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Reconstructing 20th century SST variability in the southwest pacific: A replication study using multiple coral Sr/Ca records from New Caledonia

Kristine L. DeLong
University of South Florida

Reconstructing 20th Century SST Variability in the Southwest Pacific:

A Replication Study Using Multiple Coral Sr/Ca Records From New Caledonia

by

Kristine L. DeLong

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Major Professor: Terrence M. Quinn, Ph.D.
Benjamin P. Flower, Ph.D.
David J. Hollander, Ph.D.
Gary T. Mitchum, Ph.D.

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ABSTRACT

Coral-based climate reconstructions typically have not used multiple cores from a region to capture and replicate a climate signal largely because of concerns focused on coral conservation, analytical expense, and time constraints. Coral Sr/Ca reproducibility through the 20th century was investigated using three intra-colony and three inter-colony coral records, from the reefs offshore of Amédée Island, New Caledonia. Different sampling resolutions were examined in coral Sr/Ca (fortnightly and monthly) and $\delta^{18}O$ (fortnightly, monthly, and seasonally) as well as similar scale subsampling of the daily in situ SST record. The mean coral Sr/Ca, $\delta^{18}O$, and daily SST values do not change as a function of sampling resolution. The coral Sr/Ca signal is highly reproducible; the average absolute offset between coeval Sr/Ca determinations between any two coral Sr/Ca time series is 0.036 mmol/mol (~0.65 ºC), which is less than twice the analytical precision of the coral Sr/Ca measurements. The stack average of the monthly coral Sr/Ca

variations and monthly anomalies are significantly correlated with monthly in situ SST (r = -0.95, -0.56, respectively, $p < 0.05$, n = 304) for the period 1967 to 1992 and monthly 1º gridded SST data product (r = -0.95, -0.53, respectively, $p < 0.05$, n = 1198) for the period 1900 to 1999. The coral Sr/Ca-SST reconstruction exhibits decadal-scale fluctuations that exceed those observed in the gridded SST time series, which may reflect true differences between the SST at a shallow reef site and those averaged over a 1º-grid box or they may reflect inadequacies in the methodology used to create the gridded SST product when few observations are available. A warming trend of ~0.6 ºC is observed in the coral Sr/Ca-SST record. Monthly coral Sr/Ca records and seasonally resolved coral $\delta^{18}O$ record from this site share variance in the latter half of the 20th century, but not in the early 20th century, suggestive of a change in seawater $\delta^{18}O$.

1. Introduction

Coral scleroclimatology, the use of corals as a proxy indicator of climate variability [*Gagan, et al.*, 1997; *Cronin*, 1999], is a relatively young field of study compared to the century-old study of climate using tree rings (i.e., dendroclimatology) and these two fields of study share many similarities. A record of climate variation can be reconstructed from trees and massive corals because many tree species and massive corals have long life spans that often exceed 100 years, both have growth recorded in annual bands, both are amenable to absolute dating by counting annual growth bands, and both are amenable to geochemical studies. These two climate proxies have successfully been used to generate climate records that are highly resolved (≤1 year) and span many centuries. The similarities between coral scleroclimatology and dendroclimatology have lead to the suggestion to apply proven tree-ring methodologies to coral-based studies in order to improve coral-based climate reconstructions [e.g., *Dunbar and Cole*, 1992; *Briffa*, 1995; *Cook*, 1995; *Barnes and Lough*, 1996; *Dunbar and Cole*, 1996; *Druffel*, 1997; *Lough and Barnes*, 1997; *Crowley, et al.*, 1999; *Trenberth and Otto-Bliesner*, 2003; *Lough*, 2004]. However, the straightforward application of tree-ring methodologies to coral-based climate reconstructions has limitations. Dendroclimatologists have relatively open access to their proxy, relatively uncomplicated sampling procedures, and relatively economical analytical expenses; whereas, scleroclimatologists have limited access to their proxy on account of coral conservation concerns, challenging sampling procedures due to the coral's habitat, and analytical limitations owing to geochemical analysis expense and time constraints. Despite these challenges, paleoclimatologists have begun to apply methodologies from dendroclimatology to coral-based climate reconstructions. Initial applications of four standard tree-ring methodologies in coral studies include: 1) chronology verification using cross-dating of concurrent records [e.g., *Dodge and Lang*, 1983; *Cole, et al.*, 1993; *Guilderson and Schrag*, 1999; *Linsley, et al.*, 1999; *Linsley, et al.*, 2000; *Urban, et al.*, 2000; *Hendy, et al.*, 2003; *Linsley, et al.*, 2006]; 2) merging of successive individual coral records into one extended record [e.g., *Dunbar, et al.*, 1994; *Cobb, et al.*, 2003b]; 3) calibration-verification of the coral climate signal reconstruction [e.g., *Crowley, et al.*, 1999; *Quinn and Sampson*, 2002; *Stephans, et al.*, 2004; *Ourbak, et al.*, 2006; *Smith, et al.*, 2006]; and 4) the replication of coeval records to verify a common climate signal between records [e.g., *Cole, et al.*, 1993; *Tudhope, et al.*, 1996; *Felis, et al.*, 2003; *Stephans, et al.*, 2004; *Linsley, et al.*, 2006].

The establishment of an accurate chronology is essential to any paleoclimate reconstruction whether the chronology is for a single coral core or many cores spanning centuries. *Knutson et al.* [1972] recognized annual density bands in the X-radiographs of massive corals and suggested the use of massive corals as proxy climate recorders. Typically, coral chronologies are established by counting the annual density bands visible in X-radiographs and verified against either 1) the annual cyclicity in skeletal geochemistry ($\delta^{18}O$, $\delta^{13}C$, or Sr/Ca) [e.g., *Dunbar, et al.*, 1994; *Linsley, et al.*, 1999]; 2) applicable climate indices such as the Southern Oscillation Index (SOI) and El Niño-Southern Oscillation (ENSO) [e.g., *Guilderson and Schrag*, 1999; *Cobb, et al.*, 2003b]; or 3) records of volcanic eruptions [e.g., *Crowley, et al.*, 1997]. Cross-dating is possible with two or more coral records and can be used to estimate the accuracy of counting annual density bands in a single coral record [e.g., *Cole, et al.*, 1993; *Guilderson and Schrag*, 1999; *Linsley, et al.*, 2000; *Urban, et al.*, 2000; *Hendy, et al.*, 2002; *Cobb, et al.*, 2003b; *Linsley, et al.*, 2006]. In addition to annual density band counting, radio isotope dating can be applied to corals of unknown age. *Cobb et al.* [2003a] dated fossil corals from Palmyra Island (Central Pacific) by high precision U/Th techniques and concatenated individual overlapping records into a well-replicated, extended record of monthly resolved ENSO variability over the past 1100 years [*Cobb, et al.*, 2003b].

Once the chronology is established, a coral variable (i.e., linear extension, density, $\delta^{18}O$, or Sr/Ca) is measured and a transfer function or calibration is determined to translate the proxy variations to climatic variations (i.e., temperature or precipitation) over a common time period or calibration interval. The regression methods used in determining calibrations in tree ring and coral studies differ; however, the statistical approaches for verification can be used with both corals and tree rings [*Briffa*, 1995; *Cook*, 1995; *Crowley, et al.*, 1999; *Quinn and Sampson*, 2002]. *Fritts et al.* [1979] presented calibration and verification techniques for dendroclimatology to test calibrated proxy variations against an independent data set in order to assess reliability of the reconstruction inside and outside the calibration interval. Sources of independent data sets include meteorological/oceanographic observations, other proxy data, and historical observations. *Fritts et al.* [1979] recognized that for some locations, two independent data sets may not be available and they suggest splitting the calibration climate data set to create a “calibration interval” and a “verification interval.” The availability of two local climate data sets for most coral studies is quite unlikely and many coral studies do not have any local climate observations. *Crowley et al.* [1999] suggested coral-based studies make use of data from a local grid extracted from global databases such as HadISST [*Rayner, et al.*, 2003], GISST [*Parker, et al.*, 1995], ERSST [*Smith and Reynolds*, 2004], and COADS [*Woodruff, et al.*, 1998] for calibration and verification. Global sea surface temperature (SST) data sets typically span the last 120 years and can be split into long calibration and verification intervals. Additionally, the SST data sets can be used to assess whether the coral variations are recording a local climate signal or larger-scale climate variability [*Crowley, et al.*, 1999].

Fritts et al. [1979] recommended additional calibration and verification tests using other proxy data. Calibration and verification tests in coral-based climate studies may include replication of coral records and comparing results from other proxies measured from the same coral samples. The need for replication in coral-based climate studies was outlined in *Lough et al.* [2004], which compared twenty previously published coral records from the Pacific and found inconsistencies between the records leading them to question the validity of interpreting a single, long coral record due to the possibility of non-climatic influences dominating the geochemical record. The coral-based studies that include replication have primarily focused on climate signal verification at either the local level [e.g., *Alibert and McCulloch*, 1997; *Guilderson and Schrag*, 1999; *Linsley, et al.*, 1999; *Linsley, et al.*, 2000; *Urban, et al.*, 2000; *Cardinal, et al.*, 2001; *Cobb, et al.*, 2003b; *Felis, et al.*, 2003; *Bagnato, et al.*, 2004; *Stephans, et al.*, 2004] or the regional level [e.g., *Tudhope, et al.*, 1996; *Gagan, et al.*, 1998; *Urban, et al.*, 2000; *Hendy, et al.*, 2002] (Table 1). Local replication studies for *Porites spp*. have shown mean coral $\delta^{18}O$ differences ranging from less than analytical precision (±0.05‰)

[*Cobb, et al.*, 2003b], up to 1.28‰ in the Gulf of Aqaba, Red Sea [*Felis, et al.*, 2003]. The large mean differences observed in the Gulf of Aqaba were attributed to growth rate (i.e., extension rate) variability between corals at this location, where slow growing corals yielded higher mean coral $\delta^{18}O$ values [*Felis, et al.*, 2003]. Mean coral Sr/Ca differences range from 0.01 mmol/mol, ~0.2 ºC for monthly resolved *Porites* in New Caledonia [*Stephans, et al.*, 2004] to 0.14 mmol/mol, ~0.7 ºC for annually resolved *Porites* in Fiji [*Linsley, et al.*, 2006]. *Linsley et al*. [2006] found high correlation between annually resolved coral $\delta^{18}O$ variations for corals from the same location (r^2 = 0.60, Fiji; r^2 = 0.50 to 0.60, Rarotonga) and low correlation between annually resolved coral Sr/Ca variations for corals from the same location (r^2 = 0.22, Fiji; r^2 = 0.006 to 0.18, Rarotonga). The high correlation in the coral $\delta^{18}O$ variations negates growth-related effects being the cause of the low Sr/Ca coherence since analyses were run from splits of the same sample. *Linsley et al*. [2006] found no evidence of secondary aragonite in thin section analysis and suggested some unknown complicating factor had influenced the coral Sr/Ca in some sections of the coral record. *Smith et al*. [2006] found a mean coral Sr/Ca difference of 0.04 mmol/mol between two *Montastrea faveolata* cores collected from separate colonies at Looe Key, Florida, a difference that could not be attributed to growth related effects; however, *Smith et al*. [2006] found indications of Sr/Ca variations in seawater chemistry due to continental influences.

Dendroclimatic studies typically utilize two cores from the same tree in their studies in order to cross verify the age model and to perform a calibration and verification assessment of the climate signal at the individual level. Few coral-based climate studies have utilized replication at the intra-colony level to cross verify age models and verify calibration of the climatic signal at the colony level. *Cole et al*. [1993] used two cores from the same *Porites* colony to verify their age model and complete their 96-year coral $\delta^{18}O$ record from Tarawa Atoll, Republic of Kiribati and report excellent replication of $\delta^{18}O$ between overlapping regions between cores and between transects on the same coral slab. *Alibert and McCulloch* [1997] sampled along the major growth axis and the adjoining margin between adjacent corallite fans on a *Porites* from Great Barrier Reef, Australia and documented a significant change in coral Sr/Ca, which translated into temperature difference of 1 to 3 ºC for samples from the same colony. These authors concluded, as other have, that sampling the coral skeleton in a region other than the major growth axis is to be avoided.

With the addition of coral trace elemental ratios as SST proxies (i.e., Sr/Ca, Mg/Ca, U/Ca, and Ba/Ca), investigators can use both coral trace element variations and coral $\delta^{18}O$ variations to perform calibration and verification tests of the coral-SST signal [e.g., *Beck, et al.*, 1992; *Crowley, et al.*, 1999; *Quinn and Sampson*, 2002; *Stephans, et al.*, 2004; *Linsley, et al.*, 2006; *Smith, et al.*, 2006]. *Quinn and Sampson* [2002] performed calibration and verification tests of five coral geochemical proxies (Sr/Ca, Mg/Ca, U/Ca, Ba/Ca, and $\delta^{18}O$) from a *Porites lutea* coral sampled offshore of Amédée Island, New Caledonia. They found $\delta^{18}O$ and Sr/Ca had the highest fidelity with SST (r^2 = -0.84, $\delta^{18}O$; r^2 = -0.84, Sr/Ca); Mg/Ca and U/Ca had moderate coherence with SST (r^2 = 0.55, Mg/Ca; r^2 = 0.47, U/Ca) and Ba/Ca had little coherence with SST [*Quinn and Sampson*, 2002]. *Stephans et al*. [2004] assessed reproducibility of coral Sr/Ca and $\delta^{18}O$ between four cores (two intra-colony and three inter-colony) collected offshore from Amédée Island, New Caledonia and found high correlation ($r \geq 0.80$, Sr/Ca; $r \geq 0.70$,

$\delta^{18}O$) for monthly and seasonal variations for the period 1967 to 1992. *Stephans et al.* [2004] found additional confidence in the geochemical to SST transfer function by stack averaging the individual records ($r \geq -0.91$, Sr/Ca-SST; $r \geq -0.87$, $\delta^{18}O$-SST) and concluded no biological influence on the sclerothermometer over the interval examined at their location.

This study expands upon previous studies [*Quinn, et al.*, 1996; *Quinn, et al.*, 1998; *Crowley, et al.*, 1999; *Stephans, et al.*, 2004] by using five coral cores, three intra-colony and two inter-colony, from the reefs offshore of the Amédée Lighthouse, New Caledonia. The goals of this study include: 1) expanding the sample resolution test to coral Sr/Ca and to higher resolution sampling, 2) extending the test of reproducibility in coral Sr/Ca to span the entire 20th century, 3) assessing the stack coral Sr/Ca record using dendrochronology methods, 4) comparing coral Sr/Ca variations with local SST, 5) verification of the coral Sr/Ca-SST calibration with gridded SST data products for longer periods of time, and 6) comparing coral Sr/Ca to coral $\delta^{18}O$ variations between this and previous studies.

2. Study Area

New Caledonia (22ºS, 166ºE) is located in the southwest tropical Pacific Ocean (Figure 1) and has an extensive barrier reef, which developed during high stands of sea level during the late Quaternary; Holocene coral reef development started ~8500 years ago [*Cabioch, et al.*, 1996]. Ocean circulation between the eastern coast of New Caledonia and the Loyalty Islands is from the northwest to southeast (Loyalty Current or Vauban Current) carrying warm, low salinity waters from Vanuatu in the north [*Hénin, et al.*, 1984; *Rougerie*, 1986; *Hénin and Cresswell,* 2005]. Unlike the permanent Loyalty Current on the eastern coast, the direction of ocean circulation along the western coast of New Caledonia varies with the strength of the trade winds between the flows to the northwest and flows to the southeast [*Hénin, et al.*, 1984; *Hénin and Cresswell*, 2005]. New Caledonia's climate is tropical and influenced by the annual variations in latitude of the South Pacific Convergence Zone (SPCZ) to the north and the subtropical anticyclonic belt to the south [*Morliere and Rebert*, 1986; *Pesin, et al.*, 1995]. New Caledonia experiences warm wet summers (January to March) when the SPCZ is in its southernmost location and cool dry winters (July to September) when the SPCZ is in its northernmost location (Figure 1 and 2) [*Morliere and Rebert*, 1986; *Pesin, et al.*, 1995]. The southeast coast of New Caledonia experiences the highest annual average precipitation (>200 cm), and the western coast experiences the lowest annual average precipitation (<130 cm) [*Morliere and Rebert,* 1986]. The east-southeast trade winds are the dominant wind pattern (Figure 1) and vary seasonally with the strongest trade winds occurring in the austral summer [*Pesin, et al.*, 1995; *Delcroix and Lenormand*, 1997; *Hénin and Cresswell*, 2005].

Amédée Island (22º28.5′S, 166º28.0′E) is located off the southwest coast of New Caledonia, 20 km south of Nouméa, behind the barrier reef and within the Boulari Pass (Figure 1). The reefs offshore of Amédée Island are well bathed by open-ocean waters and the reefs do not appear to be subjected to freshwater input from the mainland [*Quinn, et al.*, 1996; *Quinn, et al.*, 1998; *Stephans, et al.*, 2004; *Montaggioni, et al.*, 2006]. The French research group, Institut de Recherche pour le Developpement, (IRD) have collected daily SST and sea surface salinity (SSS) measurements at Amédée Island (5 m depth) since 1967 [*Delcroix and Lenormand,* 1997] making this location well suited for a coral-based climate reconstruction. The mean annual SST is 23.5 ± 1.8 ºC (1σ) and varies with a regular annual cycle; mean summer SST (January, February, and March) is 25.7 ± 0.7 ºC (1σ) and mean winter SST (July, August, and September) is 21.4 ± 0.6 ºC (1σ). SSS varies inversely to SST with a minimum in summer (35.68 ± 0.35 psu, 1σ) and a maximum in winter (35.86 ± 0.21 psu, 1σ), corresponding to increases and decreases in rainfall (Figure 2). Annual rainfall at Amédée Island averages 64 cm and is less than the average rainfall (107 cm) on the mainland at Nouméa [*Rougerie*, 1986; *Pesin, et al.*, 1995; *Montaggioni, et al.*, 2006]. A single measurement of seawater $\delta^{18}O$ from Amédée Island reef yielded a value 0.52 ± 0.06‰ SMOW (2σ) [*Beck, et al.*, 1992]. The NASA GISS global gridded data set of oxygen isotopic composition of seawater [*LeGrande and Schmidt*, 2006] reports a seawater $\delta^{18}O$ of 0.61‰ VSMOW for a 1º-grid box centered at 22.5ºS, 165.5ºE. *Ourbak et al.* [2006] determined the $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) from samples collected monthly (January 1999 to 2003) at Amédée Island (mean = 0.184 ±

0.086‰ VSMOW, 1σ) and reports the $\delta^{18}O_{sw}$ has a 0.36‰ maximal variation and the correlation (*r*) between $\delta^{18}O_{sw}$ and SSS equals 0.62. *Montaggioni et al*. [2006] determined the Sr concentration in seawater samples at 1-m depth collected monthly at Amédée Island from April 1996 to May 1998 and January 2002 to April 2003 and reports a mean Sr value of 8.3 ± 0.2 ppm (1σ), higher than the mean value for tropical surface ocean waters (7.5 ppm) [*de Villiers*, 1999]. The source of the Sr variability is unknown and needs to be addressed in further studies.

The climate of New Caledonia is influenced by Pacific basin-wide (ENSO) and local (upwelling) phenomena. During ENSO warm-phase events (El Niño), New Caledonia experiences cooler temperatures (~0.5 ºC), a decrease in precipitation (22% on average), an increase in salinity (~0.2 psu), and a shift in wind direction to south. Opposing anomalies occur during ENSO cool-phase events (La Niña) [*Morliere and Rebert*, 1986; *Delcroix and Lenormand*, 1997]. In New Caledonia, the decrease in precipitation begins about three months after the onset of the ENSO warm phase event and persists for 12 months [*Morliere and Rebert*, 1986]. SSS anomalies lag the SOI by 8 months at 17ºS and 13 months at 27ºS [*Delcroix and Lenormand*, 1997]. There is evidence of local upwelling events along the western barrier reefs that persist for periods of days to weeks [*Hénin and Cresswell*, 2005; *Alory, et al.*, 2006]. The upwelling events have been observed in satellite infrared images and hourly SST measurements on the oceanside of reef at Uitoé, 36 km northwest of Amédée Island [*Hénin and Cresswell*, 2005]. The southeasterly trade winds blow parallel to the western coast of New Caledonia and strong wind events can induce upwelling of cooler, saltier waters from depth (100 m; <23 ºC), which cools surface waters along the seaward edge of the outer reef by up to 5 ºC in the summer and 1 ºC in the winter [*Rougerie*, 1986; *Hénin and Cresswell*, 2005]. These upwelling events occur on daily to weekly timescales [*Alory, et al.*, 2006], the presence of upwelled cooler water from depth may explain some of the differences observed between in situ measurements at Amédée Island and open ocean measurements (Δ = -1.5 ºC and 0.2 psu saltier) [*Hénin, et al.*, 1984; *Delcroix and Lenormand*, 1997], and the difference observed between in situ SST and the GISST2 data set [*Parker, et al.*, 1995] for a 1º-grid box centered for Amédée Island (Δ = -1.34 ºC) [*Crowley, et al.*, 1999; *Corrège*, 2006]. Examination of the daily SST measurements from Amédée Island showed the same upwelling/cooling events noted by *Hénin et al.* [2005]; however, the magnitude is reduced by a couple of degrees (3 to 4 ºC vs. 5 ˚C). The magnitude of these cool events diminishes to values between 0 to 1 ºC when the daily SST time series is filtered to monthly resolution (Figure 3).

3. Methods

3.1 Coral Records Examined

The *Porites lutea* colonies sampled in this study were drilled in <3 m of water within the Boulari Pass, which is adjacent to Amédée Island, New Caledonia (22º28.5′S, 166º28.0′E; Figure 1) [*Quinn, et al.*, 1996; *Quinn, et al.*, 1998; *Stephans, et al.*, 2004]. Four cores (92-PAA1, 92-PAA2, 92-PAC1, and 92-PAD1) were recovered in July 1992 and a fifth core (99-PAA) was recovered in December 1999. Three cores (92-PAA1, 92-PAA2, and 99-PAA) were recovered from the same massive coral colony (PAA) and the other two cores (92-PAC1 and 92-PAD1) were collected from nearby coral colonies (~0.5 km; Figure 1).

Four of the Amédée Island cores examined in this study have been sampled in previous studies (Table 2). *Quinn et al.* [1996] reported on coral $\delta^{18}O$ and $\delta^{13}C$ variations from 92-PAA1 using monthly resolution for the period 1952 to 1992. *Quinn et al*. [1998] reported on seasonally resolved coral $\delta^{18}O$ and $\delta^{13}C$ variations for the reminder of the 92-PAA1 core (~1675 to 1952). *Crowley et al*. [1999] reported on monthly resolved coral $\delta^{18}O$ and $\delta^{13}C$ variations from 92-PAA1 for the first decade of the 20th century. Additional studies describing 92-PAA1 include *Crowley et al*. [1997], *Corrége et al*. [2001], and *Quinn and Sampson* [2002] (Table 2). *Stephans* [2003] and *Stephans et al*. [2004] sampled cores 99-PAA, 92-PAC1, and 92-PAD1 with ~monthly resolution determining coral Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$ variations for the period 1967 to 1992. This study contributes to the suite of Amédée Island records by 1) determining monthly coral

Sr/Ca variations from 92-PAA1 and 92-PAA2 for the entire 20th century, 2) extending the monthly resolved coral isotopic record for 92-PAA1 back to 1921, 3) extending the monthly resolved coral Sr/Ca record for 92-PAD1 to 1937 and for 92-PAC1 to 1950, 4) determining fortnightly resolved coral Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$ variations from 92PAA1-B to compare with monthly and seasonal variations, and 5) replicating monthly resolved coral Sr/Ca variations along parallel paths on 92-PAC1-A.

3.2 Coral Sampling

The coral cores used in this study were collected by drilling a 3.5-m long, 8-cm diameter core along the primary vertical growth axis of the coral colony and then these cores were sliced vertically to 5-mm thick slabs. Annual density bands visible on X-radiographs of these slabs were used to determine sampling paths and sampling resolution (Figure 4). The optimal sampling path is perpendicular to the annual density bands; however, the direction of growth in the corallites may be different on either side of the coral slab due to the small size of the corallites in *Porites lutea*. The sampling path was determined by locating the near vertical annual density bands on the X-radiographs and examining the coral slab under magnification to determine the growth direction of the corallites. The coral slabs were drilled using a continuous routing program (Figure 5) on a computer-aided triaxial sampler described in detail by *Quinn et al*. [1996]. This study sampled the core 92-PAA1 parallel to the path used in previous studies with a 1.4-mm diameter drill bit; sample powders were collected every 0.70 mm (~monthly resolution). Additional samples were drilled for replication tests including: 1) adjacent parallel paths on 92-PAC1-A (Figure 6), 2) parallel paths on opposing sides of 92-PAA1-

A and 92-PAA1-B (Figure 7 and 8), and 3) samples collected with fortnightly resolution (30 samples/cm) from 92-PAA1-B (Figure 9 and 10).

3.3 Geochemical Analysis

Elemental ratio (Sr/Ca) and stable isotopic ($\delta^{18}O$ and $\delta^{13}C$) measurements were made from splits of the homogenized coral sample using instrumentation at the Paleoclimatology, Paleoceanography, and Biogeochemistry Laboratory at the University of South Florida. Sr/Ca measurements were made using a PerkinElmer Optima 4300 Dual View Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) using the drift correction method described by *Schrag et al.* [1999]. Coral powder samples (90 to 236 μg) were diluted in a volume of 2% trace metal grade HNO_3 to obtain a target sample solution having ~20 ppm calcium. The overall analytical precision (1σ) of the laboratory internal gravimetric standard (IGS) used for the drift correction was ±0.010 mmol/mol (n = 730; 0.11% relative standard deviation (RSD)) based on measurements before and after each sample. An additional estimate of precision was determined using a homogenized powder of *Porites lutea* (PL), which was analyzed every fifth sample. The overall precision (1σ) of the coral standard was ±0.017 mmol/mol (n = 776; 0.19% RSD). The absolute value of the Sr/Ca for the IGS and PL coral standard has been confirmed by thermal ionization mass spectrometry (TIMS) at the University of Minnesota Isotope Laboratory.

Stable isotopes were measured using a ThermoFinnigan Delta Plus XL dual-inlet mass spectrometer with Kiel Carbonate III preparation device. Coral powder (40 to 80 μg) was reacted with phosphoric acid at 70 ºC in the Kiel device to release CO_2 gas for analysis in the mass spectrometer. The overall analytical precision (1σ) determined by analysis of NBS19 run in conjunction with coral samples was ±0.06‰ and ±0.04‰ for $\delta^{18}O$ and $\delta^{13}C$, respectively. Isotopic ratios are reported in delta (δ) notation relative to Vienna Pee Dee Belemnite (VPDB).

3.4 Sclerochronology

Two methods were employed to establish the age model for the individual coral records: counting annual density bands on the coral X-radiographs and aligning coral Sr/Ca variations to a SST record. *Quinn et al*. [1996; 1998] generated the original age model for the core 92-PAA1 using monthly and seasonal coral $\delta^{18}O$ variations. This study generated the age model for 92-PAA1 using coral Sr/Ca variations as a result of the higher correlation of coral Sr/Ca with in situ SST [*Quinn and Sampson*, 2002; *Stephans, et al*., 2004]. The conversion from depth to time domain was achieved by matching coral Sr/Ca maxima (minima) to SST minima (maxima) for each annual cycle using AnalySeries software [*Paillard, et al*., 1996] In order to maximize alignment between records, additional tie points were utilize to match mid-spring and mid-summer points between coral Sr/Ca and SST record. The SST record used for alignment is composd of the in situ SST for Amédée Island (IRD) from 1967 to 2000, and the 1º gridded SST data set extracted from the HadISST1.1 database [*Rayner, et al*., 2003] centered on 22.5ºS, 166.5ºE (referred to as HadISST_AI) from 1900 to 1967 which was adjusted to match the in situ SST mean and variance (adj. HadISST = HadISST_AI * 1.074 - 2.989). The Sr/Ca age model for each core was applied to the other geochemical records from that same core and resampled to even monthly intervals. The resampled depth record was used to calculate annual extension rate. The Sr/Ca based age model for 92-PAA1 was compared with the age models from previous studies [*Quinn, et al.*, 1996; *Quinn, et al.*, 1998; *Stephans, et al.*, 2004].

Advantages of the multiple core approach include: improved alignment between discontinuous paths, the ability to assess missing time between core sections, and the ability to perform cross validation of the chronologies of the individual cores. The multi-core alignment was achieved by matching the coral Sr/Ca variations between the cores. The alignment of coral Sr/Ca variations in depth space is cumbersome due to different sampling resolutions, variations in extension rates, and possible gaps between core sections. First, each core section was aligned to the SST record using a best-guess age assignment determined from the density-band chronology, then each core section was visually aligned with concurrent core sections, and age assignments were adjusted accordingly. A final age model for each core was generated after the cores were aligned and gaps between core sections were assessed for missing time. The age models were verified against the annual density bands and SST records. The multi-core alignment resulted in changes to the *Quinn et al*. [1996; 1998] isotope chronology and the *Stephans et al*. [2004] chronologies. The estimated error at annual scale is minimal and error at subannual scale is ±2 months.

3.5 Data Analysis

Statistical analysis of a time series containing serial correlation, non-constant variance, and non-normal distribution of errors requires methods beyond classical Gaussian-based statistics. Statistical results derived from Gaussian and non-Gaussian methods were used to facilitate comparison with other studies, which largely have used Gaussian methods; however, interpretations are based on non-Gaussian methods due to the characteristics of the data. Differences between means and variances were tested using two approaches; the classical Student's *t*-test and *F*-test, which assume independence and normal distribution of the errors, and Monte Carlo simulation using equivalent degrees of freedom determined by the Runs test [*Bendat and Piersol*, 1971]. Covariance was determined using two approaches: the Pearson Product Moment correlation coefficients, and Monte Carlo simulation. The transfer function between coral geochemistry (Sr/Ca and $\delta^{18}O$) and SST was determined by linear regression using Ordinary Least Squares (OLS), Reduced Major Axis (RMA) [*Kermack and Haldane*, 1950; *York*, 1966; *Davis*, 2002] and Maximum Likelihood Estimation (MLE) [*York and Evensen*, 2004].

OLS and RMA are special cases of the more general method of MLE [*Press, et al.*, 1992; *von Storch*, 1999; *York and Evensen*, 2004]. The OLS regression assumes the regressors (x, y) are independent (no serial correlation), the errors are normally (Gaussian) distributed, the variance is constant (homoscedasticity), and the independent variable (x) is perfectly known. The OLS normal equations can be solved with algebra and the coefficients can be calculated with simple algorithms thus, the appeal of OLS. However, in sub-annually resolved coral-based climate records some of these assumptions may be violated; x-values (i.e., temperature) are not error-free; sub-annually resolved time series may contain serial correlation due to the annual cycle; the errors in x- and y-values may not be constant (i.e., change in SST measurement method). The consequences of these violations include: underestimation of error, sensitivity to outliers, and a transfer function that may not adequately model the data [c.f., *Press, et al.*, 1992; *von Storch*, 1995; *Draper and Smith*, 1998]. Tests for the OLS assumptions are discussed in *Bendat and Piersol* [1971] and *Draper and Smith* [1998].

The issues with OLS regression methods have been examined in the coral-based paleoclimate studies. One approach used in coral-based climate reconstructions is OLS regression with only maximum and minimum values [*Linsley, et al.*, 1994; *Cardinal, et al.*, 2001; *Allison and Finch*, 2004; *Bagnato, et al.*, 2004; *Cohen, et al.*, 2004; *Corrège, et al.*, 2004; *Montaggioni, et al.*, 2006]. The maximum/minimum approach eliminates serial correlation; however, the cost is a loss in degrees of freedoms and larger error bars. The other regression method used in coral-based climate reconstructions is RMA. *York* [1966] and *York et al.* [2004] demonstrate that RMA is a special case of MLE and generalized least squares; the error in the *x*- and *y*-variables is included in RMA regression and the correlation between the errors is assumed to be zero. Several coral-based paleoclimate studies have compared transfer functions from OLS and RMA with varying results [*Shen and Dunbar*, 1995; *Quinn, et al.*, 1998; *Quinn and Sampson*, 2002; *Smith, et al.*, 2006]. *Solow and Huppert* [2004] discussed the assumption of *x*-variable (SST) having no error and present a method to correct for the SST bias for OLS calibrations by estimating the error in the observed SST. *Corrége* [2006] summarized the published coral Sr/Ca-SST equations and discussed the ongoing debate of regression methods.

The purpose of this study is not to contribute to the debate by adding another regression method; however, the regression method debate is what prompted the investigation in order to better understand the different regression methods utilized in coral-based climate reconstructions. The MLE is a generalized linear regression solution that does not assume the independent variable is error-free, allows the variance in the regressors to vary, and accounts for correlation between the errors (r_i). The *York et al.* [2004] MLE equations and algorithms produce the same results for OLS and RMA when the input parameters (σ_x, σ_y, and r_i) are set according to the respective assumptions (OLS: $r_i = 0$, $\sigma_x = 1$; RMA: $r_i = 0$, $\sigma_x \neq 0$). However, the strength of the MLE method is the ability to include error in both the independent and dependant variables, allow the variance of each regressor (σ_x, σ_y) to vary from point to point, and account for correlation between the errors (r_i). The MLE algorithms by *York et al*. [2004] assume normally distributed errors in their equations; however, the impact of using normal distribution for the errors is minor compared with other OLS violations.

4. Results

The fidelity of the coral records from New Caledonia was confirmed by examining the coral samples for secondary minerals, estimating annual extension rates, and comparing chronologies between multiple coral records. Examination of scanning electron microscope images (SEM) and petrographic thin sections of 92-PAA1 found no evidence of secondary minerals (Figure 4c). Extension rates averaged ~1 cm per year in all cores and efforts were made to avoid sampling in regions where the annual density bands were <0.6 cm in length. Annual density band chronologies for each core were confirmed by coral Sr/Ca variations, which exhibit strong annual cycles. The multi-core alignment procedure utilized in this study resulted in refinements to the previous chronologies of coral cores from New Caledonia: chronology of the core 92-PAA1 [*Quinn, et al.*, 1998] was changed by one year and the chronology of the core 92-PAD1 [*Stephans, et al.*, 2004] was changed by two years.

4.1 Multiple Sampling Resolutions

The effect of different sampling resolutions in coral Sr/Ca (fortnightly and monthly) and $\delta^{18}O$ and $\delta^{13}C$ (fortnightly, monthly, and seasonally) was investigated and the results were compared to similar scale subsampling of the daily SST time series from this site. The difference between coral Sr/Ca determinations sampled with monthly and fortnightly resolution is within analytical precision of the Sr/Ca measurement (±0.010 mmol/mol, 1σ; Figure 10). The standard deviation (1σ) in the coral Sr/Ca records changes from ±0.101 mmol/mol (fortnightly sampling) to ±0.094 mmol/mol (monthly sampling), a 6.9% reduction with respect to fortnightly resolution (Table 3). The standard deviation (1σ) in the coral $\delta^{18}O$ records changes from ±0.27‰ (fortnightly sampling) to ±0.26‰ (monthly sampling) to ±0.22‰ (seasonal sampling), a 4.0% reduction between fortnightly and monthly sampling (Table 3). The standard deviation (1σ) in the coral $\delta^{13}C$ records changes from ±0.27‰ (fortnightly sampling) to ±0.26‰ (monthly sampling) to ±0.19‰ (seasonal sampling), a 5.0% reduction between fortnightly and monthly sampling (Table 3). Overall, mean coral Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$ values do not change significantly as a function of sampling resolution. The standard deviation (1σ) in the daily in situ SST changes from ±2.0 ºC (daily sampling) to ±1.9 ºC (fortnightly sampling) to ±1.8 ºC (monthly sampling) to ±1.7 ºC (seasonal sampling), a 1.7% reduction between fortnightly and monthly sampling (Table 4 and Figure 3). The daily SST measurements are accurate within ±0.2 ºC or ±0.04ºC for monthly average SST. There is no change in the mean SST value as a function of sampling resolution.

4.2 Replication of Coral Sr/Ca Variations

Replication tests were conducted on increasing spatial and temporal scales to assess the reproducibility of *Porites lutea* coral Sr/Ca records from Amédée Island, New Caledonia. At the individual sample scale, duplicate Sr/Ca determinations of coral powder confirmed coral samples are homogeneous. The average of the absolute differences (avg_{abs}) between coeval monthly coral Sr/Ca determinations (0.022 ± 0.018 mmol/mol, 1σ; Table 5; Figure 6) is similar to analytical precision (±0.016 mmol/mol, 1σ). The next spatial scale tested reproducibility between parallel sampling paths spaced

~0.5 cm apart for a 20-year interval where the parallel path on 92-PAC1-A was sampled next to the path reported by *Stephans et al.* [2004]. The results of this test confirmed the highly reproducible nature of these parallel paths; the means and standard deviations between the parallel paths are not significantly different (Table 5) and correlation between the paths is high ($r = 0.93$, $p < 0.05$, $n = 249$; Table 5). The avg_{abs} between parallel path coral Sr/Ca determinations (0.031 ± 0.026 mmol/mol, 1σ; Table 5; Figure 6) is within analytical precision (±0.016 mmol/mol, 1σ).

An additional parallel path replication test was conducted to investigate possible differences between sampling on opposing sides of the ~0.5-cm thick coral slab (Figure 7). Coral Sr/Ca determinations from parallel paths on opposing sides of 92-PAA1-A are not significantly different (Table 6; Figure 7a), are reproducible within analytical precision, and the avg_{abs} is comparable to the parallel path test on 92-PAC1-A (Table 5 and 6). However, coral Sr/Ca determinations for parallel paths on opposing sides of 92-PAA1-B exhibit a significant divergence in coral Sr/Ca (Table 6; Figure 7c). The youngest two cycles, from 1966 to 1968, agree within analytical precision; however, before 1966, the two paths diverge and the difference (avg_{abs} = 0.093 mmol/mol) between the paths increases beyond analytical error. Closer examination of the coral slab under magnification revealed the corallites on the original sampling side of the slab were not oriented parallel to the sampling path (Figure 8), a sampling orientation that has previously been identified as problematic [e.g., *Alibert and McCulloch*, 1997]. In this specific case, samples extracted from the non-optimal sampling pathway yielded lower Sr/Ca values relative to the values produced from the other samples, which when converted to SST would produce elevated temperature values. Additional comparison of

$\delta^{18}O$, $\delta^{13}C$, and Mg/Ca between the original sampling side and opposing side of 92-PAA1-B did not reveal an offset between the opposing sides (see Appendix A). The 92-PAA2, 92-PAC1, and 92-PAD1 coral Sr/Ca records agree with the variations on the opposing side of 92-PAA1-B (Figure 11) and data from original sampling side of 92-PAA1-B were not used further in this study.

The next spatial step assessed the reproducibility of monthly coral Sr/Ca variations between synchronous cores from same coral colony (PAA; Figure 4). Two cores, 92-PAA1 and 92-PAA2, were compared for the 20th century and the third core, 99-PAA [*Stephans, et al.*, 2004], was compared with 92-PAA1 and 92-PAA2 for the period 1965 to 1992 (Table 7 and 8; Figure 11). The pattern of monthly coral Sr/Ca variations for the period 1965 to 1992 are well matched between the three cores ($r > 0.92$, $p < 0.05$, $n = 328$; Table 9; Figure 11) and the means for each core are not significantly different (Table 7). For the 20th century, the pattern of monthly coral Sr/Ca variations between 92-PAA1 and 92-PAA2 are well matched ($r = 0.93$, $p < 0.05$, $n = 1098$; Table 10; Figure 11) and the means are not significantly different (Table 8). The avg_{abs} between monthly coral Sr/Ca determinations for PAA is 0.036 ± 0.027 mmol/mol (1σ), similar to the parallel path tests (Table 11). The largest disagreement (~0.055 mmol/mol on average) in coral Sr/Ca variations spans the interval 1951 to 1959, where the 92-PAA1 coral Sr/Ca determinations are lower than 92-PAA2, 92-PAD1, and 92-PAC1 (Figure 11 and 12).

The last spatial test assessed the reproducibility of monthly coral Sr/Ca variations between coral colonies offshore from Amédée Island, New Caledonia. This study builds upon the previous study of *Stephans et al.* [2004] by extending the coral records 92-

PAC1 to 1950 and 92-PAD1 to 1937 and comparing the monthly coral Sr/Ca variations from 92-PAC1, 92-PAD1, and the three PAA coral records to assess inter-colony reproducibility (Figure 11). The means and standards deviations of five coral Sr/Ca records are not significantly different for the 20th century (Table 8), the coral Sr/Ca records are highly reproducible ($r > 0.90$, $p < 0.05$; Table 10), and the overall avg_{abs} is 0.036 ± 0.028 mmol/mol (1σ) between all records (Table 11). The adjustments made to the chronology of 92-PAD1 increased the coral Sr/Ca and $\delta^{18}O$ correlation coefficients for 92-PAD1 with the other cores and SST from those reported by *Stephans et al*. [2004] for the interval 1967 to 1992 (Table 9). There are two other differences between this study and *Stephans et al*. [2004]; 1) the 92-PAA2 coral Sr/Ca was not included in the previous study and 2) the coral Sr/Ca for 92-PAA1 was generated by this study using the same laboratory as the other cores (99-PAA, 92-PAA2, 92-PAC1, and 92-PAD1). The use of a common laboratory and standard solutions minimizes any discrepancies due to analytical procedures. The monthly coral Sr/Ca anomalies for each coral record was calculated by subtracting the respective monthly mean with respect to the period 1967 to 1992 (Figure 12). The average of the correlation coefficients between monthly coral Sr/Ca anomalies is 0.51 for the interval 1967 to 1992 (Table 9) and 0.54 for the 20th century (Table 10). The stack "master" coral Sr/Ca record for Amédée Island is composed of the average of three coral records from the same coral colony (99-PAA, 92-PAA, and 92-PAA2) to create the stack PAA colony record, which was then averaged with the inter-colony records (92-PAC1 and 92-PAD1) to create the stack record, or stack master record for Amédée. The stack monthly coral Sr/Ca variations and anomalies are significantly correlated with the individual monthly coral Sr/Ca records (Table 10).

4.3 Stable Isotopes of Oxygen and Carbon

The stack average monthly coral $\delta^{18}O$ (Figure 13) and $\delta^{13}C$ time series for the 20th century was constructed based on the age model produced using coral Sr/Ca records (Appendix B and C). The stack average monthly coral $\delta^{18}O$ record for 92-PAA1 is composed of records from three studies: 1900 to 1909 *Crowley et al.* [1999]; 1921 to 1951 this study, and 1951 to 1992 *Quinn et al*. [1996; 1998] (Figure 13, Appendix B). The monthly and seasonal isotopic records from *Quinn et al*. [1996; 1998] and *Crowley et al*. [1999] were adjusted to the multi-core chronology from this study. The monthly resolved isotopic records for 92-PAC1, 92-PAD1, and 99-PAA are from *Stephans et al*. [2004] and were adjusted in the multi-core chronology from in this study (see Appendix B). The coral $\delta^{18}O$ signal is highly reproducible for the period 1967 to 1992 as reported by *Stephans et al*. [2004] and correlation values for this study (r = 0.80 to 0.90, $p < 0.05$, n = 304) are equal to or slightly higher than those reported by *Stephans et al*. [2004] after adjustments to the chronologies. The correlation between cores for the 20th century did not vary greatly from the correlation coefficients for the period 1967 to 1992. The means between the monthly coral $\delta^{18}O$ determined by this study and the seasonal coral $\delta^{18}O$ determined by *Quinn et al*. [1998] are not significantly different for the period 1921 to 1951 (monthly, -4.22 ± 0.32‰, 1σ; seasonal, -4.32 ± 0.26‰, 1σ).

The monthly coral $\delta^{13}C$ variations between intra-colony and inter-colony cores from Amédée Island, New Caledonia do not exhibit the same signal reproducibility as observed with coral Sr/Ca and $\delta^{18}O$ variations (see Appendix C). In the multiple sampling resolution comparison (Figure 10), the coral $\delta^{13}C$ means did not vary significantly; however, the standard deviation was reduced 27% between fortnightly and seasonal resolutions. Examination of Figure 10 confirms the coral $\delta^{13}C$ is variable in nature and lacks a clear annual cycle. Comparison of intra-colony coral $\delta^{13}C$ variations was similar to the multiple resolution test: a lack of clear annual cycles with some years having one cycle and other years having two cycles (Figure 10, Appendix C). The coral $\delta^{13}C$ means did not differ significantly between cores from the same colony, 99-PAA *Stephans et al*. [2004] and 92-PAA1 *Quinn et al.* [1996; 1998], for the period 1965 to 1992; however, the correlation between the intra-colony coral $\delta^{13}C$ is lower than the coral Sr/Ca and $\delta^{18}O$ intra-colony correlation ($r = 0.54$, $p < 0.05$, $n = 329$). The means between inter-colony cores are significantly different as reported by *Stephans* [2003] and the correlation between the PAA cores and 92-PAD1 are insignificant ($p = 0.05$). The correlation between 92-PAC1 and the other colonies are significant ($r = 0.34$ to 0.44, $p < 0.05$), however the correlations are lower than the intra-colony (PAA) correlation (Appendix C).

4.4 Coral Geochemistry and SST

Variations in SST have long been known to drive, at least in part, variations in the $\delta^{18}O$ [*Epstein, et al.*, 1951; *Epstein, et al.*, 1953; *Weber and Woodhead*, 1972] and Sr/Ca [*Weber*, 1973; *Smith, et al.*, 1979; *Beck, et al.*, 1992] in coral skeletons. The monthly coral Sr/Ca variations for this study are significantly correlated with monthly in situ SST ($r > -0.91$, $p < 0.05$) and monthly HadISST_AI ($r > -0.91$, $p < 0.05$) for the period common to all records (1967 to 1992; $n = 304$; Table 9). The correlations do not vary greatly for the extended 20th century records (Table 10). The correlation between the stack average coral Sr/Ca and the HadISST_AI increased (1 to 4% for monthly, 4 to 12%

for anomalies) for the 20th century by averaging the monthly coral Sr/Ca determinations increasing the signal-to-noise ratio (Table 10). The monthly stack coral Sr/Ca anomalies are significantly correlated with in situ SST anomalies and HadISST_AI anomalies (r = -0.56, -0.55, respectively, $p < 0.05$, n = 304) for the period 1967 to 1992 (Table 9) and the HadISST_AI anomalies decreased by 2% for the stack coral Sr/Ca record extended to the year 1900 (r = -0.53, $p < 0.05$, n = 1198; Table 10). The correlation between the stack coral Sr/Ca and SST anomalies is slightly less than the correlation between in situ SST and HadISST_AI (r = 0.60, $p < 0.05$, n = 394; Table 10). The annual average of the stack coral Sr/Ca is significantly correlated with annual average in situ SST and HadISST_AI (r = -0.51, -0.69, respectively, n = 33, 100, respectively, $p < 0.05$; Table 12; Figure 14) for the 20th century; however, the correlation between some of the individual annual average coral Sr/Ca records and the in situ SST are not significant possibly attributed to the small number of observations (n = 25). The stack average of the monthly coral $\delta^{18}O$ variations is significantly correlated with both monthly in situ SST and HadISST_AI (r = -0.94, -0.94, respectively, $p < 0.05$, n = 304) for the period 1967 to 1992 and the correlation decreased for the longer 20th century interval (r = -0.89, -0.84, n = 394, 1052, respectively, $p < 0.05$).

5. Discussion

This study expands upon previous studies of coral geochemical variations at Amédée Island, New Caledonia; this location is ideal for coral paleoclimatic reconstructions due to its remote location and long in situ records of SST and SSS. An evaluation of the effect of sampling resolution on the coral $\delta^{18}O$ variations at this site was first investigated by *Quinn et al*. [1996] and *Stephans et al*. [2004] investigated the reproducibility of coral $\delta^{18}O$ and Sr/Ca signals recorded in multiple coral heads from this site. This study expands and improves upon previous studies at this location by 1) expanding the sample resolution test to coral Sr/Ca and to higher resolution sampling (section 5.1), 2) extending the test of reproducibility in coral Sr/Ca to span the entire 20th century (section 5.2), 3) assessing the stack coral Sr/Ca record using dendrochronology methods (section 5.3), 4) comparing coral Sr/Ca variations with local SST (section 5.4), 5) verification of the coral Sr/Ca-SST calibration with gridded SST data products for longer periods of time (section 5.5), and 6) comparing coral Sr/Ca to coral $\delta^{18}O$ variations between this and previous studies (section 5.6).

5.1 Sampling Resolution

Examination of the coral Sr/Ca and $\delta^{18}O$ variations sampled at different resolutions reveals that there is minimal loss in the skill of capturing the mean of the annual cycle or the mean coral Sr/Ca and $\delta^{18}O$ for the interval tested. The amplitude of the annual cycles increased with finer sampling resolutions; however, the increase was not linear, but leveled off with increasing resolution (Figure 10d); a similar tapering off was observed with the filtering of the daily in situ SST record (Figure 3b). The multiple sampling resolution comparison assumes that the difference between the parallel sampling paths utilized for each resolution is equal to or less than analytical precision. This assumption was tested for a 20-year interval on 92-PAC1 (Table 5; Figure 6), which demonstrated that the coral Sr/Ca variability between adjacent paths was within analytical precision.

Recent investigations of micron-scale variations in coral skeletal Sr/Ca concluded that micron-scale frequency variations in coral Sr/Ca are not related to SST variations [*Meibom, et al.*, 2003; *Allison and Finch*, 2004; *Cohen and Sohn*, 2004; *Sinclair,* 2005]. *Meibom et al*. [2003] observed ~monthly oscillations in coral Sr/Ca sampled at 30 μm (~daily), which they attributed to metabolic variability related to the lunar cycle. *Cohen and Sohn* [2004] attributed coral Sr/Ca variations sampled in discrete 20 μm spots (~daily) to tidal forcing. *Allison and Finch* [2004] examined differences in coral Sr/Ca between centers of calcification (COCs), which are deposited at night, and fasciculi, which are deposited during the day, in fast- and slow-growing *Porites lobata* corals from Hawaii. *Allison and Finch* [2004] observed significantly higher coral Sr/Ca values in the COCs, no significant difference in coral Sr/Ca between the fast- and slow-growing corals, and both the fasciculi and COCs exhibit large Sr/Ca heterogeneity (~1 mmol/mol) not related to temperature, which they attribute to variations in calcification rates. *Sinclair* [2005] microsampled *Porites* corals from the Great Barrier Reef, Australia and reported large-magnitude, submonthly coral Sr/Ca variability, which would equate to ~20 ºC. Unlike *Meibom et al*. [2003] and *Cohen and Sohn* [2004], *Sinclair* [2005] did not observe concentrations of variance at common periodicities and noted different variations between corals. Previous coral-based climate reconstructions contrast with micron-scale investigations, which use µm-scale sampling to recover ~1 μm^2 area from a single corallite, whereas typical coral-based climate reconstructions sample an ~1 mm^2 area which may contains multiple corallites depending on the species. This study sampled at 0.70 mm (~monthly) intervals using a 1.4 mm drill bit and each sample area contains ~1.47 mm^2 of coral skeletal material from multiple *Porites lutea* corallites (~3 to 4 corallites; see Figure 8 for detail of coral with sampling path).

A consideration in spectral analysis is appropriate sampling intervals to avoid the aliasing frequencies higher than twice the sampling interval, the Nyquist frequency, when sampling discretely [*Bendat and Piersol*, 1971; *Bloomfield*, 1976]. A continuous sampling method used by *Quinn at el*. [1996] addresses the issue of aliasing high frequencies in coral-based climate reconstructions and this method is utilized in this study and many others [e.g., *Alibert and McCulloch*, 1997; e.g., *Quinn, et al.*, 1998; *Corrège, et al.*, 2000; *Linsley, et al.*, 2000; *Hendy, et al.*, 2002; *Quinn and Sampson*, 2002; *Kilbourne, et al.*, 2004; *Stephans, et al.*, 2004; *Linsley, et al.*, 2006; *Smith, et al.*, 2006]. The continuous sampling method (Figure 5) involves drilling a channel in the coral along the maximum growth axis (see Figure 8 for detail of coral with sampling path) and removing a homogenized coral powder sample for some interval length, which in mathematical terms equates to a moving average or smoothing function. The continuous sampling method is quite different from sampling the coral skeletal material in discrete points such that minimal information along the sampling path is lost as the signal is averaged over the sampling interval. If frequencies higher than the sampling interval are present in the coral skeletal material, the continuous sampling method averages these fluctuations producing a smoothed record. The cost of smoothing or filtering data is a loss of variance. This is illustrated in the filtered in situ daily SST record (Figure 3) and multiple sampling resolution experiment (Figure 10). As the sampling interval doubled from fortnightly to seasonal (30 samples/cm to 15 samples/cm), the variance decreased in each geochemical record as expected (Figure 3 and 10; Table 3 and 4). The percent reduction in standard deviation from fortnightly to monthly for the in situ SST record (1.7% SST) was less than the coral records (6.9% Sr/Ca, 3.9% $\delta^{18}O$, and 5.0% $\delta^{13}C$). The in situ SST is discretely sampled once per day in morning observation and is not a fully continuous daily record. Therefore, the in situ SST record lacks the high frequency power (<1 day) that contributes to the overall variance in a continuous sample. The results of the sampling-resolution test reveal a minimal loss in variance and in mean value in coral Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$ for twice the sampling interval. *Allison and Finch* [2004] performed a similar test with their micron-scale investigation results and noted a reduction in variance as smoothing intervals increased and that correlation with temperature increased as smoothing reached monthly and bimonthly intervals. The results from *Allison and Finch* [2004] and from this study support the conclusion reached by *Quinn et al*. [1996] that lower sampling resolutions (seasonally to monthly) in coral Sr/Ca captures an average annual temperature signal; however, this is true for the continuous sampling method and discrete sampling may produce erroneous results if frequencies higher than twice the sampling interval (Nyquist frequency) are present.

An additional consideration in regards to sampling resolution in coral-based climatology is selecting a sampling resolution with enough resolution to establish an age model between synchronous coral records from multiple cores and sampling paths. Investigations using a single coral core typically have estimated errors in chronology of 1 to 2 years per century, when robust chronology error assessment is not possible. However, this study was able to estimate chronology error for previous Amédée studies using the five-core master chronology from this study. This study found a two-year discrepancy out of 92 years (2%) in the seasonal coral $\delta^{18}O$ record for 92-PAA1 [*Quinn, et al.*, 1996; *Quinn, et al.*, 1998], a two-year discrepancy out of 34 years in the monthly coral Sr/Ca for 92-PAD1, and zero discrepancies in the 35-year long 99-PAA and 33-year 92-PAC1 monthly coral Sr/Ca records, which equates to a 2% chronology error for the *Stephans et al*. [2004] study. The multi-core age model validates the estimated chronology error of two years per century. Whereas seasonal resolution was sufficient to establish an age model for a single coral record, this study found establishing a synchronous age model across five cores was more challenging. Multi-core alignment utilized the shape, the seasonal range, and characteristics of each cycle to match cycles between cores and sampling paths; the information contained within the annual cycles was vital in the multi-core alignment. An additional tool utilized was magnification of coral slabs to assess corallite growth direction; this tool was essential to assessing apparent synchronous sections from the X-radiograph age model where coral Sr/Ca cycles did not match (e.g., Figure 7 and 8). All five of the monthly coral Sr/Ca have high covariance ($r > 0.90$; $p < 0.05$) between each other for the 20th century. The accuracy of a multi-core alignment would have been more difficult for coral geochemical records sampled with less than monthly resolution. After establishing the age model with the monthly resolved coral Sr/Ca determinations, isotopic analysis involved only the samples included in the final age model, thus eliminating unnecessary isotopic analyses and saving analytical time and expense. For multiple-core alignment, there is little advantage for sampling at greater than monthly resolution (i.e., 30 samples/year) that justifies increasing the sampling resolution.

5.2 Replication of Coral Sr/Ca Variations

Reproducibility of coral Sr/Ca variations through the 20th century was investigated using parallel cores from the same coral colony and multiple synchronous cores from coral colonies in close proximity within the same reef. The average of the avg_{abs} between coeval monthly Sr/Ca determinations between any two coral Sr/Ca time series was 0.036 ± 0.028 mmol/mol, 1σ; Table 11), which is less than twice the absolute value of the analytical precision of the coral Sr/Ca measurements and corresponds to an average offset between any two cores of 0.65 ˚C at any point in time. An artificial source of offset between cores is inadequate alignment of coral records to the SST record and every effort was made to remove any large offsets due to conversion from depth domain to time domain.

The avg_{abs} between the coral Sr/Ca records from the same coral colony (99-PAA, 92-PAA1, and 92-PAA2) may be due to by differences in sampling resolution and sampling path. Each core from PAA was sampled at slightly different resolutions (12, 15, and 16 samples/cm; Table 2); however, the means and standard deviations are not significantly different (Table 7). The three inter-colony cores (92-PAC1, 92-PAD1, and 99-PAA) were sampled at the same resolution (16 samples/cm) and have an avg_{abs} of similar magnitude to the intra-colony cores (99-PAA, 92-PAA1, 92-PAA2), which were sampled at different resolutions (Table 11). The effects of these small differences in sampling resolutions cannot be discounted however, the influence is judged to be within the variability observed at this location.

The second possible source of variability between cores is sampling path. The cores 92-PAA2, 92-PAC1, 92-PAD1, and 99-PAA have been sampled only once and each was sampled along a maximum growth axis. The core 92-PAA1 has been sampled previously (Table 1, Figure 4) and this study sampled parallel to the path from previous studies; therefore, slightly off the maximum growth axis (<0.5cm). The parallel path test demonstrated that the coral Sr/Ca variability between adjacent paths was within twice the analytical precision and the avg_{abs} for all cores in this study (Table 11) is similar to the avg_{abs} for the parallel path test on 92-PAC1 (Table 5; Figure 6). The effect of sampling parallel to the maximum growth axis cannot be discounted, although the influence is judged to be within the analytical precision of this study.

The largest disagreement (~0.05 mmol/mol on average) in coral Sr/Ca variations between the two cores spans the interval 1951 to 1959, where the 92-PAA1 coral Sr/Ca determinations are higher than 92-PAA2 (Figure 11 and 12). The mean coral Sr/Ca values of the 92-PAD1 and 92-PAC1 records agree with the 92-PAA2 record for the period 1951 to 1959. The 1951 to 1959 section of 92-PAA1-B occurs next to the region (1960 to 1966) where the growth direction of the corallites was suboptimal (Figure 8) and the difference between samples from the original sampling side and the opposing side of 92-PAA1-B was 0.094 mmol/mol (Figure 7). Evidence of suboptimal corallite growth was not observed in the 1951 to 1959 section of 92-PAA1-B and reanalysis of the 92-PAA1-B samples did not find any analytical error. Additional geochemical analyses

($\delta^{18}O$, $\delta^{13}C$, and Mg/Ca; Appendix A) of the original sampling side and the opposing side of 92-PAA1-B for the period 1960 to 1969 did not reveal a mean offset between opposing sides of 92-PAA1-B and the offset appears to be unique to the coral Sr/Ca record. Further investigation is needed to decipher the coral Sr/Ca offset in this section of the 92-PAA1 record. Future work will include extending the sampling path on the opposing side of the slab 92-PAA1-B to assess the coral Sr/Ca variability between opposing sides of the slab and sampling an additional path on another corallite lobe on the original sampling side of 92-PAA1-B. In the stack coral Sr/Ca record, the average of the three coral colonies reduces the lower than average coral Sr/Ca values in 92-PAA1 (Figure 12).

The monthly coral Sr/Ca signal at New Caledonia for the 20th century is highly reproducible as evidenced by the high correlation between individual monthly, anomaly, and annual average coral Sr/Ca records and the high correlation between individual monthly, anomaly, and annual average coral Sr/Ca records with the respective stack coral Sr/Ca records (Tables 9, 10 and 12; Figures 11, 12, and 14). The reproducibility of the coral Sr/Ca signal for the 20th century agrees with the previous shorter interval study by *Stephans et al.* [2004] and demonstrates the reproducibility of the coral Sr/Ca signal between coral colonies for the longer 92-year interval. The coral Sr/Ca signal reproducibility results demonstrate that monthly resolved coral Sr/Ca variations from multiple cores from the same coral colony and coral colonies in close proximity are recording the same signal and the monthly coral Sr/Ca signal is primarily environmental, not biological.

5.3 Comparison with Dendrochronology Methods

This study has demonstrated that multiple monthly coral Sr/Ca records from New Caledonia share a common environmental signal, but how do these results compare with statistical methodologies utilized in tree-ring based climate studies? Dendrochronologists employ correlation analysis to assess individual chronologies against a master chronology for a region by examining correlation in 50-year windows to identify possible problems in the chronology [*Fritts*, 1976]. A similar correlation analysis with the Amédée Island monthly coral Sr/Ca records was conducted and found high correlation coefficients ($r > 0.95$, $p < 0.05$; Table 9 and 10) between the coral records and the master coral Sr/Ca record for the periods 1900 to 1999 and 1967 to 1999. Tree ring chronologies are constructed using annual growth rings, and thus have annual resolution. In order to compare the coral records on par with tree ring records, the climatological annual average (April to March) was calculated for each coral Sr/Ca record and correlation analysis was performed; the correlation coefficients ranged from 0.76 to 0.89 between the coral records and the master stack record (Table 12). High correlation among proxy records and climate records indicate "sensitive" series such as trees in semi-arid and drought stricken regions [*Fritts*, 1976]. The mean inter-series correlation coefficient ($\bar{r}$) is the mean of all correlation comparisons between trees in a region with a common signal [*Wigley, et al.*, 1984]; $\bar{r}$ equals 0.93 for monthly coral Sr/Ca determinations and 0.63 for annual average coral Sr/Ca for the period 1900 to 1999. The Expressed Population Signal (EPS) is the statistical quality of the mean chronology gauged against the hypothetically noise-free chronology (infinitely replicated) and is given by

$$\text{EPS} = \frac{N(\bar{r})}{\bar{r}(N) + (1 - \bar{r})} \qquad (1)$$

where N is the number of records (trees or coral colonies) [*Wigley, et al.*, 1984]. Dendrochronologists utilized EPS to determine the number of replicates needed to reduce the signal-to-noise ratio to an acceptable level; the closer the *EPS* value to one, the stronger the signal and fewer series are needed in the final record; the common acceptable EPS value is 0.85 (Figure 15) [*Wigley, et al.*, 1984; *Briffa*, 1995]. The EPS for this study (N = 3 coral colonies) is 0.97 for monthly coral Sr/Ca and 0.84 for annual average coral Sr/Ca; this EPS value indicates the stack coral Sr/Ca chronology is acceptable with a high signal-to-noise ratio. One reason for the difference between coral and tree-ring records is the ability to use monthly variations to construct a chronology, which gives an advantage to coral and other sub-annually resolved proxy records. To determine the number of records needed in a coral-based reconstruction using $\bar{r}$ and EPS, Figure 15 shows the number of coral records needed to produce an acceptable EPS. For a single coral record with a $\bar{r}$ of 0.85, and for two coral records with a $\bar{r}$ of 0.75, the EPS is acceptable. The $\bar{r}$ of a single record cannot be determined, but two replicates from a single colony could be utilized or the single record could be compared with an instrumental record. The EPS statistic can evaluate high frequency data but is a poor measure of low frequency replication; *Briffa* [1995] suggests bootstrapping methods to measure chronology confidence at lower frequencies. The multiple-coral record tested using statistical methods from dendrochronology demonstrate that coral Sr/Ca variations are highly reproducible and should be evaluated as equivalent to highly sensitive tree-ring records, which record a common climate signal.

5.4 Coral Sr/Ca Relationship with SST

A strong relationship between coral $\delta^{18}O$ and Sr/Ca with SST has been previously reported for corals from Amédée Island, New Caledonia [*Beck, et al.*, 1992; *Quinn, et al.*, 1996; *Quinn, et al.*, 1998; *Quinn and Sampson*, 2002; *Stephans, et al.*, 2004] and this study's expanded New Caledonia coral Sr/Ca record exhibits the same strong relationship with SST (Figure 13). The correlations between monthly coral Sr/Ca from 92-PAA1 and SST are similar to the values reported by *Quinn and Sampson* [2002]. The correlation between SST and coral Sr/Ca and $\delta^{18}O$ shows a slight improvement from correlation reported by *Stephans et al.* [2004] due to adjustments made to the chronology of 92-PAD1. Stack averaging the coral Sr/Ca records into a master coral Sr/Ca record further improved the correlation between SST and coral Sr/Ca (Table 9 and 10). The extension of the Amédée Island coral Sr/Ca record demonstrates that the monthly coral Sr/Ca signal remains strongly correlated with SST in the 20th century, both monthly in situ SST and HadISST_AI, and that the correlation remains constant for monthly anomalies and annual averages for the 20th century (Table 10 and 12). A comparison with other monthly gridded SST data products (ERSST [*Smith and Reynolds*, 2004], COADS [*Slutz, et al.*, 1985], and GISST [*Parker, et al.*, 1995]) shows similar results for grid areas centered on Amédée Island.

As discussed in the Methods section, several regression methods have been utilized in coral-based SST reconstructions and this study used a generalized MLE method [*York and Evensen*, 2004], which is similar to the generalized least squares method [*York,* 1969], to formulate the SST transfer function (coral Sr/Ca-SST and coral $\delta^{18}O$-SST). Additionally, this study made a comparison of the MLE solution to the other regression methods (OLS and RMA) used in coral-based climate reconstructions. The MLE transfer function for the monthly stack coral Sr/Ca determinations with in situ SST was estimated for the period 1967 to 1999 ($r = 0.95$, $p < 0.05$, $n = 392$) using 1) a coral Sr/Ca error matrix (σ_{xi}) based on the error estimated for each month by the deviation between the individual records and the stack record and the number of records in the stack average for that month; 2) the SST error matrix (σ_{yi}) based on type of measurement and number of observations; and 3) the estimate of correlation between the errors in SST and coral Sr/Ca (r_i). For comparison with OLS methods, the MLE transfer function was calculated with the independent variable (x) as both SST and coral Sr/Ca.

$$SST(^{\circ}C) = 193.45(\pm 1.72, 2\sigma) + Sr/Ca(mmol/mol) * - 18.514(\pm 0.187, 2\sigma) \quad (2)$$

$$Sr/Ca(mmol/mol) = 10.449\ (\pm 0.013, 2\sigma) - 0.0540(\pm 0.001, 2\sigma) * SST(^{\circ}C) \quad (3)$$

The monthly stack coral Sr/Ca determinations and the corresponding monthly in situ SST with error bars are plotted in Figure 16. The stack coral Sr/Ca determinations with only one observation have larger error bars and all the observations outside the main data cluster are single observations (Figure 16). The standard error of regression ($\sigma_{reg} = 1.35$ ºC) was calculated using effective degrees of freedom ($dof = 105$), which accounts for serial correlation; this differs from the σ_{reg} calculated using number of observations ($n = 392$; $\sigma_{reg} = 0.68$ ºC). The standard error of the slope and intercept was calculated with the weights for SST and coral Sr/Ca, which were based on the error estimate and number of observations for each month.

The implementation of MLE in this study allowed the evaluation of the OLS and RMA methods by testing the OLS assumptions, which include an error-free independent variable and the constant variance in the regressors. Typically, in coral-based SST reconstructions using OLS, SST is the independent variable and the coral geochemistry is the dependent variable so that the variable with the least amount of uncertainty is the independent variable. However, OLS does not produce the same solution when exchanging the variables (Figure 16) [*York*, 1966; *Davis*, 2002]. To illustrate the non-symmetrical nature of OLS using data from this study, the OLS regression was performed using both SST and coral Sr/Ca as the independent variable (Table 13) and applying the OLS transfer functions to solve for SST. Each OLS solution produced the same mean for SST; however, the predicted SSTs have different slopes, and the standard deviations differ by 0.26 ºC (Figure 16). RMA produces identical results regardless of which variable is dependent or independent (Table 13, Figure 16) [*York*, 1966; *Davis*, 2002]. RMA includes the variance of the dependent and independent variables in the regression (slope = σ_x/σ_y) and does not treat error in the regressors as equal, whereas major axis or Principle Component Analysis considers the variance of the dependent and independent as equal [*York*, 1966; *Davis*, 2002]. For this study, the RMA solution for coral Sr/Ca-SST reproduced the mean and the variance of the observed SST (23.51 ± 1.82 ºC, 1σ). Like RMA, MLE regression method [*York and Evensen,* 2004] includes the variance of both regressors, thus negating the need to set SST as the independent variable. The MLE solutions with independent variables transposed (equations 2 and 3) are not significantly different (Figure 16) and the MLE solution produced a small increase in the standard deviation of the predicted SST (0.02 ºC) compared with the observed SST. The MLE solution is not significantly different from the RMA solution for this study. The OLS slope is not significantly different from the RMA or MLE slope when independent variable (*x*) is Sr/Ca; however, the OLS slope is significantly different from the MLE slope when the independent variable is SST. An advantage using the *York et al*. [2004] implementation of MLE regression is the ability to weight the errors for each of the regressors instead of assuming each observation has equal variance. The stack coral Sr/Ca is the average of the five coral records used in the study; however, for each month, the number of observations can vary between one and five and therefore extra weight is given to months with multiple observations versus months with only a single observation (Figure 16).

Solow and Huppert [2004] discussed the potential for bias in OLS linear regression when SST is used as the independent variable and SST is assumed to be without error. They proposed a bias correction using an estimate of the SST measurement error. The bias noted by *Solow and Huppert* [2004] can be corrected by using a regression method that incorporates error in both regressors, such as the MLE method by *York et al*. [2004] or RMA [*Kermack and Haldane*, 1950; *Davis*, 2002]. However, the error in both regressors is needed and the MLE method requires computing power (e.g., MatLab), which is not available in many off-the-shelf statistics programs. This study was fortunate in having a daily in situ SST record in close proximity to the coral colonies in order to assess the error in the SST measurement in detail. The Amédée Island monthly SST error was estimated using the daily SST measurements and instrumental precision ($\sigma_{precision} = \pm 0.2$ ºC). The method of measuring temperature in the Amédée Island record changed in 1997 from bucket measurements to deployed automatic instrumental measurements. A histogram of the daily bucket measurements revealed ~30% of the readings were whole numbers (10% are expected to be whole numbers), which were assumed to be recording errors where readings were rounded to a whole number ($\sigma_{rounded}$ = ±0.5 ºC) and examination of the daily bucket SST record found a period of time (~1 year) where all SST readings were rounded to a whole number. The daily measurement error for the period 1967 to 1997 was increased to ±0.26 ºC to account for possibility of recording errors (80% * ±0.2 ºC + 20% *±0.5 ºC = ±0.26 ºC). The daily SST readings at Amédée Island were taken at ~7 AM local time; however, the recording time did vary over the 33-year record. *Delcroix and Lenormand* [1997] used the Amédée Island SST data set in their study and they adjusted the daily observations to 7 AM based on a mean diurnal cycle of an almost linear increase of 0.1 ºC per hour between 5 AM and 3 PM. After adjusting the daily SST to 7 AM, the monthly average SST and the monthly average error was calculated using the standard error of a mean. The Amédée Island monthly SST record contained months were where no measurements were made and the corresponding SST from the adjusted HadISST_AI record was used to complete the record. *Rayner et al.* [2003] reports the monthly HadISST1.1 error for a 2º-grid box decreased from 0.6 to 0.3 ºC for the period 1960 to 1995 and the corresponding error was used for the adjusted HadISST_AI values in the completed Amédée Island SST record. MLE regression used an error matrix containing all the error information for the in situ SST record to formulate the transfer function (equations 2 and 3) of coral Sr/Ca to SST; the mean of the SST measurement error (σ_{SST}) = 0.09 ºC ± 0.13 (1σ). If the *Solow and Hubert* [2004] SST bias (σ^2_η) introduced by OLS regression was estimated as 0.14, the bias correction would produce the same results as the MLE transfer function assuming the in situ SST is the best estimate of the true monthly SST. The σ^2_η needed to correct the OLS transfer function is an order of magnitude greater than the estimate of SST measurement variance (σ^2_η = 0.017) for the in situ SST at Amédée Island. Without

SST measurement error information, applying the *Solow and Huppert* [2004] bias correction is difficult and is reduced to a best guess. *Stephans et al*. [2004] used the same SST and some of same coral records as this study; however, they applied the *Solow and Huppert* [2004] bias correction, which is significantly different from the MLE solution for this study. A straightforward solution to the OLS bias problem discussed by *Solow and Huppert* [2004] is using a regression method such as MLE, which incorporates the error in both the dependent and independent variable.

Corrège [2006] summarized the differences between published coral Sr/Ca-SST calibration equations and found a wide variety of equations regardless of location. Similarly, the summary of published calibration equations for coral Sr/Ca-SST for New Caledonia (Table 13) shows a wide variability in the transfer function for coral Sr/Ca-SST (Δ slope = 0.031 mmol mol^{-1} ºC^{-1}) from the same location. All the studies with the exception of *Ourbak et al*. [2006] used monthly sampling resolution. The *Corrège* [2006] and *Ourbak et al.* [2006] studies were conducted at Uitoé, which is located 36 km north of Amédée Island. Possible explanations for the variability in the coral Sr/Ca-SST transfer function include: 1) analytical methods, 2) regression methods, 3) length of calibration interval, 4) sampling resolution, 5) coral variability, and 6) regression with different SST records. The studies listed in Table 13 were conducted in four different laboratories using different analytical methods and internal laboratory standards. The studies of Amédée Island corals regressed using OLS with the same in situ SST record (*Beck et al*. [1992], *Quinn and Sampson*, [2002], *Stephans et al*. [2004], and this study) are not significantly different even though coral Sr/Ca determinations were made at different labs. However, these studies are different from the studies by *Corrège et al*.

[2000] and *Montaggioni et al*. [2006] both of which used corals from Amédée Island, the same SST record, and regression with OLS. *Ourbak et al*. [2006] conducted replicate analysis of a coral from Uitoé (Figure 1) using ICP-AES and ICP-MS and found the slopes differed by 0.015 mmol/mol per ºC using the same SST record and regression method. *Quinn and Sampson* [2002], and *Corrège* [2006] discuss the need for standardized reference for coral Sr/Ca similar to the use of the standard NBS19 for coral $\delta^{18}O$. The differences between labs and methodologies needs to be considered when comparing coral Sr/Ca-SST transfer functions.

As previously discussed, the regression methods, OLS, RMA, and MLE, have the potential to introduce differences in the coral Sr/Ca-SST transfer function. Regression method can produce significantly different slopes as noted by this study (Table 13; Figure 16) and is further complicated by studies using only the maximum and minimum values for the calibration [*Montaggioni, et al.*, 2006] and studies using bias correction [*Stephans, et al.*, 2004]. *Montaggioni et al.* [2006] used OLS with maximum and minimum values and produced significantly different transfer function from the other published coral Sr/Ca-SST transfer functions for New Caledonia. The length of the calibration interval has an influence on the transfer function; the longer the calibration interval, the number of observations increases thus increasing the confidence in the transfer function. Calibrations over short intervals of time may be influenced by anomalous events such as ENSO events. The long interval studies (>20 years, Table 13) have slopes that are not significantly different (*Quinn and Sampson* [2002], *Stephans et al*. [2004], and OLS this study), and have higher goodness-of-fit coefficients with SST (*R*, Table 13). The sampling resolution may be responsible for variability in the transfer functions; however, the multiple sampling resolution test conducted by this study showed the difference between monthly and fortnightly coral Sr/Ca was insignificant. Another source of differences in the coral Sr/Ca-SST transfer functions that needs to be considered is coral Sr/Ca variability in which the corals are not recording the same signal. However, the investigations by this study and *Stephans et al*. [2004] demonstrate that different coral colonies from Amédée Island are recording the same coral Sr/Ca signal. The SST record used for regression is the last source of differences between the coral Sr/Ca-SST transfer functions. All of the Amédée Island coral studies (Table 13) used the same in situ SST record and the two Uitoé coral studies used the same Uitoé in situ SST record. *Corrège* [2006] discussed the differences in calibrating a coral record from Uitoé with SST records from a in situ source (Uitoé), a regional source (Amédée), and a gridded SST data product [IGOSS; *Reynolds, et al.*, 2002] and found significantly different slopes. An interesting future investigation would be resolving the differences between the New Caledonia records by quantifying the differences between the laboratories and then comparing all the coral Sr/Ca records to examine common signals between corals, especially between Amédée Island and Uitoé, in order to build a master coral Sr/Ca record similar to master records produced in tree ring studies. The master New Caledonia record could then be used to create a transfer function for coral Sr/Ca-SST based on all the coral records from New Caledonia. This master coral-Sr/Ca transfer function would minimize the influence of sub-optimal sampling, short record length, and individual coral colony variability on the coral Sr/Ca-SST transfer function.

5.5 Calibration and Verification

A necessary step in the calibration of a climate proxy is the verification of the calibration against an independent data set for the calibration interval (in this case, 1967 to 1999) and outside the calibration interval (in this case, 1900 to 1967). Previous Amédée Island coral Sr/Ca studies [*Quinn and Sampson*, 2002; *Stephans, et al.*, 2004] found good agreement between coral Sr/Ca-SST and gridded SST (GISST2 data set) [*Parker, et al.*, 1995] for the calibration interval (1967 to 1992) and this study supports their findings (Figure 17). *Crowley et al*. [1999] conducted a calibration and verification test of the seasonal coral $\delta^{18}O$ record from the coral core 92-PAA1 for the period 1900 to 1992 and inferred a 2.25 ºC cooling in the early 20th century from the coral $\delta^{18}O$. *Crowley et al*. [1999] conducted an additional verification test using coral Sr/Ca for the period 1898 to 1910, which did not reproduce the coral $\delta^{18}O$ results, but did verify with gridded SST.

This study takes a closer examination of the coral Sr/Ca calibration by verification over a century against the independent data set HadISST1.1 [*Rayner, et al.*, 2003] extracted from a 1º-grid centered on Amédée Island (22.5ºS, 166.5ºE). The mean of HadISST_AI for Amédée Island is greater than the mean of the in situ SST (Δ = 1.16 ºC) for the period 1967 to 1999. The difference between the gridded SST data products and in situ SST at Amédée Island and Uitoé has previously been observed [*Delcroix and Lenormand*, 1997; *Crowley, et al.*, 1999; *Hénin and Cresswell*, 2005] and may be due to localized upwelling [*Hénin and Cresswell*, 2005; *Alory, et al.*, 2006; *Montaggioni, et al.*, 2006; *Ourbak, et al.*, 2006], water depth for in situ SST measurements (10 m), time of day for in situ measurements (7 AM; c.f., Section 2), and in situ measurement method bias (bucket measurement versus deployed instrument). Verification was conducted in two reference frames: HadISST_AI adjusted to the in situ SST record (adj. HadISST), and HadISST_AI and coral Sr/Ca-SST normalized.

This study adopted of verification statistics from dendroclimatology [*Fritts,* 1976; *Fritts, et al.*, 1979; *Fritts, et al.*, 1990] to quantify the level of verification (Table 14). The correlation test between the coral Sr/Ca-SST and the independent SST is highly significant (Table 14) for all intervals examined, and the coral Sr/Ca-SST shares 86% of the HadISST_AI variance. The sign test is a nonparametric test of similarity between data sets that examines the direction of change with no consideration for magnitude [*Fritts*, 1976; *Fritts, et al.*, 1990]; the sign test found a high percentage of shared similarity for both monthly coral Sr/Ca-SST variations and coral Sr/Ca-SST anomalies for all intervals examined (Table 14). The reduction of error test is similar to the correlation coefficient squared and measures the association between predicted values and the independent data set where values close to +1 indicate high agreement [*Lorenz,* 1956; *Fritts*, 1976]; the reduction of error calculated for all intervals examined and found significant agreement ($p < 0.01$) between the records (Table 14). The product-means test is similar to the reduction of error test; however, magnitudes are considered, and the significance is tested using the t statistic [*Fritts, et al.*, 1979]. The product-means test for all intervals examined found significant agreement ($p < 0.01$) between coral Sr/Ca-SST and HadISST_AI for all intervals examined (Table 14). The verification error between coral Sr/Ca-SST and the HadISST_AI for the 20th century interval is 0.19 ºC less than the standard error of the calibration interval. The residuals over time exhibit dominance in positive residuals from 1967 to 1985 and a dominance of negative residuals from 1985 to 2000 (Figure 17c) and this pattern in the residuals may be attributed to a negative trend of 0.6 ºC over the 33-year in situ SST record that is not present in either the coral Sr/Ca or HadISST_AI during this time interval. The negative trend in the in situ SST may be a source of some of the error due to regression fitting mostly high frequencies rather than low frequencies. Overall, the calibration and verification tests demonstrate the transfer function for the monthly stack coral Sr/Ca-SST verifies in both the calibration interval and for 20th century with HadISST_AI.

The stack coral Sr/Ca record exhibits a strong coherence with the in situ SST and the 1º gridded SST data set HadISST_AI (Figure 17). The HadISST1.1 global SST database [*Rayner, et al.*, 2003] does not include the number of observations for each grid box; however, HadISST1.1 database includes SST observations from the COADS SST database [*Woodruff, et al.*, 1987; *Woodruff, et al.*, 1998] which does include the number of observations and Figure 17d shows the number of observations from the COADS database [*Woodruff, et al.*, 1998] that correspond to the 2º-grid box for Amédée Island (centered on 23ºS, 167ºE). The coherence with the gridded SST HadISST_AI is high for the late 20th century, which corresponds to a time when the number of SST observations is high (Figure 17) and when satellites are used to estimate SST around the globe. The misfit between the coral Sr/Ca-SST record and the gridded SST record is greatest in the early 20th century, a time when the number of observations in the gridded SST product is low (Figure 17). The coral Sr/Ca-SST reconstruction exhibits decadal-scale fluctuations that exceed those observed in the gridded SST time series (Figure 17), which may reflect true differences between the SST at a shallow reef site and those averaged over a 1˚-grid box or they may reflect inadequacies in the methodology used to create the gridded SST product when few observations are available. The one exception occurs during the period 1942 to 1946 when the number of observations sharply increases (Figure 17d). During World War II, Nouméa served as a base for Allied operations in the Pacific and the increase in naval activity during this time is the reason for the increase in observations. During this period, the residuals between gridded SST and the predicted SST decreases. Therefore, careful examination of SST data products is needed when these products are used for calibrating coral-based paleothermometers.

5.6 Coral Sr/Ca and $\delta^{18}O$ Variations

The stack average monthly coral $\delta^{18}O$ was evaluated using the same techniques applied to the stack coral Sr/Ca record (Appendix B). The correlation between the stack coral $\delta^{18}O$ and SST increased slightly compared with *Stephans et al.* [2004] due to adjustments made to the chronology. The transfer function for stack coral $\delta^{18}O$ to SST was calculated using the MLE regression similar to the coral Sr/Ca-SST transfer function for the period 1967 to 1999 ($r = 0.89$, $p < 0.05$, $n = 392$).

$$SST(^{\circ}C) = -6.42(\pm 0.55, 2\sigma) + \delta^{18}O(‰) * -6.85(\pm 0.13, 2\sigma) \qquad (4)$$

$$\delta^{18}O(‰) = -0.936(\pm 0.064, 2\sigma) + SST(^{\circ}C) * -0.146(\pm 0.003, 2\sigma) \qquad (5)$$

The standard error of regression ($\sigma_{reg} = 1.17$ ºC) was calculated using effective degrees of freedom ($dof = 105$). Unlike coral Sr/Ca, the RMA and OLS solutions for the monthly stack coral $\delta^{18}O$ are significantly different from each other ($p > 0.05$); however, they are not significantly different from the MLE solution. The MLE coral $\delta^{18}O$-SST transfer function is significant different ($p > 0.05$) from the *Stephans et al.* [2004] transfer function; however, the OLS solution for this study is not significantly different from

Stephans et al. [2004]. *Quinn et al.* [1998] generated $\delta^{18}O$-SST transfer functions based on 92-PAA1 using different resolutions (monthly, quarterly, and mean annual) and both in situ SST from Amédée Island and 1º gridded SST data set from GISST2 [*Parker, et al.*]. The monthly stack coral $\delta^{18}O$-SST transfer function from this study has a closer agreement with the mean annual equations from *Quinn et al*. [1998] which used the GISST2 for the SST data set. Calibration and verification tests of coral $\delta^{18}O$-SST with HadISST_AI reveal agreement in the calibration interval (1967 to 1999) and 1950 to 1900; however, the agreement declines for the early 20th century (Figure 13c); a similar lack of verification for coral $\delta^{18}O$ was noted by *Crowley et al*. [1999].

Paired analysis of coral Sr/Ca and $\delta^{18}O$ has been used in the reconstruction of sea surface salinity via its relation with $\delta^{18}O_{sw}$ [*McCulloch, et al.*, 1994; *Gagan, et al.*, 1998; *Ren, et al.*, 2003]. *Stephans et al*. [2004] assessed the fidelity of the $\delta^{18}O_{sw}$ reconstruction for Amédée Island against the in situ SSS measurements for the period 1973 to 1992 and found a modest fit between $\delta^{18}O_{sw}$ determined from coral geochemistry and in situ SSS ($r < 0.33$). Similar results were found by *Ourbak et al.* [2006] at Uitoé, 36 km north of Amédée Island (Figure 1). This study made a similar assessment of $\delta^{18}O_{sw}$ using the stack coral Sr/Ca and stack coral $\delta^{18}O$ records for the period 1973 to 1999 and the enhancements made by this study did not improve the determination of monthly $\delta^{18}O_{sw}$ from coral geochemistry in comparison to the in situ SSS record (r = 0.31, $p < 0.05$, $n = 271$; see Appendix D). As noted by *Stephans et al*. [2004], the in situ SSS record at Amédée Island has a small range (35.78 ± 0.54 psu, 2σ; Figure 2) compared with salinity range at the Great Barrier Reef, Australia [*McCulloch, et al.*, 1994] and the actual seawater $\delta^{18}O$ signal may be less than the error magnitude in the pair analysis of coral Sr/Ca and $\delta^{18}O$. *Ourbak et al*. [2006] determined the $\delta^{18}O$ of monthly seawater samples from Amédée Island for the period 1999 to 2003 and found the seawater $\delta^{18}O$ varied by ±0.17‰ VSMOW (2σ) and SSS varied by ±0.46 psu (2σ) giving a slope of 0.255 psu ‰$^{-1}$ VSMOW. The standard deviation of the $\delta^{18}O_{sw}$ determined from coral geochemistry (±0.33‰ VSMOW, 2σ) is twice the standard deviation of the seawater samples and applying the *Ourbak et al.* [2006] slope to the coral $\delta^{18}O_{sw}$ calculation gives a predicted SSS with a standard deviation more than two times greater than the observed SSS (±1.31 psu predicted from coral versus ±0.54 psu observed, 2σ). The standard deviation of our predicted $\delta^{18}O_{sw}$ and SSS is unrealistic and may reflect inadequacies in determining SSS from coral geochemistry due to error propagation and small variability in $\delta^{18}O_{sw}$ and SSS at this location. The high correlation of monthly stack coral $\delta^{18}O$ with SST ($r = -0.89$, $p < 0.05$, $n = 392$) indicates the coral $\delta^{18}O$ shares ~79% of its variance with SST and the magnitude of the $\delta^{18}O_{sw}$ signal in the coral $\delta^{18}O$ is small compared to the SST signal. The in situ SSS at Amédée Island does not vary greatly and the monthly climatology shows the SSS lags SST and rainfall by 1 to 2 months (Figure 2) and lacks a strong annual cycle in SSS compared to SST (see Appendix D).

The inability to capture monthly SSS variability using paired analysis of coral geochemistry in the last 28 years of the 20th century does not prevent the discussion of changes in $\delta^{18}O_{sw}$ for the 20th century. The 0.6 ºC trend for 20th century was observed in the monthly and annual coral Sr/Ca-SST (Figure 13 and 14). Comparison of the monthly stack coral Sr/Ca record with the seasonally resolved coral $\delta^{18}O$ record from this site showed coherence in the latter half of the 20th century but these records diverge (2.5 to 3 ºC) in the early 20th century suggestive of a change in seawater $\delta^{18}O$ (Figure 13). This observation is supported by a new monthly resolved coral $\delta^{18}O$ record (92-PAA1 for the period 1921 to 1936), which closely matches the previous seasonally resolved $\delta^{18}O$ record [*Quinn, et al.*, 1998] (Figure 13). The 2.5 to 3 ºC trend observed in the monthly and seasonal coral $\delta^{18}O$ from 1900 to 1945 (Figure 13, see Appendix D) is consistent with decreasing seawater $\delta^{18}O$, which implies a freshening of surface seawater at Amédée Island for this period. However, without a realistic relationship to equate $\delta^{18}O_{sw}$ to SSS it is not possible to assign a magnitude to the freshening. *Hendy et al*. [2002] performed paired analysis of coral Sr/Ca and $\delta^{18}O$ for the Great Barrier Reef, Australia and observed a decrease in salinity after 1870.

6. Conclusions

This study assessed the effects of sampling resolution on coral skeletal geochemistry, the reproducibility of coral skeletal geochemistry at New Caledonia, and the relation between variations in skeletal geochemistry with SST and SSS at New Caledonia.

In terms of sampling resolution, it was determined that mean coral Sr/Ca and $\delta^{18}O$ values do not change significantly as a function of sampling resolution. Similarly, no change in the mean for the in situ daily SST was observed between daily SST filtered over increasing intervals. A similar pattern was observed in the in situ SST record; however, the percent reduction in variance was smaller. The use of the continuous routing method for coral sampling results in smoothing of high frequencies (i.e., lunar or tidal) if indeed these signals are present in the coral geochemistry record. The increased sampling resolution produced smaller smoothing intervals thus increasing the resolution of the high/lows of the seasonal cycle and inflating the amplitude of the seasonal cycle; however, the inflation is not linear, but decreases with increasing resolution.

In terms of the reproducibility of coral skeletal geochemistry, multiple tests were performed. First, when the growth direction of the corallites is ~vertical and the sampling path is parallel to the major growth axis the variability between adjacent parallel sampling paths on the same coral slab is negligible for coral Sr/Ca determinations from Amédée Island, New Caledonia. Examination of corallites under magnification may be necessary to determine corallite configuration in coral species such as *Porites* where the corallites are relatively small. Second, coral Sr/Ca records from parallel cores from the same colony and multiple cores from the same reef are highly reproducible and the correlation between the coral Sr/Ca records remained significant after removing the annual cycle. These results demonstrate that monthly resolved coral Sr/Ca variations from multiple cores from the same coral colony and from the same location are recording the same Sr/Ca signal and the monthly resolved Sr/Ca signal is environmental, not biological. The replication of the coral Sr/Ca using multiple cores over the 20th century increases confidence in extending the record back to 1675 AD.

In terms of the fidelity of the coral Sr/Ca-SST relation, it is noted that the coral Sr/Ca record exhibits a strong coherence with the in situ SST and gridded SST data products. The coherence with gridded SST is high during the late 20th century, which corresponds to a time with a high number of observations and the use of remote sensing techniques to estimate SST. The misfit between the coral Sr/Ca-SST record and the gridded SST record is greatest in the early 20th century, a time when the number of observations in the gridded SST product is low. The monthly coral Sr/Ca-SST reconstruction exhibits decadal-scale fluctuations that exceed those observed in the gridded SST time series, which may reflect true differences between the SST at a shallow reef site and those averaged over a 1°-grid box or they may reflect inadequacies in the methodology used to create the gridded SST product when few observations are available. Careful examination of the SST data products is needed when they are used for calibrating coral-based paleothermometers.

The comparison of monthly coral Sr/Ca records with a seasonally resolved coral $\delta^{18}O$ record from this site showed coherence in the latter half of the 20th century, but these records diverge in the early 20th century suggestive of a change in seawater $\delta^{18}O$. This observation is supported by a new monthly resolved $\delta^{18}O$ record, which closely matches the previous seasonally resolved $\delta^{18}O$ record. A ~0.6 ºC warming trend is observed in the coral Sr/Ca-SST record. The trend observed in the coral $\delta^{18}O$ is consistent with decreasing seawater $\delta^{18}O$ from 1900 to 1945, which implies a freshening of surface seawater at Amédée Island however, without a realistic relationship to equate $\delta^{18}O_{sw}$ to SSS, it is not possible to assign a magnitude to the freshening.

Tables and Figures

Table 1. Summary of replication studies for coral-based climate reconstructions.

Coral Genus	Location	# of cores	Sampling resolution	$\delta^{18}O$ offset (‰)	$\delta^{13}C$ offset (‰)	Sr/Ca offset (mmol/mol)	Correlation (*r*)	Years	Source
Local replication studies									
Hydnophora microconos	Tarawa Atoll	2	monthly	0.06 (±0.08)	0.30 (±0.04)			1960-1979	*Cole and Fairbanks, 1990; Shen et al., 1992*
Porites	Tarawa Atoll	2	monthly	Excellent				1893-1989	*Cole et al., 1993*
Pavona clavus and gigantea	Galapagos Islands	2	annual monthly	0.40 (±0.07) species offset				Do not overlap	*Dunbar et al., 1994*
Porites	Wheeler and Davies Reef, GBR	7	submonthly			0.5 °C		1964-1985	*Ailbert and McCulloch, 1997*
Porites	Nauru Island	2	subannually	0.2	0.3			1952-1995	*Guilderson and Schrag, 1999*
Porites	Clipperton Atoll	6	subannually	0.4				1986-1994	*Linsley et al., 1999*
Porites	Maiana Atoll	4	bimonthly				0.78	1840-1994	*Urban et al., 2000*
Diploria	Bermuda	2	subannually	0.6		0.22		1971-1984	*Cardinal et al., 2001*
Porites	Palmyra	>12	monthly	<±0.05			0.67-0.87	past 1100	*Cobb et al., 2003b*
Porites	Red Sea	11	bimonthly	<1.28				1974-1998	*Felis et al., 2003*
Diploastrea	Fiji	2	monthly	0.13		0.01		1980-1996	*Bagnato et al., 2004*
Porites	New Caledonia	4	monthly	0.16 (±0.08)	1.14 (±0.06)	0.01 (±0.018)	>0.70 $\delta^{18}O$ >0.79 Sr/Ca	1967-1992	*Stephans, 2003; Stephans et al., 2004*
Porites	Fiji	2	monthly annual Sr/Ca	0.37 (±0.028)		0.14 (±0.15%)	0.77 $\delta^{18}O$ 0.47 Sr/Ca	1780-1997	*Linsley et al., 2006*
Porites	Rarotonga	3	monthly	<0.10 (±0.04)		<0.10 (±0.15%)	>0.71 $\delta^{18}O$ >0.08 Sr/Ca	1726-1997	*Linsley et al., 2006*
Montastrea faveolata	Looe Key, Florida	2	monthly	0.02 (±0.02)	0.04 (±0.06)	0.037 (±0.009)	0.57 $\delta^{18}O$ 0.53 Sr/Ca	1961-2001	*Smith et al., 2006*

Table 1. (Continued)

Coral Genus	Location	# of cores	Sampling resolution	$\delta^{18}O$ offset (‰)	$\delta^{13}C$ offset (‰)	Sr/Ca offset (mmol/mol)	Correlation (*r*)	Years	Source
Regional replication studies									
Porites	Arabian Sea	2	monthly	0.25	1.3			1973-1991	*Tudhope et al., 1996*
Porites	GBR, Indian Ocean, Indonesian	3	submonthly			0.3 °C		1988-1994	*Gagan et al., 1998*
Porites	Maiana Atoll, Tarawa, Aranuka	4	bimonthly				>0.66	1950-1989	*Urban et al., 2000*
Porites	Great Barrier Reef, Australia	8	pentannual			0.6 °C		1568-1983	*Hendy et al., 2002*

Analytical precision estimates reported in parenthesis. Sr/Ca offsets are reported as mmol/mol unless otherwise noted.

Table 2. Summary of coral-based paleoclimatological studies at Amédée Island, New Caledonia.

Study	**Geochemistry**	**Resolution (samples/cm)**	**Dates**	**Core**
Quinn et al., 1996	$\delta^{18}O$, $\delta^{13}C$	12	1951 - 1992	92-PAA1
Quinn et al., 1998	$\delta^{18}O$, $\delta^{13}C$	4	1675 - 1992*	92-PAA1
Crowley et al., 1997	$\delta^{18}O$	4	1675 - 1992*	92-PAA1
Crowley et al., 1999	$\delta^{18}O$	12	1898 - 1909*	92-PAA1
Corrége et al., 2001	Sr/Ca, U/Ca	12	1701 - 1761	92-PAA1
Quinn and Sampson, 2002	Sr/Ca, Mg/Ca, U/Ca, Ba/Ca	12	1968 - 1992	92-PAA1
Stephans, 2003 and Stephans et al., 2004	$\delta^{18}O$, $\delta^{13}C$, Sr/Ca $\delta^{18}O$, $\delta^{13}C$, Sr/Ca $\delta^{18}O$, $\delta^{13}C$, Sr/Ca	16 16 16	1966 - 1999* 1954 - 1999* 1965 - 1999*	92-PAC1 92-PAD1 99-PAA
This study	Sr/Ca Sr/Ca Sr/Ca Sr/Ca $\delta^{18}O$, $\delta^{13}C$	15 12 16 16 15	1900 - 1992 1900 - 1992 1950 - 1966 1937 - 1954 1920 - 1951	92-PAA1 92-PAA2 92-PAC1 92-PAD1 92-PAA1

* Dates adjusted to updated age model, not the original dates reported by authors.

Table 3. Multiple sampling resolutions compared between parallel paths.

	Fortnightly Sr/Ca (mmol/mol)	Monthly Sr/Ca (mmol/mol)	Fortnightly $\delta^{18}O$ (‰)	Monthly $\delta^{18}O$ (‰)	Seasonally $\delta^{18}O$ (‰)	Fortnightly $\delta^{13}C$ (‰)	Monthly $\delta^{13}C$ (‰)	Seasonally $\delta^{13}C$ (‰)
Mean	9.157	9.165	-4.36	-4.44	-4.53	-1.08	-1.15	-1.09
Median	9.149	9.164	-4.39	-4.48	-4.56	-1.10	-1.14	-1.10
Standard deviation	0.101	0.094	0.27	0.26	0.22	0.27	0.26	0.19
Variance	0.010	0.009	0.07	0.07	0.05	0.07	0.07	0.04
Maximum	9.352	9.343	-3.83	-3.86	-4.21	-0.48	-0.58	-0.79
Minimum	8.913	8.940	-4.94	-4.92	-4.87	-1.67	-1.66	-1.38
# of observations	149	149	121	65	16	121	65	16
Degrees of freedom	33	45	19	20	16	62	44	16
SE of mean	0.018	0.014	0.06	0.06	0.06	0.03	0.04	0.05
Average amplitude	-0.331	-0.285	-0.91	-0.79	-0.54	-0.38	-0.26	-0.18
% SD wrt fortnightly		6.9%		4.0%	15.7%		5.0%	26.9%
SD wrt fortnightly (°C)		0.13		0.62	1.16			

Calculations were performed over a common interval for all geochemistry (0 to 10.5 cm Sr/Ca, 0 to 4.6 cm for isotopes). Standard error (SE) of the mean calculated with effective degrees of freedom determined by Runs test. % reduction in standard deviation (SD) with respect to (wrt) either daily or fortnightly resolution.

Table 4. Filtered daily in situ SST measurements (ºC).

	Daily	Weekly	Fortnightly	Monthly	Seasonally
Mean	23.4	23.3	23.4	23.4	23.3
Median	23.2	23.3	23.3	23.3	23.0
Standard deviation	2.0	1.9	1.9	1.8	1.7
Variance	3.8	3.6	3.5	3.4	2.9
Maximum	29.0	28.6	28.2	27.6	26.5
Minimum	18.0	18.2	18.3	19.3	20.3
# of observations	10148	1409	697	317	100
Degrees of freedom	110	106	101	101	90
SE of mean	0.19	0.18	0.19	0.18	0.18
Average amplitude	11.0	10.4	9.9	8.2	6.2
% SD wrt daily		3.1%	4.3%	5.8%	12.7%
% SD wrt fortnightly				1.7%	8.9%
Precision	±0.2	±0.08	±0.05	±0.04	±0.02

Daily SST (ºC) measurements (±0.2 ºC) made by IRD at Amédée Island at 7 AM. Standard error (SE) of the mean calculated with effective degrees of freedom determined by Runs test. % reduction in standard deviation (SD) with respect to (wrt) either daily or fortnightly resolution.

Table 5. Coral Sr/Ca (mmol/mol) replication between parallel paths on 92-PAC1-A.

	1-PAC1	2-PAC1	Stack	Parallel path
Mean	9.185	9.178	9.182	9.172
Median	9.173	9.167	9.168	9.157
Standard deviation	0.099	0.104	0.101	0.115
Variance	0.010	0.011	0.010	0.013
Maximum	9.413	9.436	9.410	9.444
Minimum	8.994	8.982	9.000	8.929
# of observations	249	249	249	249
Degrees of freedom	69	67	69	69
SE of mean	0.012	0.013	0.012	0.014
Avg_{abs}	0.022 ± 0.018 (1σ)		0.031 ± 0.026 (1σ)	
Correlation	0.96		0.93	

1-PAC1 and 2-PAC2 are replicates from splits of coral powder samples, which were sampled along a path parallel to *Stephans et al*. [2004] on the coral section 92-PAC1-A (Figure 6). The determinations from each path were converted from depth space to time space for comparison. Stack is the average of each pair of determinations from 1-PAC1 and 2-PAC1. Standard error (SE) of the mean was calculated with effective degrees of freedom determined by Runs test. The average of the absolute differences (avg_{abs}) is the average of the absolute differences between each pair of monthly determinations. Correlations are significant ($p < 0.05$, $n = 249$).

Table 6. Coral Sr/Ca (mmol/mol) replication between parallel paths on opposing sides of 92-PAA1-A and 92-PAA1-B.

	92-PAA1-A original	92-PAA1-A opposing	92-PAA1-B original	92-PAA1-B opposing
Mean	9.194	9.214	9.113	9.188
Median	9.179	9.222	9.108	9.192
Standard deviation	0.095	0.089	0.104	0.104
Variance	0.010	0.007	0.011	0.011
Maximum	9.386	9.399	9.324	9.393
Minimum	9.000	9.017	8.838	8.959
# of observations	134	134	94	94
Degrees of freedom	38	38	30	28
SE of mean	0.015	0.014	0.019	0.020
Avg_{abs}	0.032 ±0.023 (1σ)		0.079 ± 0.047 (1σ)	
Correlation	0.93		0.87	

The determinations from each path were converted from depth space to time space for comparison. Standard error (SE) of the mean calculated with effective degrees of freedom determined by Runs test. The average of the absolute differences (avg_{abs}) is the average of the differences between each pair of monthly determinations. Correlations are significant ($p < 0.05$).

Table 7. Monthly coral Sr/Ca (mmol/mol) determinations from five coral records for the period 1967 to 1992.

	99-PAA	92-PAA1	92-PAA2	Stack PAA	92-PAC1	92-PAD1	Stack master	IRD SST	HadISST AI	Adj. HadISST
Mean	9.164	9.181	9.174	9.173	9.181	9.179	9.178	23.57	24.68	23.52
Median	9.158	9.176	9.173	9.170	9.167	9.167	9.170	23.63	24.70	23.53
Standard deviation	0.097	0.098	0.109	0.099	0.113	0.107	0.104	1.79	1.69	1.81
Variance	0.009	0.010	0.012	0.010	0.013	0.012	0.011	3.22	2.84	3.28
Maximum	9.345	9.388	9.419	9.374	9.448	9.452	9.397	27.60	27.81	26.88
Minimum	8.918	8.955	8.900	8.927	8.935	8.912	8.965	19.70	21.70	20.32
# of observations	304	304	304	304	304	304	304	304	304	304
DOF	84	84	84	84	84	84	84	84	84	84
SE of mean	0.011	0.011	0.012	0.011	0.012	0.012	0.011	0.20	0.18	0.20

Calculations were performed for the interval common for all records (1967 to 1992). Stack PAA is the average Sr/Ca of the three records (99-PAA, 92-PAA1, and 92-PAA2) from the same colony (PAA) and stack master is the average Sr/Ca of the three coral colonies (PAA, 92-PAC1, and 92-PAD1). IRD SST (ºC) is the in situ SST recorded offshore from Amédée Island. HadISST_AI (ºC) is the 1º-grid box extracted from HadISST1.1 database [*Rayner et al., 2003*] centered on Amédée Island (22.5ºS, 166.5ºE). Adj. HadISST (ºC) is HadISST_AI transformed to match the in situ IRD SST record (adj. HadISST = HadISST_AI*1.074 - 2.989). Standard error (SE) of the mean calculated with effective degrees of freedom (DOF) determined by Runs test.

Table 8. Monthly coral Sr/Ca (mmol/mol) determinations from five coral records for the 20th century.

	99-PAA	92-PAA1	92-PAA2	Stack PAA	92-PAC1	92-PAD1	Stack master	IRD SST	HadISST AI	Adj. HadISST
Mean	9.168	9.179	9.196	9.185	9.179	9.186	9.187	23.51	24.50	23.32
Median	9.169	9.176	9.197	9.186	9.168	9.175	9.184	23.57	24.52	23.35
Standard deviation	0.097	0.101	0.102	0.099	0.110	0.109	0.101	1.81	1.67	1.80
Variance	0.009	0.010	0.010	0.010	0.012	0.012	0.010	3.29	2.80	3.23
Maximum	9.361	9.400	9.430	9.407	9.448	9.452	9.407	27.60	28.04	27.13
Minimum	8.914	8.912	8.900	8.914	8.935	8.912	8.914	19.28	21.41	20.01
# of observations	414	1112	1098	1198	513	663	1198	394	1200	1200
DOF	92	284	288	309	135	174	309	106	307	307
SE of mean	0.010	0.006	0.006	0.006	0.009	0.008	0.006	0.18	0.10	0.10

Calculations were performed for the period 1900 to 2000. Monthly coral Sr/Ca records span 1965 to 2000 for 99-PAA; 1900 to 1992 for 92-PAA1 and 92-PAA2; 1937 to 1992 for 92-PAD1; and 1950 to 1992 for 92-PAC1. Stack PAA is the average of the three records (99-PAA, 92-PAA1, and 92-PAA2) from the same colony (PAA) and stack master is the average Sr/Ca of the three coral colonies (PAA, 92-PAC1, and 92-PAD1). IRD SST (ºC) is the in situ SST recorded offshore from Amédée Island. HadISST_AI (ºC) is the 1º-grid box extracted from HadISST1.1 database [*Rayner et al., 2003*] centered on Amédée Island (22.5ºS, 166.5ºE). Adj. HadISST (ºC) is HadISST_AI transformed to match the in situ IRD SST record (adj. HadISST = HadISST_AI*1.074 - 2.989). Standard error (SE) of the mean calculated with effective degrees of freedom (DOF) determined by Runs test.

Table 9. Correlation between monthly coral Sr/Ca variations and SST for the period 1967 to 1992.

	99-PAA	**92-PAA1**	**92-PAA2**	**Stack PAA**	**92-PAC1**	**92-PAD1**	**Stack master**	**IRD SST**	**HadISST AI**
99-PAA	1.00	0.93	0.93	0.98	0.89	0.91	0.95	-0.91	-0.91
92-PAA1	*0.65*	1.00	0.92	0.97	0.91	0.92	0.96	-0.91	-0.91
92-PAA2	*0.65*	*0.58*	1.00	0.98	0.91	0.92	0.96	-0.92	-0.92
Stack PAA	*0.88*	*0.86*	*0.87*	1.00	0.93	0.94	0.98	-0.94	-0.94
92-PAD1	*0.48*	*0.57*	*0.55*	*0.62*	0.92	1.00	0.98	-0.91	-0.93
92-PAC1	*0.37*	*0.52*	*0.48*	*0.53*	1.00	*0.54*	0.97	-0.93	-0.92
Stack master	*0.67*	*0.76*	*0.74*	*0.83*	*0.83*	*0.86*	1.00	-0.95	-0.95
IRD SST	*-0.46*	*-0.47*	*-0.44*	*-0.53*	*-0.49*	*-0.41*	*-0.56*	1.00	0.96
HadISST_AI	*-0.45*	*-0.48*	*-0.45*	*-0.53*	*-0.41*	*-0.45*	*-0.55*	*0.64*	1.00

Stack PAA is the average of the three records (99-PAA, 92-PAA1, and 92-PAA2) from the same colony (PAA) and stack master is the average Sr/Ca of the three coral colonies (PAA, 92-PAC1, and 92-PAD1). IRD SST (ºC) is the in situ SST recorded offshore from Amédée Island. HadISST_AI (ºC) is the 1º-grid box extracted from HadISST1.1 database [*Rayner et al., 2003*] centered on Amédée Island (22.5ºS, 166.5ºE). Correlations between monthly anomalies appear in italic. Anomalies are calculated as difference between each monthly measurement and the average Sr/Ca value for each month for the interval 1967 to 1992. All correlations are significant ($p < 0.05$, $n = 304$).

Table 10. Correlation between monthly coral Sr/Ca variations and SST for the 20th century.

	99-PAA	**92-PAA1**	**92-PAA2**	**Stack PAA**	**92-PAC1**	**92-PAD1**	**Stack master**	**IRD SST**	**HadISST_AI**
99-PAA	1.00	0.93	0.93	0.98	0.90	0.91	0.96	-0.91	-0.90
92-PAA1	*0.65*	1.00	0.91	0.97	0.90	0.91	0.96	-0.91	-0.93
92-PAA2	*0.64*	*0.46*	1.00	0.98	0.91	0.91	0.96	-0.91	-0.92
Stack PAA	*0.92*	*0.84*	*0.86*	1.00	0.93	0.94	0.99	-0.92	-0.94
92-PAD1	*0.49*	*0.47*	*0.52*	*0.58*	0.92	1.00	0.98	-0.91	-0.94
92-PAC1	*0.39*	*0.48*	*0.53*	*0.57*	1.00	*0.51*	0.98	-0.93	-0.93
Stack master	*0.80*	*0.76*	*0.79*	*0.92*	*0.82*	*0.86*	1.00	-0.93	-0.95
IRD SST	*-0.54*	*-0.46*	*-0.44*	*-0.58*	*-0.49*	*-0.41*	*-0.61*	1.00	0.94
HadISST_AI	*-0.48*	*-0.44*	*-0.45*	*-0.52*	*-0.41*	*-0.49*	*-0.53*	*0.60*	1.00

Stack PAA is the average of the three records (99-PAA, 92-PAA1, and 92-PAA2) from the same colony (PAA) and stack master is the average Sr/Ca of the three coral colonies (PAA, 92-PAC1, and 92-PAD1). IRD SST (ºC) is the in situ SST recorded offshore from Amédée Island. HadISST_AI (ºC) is the 1º-grid box extracted from HadISST1.1 database [*Rayner et al., 2003*] centered on Amédée Island (22.5ºS, 166.5ºE). Correlations between anomalies appear in italic. Anomalies are calculated as difference between each monthly measurement and the average Sr/Ca value for each month for the interval 1967 to 1992. The number of observations for each core is reported in Table 8. Monthly coral Sr/Ca records span 1965 to 1999 for 99-PAA; 1900 to 1992 for 92-PAA1 and 92-PAA2; 1937 to 1992 for 92-PAD1; and 1950 to 1992 for 92-PAC1. All correlations are significant ($p < 0.05$).

Table 11. Average absolute offset (avg_{abs}) between monthly coral Sr/Ca determinations (mmol/mol) for the 20th century.

	99-PAA	**92-PAA1**	**92-PAA2**	**92-PAD1**	**92-PAC1**
99-PAA		0.033	0.034	0.037	0.043
92-PAA1			0.038	0.037	0.038
92-PAA2				0.036	0.035
92-PAD1					0.034
Overall					0.036

The average of the absolute offset (avg_{abs}) is the average of the differences between each pair of monthly determinations. The cores 99-PAA, 92-PAA1, and 92-PAA2 are from the same coral colony (PAA) and the cores 92-PAD1 and 92-PAC1 are from coral colonies in close proximity to PAA.

Table 12. Correlation between annual average coral Sr/Ca variations and SST for the 20th century.

	99-PAA	**92-PAA1**	**92-PAA2**	**Stack PAA**	**92-PAC1**	**92-PAD1**	**Stack master**	**IRD SST**
99-PAA	1.00							
92-PAA1	0.61	1.00						
92-PAA2	0.74	0.50	1.00					
Stack PAA	0.92	0.81	0.89	1.00				
92-PAC1	*0.33*	0.58	0.54	0.62	1.00			
92-PAD1	0.50	0.52	0.61	0.67	0.62	1.00		
Stack master	0.76	0.80	0.84	0.95	0.85	0.89	1.00	
IRD SST	-0.52	*-0.30*	*-0.20*	-0.50	-0.43	*-0.22*	-0.51	1.00
Adj HadISST_AI	-0.62	-0.59	-0.56	-0.68	-0.52	-0.56	-0.69	0.70
# of observations	34	93	91	100	42	55	100	32

Annual averages were calculated for a climatological year (April to March). Stack PAA is the average of the three records (99-PAA, 92-PAA1, and 92-PAA2) from the same colony (PAA) and stack master is the average Sr/Ca of the three coral colonies (PAA, 92-PAC1, and 92-PAD1). IRD SST (ºC) is the in situ SST recorded offshore from Amédée Island. HadISST_AI (ºC) is the 1º-grid box extracted from HadISST1.1 database [*Rayner et al., 2003*] centered on Amédée Island (22.5ºS, 166.5ºE). The number of observations for each series is listed; however, each series spans a different period of time: 1965 to 1999 for 99-PAA; 1900 to 1992 for 92-PAA1 and 92-PAA2; 1950 to 1992 for 92-PAC1; and 1937 to 1992 for 92-PAD1. Correlations are significant ($p < 0.05$) except correlations in italic are not significant (number of observations common to both series < 26).

Table 13. Coral Sr/Ca to SST transfer functions for New Caledonia.

	Coverage	***R***	**Slope**	**Error (2σ)**	**Intercept**	**Error (2σ)**	**Error (ºC)**
x = SST, y = Sr/Ca							
MLE	1967-1999	-0.93	-0.0540	±0.001	10.449	±0.013	1.35
RMA	1967-1999	-0.93	-0.0560	±0.002	10.494		1.30
OLS	1967-1999	-0.93	-0.0522	±0.002	10.403	±0.048	1.37
Stephans et al., 2004	1967-1992	-0.93	-0.0504	±0.002	10.331	±0.055	0.67
Quinn and Sampson, 2002 OLS	1967-1992	-0.91	-0.052		10.073		0.86
Quinn and Sampson, 2002 RMA	1967-1992	-0.91	-0.057		10.12		0.78
Corrège, 2006	1993-1999	-0.96	-0.0576		10.407		
Montaggioni et al., 2006	1988-1996	-0.92	-0.081		11.08		1.3
Ourbak et al., 2006 ICP AES	1993-2002	-0.80	-0.054	±0.014	10.248	±0.360	
Ourbak et al., 2006 ICP MS	1993-2002	-0.74	-0.062	±0.014	10.451	±0.346	
Corrège et al., 2006	1981-1990	-0.79	-0.0657		10.73		1.3
x = Sr/Ca, y = SST							
MLE	1967-1999	-0.93	-18.514	±0.187	193.45	±1.719	1.35
RMA	1967-1999	-0.93	-17.844	±0.651	187.25		1.30
OLS	1967-1999	-0.93	-16.619	±0.653	176.01	±5.991	1.28
Beck et al., 1992	1980-1986		-16.013		171.6		

All corals used in the investigations were collected in the vicinity of Amédée Island except *Corrège et al*. [2006] and *Ourbak et al*. [2006] used corals collected from Uitoé, 36 km north of Amédée Island. All studies were sampled with monthly sampling resolution except *Ourbak et al*. [2006] (20 samples/year). *Montaggioni et al*. [2006] used maximum and minimum values only for OLS regression. The multiple correlation coefficient (*R*) is the square root of the goodness of fit statistic and is algebraically equivalent to correlation coefficient (*r*). For this study, the regression error was determined using effective degrees of freedom determined by Runs test. Color groups reflect investigations performed in the same laboratory. University of South Florida (blue) uses ICP-OES following *Schrag* [1999] methodology using an internal laboratory standard Sr/Ca (IGS, PL). University of California at Santa Cruz (green) uses SF-ICP-MS. IRD center in Bondy, France (red) following *Le Cornec and Corrège* [1997] methodology using an internal laboratory standard Sr/Ca (NC20) with ICP-MS. *Beck et al*. [1992] used TIMS.

Table 14. Calibration and verification statistics for coral Sr/Ca-SST determined by MLE.

	1967-2000	1900-2000	1950-2000	1900-1950
Correlation	0.93	0.95	0.94	0.96
Correlation - anomalies	0.54	0.54	0.57	0.44
Sign test	93%	94%	93%	95%
Sign test - anomalies	72%	71%	72%	71%
Reduction of error	0.85	0.67	0.81	0.86
Product-mean	16.25	32.88	21.58	27.54
Product means - anomalies	7.17	12.53	8.70	9.47
# of observations	392	1198	598	600
DOF	105	307	157	162
Regression error (ºC)	1.34			
Verification error (ºC)	1.38	1.19	1.28	1.07
Avg_{abs} (ºC)	0.42	0.46	0.50	0.42

The transfer function for coral Sr/Ca to in situ SST was determined using MLE regression [*York and Evensen*, 2004] using errors in both Sr/Ca and SST for the period 1967 to 1999 ($R = 0.93$. $p < 0.05$, $n = 392$). The transfer function for coral Sr/Ca to SST was verified against the independent data set HadISST_AI (ºC), which is the 1º-grid box, extracted from HadISST1.1 database [*Rayner et al., 2003*] centered on Amédée Island (22.5ºS, 166.5ºE). Verification statistics from dendroclimatology were utilized to verify the transfer function which include the sign test, reduction of error, and product-mean test [*Fritts*, 1976; *Fritts, et al.*, 1979]. Sign test and product-mean test are significant at the 99% confidence level. Regression error and verification error was determined using effective degrees of freedom (*dof*) determined by Runs test. The average of the absolute differences (avg_{abs}) is the average of the absolute differences between each pair of monthly determinations.

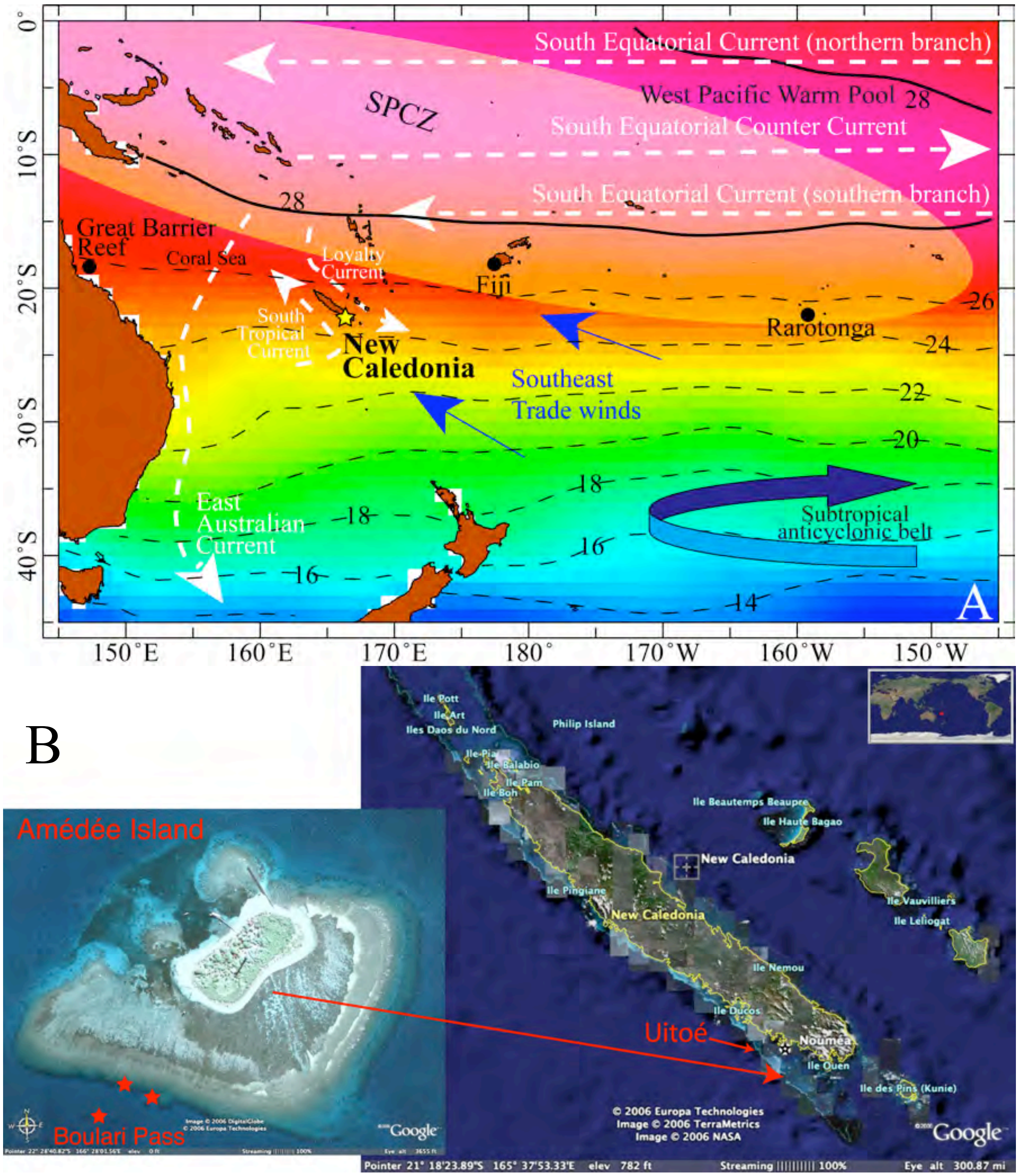


Figure 1. Map of the Southwest Pacific, New Caledonia, and Amédée Island. (a) New Caledonia is located in the southwest tropical Pacific Ocean. Map shows annual average SST (ºC) contours [*Levitus and Boyer*, 1994]. (b) Amédée Island (22º28.5′S, 166º28.0′E) is located off the southwest coast of New Caledonia, 20 km south of Nouméa, behind the barrier reef and within the Boulari Pass. The reefs offshore of Amédée Island are well bathed by open-ocean waters and the reefs do not appear to be subjected to freshwater input from the mainland [*Quinn, et al.*, 1996]. This study sampled *Porites lutea* coral colonies located within Boulari Pass (★ on inset photo).

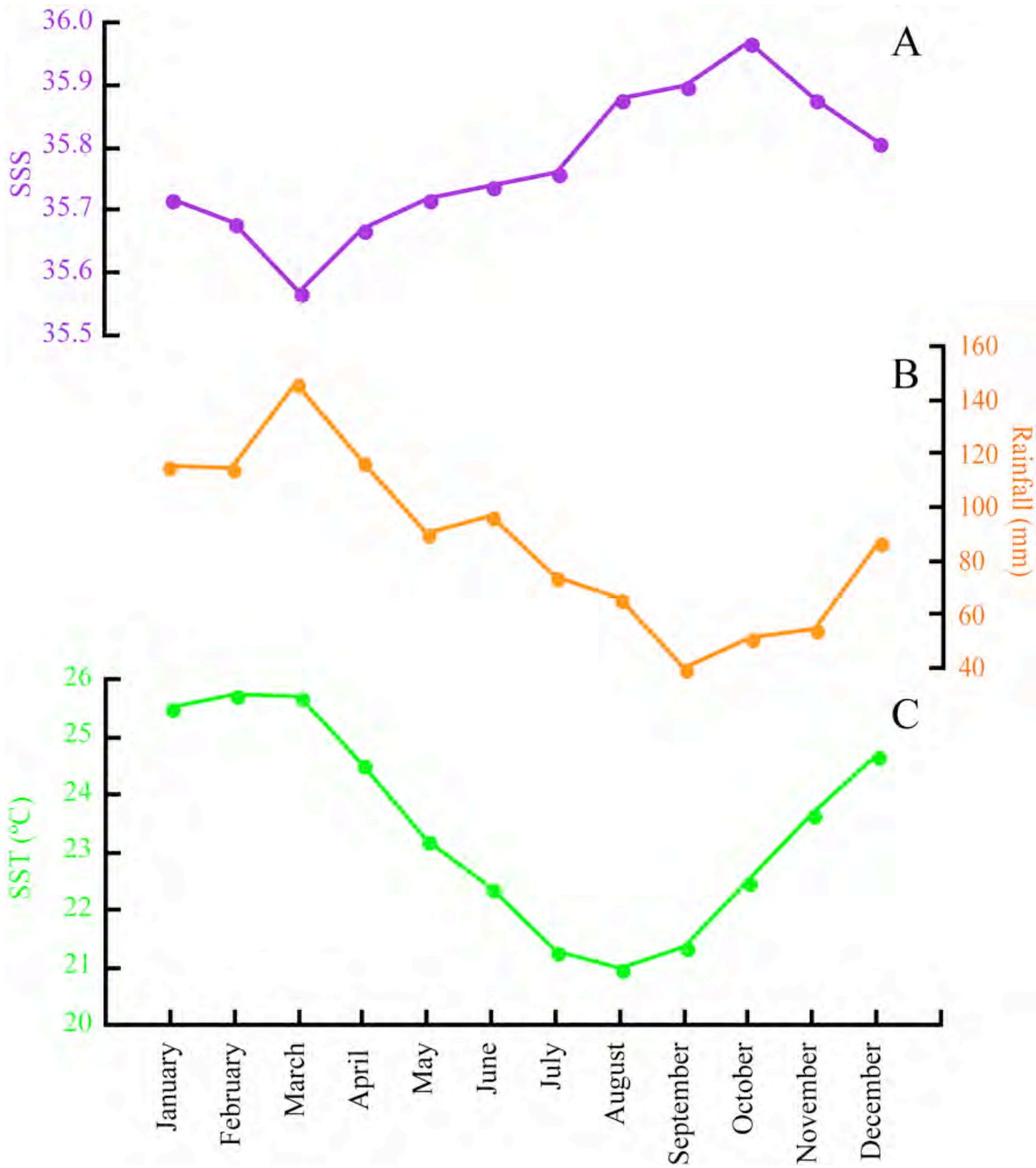


Figure 2. Monthly climatology of Amédée Island, New Caledonia. (a) Mean monthly SSS for 1974 to 1999. (b) Mean monthly rainfall for 1974 to 1999 for Nouméa, New Caledonia archived by the Global Historical Climate Network [*Peterson and Vose*, 1997]. The summer rainfall peaks coincide with minimum SSS. (c) Mean monthly SST for 1967 to 1999. IRD measured SST and SSS daily at Amédée Island since 1967 [*Delcroix and Lenormand*, 1997] and monthly averages of SST and SSS were calculated from daily measurements. New Caledonia experiences warm and wet summers when the SPCZ is in its southernmost location (Figure 1). When the SPCZ moves north in the winter, temperature drops and rainfall decreases [*Morliere and Rebert*, 1986].

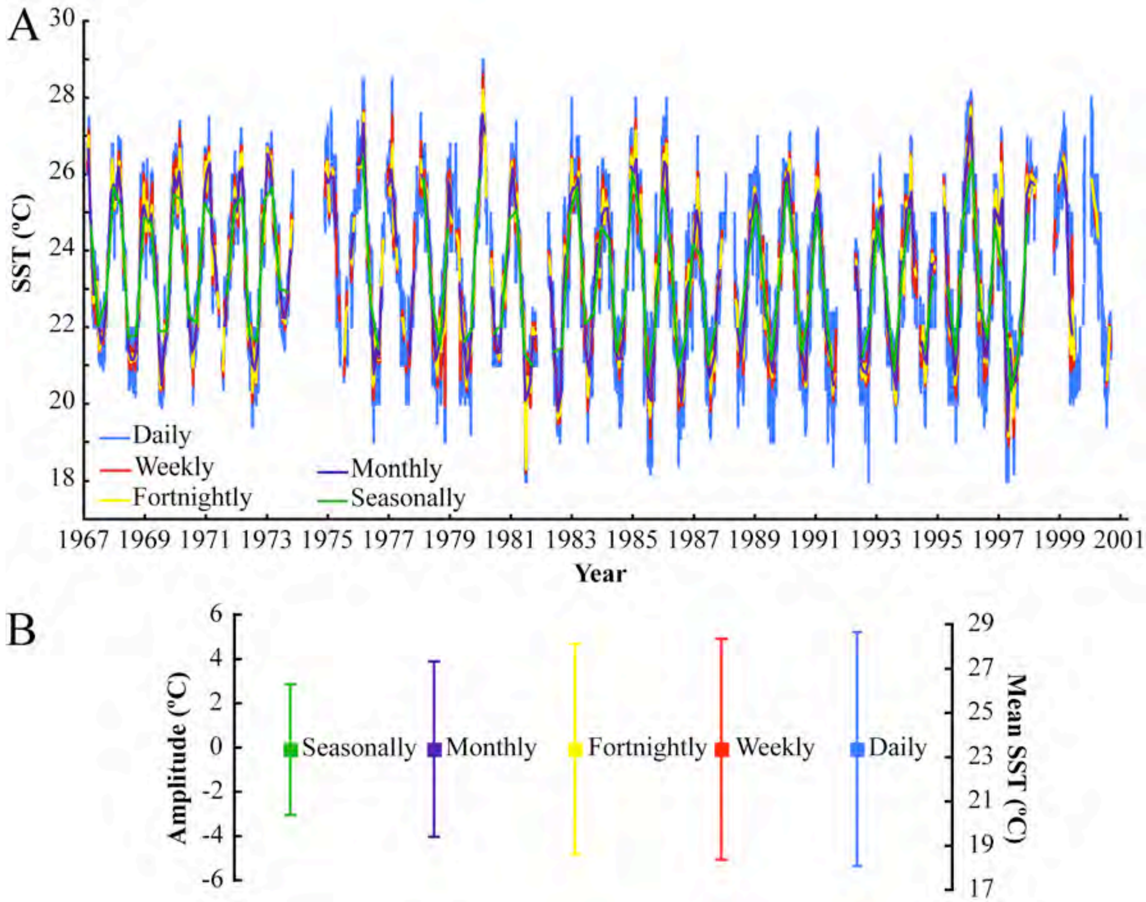
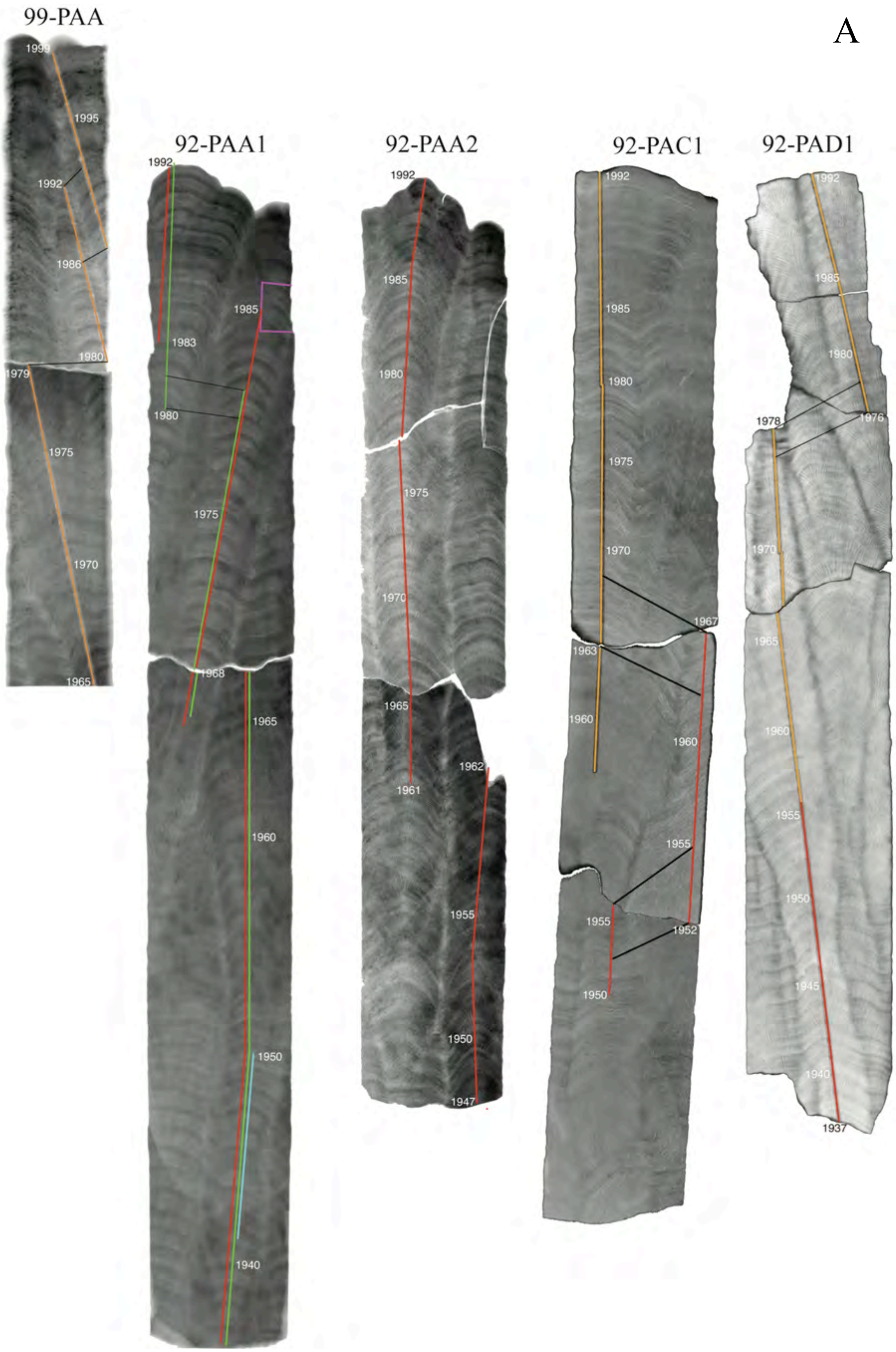


Figure 3. Filtered daily SST measurements from Amédée Island, New Caledonia. (a) Comparison of daily in situ SST in situ measurements (±0.2 ºC) filtered to various resolutions using a finite impulse response (FIR) filter. (b) Amplitude for each resolution calculated by subtracting the minimum SST from the maximum SST. The amplitude and standard deviation decrease with deceasing resolution. The means are not significantly different (Table 4).



A
99-PAA
1999
1995
1992
1986
1980
1979
1975
1970
1965
92-PAA1
1992
1985
1983
1980
1975
1968
1965
1960
1950
1940
92-PAA2
1992
1985
1980
1975
1970
1965
1962
1961
1955
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1947
92-PAC1
1992
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1967
1963
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1992
1985
1980
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1945
1940
1937

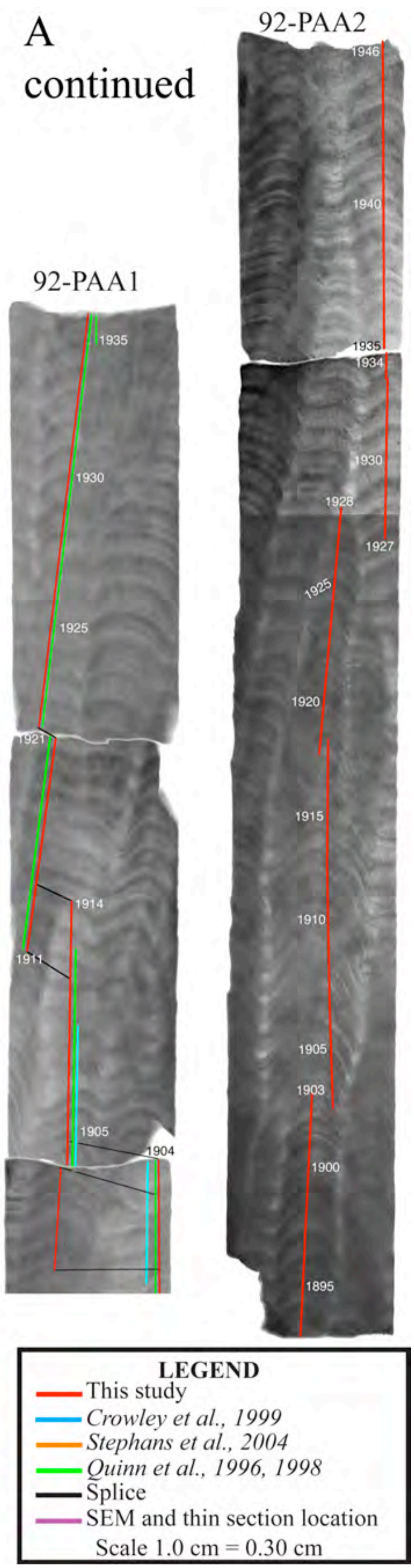

Figure 4. Coral cores sampled in this study. (a) X-radiograph positive images of five *Porites lutea* coral cores collected offshore of Amédée Island, New Caledonia. The labels for each core appear across the top, the youngest band (1999) occurs on the top of 99-PAA, and dates appear in white. Sampling paths are approximately parallel to the coral's vertical central growth axis. Sampling paths used in this study and previous studies are labeled different colors. Splices between coral drill paths are marked with black lines.

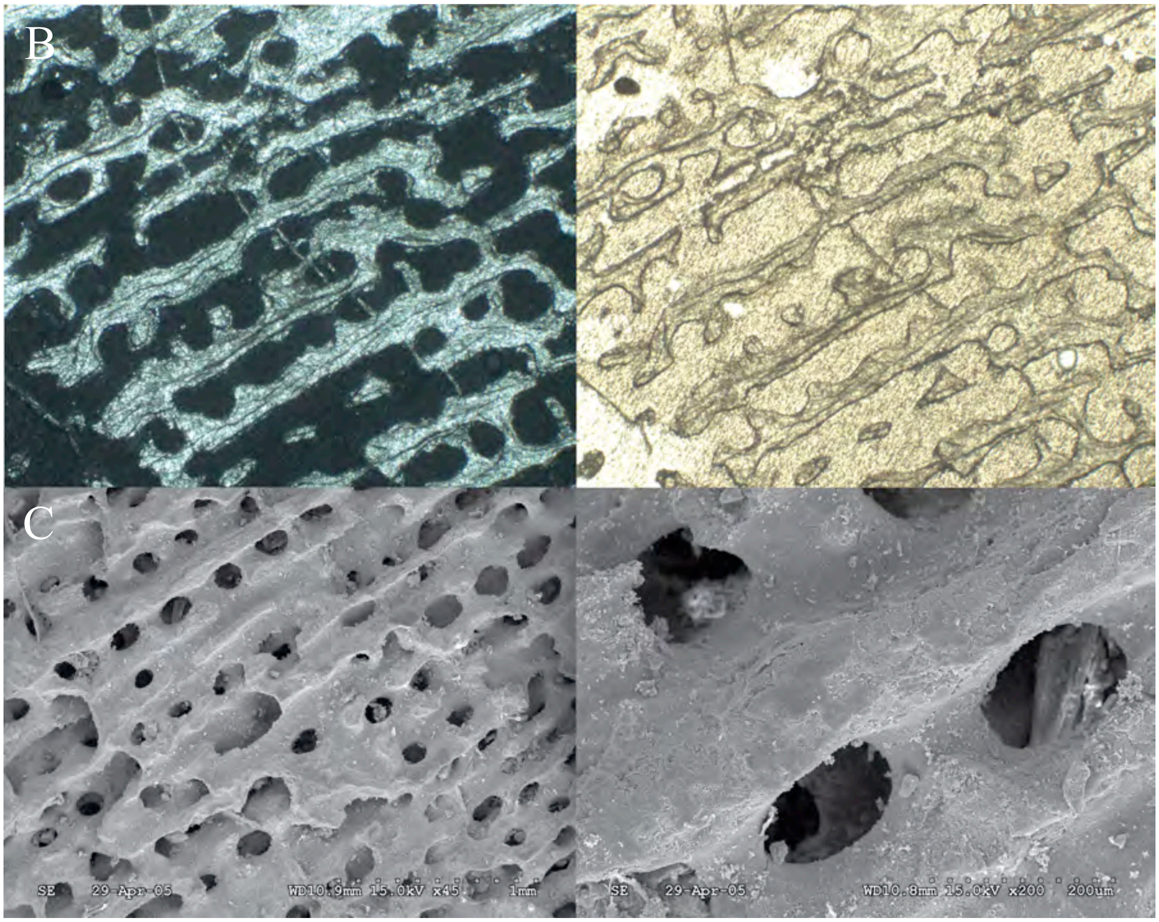

Figure 4. continued. (b) Thin section photomicrographs viewed under cross-polarized light plane (left) and transmitted light (right; field of view equals 2.6 mm in each). (c) SEM images were magnified by 45 (left) and 200 (right). Thin sections and SEM images were examined from the top of the core 92-PAA1 (Figure 4a) for the presence of secondary minerals; none were observed.

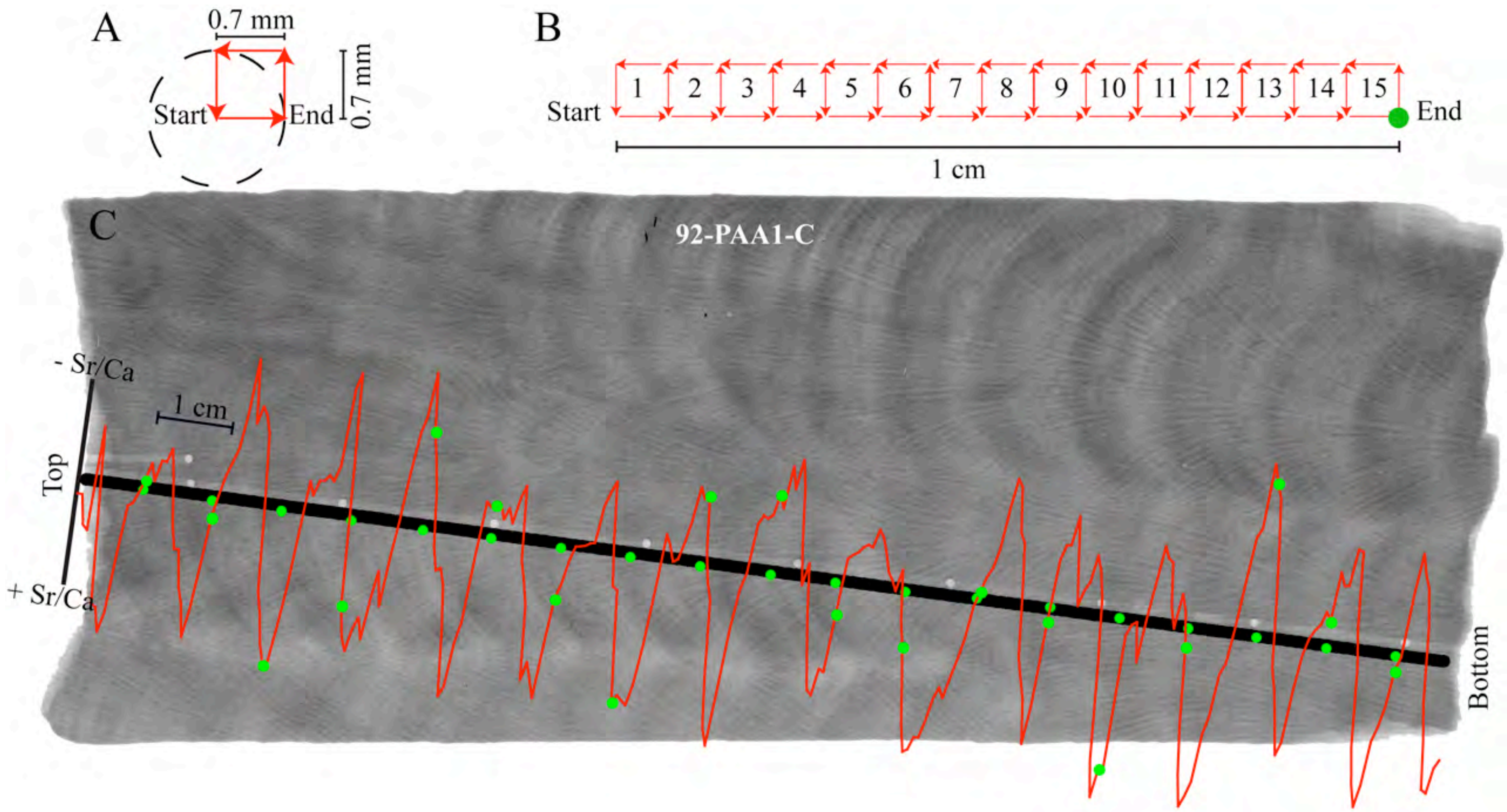

Figure 5. Continuous routing method used in coral sampling. (a) The drill path was continuously routed using computer-aided triaxial sampler programmed to drill a 0.7 mm square for each sample using a 1.4 mm drill bit (dashed circle). (b) The square pattern was repeated fifteen times over 1 cm. Divots were drilled after the fifteenth square and samples corresponding to fifteenth sample are labeled in green. (C) Positive X-radiograph of 92-PAA1-C as an example of the drill path and the corresponding annual density bands with the Sr/Ca variations superimposed (Sr/Ca axis reversed). The coral was sampled every 0.70 mm for approximately monthly sampling along maximum growth axis. Darker bands correspond to increasing Sr/Ca and lighter bands to decreasing Sr/Ca.

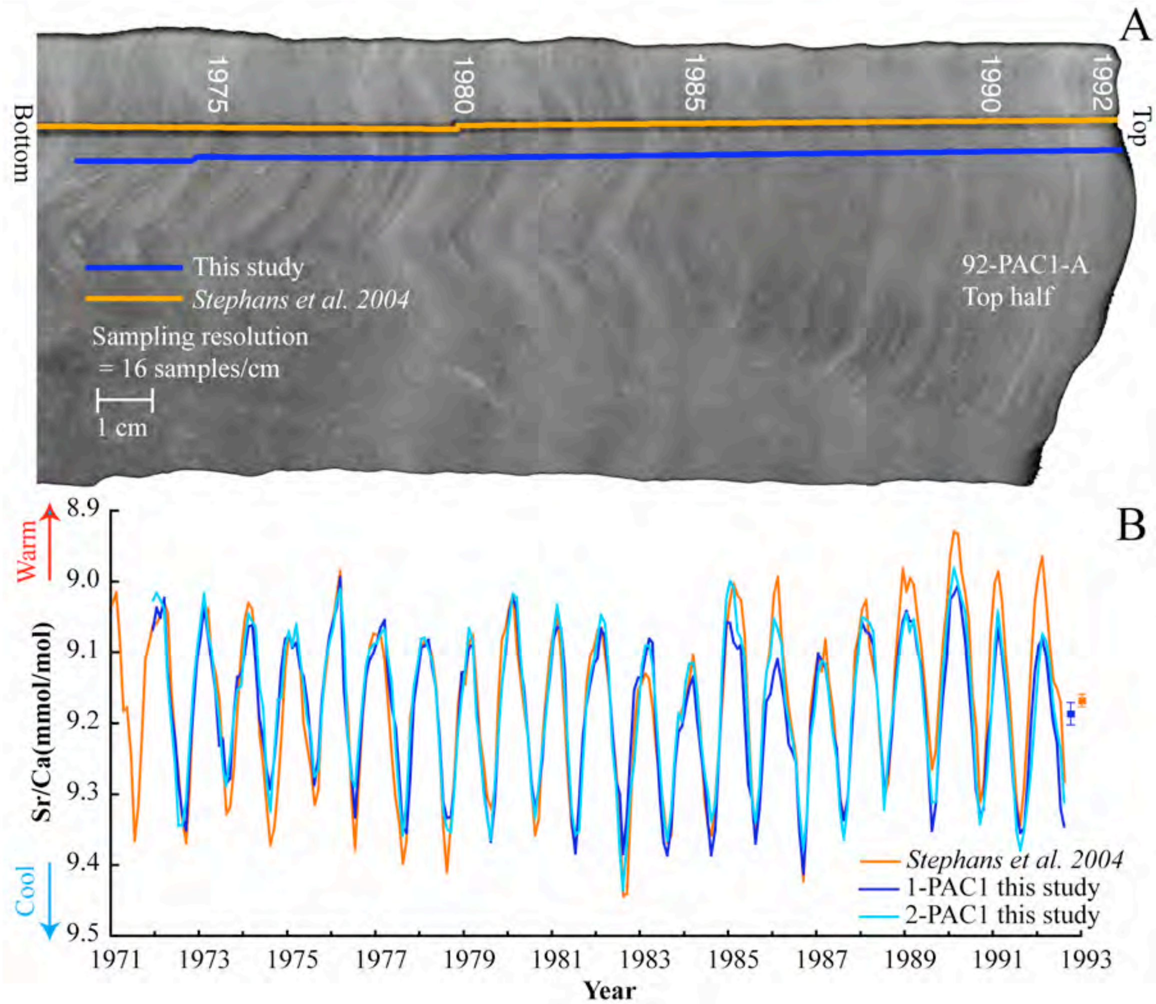

Figure 6. Parallel sampling on 92-PAC1-A. (a) The X-radiograph of 92-PAC1-A with lines marking the paths sampled by *Stephans et al.* [2004] and this study. The paths are ~0.5 cm apart and both were sampled at 16 samples/cm. (b) Coral Sr/Ca variations from duplicate Sr/Ca determinations of coral powder (1-PAC1 and 2-PAC1) and the parallel path sampled by *Stephans et al.* [2004]. The mean and variance of the replicates are not significantly different (Table 5). Correlation is high between replicates and parallel paths ($r = 0.96$, 0.93, respectively, $p < 0.05$, $n = 249$). Error bars represent analytical precision (±0.009 mmol/mol, 1σ, *Stephans et al.* [2004]; ±0.016 mmol/mol, 1σ, 1-PAC1 and 2-PAC1).

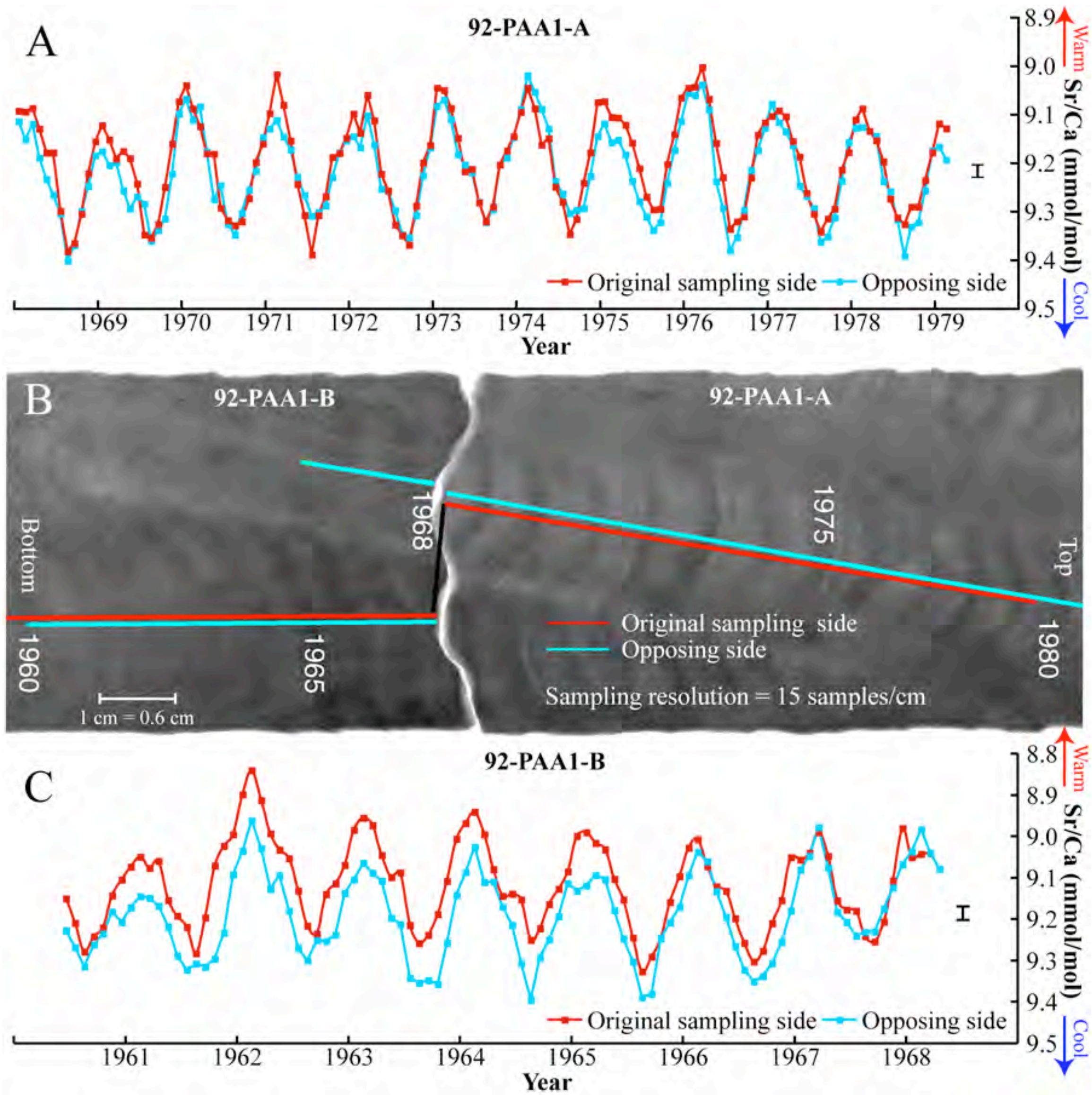

Figure 7. Parallel sampling on opposing sides of 92-PAA1-A and 92-PAA1-B. (a) Monthly coral Sr/Ca determinations from the bottom section of 92-PAA1-A from parallel sampling paths on opposing sides of the coral slab which is ~0.5 cm thick. (b) X-radiograph of the bottom section of 92-PAA1-A (right) and top section of 92-PAA1-B (left) with parallel sampling paths on each side of the coral slab marked. (c) Monthly coral Sr/Ca determinations from the top section of 92-PAA1-B from parallel sampling paths on opposing sides of the coral slab. Error bars represent analytical precision (±0.010 mmol/mol, 1σ). The agreement between the first two cycles (1966 to 1968) is very high; however, from 1960 to 1966, the two paths appear (avg_{abs} = 0.093 mmol/mol).

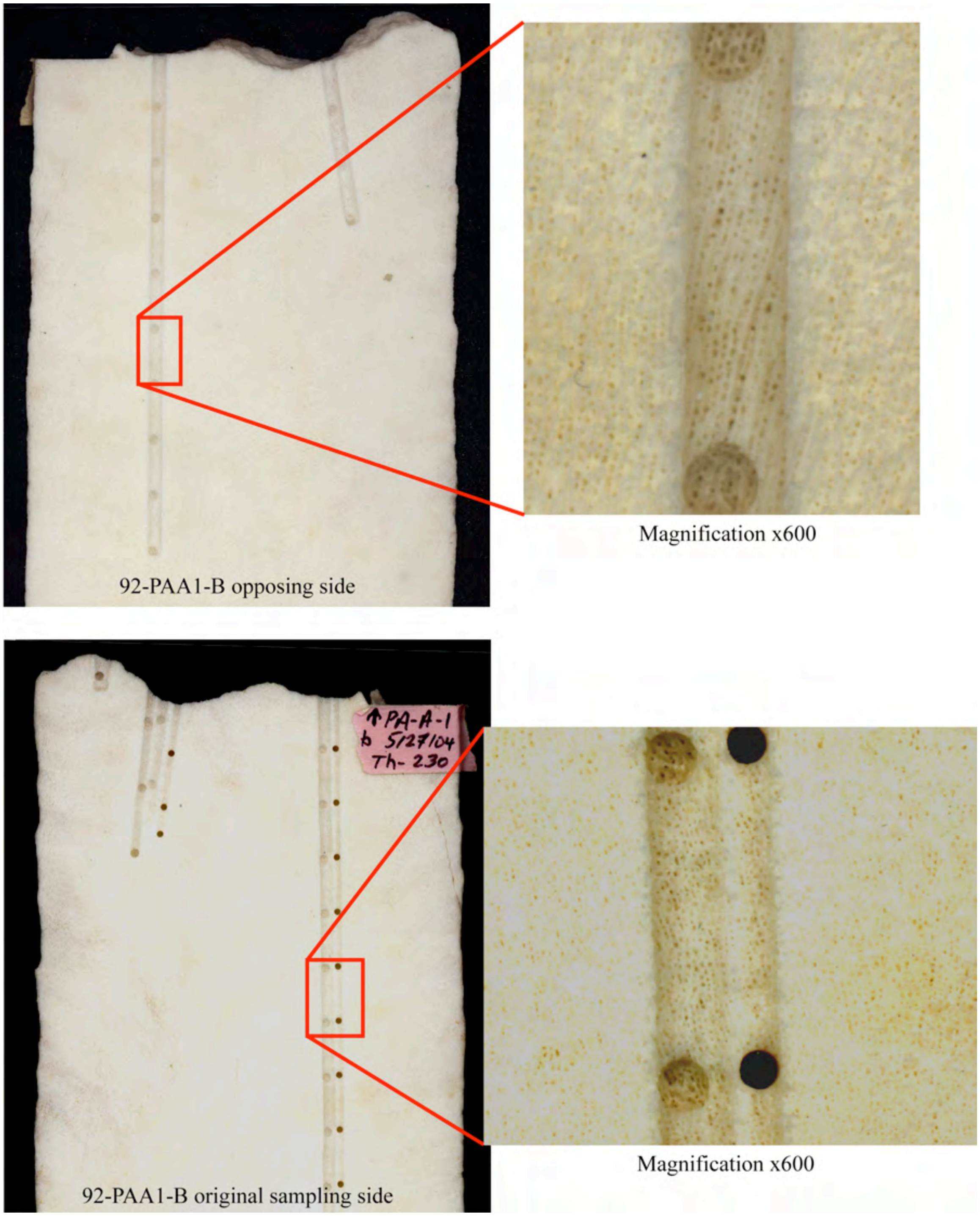

Figure 8. Scanned images of the original sampling side (bottom) and the opposing sampling side (top) of 92-PAA1-B. Images on right are the sampling path magnified to highlight the growth direction of the corallites. The corallites on the opposing side (top right) appear to be growing parallel to the sampling path; whereas, the corallites on the original sampling side of the slab are not oriented parallel to the sampling path (bottom right). The magnified image from the original sampling side of 92-PAA1-B (bottom right) corresponds to the samples in Figure 7c where a large offset occurs (1960 to 1966).

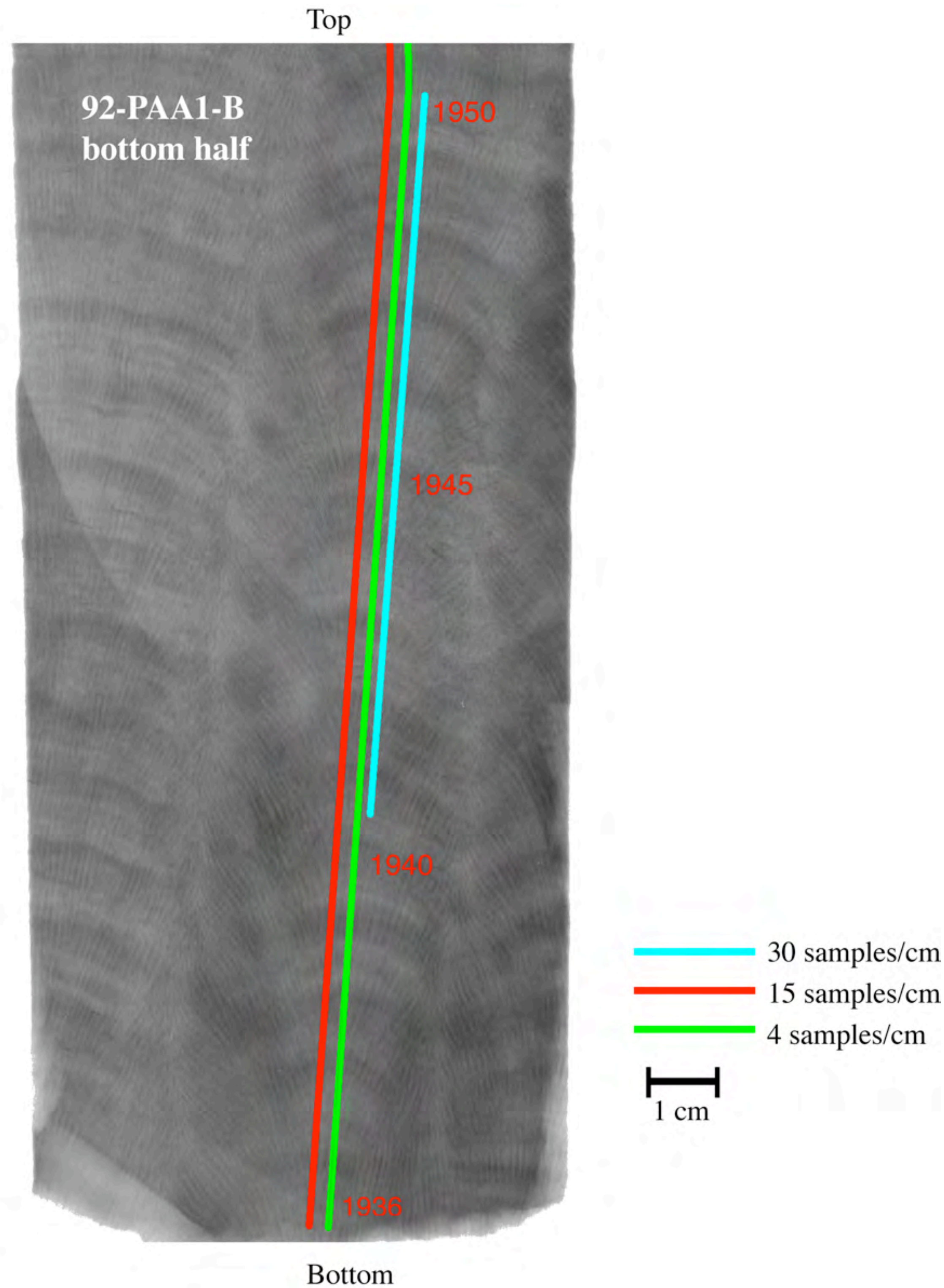

Figure 9. Coral X-radiograph with multiple sampling paths on 92-PAA1-B. The coral was originally sampled by *Quinn et al.* [1998] using a sampling resolution of 4 samples/cm. This study sampled along on either side of the *Quinn et al*. [1998] path using 15 samples/cm and 30 samples/cm; the paths are <0.5 cm apart.

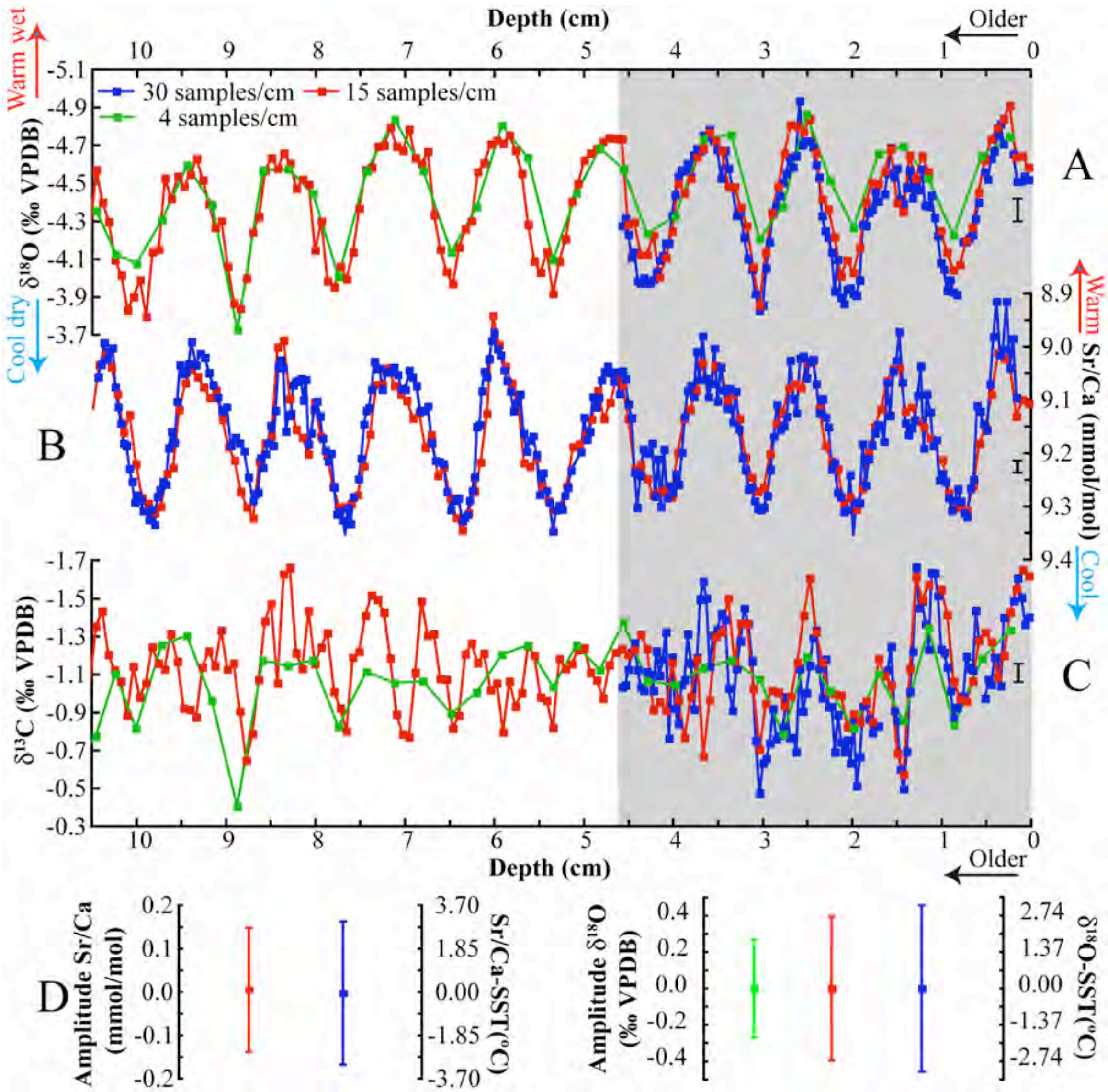

Figure 10. Sampling resolution comparison between parallel paths on 92-PAA1-B (Figure 9). Sampling resolutions were determined for coral (a) $\delta^{18}O$, (b) Sr/Ca, and (c) $\delta^{13}C$ at different sampling resolutions; 4 samples/cm (seasonally) [*Quinn, et al.*, 1998], 15 samples/cm (monthly), and 30 samples/cm (fortnightly). Seasonally and fortnightly variations were aligned with monthly variations. Error bars represent analytical precision. (d) The mean amplitude for each sampling resolution for Sr/Ca and $\delta^{18}O$. The difference between coral Sr/Ca determinations sampled with monthly and fortnightly resolution is within analytical precision of the Sr/Ca measurement. Mean coral Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$ values do not change significantly as a function of sampling resolution (Table 3). The amplitude of the annual cycles increases with finer sampling resolutions; however, the increase is not linear, but levels off with increasing resolution.

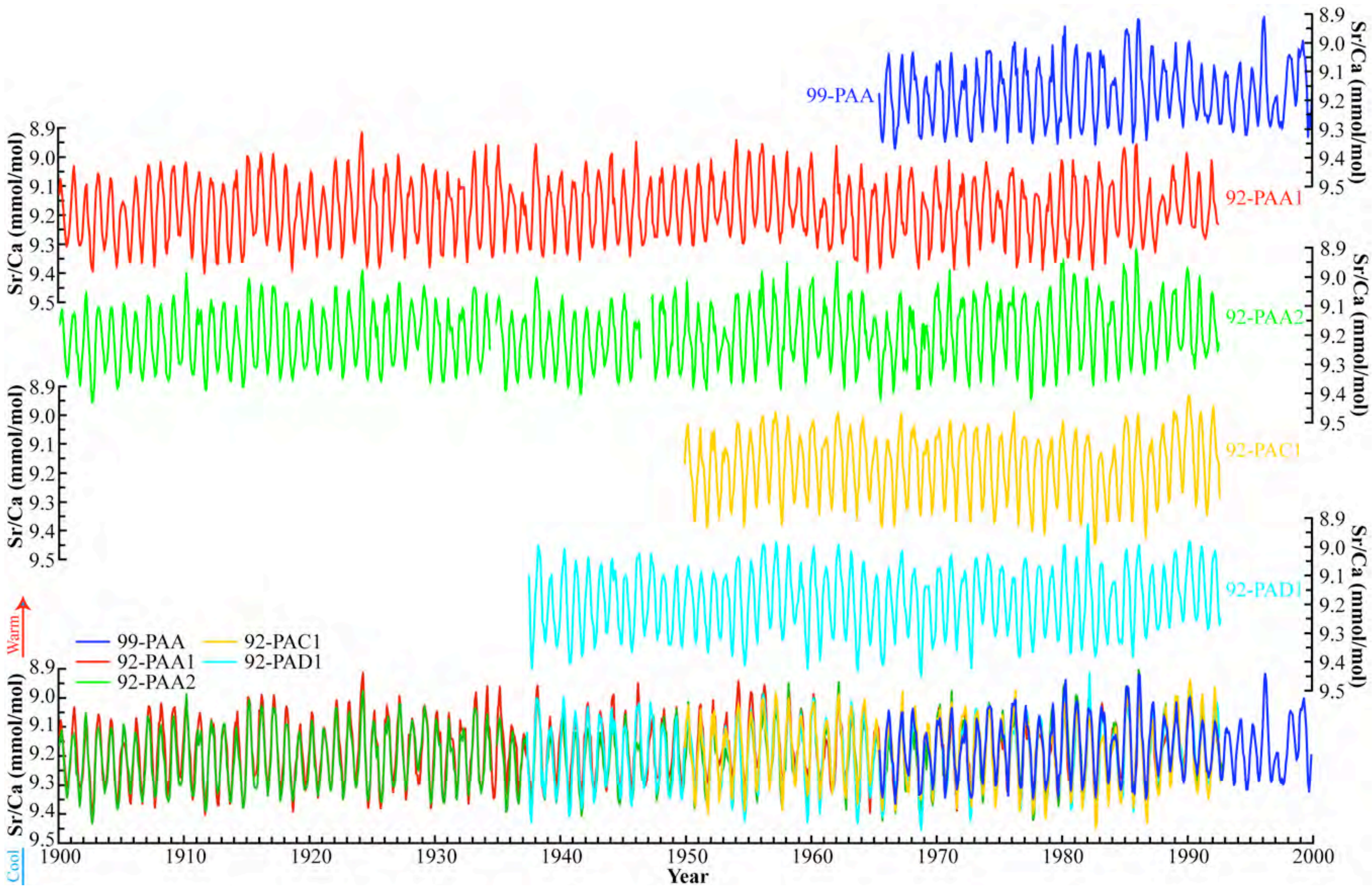
99-PAA
92-PAA1
92-PAA2
92-PAC1
92-PAD1
Sr/Ca (mmol/mol)
8.9
9.0
9.1
9.2
9.3
9.4
9.5
Warm
Cool
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year

Figure 11. Intra-colony and inter-colony monthly coral Sr/Ca variations from Amédée Island, New Caledonia. Three cores (99-PAA, 92-PAA1, and 92-PAA2) are from the same coral colony (PAA) and the other two (92-PAC1 and 92-PAD1) are colonies in close proximity to PAA (Figure 1). The bottom graph shows the five monthly coral Sr/Ca records together. Three records (92-PAC1, 92-PAD1, and 99-PAA) were originally sampled by *Stephans et al.* [2004] from 1967 to 1992 and 92-PAC1 and 92-PAD1 were extended in this study (Table 2). The means and standard deviations for the five coral Sr/Ca are not significantly different (Table 7) and the correlations between coral Sr/Ca variations is >0.89 for the period 1900 to 2000 (Table 10). Note the high degree of reproducibility between coral Sr/Ca time series.

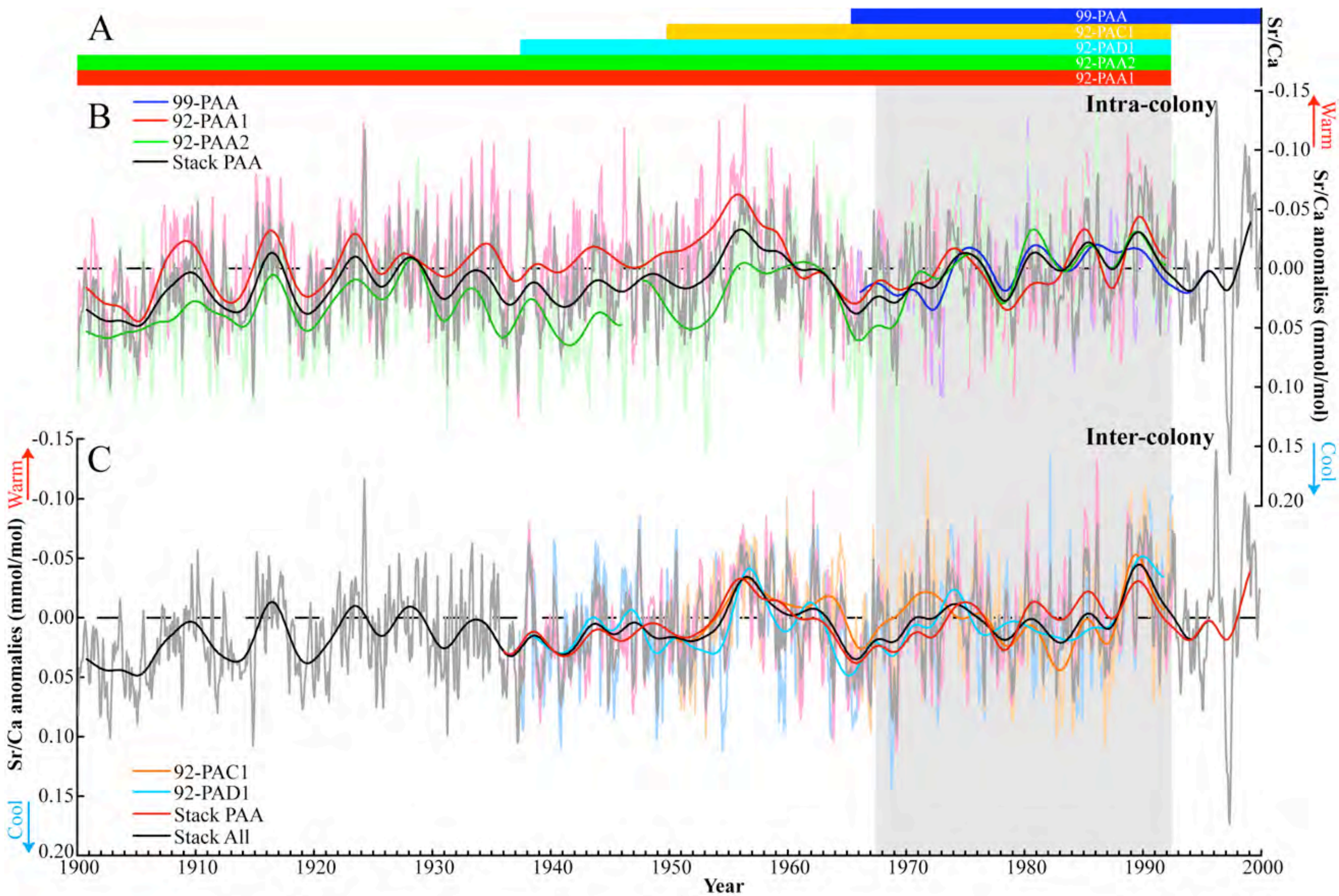
A
99-PAA
92-PAC1
92-PAD1
92-PAA2
92-PAA1
Sr/Ca
B
99-PAA
92-PAA1
92-PAA2
Stack PAA
Intra-colony
Warm
Cool
Sr/Ca anomalies (mmol/mol)
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
0.20
C
Inter-colony
92-PAC1
92-PAD1
Stack PAA
Stack All
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year

Figure 12. Intra-colony and inter-colony monthly coral Sr/Ca anomalies from Amédée Island, New Caledonia. (a) The time interval for each coral Sr/Ca record included in the stack coral Sr/Ca record. Records were separated by (b) intra-colony coral Sr/Ca records (99-PAA, 92-PAA1, and 92-PAA2) and (c) inter-colony coral Sr/Ca records (stack PAA, 92-PAC1, and 92-PAD1). The records from the PAA colony were averaged to create a stack average record for the colony PAA (b) and the records from each colony were averaged to create a stack average record of all colonies from Amédée Island (c). Anomalies were calculated as difference between each monthly measurement and the average Sr/Ca value for each month for the interval 1967 to 1992 (gray box). Each monthly coral Sr/Ca record was smoothed using a 25-month finite impulse response (FIR) filter. The means and standards deviations of five coral Sr/Ca records are not significantly different for the 20th century (Table 8), the coral Sr/Ca records are highly reproducible ($r > 0.90$, $p < 0.05$; Table 10), and the overall avg_{abs} is 0.036 ± 0.028 mmol/mol (1σ) between all records (Table 11).

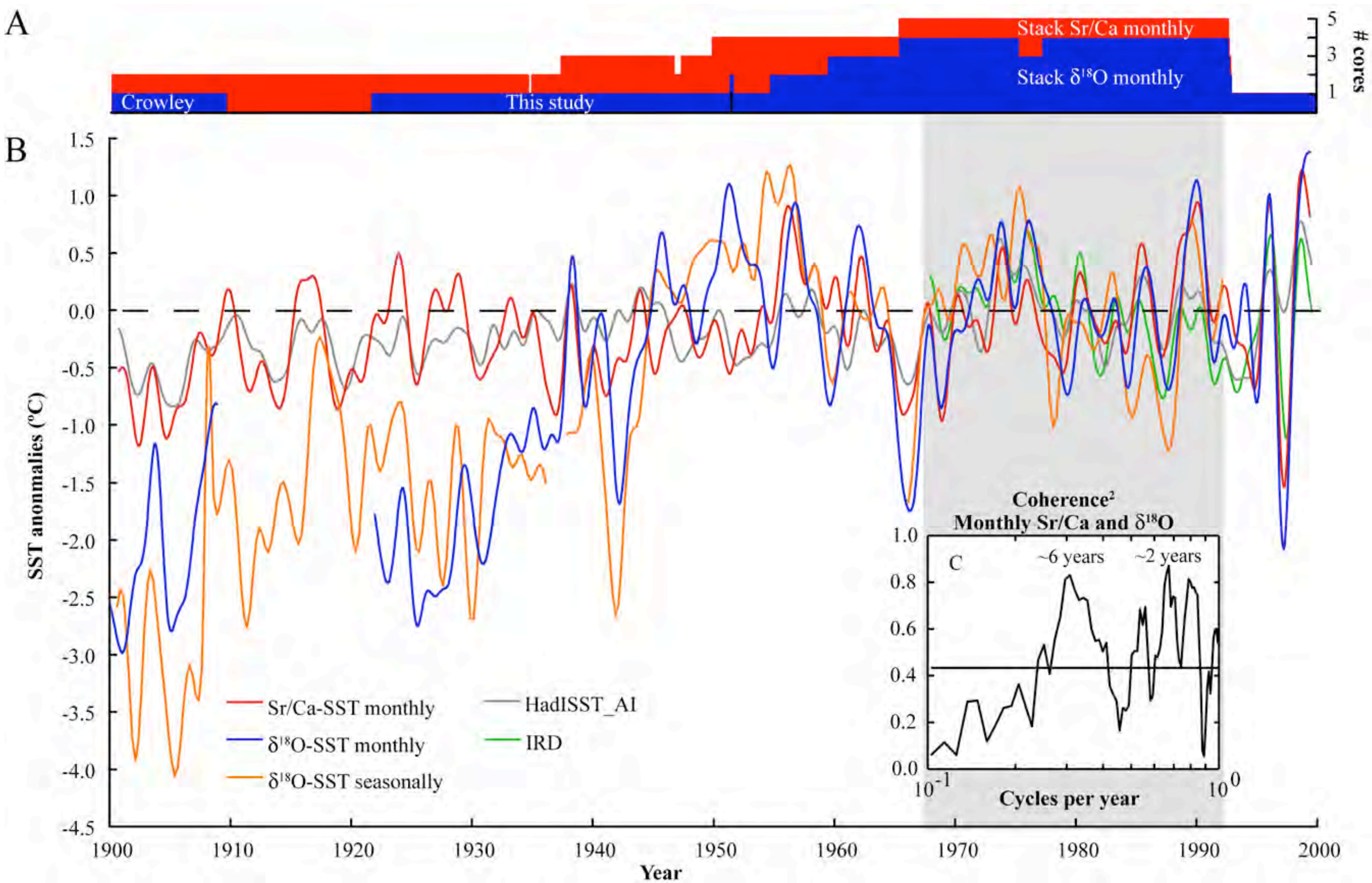
A
Stack Sr/Ca monthly
Stack δ18O monthly
Crowley
This study
cores
B
SST anomalies (°C)
Year
Sr/Ca-SST monthly
δ18O-SST monthly
δ18O-SST seasonally
HadISST_AI
IRD
Coherence²
Monthly Sr/Ca and δ18O
C
~6 years
~2 years
Cycles per year

Figure 13. Monthly stack coral Sr/Ca-SST and $\delta^{18}O$-SST anomalies compared with SST. (a) The numbers of cores averaged for each month of the stack average coral geochemical record for the 20th century. (b) Monthly stack coral Sr/Ca-SST and $\delta^{18}O$-SST anomalies compared with the in situ SST recorded offshore from Amédée Island (IRD) and the 1º-grid box extracted from HadISST1.1 database [*Rayner et al., 2003*] centered on Amédée Island (22.5ºS, 166.5ºE; HadISST_AI). Anomalies were calculated as difference between each monthly measurement and the average Sr/Ca value for each month for the interval 1967 to 1992 (gray box). Each monthly record was smoothed using a 25xw-month finite impulse response (FIR) filter and the seasonal coral $\delta^{18}O$ record was smoothed using a 2-year FIR filter. All monthly resolved $\delta^{18}O$ and Sr/Ca determinations were from splits of the same sample except for sections of 92-PAA1 from *Quinn et al*. [1998] and *Crowley et al*. [1999] (Table 2). (c) Coherence squared from cross-spectral analysis of monthly stack coral Sr/Ca and $\delta^{18}O$. Significance tested against a 95% confidence level.

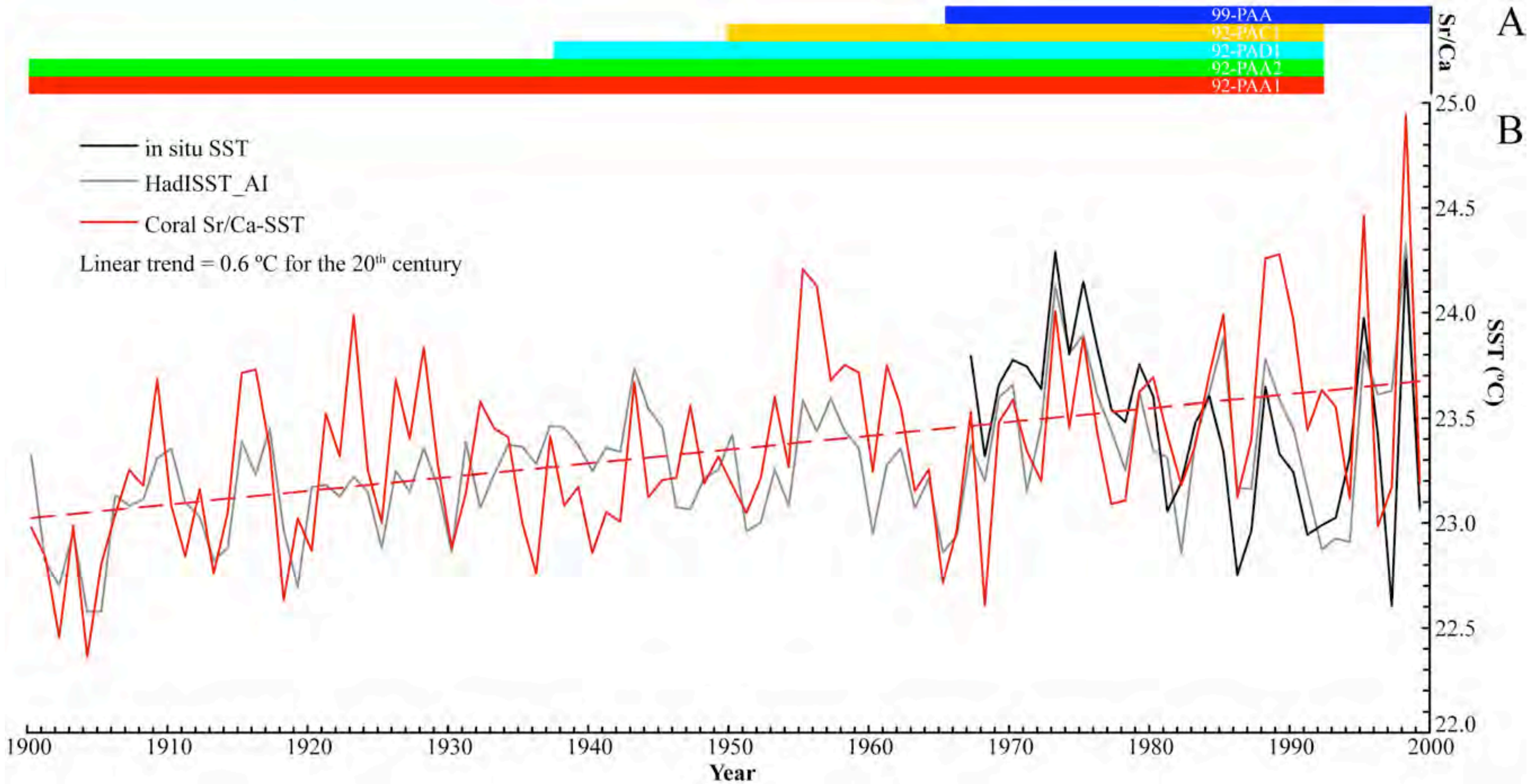

Figure 14. Annual average coral Sr/Ca-SST variations for Amédée Island. (a) The time interval for each coral Sr/Ca record included in the stack coral Sr/Ca record. (b) Annual average of stack coral Sr/Ca-SST compared with the in situ SST recorded offshore from Amédée Island (IRD) and the 1º-grid box extracted from HadISST1.1 database [*Rayner et al., 2003*] centered on Amédée Island (22.5ºS, 166.5ºE; HadISST_AI). Annual averages were calculated over a climatological year (April to March). A ~0.6 ºC warming trend is observed in the annual average coral Sr/Ca-SST for the 20th century. The correlation between annual averages of stacks coral Sr/Ca-SST and HadISST is 0.68 ($p < 0.05$, $n = 100$; Table 12). Sr/Ca-SST(ºC) = 0.006(±0.003, 2σ)*year +10.98 (±5.5, 2σ).

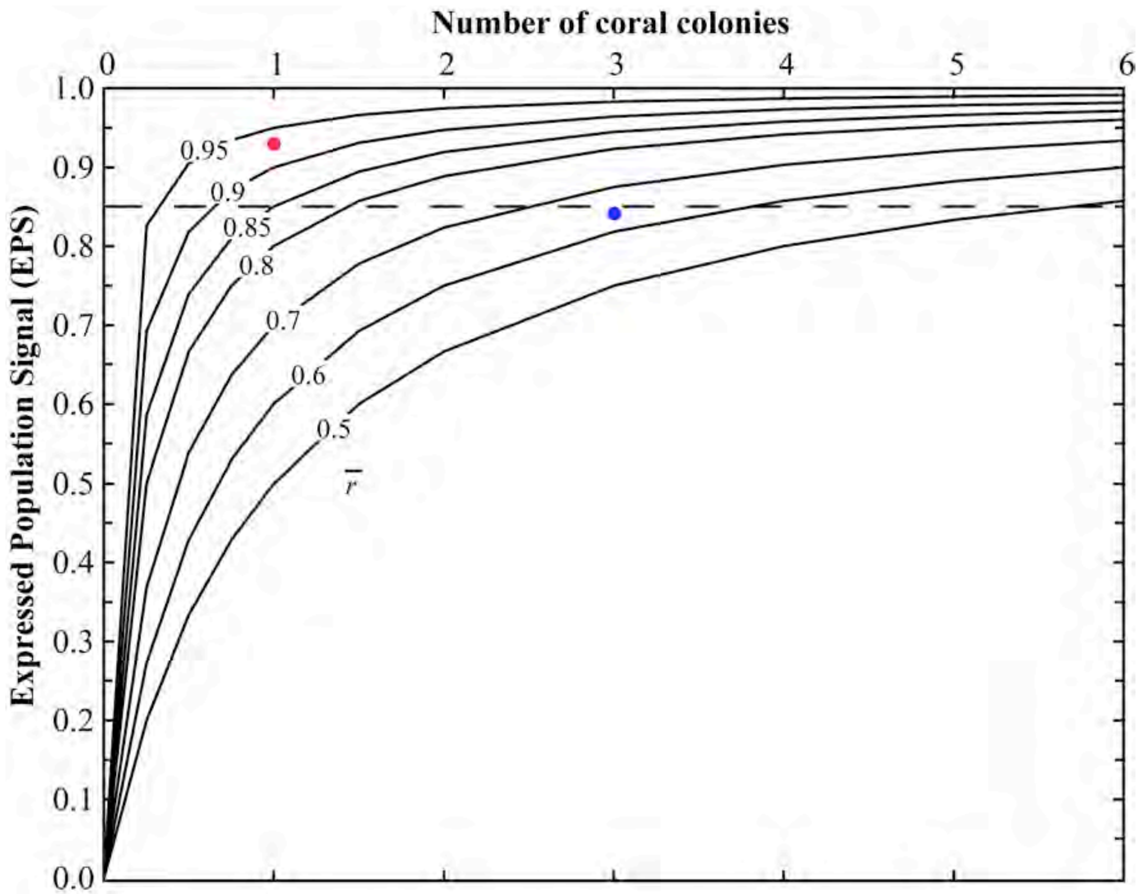

Figure 15. Expressed population signal (EPS) for coral paleoclimatological reconstructions. EPS is used in dendrochronology to assess the number of records needed to replicate a signal and judge the strength of the common signal against a perfect noise-free chronology. EPS is given by

$$\mathrm{EPS} = \frac{N(\bar{r})}{\bar{r}(N) + (1 - \bar{r})} \qquad (1)$$

where N is the number of records (trees or corals), and $\bar{r}$ is the mean inter-record correlation coefficient (trees or coral colonies) [*Wigley, et al.*, 1984]. The "acceptable" EPS value used in dendrochronology studies is ≥0.85 (dashed line) [*Wigley, et al.*, 1984]. Equation and graph adapted from *Briffa* [1995]. The EPS for the inter-colony monthly coral Sr/Ca records is 0.97 ($\bar{r}$ = 0.93, red dot) and 0.84 for annual average ($\bar{r}$ = 0.63, blue dot).

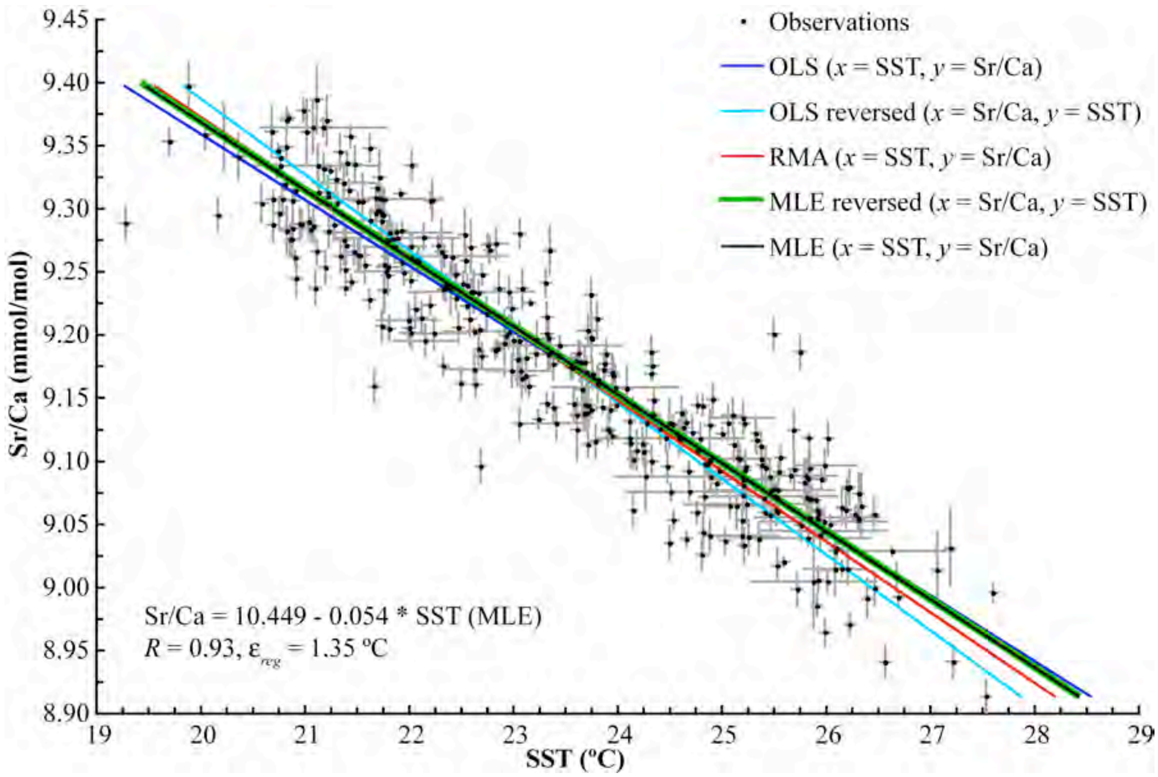

Figure 16. Regression of the coral Sr/Ca determinations with in situ SST. Transfer functions were determined using three different regression methods: OLS, RMA, and MLE for the period 1967 to 1999 ($R = 0.93$. $p < 0.05$, $n = 392$). Observations are reported with error bars for both coral Sr/Ca and SST. The stack coral Sr/Ca determinations with only one observation have larger error bars and all the observations outside the main data cluster are single observations. The larger SST error bars are adjusted HadISST_AI measurements, which were added to the in situ SST to complete the record. The standard error of regression for MLE ($\sigma_{reg} = 1.35$ ºC) was calculated using effective degrees of freedom (*dof* = 105), which accounts for serial correlation; this differs the σ_{reg} calculated using number of observations ($n = 392$; $\sigma_{reg} = 0.68$ ºC). Typically, in coral-based SST reconstructions using OLS, SST is the independent variable (x) and the coral geochemistry is the dependent variable (y) so that the variable with the least amount of uncertainty is the independent variable (x). OLS and MLE equations were reversed (x = Sr/Ca, y = SST) to demonstrate the difference in swapping the regressors (x, y); the reversed OLS solution produces a different solution whereas RMA and MLE reversed solution produces identical results (Table 13).

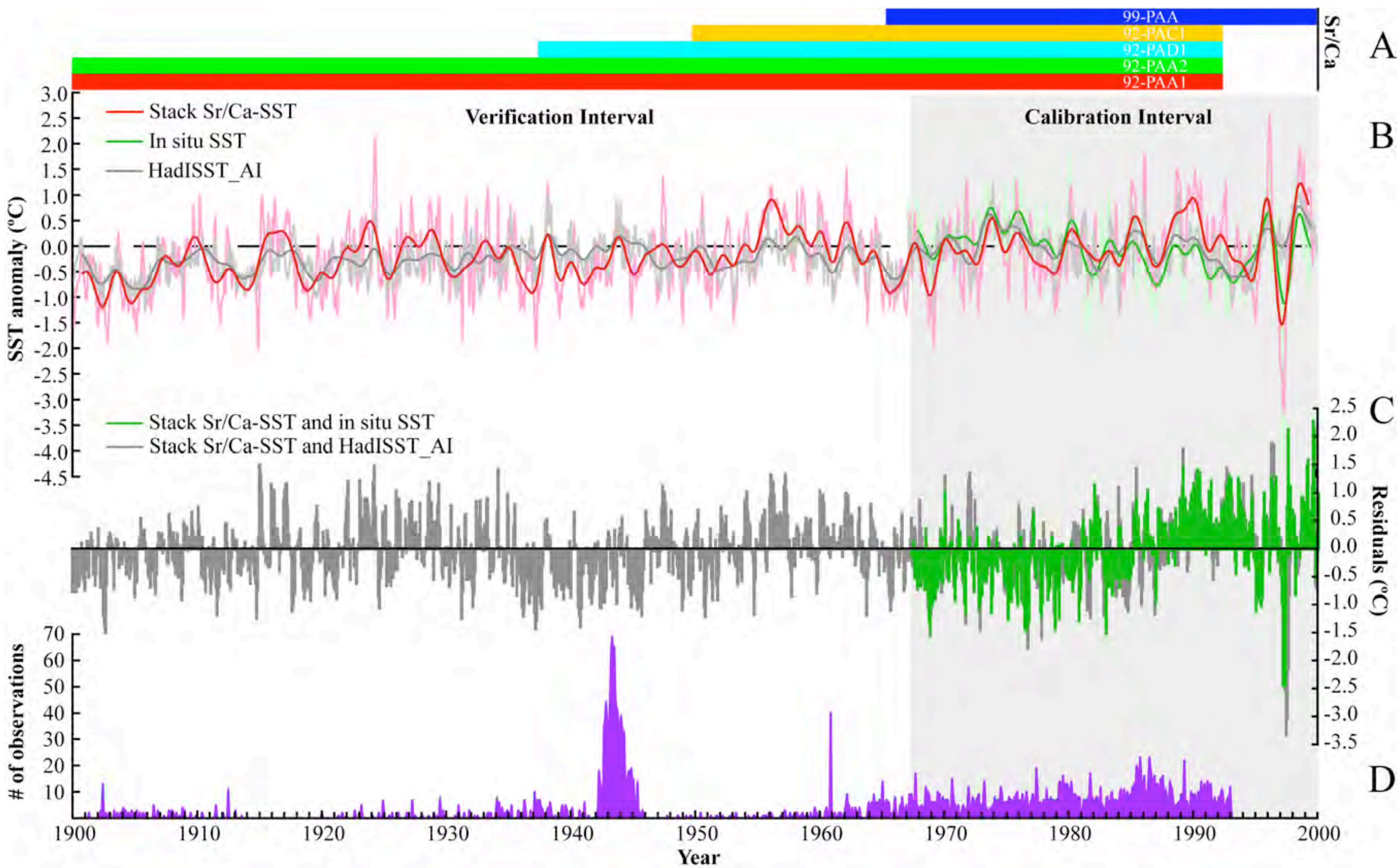
99-PAA
92-PAC1
92-PAD1
92-PAA2
92-PAA1
Sr/Ca
A
B
C
D
Stack Sr/Ca-SST
In situ SST
HadISST_AI
Verification Interval
Calibration Interval
SST anomaly (°C)
Stack Sr/Ca-SST and in situ SST
Stack Sr/Ca-SST and HadISST_AI
Residuals (°C)
# of observations
Year

Figure 17. Calibration and verification of the coral Sr/Ca-SST transfer function. (a) The time interval for each coral Sr/Ca record included in the stack coral Sr/Ca record. (b) Monthly stack coral Sr/Ca-SST anomalies with in situ SST record and HadISST_AI anomalies. Anomalies were calculated as difference between each monthly measurement and the average coral Sr/Ca-SST value for each month for the interval 1967 to 1992. Each monthly record was smoothed using a 25-month finite impulse response (FIR) filter. (c) Residuals of predicted coral Sr/Ca-SST minus the observed SST. The coral Sr/Ca was calibrated with in situ SST for the period 1967 to 1999 (gray box) and verified for the period 1900 to 1967 with the independent SST data extracted from HadISST1.1 (1º-grid centered on 22.5ºS, 166.5ºE) [*Rayner, et al.*, 2003]. (d) The number of observations from the COADS SST database [*Woodruff, et al.*, 1998] that correspond to the 1º-grid box extracted from HadISST1.1 [*Rayner, et al.*, 2003]. The HadISST1.1 global SST database [*Rayner, et al.*, 2003] is composed of mostly SST observations from the COADS SST data set [*Woodruff, et al.*, 1998] in the pre-remote sensing era.

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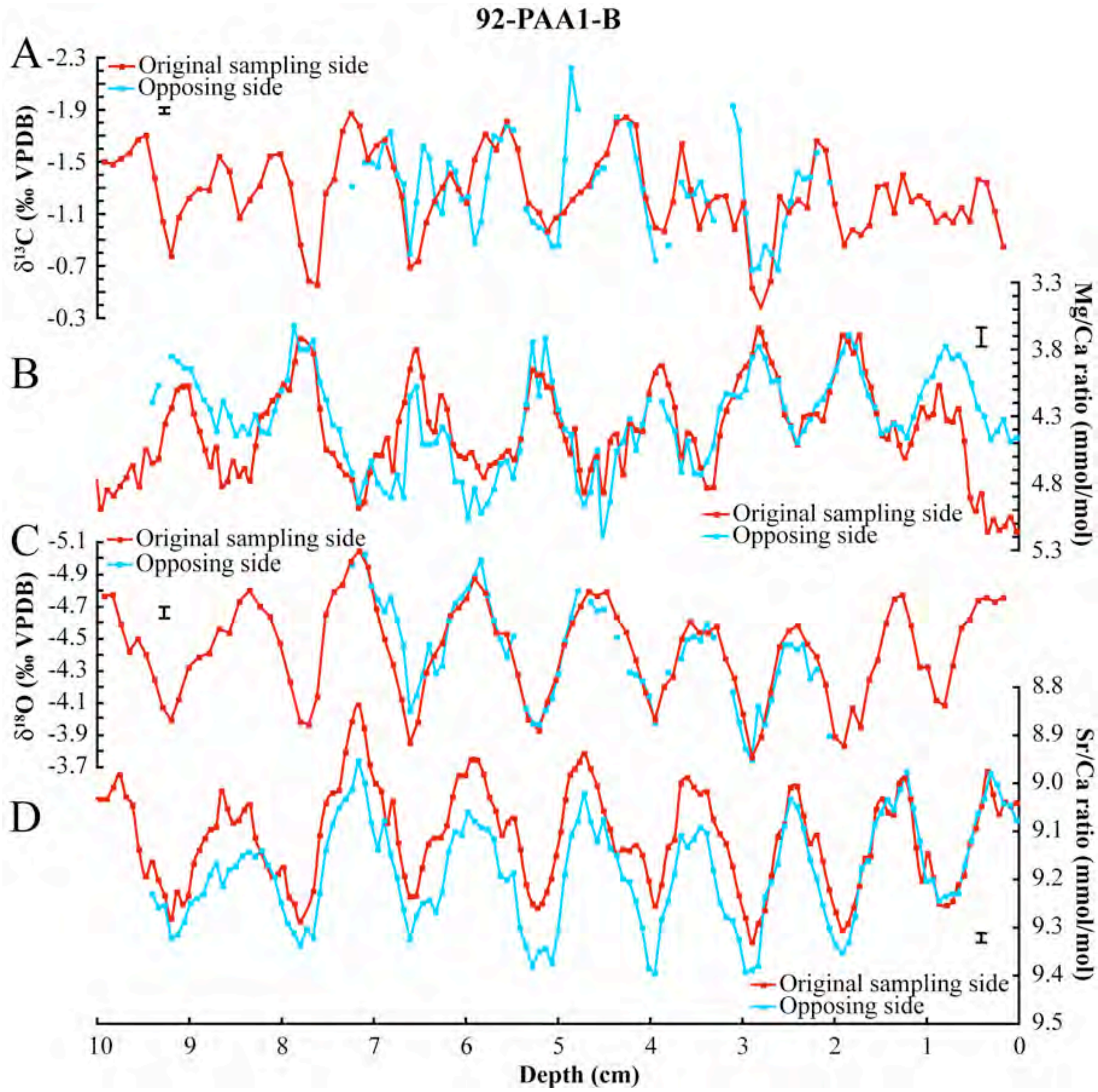
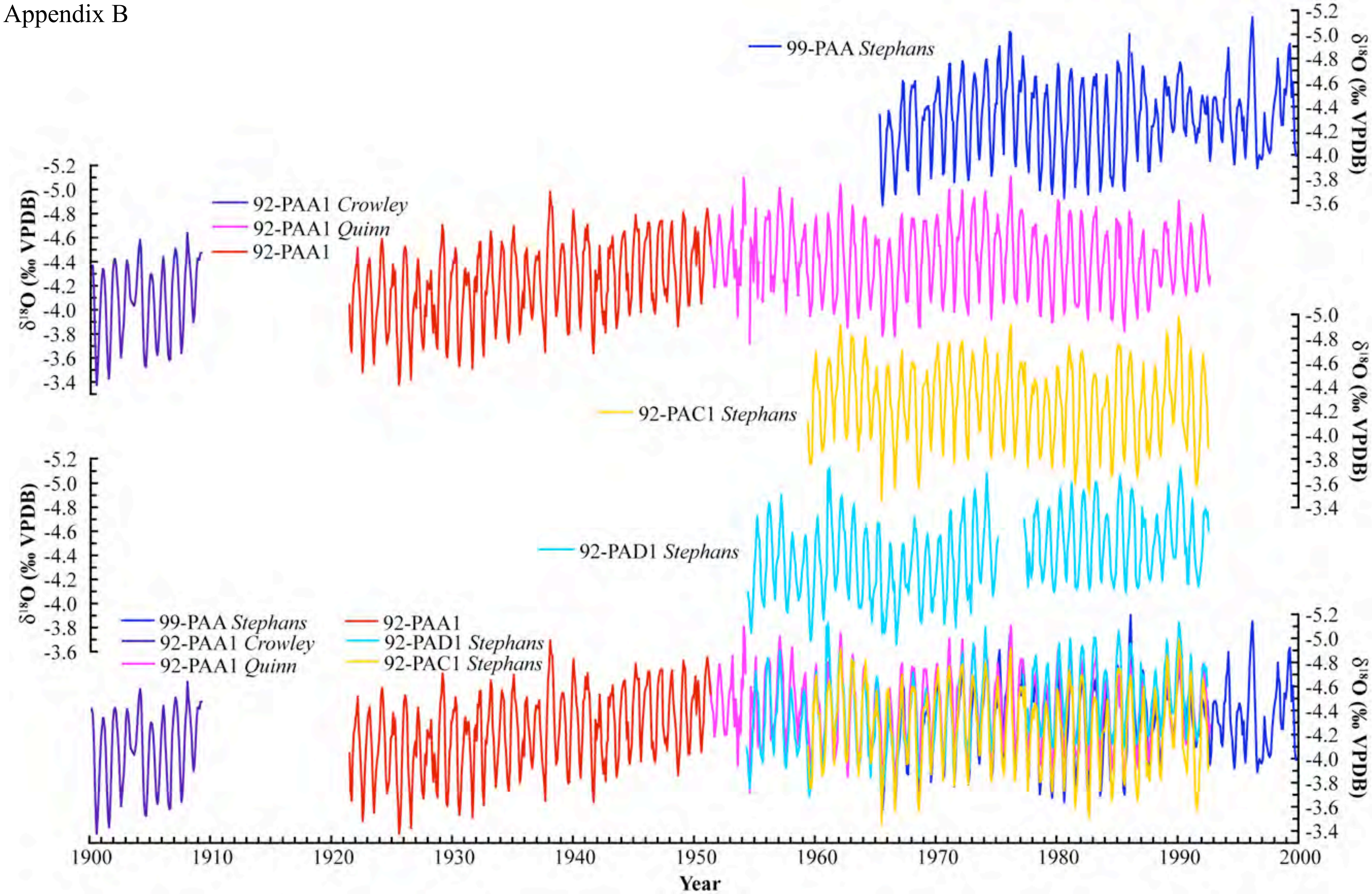
Appendices

Appendix A



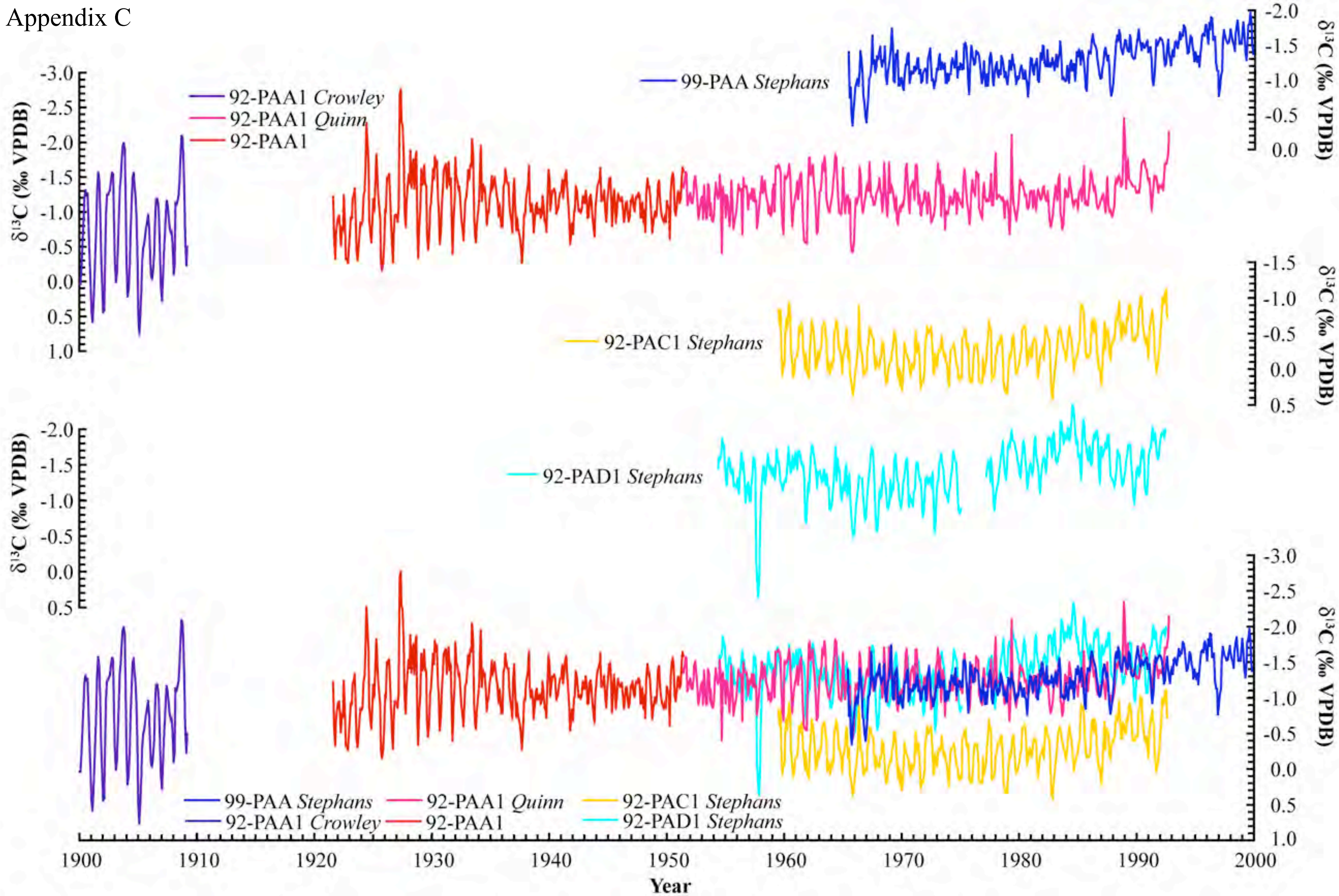
Additional coral geochemical variations from parallel sampling on opposing sides of 92-PAA1-B (Figure 7): (a) $\delta^{13}C$, (b) Mg/Ca, (c) $\delta^{18}O$, and (d) Sr/Ca. The trace elemental and isotopic ratios for the original sampling side are from two different sampling paths (Figure 4) where trace elements were measured by this study and isotopes by *Quinn et al.* [1998]. Error bars represent respective analytical precision (1σ). The agreement between monthly coral Sr/Ca determinations on opposing sides for the first two cycles (0 to 2 cm) is very high; however, from 2 to 10 cm, the two coral Sr/Ca paths diverge (avg_{abs} = 0.093 mmol/mol) but a similar divergence is not observed in the other geochemical ratios.

Appendix B



99-PAA *Stephans*
92-PAA1 *Crowley*
92-PAA1 *Quinn*
92-PAA1
92-PAC1 *Stephans*
92-PAD1 *Stephans*
δ18O (‰ VPDB)
-5.2
-5.0
-4.8
-4.6
-4.4
-4.2
-4.0
-3.8
-3.6
-3.4
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year

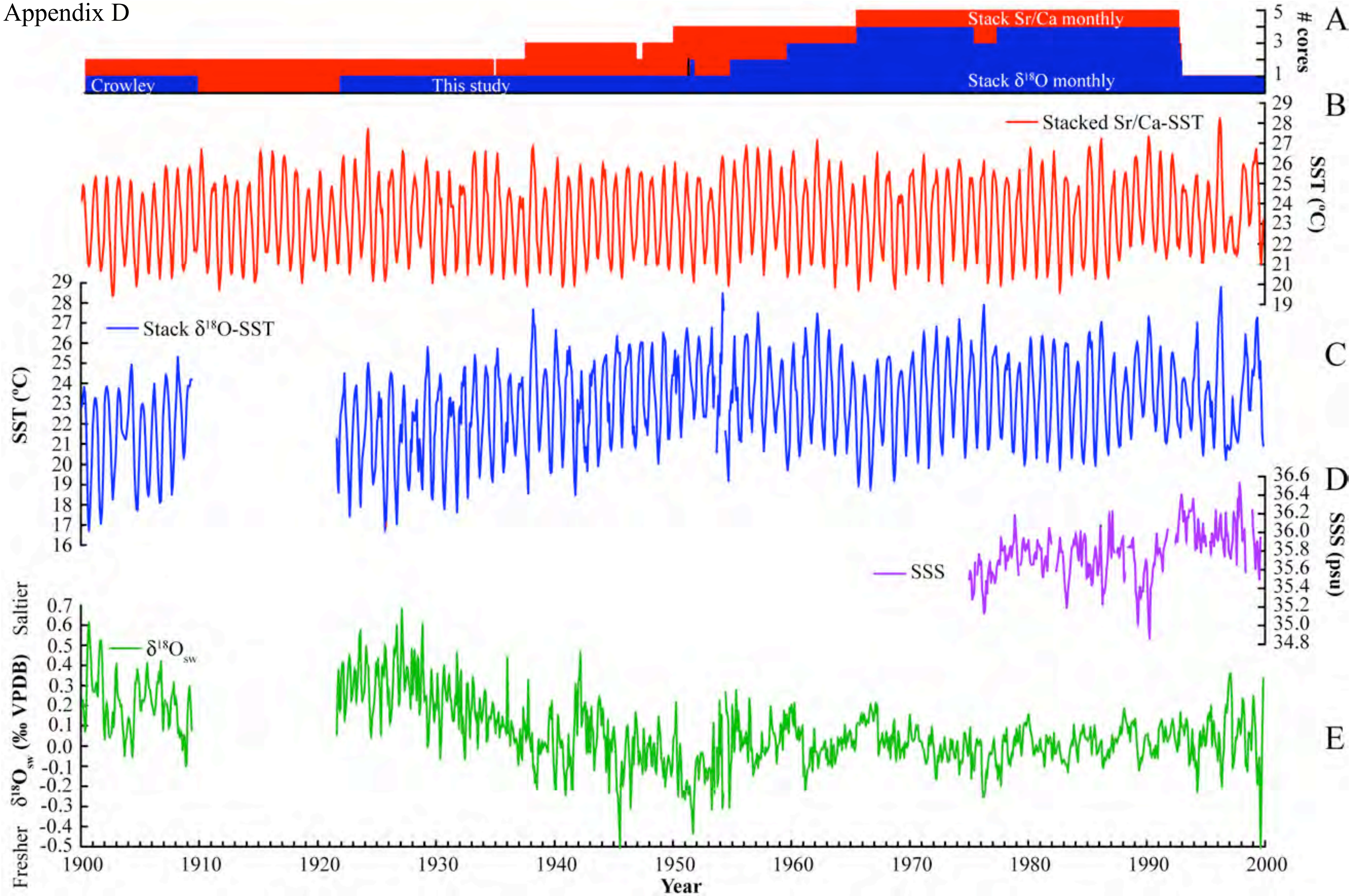
Intra-colony and inter-colony monthly coral $\delta^{18}O$ variations from Amédée Island, New Caledonia. Two cores (99-PAA and 92-PAA1) are from the same coral colony (PAA) and the other two cores (92-PAC1 and 92-PAD1) are colonies in close proximity to PAA (Figure 1). Three records (99-PAA, 92-PAC1, and 92-PAD1) were originally sampled by *Stephans et al.* [2004] back to 1967 and 92-PAC1 and 92-PAD1 were extended in this study (Table 2). The multi-core alignment resulted in changes to the *Quinn et al*. [1996; 1998] isotope chronology and the *Stephans et al*. [2004] chronologies. All monthly resolved isotopic and trace elemental determinations were from splits of the same sample except for sections of 92-PAA1 from *Quinn et al*. [1998] and *Crowley et al*. [1999] (Table 2). The means and standard deviations of the four coral $\delta^{18}O$ are not significantly different for the period 1967 to 1992. The coral $\delta^{18}O$ signal is highly reproducible for the period 1967 to 1992 as reported by *Stephans et al*. [2004] and correlation values for this study (r = 0.80 to 0.90, $p < 0.05$, n = 304) are equal to or slightly higher than those reported by *Stephans et al*. [2004] after adjustments to the chronologies.



92-PAA1 Crowley
92-PAA1 Quinn
92-PAA1
99-PAA Stephans
92-PAC1 Stephans
92-PAD1 Stephans
δ13C (‰ VPDB)
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year

Intra-colony and inter-colony monthly coral $\delta^{13}C$ variations from Amédée Island, New Caledonia. Two cores (99-PAA, and 92-PAA1) are from the same coral colony (PAA) and the other two cores (92-PAC1 and 92-PAD1) are colonies in close proximity to PAA (Figure 1). Three records (99-PAA, 92-PAC1, and 92-PAD1) were originally sampled by *Stephans* [2003] back to 1967 and 92-PAC1 and 92-PAD1 were extended in this study (Table 2). The multi-core alignment resulted in changes to the *Quinn et al*. [1996; 1998] isotope chronology and the *Stephans* [2003] chronologies. All monthly resolved isotopic and trace elemental determinations were from splits of the same sample except for sections of 92-PAA1 from *Quinn et al*. [1998] and *Crowley et al*. [1999] (Table 2). The monthly coral $\delta^{13}C$ variations between intra-colony and inter-colony cores from Amédée Island, New Caledonia do not exhibit the same signal reproducibility observed in the coral Sr/Ca and $\delta^{18}O$ variations. The mean coral $\delta^{13}C$ between cores from the same colony (99-PAA *Stephans* [2003] and 92-PAA1 *Quinn et al.* [1996; 1998]) for the period 1965 to 1992 did not differ significantly; however, the correlation between the intra-colony coral $\delta^{13}C$ is lower than the coral Sr/Ca and $\delta^{18}O$ intra-colony correlation ($r = 0.54$, $p < 0.05$, $n = 329$). The mean coral $\delta^{13}C$ between coral colonies is significantly different as reported by *Stephans* [2003] and the correlation between the PAA cores and 92-PAD1 is insignificant ($p = 0.05$). The correlation between 92-PAC1 and the other colonies is significant ($p < 0.05$), but lower than the intra-colony (PAA) correlations, which range from 0.34 to 0.44.

Appendix D



Stack Sr/Ca monthly
Crowley
This study
Stack δ18O monthly
cores
5
3
1
A
Stacked Sr/Ca-SST
SST (°C)
B
Stack δ18O-SST
SST (°C)
C
SSS
SSS (psu)
D
δ18Osw
Saltier
δ18Osw (‰ VPDB)
Fresher
E
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year

Paired analysis of coral Sr/Ca and $\delta^{18}O$ to estimate seawater $\delta^{18}O$. (a) The numbers of cores averaged for each month in the stack average coral geochemical record. (b) Monthly stack coral Sr/Ca-SST and (c) monthly stack coral $\delta^{18}O$-SST records. All monthly resolved $\delta^{18}O$ and Sr/Ca determinations were from splits of the same sample except for sections of 92-PAA1 from *Quinn et al*. [1998] and *Crowley et al*. [1999] (Table 2). (d) Monthly in situ SSS offshore of Amédée Island. (e) $\delta^{18}O_{sw}$ calculated using paired analysis of stack coral Sr/Ca and stack coral $\delta^{18}O$ variations.

$\Delta\delta^{18}O_{coral} = \Delta SST + \Delta\delta^{18}O_{sw}$

$\Delta Sr/Ca_{coral} = \Delta SST + \Delta Sr/Ca_{sw}$ ($\Delta Sr/Ca_{sw}$ is assumed to be constant)