Pliocene sea surface temperature changes in ODP Site 1125, Chatham Rise, east of New Zealand

Ashwaq T. Sabaa, Elisabeth L. Sikes, Bruce W. Hayward, William R. Howard

Abstract

Planktonic foraminiferal census counts were converted to sea surface temperature (SST) estimates using the modern analogue technique (MAT) for the middle-late Pliocene (4.0-2.37 Ma) in ODP Site 1125, north side of Chatham Rise, SW Pacific Ocean. MAT SST\textsubscript{warm} records range between 8°C and 20.5°C, and MAT SST\textsubscript{cold} records parallel that pattern but with a temperature range of 5-15°C. The modern position of Site 1125 is just north of the Subtropical Front and has an annual temperature range of 14-18°C. Pliocene warmest temperatures are 1-2°C warmer than modern summers, whereas cold season SST records are up to 6-10°C cooler than modern winters. Overall average temperatures at the site are 2-3°C cooler than modern temperatures during a time of sustained global warmth. Three major cold excursions centred on 3.35, 3.0, and 2.8 Ma showed warm season temperatures over 5°C colder than the last glacial maximum, experiencing temperatures typical of modern subantarctic waters. Two minor cold excursions at 2.7 Ma and 2.4 Ma experienced temperatures cooler than modern winters but not as cold as last glacial conditions. Cold season SSTs show a shift to warmer climate upward through the study interval, whereas warm season estimates remain essentially unchanged. We interpret the strong regional cooling of subtropical Southwest Pacific water through the middle-late Pliocene as having been caused by increased upwelling. It is also possible that the subtropical frontal zone moved north over the site in the Pliocene, however, this is considered the least likely interpretation. Our record of cool conditions in the Southwest Pacific corroborate evidence of cooler than modern conditions in other regions of the western Pacific through the mid-Pliocene despite overall global warming.

Keywords: Southwest Pacific; Pliocene; New Zealand; planktonic foraminifera; sea surface temperatures; modern analogue technique

1. Introduction

The middle Pliocene was the last interval in earth history when climate was significantly warmer than the Holocene while crucial boundary conditions such as the placement of continents...
were predominantly the same as today. Extensive palaeotemperature records, including sea surface estimates, indicate that the middle Pliocene (~4–2.7 Ma) was an extended warm period, preceding dramatic cooling associated with the formation of Northern Hemisphere ice sheets at ~2.5 Ma (cf. Dowsett et al., 1996; Raymo et al., 1996). The body of evidence shows minimal warming at low latitudes, significant warming at mid latitudes, and most extensive warming at higher latitudes. However, there are also numerous studies which indicate relatively little warming or even some cooling at mid latitudes (Dowsett and Willard, 1996; Heusser and Morley, 1996; Keigwin and Thunell, 1979). Asymmetric or variable cooling latitudinally indicates that the cause of the warming in the middle Pliocene was largely due to increased meridional heat transport rather than due to increased atmospheric CO₂ (Crowley, 1996; Dowsett et al., 1992). The extent of Antarctic ice-sheet melting and associated Southern Ocean warming during this period has been the subject of considerable debate. Studies from East Antarctica suggest large scale deglaciation (Webb and Harwood, 1991), implying warming of 5–10°C (Harwood, 1994), whereas marine-based studies suggest that the Southern Ocean warmed not more than ~3–4°C (Barron, 1996; Burckle and Pokras, 1991; Kennett and Hodell, 1993).

The climatic history of the Southern Ocean is reflected in the movement of three prominent oceanographic fronts. The Subtropical Front (STF) is considered the northern extent of the Southern Ocean and is the frontal zone marking the boundary between the subtropical gyre waters and Subantarctic waters. The Subantarctic Front (SAF) is the boundary between Subantarctic water. The Antarctic water and the Antarctic Polar Front (APF) is the southern extent of the Antarctic circumpolar current. The two southerly fronts are closely associated in some locations of the Southern Ocean and are jointly referred to as the Polar Frontal Zone (PFZ). Significant deep water masses are formed at these fronts such as Antarctic Intermediate Water (AAIW). These surface frontal zones are characterised by distinct signatures in surface oceanographic properties (e.g. Rintoul et al., 1997). Temperature gradients, which are associated with changes in flora and fauna across these fronts, serve as robust palaeo-proxies for frontal location in the marine record. The STF, the front closest to this study, is characterised as a zone of rapid change in sea surface temperature (SST) between the 10°C and 14°C winter isotherms, and between the 14°C and 18°C summer isotherms (cf. Belkin and Gordon, 1996). The STF, with its associated SST signature, is well delineated by planktonic foraminiferal faunas which can be applied to palaeoceanographic analysis (cf. Weaver et al., 1997).

Southern Ocean fronts today migrate north and south seasonally across wide areas of the ocean (Belkin and Gordon, 1996) but in some locations they appear to be guided and held in place by subsurface topography (Belkin and Gordon, 1996; Heath, 1985). This steering is particularly evident east and south of New Zealand where the Chatham Rise and Campbell Plateau are associated with the location of the STF and the SAF, respectively (Heath, 1981; Heath, 1985) (Fig. 1). It has been well established that in the past these fronts migrated north during cooler climates and to the south in warmer periods through the Pleistocene, mimicking the seasonal movement of the fronts seen today (Howard and Prell, 1992; Morley, 1989). In contrast, because of bathymetric steering, the STF seems to have remained locked on the Chatham Rise at all times over the last several glacial cycles (Sikes et al., 2002; Weaver et al., 1998). Results from ODP Site 594, located in Subantarctic waters today, indicate that the position of the STF has remained north of Site 594 and the SAF has remained to the south through this time period (Nelson et al., 1993) (Fig. 1).

Microfossil evidence suggests that the overall position of the APF and the PFZ were as much as 6° further south, and water temperatures were as much as 3–4°C warmer through the middle Pliocene (Barron, 1996; Ciesielski and Grinstead, 1986). The fronts moved north to locations similar to Holocene by the onset of Northern Hemisphere glaciation at ~2.47 Ma (Ciesielski and Grinstead, 1986). Foraminiferal oxygen isotopic records suggest slightly less warming, with Subantarctic water temperatures at most 2.5°C warm-
er than today through the middle Pliocene (Kennett and Hodell, 1993; Warnke et al., 1996).

1.1. Geological setting

Site 1125, drilled during Ocean Drilling Program (ODP) Leg 181, lies 610 km east of New Zealand’s South Island on the northern slopes of the Chatham Rise (42°33’S, 178°10’W) at 1360 m depth (Carter et al., 1999). The Chatham Rise is a 1000-km-long submerged continental plateau extending east of New Zealand at 44°S with water depths over the Rise of 400 m (Fig. 1). Sediments are affected by bottom currents along the crest of the Rise with Miocene strata exposed at places along the crest (Barnes, 1992; Carter et al., 2000). Site 1125 is in the pelagic drape area surrounding the Chatham Rise, where
hemipelagic sedimentation is known to have been continuous with little disturbance over the last few glacial cycles (Carter et al., 2000). The crest of the Chatham Rise approximates the position of the STF, which separates warm, nutrient-depleted waters in the north from cooler and more nutrient rich waters in the south.

Our study examines middle–late Pliocene SST in ODP Site 1125 immediately north of the Chatham Rise in the Southwest Pacific. It provides the first record of Pliocene SST of Southwest Pacific waters that today are subtropical and sit directly north of the STC.

2. Methods

A total of 72 samples were selected from the interval between 48 to 128 m composite depth (cmd) in Site 1125. A depth interval of 50 cm was chosen for high resolution study from 55 to 75 cmd, and a 1–3-m depth interval was chosen for lower resolution work for 48–55 cmd and 75–120 cmd. Samples of approximately 20 ml each were dried and weighed, then soaked in tap water overnight and washed over a 63-μm screen. Washed samples were dried, weighed, and sieved over a 150-μm screen. The coarser fraction (>150μm) was repeatedly split with a microsplitter until approximately 300 whole planktonic foraminiferal tests remained. All specimens were picked and mounted on a gridded slide, identified and counted for quantitative frequency determination of each species. The resulting faunal census data were converted to palaeotemperature estimates using the Modern Analog Technique (MAT).

Several methods based on quantitative faunal data have been developed to estimate past variations in surface ocean conditions (e.g. CLIMAP, 1976; Imbrie and Kipp, 1971). All SST estimation techniques are based on the same fundamental assumption: that the composition of a planktonic foraminiferal assemblage is directly or indirectly related to SST and the distribution of planktonic foraminifera in the world’s oceans have shown that specific living assemblages can generally be linked to a limited range of optimum SSTs (Bé and Hutson, 1977; Coulbourn et al., 1980). The Modern Analog Technique (MAT) is based on comparisons of fossil planktonic foraminiferal assemblages and modern core-top assemblages using statistical distance measures (Prell, 1985). The 10 best-fit core tops are chosen using squared chord distance and the weighted (using a corresponding squared chord similarity) average of their associated temperatures is the temperature estimate. There is a sample by sample estimate of the fit between down-core samples and modern core tops. Ancient samples with close modern analogues have low dissimilarity coefficients. This comprises one measure of the reliability of the estimate. A dissimilarity coefficient (squared chord distance) of zero is a perfect match, whereas a value of 2 is considered completely dissimilar (Hutson, 1977). MAT was chosen for this study to express faunal variations in terms of SST for several reasons. MAT directly relates down-core samples to core-top faunas without factorising the data and it provides a separate estimated standard deviation for each sample. Ancient samples with no close modern analogues that may provide spurious temperature estimates are identified as having high dissimilarity coefficients with respect to core-top samples (e.g. Howard and Prell, 1992). Error estimates for Quaternary MAT temperature estimates are generally < ±1.5°C (Prell, 1985), errors for Pliocene SST estimates can be expected to be somewhat greater. The dissimilarity coefficients in this study are excellent; all values are less than 0.3 which are considered acceptable matches (Anderson et al., 1989). In this study the modern SST climatology is the ‘GOSTA’ dataset (Bottomley et al., 1990).

The fundamental palaeoecological assumption inherent in the MAT approach is that extant species’ basic ecological and physiological preferences have not significantly changed through time. Pre-Pleistocene SST estimation involves differences between modern and fossil assemblages. These differences become larger with increasing age of the studied material and to account for this problem, species belonging to the same evolutionary lineage were presumed to have the same environmental preferences (Dowsett and Poore, 1990). It is assumed that if individual species’ preferences
have changed over time their abundance associations with other species should also change to produce ‘no-analogue’ samples (Hutson, 1977). The 26 species (taxonomic categories), which have been used in our analysis are shown in Table 1. In some cases, species belonging to the same evolutionary lineage have been combined together under one taxonomic category. Some species have been left out of the analysis because they are too minor, both in the down-core dataset and in the modern ocean, to be meaningful to the temperature analysis. One species we have left out is *Globorotalia oceanica* because it became extinct in the late Pliocene and there are no analogue species in this region.

### Table 1

<table>
<thead>
<tr>
<th>Pliocene planktonic foraminifera from Site 1125 and their placement in MAT categories</th>
<th>Taxonomic categories used in MAT</th>
</tr>
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<tbody>
<tr>
<td><em>Globigerina bulloides</em></td>
<td>1. <em>Orbulina universa</em></td>
</tr>
<tr>
<td><em>Globigerina eamesi</em></td>
<td>2. <em>Globigerinoides conglobatus</em></td>
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<tr>
<td><em>Globigerina falconensis</em></td>
<td>3. <em>Globigerinoides ruber</em> (total)</td>
</tr>
<tr>
<td><em>Globigerina quinqueloba</em></td>
<td>4. <em>Globigerinoides tenella</em></td>
</tr>
<tr>
<td><em>Globigerina umbilicata</em></td>
<td>5. <em>Globigerinoides sacculifer</em> (total)</td>
</tr>
<tr>
<td><em>Globigerina woodii</em></td>
<td>6. <em>Globigerinella aequilateralis</em></td>
</tr>
<tr>
<td><em>Globigerinella aequilateralis</em></td>
<td>7. <em>Globigerinella calida</em></td>
</tr>
<tr>
<td><em>Globigerinina glutinata</em></td>
<td>8. <em>Globigerina bulloides</em></td>
</tr>
<tr>
<td><em>Globigerinina uvula</em></td>
<td>9. <em>Globigerina falconensis</em></td>
</tr>
<tr>
<td><em>Globigerinoides extremus</em></td>
<td>10. <em>Globigerina digitata</em></td>
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<tr>
<td><em>Globigerinoides immaturus</em></td>
<td>11. <em>Globigerina rubescens</em></td>
</tr>
<tr>
<td><em>Globigerinoides ruber</em></td>
<td>12. <em>Globigerina hamulata</em></td>
</tr>
<tr>
<td><em>Globigerinoides triloba</em></td>
<td>13. <em>Globigerina quinqueloba</em></td>
</tr>
<tr>
<td><em>Globorotalia crassaconica</em></td>
<td>14. <em>Neogloboquadrina pachyderma</em> (sinistral)</td>
</tr>
<tr>
<td><em>Globorotalia crassaformis</em></td>
<td>15. <em>Neogloboquadrina pachyderma</em> (dextral)</td>
</tr>
<tr>
<td><em>Globorotalia crosata</em></td>
<td>16. <em>Neogloboquadrina dutertrei</em></td>
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<tr>
<td><em>Globorotalia crassaformis</em></td>
<td>17. <em>Globoquadrina conglomerata</em></td>
</tr>
<tr>
<td><em>Globorotalia ostiaria</em></td>
<td>18. <em>Globoquadrina hexagona</em></td>
</tr>
<tr>
<td><em>Globorotalia puntulata</em></td>
<td>19. <em>Pulleniatina obliquiloculata</em></td>
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<tr>
<td><em>Globorotalia punctuloides</em></td>
<td>20. <em>Globoquadrina inflata</em></td>
</tr>
<tr>
<td><em>Globorotalia scitula</em></td>
<td>21. <em>Globoquadrina truncatulinoides</em> (sinistral)</td>
</tr>
<tr>
<td><em>Globorotalia subonomoiozea</em></td>
<td>22. <em>Globoquadrina truncatulinoides</em> (dextral)</td>
</tr>
<tr>
<td><em>Globorotalia tosaeensis</em></td>
<td>23. <em>Globoquadrina hirsuta</em></td>
</tr>
<tr>
<td><em>Globoquadrina conglomerata</em></td>
<td>24. <em>Globoquadrina scitula</em></td>
</tr>
<tr>
<td><em>Neogloboquadrina humerosa</em></td>
<td>25. <em>Globoquadrina menardii</em></td>
</tr>
<tr>
<td><em>Neogloboquadrina pachyderma</em></td>
<td>26. <em>Globigerinoides glutinata</em></td>
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Species concepts followed are those of Kennett and Srinivasan (1983) and Scott et al. (1990).

3. Results

3.1. Stratigraphy

At Site 1125 two holes (1125A and 1125B; Fig. 2) were cored a few tens of metres apart to obtain overlapping core and complete coverage for the upper 200 m of the section (Carter et al., 1999). An age model for the middle and late Pliocene
Fig. 2. Chronostratigraphy and SST estimates for the middle–late Pliocene of ODP Site 1125. On the left of the figure. The colour reflectance curve is based on spectrophotometer measurements made soon after coring (Carter et al., 1999) and reflects variations in the ratio of carbonate and terrigenous sediment and is usually related to climate cycles. The magnetostratigraphic polarity record is of poor quality with solid black = normal polarity, white = reverse polarity (interpreted from Carter et al., 1999). Tephra ages have been determined by major chemistry correlation with tephra in well-dated Site 1123 (P. Shane, pers. commun.). Biostratigraphy datums are as follows: (1) FCO *Globorotalia inflata* (datum from Morgans et al., 1996); (2) FO *Pseudoemiliana lacunosa* (nannofossil, datum from Chen and Wei, unpubl.); (3) FO short dextral coiling excursion of *Globorotalia oceanica* (datum by correlation with Site 1123); (4) FO main dextral coiling excursion of *Globorotalia oceanica* (datum by correlation with Site 1123); (5) LO *Discoaster surculus* (nannofossil, datum from Chen and Wei, unpubl.); (6) FO *Globorotalia crassula* (datum from Scott et al., 1990); (7) LO *Globorotalia oceanica* (datum by correlation with Site 1123). Abbreviations: FCO, first common occurrence; FO, first occurrence; LO, last occurrence. The SST curves are based on MAT analyses of planktonic foraminiferal census data. The modern and LGM temperatures for subtropical waters at the site are indicated by dashed lines (from Weaver et al., 1998). Temperatures for the modern Subantarctic waters found just to the south of the STF are also indicated for reference.
of Site 1125 (Fig. 2) has been determined here using a combination of micropaleontology and tephrastratigraphy tied to the magnetostratigraphically well-constrained and orbitally-tuned sequence in nearby Site 1123 (Carter et al., 1999; Hall et al., 2001), which is also north of the STF. Our age model for Site 1125 is supported by poor quality magnetostratigraphy (Carter et al., 1999). Four distal tephra horizons within the Site 1125 Pliocene sequence can be correlated with similar horizons in Site 1123 on the basis of their major element chemistry in glass shards (P. Shane, pers. commun.) and their stratigraphic positions. These tephra were dated from the orbitally-tuned chronostratigraphy of Site 1123 (Hall et al., 2001) and provide ages of 2.39, 2.42, 3.45 and 3.75 Ma in the studied interval of Site 1125 (Fig. 2).

Two nannofossil datums (FO Pseudoemiliana lacunosa, LO Discoaster surculus, Chen and Wei, pers. commun.) and two planktonic foraminiferal datums (FCO Globorotalia inflata, FO Globorotalia crassula, Sabaa, 2000), that were dated elsewhere in the Southwest Pacific, (Carter et al., 1999) have been identified in Site 1125 (Fig. 2). In addition, one short and one long dextral coiling excursion of Globorotalia oceanica recorded in Site 1125 (Sabaa, 2000) can be correlated with similar excursions recorded in Site 1123 (G. Scott, pers. commun.) and dated from the orbitally-tuned chronostratigraphy of Site 1123 (Fig. 2).

3.2. Pliocene temperature estimates

Warm season SSTs ranged between 8.0°C and 20.6°C over the study interval of 4.0–2.37 Ma, while cold season SSTs display a sub-parallel pattern of variation between values of 5.0°C to 15.2°C (Fig. 2). Maximum SSTs for Site 1125 were higher than 20°C for SST_{warm} and ~15°C for SST_{cold} making the warmest times in the middle–late Pliocene, 1–2°C warmer than modern for this site. Despite this, middle–late Pliocene SSTs for Site 1125 were generally at or below modern. Average temperatures for the study interval were ~16°C for SST_{warm} and ~11°C for SST_{cold}, which are about ~2°C cooler than modern summers (18°C) and about 3°C cooler than modern winters (14°C). Pliocene seasonal SST range was ~4.7°C, i.e. slightly more than the ~4°C today.

Three cooling excursions recognised for their duration and intensity were centred on 3.34, 3.01, and 2.80 Ma. These have temperatures 8–10°C cooler than modern. Two more minor cold periods with temperature drops of ~4°C were present at 2.69 and 2.43 Ma. There were climate cycles throughout the study interval, but they are not well correlated with reflectance or carbonate content in the core (Sabaa, 2000) and due to the broad sample spacing can only be tentatively correlated with global climatic events. The coolings at 3.34 and 3.01 Ma may correspond with marine isotope stages M2 and G20, respectively (Shackleton et al., 1995). Thus they may represent global events but until an isotopic record is produced for this site these correlations are tentative at best.

Temperature oscillations in the closer sampled upper part of the studied section have a periodicity close to ~41 kyr, possibly reflecting the glacial climate oscillations of the time.

The sampling interval between 4.0 and 2.9 Ma was approximately 50,000–150,000 years or 2–6 times the sampling interval of ~8 kyr from 2.9–2.375 Ma (Fig. 2). Such a coarse sampling interval in the lower portion of the study prevents the resolution of climate cycles on orbital time scales and may have aliased the temperature record such that temperature extremes may have been missed. We averaged the SST_{warm} and SST_{cold} values for the warm intervals between the cold excursions in the respective portions of the study to allow comparison of temperatures between these intervals. Cold season SST’s in the warm intervals tended to warm slightly up section indicating that while summers remained about the same, winters warmed over the course of the study interval (Table 2).

3.3. Relative faunal abundances

The relative abundances of individual species of foraminifera can provide information that supplements the temperatures inferred from the total faunal census. Neogloboquadrina pachyderma is extremely useful in middle to high latitudes for
recording palaeoclimatic oscillations during the late Cenozoic (Bandy et al., 1971). The change in coiling direction of this species is a good qualitative palaeoclimatic indicator. The predominantly sinistral-coiling populations of this species are characteristic of cold temperatures, whereas predominantly dextral populations indicate relatively warmer water (Bandy and Theyer, 1971). Coiling ratios of *N. pachyderma* in Site 1125 show several sinistral coiling excursions which coincide with the cooling periods as determined by MAT (Fig. 3). Coiling ratios of 91% and 100% sinistral coincide with the two strongest cold intervals at 3.01 and 2.9 Ma, respectively. The proportion of dextral coiling *Globorotalia oceanica* increases in warm periods and largely mimics the coiling record of *N. pachyderma* (Fig. 3). This is opposite to the climate inference assumed for the coiling ratio of this species by Hornibrook (1981).

The relative abundances of other species such as *Orbulina universa*, *Globigerina bulloides* and *Globorotalia in£ata* show only weak associations with temperature at this site, in contrast to the strong association to SST of coiling ratios in *Neogloboquadra pachyderma* and *Globorotalia oce-

### Table 2

<table>
<thead>
<tr>
<th>Mean SST for warm intervals (Fig. 3) during warm and cold seasons (middle–late Pliocene) at Site 1125</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST warm</td>
</tr>
<tr>
<td>(°C)</td>
</tr>
<tr>
<td>Warm 5 17.9</td>
</tr>
<tr>
<td>Warm 4 15.9</td>
</tr>
<tr>
<td>Warm 3 18.1</td>
</tr>
<tr>
<td>Warm 2 17.8</td>
</tr>
<tr>
<td>Warm 1 15.5</td>
</tr>
</tbody>
</table>

Fig. 3. Relative abundances of some common planktonic foraminiferal species used in this study. SST$_{warm}$ and SST$_{cold}$ are as in Fig. 2 for reference. Today *Orbulina universa* is a subtropical species, *Globigerina bulloides* is associated with subtropical to subpolar water, *Globorotalia in£ata* is associated with upwelling, and sinistral *Neogloboquadra pachyderma* is a subpolar to polar species (Imbrie and Kipp, 1971). The coiling direction of *N. pachyderma* shows an increasing proportion of sinistral individuals with cooling temperatures. The proportion of dextral coiling *Globorotalia oceanica* increases in warm periods.
anica. G. inflata, which is associated with upwelling fauna, shows a general increase in relative abundance parallel to the upward warming trend in cold season temperatures, but this may be related to the evolutionary appearance of this species. O. universa, which is associated with subtropical waters, also shows slightly increasing abundances up section after the major cooling event at 3.0 Ma. In contrast, G. bulloides, which is associated with subpolar assemblages, has abundances that are relatively stable over the study interval.

4. Discussion

Warmest temperatures observed at Site 1125 for the middle-late Pliocene are as much as 3°C higher than present, although the average temperature for both warm and cold seasons were cooler than present conditions. Summers averaged ~2°C cooler and winters about 3°C cooler than modern. Thus, not only were average conditions slightly cooler, but the seasonality of temperature variation was somewhat greater, by about 1°C. Most published evidence indicates warmer global temperatures in this time period (e.g. Dowsett et al., 1996 and references therein). However, some low and mid-latitude western Pacific sites have recorded cooler temperatures through this period (Andersson, 1997; Heusser and Morley, 1996). Significantly, foraminiferal and diatom studies from DSDP Site 532, which sits in subtropical waters just north of the STF off southwest Africa, show both cooling and increased upwelling through this period (Dowsett and Willard, 1996). Dowsett and Willard (1996) ascribed the increased productivity through this interval to the cooling of Antarctic waters and suggested that cooling and expansion of sea ice around Antarctica increased the equator to pole thermal gradient thus increasing winds as well as enhancing the nutrient content of AAIW that upwelled as subthermocline waters at Site 532. The increasing Globorotalia inflata abundances in our core support both these suggestions (Fig. 3).

Site 1125 sits in subtropical waters north of the STF today and the annual temperature range over this site is 14–18°C. Across the STF, about 2° of latitude to the south, sit subantarctic waters with a significantly lower annual temperature range of 10–14°C (Fig. 1). During the three major and two minor cooling intervals of this study, Site 1125 experienced temperatures cooler than observed at this location in the last glacial maximum (LGM) (Weaver et al., 1998). Such temperatures are cooler than modern Subantarctic waters near the STC and closer to those observed near the SAF (Fig. 2). Thus, the temperature variations in the major cooling periods show greater swings than observed between the modern and the LGM, suggesting that the STF may have moved northward over this site several times in the middle-late Pliocene. A northward migration of the STF in the Southwest Pacific contradicts previous studies’ placements of Southern Ocean fronts predominantly to the south of their present locations for much of the Pliocene across the Southern Ocean (Barron, 1996; Ciesielski and Grinstead, 1986). Significantly, the APF is documented to have moved south or maintained its position to the south and west of New Zealand at that time (Barron, 1996) so that if the STF did move north of the Chatham Rise at times in the Pliocene while the APF maintained position or moved south, there would have been a larger area of cool subpolar waters relative to polar waters in the Southern Ocean through that time.

Regional Pleistocene SST evidence would suggest that it is unlikely that the STF moved to the north of the Chatham Rise in the Pliocene, despite the extreme cooling in the Pliocene SST record. There is strong faunal, floral, and geochemical evidence that the STF remained on the Chatham Rise even at times of significant cooling in the Pleistocene (Fenner et al., 1992; Nelson et al., 1993; Sikes et al., 2002; Weaver et al., 1998). Sea level was only ~25 m higher in the Pliocene (Kennett and Hodell, 1993) and the bathymetry of the Chatham Rise should have been sufficiently similar to anchor the front as it did in the late Pleistocene. If so, regional subtropical waters in the Pliocene were much cooler relative to Subantarctic waters and the temperature gradient across the front was much lower. The presence of cooler mid-latitude Pacific waters relative to Southern
Ocean waters fits within global reconstructions of the middle Pliocene which consistently show significant warming at high latitudes, with lesser or variable warming at low and mid latitudes (Dowsett et al., 1996).

Substantially colder mid latitude temperatures in the middle–late Pliocene relative to the Miocene have been interpreted as strong upwelling (Marlowe et al., 2000) associated with stronger winds due to an enhanced hemispheric temperature gradient (Dowsett and Willard, 1996). Stronger winds (Stewart and Neall, 1984) have been associated with cool intervals at the Rise over the last few glacial cycles (Nelson et al., 2000; Sikes et al., 2002). The upward trending increase in the abundance of the upwelling associated *Globorotalia inflata* across the study interval supports this. Alternatively, current flow around the west end of the Rise (Nelson et al., 2000) may have been sufficient in the Pliocene to affect SST at this site, whereas during the last glaciation it was not (Sikes et al., 2002). The relative cooling seen at Site 1125 supports the projections that the western Pacific may have been a locus of cooling in the middle–late Pliocene. Cooling in the New Zealand area was more likely due to upwelling, similar to the Southeast Atlantic (Marlowe et al., 2000) rather than the northward migration of Southern Ocean waters.

The small warming trend seen in cold season reconstructions across the study interval indicates that during warm intervals the summers were maintaining similar temperatures while winters were warming slightly, thereby reducing the seasonality of the area (Table 2; Fig. 2). The time period between 2.7 and 2.45 Ma is notable in this study for its extended record of warmth and lack of strong cool periods relative to the rest of the Site 1125 record studied. The increase in the abundance of *Orbulina universa* through time at Site 1125 is evidence that subtropical conditions were increasingly prevalent in warm periods, while the lack of change in the *Globigerina bulloides* abundances suggests that subpolar conditions were not. This is opposite to what would be expected, particularly between 2.7 and 2.4 Ma when there was the onset of Northern Hemisphere glaciation and evidence of cooling elsewhere in the Southern Ocean (Hodell et al., 1991), but we have no explanation for this phenomenon. The younger minor cooling at 2.44 Ma is likely associated with the onset of northern glaciation, but because our record ends shortly after that, it is difficult to assess if there was a lasting impact at this site.

Cooling periods at this site coincide with observations of cool periods elsewhere. Site 806 in the western Equatorial Atlantic shows an extended cooling period between 3.35 and 3.05 Ma (Andersson, 1997) and oxygen isotope records from Site 606 in the North Atlantic has enrichment events at ~3.1, 2.7, 2.6, and 2.4 Ma (Keigwin, 1986). The synchronicity suggests that much of the large amplitude climatic signal at this site is globally driven, but detailed correlations must await isotopic stratigraphy for this site.

The distribution of *Neogloboquadrina pachyderma* in modern New Zealand waters shows a transition from mostly dextral populations associated with the STF, through to predominantly sinistral populations south of about 48°S in Subantarctic waters (Kennett, 1976). The presence of coiling ratios of over 80% sinistral associated with the extreme cooling periods of the Pliocene strongly indicates that similar conditions existed here in the Pliocene. Our observation that the ratio of dextral coiling *Globorotalia oceanica* increases in warm periods is well supported by both comparison to the temperature record and the similar response of the coiling ratio of *N. pachyderma* in this site. The extinction of the dextral form (and indeed of the species itself) at the beginning of a cool period at the top of our study interval is additional evidence that this form was intolerant of colder SSTs and indicates that strong cooling associated with the onset of Northern Hemisphere glaciation may have occurred immediately after our study interval.
5. Conclusions

We report here on a record of SST for subtropical waters just north of the subtropical front east of New Zealand based on foraminiferal assemblages for the middle–late Pliocene. SSTs in this location, although having brief periods 1–2°C warmer than today, were largely cooler than modern SSTs and often cooler than SST reconstructions for the LGM. Specifically:

(1) Average temperatures at this site over the study interval are 2–3°C cooler than modern. Summer temperature maximums were 1–2°C warmer than modern whereas winter temperature minimums were 6–10°C cooler. Although maximum temperatures were 1–2°C warmer than modern, these warm intervals are brief and not sustained through the Pliocene at this site. Cool conditions in the Southwest Pacific corroborate evidence of cooler than modern conditions in other regions of the western Pacific through the middle Pliocene (Andersson, 1997; Heusser and Morley, 1996) despite overall global warming.

(2) Cool periods through the study interval were frequent, with SSTs as cold as Subantarctic waters in this location during the LGM. This suggests strong regional cooling of subtropical Southwest Pacific water through the middle–late Pliocene. Alternatively, increased upwelling may have cooled surface waters by a substantial amount with conditions similar to those off southwest Africa for the same interval (Dowsett and Willard, 1996; Marlowe et al., 2000). It is also possible that the subtropical frontal zone moved north over this location at numerous times in the Pliocene, but given the lack of evidence for this in the Pleistocene, this is considered the least likely interpretation.

(3) Major cooling excursions of 6–10°C occurred at 3.35, 3.0, and 2.8 Ma and minor coolings both shorter in duration and lower magnitude (~4°C cooling) occurred at 2.7 and 2.4 Ma. These may be associated with global events, but the correlation remains tentative until improved stratigraphy for this site is available.

(4) Average warm season temperatures remained stable throughout the study period, even in the late Pliocene, while cool season temperatures appear to have warmed slightly. This warming occurred in the lead up to Northern Hemisphere glaciation (2.9–2.4 Ma), suggesting that, at least regionally, mid-southern latitudes remained warm as Antarctica cooled.

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