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Fronts and upper ocean thermal variability south of New Zealand

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Abstract: The structure and variability of Southern Ocean fronts south of New Zealand are described based on fifteen summer expendable bathythermograph (XBT) sections obtained between 1994 and 2001. The temperature variability north of 60°S is dominated by meanders and meridional shifts of the Sub-Antarctic Front (SAF), which often bifurcates to form northern and southern branches. The northern branch follows the southern edge of the Campbell Plateau, while the southern branch is found over the abyssal plain of the south-west Pacific Basin. The northern and southern branches of the SAF can be separated by as much as 900 km. Intense eddies or meanders of the SAF displace isotherms by as much as 5 degrees of latitude from their positions when such features are absent. The Polar Front (PF) position is more stable in time, although cold-core features associated with eddies or meanders of the front are occasionally observed between the southern SAF and the PF. The position of the southern ACC front is extremely stable, consistently overlying the 3000 m isobath on the northern flank of the Pacific-Antarctic/south-east Indian Ridge.

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Key words: Antarctic Circumpolar Current, Southern Ocean, Sub-Antactic Front, XBT

Introduction

The Antarctic Circumpolar Current (ACC) extends unbroken around Antarctica and is the primary means by which water, heat and other properties are exchanged between the ocean basins in the Southern Ocean. As these exchanges are an important control on mean global climate, sustained hydrological observations are essential to describe and understand the physical processes which are responsible for the variability of the ACC.

Most of the flow of the ACC is concentrated in a number of fronts which separate different water masses or dynamical regimes. The main fronts in the Pacific sector are the Sub-Tropical Front (STF), the Sub-Antarctic Front (SAF), the Polar Front (PF), and Southern ACC Front (sACCf) (using the abbreviation for this based on Orsi *et al.* 1995). In the last decade, historical hydrographic, altimeter, and sea surface temperature data have been analysed by several authors to produce climatological pictures of the ACC frontal structure in this region (e.g. Gille 1994, Orsi *et al.* 1995, Belkin & Gordon 1996, Moore *et al.* 1999). However, the lack of repeat sections means that there is little information on the variability of the fronts in the Pacific sector. To partially fill this gap, the Climatic Long-term Interaction for the Mass balance in Antarctica (CLIMA) project of the Italian National Research Program in Antarctica (PNRA) has occupied high density XBT (expendable bathythermograph) lines between New Zealand and the Ross Sea since 1994. Specifically, fifteen summer XBT sections have been obtained near the P14S WOCE (World Ocean Circulation Experiment) line. This paper describes the frontal structure and evolution of the upper ocean between New Zealand and Antarctica, updating and improving the preliminary results reported in Russo *et al.* (1999) for the first two years of sampling.

Data

The Italian vessel *Italica* was used to obtain 15 XBT sections between 1994 and 2001, along a line from the edge of the continental shelf south of New Zealand to the continental shelf of the Ross Sea (Fig. 1). The cruise track was modified depending on weather conditions and the location of sea ice close to Antarctica. The majority of the transects were occupied at high density (every 10 nautical miles, or about 20 km), although faulty probes and poor weather conditions occasionally led to larger gaps. Most of the observations reached the maximum working depth of the Sippican T7 XBT of about 760 m. Data were measured with a vertical resolution of 0.65 m. Each XBT profile was carefully quality controlled to remove obvious spikes. The raw data with recorded temperature at 0.65 m depth intervals were linearly interpolated to 1 m depth intervals and smoothed with a 5-point moving average.

The 2600 km long transect was generally completed in 5–6 days, so each section provides a roughly synoptic picture of the upper ocean thermal structure across the Southern Ocean south of New Zealand. The vessel operates only in the summer field season. The observations span the period from November to March in 1994–95 and 1997–98, and are limited to January and February in the other years.

Identifying fronts in XBT sections

A front is a narrow region where an abrupt change in water

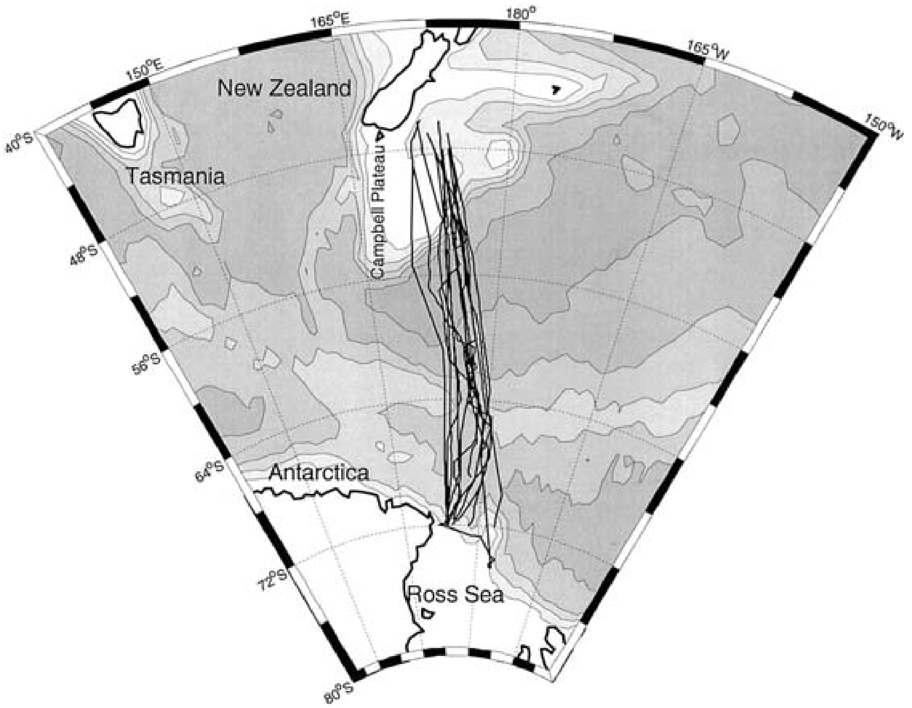


Fig. 1. Map of the cruise tracks. Depth interval is 1000 m.

properties takes place; such changes are often related to enhanced horizontal property gradients at various depths and to strong geostrophic flow. Thermohaline fronts are one of the most noticeable features in vertical sections across the Southern Ocean. Most of these fronts extend unbroken around Antarctica, helping to discriminate the different water regimes and current systems particularly in the upper layers of the oceans. Recent literature on the structure of the ACC generally recognizes three major fronts: the SAF, the PF, and the sACCf. The zone of uniform water characteristics between the SAF and the PF is commonly referred as the Polar Front Zone (PFZ), while the area from the PF to the Antarctic continent is indicated as the Antarctic Zone (AZ) (Whitworth 1980, Olbers *et al.* 1992, Orsi *et al.* 1995, Belkin & Gordon 1996).

South of New Zealand the streamlines of the geostrophic velocity are displaced to the south by the topographic forcing of the Campbell Plateau (Orsi *et al.* 1995). Consequently, the fronts in this region are also found further south than in the adjacent basins of the Pacific and Indian sector of Southern Ocean (Park *et al.* 1993, Read & Pollard 1993, Bryden & Heath 1985). Only the STF, which marks the separation between the sub-Antarctic surface water and the sub-tropical surface water, is not deflected south and instead, remains close to the coast of the south island of New Zealand. Our measurements begin further south and thus they do not cross the STF.

To map the location of the fronts, it is often useful to identify the central position of the front using the axial properties at a given level. A variety of criteria have been used to identify fronts of the ACC (useful summaries can be found in Peterson & Stramma (1991) and Belkin & Gordon (1996)). Here we use definitions based on temperature (T) since we rely on XBT sections to identify the fronts (Table I). Some authors (e.g. Orsi *et al.* 1995) used potential temperature to classify fronts but we can only use *in situ* temperature (since we do not have salinity data); in any case the difference is very small at these shallow depths.

To identify the sACCf we have used the definition from Orsi *et al.* (1995):

T > 1.8°C along the T-max at depth > 500 m, farther north;

T < 0°C along the T-min at depth < 150 m, farther south.

Table I. Criteria for front definitions.

Front	Definition	Reference
Southern Antarctic Circumpolar Current Front (sACCf)	T > 1.8°C along the Tmax at depth > 500 m, farther north; T < 0°C along the Tmin at depth < 150 m, farther south.	Orsi *et al.* 1995.
Polar Front (PF)	T < 2°C at 200 m, farther south.	Botnikov 1963, Orsi *et al.* 1995.
Subantarctic Front (SAF)	Maximum temperature gradient in the range 3–8°C at 300 m.	Belkin 1990.
Northern Sub-Antarctic Front (NSAF)	Maximum temperature gradient in the range 4–7°C at 300 m.	Rintoul *et al.* 1997.
Southern Sub-Antarctic Front (SSAF)	Maximum temperature gradient in the range 3–4°C at 300 m.	Rintoul *et al.* 1997.

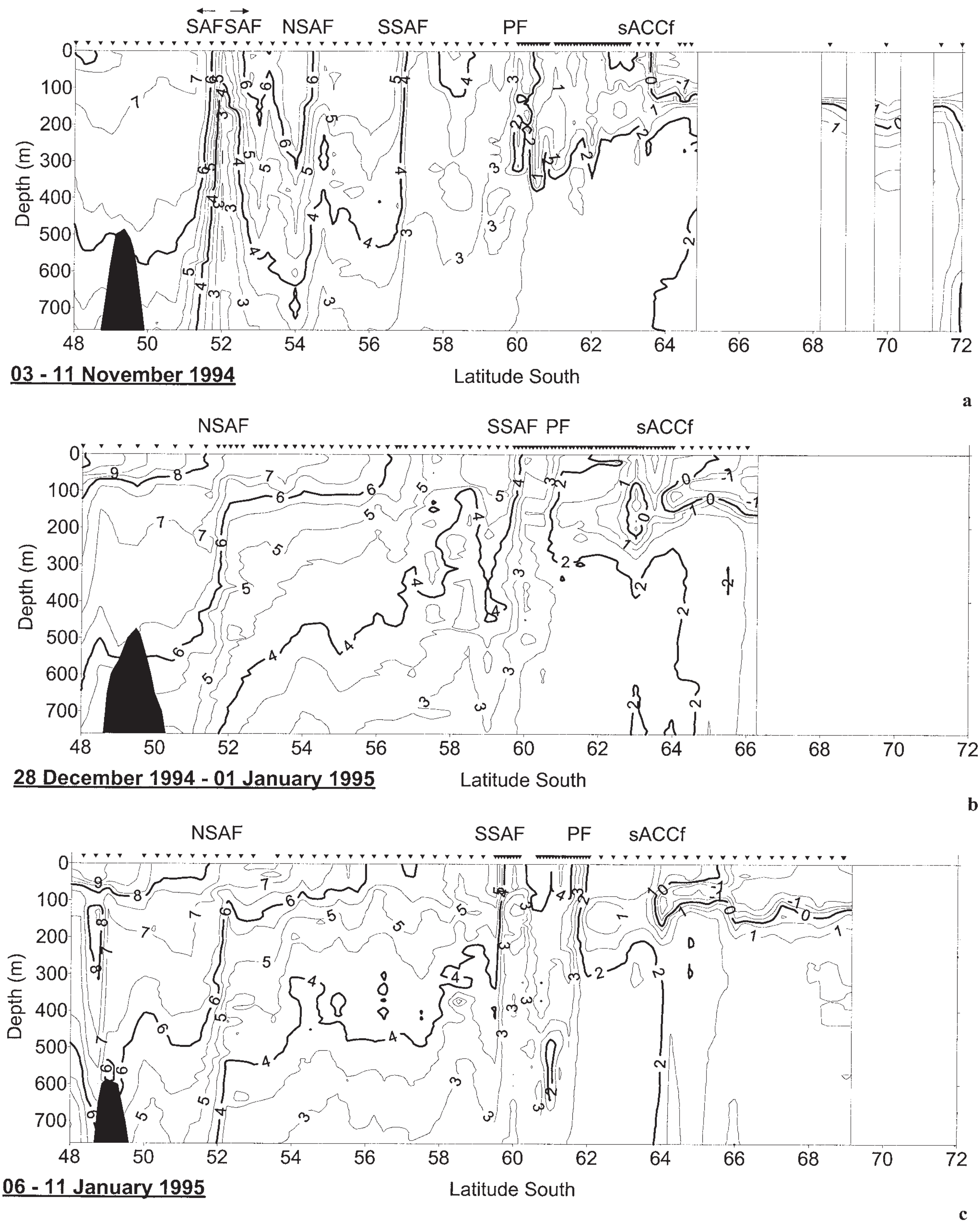
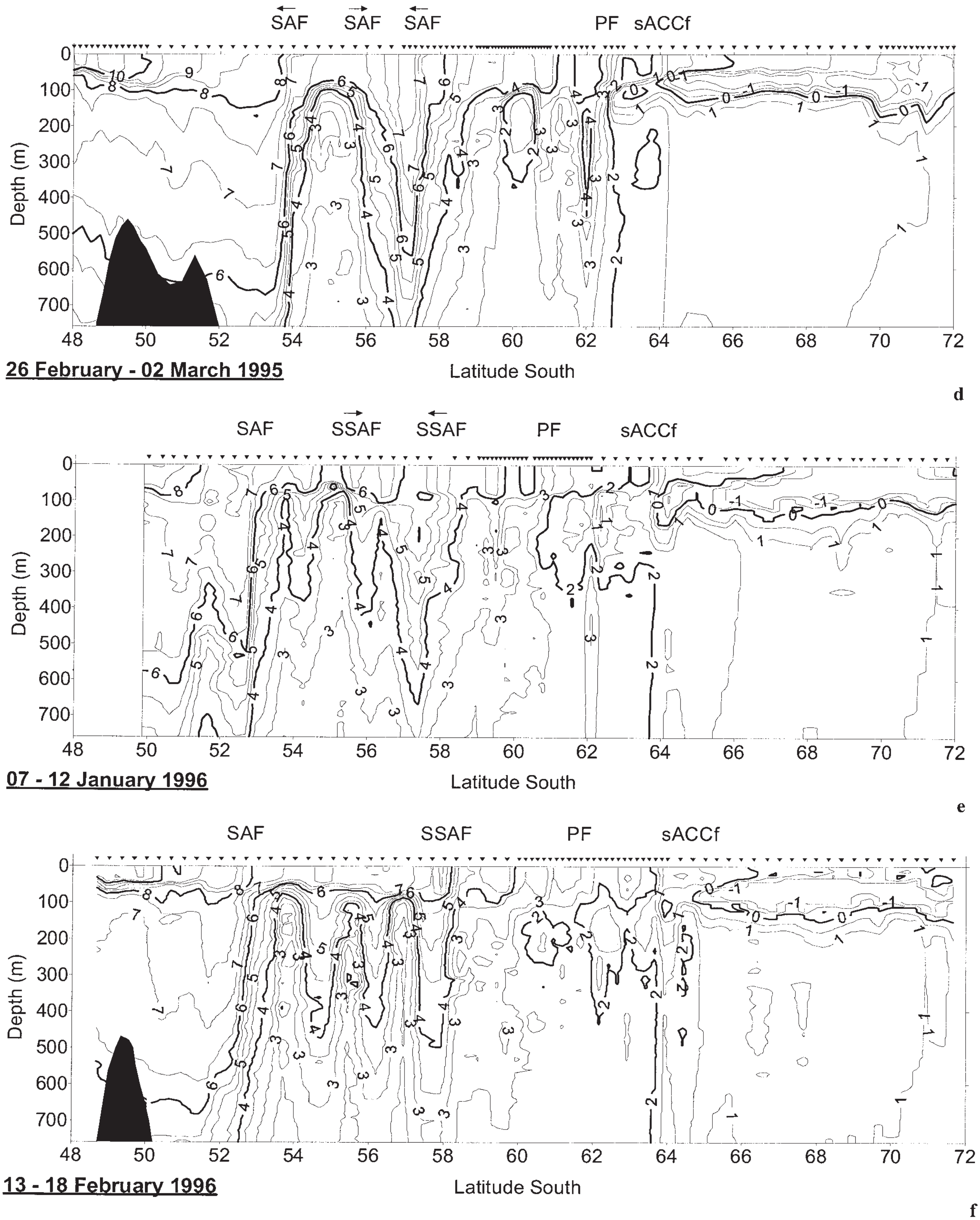


Fig. 2a–o. Temperature sections between New Zealand and Antarctica during the 1994/95–2000/01 summers. Station locations are indicated above each plot. Contour interval is 0.5°C. The locations of the Sub-Antarctic Front (SAF) and/or its northern (NSAF) and southern (SSAF) bifurcations, the Polar Front (PF), and the southern ACC Front (sACCf) are shown. Arrows at the top of the panels indicate the thermal gradient direction of the front.



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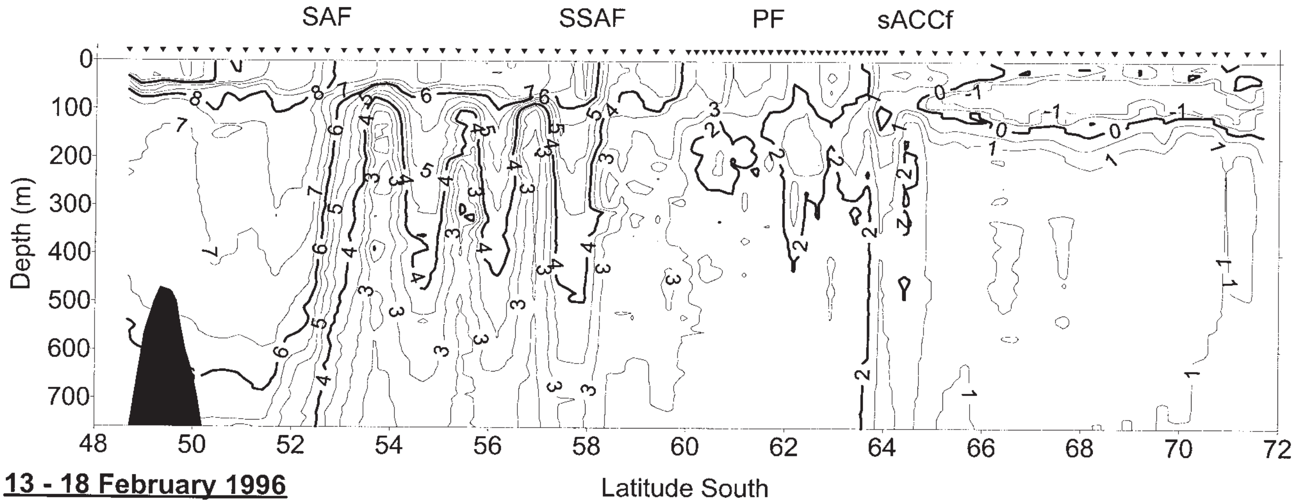

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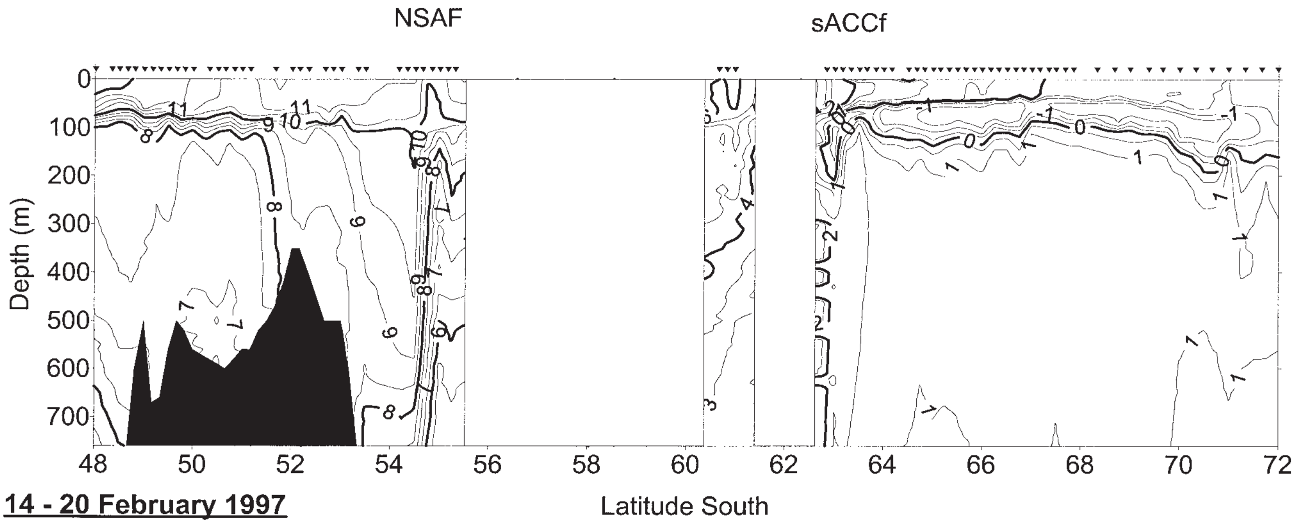

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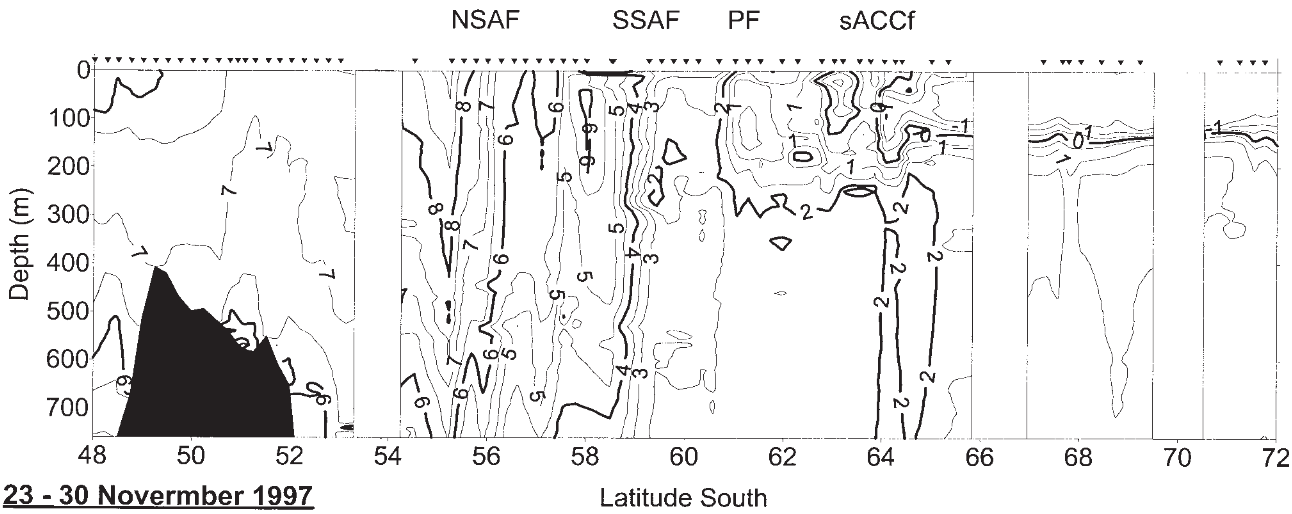

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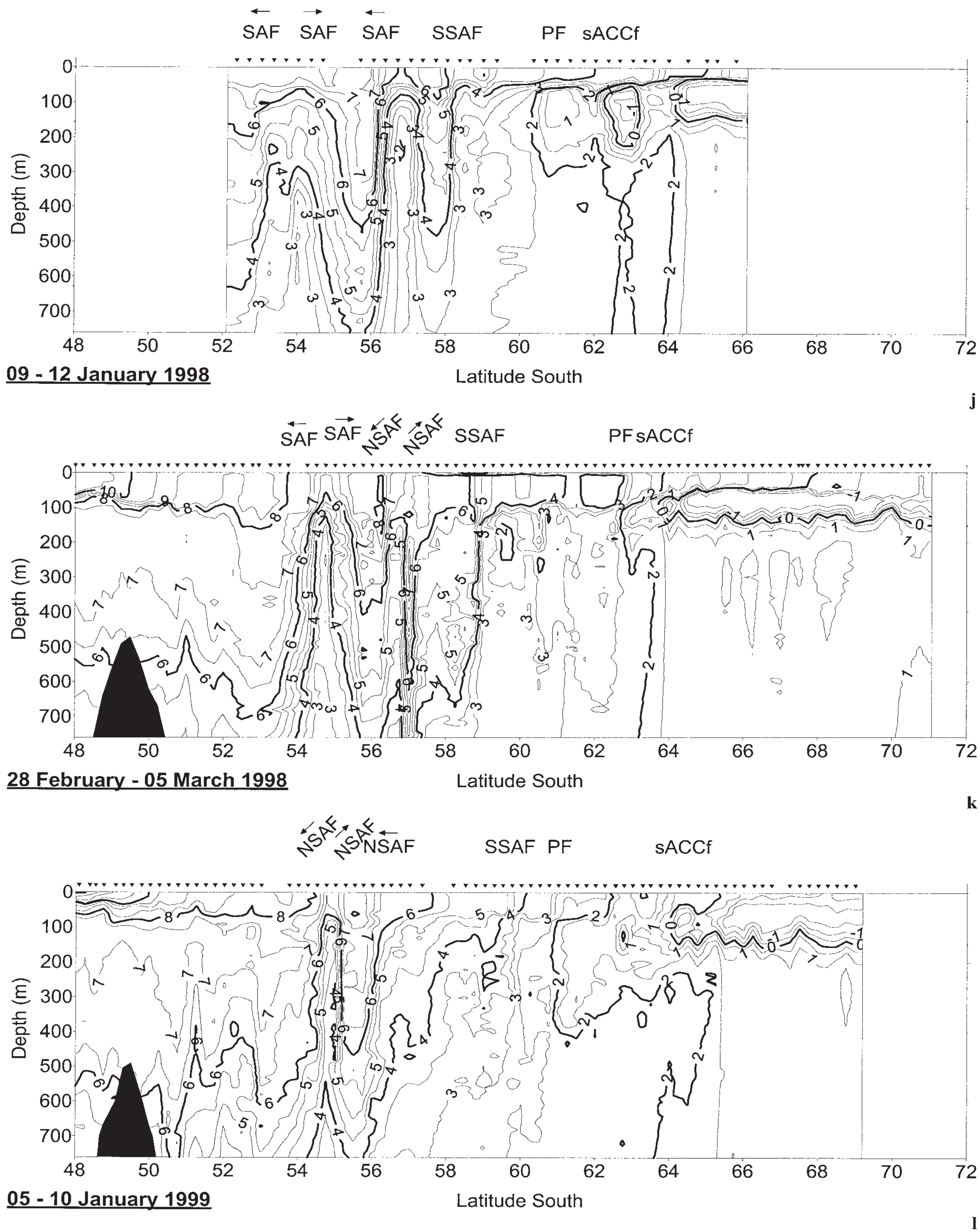

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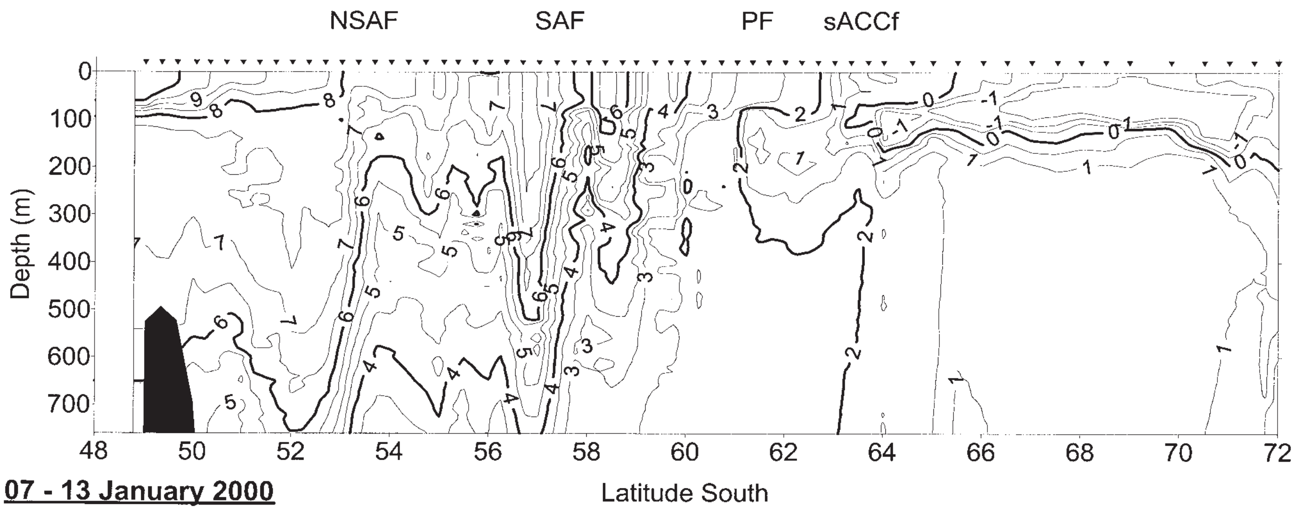

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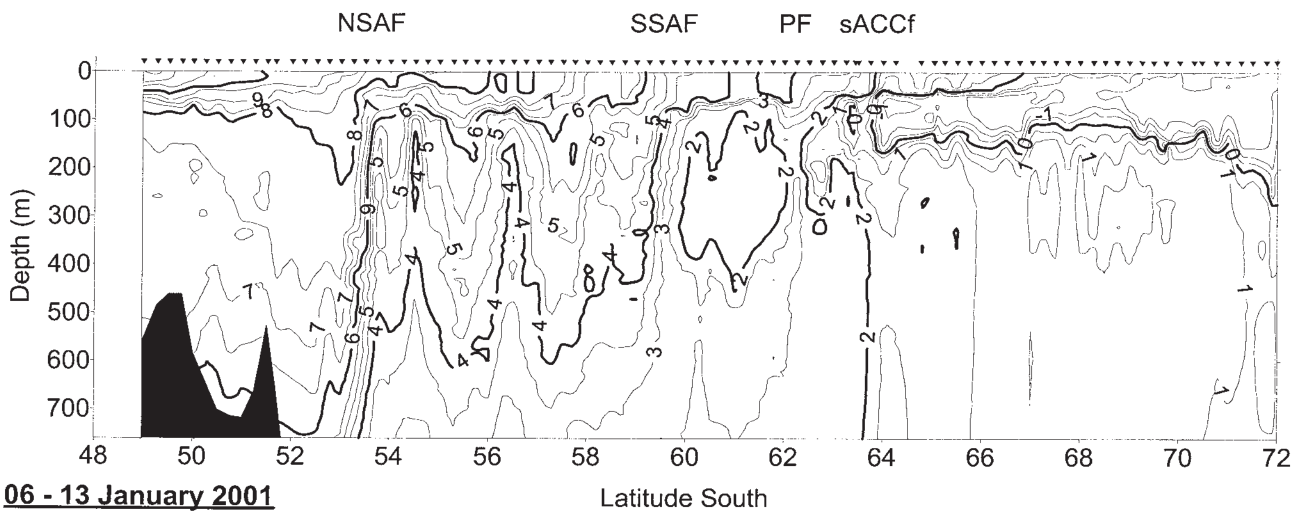

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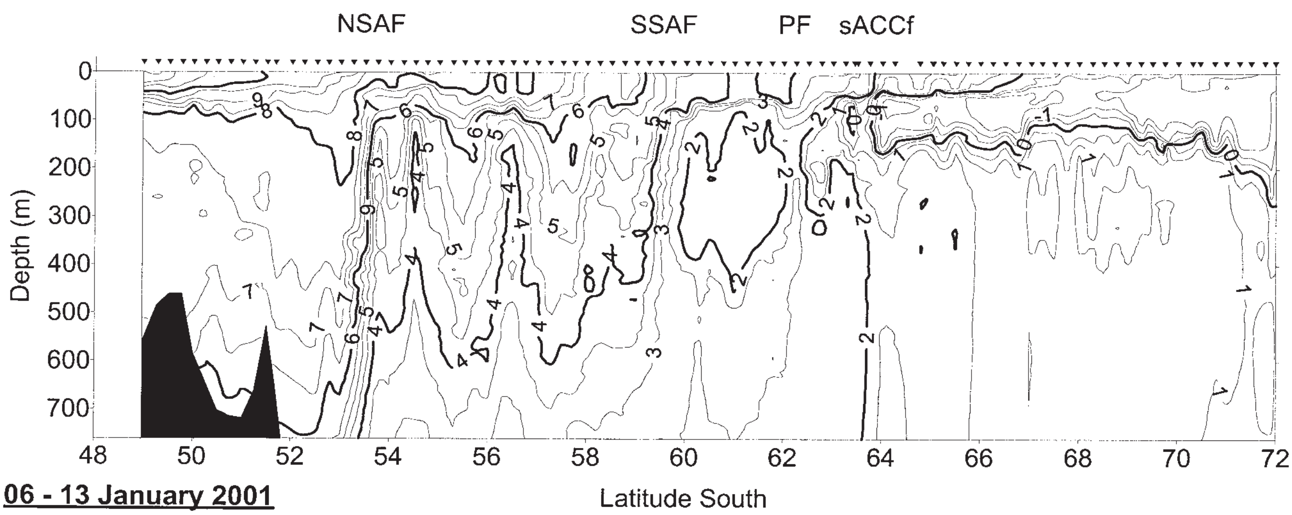

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The sACCf, unlike the other Southern Ocean fronts, does not separate distinct surface water masses: the relatively fresh Antarctic Surface Water (AASW) occupies the surface layer between the Antarctic continental shelf and the Polar Front. The sACCf is associated with a meridional density gradient and hence a maximum in (eastward) geostrophic velocity (Orsi *et al.* 1995).

The northern limit of the AASW indicates the location of the PF which is characterized by a large surface temperature gradient ($\Delta T > 2°C$) and by the maximum northward extent of the 2°C isotherm between 200–300 m. Therefore, in this work, the temperature minimum is used to define the location of the PF, in particular: $T < 2°C$ at 200 m, farther south (Botnikov 1964, Orsi *et al.* 1995).

The SAF represents the main core of eastward flow associated with the ACC at this longitude. The presence of a pronounced salinity minimum immediately to the north generally provides a reliable indicator of the SAF (Whitworth & Nowlin 1987). In the absence of salinity data, we need to rely on a temperature based criterion to define the SAF location. Belkin (1990) and Belkin & Gordon (1996) identify the SAF by the maximum temperature gradient in the range 3–8°C at a depth of 300 m (Belkin 1990). Orsi *et al.* (1995) associate the SAF with the location where the temperature at 400 m depth is greater than 4–5°C, further north. These different definitions lead to very different positions of the SAF in the New Zealand sector. Orsi *et al.* (1995) show the SAF turning to the south, while Belkin & Gordon (1996) show the SAF following the edge of the Campbell Plateau before turning offshore. As shown in the following section, results suggest both are correct: there are two branches of the SAF south of New Zealand, as already noted by Russo *et al.* (1999) from a few sections south of New Zealand and also observed south of Tasmania by Rintoul *et al.* (1997). The northern branch (NSAF) is associated with a maximum temperature gradient in the temperature range from 4°–7°C at 300 m, while the southern branch is characterized by a thermal gradient between 3°C and 4°C. The former is also associated with significant meridional salinity gradients, while the latter shows negligible salinity gradient at this depth (Rintoul *et al.* 1997). The NSAF also coincides with the presence of a pronounced salinity minimum to the north, consistent with the SAF definition of Whitworth & Nowlin (1987).

Frontal structure and variability

In this section we use data collected from 15 XBT sections to describe the structure and variability of the fronts south of New Zealand. Figure 2a–d shows a sequence of four sections collected from November 1994 to the beginning of March 1995. In November 1994 the SAF appears at 51.5°S (Fig. 2a) and it is also detected, with a reversed gradient (temperature growing southward) at 52.5°S, suggesting the presence of a cold eddy/meander in this area. Further south the SAF is split into its northern (54°S) and southern (57°S) branches. Both branches extend to the sea surface and produce a front in sea surface temperature. Between the two branches of the SAF, the upper 500 m of the water column is only weakly stratified at a temperature of 4°C to 5.5°C. The PF is located at 60°S and the sACCf at 63.5°S. This section was obtained early in the spring before the summer surface heating began; as a result, there is no temperature minimum layer (TML, $T < 1°C$) in the south, where the cold winter water extends from the surface to 200 m in the southern part of the section.

Fifty five days later the thermal structure is completely changed (Fig. 2b). The NSAF is located between 51°S and 53°S, with a relatively weak meridional temperature gradient. The cold eddy/meander is not present in January and the SSAF has shifted from 57°S to 60°S. The distance between the two expressions of the SAF is about 900 km. At this time in the season, only the SSAF has a detectable signature in SST. The surface expression of the NSAF appears to have been eroded by the summer warming. The third section (Fig. 2c) was sampled a week later and looks very similar to the previous section.

At the end of February/beginning of March the thermal structure is again very different from the earlier sections (Fig. 2d). The northern part of the section is dominated by a large meander (or eddy) centred at 55°S, with a diameter of about 240 km at a depth of 400 m. This feature has no cold surface expression, suggesting that the eddy/meander has persisted long enough for the surface signature to be erased by heat input from the atmosphere. The core of the eddy/meander at 55°S contains water cooler than 2.5°C at 200 m depth: in the early January section (Fig. 2c), water this cool is only found at this depth south of the SSAF near 60°S. South of the cold feature is a warm-core eddy or meander with a core temperature greater than 7.5°C at 200 m depth at 57°S. In early January, water this warm was not found at this depth south of 51°S. In addition, a cold nucleus of water of Antarctic origin at 60°S appears to have originated from the PF. The PF and sACCf are closer to each other in Fig. 2d than observed earlier in the season, but they are still distinct.

Figure 2e–f shows the sections performed in January and February 1996. Both sections show an interesting structure formed by three cold cores located between the NSAF and the SSAF. This meandering appears to be forming at the beginning of January, and one month later it is fully developed in the same location. It is interesting to note that, while the size of the structures is more or less the same, one month later the eddies have increased in strength and include a nucleus of cold ($T \approx 2.0°C$) waters of Antarctic origin (AASW). The cold features do not reach the surface and instead are capped by warm ($T > 7°C$) surface water. Comparing Fig. 2e and 2f, the SAF, PF and sACCf remain in more or less the same position from the beginning of January to the middle of February.

Two sections were performed during the summer 1996/97 (Fig. 2g & h), but due to faulty probes and poor weather the section sampled in February was incomplete. In the section sampled at the end of January the latitudinal band between 51.5°S and 58°S shows multiple crossings of the branches of the SAF, suggesting a complex meandering and bifurcation of the SAF. The PF is located at 62°S, while the sACCf was not sampled. The incomplete section of February 1997 shows only a step NSAF at 55°S and the sACCf at 63°S. The TML is fully developed from the sACCf to 67°S.

During summer 1997/98 the route between New Zealand and Antarctica was sampled three times (Fig. 2i, j & k). The SAF is split into the NSAF (56°S) and the SSAF (59°S) in November, while in January and February/March a number of alternating warm and cold features associated with the meandering and splitting of the SAF are found. Particularly in January the meander is able to entrap cold ($T < 2°C$) water of Antarctic origin up to 200 m. The PF remains in a stable position in November and January, and moves southward at the end of the summer. The sACCf does not substantially change its location.

During the two following summers (1998/1999 and 1999/2000) the line between New Zealand and Antarctica was sampled only once per year (Fig. 2l & m) so we have no information on the variability in these years. In January 1999 a number of meanders or eddies occupy the northern half of the section. Both branches of the SAF are found relatively far south compared to the other sections discussed. In January 2000 the NSAF crosses the section near 53.5°S, meanders back to the west near 56°S, and finally joins the SSAF to form a single intense SAF near 57.5°S, with temperatures decreasing from > 7.5°C to < 3.5°C in less than 100 km.

The January and February 2001 sections (Fig. 2n & o) are relatively similar. Both show a strong front immediately south of the Campbell Plateau with one or more meanders to the south. Between January and February the SSAF shifts to the north, decreasing the separation between the NSAF and the SSAF from 360 to 210 nautical miles in 45 days. In January a nucleus with water colder than 2°C is detected from 100 to 450 m depth between the SSAF at 60°S and the PF at 62°S. From a single section it is not possible to say whether the feature is a meander of the PF or an isolated ring. It was noted that relatively warm water occupies the interior of the core (it is not colder than 1.5°C, while temperatures decrease to < 1°C across the PF at this depth) and it can be speculated therefore, that this nucleus has been detached from the PF some time before and progressively heated.

Discussion

Based on these summer XBT sections, the frontal structure south of New Zealand can be summarized as follows.

The sub-Antarctic Front

The most conspicuous feature in the sections is the SAF. Temperature at 400 m increases from less than 3°C south of the SAF to greater than 7°C north of the front. However, the structure of the SA is complex in this eddy-rich region and temperature rarely increases monotonically from south to north (e.g. on only 3 out of 15 sections does the 4°C isotherm steadily shoal to the south across the section). Usually the increase in temperature occurs in two steps: the strongest temperature gradients are found in the northern branch at a temperature between 4.5°C and 7.0°C at 400 m depth, while the southern branch coincides with a weaker meridional gradient between 3°C and 4.5°C. On 7 out of 15 sections the SAF crosses the section near the northern end in a single intense front, then part or all of the front meanders back to the west before turning east to cross the section again further to the south (Fig. 2a, d, e, f, j, k, o). On only one of the sections does the SAF remain as a single "merged" front everywhere along the section (Fig. 2d). On the other sections, the SAF splits into northern and southern branches. On five of the 15 sections, the two branches are always distinct (e.g. Fig. 2b, c, g, i, l) and in some cases they can be separated by as much as 900 km (e.g. Fig. 2b).

Defining the location of the fronts is obviously complicated by the presence of multiple eddies or meanders associated with the branches of the SAF. To compare the position of the fronts on different sections in a consistent way, we have dealt with multiple crossings by taking the northernmost expression of the NSAF to define the location of that branch, and the southernmost expression of the SSAF to define the location of the southern branch. When the SAF is present as a single merged front, we have defined the NSAF to coincide with the northernmost crossing and

Table II. Latitude of the observed fronts. When only a single coherent SAF was present (i.e. a single high temperature gradient band in the 3–8°C temperature band) its northern location has been associated to the NSAF, and its southern location to the SSAF.

Sampled period	NSAF °S	SSAF °S	PF °S	sACCf °S	Fig.
03–11 November 1994	51.5	56.9	60.2	63.6	2a
28 December 1994–01 January 1995	52.0	59.8	60.9	63.8	2b
06–11 January 1995	51.9	59.6	61.9	63.8	2c
26 February–02 March 1995	53.8	57.7	62.7	63.8	2d
07–12 January 1996	52.8	57.8	60.9	63.8	2e
13–18 February 1996	53.0	58.0	61.7	64.5	2f
27 January–01 February 1997	53.7	57.3	62.0	x	2g
14–20 February 1997	54.8	x	x	62.9	2h
23–30 November 1997	55.6	58.9	60.8	63.9	2i
09–12 January 1998	52.8	58.0	60.3	62.5	2j
28 February–05 March 1998	54.0	58.9	62.8	63.8	2k
05–10 January 1999	54.5	59.7	61.0	64.0	2l
07–13 January 2000	53.1	57.5	61.1	63.1	2m
06–13 January 2001	53.4	59.2	62.5	63.9	2n
22–26 February 2001	54.5	58.5	62.8	63.2	2o
Mean	53.4	58.4	61.5	63.6	
S.D.	1.2	0.9	0.9	0.5	

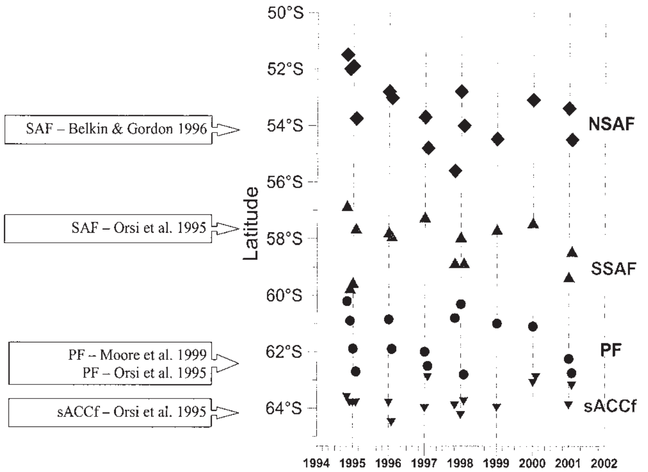

Fig. 3. Latitudinal variability of the front locations in time (diamonds = NSAF, upward triangles = SSAF, circles = PF, downward triangles = sACCf). The average position of the SAF (Orsi *et al.* 1995, Belkin & Gordon 1996 – see Fig. 4 which summarize previous works of the same authors), of the PF (Orsi *et al.* 1995, Moore *et al.* 1999), and of the sACCf (Orsi *et al.* 1995) are also shown.

the SSAF to coincide with the southernmost crossing of the section by the SAF. Defined in this way, the difference in latitude between the NSAF and the SSAF indicates the width of the zone influenced by the meandering branches of the SAF. The fronts are indicated in Fig. 2 to illustrate the approach. The latitude of each of the fronts is shown in Table II and plotted in Fig. 3. The mean latitude of the NSAF is 53.4°S, with a standard deviation of 1.1 degrees and a range from 51.5°S to 55.6°S. The mean latitude of the SSAF is 58.4°S, with a S.D. of 0.9 degrees and a range from 56.9°S to 59.8°S. There is no clear temporal trend in the latitude of the NSAF and SSAF (Fig. 3).

Polar Front

The latitude of the PF is given in Table II and Fig. 3. On each of the sections, the northernmost extent of the TML cooler than 2°C at 200 m (the criteria we use to define the PF) coincides with an enhanced gradient in sea surface temperature. The PF south of New Zealand was never observed to consist of multiple branches, unlike south of Tasmania where two distinct branches of the PF are consistently observed (Rintoul *et al.* 1997, Rintoul & Bullister 1999, Rintoul & Sokolov 2001). Multiple polar fronts have been recognized also in other parts of the Southern Ocean (e.g. Nowlin *et al.* 1977, Sievers & Nowlin 1984, Sparrow *et al.* 1996, Moore *et al.* 1999). The mean latitude of the PF is 61.5°S, with a standard deviation of 0.9 degrees and a range from 60.2°S to 62.8°S. On a few occasions, cold-core eddies or meanders spawned from the PF are observed, but on the whole the PF is less prone to meandering than the SAF.

Southern ACC Front

The two November sections show that prior to the onset of summer warming of the surface layer the 0°C isotherm outcrops in an enhanced SST gradient which defines the sACCf. Once the surface mixed layer begins to warm, the northern extent of the TML cooler than 0°C is a reliable indicator of the front, as suggested by Orsi *et al.* (1995). The

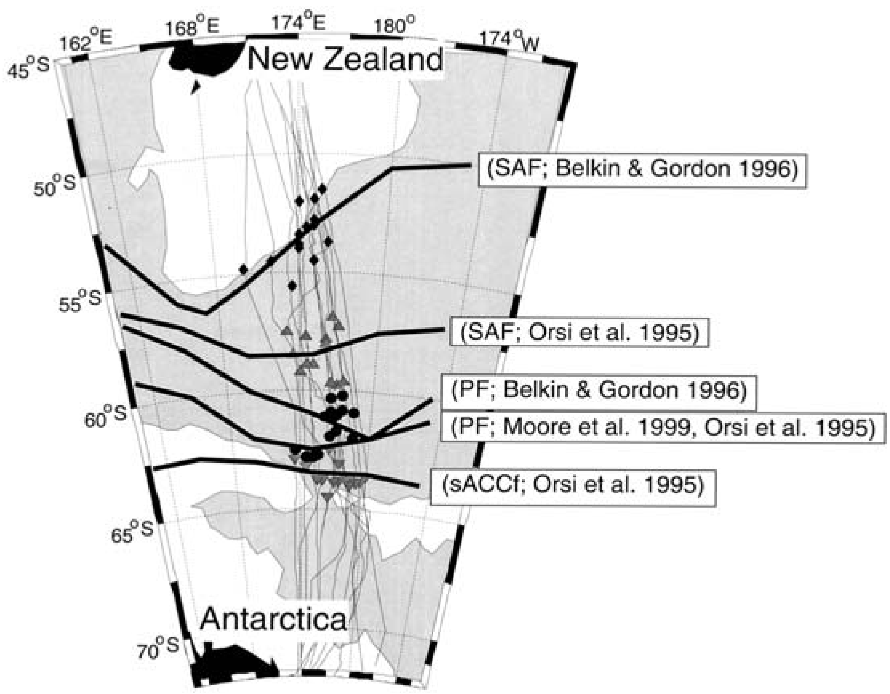

Fig. 4. Map of our front locations (diamonds = NSAF, upward triangles = SSAF, circles = PF, downward triangles = sACCf). These positions are compared with the mean paths of the SAF (Orsi *et al.* 1995, Belkin & Gordon 1996), of the PF (Orsi *et al.* 1995, Moore *et al.* 1999), and of the sACCf (Orsi *et al.* 1995). Depths deeper than 3000 m are shaded.

sACCf also coincides with a deepening of the TML to the north. The position of the sACCf is very constant in time, with a mean of 63.8°S and a standard deviation of only 0.4 degrees (Table II, Fig. 3). It is found near the 3000 m isobath, on the northern flank of the Pacific–Antarctic/south-east Indian Ridge.

Table II and Fig. 3 suggest the position of the PF and NSAF varies significantly. There is also a hint that perhaps both of these fronts shift to the south through the course of the summer, as noted earlier for the PF by Russo *et al.* (1999). However, when the front locations are plotted on a map of the cruise tracks, it becomes clear that much of the apparent variability in front locations is due to changes in the cruise track rather than changes in time (Fig. 4). The NSAF is almost always found over the continental slope at the southern edge of the Campbell Plateau. The cruise track generally shifts towards the west during summer, as the sea ice retreats and the ship can make a more direct transit from New Zealand to the Italian station at Terra Nova Bay. Since the continental slope angles from south-west to north-east, the NSAF appears to shift to the south as the cruise track shifts to the west. Similarly, the PF was encountered further to the north on the eastern cruise tracks occupied early in the season, and further south on the western cruise tracks.

The fronts found near steep topography (the NSAF and the sACCf) tend to follow the bathymetry. The SSAF, on the other hand, is found in the deep south-west Pacific basin and its path is not controlled by the bathymetry; as a result, the position of the SSAF is more variable than the other fronts. The PF closely follows the 4000 m isobath west of 175°E, where the topography is steep, but becomes less constrained by the bathymetry further east, where the slope of the ridge is less steep.

A strong topographic control on the fronts has been noted in many studies (e.g. Gordon *et al.* 1978, Lutjeharms & Baker 1980, Gille 1994). More recently Moore *et al.* (1999) commented on the tendency for fronts to be strongly steered by the bottom topography when the bottom slope is steep. Using an inertial jet model Craneguy & Park (1999) clarified the key role of the local bathymetry and the current velocity for the separation mechanisms between SAF and PF.

The presence of two branches of the SAF south of New Zealand explains the difference between the SAF position on the maps of Orsi *et al.* (1995) and Belkin & Gordon (1996, Fig. 4 which summarizes previous works of the same authors). Some results of other authors (e.g. Burling 1961, Gordon *et al.* 1977, Heath 1981, Stramma *et al.* 1995) support our conclusion that there are two branches of the SAF at this longitude, one near the edge of the Campbell Plateau and one in deep water farther south. The splitting of the SAF is also clear in maps of mean dynamic height (e.g. Gordon *et al.* 1978), which show streamlines that pass north of Macquarie Island in the SAF diverging south of New Zealand, with one branch following the edge of the Campbell Plateau and a second branch continuing nearly due east.

Figure 4 shows that the NSAF as we have defined it here coincides with Belkin & Gordon's location of the SAF, and our SSAF coincides with Orsi *et al.*'s location of the SAF. The PF correspond with the slightly different positions shown by Belkin & Gordon (1996) and by Moore *et al.* (1999) (which in turn, in this area, match the location shown in Orsi *et al.* 1995). The sACCf is found in this work at the same location marked in Orsi *et al.* (1995).

Eddies and meanders

The XBT sections cross numerous eddies and/or meanders of the SAF north of 58°S. Similar features have been observed in previous sections south of New Zealand (e.g. Gordon 1975, Piola & Georgi 1982). This region also shows up as an eddy "hot spot" in maps of sea surface height variability from satellite altimetry (e.g. Gille & Kelly 1996, Wunsch & Stammer 1995). The reasons for a maximum in eddy energy south of New Zealand have not been completely explained, but probably include the interaction of the current with the large topographic obstacle of the Campbell Plateau (Yaremchuk *et al.* 2001). The features observed in the XBT sections are large in amplitude, and result in displacements of isotherms by as much as 500 km to the north or south from the latitude at which they are found on sections with no large meanders. These large perturbations to the thermal structure may play an important role in the meridional flux of heat, freshwater and nutrients. For example, in Fig. 2a at 52°S the temperature at 400 m depth ranges from 2.5°C to 7.5°C. The significance of the eddies and meanders to the meridional heat flux depends on whether the anomalies mix with the surrounding water masses and "surrender" their heat or whether they are "re-absorbed" by the front before substantial mixing occurs.

From the infrequent XBT sections we cannot comment on the fate of the eddies. Preliminary work has shown that the features are sufficiently large to have a signature in sea surface height. We plan a follow-up study where satellite altimetry will be used to follow the life cycle of individual rings and meanders. In particular, we are interested in where rings and eddies are generated, their movement and evolution with time, and their ultimate fate.

Conclusions

A new data set of high resolution XBT observations enable us to describe the structure and variability of the main ACC fronts south of New Zealand. The observed period is from the austral summer 1994/95 to 2000/2001; these observations are still in progress and will allow longer period changes to be analysed in the future.

The SAF regularly bifurcates into northern and southern branches in this region. The northern branch closely follows the edge of the Campbell Plateau; the southern branch is found over the abyssal plain of the South-west Pacific Basin. The existence of two distinct branches of the SAF explains why Orsi *et al.* (1995) and Belkin & Gordon (1996) found different paths for the SAF south of New Zealand. Intense eddies or meanders of the SAF dominate the thermal structure north of 58°S and may contribute to the meridional flux of heat and other properties. The PF is more stable in position than the SAF, although occasional cold-core meanders or rings originating from the PF are observed north of the front. The sACCf is consistently found over the northern flank of the mid-ocean ridge.

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