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Key Points:

- Early Holocene optimum in southwest Pacific restricted to south of the subtropical front
- Faunal assemblages suggest reduced northern inflow of Subantarctic Surface Water, likely due to reduced westerly wind intensity in sector
- Conceptual model of early Holocene circulation supported by results from modern climate analog tool (PICT)

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Data Set S1

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Evidence for a Holocene Climatic Optimum in the southwest Pacific: A multiproxy study

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Abstract The early Holocene sea surface temperature (SST) gradient across the subtropical front (STF) to the east of New Zealand was ~2°C (measured between core sites MD97-2121 and MD97-2120): considerably less than the ~6°C modern gradient between the two core sites. We document the surface ocean temperatures east and south of New Zealand during the early and middle Holocene, to test and expand upon this reconstruction. This new study samples a latitudinal transect of seven sediment cores from 37°S to 60°S in the southwest Pacific from subtropical waters north of New Zealand to polar waters in the Southern Ocean. Our compilation of SST proxies consists of 525 SST estimates from five different methods and includes 243 new data points. We confirm that an early Holocene warm peak in this region was mostly restricted to the area immediately south of the STF, which resulted in a lower temperature gradient across the STF than in modern times. However, there is no change in Holocene SST south of the polar front. Faunal assemblages suggest an early Holocene meridional expansion of fauna characteristic of the modern subtropical front in the Bounty Gyre. We suggest that such an expansion could be achieved by a reduced inflow of Subantarctic Surface Water into the Bounty Gyre. Results from a modern-analog matching platform called the Past Interpretation of Climate Tool (PICT) suggest that the early Holocene SST is most consistent with reduced westerly winds in the New Zealand sector of the Southern Ocean.

1. Introduction

The midlatitudes of the Southern Hemisphere experienced an early Holocene peak in surface temperature [Leduc *et al.*, 2010; Marcott *et al.*, 2013]: between 11 ka and 7 ka BP, sites located between 30 and 60°S were on average 1°C warmer than present [Marcott *et al.*, 2013]. With increased warming predicted for the end of the 21st century, such records of early Holocene warmth can provide insight into the oceanographic conditions and regional rearrangements of surface currents that may occur with anthropogenic warming in coming decades.

The limited number of high resolution paleotemperature records currently available from the southwest Pacific Ocean reveals a more complex pattern than a homogeneously warmer early Holocene. Sea surface temperature (SST) south of the subtropical front (STF) reached a maximum during the early Holocene [Bostock *et al.*, 2015; Pahnke *et al.*, 2003], while Holocene SSTs immediately to the north of the STF at core site MD97-2121 apparently peaked later, between 10 ka and 4 ka [Pahnke and Sachs, 2006]. This variability of early Holocene warmth in the southwest Pacific across the STF partly correlates with the local variability in insolation [Berger and Loutre, 1991], with a pronounced negative anomaly in December insolation centered on the southern subtropics during the early Holocene. However, southwest Pacific SST evolution through the Holocene does not correlate with local insolation variability, which shows a maximum in the late Holocene, when there is evidence of cooling.

Although there is considerable evidence that the STF is a spatially stable feature east of New Zealand along the crest of the Chatham Rise, these records suggest that during the early Holocene, the SST gradient across the STF (measured between core sites MD97-2121 and MD97-2120) was ~2°C. This gradient is considerably less than the modern gradient between the two core sites across the STF, which is ~6°C. For comparison, the meridional gradient along a similar distance of midlatitude ocean away from fronts is ~4–5°C [Ridgway *et al.*, 2002].

Figure 1. Location map of the southwest Pacific study area, including surface water circulation and core sites. TF = Tasman Front; STF = subtropical front; SAF = subantarctic front; PF = polar front, SACCF = Southern Antarctic Circumpolar Current Front. subtropical surface water (STW) is north of the STF; subantarctic surface water (SAW) is found south of the front [Chiswell et al., 2015; Sokolov and Rintoul, 2002]. Orange represents warmer currents, while blue to purple represent cooler currents.

In this study, we seek to reconcile and understand these paleo-interpretations that are at odds with our understanding of modern circulation, by

1. Documenting the surface circulation east and south of New Zealand during the early Holocene using multiproxy SST records and fossil assemblage based indicators of surface water masses from a meridional transect of high-resolution cores between 36.9°S and 59.6°S;
2. Establishing how spatially heterogeneous temperature anomalies may be reconciled using a paradigm of atmospheric regimes that can be explored using the Past Interpretation of Climate Tool (PICT).

1.1. Modern Oceanographic Setting

The surface circulation of the midlatitudes of the southwest Pacific is complicated by a number of factors, including the complex bathymetry, characterized by a series of submerged ridges and plateaus along with the New Zealand landmass; the interaction between warm waters from the subtropics and cool waters from the Southern Ocean; and the strong influence of the southwesterly winds, which are made up of multiple jets in this region of the world [Bostock et al., 2015; Chiswell et al., 2015]. This combination of factors creates an energetic circulation with strong western boundary currents and fronts [Chiswell et al., 2015].

Northern New Zealand is influenced by warm subtropical waters (STW) that originate from the East Australian Current that flows in from the tropics and down the east coast of Australia (Figure 1). These warm waters flow across the Tasman Sea into the New Zealand region along the Tasman Front, which curves around the east coast of the North Island. As this current interacts with the underlying topography of the Tasman Sea and northern New Zealand, it produces semipermanent eddies [Chiswell, 2005]. The STW flows south along the east coast of the North Island until it reaches the Chatham Rise, whose northern side deflects it eastward [Uddstrom and Oien, 1999] to form the northern boundary current for the STF. A small amount of warm STW, originating from the Tasmanian retroflection, also flows around the south of New Zealand within the STF and heads north along the east coast of the South Island [Chiswell, 1996; Sutton, 2003], before also

Table 1. Core Information, Number of Age Control Data <15 ka, and Number of Sea Surface Temperature Proxies <11.5 ka^a

Name	Latitude	Longitude	Water Depth	Surface Water	¹⁴ C Ages	Tephra	ΔR, Years	11 ka Depth, m	Dinocysts	Foraminifera	Mg/Ca	U ₃₇	Radiolaria
H214	−36.93	177.44	2045	STW	11 ²	3 ²	0	1.15	16 ¹	17 ²			2 ¹
MD97-2121	−40.38	177.99	2314	STW	14 ^{1,3}	8 ³	0	4.08	18 ¹	20 ¹	30 ⁶	102 ⁵	
DSDP594,594B	−45.52	174.95	1204	SAW	6 ^{1,8,3,1}		0	1.64	17 ¹	15 ^{7,1}			
MD97-2120	−45.53	174.93	1210	SAW	10 ⁹		0	0.72			18 ⁹	61 ⁵	
TAN1106-15	−47.39	166.01	2544	STW/STFZ	6 ¹		0	1.97	15 ¹	16 ¹		24 ¹	2 ¹
TAN1106-43	−50.45	164.88	3670	STFZ/SAW	5 ^{1,10}		100	0.8	14 ¹	16 ^{1,10}		24 ¹	10 ¹
TAN1302-96	−59.09	157.05	3544	CSW	3 ¹		200	0.5		4 ¹			20 ¹
E27-23	−59.62	155.24	3182	CSW	22 ¹¹		400	5.26					49 ¹

^aSTW = subtropical surface water, SAW = subantarctic surface water, STFZ = zone of mixing around the subtropical front, CSW = circumpolar surface water. References: 1, this study; 2, Samson *et al.* [2005]; 3, Carter *et al.* [2008]; 4, Skinner *et al.* [2015]; 5, Pahnke *et al.* [2008]; 6, Marr *et al.* [2013]; 7, Wells and Okada [1997]; 8, Barrows *et al.* [2007]; 9, Pahnke *et al.* [2003]; 10, Bostock *et al.* [2015]; 11, Ferry *et al.* [2015].

being deflected eastward along the southern Chatham Rise at 44°S [Uddstrom and Oien, 1999]. However, modern oceanographic measurements of the Southland Current have found it to be predominantly composed of subantarctic waters (SAW) [Sutton, 2003].

The STF marks the northern boundary of the Southern Ocean and separates warm, salty, nutrient-poor STW (0–200 m depth), from fresh, cool, nutrient-rich SAW to the south [Belkin and Gordon, 1996; Nodder and Northcote, 2001]. The STF is characterized by steep temperature, salinity and nutrient (nitrate and phosphate) gradients in the upper 200 m and can range from a broad transition zone in the Tasman Sea to a relatively narrow, well-constrained, front east of New Zealand [Chiswell *et al.*, 2015; Smith *et al.*, 2013]. South and east of New Zealand the STF is strongly controlled by ocean bathymetry, being forced south around the South Island and through gaps in the Macquarie Ridge and Campbell Plateau [Smith *et al.*, 2013] and pinned to the Chatham Rise [Uddstrom and Oien, 1999].

In the Southern Ocean, the flow is dominated by the Antarctic Circumpolar Current (ACC), which flows clockwise around the Antarctic continent and is driven by strong westerly winds between 45°S and 55°S [Orsi *et al.*, 1995]. The ACC is bound to the north by the Subantarctic Front (SAF) and to the south by the Southern ACC Front, with the polar front (PF) positioned in between. Circumpolar Surface Water (CSW) is the prevalent surface water south of the SAF [Chiswell *et al.*, 2015; Sokolov and Rintoul, 2002]. From north to south, each of these fronts marks a distinct decline in sea surface height, temperature, and salinity and an increase in nutrients. As the ACC extends through the full water column depth, these fronts are deflected by the bathymetry as they circumscribe the Southern Ocean, and south of New Zealand they are forced through gaps in the Macquarie Ridge [Sokolov *et al.*, 2006] and south and east around the Campbell Plateau [Neil *et al.*, 2004].

2. Materials and Methods

2.1. Core Sampling and Age Models

Seven core sites, forming a meridional transect from eastern North Island, New Zealand (latitude 36.9°S), to south of the Antarctic Polar Front (59.6°S), were selected. Summary information on each core site is provided in Table 1, and a location map is shown in Figure 1.

The target sample resolution at each core was <500 years between 6 and 12 ka cal yr BP, although sampling was undertaken prior to additional radiocarbon ages being analyzed.

Chronology for each core is based principally on ¹⁴C ages from planktonic foraminifera and tephra where available. In addition to 86 published ages across the cores, 16 new ¹⁴C ages from planktonic foraminifera were obtained for this study. Accelerator mass spectrometry ages were converted to calendar ages before present (BP) by calibration against the Marine13 curve [Reimer *et al.*, 2013] using the open-source software “R” (www.p-project.com) package Bchron [Haslett and Parnell, 2008]. The procedure included correction for regional surface water reservoir ages for the Southern Ocean sites

where $\Delta R > 0$ [Butzin *et al.*, 2005; Stuiver and Reimer, 1993] (Table 1). Tephra previously identified in core H214 [Samson *et al.*, 2005] and MD97-2121 [Carter *et al.*, 2008] were also used to constrain the age models, using updated tephra ages from Lowe *et al.* [2013]. In order to ensure a consistent approach, new age models for each core were developed using the Bayesian age-depth modeling functionality in Bchron. Age/depth models developed for each core are provided in supporting information Figure S1, and age control data are in the supporting information.

Core MD97-2120, from the southern flank of the Chatham Rise, was unavailable for new sampling, so nearby cores DSDP594 and DSDP594B, 31 km west of MD97-2120, were sampled for the new dinocyst and foraminifera data generated for this paper. A splice of the DSDP594-594B cores was made by wiggle-matching magnetic susceptibility measurements from each core, from which a linear relationship of DSDP594 depth = $1.1014 \times \text{DSDP594B depth} - 0.0024$ was extracted, supported by four ^{14}C ages from DSDP594 and three ^{14}C ages from DSDP594B.

Data were collated into an early Holocene time slice of 11.8–9.8 cal ka BP and a mid-Holocene interval of 8–6 cal ka BP, to allow comparison with other regional studies and the global Holocene divisions suggested by Walker *et al.* [2012].

2.2. Sea Surface Temperature Proxies

Due to the considerable spread of the latitudinal gradient, wide range of depositional settings, and variable predictive error of different proxies, mean annual SST was estimated using a range of methods and using a combination of 252 new and 362 published estimates (Table 1). Transfer functions from assemblages included foraminifera (51 new, 90 published samples), radiolaria (73 new samples), and dinoflagellate cysts (80 new samples), $U_{37}^{K'}$ (48 new, 193 published samples), and Mg/Ca measured on planktonic foraminifera *Globigerina bulloides* and *Globigerinoides ruber* (79 published samples). Surface circulation was reconstructed by inferring water masses using fossil assemblages, including foraminifera, radiolaria, and dinocysts.

Each of these proxies has its own assumptions and caveats. We assume that fossilized microfossils are representative of, and inhabited, the same habitats as their living counterparts. Trap experiments demonstrate that most of these organisms flourish in spring or summer, but as seasonal variability is spatially inconsistent and seasonal temperature has comparable predictive success to mean annual temperature in this region because of low seasonality in the training sets, mean annual SST is reconstructed. All the proxies used in this study are trained/calibrated to mean annual temperature; however, we are mindful that offsets between different SST records could represent seasonal biases and also different habitats (i.e., organisms living deeper in the water column). We also assume that there has been limited lateral transport or dissolution of the organic, carbonate, or siliceous remains that may have altered the chemistry or assemblage composition at each core site. By using several proxies, we hope to overcome some of these potential biases in the SST estimates and provide a consensus SST for each core location (see below for the method we used to determine a consensus SST).

Alkenone analysis followed sample processing procedures described in Calvo *et al.* [2003] and Kornilova and Rosell-Melé [2003]. In summary, 3–4 g of freeze-dried sediment were extracted with a dichloromethane/methanol mixture using a Microwave Accelerated Reaction System, model MARS-6. The extracts were then evaporated to dryness under a N_2 stream. Potassium hydroxide in methanol (6%) was used to hydrolyze wax esters and eliminate interferences. After derivatization with bis(trimethylsilyl) trifluoroacetamide, extracts were dissolved in toluene and then injected in an Agilent Series 7890A Gas Chromatograph with a flame ionization detector and equipped with a VF-1 ms capillary column (60 m, 0.25 mm i.d., and 0.25 μm film thickness). Alkenone-derived SSTs were reconstructed using the relationship $U_{37}^{K'} = 0.0709 + 0.0322 \times \text{SST}$ [Conte *et al.*, 2006], and the standard error of estimation is 1.1°C. Additional published data are available for MD97-2121 and MD97-2120 [Pahnke and Sachs, 2006] and were recalculated to the Conte *et al.* [2006] relationship. Coccolithophores, which produce the alkenones, predominantly grow in stratified surface waters and bloom during spring and summer, and thus, alkenone SST are more likely related to spring/summer SST [Sikes *et al.*, 2002, 2005], although the calibration itself is to mean annual temperature.

Planktonic foraminifera census counts were made on the $>150 \mu\text{m}$ size fraction. Mean annual sea surface temperatures were estimated using the modern analog technique, using a 1223-sample training set of core top assemblages [Cortese *et al.*, 2013] and the R package rioja. This transfer function has a root mean square

error of $\sim 1.2^{\circ}\text{C}$ and a root mean squared error of prediction of $\sim 2.1^{\circ}\text{C}$ when the west Pacific samples are excluded and the remainder of the modern data set used for training [Prebble, 2012]. Previously published assemblage data and SST estimates using the modern analog technique and earlier (but substantially similar) versions of the same training set were available for cores H214 [Samson *et al.*, 2005], MD97-2121 [Carter *et al.*, 2008], DSDP594 [Wells and Okada, 1997], and TAN1106-43 [Bostock *et al.*, 2015]. In this region the highest production of foraminifera is in the spring [King and Howard, 2001; Northcote and Neil, 2005; Sikes *et al.*, 2002], and thus, foraminiferal assemblages most likely represent the spring SST (which, given the low variability in seasonality in the region, is the same as the mean annual SST rescaled).

Radiolarian sample processing followed Cortese and Prebble [2015]. For the modern reference data set [Cortese and Prebble, 2015], 243 radiolarian taxa were identified, and their relative abundances were used as input for an Imbrie and Kipp transfer function run with a seven factor model, by using the software package PaleoToolBox [Sieger *et al.*, 1999]. The resulting calibration equation has a standard error of estimate of $\pm 1.3^{\circ}\text{C}$. Sediment trap observations from SAW and STW east of New Zealand indicate highest radiolarian fluxes between August and December in both water masses suggesting these taxa may represent variability during late winter/spring [Prebble *et al.*, 2013a].

Dinoflagellate cysts census counts were made on samples processed using standard Quaternary methods [Mertens *et al.*, 2009]. Mean annual sea surface temperature was estimated using the modern analogue technique, using a 311-sample training set of core top assemblages from the Southern Hemisphere [Prebble *et al.*, 2013b, and references therein], and the R package rioja. This transfer function has a root mean square error of 1.6°C between 10 and 22°C mean annual temperature. Seasonality of dinoflagellate cyst flux varies in the southwest Pacific: while there is a pronounced spring production in STW, seasonal variation is muted in SAW [Prebble *et al.*, 2013a].

Previously published single species Mg/Ca ratios from planktonic foraminifera *G. bulloides* and *G. ruber*, and their corresponding SST estimates, for MD97-2121 [Marr *et al.*, 2013] and MD97-2120 [Pahnke *et al.*, 2003] were also used in the SST compilation. We used the original published data and calibrations.

2.3. Consensus SST From All Proxies

A consensus mean annual SST record was developed for each site by using a Monte Carlo simulation of 1000 iterations around each sample point, based on a normal distribution (the *rnorm* function in R) constrained by the sample-specific age uncertainty from the age-depth model and the proxy-specific temperature errors derived from modern cross-validation observations. For each 500 year bin from 11.5 to 5.5 ka cal yr BP, 1σ and 2σ confidence intervals were calculated for mean annual SST, dividing the number of simulation points by 1000 to obtain the $n - 1$ degrees of freedom. This provides a reliable indication of time intervals and locations that have relatively robust SST reconstructions (i.e., agreement between proxies, well constrained chronology, and densely sampled) compared to those that do not. As well as explicitly considering the known uncertainties in the SST proxies, the advantage of this approach is that it allows clear comparison between core sites with varying precision of age models and between SST proxies of varying quality. One source of bias in this approach arises in the different sample resolution between proxies. For example, at site MD97-2121, there are three to five times more Holocene alkenone measurements (102) than for the other three SST proxies considered (Table 1): clearly, alkenones will have a disproportionate influence on a consensus estimate. We assess the extent to which this effect influences our conclusions in two ways: by examining proxy-specific box plots of the SST and also by considering proxies separately and in combination during the PICT analysis (both described below).

To compare the early Holocene SST estimates with modern gradients, mean annual SST ± 1 sigma was extracted using the 2D extrapolation function in the World Ocean Atlas of a weighted-average grid from the CSIRO 2009 Atlas of Regional Seas [Ridgway *et al.*, 2002].

2.4. Water Mass Proxies

In addition to SST, fossil assemblages were also used to infer the relative contribution of different surface water masses at the core sites through time. This is arguably a more robust approach than extracting a single environmental variable (e.g., SST) from a fossil assemblage. It acknowledges that variation of biological assemblages correlate to a range of environmental gradients, for example, temperature, nutrients, mixing, and seasonality of production. It is the combination of these factors that distinguishes surface water

masses and controls the biological assemblages within them. As the modern distribution of each subfossil group has been described using different methods, slightly different metrics have been necessarily adopted to identify species assemblages as suitable water masses proxies. Nonetheless, all microfossil groups include assemblages which can be used as proxies for STW, SAW, mixed water associated with the zone about the STF, and CSW [Cortese and Prebble, 2015; Prebble *et al.*, 2013b; Scott, 2013].

Foraminiferal species abundances for all assemblages compiled in this study were linked to water masses by using a Random Forest decision matrix from R package “randomForest” to assign each fossil assemblage to one of five spatially coherent assemblage clusters observed in core top samples east of New Zealand [Scott, 2013]. For radiolaria, factor analysis is used to assign each sample to modern clusters observed to have distributions corresponding to surface oceanography in the New Zealand region [Cortese and Prebble, 2015]. For dinoflagellate cysts, a nearest-neighbor match using the chord dissimilarity index in the R software package rioja was used to assign each fossil assemblage to one of the four assemblage clusters observed in core top samples around New Zealand [Prebble *et al.*, 2013b, 2016], by selecting the five most similar modern samples.

2.5. Comparison With PICT Spatial Field Analyses

2.5.1. Principles of PICT

The Past Interpretation of Climate Tool (PICT; <http://pict.niwa.co.nz/>) is a research platform that allows paleoclimate data to be integrated and interpreted in an atmospheric circulation regime context [Lorrey *et al.*, 2014]. PICT relies on basic principles that are contained in a low-order climate model for the Pleistocene, in which multiple forcing factors working in unison (such as insolation, solar variability, greenhouse gases, volcanism, land-cover, and low-frequency atmospheric regimes) all contribute in different proportions to the mean climate state [Maasch and Saltzman, 1990]. By changing the frequency of atmospheric circulation regimes through time, but holding all other forcing factors constant, the local surface climate may be pushed toward a different climatic outcome (e.g., wetter/drier, cooler/warmer, and windier/calm) [Jiang *et al.*, 2013; Lorrey *et al.*, 2007, 2008]. The basis for PICT relies on those fundamentals and is supported by modern climate analyses [Lorrey *et al.*, 2007, 2008] that show atmospheric circulation changes generate spatially distinct, long-term surface climate shifts [Lorrey *et al.*, 2007]. PICT relies on spatiotemporal stability of local surface climate responses to incident circulation. Physical processes that are linked to atmospheric circulation (like advection, orography, and wind stress) generate specific outcomes at a site, despite the relative waxing and waning proportional influence of climate that contribute to macroscale circulation phenomena (e.g., El Niño–Southern Oscillation, Southern Annular Mode, and Interdecadal Pacific Oscillation). For time intervals older than late Holocene, and where seasonality may be influential on a type of proxy, radiative forcing needs to be accounted for before the contribution of atmospheric circulation to past surface temperature can be isolated. In this study, we assume that the radiative forcing and other forcing factors had nominal influences on the change from the early to mid-Holocene.

2.5.2. PICT Operational Details

The PICT uses modern climate reanalysis data for the last ~40 years to find “closest matches” to the paleoclimate data that are fed into the platform. First, a palaeoclimate anomaly (calculated with respect to modern day) is entered into the PICT platform with other site metadata (location, type of proxy archive, seasonal response to climate, etc). Second, the gridded modern climate reanalysis data for the paleoclimate site are detrended, and the modern analog years that most closely match the paleoclimate anomaly are selected (typically 7 or 8). Third, the associated reanalysis spatial field patterns for each of the selected analog years are composited into an average field pattern (using inverse distance weighting). PICT produces spatial field composite patterns for near surface atmospheric pressure, mid-atmosphere pressure, sea surface temperature anomalies, meridional wind, and zonal wind. These composite field plots can then be used to illustrate what mean annual climate conditions were associated with specific palaeoclimate anomalies at a given site.

While PICT was originally constructed as a tool to explore terrestrial climate proxies from the New Zealand landmass [Lorrey *et al.*, 2014], a recent upgrade including marine reanalysis data offers the opportunity to use proxies of sea surface conditions as an input. Thus, this study represents the first application of PICT using marine paleoclimate data. The modern marine climate time series used to calibrate the early to mid-Holocene change was the Extended Reconstructed Sea Surface Temperature (ERSST) v4 gridded reanalysis data set including years between 1972 and 2014 [Huang *et al.*, 2015].

The PICT can be used in several ways to examine past circulation using surface temperature proxies. One way is to develop a paleoclimate time slice where the paleo-anomalies are expressed relative to modern conditions [see example in *Lorrey et al.*, 2014]. An alternative way is to compare the differences (i.e., the change) between two consecutive time slices. We use the latter approach in this study, where the difference in surface temperature between the early and mid-Holocene was fed into PICT to characterize past change.

To prepare the paleo-SST data for PICT, we calculated each reconstruction SST (expressed as an anomaly from modern) for an early Holocene (11.8–9.8 ka) and a mid-Holocene (8–6 ka) time slice. Next, we calculated the SST change between those two time slices (early Holocene time slice mid-Holocene time slice) to represent the surface climate shift at each site from the early to mid-Holocene. These derived values were fed into the PICT platform along with site metadata.

2.5.3. Interpretation of Wider Spatial Fields Using PICT

One strength of PICT is that it allows inferences to be made about the regional or hemispheric climate systems, using a local-scale network of paleodata. To do this, PICT employs a series of statistical analyses [*Lorrey et al.*, 2014] that are applied to the mean spatial field patterns to produce confidence intervals that indicate how well the selected analog years match each other and over what spatial regions they match best. The output of this statistical analysis is an illustration of areas where past anomalies are significantly different from that expected by random chance. See *Lorrey et al.* [2014] for more details.

We employed PICT outputs to interrogate our SST proxy data in three ways:

1. To establish the regional and hemispheric climate patterns that best match the change in proxy data, we observe between early and middle Holocene time,
2. To establish whether there is a significant difference in PICT outputs due to proxy type or marine sediment core location (i.e., comparing results constrained by single proxy types (e.g., only alkenone SST estimates), with the consensus reconstructions), and
3. To establish the extent to which early to mid-Holocene change from other independent paleorecords across the Southern Hemisphere reveals change consistent with that “predicted” by the PICT output.

3. Results

3.1. Sea Surface Temperature

Individual and consensus SST and water mass proxy results for 12–6 ka cal yr BP for each site are shown in Figure 2. At site H214, the consensus SST estimate showed a slightly higher temperature prior to 11 ka cal BP compared to the following 5 kyr. This pattern was driven by a pronounced peak in foraminiferal SST estimates of 19°C prior to 11 ka cal BP. In contrast, the dinoflagellate cyst SST estimates were ~17°C for H214 and varied by less than 0.5°C, indicating that the early Holocene was no warmer than the mid-Holocene period.

The consensus SST estimate at site MD97-2121 showed a cooler (<16°C) early Holocene prior to 11.5 ka cal BP, followed by a gradual rise to a peak of almost 18°C between 9 and 7 ka cal BP. At the scale of the 500 year time slices, the structure of the consensus SST estimate was strongly influenced by the high resolution U^{K}_{37} -SST record at MD97-2121, which had a similar number of estimates to the other five SST proxies combined (~70). The main departure from the U^{K}_{37} -SST record in the consensus stack was the absence of the brief SST peak at 9 ka cal BP. The four non-alkenone SST estimates were highly variable: while the range of U^{K}_{37} -SST estimates between 12 and 6 ka cal BP was only 2.2°C, dinoflagellates and foraminifera had a range of 4.1°C and 4.7°C, respectively, and the Mg/Ca SST estimates had ranges of 5.2°C and 6.9°C from *G. ruber* and *G. bulloides*, respectively.

South of the STF, the consensus SST estimate at sites MD97-2120 and DSDP594 indicated a cooling from ~13°C prior to 11.5 ka cal BP to ~11°C by 8.5 ka cal BP. As with site MD97-2121, this pattern was strongly influenced by a relatively high-resolution U^{K}_{37} record from MD97-2120, but Mg/Ca ratios from *G. bulloides* also indicated a relatively warm early Holocene. In contrast, SST estimates from dinoflagellates and foraminifera from site DSDP594 did not indicate significant SST changes between 12 and 6 ka cal BP.

Although almost 2° south of DSDP 594/MD97-2120, due to the complex surface ocean circulation around New Zealand (Figure 1), site TAN1106-15 is within the present day subtropical frontal zone and relatively close to the coast compared to the other core locations. A relatively wide spread of ~3°C (95% range; Figure 2) was observed between the three SST proxies from this site. SST estimates from dinoflagellates

Figure 2. Sea surface temperature and surface water mass indicators from faunal assemblages for or the time interval 12–6 ka. (a) Sea surface temperature proxies are as follows: circle = foraminifera assemblages, triangle = dinoflagellate cyst assemblages, + = Mg/Ca from *G. bulloides*, x = Mg/Ca from *G. ruber*, diamond = $U^{K_{37}}$, down triangle = radiolarian assemblages. Consensus SST estimates (method discussed in text) are shown in gray bands, 1 sigma = dark gray, 2 sigma = light gray. (b) Surface water mass indicators from radiolaria, foraminifera, and dinoflagellate cyst assemblages. Vertical color bars on the far right indicate the modern (core top) affinities for each fossil group at each site. Color codes approximately align to STW = orange, STF/Bounty Gyre = green, SAW = blue, CSW = gray, but for actual distributions see maps in Figure 4. The pink vertical bars show the 500 year time slices sampled for Figure 4, and the wider peach vertical bars show the 2000 year time slices 11.8–9.8 ka and 8–6 ka sampled for PICT analysis.

suggest a relatively warm early Holocene, up to 2–3°C above mid-Holocene SSTs. $U_{37}^{K'}$ -SSTs suggest a slightly warmer early Holocene, while foraminifera and the consensus SST estimate did not indicate significant SST changes over the 12–6 ka time interval.

All three SST proxies (foraminifera, $U_{37}^{K'}$, dinoflagellates) at site TAN1106-43 indicated a warmer early Holocene, with the consensus SST estimate being approximately ~1°C higher prior to 9.5 ka cal BP than the following 4 kyr. Radiolarian estimates were available for two samples (at 8.3 and 11.2 ka cal BP), both suggesting an SST of 11.2°C, in line with the consensus estimate.

Radiolarian data from both CSW sites TAN1302-96 and E27-23 show very low variability, as SSTs remain within approximately 0.6°C of the average for the whole interval (1.3°C): within the calibration error of the transfer functions. The consensus SST estimates showed no temperature change between early and late Holocene time.

3.2. Water Mass Proxies

At site H214, foraminifera and dinoflagellate assemblages showed a consistent affinity to STW between 12 and 6 ka cal BP (Figure 2). The two radiolarian assemblages available from the mid-Holocene are similar to modern core top assemblages from the area, although with a SAW influence in one sample.

More variability was observed at site MD97-2121. Foraminiferal assemblages were consistent with STW, with the exception of a single sample at 10.5 ka cal BP where an assemblage similar to those today found south of the Chatham Rise was observed. During this time interval, the background dinoflagellate assemblage displays STF affinity, but a STW dinoflagellate cyst assemblage, similar to those found north of the site today, makes its first appearance.

Site TAN1106-15, situated within the modern STF, had foraminiferal and dinoflagellate cyst assemblages consistent with STF affinity between 12 and 6 ka cal BP. In addition to the STF affinity, one foraminifera sample at 11.5 ka cal BP had an assemblage similar to modern STW, and a second sample at ~7750 yr cal BP had an assemblage similar to modern SAW. Prior to ~9800 yr cal BP, dinoflagellate cyst assemblages had greatest similarity to modern STW assemblages. Following this time interval, most samples had modern SAW assemblages.

South of the STF, the 10.5–9.5 ka cal BP interval is also characterized by a departure from modern conditions at sites MD97-2120 and DSDP594. While foraminiferal assemblages showed a consistent STF affinity for the entire early to mid-Holocene, which is the same as observed in core tops in the area, three dinoflagellate cyst samples assemblages indicated a reduced SAW and increased STF influence compared to the present over this time interval, while the SAW influence was predominant for dinoflagellate cyst assemblages over the remainder of the record.

Although radiolarian assemblages were not sufficiently abundant for SST reconstruction at site TAN1106-43, samples with a census count of >100 specimens have been used for surface water assessment. Factor analysis indicated a reduced affinity to modern CSW (and increased STW affinity) prior to ~10 ka cal BP, compared to middle Holocene samples. The dinoflagellate cyst record had samples with SAW affinity between 12 and 6 ka cal BP, with two samples, at 8.5 ka cal BP and 10.25 ka cal BP, also showing STF affinity. The foraminiferal assemblages from the site showed alternating affinity, between STF and SAW.

Radiolaria assemblages at sites TAN1302-96 and E27-23 showed unchanged affinity between 12 and 6 ka cal BP, with a similarity to modern CSW assemblages.

3.3. PICT Results

PICT results constrained by all 19 available SST proxies showed a distinct split between two circulation regimes, with the modern analog years selected for one (majority) group of proxy time series significantly different to another (minority) group (Figure S2a). Although all proxies indicated a significant change in southwesterly flow over New Zealand occurred from the early to mid-Holocene, 13 of 19 proxies indicated significant increases, while the remaining 6 of 19 proxies indicated significant decrease (Figure S2a). The proxies whose modern analogs are consistent with an increase in southwesterly flow between early and mid-Holocene time likely reflect the change in the latitudinal temperature gradient that is observed from the SST reconstructions, which would have altered the geostrophic winds, the position of the circumpolar jet and the midlatitude steering winds, and therefore also synoptic type occurrences. Rather than

Figure 3. Outputs from the PICT analysis, constrained by the 13 SST proxies that showed alignment (discussed in text). The figures show the reconstructed *change* in climate parameters between the early Holocene (11.8–9.8 ka cal BP) and mid-Holocene (8–6 ka cal BP) time slices. For example, a negative change in SST indicates a cooling between the early to mid-Holocene (i.e., a relatively warm early Holocene). (a) Change in geopotential height at 1000 hPa (approximately sea level) between early and middle Holocene. (b) Change in mean annual SST between early and middle Holocene. (c) Change in zonal wind speed at 850 hPa (approximately 1.5 km altitude). Locations of comparison paleoclimate data mentioned in the text are shown in Figures 3b and 3c, while red polygons on maps enclose areas where consensus between analog years selected by PICT exceeds 95%; i.e., areas where there is high confidence that the output is a consistent match with the constraining proxy data.

attempting to reconcile these conflicting results, we conducted a second experiment of PICT analysis that is constrained only by the 13 “majority” proxies identified above for the analysis in the following section (and Figure 3), to determine if this produced a clearer result.

The PICT results that contrast our early and mid-Holocene time slices suggest significant changes in the atmospheric pressure and SST across the Southern Hemisphere developed from the early to mid-Holocene (Figure 3). The key changes in atmospheric pressure from early to mid-Holocene includes an increase in the frequency of “lows” to the south of New Zealand and in the southern Indian Ocean, and an increase of “highs” to the south of Australia (Figure 3a). The decrease in SST in the ocean around New Zealand to the south of the STF is observed in the PICT results (from the data in this study) and is accompanied by a large area of warming (i.e., cooler early Holocene) south of Australia and in the ocean east of New Zealand. An increase in westerly circulation anomalies in the New Zealand sector between 40 and 65°S (i.e., a less wind early Holocene) and a decrease in westerly circulation south of Australia are also evident in the PICT output (Figure 3c). It is important to note that the anomalies in westerly circulation were generally not significantly different from normal for most of the Southern Hemisphere: i.e., there are only small areas in which there is strong consensus between the selected analog years that have been combined to make the mean spatial field pattern (Figure 3c).

3.4. Proxy-Specific Influence on Consensus SST and PICT Results

The multiproxy consensus approach we have taken is susceptible to bias arising from the uneven sampling density of different proxies at some sites. There is also the possibility of other forms of bias, for example, arising from seasonal differences or variable taphonomy

between proxies. This could result in proxy estimates of SST that represent samples of different seasons or spatial areas of the surface ocean. We consider the degree to which the various SST proxies align, where SST is plotted as anomalies from present mean annual temperature for the 11.8–9.8 ka cal BP and 8–6 ka cal BP time intervals (Figure S4). We find that the consensus SST from each site is shown to overlap the 25th and 75th percentile range of each proxy type, with only two exceptions. The exceptions are the SST estimates using foraminiferal assemblages from site TAN1106-15, which are cooler than the consensus for both the early and mid-Holocene. We conclude that in most cases, the variability within the proxies is at least as great as that between them. Inspection of Figure S4 indicates that there does not appear to be any one proxy type (due to either uneven sampling effort or other reasons) that has contributed a consistent bias to the consensus SST estimates (i.e., always colder or warmer than the consensus).

We observed a similar outcome in our PICT analysis. Different circulation patterns do not arise due to proxy type, or the spatial location of the proxy data. The PICT outputs generated solely using foraminifera, solely using dinoflagellates, and solely using alkenone SST reconstructions show coarsely similar spatial patterns for the early to mid-Holocene changes in geopotential height, SST patterns, and wind flow anomalies (albeit with confidence interval differences that can be seen across the fields and overall climate changes that are generally weak; Figures S3b–S3d). The highest levels of confidence between the three proxy-specific ensembles (alkenones, dinoflagellates, and foraminifera) were observed for an increase in geopotential height south of Australia and in the Southern Indian Ocean, an increase in mean annual SST in the Indian Ocean sector of the Southern Ocean, and a cooling south of New Zealand (Figures S3b–S3d).

In the PICT analyses constrained by individual proxy types, the strongest spatial coherency (and largest geographical areas of high confidence) was observed for reconstructions based on foraminifera (four of five sites), followed by alkenones (three of four sites), then dinoflagellates (three of five in agreement; Figures S3b–S3d).

4. Discussion

4.1. Two Modes of Ocean Circulation

Inspection of latitudinal gradients from the consensus SST records generated in this study reveals two “modes” during the interval 12–6 ka cal BP (Figures 4 and S5).

The first mode, between 12 and 9 ka cal yr BP, is characterized by (1) SSTs within the modern range at all sites north of the STF, (2) higher than present SST at the three STF/SAW sites (MD97-2120, TAN1106-15, and TAN1106-43), and (3) SST within modern conditions at the two CSW sites (TAN1302-96 and E27-23).

In the second mode, between 9 and 6 ka cal yr BP, the consensus SST for all sites is within the modern range, with the exception of SAW site TAN1106-43, which was likely warmer than present, (i.e., outside the 1-sigma error range).

The latitudinal SST values and surface water circulation of two 500 year time slices representative of these two modes are illustrated in Figure 4.

Although the reconstructed SST north of the STF between 12 and 9 ka cal yr BP was within the modern range, the latitudinal SST gradient between MD97-2121 to the north and TAN1106-43 to the south of the STF (covering at least 8° of latitude) was as small as 3–4°C (compared to modern observations of a gradient of 5–8°C). This expanded area of relative warmth and subdued latitudinal gradient compared to present around the STF was accompanied by an expansion north and south of faunal associations representative of the STF and Bounty Trough region. Figure 4b shows that one sample with foraminiferal assemblages similar to those found in the modern Bounty Gyre was seen north of the STF during this interval, while Figure 4c shows dinoflagellate cyst assemblages in northern SAW most similar to those found beneath modern STF/STW of the Canterbury Shelf, east of the North Island of New Zealand. Finally, factor analysis of early Holocene radiolarian samples from SAW site TAN1106-43 shows greater similarity to assemblages today found north of the STF east of the New Zealand (Figure 4d).

The latitudinal SST gradient of the second “mode,” between 9 and 6 ka cal yr BP, is very similar to the modern latitudinal SST gradient, with the exception of warmer than present conditions at one southern STF/northern SAW (Site TAN1106-43). Compared to the early Holocene, the latitudinal temperature gradient across the STF during the middle Holocene was steeper. The distribution of foraminiferal assemblages at all sites were more

Figure 4. (left) Latitudinal transect of SST for two 500 year time slices: (a) 11–10.5 ka cal yr BP and (e) 8–7.5 ka cal yr BP, compared to modern mean annual SST. Light gray ribbons in Figures 4a and 4e are modern SST, while dark gray ribbons are 1 sigma paleo SST estimates from Figure 2. Particular anomalies of interest discussed in the text are highlighted in red boxes. Core sites in SST plots are shown in degrees north STF [Orsi *et al.*, 1995], to rank sites in order of decreasing SST, which in this region is not aligned with latitude. Right: Sea surface indicators from fossil assemblages for the same two time intervals compared to modern core top assemblages. For all sea surface water mass indicators, fossil time slice assemblages are shown in colored rectangles, over the modern core top conditions which are shown in polygons. Color codes approximately align to STW = orange, STF/Bounty Gyre = green, SAW = blue, CSW = gray. (b, f) Foraminifera surface water indicators. (c, g) Dinoflagellate cyst surface water indicators. (d, h) Radiolarian surface water indicators.

similar to modern core tops during this time than during the early Holocene, with no Bounty Gyre assemblages observed north of the STF (Figure 4f). Dinoflagellate assemblages are also very similar to modern (Figure 4g), with the main departure from modern being a southward extension of northern assemblages, currently found around site H214, observed at site MD97-2121.

The concentration of warmth south of the STF during the early Holocene and the concurrent spatial expansion of Bounty Gyre/STF faunal assemblages imply a regional surface water circulation different from the present. Our preferred conceptual model is for reduced flow of SAW across the Pukaki Saddle into the Bounty Trough during this early Holocene interval (Figure 5, right) compared to present times (Figure 5, left). This reduction in the flow of colder water into this area would have had the effect of reducing the thermal gradient across the STF, allowing meridional expansion of the Bounty Gyre/STF faunal assemblages, creating the more diffuse STF, as previously suggested by Bostock *et al.* [2015].

Reduced inflow of SAW into the Bounty Gyre was likely caused by some combination of southward migration, or reduced velocity, of the northern ACC flow in this sector, which in turn would reflect reduced westerly wind intensity in that area. Unfortunately, there is a gap in our core transect as no cores have been collected between the SAF and PF due to erosion of sediment in this region by the strong currents associated with the ACC and the complex, restrictive, bathymetry of Macquarie Ridge and Campbell Plateau [Carter and McCave, 1997].

This reduction in frontal gradients appears to be in contrast to the west Tasman Sea, where it appears that the STF was forced south by invigoration and southward extension of the East Australian Current during the early Holocene [Bostock *et al.*, 2006; Sikes *et al.*, 2009]. It is interesting to note that early Holocene warming is not observed around the PF in the southwest Pacific in this study (Figure 2), given the pronounced early Holocene warmth we report at the STF to the north and early Holocene warmth reported from around Antarctica, including the Antarctic Peninsula [Mulvaney *et al.*, 2012; Shevenell *et al.*, 2011] and the Ross Sea [Masson *et al.*, 2000].

Figure 5. (left) Cartoon of modern circulation, (right) compared to our conceptual model of surface water circulation during the early Holocene, showing reduced inflow of SAW into the Bounty Gyre (BG), reduced intensity of flow along the SAF, and expanded zone of STF mixing.

4.2. Early to Mid-Holocene Circulation Change Using PICT

Our conceptual model of circulation change between the early and middle Holocene of elevated SST south of the STF during the early Holocene, associated with reduced westerly wind intensity in that area, is supported by the PICT results. We explore the following visualizations from PICT: geopotential height anomalies (Figure 3a), the SST anomalies (Figure 3b), and the zonal wind speed changes (Figure 3c).

The relative position of the “anticyclonic” geopotential height anomalies (Figure 3a) of more frequent “highs” south of Australia and more “lows” southeast of New Zealand during the mid-Holocene compared to early Holocene time would have promoted an increase in southerly quarter flow across the New Zealand region. The resulting wind stress would have increased transport of anomalously cooler southern waters into the Tasman Sea sector by mid-Holocene time and shifted oceanic fronts in that region northward (or condensed them). The increased westerly flow across the region south of the South Island between early and mid-Holocene time (Figure 3c) would also have had an impact on increasing the vigor of the ACC in the southwest Pacific sector of the Southern Ocean.

The PICT SST anomaly results (Figure 3b) are consistent with proxy data, showing a cooling in the New Zealand region and south into the Southern Ocean between early and mid-Holocene time (i.e., a warmer early Holocene) in the area. Although the northern spatial extent of the early Holocene warm anomaly, along the East Coast of New Zealand north of the modern STF, covers a larger geographical area than seen in our SST results (Figure 4a), the faunal assemblage water mass indicators (Figures 4b and 4c) suggest that anomalously warm conditions extended north of the STF during the early Holocene.

The changes in zonal wind speed in the ocean around New Zealand suggested in the PICT results, where lower zonal wind speed occurred during the early Holocene relative to the mid-Holocene (Figure 3c), are consistent with our hypothesized mechanism for the surface circulation we have inferred from the SST proxy records. This pattern is clear in the PICT results, both for the analyses constrained by individual proxy types (Figures S3b–S3d) and the multiproxy ensemble runs (Figure S3a). However, as has been noted above, the inferred changes in zonal wind speed are statistically significant over only limited geographical areas.

4.3. Comparison of PICT Results With Data From the Southern Hemisphere

We explored the degree to which the changes between early and mid-Holocene time as indicated by PICT were consistent with other Southern Hemisphere proxy data. The PICT outputs suggest there is spatial variability in the change of westerly wind intensity between the early and mid-Holocene. Can these

heterogeneous patterns help to reconcile conflicting results from previous regional studies of the early Holocene? To some extent, they do. Foraminiferal assemblages from site MD03-2611 suggest a stronger Leeuwin Current, consistent with stronger early Holocene westerlies in the Australian sector [Moros *et al.*, 2009], which is consistent with the PICT results (Figure 3c). On the western margin of South America, the PICT results suggest the change in wind intensity varied with latitude along the continent, from a decrease (i.e., windier early Holocene) in the south and a weak increase to no change further north (Figure 3c), while a decrease in wind intensity is predicted for the central Pacific Ocean and west Atlantic. Moreno *et al.* [2010] interpret westerly wind intensity minima between 7.8 and 1.5 ka BP from their sites on the western margin of South America. However, the indices they derive for wind intensity either side of that minima, which occurs between the two time slices reconstructed in this study, have similar values. In other words, a PICT result of “no change” is consistent with their data. In contrast, Lamy *et al.* [2010] suggest a decrease in westerly wind intensity on the western margin of South America between the early and mid-Holocene, which is consistent with the PICT results. Finally, in the western South Atlantic, stable isotope data from foraminifera have been used to suggest a gradual poleward movement of westerly winds of about 1–1.5° from the early to the mid-Holocene, a change not observed in the PICT output [Voigt *et al.*, 2015]. It is worth noting that the changes in wind intensity across southern South America predicted by the different PICT analyses are variable (i.e., Figure S3), and we have used no South Atlantic data in our analysis. While we see consistent changes in predicted wind intensity in the southwest Pacific between the different PICT analyses generated in this study, the signal is considerably less consistent far from the constraining proxy sites, such as in the east Pacific and Atlantic (Figures 3 and S3).

We also tested the consistency of the early to mid-Holocene SST correlations identified by the PICT platform, by comparing regions of SST anomalies from the model output with independent proxy records from around the Southern Hemisphere. The direction of change between early and mid-Holocene for most proxy data we compiled from across the Hemisphere matches the pattern predicted by PICT generated from our seven New Zealand core sites (Figure 3b). South of Australia, early Holocene SSTs are cooler than mid-Holocene at site MD03-2611 [Calvo *et al.*, 2007] and in three of the four SST proxies presented from core site MD06-2607 [Lopes Dos Santos *et al.*, 2013]. East of southern Africa, SSTs at site GeoB12615-4 show no significant change [Romahn *et al.*, 2014], while the nearby WIND-28k core shows slightly higher SSTs during the early Holocene than mid-Holocene [Kiefer *et al.*, 2006] in disagreement to the change predicted by PICT (Figure 3b). No records were found showing the early to mid-Holocene SST change within the central Pacific sector delimited in Figure 3b, and although difficult to compare directly, palm pollen from an Easter Island lake record indicates a warmer early Holocene than mid-Holocene [Cañellas-Boltà *et al.*, 2016]. Finally, SST estimates from site MD88-770 in the southeast Indian Ocean do not show a clear change between early and mid-Holocene [Barrows *et al.*, 2007], despite a prediction of warming in the PICT output. Thus, while the PICT tool provides some insights on the climate mechanisms behind the observed paleoclimate patterns in space and time, there is still some disagreement between proxy records and the SST and circulation patterns generated using PICT. Generally, the disagreements in PICT outputs seem to become more pronounced with increased geographical distance from the input data. As such, a larger PICT analysis inclusive of more widely spaced data may yield more coherent results from which hemispheric-scale spatial heterogeneity could be interpreted with greater confidence.

5. Conclusions

In this study, we documented surface ocean temperatures east and south of New Zealand during the early Holocene using multiproxy SST records and fossil-assemblage indicators of surface water masses.

Multiproxy mean annual SST estimates from five different SST proxies confirm the previous observations that an early Holocene warm peak in the region of New Zealand was mostly restricted to the area immediately south of the STF. This appears to have resulted in a lower temperature gradient across the STF during the early Holocene. South of the PF, there was no change in SST observed in our data.

Faunal assemblages suggest that warmer conditions in this area were accompanied by meridional expansion of fauna characteristic of the modern STF and the Bounty Gyre. We suggest that such an expansion of faunas with these surface water affinities could be achieved by a reduced inflow of SAW across the Pukaki Saddle

into the Bounty Gyre. This was likely caused by a combination of southward migration, or reduced intensity, of the northern ACC flow in this sector.

Results from PICT suggest that the SST pattern observed during the early Holocene is consistent with reduced westerly winds in the New Zealand sector of the Southern Ocean. The PICT interpretations are largely, although not completely, consistent with SST proxy data from other regional studies of early to mid-Holocene climate, which might contribute to future PICT analyses covering a larger geographical area.

We find no evidence for a spatially widespread climatic optimum during the early or mid-Holocene in the southwest Pacific. Changes in westerly winds, and SST, likely varied across the region, and the Southern Hemisphere, through the Holocene.

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