased biodiversity also influence the distribution and behaviour of organisms at higher trophic levels<sup>7</sup>. Fronts create ecological niches occupied by particular species<sup>20,54,55,61</sup>. For example, king penguins (*Aptenodytes forsteri*) forage in the Antarctic polar frontal zone and target mesoscale features such as

thermal fronts<sup>62–66</sup>, travelling further in years when the position of the front is further from their breeding and moulting grounds<sup>67,68</sup>. Southern Ocean seabird assemblages are reported as being associated with specific water-masses, including interfrontal zones<sup>69–71</sup>. There is evidence that marine predators use environmental conditions, such as temperature, as an indication of prey availability<sup>66</sup>.

The relationship between fronts and the distribution of marine animals is less clear than that for phyto- and zooplankton, owing to their capacity to conduct basin-scale movements and the dictates of species-specific life histories. For example, Antarctic fur seals (*Arctocephalus gazella*) travel to the Antarctic polar frontal zone<sup>72–74</sup> to take advantage of elevated productivity shaped by the large-scale oceanography<sup>75</sup>, while southern elephant seal (*Mirounga leonina*) populations can be divided into 'locals' that exploit a few frontal features, or 'roamers' that forage in multiple different heterogeneous environments<sup>76</sup>. Central place foragers, such as seals and penguins, need to return regularly to breeding sites, whereas some species, such as the wandering albatross (*Diomedea exulans*), can range over vast distances<sup>77</sup>.

Great advances in biotelemetry tools for animal tracking, coupled with the availability of higher-resolution ocean observations, have enabled greater understanding of relationships between marine animals and complex ocean processes. For example, southern elephant seals and macaroni penguins (*Eudyptes chrysolophus*) are now known to interact with and forage in regions of high eddy formation and filaments associated with ACC fronts<sup>78–82</sup>. However, the relationships between biology and environmental conditions are often qualitative<sup>83</sup> or restricted to a few individuals<sup>79</sup>. As such, the challenge for biologists is to integrate observations of animal behaviours with the fine-scale physical and biological properties of Southern Ocean fronts. Earlier perceptions of Southern Ocean fronts as a 'line in the sea' can be too simplistic, and at odds with what is now known about the behaviour of many predators. Recognition of the spatial and temporal dynamics of fronts, along with tools that enable biologists to identify oceanographic features at scales and times congruent with the behaviour of marine predators, will enable deeper insights into the factors that limit biological production, how this propagates up the food chain, and why organisms aggregate where they do.

### Climate change and Southern Ocean fronts

The Southern Ocean is both warming<sup>8,84</sup> and freshening<sup>84,85</sup>, and there is evidence that the strong westerly winds that drive the ACC are both intensifying and shifting to the south<sup>86</sup>. These trends are expected to continue with ongoing climate change<sup>50,87,88</sup>. Given the importance of ACC fronts to the ecosystems of the Southern Ocean and the climate system, assessing and predicting how they will respond to a changing climate is vital. However, research on this question has suffered from much of the same confusion that pervades the literature on ACC fronts as a whole, owing to inconsistent frontal definitions, nomenclature and methodologies. In this section, we discuss the observed and projected changes in ACC fronts and the implications of such changes on Southern Ocean ecosystems.

### Observed and projected changes in Southern Ocean fronts.

Studies of trends in the structure or position of ACC fronts and jets have been hampered by a lack of long-term observations<sup>1</sup>. However, the development of 'contour'-type methods (see section on 'Practical definitions of fronts') that link hydrographic fronts with surface phenomena observed by satellites has enabled the multidecade-long satellite record to be exploited to study the variability of ACC fronts. A wave of studies using these methods established a tentative consensus: over the satellite altimetry period (from 1993 onwards), the main fronts of the Southern Ocean had generally shifted south by about 0.5–1.5° (60 km on average) over a period of around 15 years (refs. <sup>31,33,34,89</sup>). Frontal variability was found to

be larger away from bathymetric features with large spatial scales, which tend to constrain frontal movements. Several of these studies noted that the position of ACC fronts were sensitive to changes in atmospheric forcing due to large-scale climate modes such as El Niño/La Niña<sup>31,34</sup>. These conclusions were generally supported by studies using the previous generation of climate models (those associated with the Coupled-Model Intercomparison Project 3 (CMIP3) multimodel ensemble) that projected a poleward trend in frontal locations driven by changes in winds, which would probably continue into the future<sup>86,90</sup>. On the strength of the consensus that emerged between 2007 and 2015, the observed warming in the Southern Ocean was interpreted as a signature of regionally localized southward shifts of the ACC fronts<sup>8,33,91,92</sup>.

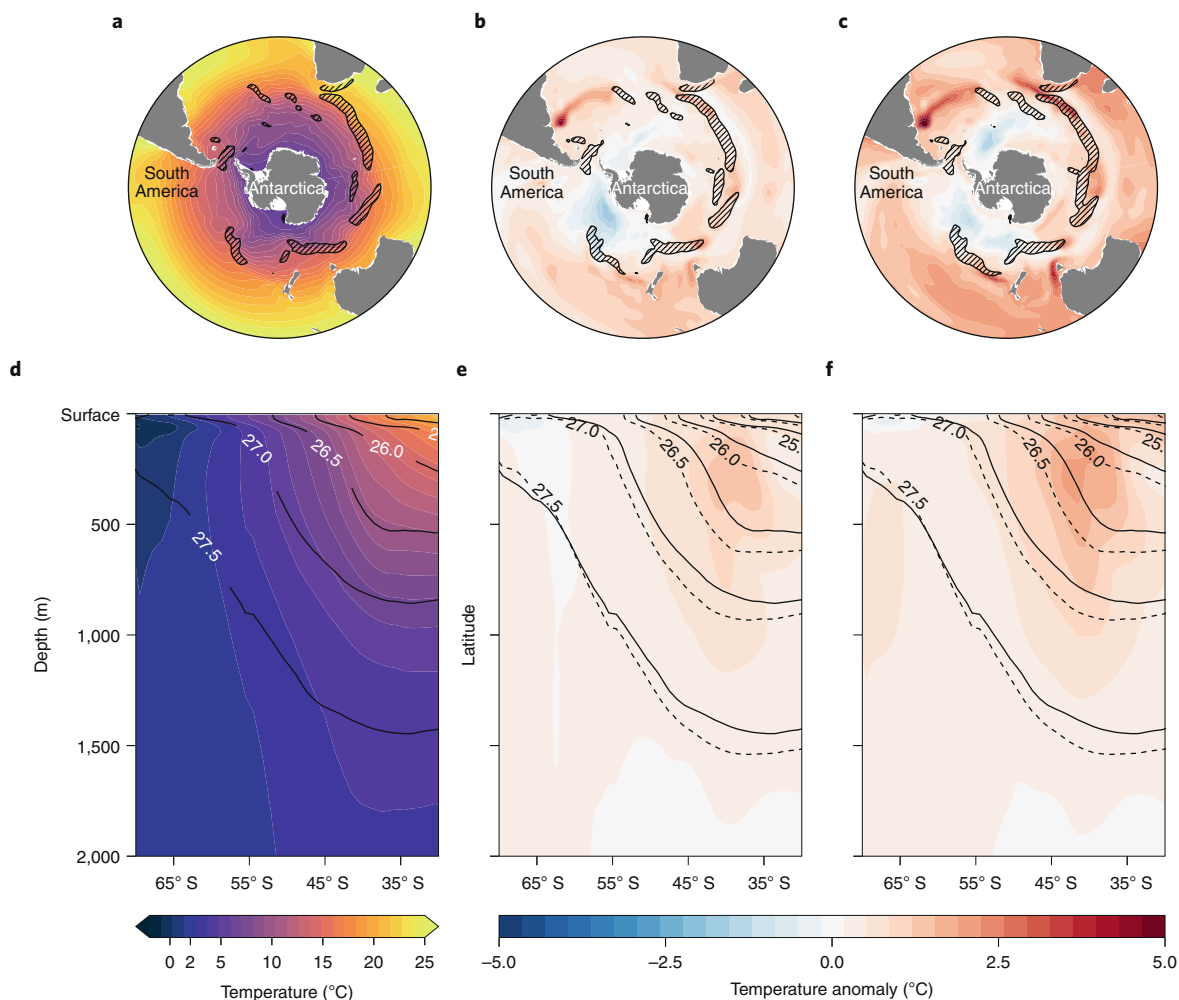
The primary assumption of these analyses is that if a contour of SSH shifts, then its associated fronts will shift with it. However, more recent work using 'local' definitions (see above) has shown that this is not necessarily true, with numerous studies failing to detect any long-term trend in the position of the ACC fronts<sup>19,25,41,42,93,94</sup>, although there is some evidence of localized frontal movements and changes in frontal intensity<sup>40,41</sup>. Additionally, some recent studies provide only limited evidence of a systematic response of fronts to changing atmospheric forcing<sup>25,35,42</sup>. More modern climate models, such as those within the CMIP5 multimodel ensemble, show no systematic shift in frontal locations<sup>35,84,88,95</sup>. Instead, most recent modelling studies predict an increase in the strength of the Southern Ocean's eddy field and stratification, as well as a moderate increase in the rate of upwelling of deep waters<sup>16</sup>.

In Fig. 5, we illustrate the projected Southern Ocean climate change using output from a modern climate model, the GFDL-ESM2M<sup>96</sup>, forced by two scenarios for greenhouse gas concentration: a medium emissions scenario (Representative Concentration Pathway 4.5), and a high one (Representative Concentration Pathway 8.5). In both cases, the temperature of the Southern Ocean is projected to increase substantially, which would result in a considerable southward shift of SST and SSH contours by the year 2100. However, in both climate projections considered here, there is little to no shift in position of either regions of high SSH gradients (Fig. 5a–c) or strong isopycnal slopes (Fig. 5d–f), both of which are indicative of fronts. We note that this analysis has been undertaken using a single climate model, and different individual models can give divergent results<sup>88</sup>.

The SST and SSH contours that are often used to track frontal positions are sensitive to large-scale thermal expansion and steric sea-level rise occurring as a result of global climate change<sup>94</sup>. As such, although the locations of a particular SST or SSH contour may have shifted, their spatial gradients are largely insensitive to changes in the ocean's broad-scale structure<sup>93</sup>. This more recent work has led to the new consensus that ACC fronts have not shifted southward in the past decades, and the observed warming is now explained by changes in the wind-driven overturning circulation that accumulates heat within the ACC<sup>8,97</sup>.

**Impact of frontal changes on ecosystems.** If ACC fronts were to shift south as a result of climate change, there would be a number of ecological implications: the structure and environmental conditions of the Southern Ocean's bioregions would be likely to change<sup>9,61</sup>; there would be modifications in the distribution of nutrients and phytoplankton that form the base of the trophic web<sup>61</sup>; and there would be changes in distance required for animals to travel from breeding and moulting sites to foraging grounds<sup>9,67,68,98</sup>.

Studies seeking to understand the ecological implications of frontal shifts frequently use global front definitions, which may not be appropriate for the study of variability and change in ACC fronts. Additionally, more recent research has highlighted that fine-scale features, such as eddies and submesoscale currents, are as important as the mesoscale fronts for certain species<sup>21,82</sup>, and that these



**Fig. 5 | Climate change in the Southern Ocean.** **a**, SST for the period 1985–2005 from a historical climate model simulation. **b**, **c**, The SST anomaly for the period 2080–2100 (relative to 1985–2005) for (b) medium (Representative Concentration Pathway RCP4.5) and (c) high (RCP8.5) emissions scenarios. Hatched regions correspond to SSH gradients greater than 10 cm per 100 km (indicative of fronts or strong surface currents). **d–f**, As for **a–c**, but a circumpolar (zonal) mean section (that is, average along lines of latitude). Solid lines show the density contours (isopycnals) for the period 1985–2005, while the dashed lines show isopycnals for the period 2080–2100 for the RCP4.5 (e) and RCP8.5 (f) scenarios. The climate model is the Geophysical Fluid Dynamics Laboratory ESM2M<sup>96</sup>, part of the CMIP5 multimodel ensemble.

features are unlikely to be represented in the climate change projections from coarse-resolution climate models<sup>88</sup>.

Future projections of Southern Ocean climate are uncertain, and numerous phenomena associated with ACC fronts of biological significance, such as the strength of the eddy field and the role of fronts as barriers to mixing, are potentially impacted by climate change. In addition, some climate projection predict a decoupling of the biogeochemical fronts from the physical fronts<sup>47</sup>, which would have implications for animals that use temperature as a proxy for prey availability<sup>66</sup>. Therefore, although fronts might not shift meridionally, some aspects of the habitat are likely to change.

### The Southern Ocean fronts ‘user guide’

The rapid change in our understanding of the ACC, its fronts, and how they shape Southern Ocean ecosystems has resulted in confusion. How best one can proceed with a study of Southern Ocean physics, chemistry or biology? Which frontal definition should one use and why? How can one infer and attribute changes in the ACC? However, despite the complex nature of the ACC and its ecosystems, there has been extraordinary progress over the past decade, made possible primarily through the expansion of the Southern Ocean

Observing System (SOOS)<sup>99</sup>. Continued progress will depend on effective exploitation of these new data systems. To this end, we now present some broad advice to aid researchers.

**Defining ACC fronts and jets.** The choice of frontal definition can have a large impact on the results of a study, with particularly strong implications for the study of variability and change<sup>12,35</sup>. ‘Local’ definitions derive all information required for their definition from the neighbourhood of the front itself, whereas ‘global’ definitions, such as the contour method<sup>5</sup>, define fronts using information from a wide geographical region. We emphasize that there is no ‘correct’ frontal definition; the choice of a definition should always be guided by the objectives of the study and the available data. The advantages and disadvantages of each approach, and potential use cases are summarized in Table 1. For studies of time-averaged or broad-scale properties, global methods have several advantages: they are able to link jets and the hydrographic fronts, and their continuous representation allows geographically distant frontal features to be connected. Global-type definitions are also generally useful for linking surface fields observable by satellite with interior water-masses<sup>4,31,34</sup>, and for defining along-front coordinate systems<sup>24,29</sup>.



**Table 1 | Comparison between standard frontal definitions**

	Global	Local
Example definitions	Water-mass criteria <sup>3,22</sup> Contour fitting <sup>4,5,7</sup>	Gradient thresholding <sup>12,27,35,39</sup> Skewness/kurtosis <sup>27,42</sup> Probability density functions (PDFs) <sup>14,23</sup> Profile similarity/clustering <sup>43,44</sup>
Advantages	Accurate time-mean locations <sup>5,12</sup> Smooth, continuous fronts <sup>32</sup> Links distant regions <sup>32</sup> Links jets to water-masses/hydrography <sup>4</sup> Simple to interpret <sup>7,68</sup>	Unambiguous definition <sup>12,25</sup> Identifies changes in frontal structure <sup>25,36</sup> Identifies mixing barriers <sup>13</sup> No spurious variability <sup>35</sup> Number of fronts can vary spatiotemporally <sup>25,35</sup>
Disadvantages	Imperfect tracking of high gradients <sup>35</sup> Spurious variability <sup>35,94</sup> Sensitivity to sea-level rise/warming <sup>24</sup> Must choose number of fronts in advance <sup>24</sup> Does not represent changes in frontal structure <sup>25,35</sup>	Sensitive to noise/eddies <sup>12</sup> Must specify a threshold parameter <sup>12</sup> Difficult to interpret <sup>25</sup> Difficult to link jets to hydrology/water-masses <sup>12</sup>

Local definitions, by contrast, do not require the number of fronts to be specified in advance, and might better reflect regionally localized dynamics. However, interpreting their results is less straightforward than for global methods. We favour a probabilistic interpretation of frontal locations: instead of seeking to identify the location of a front at any given time, one should instead determine an envelope of where fronts are likely to be found over a time-period of interest. An example of this approach is presented in Fig. 4.

#### Methodological choices for the study of variability and change.

The assessment of shifts in the location of Southern Ocean fronts has been mired in controversy over the past decade, with disagreement over the interpretation regarding the observed changes in the ACC (see 'Climate change and Southern Ocean fronts'). This controversy stems from the methodological differences between studies that find frontal shifts in the observation record and those that do not. Typically, studies that have found long-term frontal shifts used contour-type methods, whereas those that did not do so used local-type definitions. Given this controversy, we urge all researchers to be extremely prudent when assessing changes in the ACC's frontal structure. Readers are advised to consider their choice of frontal definition carefully, as naïve application of the contour method can lead to spurious variability and trends in frontal locations<sup>94</sup>. In cases where fronts are not required to be continuous, we favour the use of local frontal definitions in studies of variability and change. However, if a continuous, global frontal definition is sought, we then strongly encourage researchers to demonstrate that the variability and trend provided by the chosen global definition do track variability and trends of the water-masses structures.

Southern Ocean fronts and the eddies responsible for their formation are mesoscale features. To represent the physics of jets, fronts and eddies, ocean models must have horizontal grid spacing less than about 10 km over most of the Southern Ocean. Running ocean models at this resolution requires vast computational resources, currently impractical for long climate studies. Despite this, low-resolution climate models are still able to produce realistic broad-scale water-mass distributions in the Southern Ocean and are useful for assessing potential changes in the Southern Ocean environment<sup>88,97</sup>. They are, however, incapable of representing the fine-scale features of fronts, and their outputs must be interpreted with care.

#### Perspectives for the future

Advances in physical oceanography made possible by new data sources and analysis techniques have begun to resolve previously

contentious questions regarding the nature of Southern Ocean fronts. For example, the role of ACC fronts in shaping broad-scale heat fluxes, the upwelling and subducting of water-masses, and the distribution of nutrients throughout the global ocean are now broadly understood. Additionally, it is now broadly accepted that the mean positions of the ACC fronts have not changed in response to recent climate change. However, fundamental questions remain unresolved: in particular, the relationship between surface features detected by satellites and hydrographic fronts is still unclear in all but a few special cases.

Despite this recent progress, much work remains to translate our improved understanding of the physics of the Southern Ocean into improved understanding of its ecosystems and its role in the greater climate system. For example, the role of fronts in shaping ecosystems and bioregions must now be reevaluated in light of our updated knowledge of their dynamics. In particular, clear relationships between filamentary fronts revealed by satellites and productive environmental conditions capable of supporting complex marine ecosystems are yet to be demonstrated. The response (if any) of the ACC fronts to the ongoing climate change, and any downstream impact on the climate system through their influence on the Southern Ocean carbon sink or southward heat flux is also poorly understood and not well represented in climate models. Theoretical understanding of the mechanisms of front formation and variability also remains incomplete.

Progress on these questions remains hampered, as was so often the case in the past, by insufficient data. In particular, biogeochemical data, such as observations of dissolved oxygen, CO<sub>2</sub> and nutrients, are severely limited. The future, however, holds great hope for further breakthroughs. In particular, the increasing number of Argo floats equipped with biogeochemical sensors, as well as improving capabilities of new observing platforms such as ocean gliders, promise to shed light on these and other outstanding questions. The utility of equipping marine animals with oceanographic instruments has only recently been realized, and continued exploitation of these data could also lead to new advances<sup>11</sup>.

However, in our opinion, the greatest obstacle to further progress on these and many other outstanding questions is the compartmentalizing of researchers into specialities. The complexity of the region severely limits the potential progress of a single domain specialist when seeking to make inferences regarding the system as a whole. It is our view that the greatest potential for progress lies in facilitating further cross-disciplinary collaboration. A successful example of this cross-disciplinary collaboration is the Marine Mammals Exploring the Oceans Pole to Pole project<sup>11</sup>, which equips marine



mammals with miniature temperature and salinity sensors, and has yielded a plethora of new results.

Received: 9 August 2019; Accepted: 15 January 2020;

Published online: 24 February 2020

## References

- Rintoul, S. R. & Naveira Garabato, A. C. in *Ocean Circulation and Climate: A 21st Century Perspective* Vol. 103 (Siedler, G. et al.) 471–492 (Academic, 2013).
- Deacon, G. *The Hydrology of the Southern Ocean*. *Discovery Reports* (Cambridge Univ. Press, 1937).
- Orsi, A. H., Whitworth, T. & Nowlin, W. D. On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep Sea Res. Part I* **42**, 641–673 (1995).
- Sokolov, S. & Rintoul, S. R. Structure of Southern Ocean fronts at 140° E. *J. Mar. Syst.* **37**, 151–184 (2002).
- Sokolov, S. & Rintoul, S. R. On the relationship between fronts of the Antarctic Circumpolar Current and surface chlorophyll concentrations in the Southern Ocean. *J. Geophys. Res. Oceans* **112**, C07030 (2007).
- Grant, S., Constable, A., Raymond, B. & Doust, S. *Bioregionalisation of the Southern Ocean: Report of the Experts Workshop* (ACE-CRC and WWF Australia, 2006).
- Bost, C. A. et al. The importance of oceanographic fronts to marine birds and mammals of the southern oceans. *J. Mar. Syst.* **78**, 363–376 (2009).
- Sallée, J. B. Southern Ocean warming. *Oceanography* **31**, 52–62 (2018).
- Constable, A. J. et al. Climate change and Southern Ocean ecosystems. I: How changes in physical habitats directly affect marine biota. *Glob. Change Biol.* **20**, 3004–3025 (2014).
- Rogers, A. D. et al. Antarctic futures: an assessment of climate-driven changes in ecosystem structure, function, and service provisioning in the Southern Ocean. *Annu. Rev. Mar. Sci.* **12**, 87–120 (2019).
- Treasure, A. et al. Marine mammals exploring the oceans pole to pole: a review of the MEOP consortium. *Oceanography* **30**, 132–138 (2017).
- Chapman, C. C. Southern Ocean jets and how to find them: improving and comparing common jet detection methods. *J. Geophys. Res. Oceans* **119**, 4318–4339 (2014).
- Naveira-Garabato, A. C., Ferrari, R. & Polzin, K. L. Eddy stirring in the Southern Ocean. *J. Geophys. Res. Oceans* **116**, C09019 (2011).
- This paper provides a detailed examination of the ‘mixing barrier’ effect in Southern Ocean fronts, central to their role in the climate system.**
- Thompson, A. F. & Sallée, J.-B. Jets and topography: jet transitions and the impact on transport in the Antarctic circumpolar current. *J. Phys. Oceanogr.* **42**, 956–972 (2012).
- Chapman, C. & Sallée, J.-B. Isopycnal mixing suppression by the Antarctic Circumpolar Current and the Southern Ocean meridional overturning circulation. *J. Phys. Oceanogr.* **47**, 2023–2045 (2017).
- Morrison, A., Frölicher, T. & Sarmiento, J. L. Upwelling in the Southern Ocean. *Phys. Today* **68**, 27–32 (2015).
- Stukel, M. R. et al. Mesoscale ocean fronts enhance carbon export due to gravitational sinking and subduction. *Proc. Natl Acad. Sci. USA* **114**, 1252–1257 (2017).
- Williams, R. G., Wilson, C. & Hughes, C. W. Ocean and atmosphere storm tracks: the role of eddy vorticity forcing. *J. Phys. Oceanogr.* **37**, 2267–2289 (2007).
- Chambers, D. P. Using kinetic energy measurements from altimetry to detect shifts in the positions of fronts in the Southern Ocean. *Ocean Sci.* **14**, 105–116 (2018).
- d’Ovidio, F., De Monte, S., Alvain, S., Dandonneau, Y. & Lévy, M. Fluid dynamical niches of phytoplankton types. *Proc. Natl Acad. Sci. USA* **107**, 18366–18370 (2010).
- Lévy, M., Franks, P. J. S. & Shafer Smith, K. The role of submesoscale currents in structuring marine ecosystems. *Nat. Commun.* **9**, 4758 (2018).
- Belkin, I. M. & Gordon, A. L. Southern Ocean fronts from the Greenwich meridian to Tasmania. *J. Geophys. Res. Oceans* **101**, 3675–3696 (1996).
- Thompson, A. F., Haynes, P. H., Wilson, C. & Richards, K. J. Rapid Southern Ocean front transitions in an eddy-resolving ocean GCM. *Geophys. Res. Lett.* **37**, <https://doi.org/10.1029/2010GL045386> (2010).
- Langlais, C., Rintoul, S. & Schiller, A. Variability and mesoscale activity of the Southern Ocean fronts: identification of a circumpolar coordinate system. *Ocean Model.* **39**, 79–96 (2011).
- Chapman, C. C. New perspectives on frontal variability in the Southern Ocean. *J. Phys. Oceanogr.* **47**, 1151–1168 (2017).
- Hughes, C. W. & Ash, E. R. Eddy forcing of the mean flow in the Southern Ocean. *J. Geophys. Res. Oceans* **106**, 2713–2722 (2001).
- Hughes, C. W., Thompson, A. F. & Wilson, C. Identification of jets and mixing barriers from sea level and vorticity measurements using simple statistics. *Ocean Model.* **32**, 44–57 (2010).
- Dufour, C. O. et al. Role of mesoscale eddies in cross-frontal transport of heat and biogeochemical tracers in the Southern Ocean. *J. Phys. Oceanogr.* **45**, 3057–3081 (2015).
- Chapman, C. & Sallée, J.-B. Can we reconstruct mean and eddy fluxes from Argo floats? *Ocean Model.* **120**, 83–100 (2017).
- Rintoul, S. The global influence of localized dynamics in the Southern Ocean. *Nature* **558**, 209–218 (2018).
- Sallée, J. B., Speer, K. & Morrow, R. Response of the Antarctic Circumpolar Current to atmospheric variability. *J. Clim.* **21**, 3020–3039 (2008).
- Sokolov, S. & Rintoul, S. R. Circumpolar structure and distribution of the Antarctic Circumpolar Current fronts: 1. Mean circumpolar paths. *J. Geophys. Res. Oceans* **114**, <https://doi.org/10.1029/2008JC005108> (2009).
- Sokolov, S. & Rintoul, S. R. Circumpolar structure and distribution of the Antarctic Circumpolar Current fronts: 2. Variability and relationship to sea surface height. *J. Geophys. Res. Oceans* **114**, <https://doi.org/10.1029/2008JC005248> (2009).
- Kim, Y. S. & Orsi, A. H. On the variability of Antarctic Circumpolar Current fronts inferred from 1992–2011 altimetry. *J. Phys. Oceanogr.* **44**, 3054–3071 (2014).
- Graham, R. M., de Boer, A. M., Heywood, K. J., Chapman, M. R. & Stevens, D. P. Southern Ocean fronts: controlled by wind or topography? *J. Geophys. Res. Oceans* **117**, <https://doi.org/10.1029/2012JC007887> (2012).
- Describes in detail the problems with ‘global’ methods for studying the variability, and the insensitivity of fronts to changes in wind forcing.**
- Thompson, A. F., Haynes, P. H., Wilson, C. & Richards, K. J. Rapid Southern Ocean front transitions in an eddy-resolving ocean GCM. *Geophys. Res. Lett.* **37**, <https://doi.org/10.1029/2010GL045386> (2010).
- Rhines, P. B. Jets. *Chaos* **4**, 313–339 (1994).
- Meijers, A. J. S. et al. The role of ocean dynamics in king penguin range estimation. *Nat. Clim. Change* **9**, 120–121 (2019).
- Moore, J. K., Abbott, M. R. & Richman, J. G. Location and dynamics of the Antarctic Polar Front from satellite sea surface temperature data. *J. Geophys. Res. Oceans* **104**, 3059–3073 (1999).
- Dong, S., Sprintall, J. & Gille, S. T. Location of the Antarctic Polar Front from AMSR-E satellite sea surface temperature measurements. *J. Phys. Oceanogr.* **36**, 2075–2089 (2006).
- Freeman, N. M., Lovenduski, N. S. & Gent, P. R. Temporal variability in the Antarctic Polar Front (2002–2014). *J. Geophys. Res. Oceans* **121**, 7263–7276 (2016).
- Shao, A. E., Gille, S. T., Mecking, S. & Thompson, L. Properties of the Subantarctic Front and Polar Front from the skewness of sea level anomaly. *J. Geophys. Res. Oceans* **120**, 5179–5193 (2015).
- Pauthenet, E. et al. Seasonal meandering of the Polar Front upstream of the Kerguelen Plateau. *Geophys. Res. Lett.* **45**, 9774–9781 (2018).
- Jones, D. C., Holt, H. J., Meijers, A. J. S. & Shuckburgh, E. Unsupervised clustering of Southern Ocean Argo float temperature profiles. *J. Geophys. Res. Oceans* **124**, 390–402 (2019).
- Sallée, J.-B., Matear, R., Rintoul, S. & Lenton, A. Localized subduction of anthropogenic carbon dioxide in the Southern Hemisphere oceans. *Nat. Geosci.* **5**, 579–584 (2012).
- Palter, J. B., Sarmiento, J. L., Marinov, I. & Gruber, N. in *Chemical Oceanography of Frontal Zones* (ed. Belkin, I. M.) <https://doi.org/10.1007/978-2013-241> (Springer, 2013).
- Review of global biogeochemical fronts provides additional detail on processes described here, as well as a discussion of cross-frontal transport properties.**
- Freeman, N. M. et al. The variable and changing Southern Ocean silicate front: insights from the CESM Large Ensemble. *Glob. Biogeochem. Cycles* **32**, 752–768 (2018).
- Langlais, C. L. et al. Stationary Rossby waves dominate subduction of anthropogenic carbon in the Southern Ocean. *Sci. Rep.* **7**, 17076 (2017).
- Klocker, A. Opening the window to the Southern Ocean: the role of jet dynamics. *Sci. Adv.* **4**, eaao4719 (2018).
- Model-based study that demonstrates the importance of frontal jet interaction with bathymetry for driving upwelling and subduction.**
- Rintoul, S. R. et al. Choosing the future of Antarctica. *Nature* **558**, 233–241 (2018).
- Llort, J. et al. Evaluating Southern Ocean carbon eddy-pump from biogeochemical-Argo floats. *J. Geophys. Res. Oceans* **123**, 971–984 (2018).
- Using data from new biogeochemical Argo floats, this study clarifies the role of mesoscale features, including fronts, on the subduction of surface water into the ocean interior.**

52. Venables, H. & Moore, C. M. Phytoplankton and light limitation in the southern ocean: learning from high-nutrient, high-chlorophyll areas. *J. Geophys. Res. Oceans* **115**, <https://doi.org/10.1029/2009JC005361> (2010).
53. Bristow, L. A., Mohr, W., Ahmerkamp, S. & Kuypers, M. M. M. Nutrients that limit growth in the ocean. *Curr. Biol.* **27**, R474–R478 (2017).
54. Sokolov, S. & Rintoul, S. R. On the relationship between fronts of the Antarctic Circumpolar Current and surface chlorophyll concentrations in the Southern Ocean. *J. Geophys. Res. Oceans* **112**, <https://doi.org/10.1029/2006JC004072> (2007).
55. Thomalla, S. J., Fauchereau, N., Swart, S. & Monteiro, P. M. S. Regional scale characteristics of the seasonal cycle of chlorophyll in the Southern Ocean. *Biogeosciences* **8**, 2849–2866 (2011).
56. Graham, R. M., De Boer, A. M., van Sebille, E., Kohfeld, K. E. & Schlosser, C. Inferring source regions and supply mechanisms of iron in the Southern Ocean from satellite chlorophyll data. *Deep Sea Res. Part I* **104**, 9–25 (2015).
57. NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. *Moderate-Resolution Imaging Spectroradiometer (MODIS) Terra Chlorophyll Data* (NASA, 2018).
58. Hunt, B. P. V. & Hosie, G. W. Zonal structure of zooplankton communities in the Southern Ocean south of Australia: results from a 2150 km continuous plankton recorder transect. *Deep Sea Res. Part I* **52**, 1241–1271 (2005).
59. Koubbi, P. et al. Spatial distribution and inter-annual variations in the size frequency distribution and abundances of *Pleuragramma antarcticum* larvae in the Dumont d'Urville Sea from 2004 to 2010. *Polar Sci.* **5**, 225–238 (2011).
60. O'Toole, M., Guinet, C., Lea, M.-A. & Hindell, M. Marine predators and phytoplankton: how elephant seals use the recurrent Kerguelen plume. *Mar. Ecol. Prog. Ser.* **581**, 215–227 (2017).
61. Deppeler, S. L. & Davidson, A. T. Southern Ocean phytoplankton in a changing climate. *Front. Mar. Sci.* **4**, <https://doi.org/10.3389/fmars.2017.00040> (2017).
62. Charrassin, J. B., Park, Y.-H., Le Maho, Y. & Bost, C.-A. Penguins as oceanographers unravel hidden mechanisms of marine productivity. *Ecol. Lett.* **5**, 317–319 (2002).
63. Charrassin, J. B. & Bost, C. Utilisation of the oceanic habitat by king penguins over the annual cycle. *Mar. Ecol. Prog. Ser.* **221**, 285–297 (2001).
64. Charrassin, J. B., Park, Y.-H., Le Maho, Y. & Bost, C.-A. Fine resolution 3D temperature fields off Kerguelen from instrumented penguins. *Deep Sea Res. Part I* **51**, 2091–2103 (2004).
65. Sokolov, S., Rintoul, S. R. & Wienecke, B. Tracking the polar front south of New Zealand using penguin dive data. *Deep Sea Res. Part I* **53**, 591–607 (2006).
66. Scheffer, A., Trathan, P. N. & Collins, M. Foraging behaviour of king penguins (*Aptenodytes patagonicus*) in relation to predictable mesoscale oceanographic features in the Polar Front Zone to the north of South Georgia. *Prog. Oceanogr.* **86**, 232–245 (2010).
- Study of a marine predator that successfully integrates biotelemetry data with environmentally remote sensed data to conclusively reveal the interactions between biology and environmental conditions.**
67. Péron, C., Weimerskirch, H. & Bost, C.-A. Projected poleward shift of king penguins (*Aptenodytes patagonicus*) foraging range at the Crozet Islands, southern Indian Ocean. *Proc. R. Soc. B* **279**, 2515–2523 (2012).
68. Cristofari, R. et al. Climate-driven range shifts of the king penguin in a fragmented ecosystem. *Nat. Clim. Change* **8**, 245–251 (2018).
69. Hunt, G. L. Jr, Harrison, N. M. & Cooney, R. T. The influence of hydrographic structure and prey abundance on foraging of least auklets. *Stud. Avian Biol.* **14**, 7–22 (1990).
70. Woehler, E., Raymond, B. & Watts, D. J. Convergence or divergence: where do short-tailed shearwaters forage in the Southern Ocean? *Mar. Ecol. Prog. Ser.* **324**, 261–270 (2006).
71. Commins, M. L., Ansong, I. & Ryan, P. G. Multi-scale factors influencing seabird assemblages in the African sector of the Southern Ocean. *Antarct. Sci.* **26**, 38–48 (2014).
72. Lea, M.-A. & Dubroca, L. Fine-scale linkages between the diving behaviour of Antarctic fur seals and oceanographic features in the southern Indian Ocean. *ICES J. Mar. Sci.* **60**, 990–1002 (2003).
73. Lea, M.-A. et al. Impacts of climatic anomalies on provisioning strategies of a Southern Ocean predator. *Mar. Ecol. Prog. Ser.* **310**, 297–310 (2006).
74. Guinet, C. et al. Spatial distribution of foraging in female Antarctic fur seals *Arctocephalus gazella* in relation to oceanographic variables: a scale-dependent approach using geographic information systems. *Mar. Ecol. Prog. Ser.* **219**, 251–264 (2001).
75. Béhagle, N. et al. Acoustic micronektonic distribution is structured by macroscale oceanographic processes across 20–50 °S latitudes in the South-Western Indian Ocean. *Deep Sea Res. Part I* **110**, 20–32 (2016).
76. Gordine, S. A., Fedak, M. A. & Boehme, L. The importance of Southern Ocean frontal systems for the improvement of body condition in southern elephant seals. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **29**, 283–304 (2019).
77. Weimerskirch, H., Åkesson, S. & Pinaud, D. Postnatal dispersal of wandering albatrosses *Diomedea exulans*: implications for the conservation of the species. *J. Avian Biol.* **37**, 23–28 (2006).
78. Bailleul, F., Cotte, C. & Guinet, C. Mesoscale eddies as foraging area of a deep-diving predator, the southern elephant seal. *Mar. Ecol. Prog. Ser.* **408**, 251–264 (2010).
79. Della Penna, A., De Monte, S., Kestenare, E., Guinet, C. & d'Ovidio, F. Quasi-planktonic behavior of foraging top marine predators. *Sci. Rep.* **5**, 18063 (2015).
80. Cotté, C., d'Ovidio, F., Dragon, A.-C., Guinet, C. & Lévy, M. Flexible preference of southern elephant seals for distinct mesoscale features within the Antarctic Circumpolar Current. *Prog. Oceanogr.* **131**, 46–58 (2015).
81. Hindell, M. A. et al. Circumpolar habitat use in the southern elephant seal: implications for foraging success and population trajectories. *Ecosphere* **7**, e01213 (2016).
82. Siegelman, L., O'Toole, M., Flexas, M., Rivière, P. & Klein, P. Submesoscale ocean fronts act as biological hotspot for southern elephant seal. *Sci. Rep.* **9**, 18063 (2019).
- This paper exploits a modern and unique dataset to reveal insights into both physical and biological systems that influence marine mammal behaviour.**
83. Nel, D. C. et al. Exploitation of mesoscale oceanographic features by Grey-headed Albatrosses (*Thalassarche chrysostoma*) in the southern Indian Ocean. *Mar. Ecol. Prog. Ser.* **217**, 15–26 (2001).
84. Swart, N. C., Gille, S., Fyfe, J. C. & Gillett, N. P. Recent Southern Ocean warming and freshening driven by greenhouse gas emissions and ozone depletion. *Nat. Geosci.* **11**, 836–841 (2018).
85. Jones, J. et al. Assessing recent trends in high-latitude Southern Hemisphere climate. *Nat. Clim. Change* **6**, 917–926 (2016).
86. Fyfe, J. C. & Saenko, O. A. Simulated changes in the extratropical Southern Hemisphere winds and currents. *Geophys. Res. Lett.* **33**, <https://doi.org/10.1029/2005GL025332> (2006).
87. Bracegirdle, T. J. et al. Assessment of surface winds over the Atlantic, Indian, and Pacific Ocean sectors of the Southern Ocean in CMIP5 models: historical bias, forcing response, and state dependence. *J. Geophys. Res. Atmos.* **118**, 547–562 (2013).
88. Meijers, A. J. S. The Southern Ocean in the Coupled Model Intercomparison Project phase 5. *Phil. Trans. R. Soc. A* **372**, 20130296 (2014).
89. Billany, W., Swart, S., Hermes, J. & Reason, C. J. C. Variability of the Southern Ocean fronts at the Greenwich Meridian. *J. Mar. Syst.* **82**, 304–310 (2010).
90. Downes, S. M., Budnick, A. S., Sarmiento, J. L. & Farneti, R. Impacts of wind stress on the Antarctic Circumpolar Current fronts and associated subduction. *Geophys. Res. Lett.* **38**, <https://doi.org/10.1029/2011GL047668> (2011).
91. Gille, S. T. Decadal-scale temperature trends in the Southern Hemisphere ocean. *J. Clim.* **21**, 4749–4765 (2008).
92. Meijers, A. J. S., Bindoff, N. L. & Rintoul, S. R. Frontal movements and property fluxes: contributions to heat and freshwater trends in the Southern Ocean. *J. Geophys. Res. Oceans* **116**, <https://doi.org/10.1029/2010JC006832> (2011).
93. Böning, C., Disper, A., Visbeck, M., Rintoul, S. & Schwarzkopf, F. The response of the Antarctic Circumpolar Current to recent climate change. *Nat. Geosci.* **1**, 864–869 (2008).
94. Gille, S. T. Meridional displacement of the Antarctic Circumpolar Current. *Phil. Trans. R. Soc. A* **372**, 20130273 (2014).
95. Meijers, A. J. S. et al. Representation of the Antarctic Circumpolar Current in the CMIP5 climate models and future changes under warming scenarios. *J. Geophys. Res. Oceans* **117**, <https://doi.org/10.1029/2012JC008412> (2012).
96. Dunne, J. P. et al. GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models. Part I: Physical formulation and baseline simulation characteristics. *J. Clim.* **25**, 6646–6665 (2012).
97. Armour, K. C., Marshall, J. C., Scott, J., Donohoe, A. & Newsom, E. R. Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. *Nat. Geosci.* **9**, 549–554 (2016).
98. Bost, C. et al. Large-scale climatic anomalies affect marine predator foraging behaviour and demography. *Nat. Commun.* **6**, 8220 (2015).
99. Newman, L. et al. Delivering sustained, coordinated, and integrated observations of the Southern Ocean for global impact. *Front. Mar. Sci.* **6**, 433 (2019).
100. García, H. E. et al. in *World Ocean Atlas 2018* (ed. Mishonov, A.) 35 (NOAA, 2018).

## Acknowledgements

C.C.C. received funding through the CSIRO Decadal Climate Forecasting Project and the Earth Systems and Climate Change Hub of the Australian Government's National Environmental Science Program. A.M. acknowledges support from the ARC Centre of Excellence for Climate Extremes (CE170100023). The Ssalto/Duacs altimeter products were produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS) (<http://www.marine.copernicus.eu>). J.-B.S. received funding from the

European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement 637770).

### Author contributions

This Review was conceived by C.C.C. and M.-A.L., with input from J.-B.S. C.C.C. led the drafting effort and created all figures, with input from all authors. Table 1 was developed by C.C.C. and A.M. All authors contributed to the final article.

### Competing interests

The authors declare no competing interests.

### Additional information

**Correspondence** should be addressed to C.C.C.

**Peer review information** *Nature Climate Change* thanks Julian Gutt, Sebastiaan Swart and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

**Reprints and permissions information** is available at [www.nature.com/reprints](http://www.nature.com/reprints).

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© Crown 2020