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

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1 **The Southern Ocean is a critical component of the global climate system and an important ecoregion that contains a**
2 **diverse range of interdependent flora and fauna. The Southern Ocean also hosts numerous *fronts*: sharp boundaries**
3 **between waters with different characteristics. As they strongly influence exchanges between the ocean, atmosphere**
4 **and cryosphere, fronts are of fundamental importance to the climate system. However, rapid advances in physical**
5 **oceanography over the past 20 years have challenged previous definitions of fronts and their response to**
6 **anthropogenic climate change. Here, we review the implications of this recent research for the study of climate,**
7 **ecology and biology in the Southern Ocean. We include a frontal definition “user guide” to clarify the current debate**
8 **and facilitate future research.**
9

10 The Southern Ocean, generally defined as the global ocean south of about 35°S that encircles the Antarctic continent, is unique
11 oceanographic environment due to the lack of continental barriers blocking its flow and the strong winds that blow over its
12 surface¹. At large scales, the Southern Ocean is characterised by both the intense eastward flowing Antarctic Circumpolar
13 Current (ACC), one of the most powerful current systems on Earth, and strongly tilted isopycnals (lines of constant density)
14 that shallow to the south.
15

16 Observations of the Southern Ocean dating back to the *Discovery* expedition in the 1920s revealed that the transition from
17 warmer subtropical waters to colder Antarctic waters does not occur smoothly, but is concentrated into a series of sharp
18 transition zones, aligned generally east-west, that have come to be called fronts². Further observations revealed that salinity,
19 oxygen, nutrients and various other tracers showed similar behaviour, and that between the fronts, water properties are
20 relatively homogeneous. As such, fronts delimit the boundaries between different *water-masses* with distinct environmental
21 characteristics³. These fronts also tend to coincide with the location of narrow yet very intense currents known as “jets”⁴ that
22 dominate the ACC’s flow⁵. The Southern Ocean is divided by fronts into a number of distinct biophysical zones, and hence a
23 number of distinct habitats, which in turn support distinct biota^{6,7}. Numerous studies have shown that seabirds and marine
24 mammals tend to congregate and forage in and around fronts⁷. As the Earth continues to warm due to anthropogenic climate
25 change, it is vital that we understand how these fronts and jets will respond to changes in the global climate system, and what
26 influence that might have on associated ecosystems^{8–10}.
27

28 Due to its remoteness and harsh climate, undertaking field studies in the Southern Ocean is both difficult and expensive. As a
29 result, the Southern Ocean is amongst the most data-sparse of all major ocean basins, which has hindered progress on key
30 questions regarding its dynamics and ecological communities¹⁰. In recent decades however, a deluge of new data from
31 satellites and Argo profiling floats, along with ever increasing numerical modelling capabilities, have dramatically changed our
32 understanding of the Southern Ocean. Concurrently, advances in microelectronics have enabled researchers to track individual
33 animals over long periods of time, and relate their behaviour to environmental conditions¹¹.
34

35 The unprecedented detail provided by these new data has caused the community to question longstanding and fundamental

36 ideas about the nature of the ACC and its fronts. In particular, seemingly simple questions such as: *what is a front? how many*
37 *fronts are there? are “fronts” and “jets” the same thing?* and *what role do fronts play in the Southern Ocean ecosystem?* have
38 been revisited as new data and methodologies have become available¹². A changing conceptual understanding of the ACC has
39 occasionally resulted in surprising disagreements: studies using the same data but different methodologies have arrived at
40 dramatically different conclusions. The conflicting definitions of a front, the often technical nature of the debates, and the fact
41 that the terms “front” and “jet” are often used interchangeably has resulted in a degree of confusion.

42
43 The purpose of this article is to summarise our current understanding of Southern Ocean fronts and the potential impact of
44 recent research in physical oceanography outside of the domain. We will make clear areas of consensus and those where
45 substantial debate still remains. Our synthesis is aimed at the the broader oceanographic community and marine biologists that
46 may not have been aware of these recent advances or how to best exploit new data and techniques to answer outstanding
47 questions. To this end, we include a Southern Ocean fronts “users guide” to facilitate future research.

48 1 The Physical Oceanography of Southern Ocean Fronts

49 The existence of fronts in the Southern Ocean has important implications for both the physical oceanography of the region and
50 the entire climate system. For example, enhanced density gradients near fronts support, via thermal wind, strong jets. Frontal
51 jets are responsible for the majority of the ACC transport and act as barriers to horizontal mixing: it is more difficult to move
52 tracers across a jet than along it^{13–15}. Frontal regions are also sites of pronounced exchange between the deep and surface
53 ocean: both the upwelling (rising) of deeper waters and subduction (descending) of surface waters to the abyssal ocean is
54 enhanced in frontal zones^{16,17}. Additionally, fronts can catalyse the generation of meso-scale “eddies”^{18,19} and sub-meso scale
55 “filaments” which are able to bring nutrients from the deep ocean to the surface where they can be consumed by biological
56 components of the system^{20,21}. These details are shown schematically in Fig. 1.

57
58 Historically, fronts in the Southern Ocean have been defined as the boundary between two zones with distinct water-mass
59 properties². By compiling hydrographic data obtained from research cruises over many decades, researchers built what has
60 become known as the *traditional* view of Southern Ocean fronts: three fronts denoted, (from north to south) the Subantarctic
61 Front; the Polar Front and the Southern ACC Front^{3,22} (Fig. 2a). Occasionally, the three front view is augmented by the
62 addition of the Subtropical Front to the north, and the Southern Boundary Front near Antarctica, although their dynamics are
63 distinct from the main ACC fronts, and, as such, are often not considered part of the ACC⁵. Each front was thought to be
64 circumpolar in extent, deep reaching, co-located with prominent eastward flowing jets, and strongly steered by bathymetry^{3,22}.

65
66 By necessity, the traditional view of ACC fronts was a time-averaged view: it took decades to assemble a database of
67 hydrographic profiles capable of representing the broad-scale structure of the ACC. However, since fronts are sharp boundaries
68 between two different water masses, they manifest as strong horizontal gradients in fields such as sea-surface temperature or
69 sea-surface height that can be observed by satellites. With the availability of high-resolution satellite data in the 1980s and
70 1990s, it became apparent that the Southern Ocean is more complex than the traditional view would suggest (Fig. 2b) and that
71 the ACC is not composed of a distinct number of coherent, circumpolar fronts, but of an intricate web of thin filaments that can
72 spontaneously form and disappear, split and merge, meander and drift, bearing little resemblance to the traditional view of the
73 ACC. Crucially, there is no settled answer to how many ACC fronts exist, as the number of fronts vary both temporally and
74 spatially^{23–25}.

75
76 During the satellite era, it was established that fronts in the Southern Ocean arise primarily by complicated, nonlinear
77 interaction between the mean flow and turbulent eddies: In some regions of the ACC, meso-scale eddies accelerate jets and
78 sharpen tracer gradients^{18,26}. Jets also act to suppress mixing; regions with strong jets tend to have dramatically reduced
79 meridional (north-south) exchange of heat and other tracers¹³. Conversely, regions with weaker jets, which typically occur
80 downstream of large bathymetric features, the transport barrier effect is weaker, and elevated north-south exchanges are found
81 in these “leaky” jet regions^{13,14,27–30}.

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

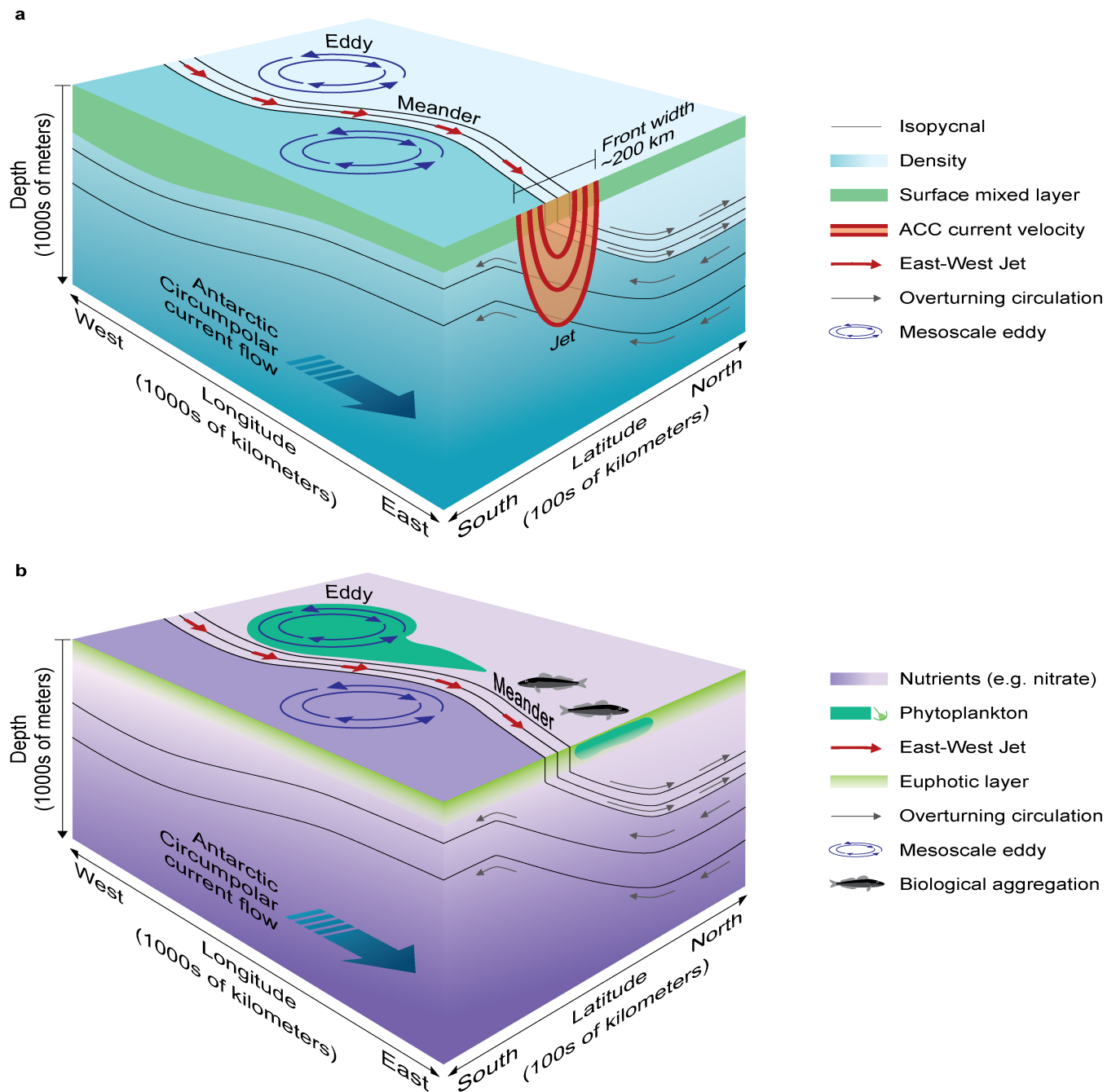


Figure 1. Illustrations of Antarctic Circumpolar Current fronts. Schematic showing the **a** physical and **b** biogeochemical characteristics of an idealized ACC front. In the frontal region, isopycnals are bunched closely together and slope strongly towards the surface. Strong geostrophic ocean currents, known as jets, are associated with the density front due to the thermal wind relationship. The front separates regions of high and low density (**a**), and high and low nutrient concentrations (**b**), as the jet tends to inhibit cross-frontal exchange. Straining by the jet and the downstream transport of nutrients such as iron acts to deform and elongate an idealized chlorophyll patch (**b**), and upwelling/subduction of water associated with the overturning circulation is indicated by thin arrows.

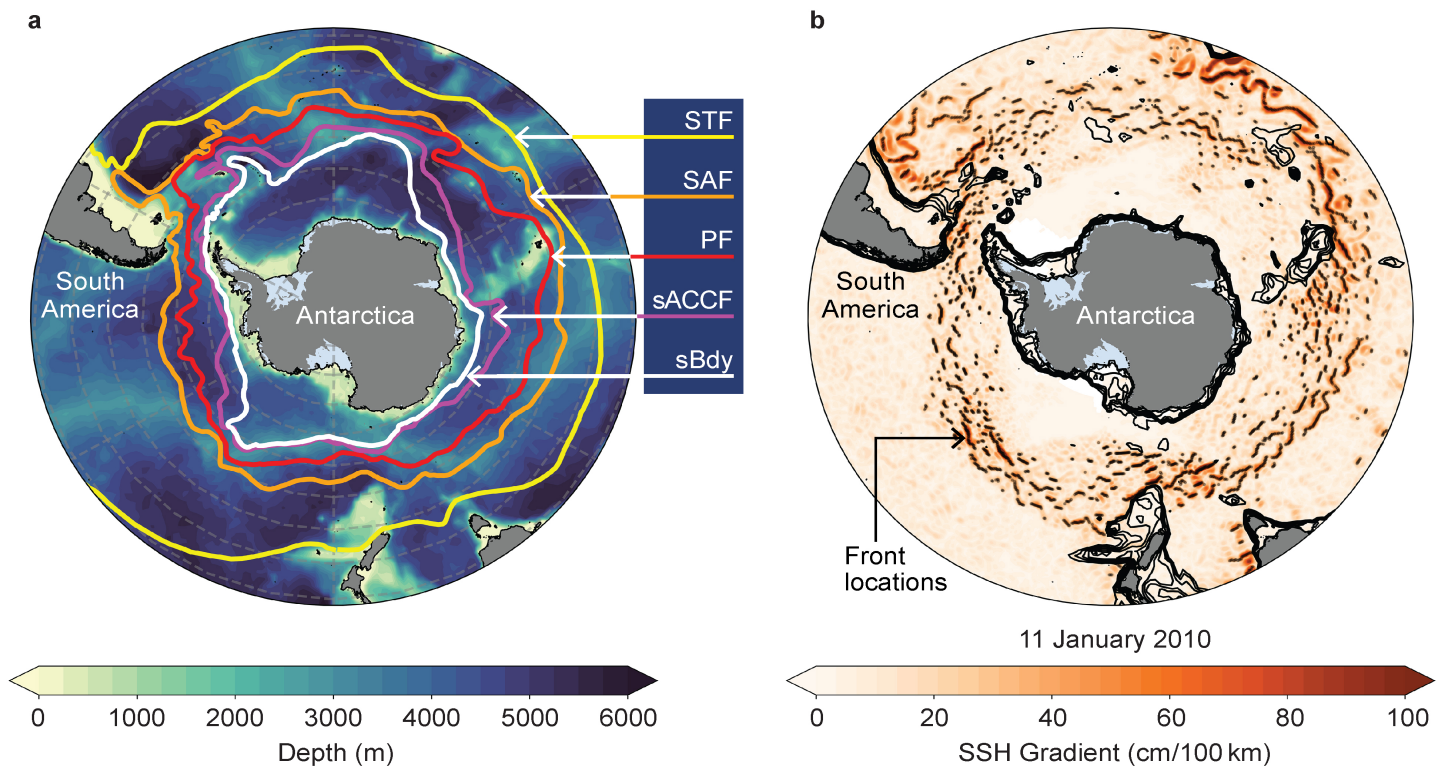


Figure 2. The changing conception of the Antarctic Circumpolar Current and its fronts: **a** smooth, continuous, circumpolar fronts determined by Orsi and collaborators³ using historical hydrographic data and applying water mass criteria (for example, a particular temperature value at a certain depth) to define their locations. The named fronts are, north to south, the subtropical front (STF); the subantarctic (SAF); the polar (PF); the southern ACC (sACCF); and the Southern Boundary (SBdy) fronts. Colors show the ocean depth, illustrating the strong steering of the fronts by submarine bathymetric features. **b** A daily snapshot (11th of January, 2010) of the gradient of Sea-Surface Height (SSH) obtained from the gridded AVISO satellite altimetry product (colors). Broken black lines indicate the location of fronts or jets on this date determined by SSH gradient thresholding²⁵. Solids contour lines are isobaths (contour interval of 1000m).

89 structure over the entire ACC^{25,35,36}.
 90

91 2 Practical Definitions of Fronts

92 In his seminal review of fluid dynamical jets, Rhines stated that “*It is not easy to give a precise definition of a jet of fluid motion,*
 93 *but most of us know one when we see it*”³⁷. This statement could also apply to Southern Ocean fronts: while the conceptual
 94 idea of a front as a water-mass boundary is universally accepted, there is no single, precise definition of a front. In practice, a
 95 wide variety of definitions are used¹². Inconsistent frontal definitions, and conflicting nomenclature has led to a great deal of
 96 confusion about what is, and what is not, a front³⁸.
 97

98 Early studies based on hydrographic data typically used water-mass criteria, such as a particular value of temperature, to define
 99 a front^{3,22}. However, with the changing view of the ACC, these definitions have been reevaluated. Currently, frontal definitions
 100 fall into two broad classes¹²:

- 101 1. **Local** definitions use criteria found in the immediate neighbourhood of a geographic location to determine if a front is
 102 present. Gradient thresholding is probably the most commonly employed local method: a front is detected should the
 103 gradient of some quantity (typically sea-surface temperature (SST)^{39–41} or sea-surface height (SSH)^{12,25,26}) exceed some
 104 pre-defined threshold. However, other local definitions exist, such as those based on statistical properties^{14,27,36,42} or the
 105 dissimilarity of nearby hydrographic profiles^{43,44}. Locally defined fronts are not necessarily continuous, and the number
 106 of fronts can vary in space and time;

107 2. **Global** definitions seek to identify some quantity, for example a particular value of temperature or SSH, that one can use
108 to identify a front over some region, or even the entire ACC⁵. Fronts defined using global definitions are generally
109 continuous in space and the number of fronts is chosen *a priori*²⁴.

110 Typically, biologists define fronts based on SST criteria, while physical oceanographers generally use SSH. There is a subtle
111 difference between these oceanographic variables: the SST seen by satellites is strictly the near surface temperature, while the
112 SSH is a function of both the temperature and salinity throughout the entire water column. As such, SST reflects surface ocean
113 conditions, while SSH is influenced by both surface and sub-surface processes.

114
115 That global frontal definitions resemble older water-mass definitions is no coincidence, as they arose from work seeking to
116 resolve the discrepancy between the traditional and dynamic views of the ACC. These studies showed that regions of, for
117 example, high sea-surface height gradients were consistently associated with both hydrographic fronts and particular values of
118 sea-surface height itself^{4,5,31-34}. By finding the sea-surface height or temperature value most closely associated with high
119 gradients or water-mass criteria, one obtains a definition of a front that is both time variable, yet spatially continuous.

120
121 However, it has been shown that the value of temperature or SSH associated with a particular front may not perfectly align with
122 high gradient regions over the entire region of interest, leading to the suggestion of the presence of a front where it may, in fact,
123 be absent³⁵. Additionally, the frontal structure is variable in both time and space, and a value of (for example) SSH
124 representative of a front at one location or time may not be representative at another^{14,25,35,36}. These phenomena are illustrated
125 in Fig 3, which shows a time-series of the gradient of satellite derived SSH at two longitudes in the Southern Ocean, together
126 with contours of SSH associated with five major ACC fronts. While the SSH contours represent the mean positions of the
127 fronts very well, the contours frequently drift off high gradient regions, or persist during periods without high SSH gradients.

128
129 Both local and global definitions of fronts have advantages and disadvantages, and the choice of definition must be based on the
130 nature of the scientific question being posed. Advice for choosing frontal definitions is presented in Sec. 5

131 3 Fronts, Biogeochemistry and Ecosystems in the Southern Ocean

132 The unique oceanographic conditions of the Southern Ocean have profound implications for the ecology of the region and
133 biogeochemical cycles that influence the climate system. As a result of its steeply sloped isopycnals, it is in the Southern Ocean
134 that nutrient and CO₂ rich *deep* water masses, so-called as they are found at a depth greater than 1km throughout most of the
135 global ocean, upwell to the ocean surface¹⁶. Once at the ocean surface, these formerly deep waters are able to exchange heat
136 and CO₂ with the atmosphere⁴⁵, and their nutrients may be consumed by biology confined to the euphotic zone⁷.

137
138 Southern Ocean fronts are thought to play a key role in the global distribution of important nutrients, such as nitrates, through
139 two primary mechanisms⁴⁶:

- 140 1. fronts act as sites of enhanced vertical exchange between the deep and surface ocean; and
- 141 2. the “mixing barrier” effect for frontal jets reduces the exchange of tracers across fronts;

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

147 However, there is a paucity of high resolution biogeochemical data in the Southern Ocean. As such, the impact of the
148 filamented, dynamic fronts (discussed in Sec. 1) on the nutrients and other tracers is poorly understood. However, recent work
149 has shown that the upwelling and subduction in the Southern Ocean is controlled by the complex interactions between the
150 frontal jets, large bathymetric features, and surface winds^{45,48,49}. As such, the upwelling of nutrients and subduction of CO₂
151 into the ocean interior is localized to regions where fronts interact with bathymetry⁴⁹⁻⁵¹.

152
153 Similar frontal dynamics also influence the ecology of the Southern Ocean from the base to the top of the trophic chain. While
154 upwelling of deep waters supplies the Southern Ocean with large quantities of nitrates, phosphates and silicates, the region is a
155 known “high nutrient, low chlorophyll” zone due to iron limitation^{52,53}. However, downstream of several islands scattered
156 throughout the Southern Ocean, as well as near the South American continental shelf, phytoplankton concentrations can be
157 relatively high^{52,54-56}, as illustrated in Fig. 4b,c using satellite derived chlorophyll-a concentrations⁵⁷. Phytoplankton blooms

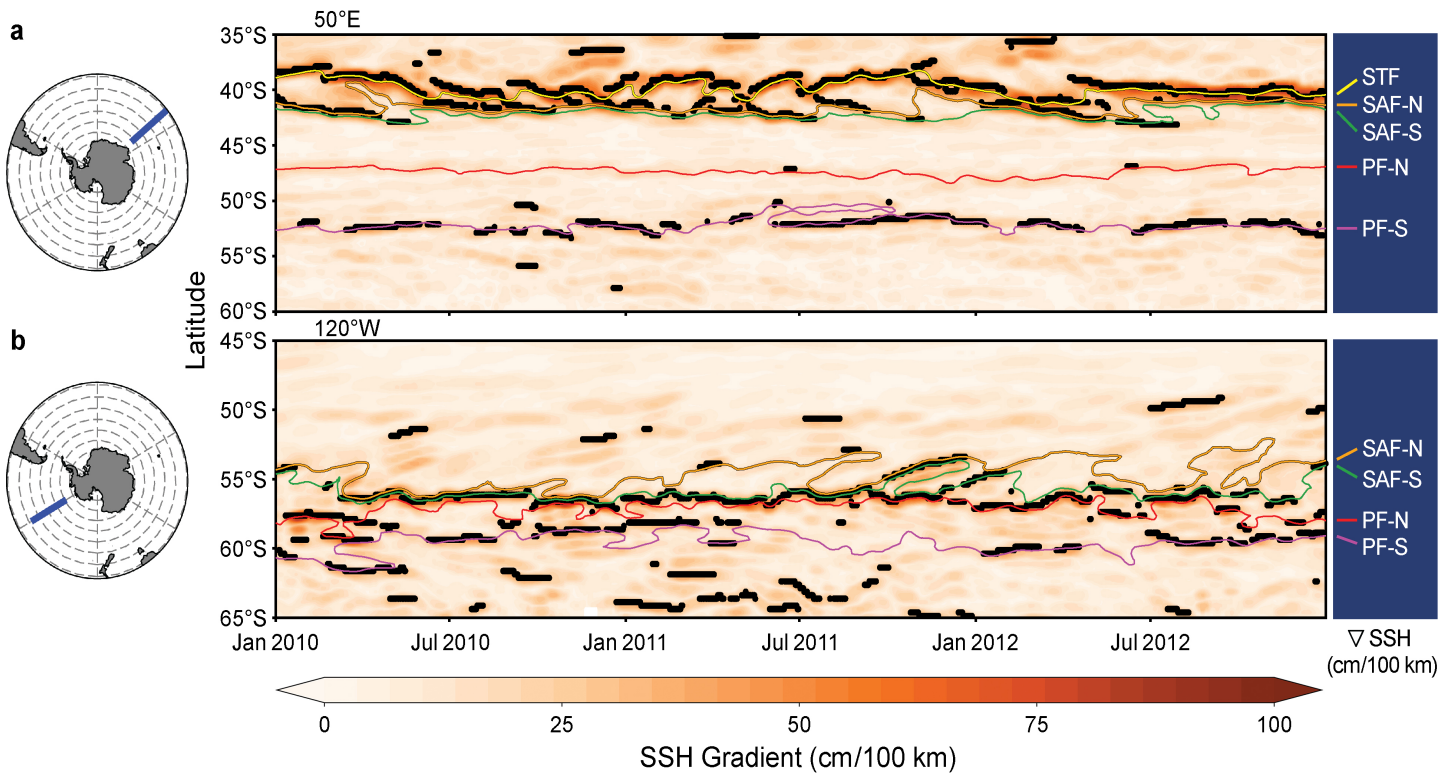


Figure 3. A cautionary example of using sea-surface height to track fronts. Colors show a latitude/time (Hovmöller) diagrams of sea-surface height gradient (obtained from the AVISO gridded satellite altimetry product) from the 1st of January 2010 to the 31st of December 2013 at locations in the (a) south-west 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 sub-tropical front (STF), 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 Chapman (2017)²⁵. The black dots indicate the location of fronts determined from SSH gradient thresholding²⁵. The SSH contours do not always follow the high SSH gradient regions and occasionally identifies fronts where gradients are weak. This example is inspired by the work of Graham and colleagues³⁵

158 are initiated in regions where frontal jets interact with bathymetry, bringing iron-rich sediments to the surface^{49,54}. Jets then
 159 export these high iron concentrations downstream, which can extend phytoplankton blooms hundreds or even thousands of
 160 kilometers downstream of the iron source regions⁵⁶, as shown for the Kerguelen Plateau region in Fig. 4d. Zooplankton that
 161 graze on phytoplankton, such as krill, congregate in these productive regions, and are, in turn, targeted by many larger Antarctic
 162 predators, including fish, squid, seabirds and mammals^{58–60} (Fig. 4e).

163
 164 At the fronts themselves, the dynamic nature of the oceanography may result in increased biomass and biodiversity as the
 165 inter-frontal communities interact⁵⁸. This increased biodiversity also influence the distribution and behaviour of organisms at
 166 higher trophic levels⁷. Fronts create ecological niches occupied by particular species^{20,54,55,62}. For example, King penguins
 167 (*Aptenodytes forsteri*) forage in the Antarctic Polar Frontal Zone and target meso-scale features such as thermal fronts^{63–67},
 168 travelling further in years when the position of the front is further from their breeding and moulting grounds^{68,69}. Southern
 169 Ocean seabird assemblages are reported as being associated with specific water masses, including interfrontal zones^{70–72}. There
 170 is evidence that marine predators use environmental conditions, such as temperature, as an indication of prey availability⁶⁷.

171
 172 The relationship between fronts and the distribution of marine animals is less clear than that for phyto and zooplankton, due to
 173 their capacity to conduct basin-scale movements and the dictates of species-specific life histories. For example, Antarctic fur
 174 seals (*Arctocephalus gazella*) travel to the Antarctic Polar Frontal Zone^{73–75} to take advantage of elevated productivity shaped
 175 by the large-scale oceanography⁷⁶, while southern elephant seal (*Mirounga leonina*) populations can be divided into “locals”
 176 that exploit a few frontal features, or “roamers” who forage in multiple different heterogeneous environments⁷⁷. Central place
 177 foragers, such as seals and penguins, need to regularly return to breeding sites, whereas some species, such as the wandering
 178 albatross (*Diomedea exulans*), can range over vast distances⁷⁸.

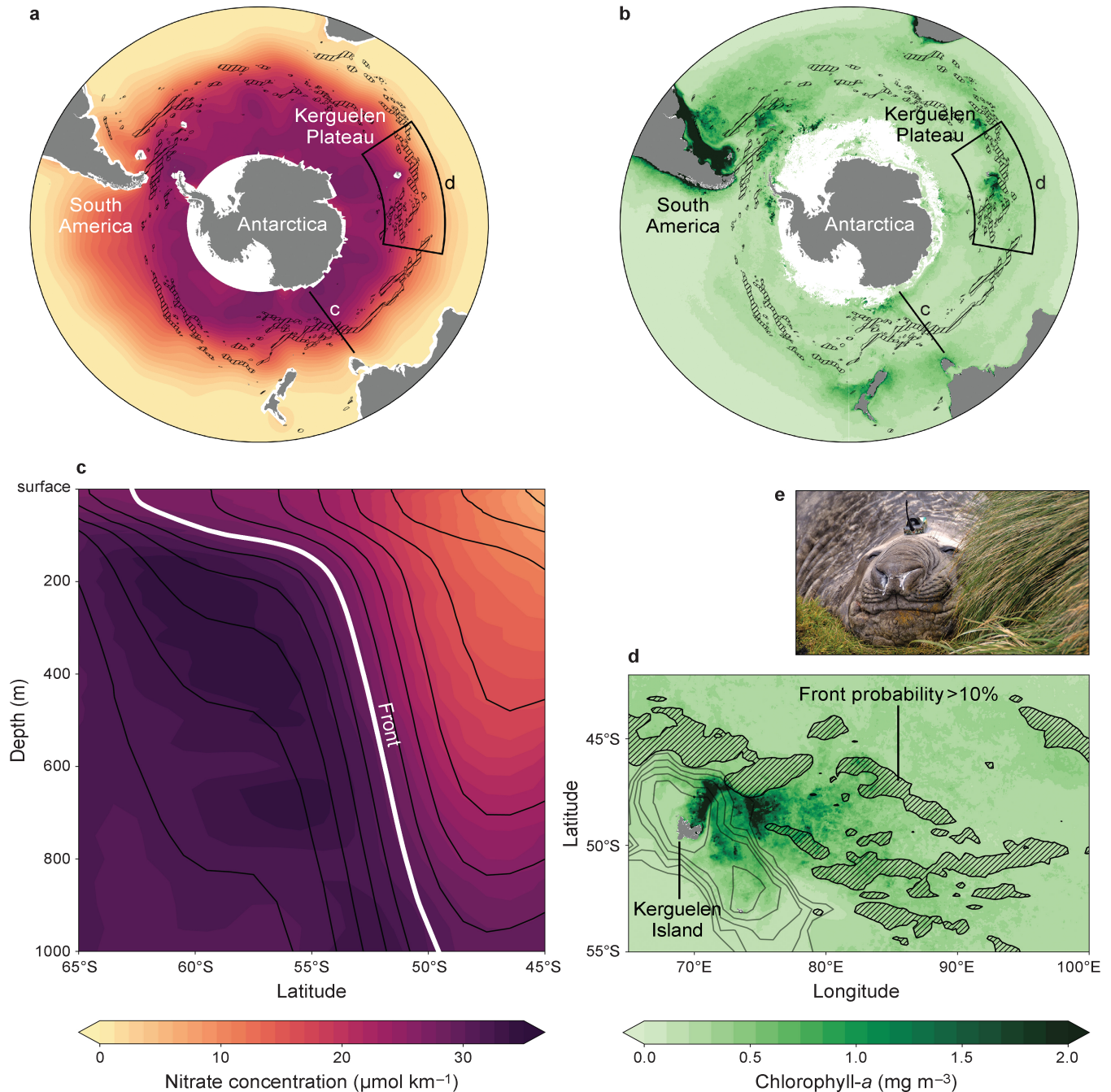


Figure 4. The influence of fronts on nutrients and phytoplankton blooms. **a** The springtime (September to December) mean concentrations of nitrates (NO_3^-) from the World Ocean Atlas 2018 (WOA18)⁶¹; **b** 2003-2018 November time mean Chlorophyll-a concentration, a proxy for phytoplankton concentration, from MODIS ocean color satellite system⁵⁷. **c** Depth/latitude transect between Tasmania and Antarctica (along 140° , shown as a thin black line in panel **a**) showing the spring mean WOA18 nitrate concentration from the surface to 1000m depth. The thin black lines are lines of constant surface referenced potential density (σ_θ), also from WOA18, while the white line shows the approximate location of the nitrate front; **d** MODIS 2003-2018 November time mean chlorophyll-a concentrations near Kerguelen Island, showing the extent of the seasonal bloom. Thin grey lines are bathymetric contours (contour interval: 500m). In panels **a**, **b** and **c**, hatching shows regions where the probability of encountering a front is greater than 10% (from Chapman 2017²⁵); and **e** A Kerguelen southern elephant seal, equipped with a miniaturized temperature, salinity and depth sensor. Southern Elephant seals are known to forage in the Kerguelen phytoplankton plume (photo: Mark Hindell)

179
180 Great advances in biotelemetry tools for animal tracking, coupled with the availability of higher resolution ocean observations,
181 have enabled greater understanding of relationships between marine animals and complex ocean processes. For example,
182 southern elephant seals and macaroni penguins (*Eudyptes chrysolophus*) are now known to interact with and forage in regions
183 of high eddy formation and filaments associated with ACC fronts^{79–83}. However, the relationships between biology and
184 environmental conditions are often qualitative⁸⁴ or restricted to a small number of individuals⁸⁰. As such, the challenge for
185 biologists is to integrate observations of animal behaviours with the fine-scale physical and biological properties of Southern
186 Ocean fronts. Earlier perceptions of Southern Ocean fronts as a “line in the sea” can be too simplistic, and at odds with what is
187 now known about the behaviour of many predators. Recognition of the spatial and temporal dynamics of fronts, along with
188 tools that enable biologists to identify oceanographic features at scales and times congruent with the behavior of marine
189 predators, will enable deeper insights into the factors that limit biological production, how this propagates up the food chain,
190 and why organisms aggregate where they do.

192 4 Climate Change and Southern Ocean Fronts

193 The Southern Ocean is both warming^{8,85} and freshening^{85,86} and there is evidence that the strong westerly winds that drive the
194 ACC are both intensifying and shifting to the south⁸⁷. These trends are expected to continue with ongoing climate
195 change^{50,88,89}. Given the importance of ACC fronts to the ecosystems of the Southern Ocean and the climate system, assessing
196 and predicting how they will respond to a changing climate is vital. However, research on this question has suffered from much
197 of the same confusion that pervades the literature on ACC fronts as a whole due to inconsistent frontal definitions,
198 nomenclature and methodologies. In this section, we discuss the observed and projected changes in ACC fronts and the
199 implications of such changes on Southern Ocean ecosystems.

201 4.1 Observed and projected changes in Southern Ocean fronts

202 Studies of trends in the structure or position of ACC fronts and jets have been hampered by a lack of long term observations¹.
203 However, the development of the “contour” type methods described in section 2 that link hydrographic fronts with surface
204 phenomena observed by satellites, enabled the multi-decade long satellite record to be exploited to study the variability of ACC
205 fronts. A wave of studies using these methods established a tentative consensus: over the satellite altimetry period (from 1993
206 onwards) the main fronts of the Southern Ocean had generally shifted south by ~ 0.5 – 1.5° (60 km on average) over a period of
207 around 15 years^{31,33,34,90}. Frontal variability was found to be larger away from large bathymetry which tends to constrain
208 frontal movements. Several of these studies noted that the position of ACC fronts were sensitive to changes in atmospheric
209 forcing due to large-scale climate modes such as El-Niño/La-Niña^{31,34}. These conclusions were generally supported by studies
210 using the previous generation of climate models (those associated with the Coupled-Model Intercomparison Project 3 (CMIP3)
211 multi-model ensemble), that projected a poleward trend in frontal locations driven by changes in winds, and would likely
212 continue into the future^{87,91}. On the strength of the consensus that emerged between 2007 and 2015, the observed warming in
213 the Southern Ocean was interpreted as a signature of regionally localized southward shifts of the ACC fronts^{8,33,92,93}.

214
215 The primary assumption of these analyses is that if a contour SSH shifts, then its associated fronts will shift with it. However,
216 more recent work employing “local” definitions (see section 2) has shown that this is not necessarily true, with numerous
217 studies failing to detect any long-term trend in the position of the ACC fronts^{19,25,41,42,94,95}, although there is some evidence
218 of localized frontal movements and changes in frontal intensity^{40,41}. Additionally, some recent studies provide only limited
219 evidence of a systematic response of fronts to changing atmospheric forcing^{25,35,42}. More modern climate models, such as
220 those within the CMIP5 multi-model ensemble, show no systematic shift in frontal locations^{35,85,89,96}. Instead, most recent
221 modelling studies predict an increase in the strength of the Southern Ocean’s eddy field and stratification, as well as a moderate
222 increase in the rate of upwelling of deep waters¹⁶.

223
224 In Fig. 5 we illustrate the projected Southern Ocean climate change using output from a modern climate model, the
225 GFDL-ESM2M⁹⁷, forced by two greenhouse gas concentration scenarios: a medium (Representative Concentration Pathway
226 4.5), and a high (Representative Concentration Pathway 8.5) emissions scenario. In both cases, the temperature of the Southern
227 Ocean is projected to increase substantially, which would result in a significant southward shift of SST and SSH contours by
228 the year 2100. However, in both climate projections considered here, there is little to no shift in position of either regions of
229 high SSH gradients (dashed contours in Fig. 5a,b,c) or strong isopycnal slopes (dashed contours in Fig. 5d,e,f), which are
230 indicative of fronts and strong ocean currents.

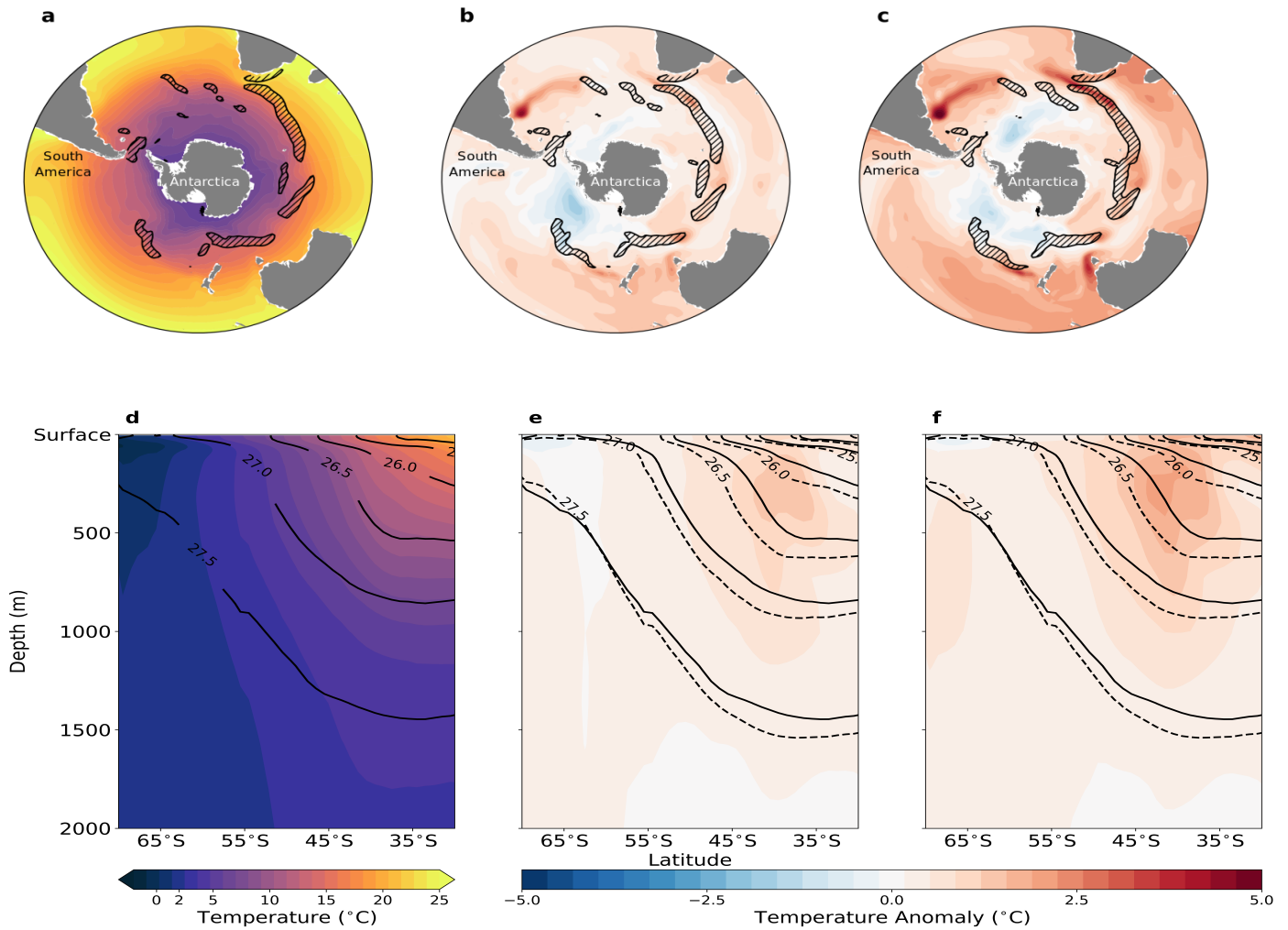


Figure 5. Climate change in the Southern Ocean. **a** the sea-surface temperature (SST) for the period 1985-2005 from a historical climate model simulation; **b** and **c** the SST *anomaly* for the period 2080-2100 (relative to 1985-2005) for a (**b**) medium (Representative Concentration Pathway 4.5); and (**c**) high (Representative Concentration Pathway 8.5) emissions scenarios. Hatched regions correspond to sea-surface height gradients greater than 10cm/100km (indicative of fronts or strong surface currents). **d**; **e**; and **f** as for **a**, **b**, and **c** but a longitudinal (zonal) mean section across the Southern Ocean. 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 ESM2M⁹⁷, part of the CMIP5 multi-model ensemble.

232 The SST and SSH contours that are often used to track frontal positions are sensitive to large-scale thermal expansion and steric
233 sea-level rise occurring as a result of global climate change⁹⁵. As such, while the locations of a particular SST or SSH contour
234 may have shifted, their spatial *gradients* are largely insensitive to changes in the ocean's broad-scale structure⁹⁴. This more
235 recent work has led to the new consensus that ACC fronts have not shifted southward in the past decades, and the observed
236 warming is now explained by changes in the wind-driven overturning circulation that accumulates heat within the ACC^{8,98}.

238 4.2 Impact of frontal changes on ecosystems

239 If ACC fronts were to shift south as a result of climatic change, there would be a number of ecological implications: the
240 structure and environmental conditions the Southern Ocean's bioregions would likely change^{9,62}; there would be modifications
241 in the distribution of nutrients and phytoplankton that form the base of the trophic web⁶²; and changes in distance required for
242 animals to travel from breeding and moulting sites to foraging grounds^{9,68,69,99}.

244 Studies seeking to understand the ecological implications of frontal shifts frequently employ global front definitions, which may
245 not be appropriate for the study of variability and change in ACC fronts. Additionally, more recent research has highlighted that
246 fine-scale features, such as eddies and submeso-scale currents, are as important as the meso-scale fronts for certain species^{21,83},
247 and that these features are unlikely to be represented in the climate change projections from coarse resolution climate models⁸⁹.

249 Future projections of Southern Ocean climate are uncertain, and numerous phenomena associated with ACC fronts of
250 biological significance, such as the strength of the eddy field and the role of fronts as barriers to mixing, are potentially
251 impacted by climate change. In addition, some climate projection predict a decoupling of the biogeochemical fronts from the
252 physical fronts⁴⁷, which would have implications for animals that use temperature as a proxy for prey availability⁶⁷. Therefore,
253 while fronts might not shift meridionally, some aspects of the habitat are likely to change.

255 5 The Southern Ocean Fronts Users' Guide

256 The rapid change in our understanding of the ACC, its fronts, and how they shape Southern Ocean ecosystems has resulted in
257 confusion. How best one can proceed with a study of Southern Ocean physics, chemistry or biology? Which frontal definition
258 should one use and why? How can one infer and attribute changes in the ACC? However, despite the complex nature of the
259 ACC and its ecosystems, there has been extraordinary progress over the last decade, made possible primarily through the
260 expansion of the Southern Ocean Observing System (SOOS)¹⁰⁰. Continued progress will depend on effective exploitation of
261 these new data systems. To facilitate this, we now present some broad advice to aide researchers.

263 Defining ACC fronts and jets

264 The choice of frontal definition can have a large impact on the results of a study, with particularly strong implications for the
265 study of variability and change^{12,35}. "Local" definitions derive all information required for their definition from the
266 neighbourhood of the front itself, while "global" definitions, such as the contour method⁵, define fronts using information from
267 a wide geographic region. We emphasize that there is no "correct" frontal definition; the choice of a definition should always be
268 guided by the objectives of the study and the available data. The advantages and disadvantages of each approach, and potential
269 use cases are summarized in Table 1. For studies of time-averaged or broad-scale properties, global methods have several
270 advantages: they are able to link jets and the hydrographic fronts, and their continuous representation allows geographically
271 distant frontal features to be connected. Global type definitions are also generally useful for linking surface fields observable by
272 satellite with interior water-masses^{4,31,34}, and for defining along-front coordinate systems^{24,29}.

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

280 Methodological choices for the study of variability and change

282 The assessment of shifts in the location of Southern Ocean fronts has been mired in controversy over the last decade, with
283 disagreement over the interpretation regarding the observed changes in the ACC (see section 4). The root cause of this
284 controversy stems from the methodological differences between studies that find frontal shifts in the observation record, and

	Global	Local
Example Definition	Water mass criteria ^{3,22} Contour fitting ^{4,5,7}	Gradient thresholding ^{12,27,35,39} Skewness/Kurtosis ^{27,42} Probability Density Functions (PDFs) ^{14,23} Profile similarity/clustering ^{43,44}
Advantages	Accurate time mean locations ^{5,12} Smooth, continuous fronts ³² Links distant regions ³² Links jets to water masses/hydrography ⁴ Simple to interpret ^{7,69}	Unambiguous definition ^{12,25} Identifies changes in frontal structure ^{25,36} Identifies mixing barriers ¹³ No spurious variability ³⁵ Number of fronts can vary spatio-temporally ^{25,35}
Disadvantages	Imperfect tracking of high gradients ³⁵ Spurious variability ^{35,95} Sensitivity to sea-level rise/warming ⁹⁵ Must choose number of fronts in advance ²⁴ Does not represent changes in frontal structure ^{25,35}	Sensitive to noise/eddies ¹² Must specify a threshold parameter ¹² Difficult to interpret ²⁵ Difficult to link jets to hydrology/water masses ¹²

Table 1. A comparison between standard frontal definitions

285 those that do not. Typically, studies that have found long term frontal shifts used contour type methods, while those that did not,
286 employed local type definitions. Given this controversy, we urge all researchers to be extremely prudent when assessing
287 changes in the ACC's frontal structure. Readers are advised to carefully consider their choice of frontal definition, as naïve
288 application of the contour method can lead to spurious variability and trends in frontal locations⁹⁵. In cases where fronts are not
289 required to be continuous, we favour the use of local frontal definitions in studies of variability and change. However, if a
290 continuous, global frontal definition is sought, we then strongly encourage researchers to demonstrate that the variability and
291 trend provided by the chosen global definition do track variability and trends of the water-masses structures.

292
293 Southern Ocean fronts and the eddies responsible for their formation are *mesoscale* features. In order to represent the physics
294 of jets, fronts, and eddies, ocean models must have horizontal grid spacing less than about 10 km over most of the Southern
295 Ocean. Running ocean models at this resolution requires vast computational resources, currently impractical for long climate
296 studies. Despite this, low-resolution climate models are still able to produce realistic broad scale water-mass distributions in the
297 Southern Ocean and are still useful for assessing potential changes in the Southern Ocean environment^{89,98}. They are, however,
298 incapable of representing the fine-scale features of fronts and their outputs must be interpreted with care.
299

300 6 Perspectives for the future

301 Advances in physical oceanography made possible by new data sources and analysis techniques have begun to resolve
302 previously contentious questions regarding the nature of Southern Ocean fronts. For example, the role of ACC fronts in shaping
303 broad-scale heat fluxes, the upwelling and subducting of water-masses, and the distribution of nutrients throughout the global
304 ocean are now broadly understood. Additionally, it is now broadly accepted that the mean positions of the ACC fronts have not
305 changed their position in response to recent climate change. However, numerous areas of disagreement exist concerning
306 fundamental questions. In particular, the relationship between surface features detected by satellites and hydrographic fronts is
307 still unclear in all but a few special cases.
308

309 Despite this recent progress, much work remains to translate our improved understanding of the physics of the Southern Ocean
310 into improved understanding of its ecosystems and its role in the greater climate system. For example, the role of fronts in
311 shaping ecosystems and bioregions must now be reevaluated in light of our updated knowledge of their dynamics. In particular,
312 clear relationships between filamentary fronts revealed by satellites, and productive environmental conditions capable of

313 supporting complex marine ecosystems are yet to be demonstrated. The response (if any) of the ACC fronts to the ongoing
314 climate change, and any downstream impact on the climate system through their influence on the Southern Ocean carbon sink
315 or southward heat flux is also poorly understood and not well represented in climate models. Theoretical understanding of the
316 mechanisms of front formation and variability also remains incomplete.

317
318 Progress on these questions remains hampered, as was so often the case in the past, by insufficient data. In particular,
319 biogeochemical data, such as observations of dissolved oxygen, CO₂, and nutrients, is severely limited. The future, however,
320 holds great hope for further breakthroughs. In particular, the increasing number of Argo floats equipped with biogeochemical
321 sensors, as well as improving capabilities of new observing platforms such as ocean gliders, promise to shed light on these and
322 other outstanding questions. The utility of equipping marine animals with oceanographic instruments has only recently been
323 realised, and continued exploitation of these data could also lead to new advances¹¹.

324
325 However, in our opinion, the greatest obstacle to further progress on these and many other outstanding questions is the
326 compartmentalisation of researchers into specialities. The complexity of the region severely limits the potential progress of a
327 single domain specialist when seeking to make inferences regarding the system as a whole. As such, it is our view that the
328 greatest potential for further progress lies in facilitating further cross-disciplinary collaboration. A successful example of this
329 cross-disciplinary collaboration is the Marine Mammals Exploring the Oceans Pole to Pole project¹¹, which equips marine
330 mammals with miniature temperature and salinity sensors, and has yielded a plethora of new results. Projects such as these
331 represent a “gold standard” for interdisciplinary collaboration.

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