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U/Th-dated sclerosponges from the Indonesian Seaway record subsurface adjustments to west Pacific winds

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Abstract. Stable isotope records from sclerosponges collected at 10-20 m depth in the Indonesian Seaway and Solomon Islands are particularly well suited for reconstructing century-scale trends in ambient temperature variability and the oceanic uptake of fossil fuel carbon. Basal U/Th dates demonstrate that the sclerosponges analyzed are 85-100 years old. Isotopic records from the Indonesian specimens suggest a strong subsurface cooling over the past 20 years that is not manifested in either surface instrumental or shallower coral proxy records. However, analysis of observed subsurface temperatures in Indonesia, observed winds in the west Pacific, and simulated subsurface temperatures from a steady state general circulation model hindcast forced by observed winds combine to suggest that thermocline adjustments could account for at least part of the recent cooling inferred from the Indonesian sclerosponges. If so, the sclerosponge data suggests that, on average, the west Pacific thermocline has shoaled significantly over at least the past 2 decades.

1. Introduction

Recognition of the century scale trends in the three dimensional structure of the tropical warm pools is a necessary prerequisite for testing recent hypotheses concerning decadal-scale climate oscillations or seemingly sudden shifts in climate [*Trenberth and Hurrel*, 1994; *Graham*, 1994]. In fact, current debate on the generation of decadal-scale variability in the tropics, including its relationship with midlatitude variability, rests critically on subsurface processes. For example, *Gu and Philander* [1997] suggest that subsurface warming in the eastern equatorial Pacific during the 1987 El Niño-Southern Oscillation (ENSO) event marked the arrival of a warm anomaly subducted years earlier in the N. Pacific. By contrast, recent studies by *Miller and Schneider* [1998] and *Schneider et al.* [1999a] suggest that temperature anomalies subducted in the Pacific gyre north of 18°N propagate southwestward but do not reach the equator; in this view, subsurface temperature anomalies at lower latitudes are produced by baroclinic adjustments of the thermocline in response to Ekman pumping, with no apparent midlatitude influence.

Equally important to these dynamical considerations, radiative processes are also affected by the vertical structure of the ocean, even in areas not characterized by active upwelling. For example, high rainfall can cause the development of a strong halocline at shallow depths in the warm pools, and evaporative cooling and cloud cover may serve as a thermostat for surface temperature variability [*Graham and Barnett*, 1987].

Unfortunately, reliable subsurface data [*White*, 1995] are limited to the last 2 decades. Tropical surface temperature reconstructions have been extended through this century using available instrument data [*Kaplan et al.*, 1998] and coral proxy data [*Cole et al.*, 1992, 1993; *Evans et al.*, 1998]. Yet the majority of subsurface observations are expendable bathythermograph (XBT) data concentrated along major trade routes, and only the most recent observational campaigns, [e.g. *McPhaden*, 1993], have been designed to produce continuous three-dimensional time series in the climatically significant regions of the tropical Pacific. Thus it is difficult to evaluate different proposed mechanisms for decadal-centennial-scale variability with observations, and on statistical grounds alone, it remains unclear whether the events such as the widespread temperature increase after 1976-1977 reflect a continuous oscillation, a step-like "regime shift," or the expression of a secular trend [*Zhang et al.*, 1997].

While it might seem that coral proxy records could be developed to fill out the needed array of subsurface observations, the typical habitat of large coral colonies makes this development unlikely. Large multicentury coral colonies are rare on deeper reef sections, and diver-assisted underwater coring operations become difficult and hazardous much below 15 m. The problem is compounded by the fact that proxy records of shallow water variability may not be a good guide to subsurface variability.

The purpose of this paper is to explore the climatic information contained in a seldom-studied group of coralline reef sponges, called sclerosponges, that offer an alternative approach for reconstructing past subsurface variability. Here we use stable isotope records obtained from radiometrically dated tropical sclerosponges to describe subsurface variability at several sites in the western equatorial Pacific. The sclerosponge records, collected at depths ranging from 10 to 20 m, reveal a pattern of low frequency thermocline undulations of progressively increasing amplitude through the twentieth century. The most prominent examples are the Indonesian sclerosponge records, taken from sites where the seasonal thermocline today intersects the specimens' collection depth. Though a variety of processes can affect local thermocline depth in the Indonesian Seaways, we argue that the the Indonesian sclerosponge records reflect the influence of large-scale wind forcing across the western Pacific.

2. Sclerosponge Records

Sclerosponges are characterized by hard, laminated calcium carbonate skeletons similar to that of hermatypic corals. They occur in the tropics at depths ranging from 5 to 150 m, and can attain ages exceeding 400 years [*Worheide et al.*, 1997]. The Indo-Pacific species *Astrosclera willeyana* and *Acanthochaetes*

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wellsi are found in dark, well-flushed caves on vertical reef walls [*Reitner et al.*, 1996], while the Caribbean species *Ceratoporella nicholsoni* is common on deeper sections of the reef front [*Hartman and Goreau*, 1970]. *Swart et al.* [1998] provide a general review of the potential for proxy reconstructions in sclerosponges, including a photograph of skeletal morphology.

Sclerosponges have an important geochemical feature that differentiates them from hermatypic reef corals. Coral skeleton stable isotope values are typically several per mil lower than those expected from stable isotopic equilibrium with seawater. By contrast, sclerosponges lack zooxanthellae, and they deposit skeleton slowly (0.2 to 1.0 mm/yr), with no apparent stable isotopic disequilibrium. Therefore, stable isotope time series developed from sclerosponges can be interpreted more confidently in terms of the physical properties of seawater, without potential isotopic artifacts arising from past changes in metabolism over the specimen's growth history. *Druffel and Benavides* [1986] were the first to exploit this feature of sclerosponges; they measured skeletal carbon isotope ratios in *Ceratoporella* to estimate historical Suess-effect shifts in atmospheric $\delta^{13}C$ ratios due to the burning of ^{12}C-rich fuels. More recently, *Böhm et al.* [1996] measured $\delta^{13}C$ trends in *Ceratoporella* from Jamaica and *Acanthochaetes* from New Caledonia, and *Worheide et al.* [1997] developed $\delta^{13}C$ and $\delta^{18}O$ isotope records from *Astrosclera* and *Acanthochaetetes* from the Great Barrier Reef.

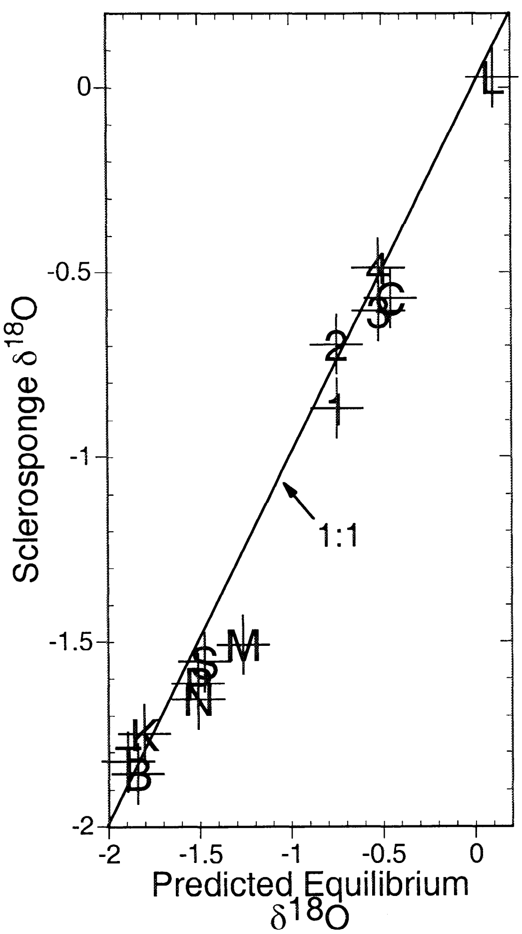

Figure 1. Comparison of sclerosponge $\delta^{18}O$ to predicted mean annual $\delta^{18}O$ for aragonite (or high-Mg calcite) precipitated in isotopic equilibrium with seawater [*Friedman and O'Neil*, 1977]. Specimens are *Astrosclera* (aragonite) from: Kapoposang Is. (K), Bunaken Is. (B), and Kapota Is. (T) in the Indonesian Seaway; Nauru (N); the Solomon Is. (S); and Western Samoa (M); *Acanthochaetes* (high-Mg calcite) from Palau (P); and *Ceratoporella* (aragonite) from Lee Stocking Island, Bahamas (L). Also shown are measurements of *Ceratoporella* and *Acanthochaetes* by *Druffel and Benavides* [1986] and *Böhm et al.* [1996] from Jamaica (1, 2, 3, 4) and New Caledonia (C).

It is useful to illustrate that sclerosponge oxygen isotope ratios, as with the carbon isotopes, show no evidence of strong disequilibrium, even across a fairly wide range of values. For example, measured sclerosponge $\delta^{18}O$ values can be compared to predicted values of aragonite $\delta^{18}O$ precipitated in stable isotopic equilibrium with seawater (Figure 1). Equilibrium aragonite $\delta^{18}O$ values were estimated from the *Friedman and O Neil* [1977] equations for calcite then applying calcite to aragonite fractionation factors [*Tarutani*, 1969], using atlas temperature data [*Levitus et al.*, 1994a, 1994b; *Reynolds and Smith*, 1994]. Seawater $\delta^{18}O$ concentrations were estimated from atlas salinity data [*Levitus et al.*, 1994a, b] and the salinity and seawater $\delta^{18}O$ relationships from *Fairbanks et al.* [1992.] Also shown are values for several *Astrosclera* and *Acanthochaetetes* specimens we collected in the west Pacific; predicted equilibrium $\delta^{18}O$ values for the specimens from Indonesia are constrained by our field observations of temperature, salinity, and seawater $\delta^{18}O$ (described in more detail later). Most of the values plot close to the 1:1 line; there is some scatter, but the discrepancies are small and probably arise from the relatively imprecise atlas estimates of subsurface temperature, salinity, and seawater $\delta^{18}O$. Even though the concept of stable isotopic equilibrium is exceedingly difficult to define with precision, we can say that there is no evidence of strong metabolically induced disequilibrium in any of the sclerosponge data.

One potential disadvantage of sclerosponges is that they lack annual density bands and must be dated radiometrically. *Benavides and Druffel* [1986] used $\Delta^{14}C$ and ^{210}Pb, while *Bohm et al.* [1996] and *Worheide et al.* [1997] used $\Delta^{14}C$. However, these methods do not deliver the level of temporal precision that is necessary for higher-resolution (decadal-scale) paleoceanographic reconstructions. In this study, we use the more precise method of $^{230}Th/^{234}U$ dating, measured by thermal ionization mass spectrometry (TIMS) [*Edwards et al.*, 1987]. We show here that this method provides a precision that is appropriate for resolving decadal trends in ocean properties.

3. Sample Sites

As part of a larger study of variability in the tropical Pacific, specimens of *Astrosclera willeyana* were collected in 1995 at depths of 10-20 m from one site in the Solomon Islands and three sites in the Indonesian Seaway (Figure 2). The Solomon Islands site is located in the Florida group (10°S, 160°E) and lies within the region of the west Pacific warm pool strongly influenced by the South Pacific Convergence Zone. Kapoposang Island in the southeastern Makassar Strait (4°40'S, 118°55'E) and Bunaken Island in the eastern Sulawesi Sea (1°38' N, 124°45' E) are each bathed by through flowing surface waters supplied year round by the North Equatorial Current [*Ffield and Gordon*, 1992; *Ilahude and Gordon*, 1996; *Moore et al.*, 1997]. Kapoposang lies on the main Pacific to Indian Ocean throughflow pathway, while Bunaken is under the influence an east flowing throughflow branch that, instead of entering the Makassar Strait, retroflects within the Sulawesi Sea and exits the archipelago to supply the

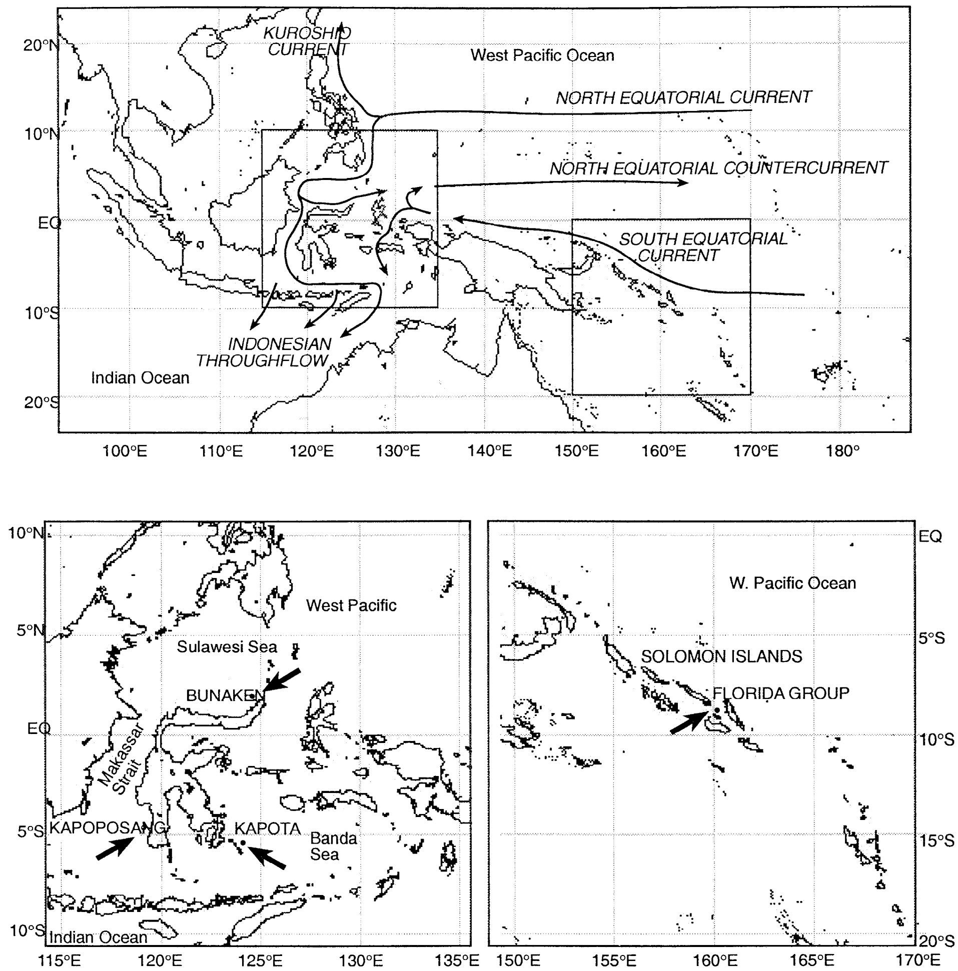

Figure 2. Site map for the sclerosponge samples analyzed.

North Equatorial Countercurrent [*Lukas et al.*, 1991]. Kapota Island in the western Banda Sea (5°S, 124°E) is under the influence of a secondary throughflow pathway supplied by the South Equatorial Current.

Recent hydrographic studies of the Indonesian Seaway indicate that the Makassar Strait and the Sulawesi Sea are highly stratified and variable on seasonal timescales [*Ilahude and Gordon*, 1996]. During the SE monsoon (SEM) dry season, surface salinities are 34.40-34.45 per mil and sea surface temperature (SST) is ~ 27°C. A well-defined salinity maximum representing the through flowing North Pacific Subtropical Water (NPSW) is found within the main thermocline at 80-200 dbar. Salinity of the core layer of the NPSW is 34.6-34.7 per mil, with temperatures of 22°-24°C. During the NW monsoon (NWM) wet season, freshwater from rivers floods the sea surface, lowering surface salinities (to as low as 31.6 per mil in the Makassar Strait) and producing a sharp halocline in the upper 100 dbar. During the NWM the NPSW core is more attenuated, suggesting reduced advective replacement and lower throughflow [*Ilahude and Gordon*, 1996].

For a localized illustration of these processes, continuous temperature measurements made during 1992-1993 at Kapoposang Island at 3 and 27 m, in conjunction with weekly salinity and seawater $\delta^{18}O$ measurements at 3 m and 20 m (see methods), revealed substantial stratification in the upper 30 m of the water column during both the SEM and the NWM (Figure 3). The temperature measurements show that subsurface temperatures were cooler by 1°-2°C during the SEM. The salinity measurements detected the development of a thin halocline during NWM, when surface salinities were 0.5-0.8 less than at 20 m. During the transition from the NWM to the SEM, the subsurface-to-surface temperature differential increased from 0.7°C in March to 2.0°C in August (when the monthly mean 27 m temperature dropped to its minimum value of 25.2°C), indicating a shoaling of the seasonal thermocline.

These measurements of seasonal differences between surface and subsurface temperature and salinity at Kapoposang are certainly large enough to influence sclerosponge skeletal chemistry. For example, aragonite precipitated in equilibrium with seawater at 20-27 m should be ~0.3‰ more positive in $\delta^{18}O$ during March-September. Thus the seasonal stratification in the upper waters of the Indonesian Seaway is intense enough to allow $\delta^{18}O$ in sclerosponges (collected at 20-30 m depth) to record subsurface variability independent of the surface variability, even over these relatively shallow depth ranges.

4. Methods

The largest specimens from each site were selected for stable isotopic analysis. Powder samples were collected using a variable speed drill at 0.5 mm increments along the growth axis of each specimen. Samples were reacted sequentially in a common bath of orthophosphoric acid at 90°C for 20 min by an automated carbonate device and analyzed using a Finnegan 252 gas source mass spectrometer. Long-term (multiyear) external precision (1s), deduced from parallel determinations of the NBS 19 standard, is <0.05‰ for $\delta^{13}C$ and <0.08‰ for $\delta^{18}O$.

The innermost (basal) part of each specimen was dated by $^{230}Th/^{234}U$ disequilibrium at Lamont-Doherty. Isotopic abundances were measured TIMS using methods similar to those outlined by *Edwards et al.* [1987]. Full details of the technique will be presented elsewhere. Approximately 1-2 g of skeleton was cut from the interior of the specimen slab. A mixed $^{229}Th/^{233}U$ spike was added, and the weighed sample was dissolved in concentrated HNO_3. Th and U were separated using coprecipitation with added Fe, then purified by ion chromatography. Isotopic abundances were determined by TIMS on a VG Sector mass spectrometer. The calculated ages were corrected for small measured amounts of common Th (^{232}Th) using the isotopic composition of crustal Th.

Field temperature measurements were made using Tempmentor brand thermistors at 2 hourly increments with a precision of ±0.1°C. Salinity and $\delta^{18}O$ measurements were made on 150 mL water samples collected at weekly intervals, weather permitting. Conductivity measurements were made using a handheld meter calibrated against a KCl standard. Seawater $\delta^{18}O$ was measured by CO_2 equilibration on a VG Prism gas source mass spectrometer at Lawrence Berkeley Laboratory (Don DePaolo). Precision on the measurement of a calibrated laboratory water standard (TW-1) is ±0.1‰$_{SMOW}$ for $\delta^{18}O$. Linear regression of seawater $\delta^{18}O$ on salinity at Kapoposang yields the mixing line: $\delta^{18}O_{SMOW} = 0.269S + -9.50$, $r = 0.95$, $N = 32$. This mixing line is taken as representative for Indonesian Seaway waters.

5. Results

5.1. Chronology and Resolution

To be climatically useful, the time series from young sclerosponges must be accurate and precise to within a few years error. U/Th methods in young corals clearly have the potential to meet these demands [*Edwards et al.* ,1987]; our results represent the first attempt to apply the method to sclerosponges.

Uranium concentrations in the sclerosponges we dated are higher and more variable than in corals, ranging from 6 to 9 ppm (Table 1.). These high values could be taken as a sign of incorporation of uranium above that dissolved in seawater

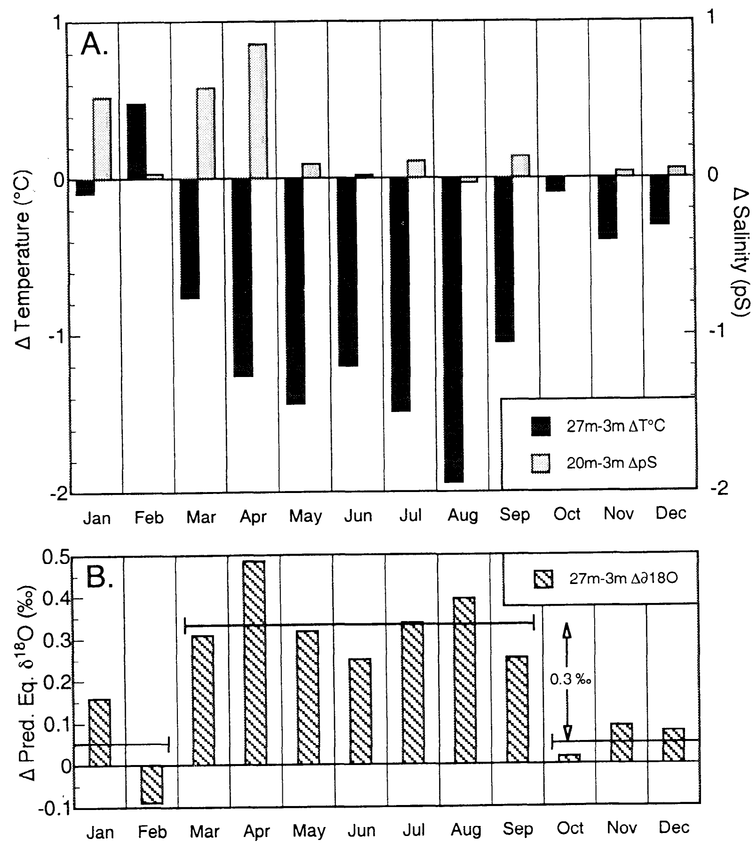

Figure 3. (a) Seasonal progression of subsurface differences in temperature, salinity, and predicted equilibrium calcite $\delta^{18}O$ at Kapoposang Island (Makassar Strait, Indonesia) based on field observations collected during 1992-1993. (b) Seasonal variability in thermocline and halocline depth in the Makassar Strait which produces relatively large seasonal differences between surface and subsurface calcite $\delta^{18}O$ (~0.3‰ during March-September). These data indicate that isotopically detectable subsurface temperature variability can occur independently of the surface variability in the Makassar Strait, even over relatively shallow depth ranges (3-30 m).

Table 1. U/Th Dating Results

Specimen	Collected Depth, m	Mean Distance From Rim, mm	U, mg/g	^{232}Th, pg/g	^{230}Th/^{234}U, activity x 10^{-4}	δ^{234}U, ‰	Age, years	Corrected Age, years
Bunaken-1	20	30 ±5	6.76	1340	5.151	142 ±6	56.0	51.5 ±1.8
Bunaken-1	20	50 ±5	5.49	1357	7.516	140 ±8	81.8	76.1 ±2.7
Kapoposang-1	20	32 ±4	9.57	9351	9.568	145 ±3	104.1	81.9 ±8.9
Solomon-1	17	62 ±7	6.36	1250	9.484	146 ±4	103.2	98.7 ±3.6
Kapota-1	10	58 ±6	6.79	2826	8.431	143 ±3	91.7	82.3 ±3.4

Mean distance refers to the average depth and interval over which skeletal material was sampled. Age and corrected age given in years prior to 1996. Corrected age is reduced for inclusion of ^{230}Th with common ^{232}Th using crustal ^{230}Th/^{232}Th; uncertainty includes uncertainty in common Th correction. All uncertainties are given as $\pm 2\sigma$.

(roughly 3 ppm). However, it is important to recognize that the equilibrium distribution coefficient for uranium in aragonite is not well known, and thus there is no established reason to be suspicious of such high uranium concentrations. A more diagnostic indication of the reliability of the uranium series dates is that measured values of δ^{234}U (defined as per mil deviation of ^{234}U/^{238}U from secular equilibrium) are within the narrow range of 145 ±5 observed in modern seawater [e.g., *Chen et al.*, 1986]. *Astrosclera* has slightly higher detrital ^{232}Th than hermatypic corals, and these levels of common thorium result in age corrections that are of the order of 5 years. Overall, the calculated ages for the dated specimens range from 51 to 99 years, with uncertainties of 4-11% (2σ). This level of precision represents a significant improvement over the precision of ^{210}Pb or radiocarbon dating for samples as young as these.

We converted the stable isotope depth series to time series by assuming linear growth. Linear concordance between the two Bunaken U/Th dates can be achieved, within the limits of precision, using dates of 1917 (1920-3 yrs) and 1948 (1945+3 yrs). For the Kapoposang, Kapota, and Solomon Island series, the basal ages were used (1911, 1914 and 1897, respectively). Considering the lack of obvious variability in growth rate, the amount of skeletal material dated, and analytical precision of the U/Th dates, this initial dating effort yielded a temporal accuracy of the order of ±10 years.

Cross-checks on the U/Th chronologies can be made by comparing the sclerosponge δ^{13}C records to measurements of atmospheric δ^{13}C to 1978 (Figure 4) from the Law Dome ice core record [*Francey et al.*, 1999] and the average of flask measurements since 1978 at Mauna Loa and the South Pole [*Keeling et al.*, 1995]. Since sclerosponge aragonite shows no apparent carbon isotopic disequilibrium with respect to ambient seawater, the time history of Suess effect δ^{13}C depletion through the twentieth century should be broadly similar in all the records. In fact, all the dated sclerosponge δ^{13}C records agree well with the atmospheric δ^{13}C record (especially the Kapota and Solomons records), and the level of agreement lends credence to the U/Th dates. Thus the δ^{13}C records provide complementary chronological constraints for the proxy records, analogous to the utility of δ^{18}O in deep- sea sediment cores.

One might expect local variability in oceanic carbon cycling to create some differences among the δ^{13}C records. In general, carbon isotopic equilibrium between the atmosphere and surface water dissolved inorganic carbon (DIC) is <60% complete because the isotopic equilibration time for surface water DIC with respect to atmospheric CO_2 is long (~10 years), comparable to the average residence time for surface waters in contact with the atmosphere. Consequently, the penetration depth for the anthopogenic ^{12}C signature in the ocean is variable, and the sclerosponge records reflect the regional differences in this uptake. For example, the Kapota and Solomons Suess-effect δ^{13}C decreases are about 50% of the observed atmospheric depletion, in agreement with sclerosponge δ^{13}C decreases observed elsewhere [*Druffel and Benavides*, 1986; *Bohm et al.*, 1996; Worheide *et al.*, 1997], while the Bunaken and Kapoposang Suess effect δ^{13}C decreases are only ~30% of that in the atmosphere. This application of the sclerosponge archive will be treated in more detail elsewhere, but as we will discuss, the details of the δ^{13}C records probably do have some bearing on the interpretation of climate proxy records.

All the sclerosponge isotopic time series show significant oscillations on (roughly) interannual timescales, and therefore one additional chronological issue is the ultimate temporal resolution of the proxy records. Microstructural studies by *Worheide et al.* [1997] describe a two-stage calcification process occurring within the live tissue layer of *Astrosclera.* Siliceous spicules (60-150 mm in length) in the soft tissue are fixed in a basal calcareous skeleton to form a lightweight, open framework. This framework is then infilled by inorganically precipitated aragonite spherulites to form the bulk of the skeletal mass. Though there is no definitive estimation of the timescale for this secondary aragonite precipitation, it does create some uncertainty in the degree of temporal smoothing at the highest frequencies. This uncertainty, combined with our specimens' growth rate, our sampling interval, and the precision of the dates, presently limit us to consideration of decadal trends. However, in principle, it is possible that appropriately selected sclerosponge records (particularly from the faster growing species *Acanthochaetetes wellsi*) could be applied to the problem of interannual variability.

5.2. Climate Records: Proxy and Instrumental

The δ^{18}O time series (Figure 5) from the deeper Indonesian sclerosponges all show significant trends during the last century. The Bunaken record, from 20 m depth, shows a low- frequency oscillation through the first half of this century followed by a strong shift of +0.6‰ since ~1960. The Kapoposang record, also from 20 m, shows a similar pattern, recording a post-1970 shift of +0.5‰. Stable isotope time series prepared from replicate specimens collected at Bunaken and Kapoposang (and roughly dated by peak matching and Suess effect ^{13}C depletion rates) confirm these recent δ^{18}O shifts to more positive values. The Kapota record, from 10 m depth, shows a positive δ^{18}O shift of +0.2‰ which occurs in the 1940s, at about the same time the Bunaken δ^{18}O record attains peak minimum values. In contrast, the Solomon Islands δ^{18}O record (17 m depth) shows no strong trends, and instead is characterized by interdecadal oscillations with maximum amplitude of 0.2‰ and a period of ~30 years.

Interpreted in terms of temperature and salinity, the δ^{18}O time series from the Indonesian sclerosponges indicate shifts at Bunaken and Kapoposang since 1970 of ~ -2.5°C (if entirely

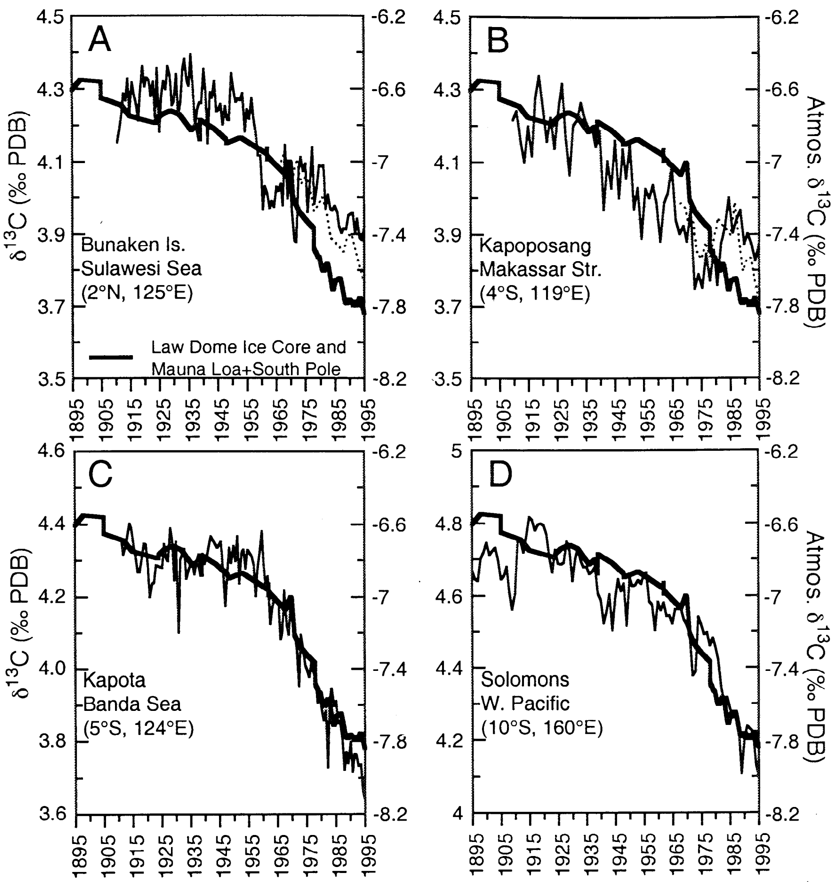

Figure 4. Comparison of sclerosponge δ13C records to measurements of atmospheric δ13C from ice cores at Law Dome, Antartica (1885-1978) [*Francey et al.*, 1999] and averaged flask measurements from Mauna Loa, Hawaii, and the South Pole (1978-1995) [*Keeling et al.*, 1995]. Note the 2:1 difference in scales for atmospheric δ13C (right) and sclerosponge δ13C (left). Age models assume linear growth and are constrained by a Th/U date at the base of each sponge. Dashed lines indicate records from different specimens collected at the same site, dated by assuming the growth rate determined for the Bunaken specimen (0.7 mm/yr).

temperature), -2.0 per mil salinity (if entirely freshwater flux), or some combination between these extremes. Neither of these possibilities can be explained by regional SST and rainfall trends, which we have estimated from the *Kaplan et al.* [1998] 5°x5° optimally smoothed sea surface temperature anomaly in 15°N-15°S, 115°E-145°E (eastern Indonesian seas), and from zonally averaged gridded precipitation data (NOAA NCEP GCPS) in 15°N-5°S, 95°E-140°E (insular Southeast Asia); nor do these sclerosponge trends resemble the long-term trend of Bunaken surface waters captured by a 121 yr coral $\delta^{18}O$ record at that site (M. Moore et al., Patterns of interdecadal and ENSO variability in the equatorial Pacific from corals, submitted to the *Journal of Geophysical Research*, 1999). The trends for the coral and instrumental series were estimated by singular spectrum analysis (SSA) and multichannel singular spectrum analysis (MSSA), respectively; both methods are data-adaptive techniques well-suited for trend estimation in short, noisy time series [*Vautard et al.*, 1992; *Plaut and Vautard*, 1994; *Jiang et al.*, 1995]. The instrumental and coral time series were reduced to annual means, and the longest possible windowing dimensions (*N*/3) were used to maximize the accuracy of the trend estimates.

The surface instrumental and proxy observations (Figures 6a-6c) indicate that SST in the Indonesian Seaway has increased by about +0.45°C since the early 1900s, similar to the global trend [*Kaplan et al.*, 1998]. Annual precipitation in Southeast Asia has decreased by ~10 mm since 1920, with the largest changes occurring north of the equator (~ -20 mm). Analyses of station precipitation data in Southeast Asia by *Nitta and Kachi* [1994] obtained similar results. A regional increase in SST of 0.45°C should produce a $\delta^{18}O$ shift of at least -0.1‰, while a regional decrease in rainfall of < 1% (taking 2500 mm as representative annual mean) should have a negligible effect on surface water $\delta^{18}O$. The Bunaken coral $\delta^{18}O$ trend shows a shift of about -0.17‰ since 1900, equivalent to a sea surface temperature increase of about +0.8°. Low-frequency oscillations in the coral $\delta^{18}O$ trend appear to match similar oscillations in the regional SST trend, and furthermore, the coral $\delta^{18}O$ trend shows no evidence of a compensating increase in surface water $\delta^{18}O$, as might be expected with a deficit in rainfall. From these considerations, we conclude that coral $\delta^{18}O$ trend at Bunaken captures the regional surface water trend to increased temperatures in the late twentieth century, even though it is weak.

If the deeper sclerosponges do not record these trends in surface conditions, then it is appropriate to consider subsurface temperature observations in the Indonesian Seaway. Though these data are sparse and not well characterized in terms of quality, *White* [1995] produced gridded temperature anomalies, consisting of all available BT, CTD, and XBT observations (1955-1996), optimally interpolated to 2° latitude by 5° longitude and 11 standard depth levels (0-400 m). The data show a strong cooling trend in subsurface temperatures (maximized at the 120 m depth level), with little or no change in surface temperatures. For illustration purposes, we have plotted these 120 m temperature trends in different regions with the sclerosponge records from the same region (Figure 7). The Bunaken and Kapoposang scleroponge records are generally consistent with the trends at depth, while the other two sclerosponge records are not. It is important to point out that the apparent match in amplitude (Bunaken sclerosponge $\delta^{18}O$ and the 120 m temperature both suggest a cooling of ~2°C) does not hold for comparisons with 20-30 m instrumental temperature estimates. Therefore, the scale of the sclerosponge $\delta^{18}O$ trends is significantly larger than one would infer from the available subsurface observations, even though the direction of the trends is consistent.

5.3. Influence of Winds: Observations and Model

What process(es) might be driving this low frequency variability in the deeper layers at or above the thermocline? The most obvious possibility is that the Indonesian thermocline changes reflect an adjustment to large-scale wind forcing. This connection is perhaps more readily recognized if the *White* [1995] subsurface temperature anomalies at 0-400 m are cast in a time-depth plot (Figure 8a). Clearly, the most intense anomalies occur between 120 and 160 m, corresponding to the depth of the main thermocline. Well-defined anomalies associated with ENSO variability can be identified during 1970-1996, with warm (cool) anomalies occurring up to 1 year after an ENSO cool (warm) event. Prior to 1970, the interannual anomalies are not as well defined, probably because of inadequate data density. The interannual variations in temperature undoubtedly reflect variations in the E-W tilt of the Pacific thermocline in response to remote wind forcing during ENSO phase changes [*Chao and Philander*, 1993]. Warm (cool) anomalies are produced by anomalous depression (shoaling) of the thermocline during ENSO cool (warm) events.

On longer timescales it apparent from Figure 8a that the 120 m level is dominated by warm anomalies prior to 1980, while the more recent period is dominated by cool anomalies. It is not possible to separate ENSO and lower-frequency variability with such few observations, but the nature of the trend can be seen in the progressive cooling of the maximum and minimum extrema realized with each ENSO phase change. This pattern suggests a progressive shoaling of the thermocline in the latter decades.

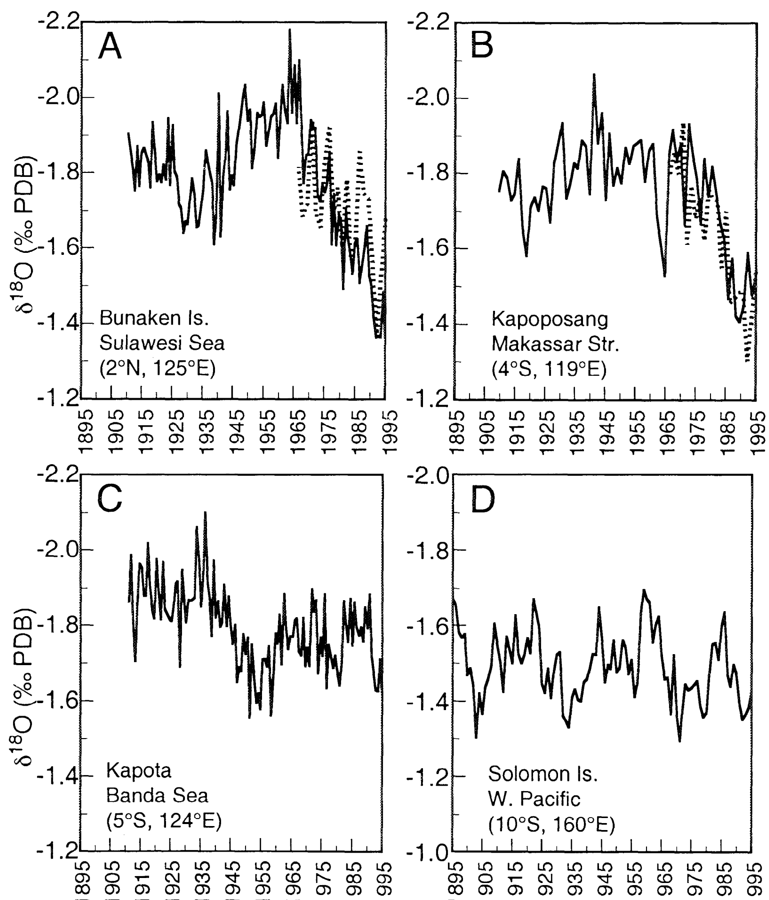

Figure 5. Sclerosponge δ18O records from the Indonesian Seaway and the Solomon Islands. Y axes are reversed so that the data correspond to temperature. Age models assume linear growth and are constrained by a Th/U data at the base of each sponge. As in Figure 4, dashed lines indicate records from separate specimens collected at the same site.

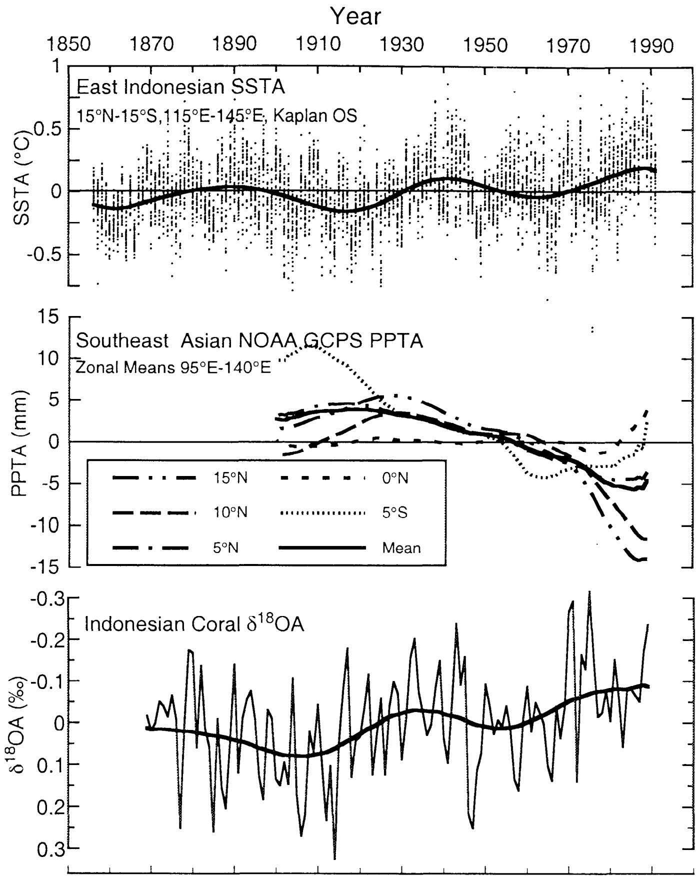

Figure 6. Low-frequency variability in Indonesian Seaway sea surface temperature, rainfall, and coral $\delta^{18}O$. Sea surface temperature anomaly (SSTA) data are optimally-smoothed gridded data from *Kaplan et al.* [1998], and rainfall data are NOAA Global Climate Perspective System gridded anomalies. Coral data are from a *Porites* core collected at 3 m depth at Bunaken Island. The coral $\delta^{18}O$ trend was estimated by single-channel singular spectrum analysis [*Vautard et al.*, 1992], using m = 20 yr. Coral data are monthly means, smoothed with a 13pt running mean. Surface trends in Indonesia are characterized by a regional SST warming trend (a) with little or no reduction in regional rainfall (b).

We explored the possibility that trends in surface winds (Figure 8b) could be responsible for the trend in subsurface temperature anomalies (figure 8a) observed in Indonesia. Florida State University (FSU) wind pseudostress anomalies [*Stricherz et al.*, 1992, 1997] were averaged for the epochs 1965-1975 and 1985-1995, and differences were computed. These two epochs correspond to periods when subsurface temperature anomalies in Indonesia are anomalously warm (1965-1975) and anomalously cool (1985-1995). The data were exposed to a 3 year low-pass filter prior to averaging. The epoch differences in mean pseudostress magnitude (abs(u) + abs(v)) were also computed; these are shown in Figure 9b as a contour plot with a contour interval of 20 dyn/ cm^2.

These plots reveal a large-scale pattern in the equatorial Pacific centered at ~160°W. The western equatorial Pacific shows a shift to weakened wind strength, with eastward zonal anomalies (westerlies), while the central and eastern equatorial Pacific show a shift to increased wind strength and westward zonal anomalies (easterlies). Largest changes in the windfield occur off the equator west of the dateline, with a shift to strong westward and equatorward anomalies observed between 10°-22° in both hemispheres. This pattern is reminiscent of the ENSO warm phase wind anomaly pattern that produces thermocline shoaling in the western Pacific [*Chao and Philander*, 1993]. These wind trends have been noted previously [*Harrison*, 1989], though their physical reality has been questioned [e.g., *Cardone et al.*, 1990]. More recent studies suggest that observed wind trends are dynamically consistent with observed shifts in sea level air pressures [e.g., *Inoue and Bigg*, 1995]. *Graham* [1994] recovered essentially the same spatial pattern using a different wind product, further demonstrating that the wind trend is the consequence of more frequent deep atmospheric convection over the central equatorial Pacific.

The effect of such wind trends on subsurface temperature data can be illustrated by a steady state general circulation model (GCM) hindcast forced by FSU wind stresses (1962-1996) between 18°N-18°S by *Schneider et al.* [1999b]. This experiment was motivated by previous analyses of observations and model results [*Schneider, et al.* 1999a] on the low frequency adjustments of the tropical Pacific thermocline to tropical wind forcing. In the model experiment depicted here, anomalous wind forcing was applied to the model (the Hamburg Ocean Primitive Equation model (HOPE)) within 18° of the equator and decreased to zero at 23° latitude. SST was relaxed to climatology, wind pseudostress was converted to wind stress using a constant drag coefficient, and no throughflow is permitted. Because the model was forced with climatological SST, the simulation should not generate temperature anomalies on interannual or longer timescales unless strongly affected by ocean dynamics.

Figure 9a compares mean annual model thermocline temperature anomalies (150 m) and observed 120 m temperature anomalies [*White*, 1995] for the same spatial domain in the Indonesian Seaway. Though the model thermocline response is more energetic, there is good agreement with the observations ($r = 0.56$). The simulation successfully reproduces the interannual variability and the decadal cooling trend from 1970-1996. Results of this experiment indicate that the thermocline in the Indonesian Seaway should respond directly to the tropical wind stress curl on decadal frequencies.

Furthermore, trends in observed 120 m temperature anomalies in the Indonesian Seaway (Figures 9b-9d) are well-correlated with trends in FSU wind pseudostress time series for the regions of the western Pacific characterized by strong temporal trends. Average monthly pseudostresses were computed for three latitude bands between 148°-180°E (7°N-7°S, 9°N-17°N, and 9°S-17°S) and smoothed by a 13-point running mean. High correlations were found to zonal wind anomalies in the equatorial W. Pacific, $r = -0.77$ (Figure 9a) and to meridional wind anomalies, particularly in the south Pacific off-equatorial region, $r = -0.85$ (Figure 9b). All of the observed wind time series lead the observed 120 m temperatures by 1 year, in agreement with the model experiments by *Schneider et al.* [1999a].

6. Discussion

Trend analysis of twentieth century climate data (and, for that matter, proxy data) is an exercise fraught with uncertainties, but we believe the characteristics of sclerosponges render them particularly suitable for reconstructing low-frequency changes in large-scale ocean dynamics. The lack of any obvious metabolic effects on the isotopic composition of the skeleton and the high degree of reproducibility between different specimens from the same site add to the reliability of these trends. Furthermore, the fact that specimens from some sites show no long term-trend suggests that in general, age-related biases do not influence the sclerosponge time series.

The direction and magnitude of change observed in the Indonesian sclerosponges is impossible to reconcile with the surface instrumental record alone because SST compilations invariably indicate warming thoughout the century. The Bunaken and Kapoposang sclerosponges show cool isotopic temperatures during the 1920-1930s, warm isotopic temperatures during the 1950-1960 s, and very strong cool temperatures that are perhaps associated with the 1976-1977 climate shift (though the precision of the age model is not sufficient to establish exact correlations). In fact, these sclerosponge records, nearly a century in length,

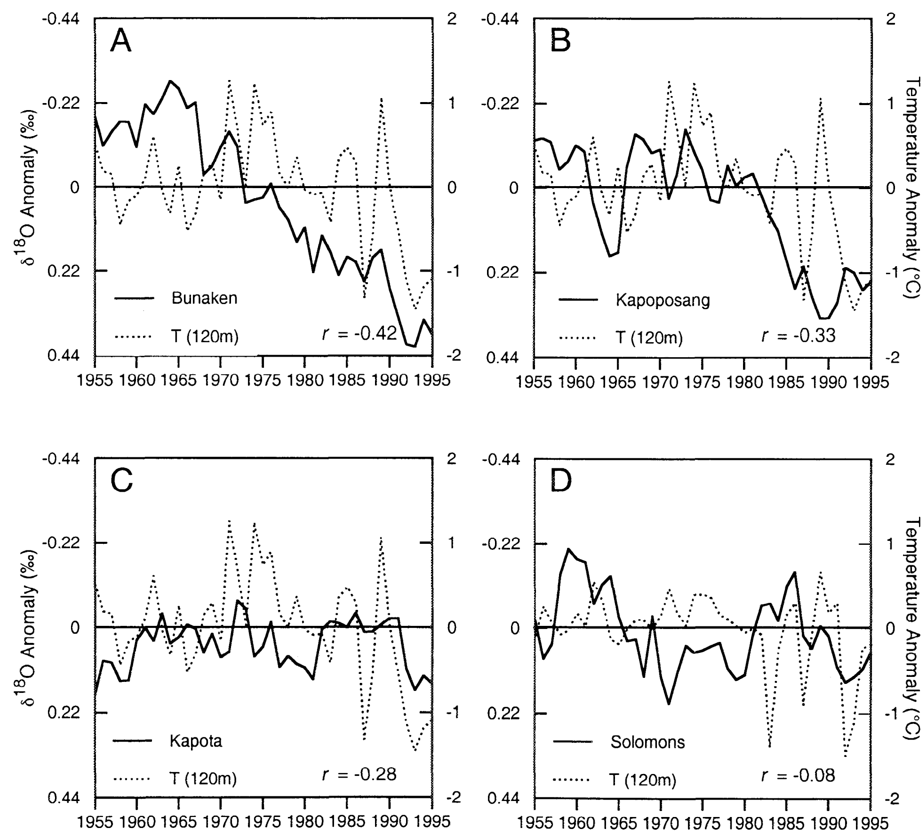

Figure 7. (a) Bunaken, (b) Kapoposang, and (c) Kapota sclerosponge δ18O anomaly records, compared to the *White* [1995] average 120 m temperature anomaly for the region enclosing the sites (4°N-4°S, 110°E-135°E). (d) Solomons sclerosponge δ18O record and the *White* [1995] average 120 m temperature anomaly time series for the region enclosing the site (6°S-14°S, 150°E-175°E). Data are annual means, and δ18O axes are reversed and scaled to temperature.

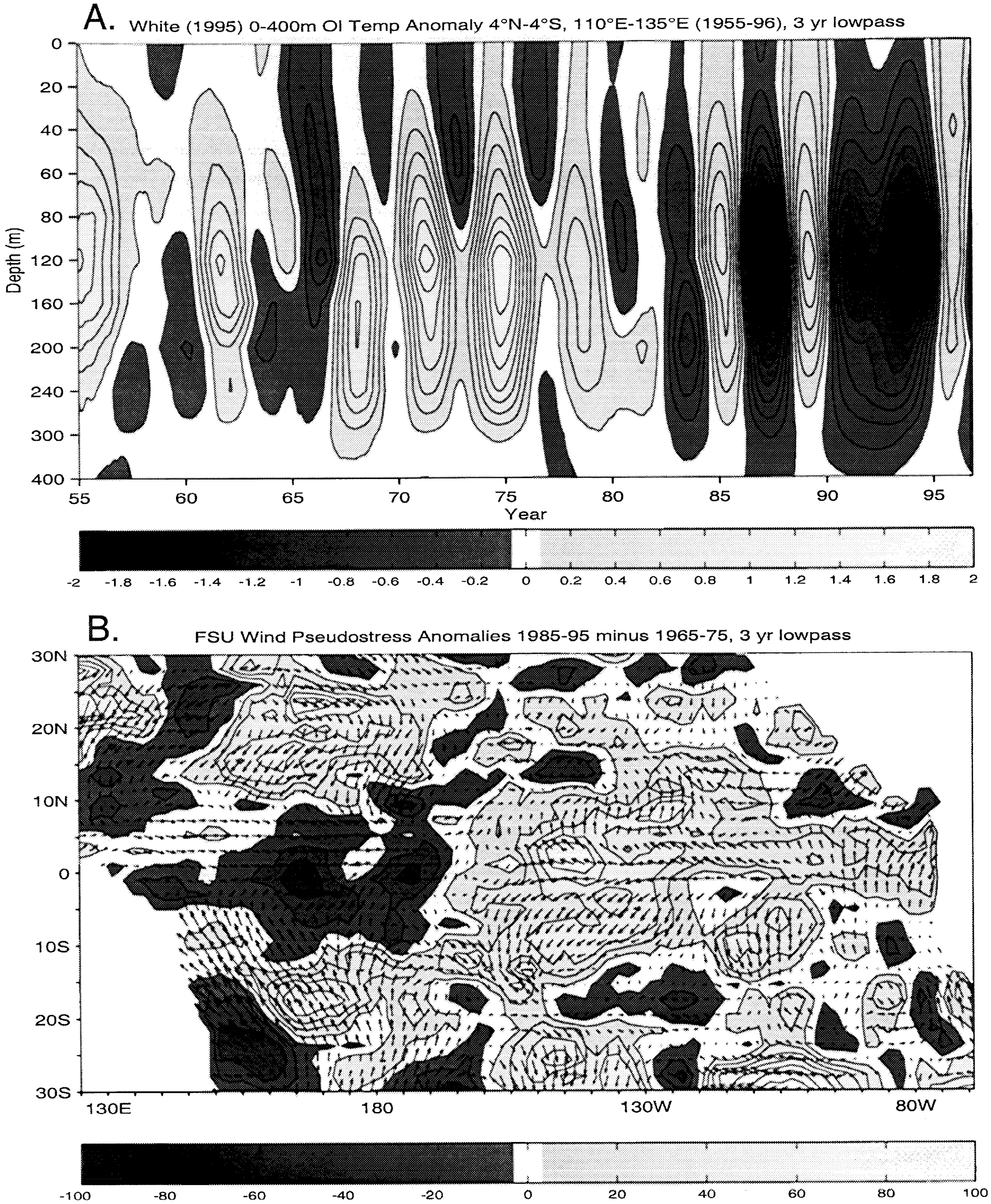

Figure 8. (a) Evolution of subsurface temperature anomalies in the Indonesian Seaway from *White* [1995] optimally interpolated temperature data. Data have been exposed to a 3 yr lowpass filter; contour interval is 0.2°C. Warm anomalies (+1.0°C) dominate the 120 m depth level prior to 1980, while after 1980 cool anomalies (-1.8°C) predominate. Subsurface anomalies can also be seen intruding into the shallow depth ranges (20-40 m) where the sclerosponges were collected. Oscillations in temperature at 120 m reflect undulations of the main thermocline following ENSO phase changes. (b) Epoch differences in Florida State University (FSU) wind observations. Plotted are differences in averaged wind psuedostress anomalies for 1965-1975 and 1985-1995. Data were exposed to a 3 yr low pass filter prior to averaging. Epochal differences in FSU wind observations show a shift to weak westerly anomalies in the equatorial west Pacific and strong equatorward anomalies in the north and south Pacific.

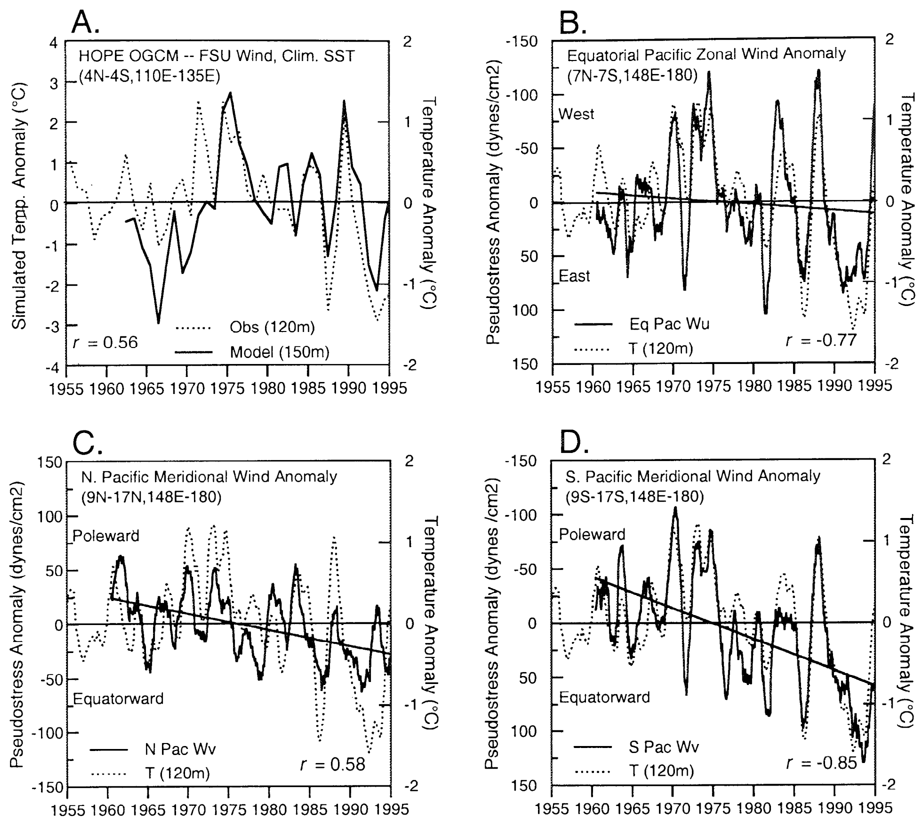

Figure 9. (a) Time series of 150 m temperature anomalies in the Indonesian Seaway from a general circulation model hindcast [*Schneider et al.*, 1999b], forced by FSU wind stresses (1962-1996) using climatological SST, compared to *White* [1995] 120m temperature anomalies. Data are annual averages for the region 4°N-4°S, 110°E-135°E. (b) zonal winds for 7°N-7°S, Mean west Pacific equatorial and off-equatorial FSU wind psuedostresses (148°E-180), (c) meridional winds for 9°N-17°N, (d) meridional winds for 9°S-17°S, compared to *White* [1995] observed 120m temperature anomalies for the region 4°N-4°S, 110°E-135°E. Wind data have beén smoothed by a 13 point running mean, and temperature data have been lag adjusted by 1 year. Trend in wind data is indicated by heavy lines.

suggest that the cooling during the most recent decades is the strongest of the twentieth century. The available subsurface observations are consistent with at least the direction if not the magnitude of these proxy records: Both suggest a thermocline response to wind variability on decadal timescales. The connection between the sclerosponge records, subsurface temperature trends, and changes in the wind forcing has a relatively simple physical basis. To first order, the east-west tilt of the Pacific thermocline must be in Sverdrup balance with the integral of the wind stress curl, and it is widely acknowledged that the thermocline in this region is indeed strongly forced by tropical wind variability on interannual timescales. There is no reason to believe that this same mechanism would not apply on longer timescales, and therefore we favor this explanation for the trend in the Indonesian sclerosponges.

Still, the circulation and bathymetry of the Indonesian Seaway is sufficiently complicated that a decadal-scale baroclinic response to wind forcing obviously will not be realized everywhere. In this respect, it is perhaps not surprising that the Kapota sclerosponge record, located off the main axis of throughflow, has a different structure than those from Kapoposang and Bunaken. (It is also important to note that the Kapota record is shallower and is therefore more susceptible to surface water influences).We have assumed, by default, that the two records nearest the main throughflow route reflect changes in the sourcewater from the North Pacific. However, more localized monsoonal processes could also contribute to the details of the vertical structure along the throughflow route. At present, it is difficult to speculate on the specific influences of these local processes, separate from the large-scale trends that we have emphasized. However, the consistency between the Bunaken and Kapoposang specimens (at the entrance and directly downstream in the throughflow path, respectively) indicates that highly localized influences, such as "island effects," for example, are not responsible for the main trends observed.

Carbon isotope evidence also adds support for the general interpretation of the scelerosponge $\delta^{18}O$ records. One expectation of thermocline shoaling in the western. Pacific might be a shift in the $\delta^{13}C$ of water DIC. While the Solomons and Kapota $\delta^{13}C$ records follow closely the atmospheric $\delta^{13}C$ trend, the Bunaken and Kapoposang $\delta^{13}C$ records show depletions that are less than one might expect from the atmospheric $\delta^{13}C$ records. The main difference between the sclerosponge $\delta^{13}C$ records is that the Bunaken and Kapoposang $\delta^{13}C$ records show a slower rate of depletion than do the Kapota and Solomons $\delta^{13}C$ records after 1970. This may be evidence of anthropogenically unaltered subsurface water (more enriched in ^{13}C) penetrating into shallower depths. This explanation is consistent with a shoaling of the thermocline because the nutricline is deeper than the thermocline at these sites.

Corroborative evidence for a decadal-scale adjustment of the equatorial Pacific thermocline during 1976-1977 can also be found in high-resolution coral radiocarbon records from the Makassar Strait and the Galapagos. Coral $\Delta^{14}C$ in the Makassar Strait [*Moore et. al.*, 1997] shows a large (~ 50‰) reduction in seasonal radiocarbon maxima after 1976, indicating the increased presence of ^{14}C depleted thermocline water in west Pacific surface waters. Coral $\Delta^{14}C$ in the Galapagos [*Guilderson and Schrag*, 1998] shows a shift to more positive seasonal radiocarbon minima at this same time, indicating the reduced presence of ^{14}C-depleted thermocline water in east Pacific surface waters. These $\Delta^{14}C$ observations are most easily explained by an adjustment of the E-W tilt of the Pacific thermocline, with shoaling in the west and deepening in the east, and a consequent downstream influence on throughflow waters.

None of the various lines of evidence for subsurface change (and driving forces behind these changes) would be completely satisfying on their own. On the other hand, the combination of the proxy records, the observations, and the ocean model results forms a seemingly consistent picture of climate variability in the west Pacific over this century. We believe that this specific example underscores the utility of sclerosponge records for providing a more dimensionally complete view of tropical ocean dynamics. Higher-resolution and better dated sclerosponge time series undoubtedly can be produced through microsampling and application of multiple U/Th dates utilizing lesser amounts of skeleton. Furthermore, because of the great depth range of sclerosponges it should be possible to reconstruct historical variability of the main thermocline at its most active depths using specimens collected from open ocean reef sites by submersibles or remote operated vehicles.

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