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A 900 year stable isotope record of interdecadal and centennial change from the California Current

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Abstract. This paper describes the development of a high-resolution record of interdecadal and centennial variability of ocean climate of the California Current from continuous 5 year sampling intervals based on varve counts from Santa Barbara Basin sediments. We show the importance of the choice of species and size fraction as well as the practice of making multiple measurements per interval to obtain a clear environmental signal capable of resolving interdecadal change. Changes in temperature and salinity from oceanographic surveys of the past 50 years indicate that thermal variability dominates the $\delta^{18}O$ signal. A $\delta^{18}O$ record from *Neogloboquadrina dutertrei* spanning 1030-1905 A.D. contains interdecadal thermal fluctuations within the upper thermocline that are centered around periods of roughly 55, 70, and 90 years. The interdecadal changes comprise the major share of total variability compared to a low-amplitude mode of underlying multicentennial variability corresponding to the Medieval Warm Period and the Little Ice Age.

1. Introduction

The problem of detecting effects of anthropogenic forcing on natural climate change has led to a significant research effort to understand the nature of interdecadal to centennial variability of the climate system [*Martinson et al.*, 1995]. The lack of both instrumental and proxy records documenting multidecadal through multicentennial variability is particularly acute for the oceans [*Wunsch*, 1992] and severely hampers investigation of climate change over these timescales. Although a detailed history of the tropical oceans is emerging from the study of coral records [e.g., *Dunbar et al.*, 1994], marine varve records from extratropical sites that focus on interdecadal to centennial variability [e.g., *Baumgartner et al.*, 1992; *Biondi et al.*, 1997] are still fairly rare. Interest in the midlatitudes of the North Pacific has been heightened with observations of interdecadal changes of state affecting a multitude of physical and biological properties [*Ebbesmeyer et al.*, 1991; *Roemmich and McGowan*, 1995; *Mantua et al.*, 1997]. The principal objective of this work is to document the natural modes of interdecadal and centennial variability of the California Current system. We approach this through development of a robust time series of stable isotope variability over the past millenium from the varved sediments of the Santa Barbara Basin (Figure 1). We examine the character of both the signal and the noise contained within the series and relate these to observed environmental variability within this region over the last 50 years. We infer past climatic changes based on our findings.

The Santa Barbara Basin is well known for its preservation of seasonal differences in particle density and composition at the basin floor which result in annual laminae pairs or varves [*Soutar and Crill*, 1977]. The presence of nearly anoxic bottom waters and high sedimentation rates result in a unique sedimentary record that allows high-resolution climate reconstructions on interannual to millenial timescales [*Lange et al.*, 1996]. The combination of source waters from the regional oxygen minimum zone, high residence times within the basin and the respiration of abundant organic matter account for the depleted oxygen levels in the bottom water [*Hulsemann and Emery*, 1961]. The low oxygen conditions prevent benthic macrofauna from inhabiting and disturbing the sediment.

Several studies have examined high-resolution environmental changes through isotopic signatures of planktonic foraminifera in Santa Barbara Basin sediments. *Dunbar* [1983] and *Weinheimer et al.* [1999] compared $\delta^{18}O$ measurements on *Globigerina bulloides* from box cores with instrumental records and found some relationship to ENSO variability and decadal-scale climate off southern California. *Hendy and Kennett* [1999] made measurements on *G. bulloides* and *Neogloboquadrina pachyderma* from ~14 year intervals every 50-70 years in the late Quaternary and found large changes corresponding to Dansgaard-Oeschger cycles in the North Atlantic. However, there has been no previous down core isotope work with the continuity and resolution to quantify interdecadal- and centennial-scale changes in ocean climate.

The principal sources contributing to the isotopic values from foraminifera tests are the extrinsic environmental variability, intrinsic physiological processes, and the analytical error. The predominant environmental signal of a particular species represents the species' preferred habitat when abundance is highest [*Hemleben et al.*, 1989]. The temporal sources of environmental variability in this study are associated with seasonal, interannual, interdecadal, and multicentennial timescales. The $\delta^{18}O$ composition of calcite reflects changes in temperature and salinity [*Spero and Lea*, 1996], while the $\delta^{13}C$ values of dissolved organic carbon in the oceans vary with nutrients and apparent oxygen utilization [*Deuser and Hunt*, 1969; *Kroopnick*, 1985]. The processes that maintain the $\delta^{13}C$ relationship operate parallel to those determining other nutrient profiles, varying with nutrient input and productivity responses.

There are generally species-specific differences in $\delta^{18}O$ due to physiological processes that also change with growth [*Berger et*

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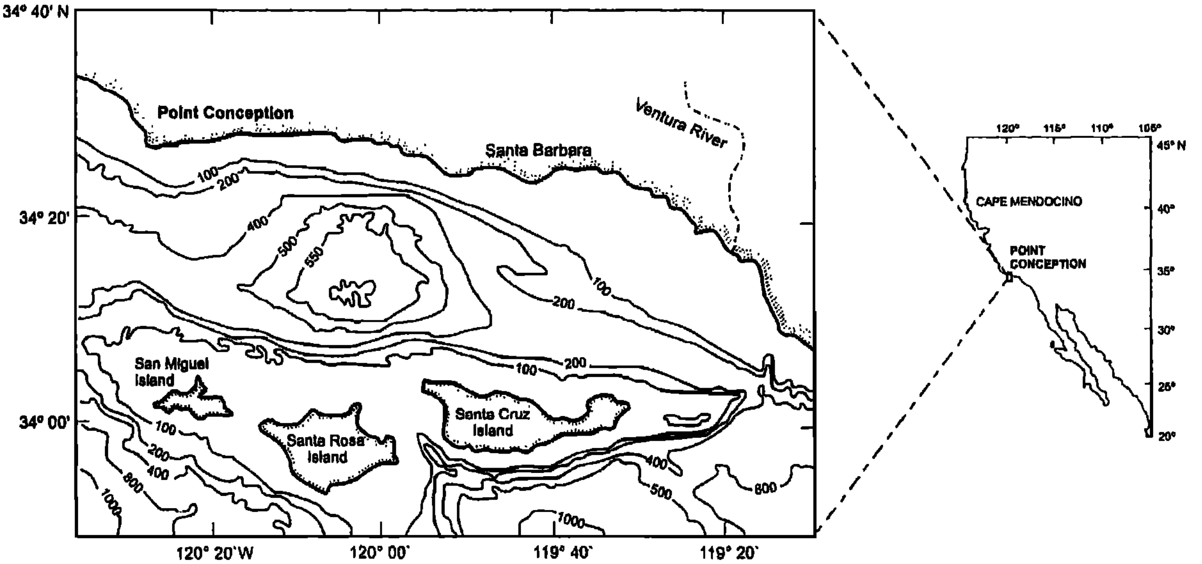

Figure 1. Location and bathymetry (in meters) of the Santa Barbara Basin.

al., 1978; *Spero and Lea*, 1996]. Consequently, isotopic analyses must be limited to narrow size fractions for consistency in tracking changes in ambient waters. In order to establish the optimum species and size fraction for developing a long time series we examined the isotopic signals and variability contained in two size fractions of *Neogloboquadrina dutertrei* and *Orbulina universa* from continuous 5 year intervals. These species were selected because of our interest in creating a record reflecting stable conditions in the upper thermocline (*Sautter and Thunell*, 1991a, 1991b; *Ortiz et al.*, 1995). On the basis of our initial study we selected the larger size fraction of *N. dutertrei* to develop a 900 year isotopic record.

2. Methods

The material used in this study was obtained from a 2.7 m long Kasten core, designated SBKC 9110-2, taken from a depth of 585 m near the center of the Santa Barbara Basin (Figure 1). This core was divided into five subsections for transport and processing [see *Baumgartner et al.*, 1996]. The core subsections were cut into six vertical slabs and X-radiographed to show the laminated structure of the annual varves. Four slabs were cut to 2.5 cm width to be used for analyses while the other two slabs were cut to 1 cm width for fine resolution in the X-radiographs. A detailed chronology was developed based on visual identification of individual varves from the X-radiographs of the two thin slabs. This chronology is anchored by the well-established varve count from several box cores extending to 1880 that has been verified by ^{210}Pb dating [*Soutar and Crill*, 1977]. Centimeter-scale homogenous layers, identified as instantaneously deposited gravity flows [*Hulsemann and Emery*, 1961], were excluded from analysis. Uncertainty in the varve count increases down core owing to occasional diminished clarity in laminae structure or erasure of laminae by gravity flows. We estimate that the cumulative uncertainty in the varve count is ±15 years at 1030 A.D. Comparison of the varve sequence in this core to the equivalent stratigraphic interval in two other Kasten cores from the basin constrains our chronology and indicates that 20 years of varve deposition extending from ~1800 to 1820 are missing in the core used for this study relative to the other two cores. The hiatus appears to be the result of erosion by a gravity flow.

The four slabs of 2.5 cm thickness were each subsampled into continuous sequences of whole 5 year intervals based on the chronology and processed independently. The sampling error associated with the excision of each 5 year interval may be as high as 1 year but would not be propagated down core. Material from the 300-700 μm fraction from each of the four slabs was combined into one 5 year sample. To investigate variability in δ^{18}O and δ^{13}C related to size, we measured the down core signals in two size fractions of *O. universa* and *N. dutertrei*. For *N. dutertrei* we picked the 300-400 and 400-700 μm classes on the basis of the width of the shortest axis of five or six chambered individuals. For *O. universa* we separated tests into 300-420 and 420-700 μm size fractions by measuring the diameter of the tests. Individuals were observed to be gametogenic, and there was no evidence of recrystallization.

The number of tests used to obtain a single measurement is an important consideration because of the large range of isotopic variability found among tests in a sample [*Killingley et al.*, 1981]. Averaging multiple measurements made with a representative number of tests is an effective means of reducing analytical and environmental variability associated with a single sample interval [*Schiffelbein and Hills*, 1984]. Because we are working with finer temporal resolution than most isotopic studies on foraminifera and our expected signal is of smaller magnitude, the variance within samples is likely to be particularly important. Environmental variability due to depth distribution, and intrannual and interannual factors is expected to lie both within and between intervals. The longer-period interdecadal and centennial changes are the main signals of interest sought in the down core sampling. We ran two replicates per interval where possible, using seven individuals from the larger size class of *N. dutertrei* and eight to nine in the smaller size class. The abundance of *O. universa* was considerably lower than *N.*

dutertrei, and in many intervals we were limited to a single sample per interval or forced to combine individuals from several adjacent intervals for a single measurement. Four to five individuals were used in the larger size class and from five to six were used in the smaller size class. Isotope analyses were done on the Finnigan/MAT-252 mass spectrometer at Scripps Institution of Oceanography and expressed relative to the Peedee belemnite (PDB) standard. The machine error, defined by the standard deviation of 113 standard measurements over the period from which samples were run, is <0.06 and 0.03 for $\delta^{18}O$ and $\delta^{13}C$ respectively.

On the basis of results from the preliminary analysis we focused on the larger size class of *N. dutertrei* to develop a continuous down core series, although we placed a tighter upper limit on the test size. Seven individuals of *N. dutertrei* from the 400-500 μm range, as measured by the shortest axis, were used for each interval wherever possible. For this series we made at least three replicates per interval wherever material permitted. In intervals where variability was high and sufficient tests were available we analyzed one or two additional replicates. For intervals with low abundances we were limited to one or two measurements, sometimes consisting of four to six individuals. In one of the intervals (1360-1365 A.D.), insufficient tests were present to run an analysis. Owing to analytical problems, samples from the period 850-1030 A.D. were lost, and our series thus begins at 1030 A.D.

3. Results

3.1 Sources of Variability

The $\delta^{18}O$ measurements presented in Figure 2 show down core temporal shifts and variance within the sample intervals as a function of species and test size. The $\delta^{13}C$ measurements are not shown here but yield similar patterns of variability. The replicate measurements for the two size fractions of both species demonstrate that variability within the 5 year intervals comprises a large portion of the total variance.

The larger size fraction of *N. dutertrei* shows a marked shift toward simultaneous depletion of $\delta^{18}O$ and enrichment of $\delta^{13}C$ (Figures 2 and 3). Although the shift between size classes is considerably less marked for *O. universa*, the difference is significant for both the $\delta^{18}O$ and $\delta^{13}C$ measurements (*t* test, $p < 0.01$ in each case). The enrichment of $\delta^{18}O$ in the smaller size fractions differs from the general trend exhibited by most species that is attributed to a decrease in physiological effects [*Berger et al.*, 1978]. The shift toward heavier $\delta^{18}O$ values in smaller size fractions suggests that environmental effects are masking offsets that may exist between size classes owing to physiological processes [*Dunbar*, 1983; *Wefer et al.*, 1983]. An increase in $\delta^{13}C$ with size is the typical trend observed in most species and is also expected from warm, surface waters depleted in $\delta^{18}O$. It is difficult to determine whether the increase in $\delta^{13}C$ associated with the larger size class is intrinsic, environmental, or a combination

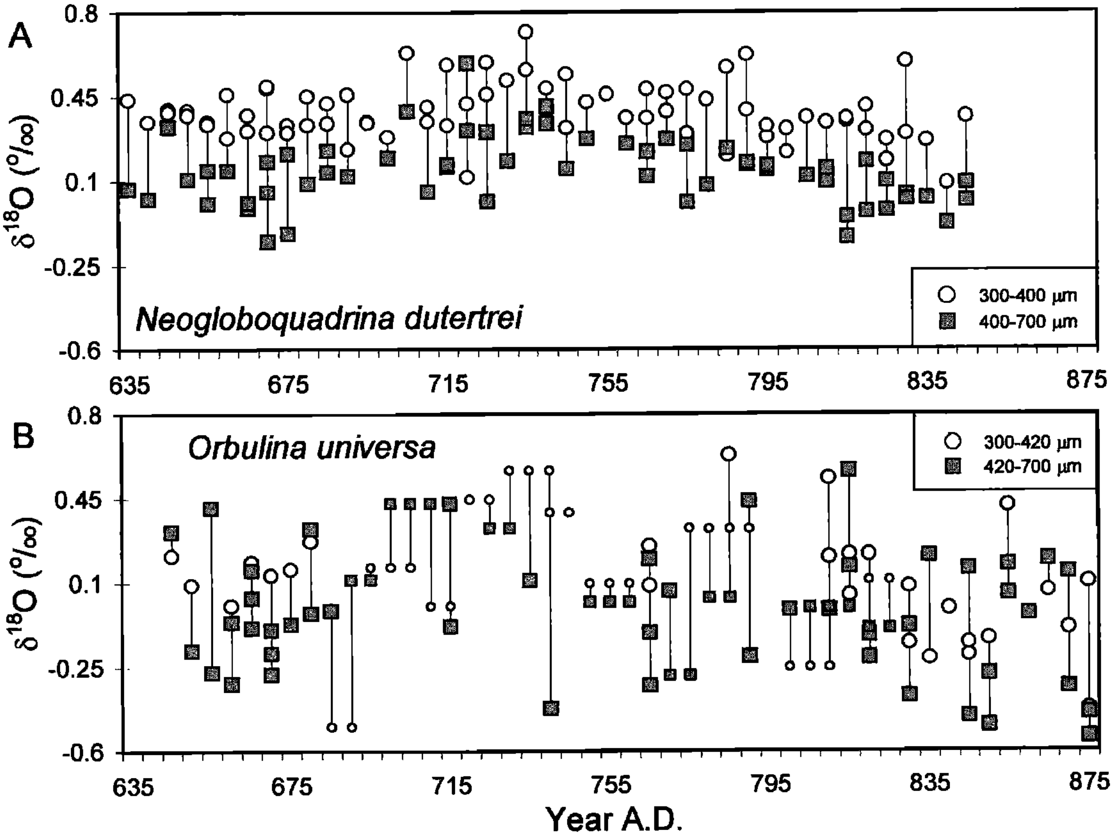

Figure 2. Time series of the $\delta^{18}O$ values of the two size fractions of (a) *Neogloboquadrina dutertrei* and (b) *Orbulina universa* from 630-875 A.D. in Kasten core SBKC 9110-2. The smaller symbols in the *O universa* series represent cases where tests were combined from two or more intervals to make a measurement.

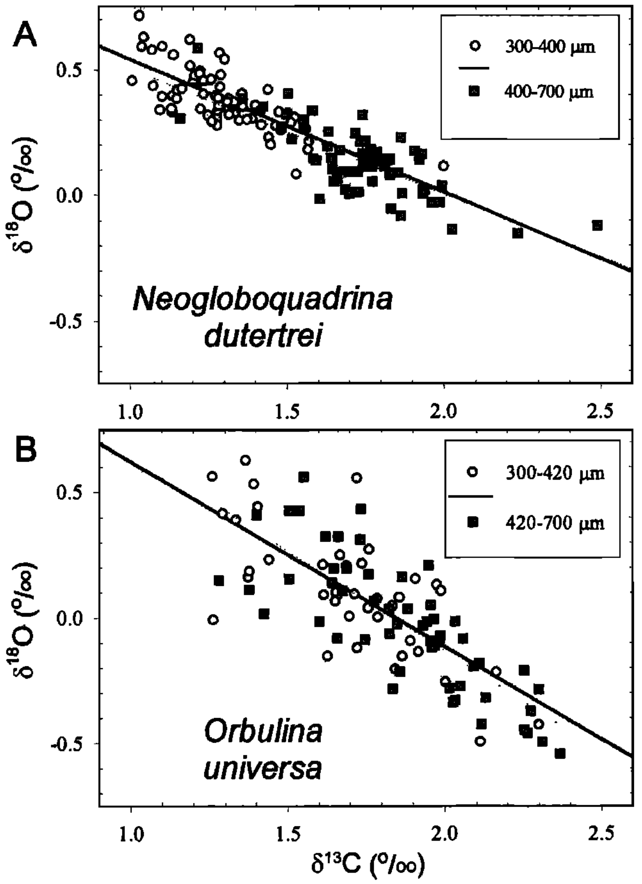

Figure 3. Scatterplots illustrating the $\delta^{18}O$ - $\delta^{13}C$ relationships for the different size fractions of (a) *N. dutertrei* and (b) *O. universa* analyzed for the period 630-875 A.D. There is a large offset in the values of *N. dutertrei* between size fractions although the relationships between the two variables is similar for both the smaller ($y = -0.53x + 1.07$; $r^2 = 0.54$; $p < 0.0001$) and larger ($y = -0.50x + 1.00$; $r^2 = 0.56$; $p < 0.0001$) size fractions. *O. universa* shows similar values and slopes between the smaller ($y = -0.74x + 0.52$; $r^2 = 0.52$; $p < 0.0001$) and larger ($y = -0.80x + 0.64$; $r^2 = 0.64$; $p < 0.0001$) size fractions.

of both. However, the negative relationship between $\delta^{18}O$ and $\delta^{13}C$ values (Figure 3) is expected for species dwelling within the thermocline as these waters are characterized by enriched $\delta^{18}O$ in association with depleted $\delta^{13}C$ [*Sautter and Thunell*, 1991a].

The temporal signal consists of variability among the average values of the replicates from the down core sequence of intervals. The variability within the intervals (between replicate measurements) is considered to be noise that obscures the down core signal. The signal to noise ratios for the oxygen and carbon isotope measurements in Figure 2 are determined from a one-way analysis of variance (ANOVA) given in Table 1. The ANOVA was done on the combined measurements of both size fractions of *O. universa* because of the limited number of intervals with replicate measurements available, the presence of several intervals where tests were combined to run a single measurement, and the smaller offsets in values due to size. In order to focus on the species-specific effect and to eliminate the effect of size from this analysis of *O. universa* the difference in the average $\delta^{18}O$ and $\delta^{13}C$ values of all measurements made in each size fraction was added to the larger size fraction (to correct for the offset). For each species and size class analyzed the $\delta^{18}O$ and $\delta^{13}C$ series show similar signal to noise ratios, but they differ considerably when compared across species and size classes (Table 1). We selected the larger size fraction of *N. dutertrei* to develop a continuous down core record (Figures 4 and 5) because of the greater strength of its temporal signal and relatively higher abundances in the core[1]. We further limited our constraints on test size to the 400-500 μm size class because of the strong isotopic separation in size classes (Figure 3).

Results of the ANOVA presented in Table 2 indicate that the down core $\delta^{18}O$ signal of the 900 year record (Figures 4) is more than twice the noise and the $\delta^{13}C$ signal (Figure 5) is nearly 3 times the noise contained within replicate measurements. A 200 year segment at the beginning of the series is expanded to allow a detailed comparison of the temporal signal to the noise within intervals (Figures 4b and 5b). The standard deviation of machine error of $\delta^{18}O$ (<0.06) is comparable to the down core average of the standard deviations within the intervals (0.075). Thus a large portion of the $\delta^{18}O$ variability within intervals (Figure 4) can be attributed to machine error. The average standard deviation of replicate $\delta^{13}C$ values (0.11) is several times greater than the machine error (<0.03), suggesting that the noise in the $\delta^{13}C$ series is largely due to sources other than machine error. These comparisons are placed in perspective by considering that the signal to noise ratio of the $\delta^{13}C$ series is considerably higher than the $\delta^{18}O$ series even though the standard deviation of the $\delta^{13}C$ series is higher.

Figure 6 shows the effect that increasing the number of replicate measurements has on estimating the average value of an interval. The change in the average $\delta^{18}O$ value is defined as the difference between the average value for an interval before a replicate is run and the new average values resulting from successive measurements. The precision in estimating the average $\delta^{18}O$ value of an interval is indicated in Figure 6a by the plots of cumulative frequency of the changes in average values. The cumulative frequency plot shows that the average value of an interval changes from 0 to 0.14‰ 95% of the time and from 0 to 0.10‰ 90% of the time when making a second measurement within an interval. A third replicate is needed for 95% of the cases to change by <0.10‰. Note also that the difference between replicates is twice the change in the average value of two replicates and can be as high as 0.40‰ (Figure 6b), which occurred in several cases (Figure 4). This analysis indicates that replicate measurements are essential to developing a reliable time series capable of resolving interdecadal variability.

3.2 The Down Core Isotopic Signal

The coefficients of determination (r^2 values) given in Table 3 indicate the portion of down core variability shared among the six time series listed in Table 1. The series with the largest signal to noise ratios share the largest portion of down core variance even though they are from different species (Table 3 (top)). The lack of shared variance between the $\delta^{13}C$ series of the smaller size fraction of *N. dutertrei* and the remaining series stands out in contrast to the strong negative relationships seen within each

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[1] Data for Figure 4 are available electronically at World Data Center-A for Paleoclimatology, NOAA/NGDC, 325 Broadway, Boulder, CO 80303 (e-mail: paleo@mail.ngdc.noaa.gov; URL: http://www.ngdc.noaa.gov/paleo).

Table 1. Relative Sources of the Variance in the Isotopic Time Series of *Neogloboquadrina dutertrei* and *Orbulina universa* (Figure 2)[a]

Series	Source of Variation	Mean Square	*df*	F Ratio	F Critical$_{(0.05)}$	p
N. dutertrei $\delta^{18}O$ (400-700 μm)	signal (down core)	0.033	19	2.88	2.13	<0.05
	noise (within intervals)	0.012	20			
N. dutertrei $\delta^{13}C$ (400-700 μm)	signal (down core)	0.078	19	3.00	2.13	<0.01
	noise (within intervals)	0.026	20			
N. dutertrei $\delta^{18}O$ (300-400 μm)	signal (down core)	0.015	29	1.13	1.84	NS
	noise (within intervals)	0.013	30			
N. dutertrei $\delta^{13}C$ (300-400 μm)	signal (down core)	0.030	29	1.13	1.84	NS
	noise (within intervals)	0.027	30			
O. universa $\delta^{18}O$ (300-700 μm)	signal (down core)	0.092	39	1.63	1.57	<0.05
	noise (within intervals)	0.056	70			
O. universa $\delta^{13}C$ (300-700 μm)	signal (down core)	0.089	39	1.52	1.57	<0.10
	noise (within intervals)	0.058	70			

[a] The relative strength of the down core signal compared to the noise (within intervals) is given by the F ratio. Not significant (NS).

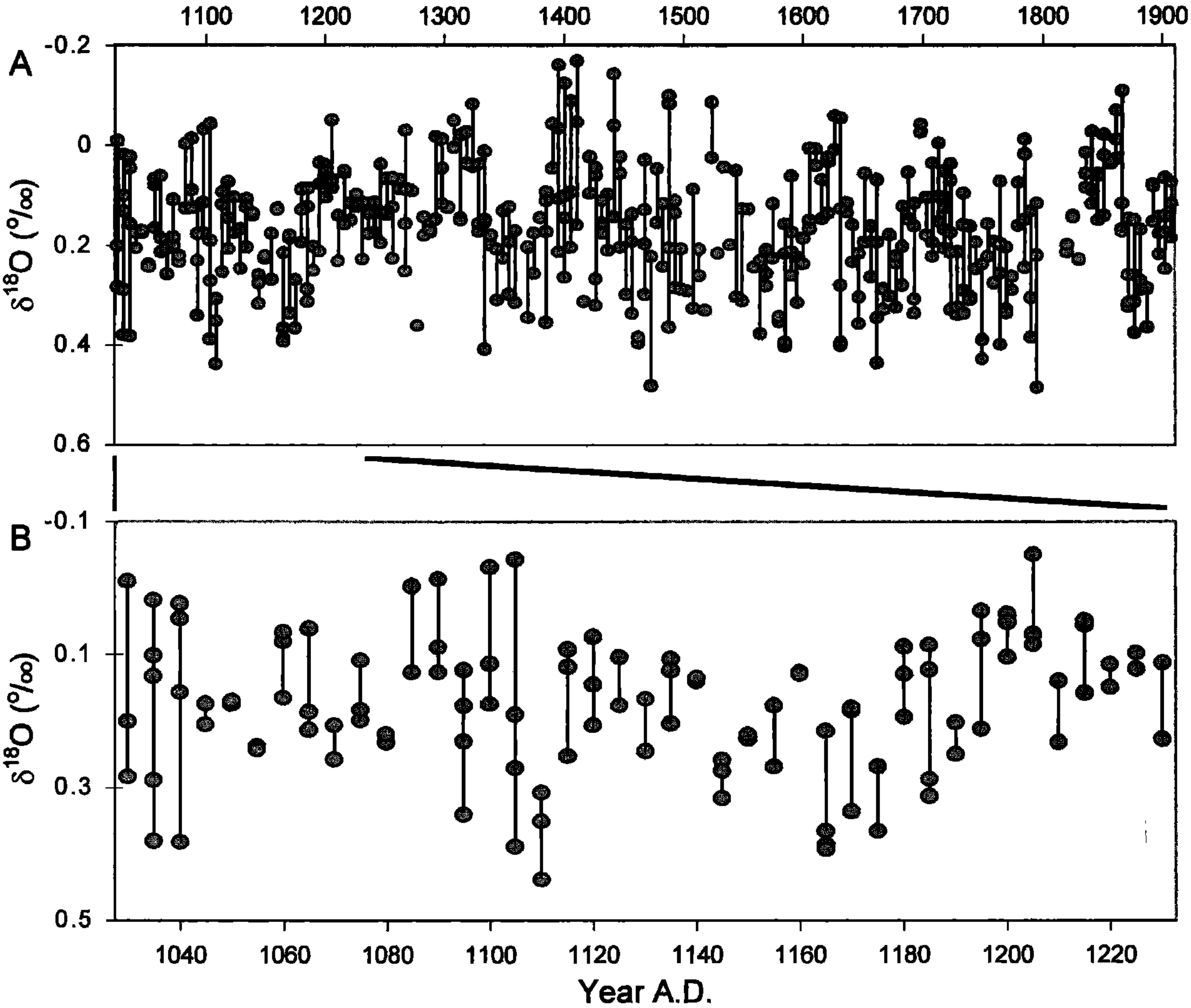

Figure 4. (a) Time series plot of the $\delta^{18}O$ measurements on the 400-500 μm size class of *N. dutertrei* through the period of 1030-1905 A.D. Each sample interval encompasses a 5 year period. Variability within a particular 5 year interval is emphasized by the vertical lines. While measurements in most intervals show a fairly limited range of values, some intervals have ranges approaching the total down core range. (b) The first 200 years of the series expanded to emphasize the variability and range of measurements within an interval. Note that the ordinate axis is inverted.

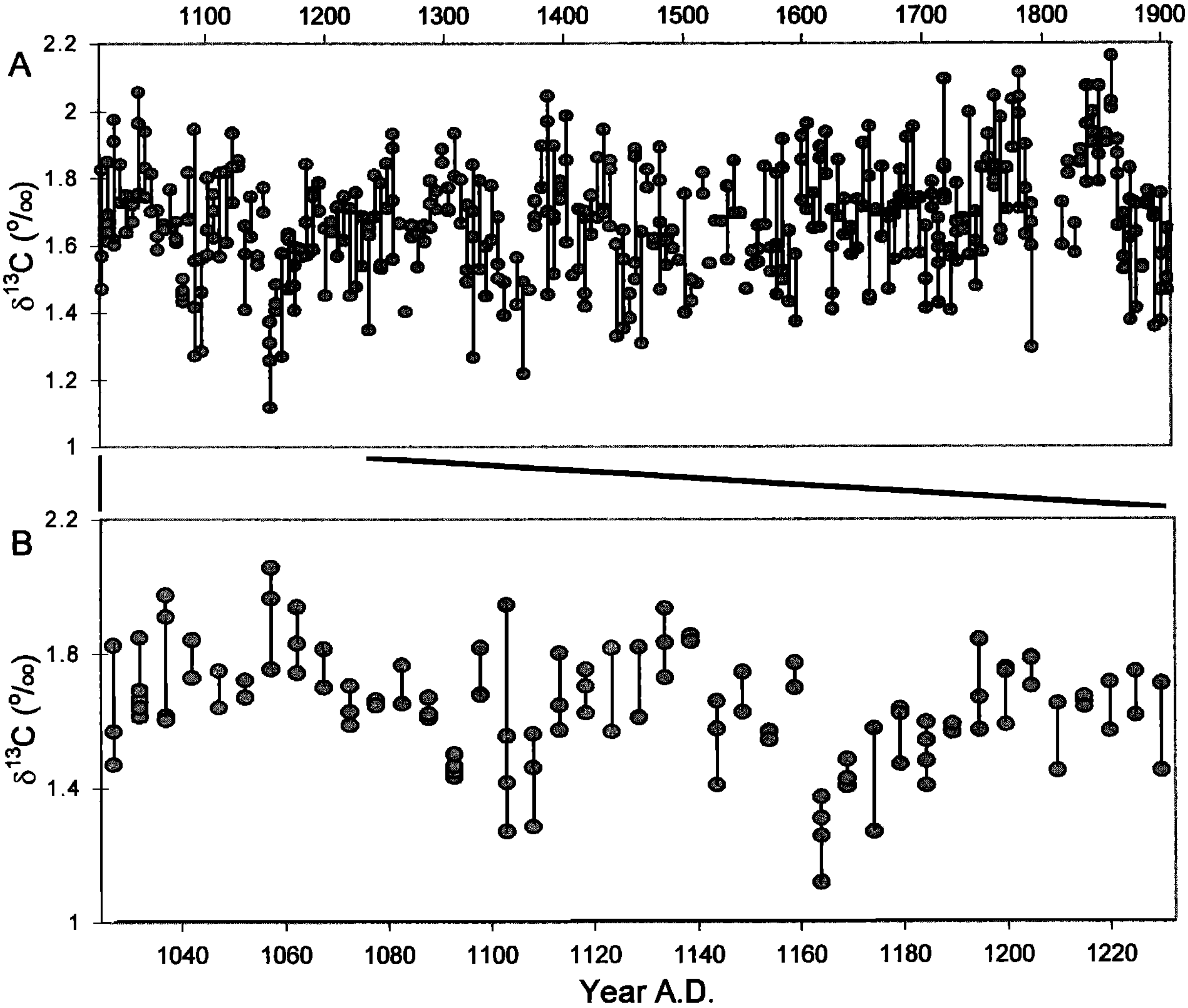

Figure 5. Same as Figure 4 but for the $\delta^{13}C$ measurements.

species and size fraction (Figure 3). The lack of shared variability between the $\delta^{13}C$ series of the different size fractions of *N. dutertrei* is consistent with the greater sensitivity of the carbon pool to changes in seasonality and depth compared to that of temperature and salinity. The greater shared variance in the $\delta^{18}O$ series indicates that the different species and size fractions are recording similar temperature and salinity signals.

The dominant timescales of the down core $\delta^{18}O$ variability in the *N. dutertrei* record are illustrated in Figure 7. The time series of the average values of measurements made within intervals, shown in Figure 7a by the thick line, was filtered with a lowess filter [*Cleveland*, 1979] using an f value of 0.04 to remove periods shorter than 15 years. This low-pass filter eliminates high-frequency variability considered here as white noise and emphasizes the interdecadal-scale variability plotted in Figure 7b. The average values shown in Figure 7a were also filtered with a stronger lowess filter (f=0.2) to show the low-frequency mode of variability with periods >150 years (Figure 7c). Note that the series in Figure 7b contains both the interdecadal and centennial modes of variability.

In order to examine the periodicities of the interdecadal variability the low-frequency record (Figure 7c) was subtracted

Table 2. Relative Sources of the Variance in the Down Core Series of *N. dutertrei* (400-500 μm) of Figures 4 and 5

Series	Source of Variation	Mean Square	*df*	*F* Ratio	*F* Critical $_{(0.05)}$	*p*
N. dutertrei $\delta^{18}O$	signal (down core)	0.021	156	2.13	1.25	< 0.0001
	noise (within intervals)	0.010	272			
N. dutertrei $\delta^{13}C$	signal (downcore)	0.049	156	2.79	1.25	< 0.0001
	noise (Within intervals)	0.018	272			

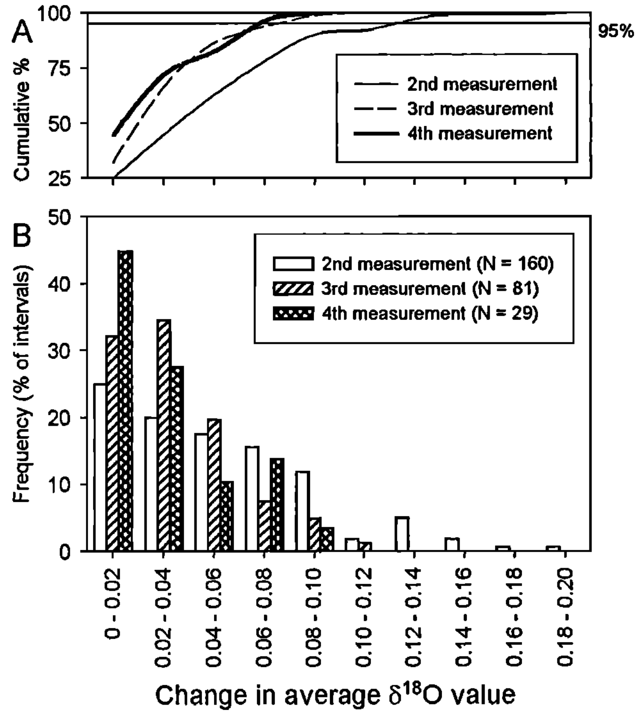

Figure 6. Illustration of the effects that an additional measurement of δ^{18}O from *N. dutertrei* has on the average isotopic value of a 5 year interval in the data set of Figure 4. The change in the average δ^{18}O value is the difference between the average value for an interval and the new average value after making an additional measurement. (a) The cumulative frequency of all cases. (b) Shows the distribution of the magnitude of change in the average value with each additional measurement.

from the high-frequency variability of Figure 7b for the interval of 1030-1800. A spectral analysis from the resulting series is presented in Figure 8. Owing to the nature of the 5 year intervals, the inherent variability associated with them, and the chosen smoothing function, periods <25 years may not be well resolved. The principal peaks distinguished in spectral power are located between 40 and 42 years, 53 and 58 years, 67 and 75 years, and 85 and 98 years.

4. Discussion

4.1 Sources of Variability

The four sources of variability in the isotopic measurements of *N. dutertrei* and *O. universa* examined here are due to (1) species differences, (2) different size classes of each species, (3) the noise associated with the imperfect recording and sampling of the signal, and (4) the down core temporal signal of each species and size fraction. While a trend toward enriched δ^{18}O in larger size classes of *N. dutertrei* occurs in open ocean regions, the opposing pattern found here has been described for other upwelling systems, in which strong environmental forcing overwhelms the changes in physiological processes associated with size [*Wefer et al.*, 1983; *Kroon and Darling*, 1995]. Cooler waters result in smaller final sizes, thus causing the isotopic signal of different size classes to reflect different environmental conditions [*Bijma et al.*, 1992]. The strong environmental fluctuations characterizing the eastern boundary conditions off southern California likely play a role in the change of δ^{18}O values with test size and appear to mask the effects of physiological processes on the δ^{18}O values.

The significant down core variability in both isotopes of the larger size fraction of *N. dutertrei* (Tables 1 and 2) illustrates the environmental signal that can be reconstructed from isotopic measurements on decadal to centennial timescales. The processes responsible for decadal- to centennial-scale variability have a greater influence on the average isotopic values than do the processes occurring within a 5 year period. The shared down core variance between the two species and different size classes (Table 3), which have different temporal and depth habitats, further indicates that the down core variability is due to large-scale environmental change over decadal to centennial timescales.

Analysis of the 429 measurements on groups of four to seven tests of *N. dutertrei* show that three measurements are necessary to gain a 95% level of precision in estimating the average δ^{18}O value within 0.1‰ for an interval, while a 90% level of precision

Table 3. Levels of Down Core Variance Shared Between the Different Time Series of *N. dutertrei* and *O. universa* in Table 1 (and Figure 2)

		O.universa (300-700 µm)				
		δ^{18}O		δ^{13}C		
	Source of Variation	r^2	p	r^2	p	*df*
N. dutertrei (400-700 µm)	δ^{18}O	0.18	< 0.01	0.19	< 0.01	37
	δ^{13}C	0.11	< 0.05	0.24	< 0.01	37
		N. dutertrei (300-400 µm)				
		δ^{18}O		δ^{13}C		
	Source of Variation	r^2	p	r^2	p	*df*
N. dutertrei (400-700 µm)	δ^{18}O	0.19	< 0.01	0.03	NS	37
	δ^{13}C	0.10	0.05	0.01	NS	37
O. universa (300-700 µm)	δ^{18}O	0.15	< 0.05	0.03	NS	40
	δ^{13}C	0.05	NS	0.07	NS	40

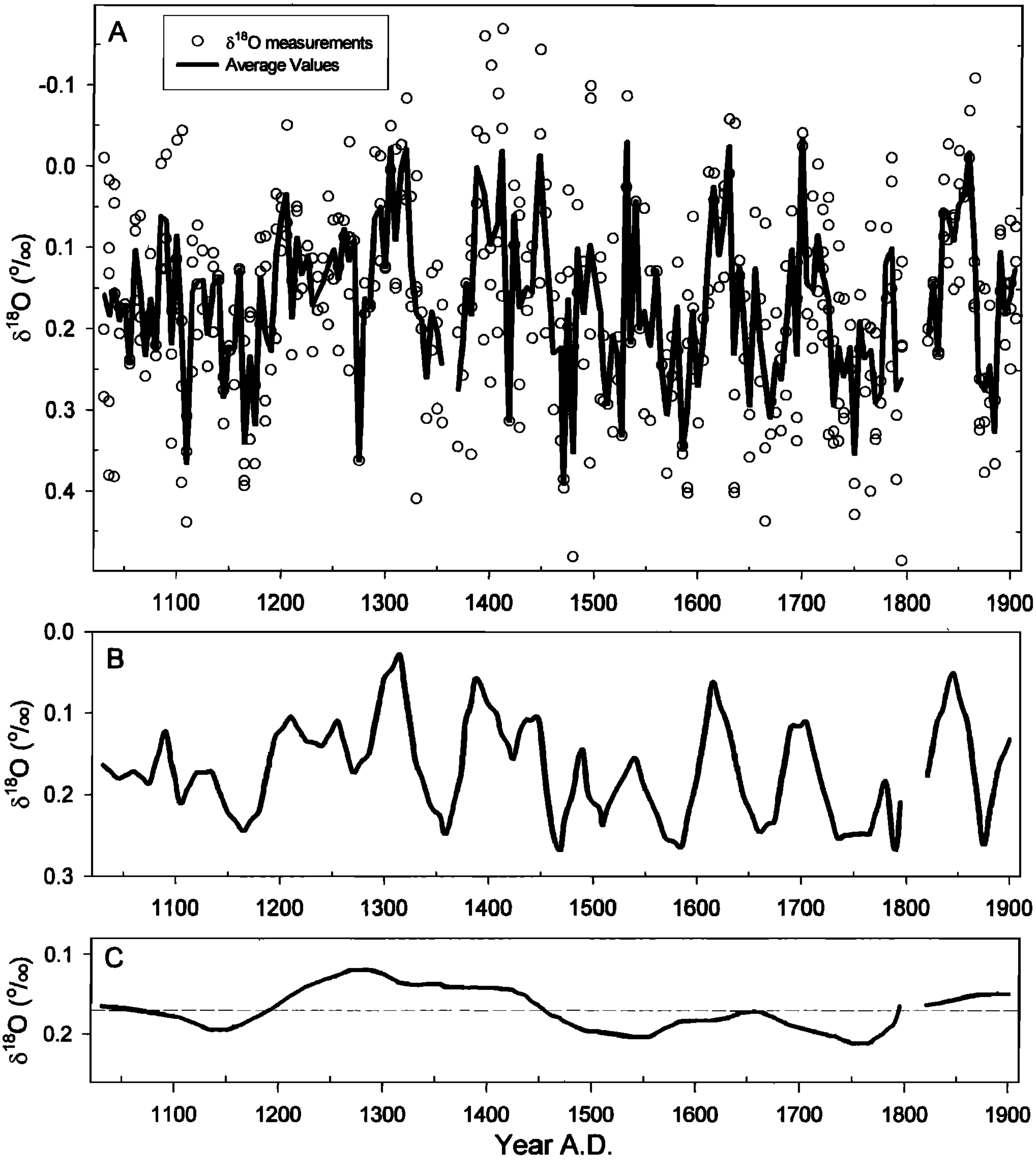

Figure 7. Partitioning the total down core variability in the *N. dutertrei* time series of core SBKC 9110-2 into the different modes of variability. (a) The averaged values for each interval and all the δ^{18}O measurements that contribute to each average value. (b) Lowess smoothing (f=0.04) of averaged δ^{18}O values to emphasize the variability over the interdecadal timescale (>15 years). (c) Lowess smoothing (f=0.2) of the average values to show multicentennial scale variability (>150 years). Note the consistent scaling between graphs that shows the relative variance in each mode of variability, the hiatus from 1800 to 1820 A.D., and the inverted ordinate axis to be consistent with changes in temperature. The ranges of the series are (a) 0.42, (b) 0.24, and (c) 0.09$^{0}/_{00}$ while the range of all measurements in (a) is 0.66$^{0}/_{00}$.

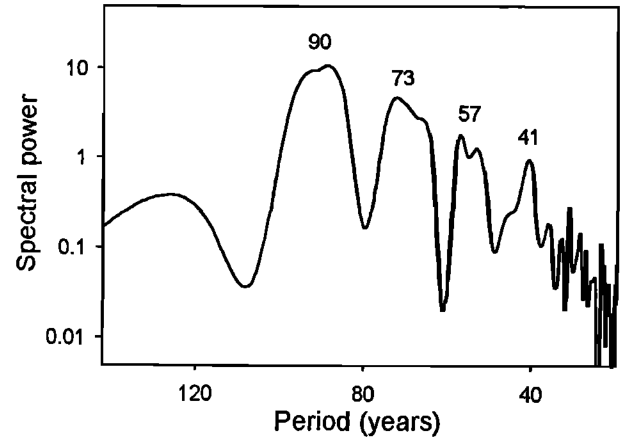

Figure 8. Periodogram of spectral power of the time series in Figure 7b with the low-frequency variability (Figure 7c) subtracted to emphasize the interdecadal modes of variability. The spectral peaks are indicated.

can be obtained with two measurements (Figure 6a). Variability between replicate measurements approaches the magnitude of interdecadal- and centennial-scale environmental signals shown in Figure 7b. *Schiffelbein and Hills* [1984] examined the $\delta^{18}O$ variance within several species from Holocene and late Pleistocene sediments using measurements on one to four tests. They found that over 30 tests are required for a single measurement on a given species to approach a 90% confidence level in estimating the average $\delta^{18}O$ value to within 0.15°/oo of the mean. Their lower confidence level incorporates the effects of variability among tests with the machine error associated with making a single measurement. While increasing the number of tests per measurement reduces variability present among tests, they found that making multiple measurements per interval is the most effective way to reduce total data variance and the only way to suppress the effects of machine error. This study clearly demonstrates that high-resolution isotope studies require replicate measurements, each with a representative number of tests, to reduce inaccuracy due to machine error and environmental variability to within acceptable limits relative to the down core signal.

4.2 Observed Environmental Variability and Signal to Noise Ratios

The nature and scale of environmental variability contributing to the noise within the five year intervals (Figures 4 and 7a) are exemplified by the variability illustrated in Figure 9. The depth-time plots of temperature and salinity from *Eber* [1977] depict the strong warming and subsequent cooling associated with the El Niño-Southern Oscillation (ENSO) event affecting the California coastal ocean between 1958 and 1961. We can make a rough estimate of the maximum expected interannual noise in $\delta^{18}O$ by examining the range of August-September temperatures and salinities at 25 m, the habitat considered to be most representative of the test production of *N. dutertrei*. Temperatures range from a high of 14.5°C (1958) to a low of 12.7°C (1961), a difference of 1.8°C. The salinity increases by ~0.3 psu during this period. These interannual differences would produce changes in the $\delta^{18}O_e$ (calculated $\delta^{18}O$ of equilibrium calcite) of roughly 0.55°/oo in California waters [*Spero and Lea*, 1996], which is nearly equal to the total range of down core measurements in Figure 4. *Thunell et al.* [1999] reported interannual change of this magnitude in *G. bulloides* from a sediment trap study in the Santa Barbara Basin that extends from "normal" conditions in 1996 to very strong El Niño conditions in 1997. The same study found seasonal changes of up to 1.5°/oo. Because the ranges of most replicate values in Figure 4 are considerably less than the range of seasonal and interannual variability, we deduce that our practice of using four to seven tests per measurement is generally effective in averaging environmental conditions over the 5 year period of sampling.

Figure 9 emphasizes how interannual changes, superimposed on the annual cycle of large-scale upwelling and downwelling, influence the habitat of *N. dutertrei*. In 1958 and 1959 each isotherm (isohaline) is considerably deeper throughout the annual cycle relative to their positions throughout 1960 and 1961. This variability is the local manifestation of adjustments in the density field along the eastern boundary of the Pacific that are driven by the annual cycle and interannual changes in Ekman pumping due to large-scale variability in the wind field [*Lynn and Simpson*, 1987; *Simpson*, 1992; *Miller*, 1996]. The temperature structure is further modified by surface heating and cooling [*Simpson*, 1992; *Miller et al.*, 1994]. Since temperature decreases with depth, while salinity increases, the effect of isopycnal shoaling will be to increase the $\delta^{18}O_e$ owing to both temperature and salinity. However, as the effect of 1°C on $\delta^{18}O_e$ is 0.23°/oo and the effect of 1 psu is roughly 0.4°/oo in California Current waters [*Spero and Lea*, 1996] the effects of changes in temperature on $\delta^{18}O_e$ are several times greater than the effects of salinity (compare Figures 9a and 9b). Thus the temperature range between the 10° and 14°C isotherms represents a change of roughly 1°/oo on $\delta^{18}O_e$. The range of salinity between the 33.6 and 34.0 isohalines covers a greater portion of the water column but would only change $\delta^{18}O_e$ by 0.16°/oo. The $\delta^{13}C$ composition of the water would likely follow the seasonal and interannual patterns of temperature and salinity seen in Figure 9, with lower $\delta^{13}C$ ratios associated with deeper waters. However, owing to the rapid biological uptake of ^{12}C in response to upwelling of nutrient-rich waters [*Sautter and Thunell*, 1991a] the fluctuations of $\delta^{13}C$ are expected to be more variable than changes in $\delta^{18}O_e$.

Large differences in the down core signals and signal to noise ratios associated with species and size fractions (Table 1) are probably best explained by differences in habitat. Throughout the California Current, *O. universa* shows a widespread range in flux through different seasons of the year, while *N. dutertrei* has a better defined seasonal range in flux, although the range varies with location [*Sautter and Thunell*, 1991b; *Ortiz and Mix*, 1992; *Kincaid et al.*, 2000]. The greater isotopic variability in *O. universa* (Figures 2 and 3) can be explained by test production under a wider range of environmental conditions, while the lower range for each size fraction of *N. dutertrei* suggests test production under more limited season and depth ranges. Since the signal to noise ratios differ between size classes of *N. dutertrei* (Tables 1 and 2), the size class selected for analysis, and the environmental signal which it contains, can affect signal to noise ratios. The higher signal to noise ratio of the larger size fraction of *N. dutertrei* would result from test production during the season of highest stability and temperatures in the upper thermocline, when multiyear variability in near-surface processes is greatest (Figure 9).

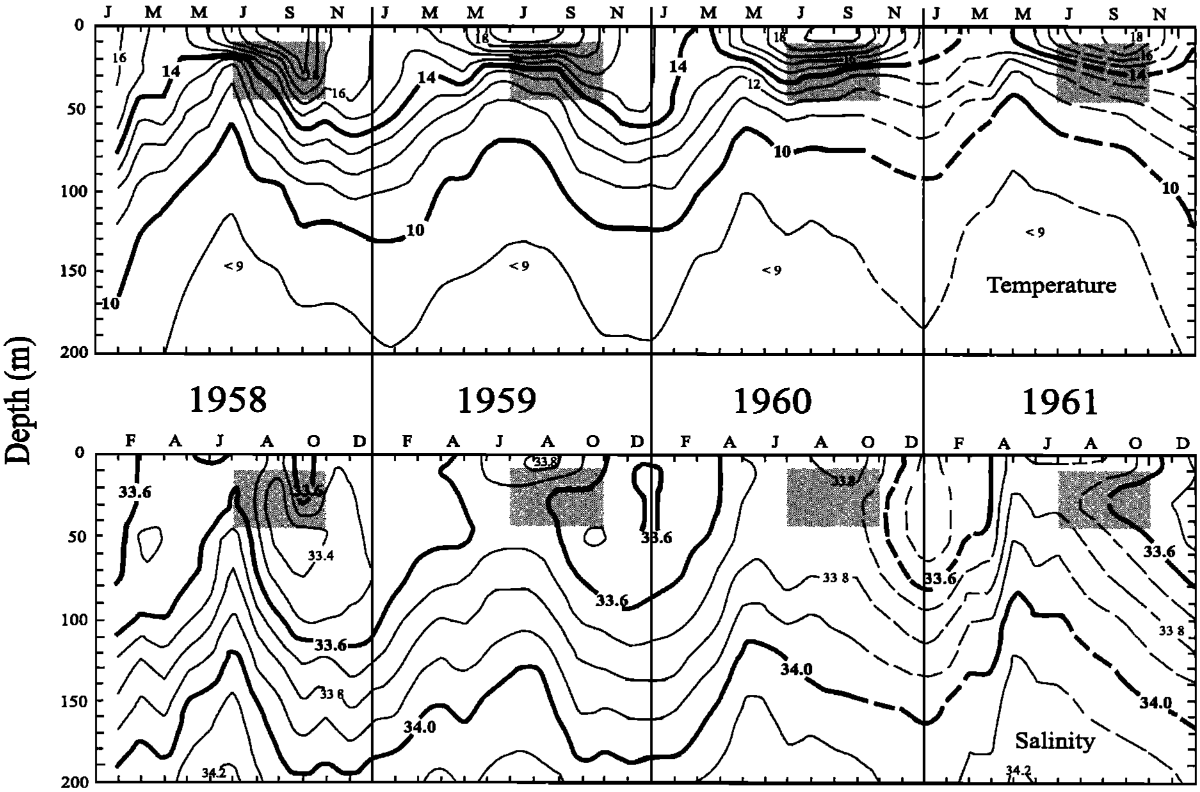

Figure 9. Depth-time plots of temperature and salinity down to 200 m over a 4 year period at a station roughly 100 nautical miles south of the Santa Barbara Basin and 85 nautical miles west of San Diego (32°55' N, 118°56' W). This station was occupied by the California Cooperative Oceanic Fisheries Investigation (CalCOFI) program nearly every month from January 1958 to October 1960 and in January, April, May, July, and October of 1961. This particular station (90.45) was chosen for illustration because it shows significant interannual change over a period similar to our five-year sampling interval and resolves the annual cycle. The shoaling and depression of the permanent thermohaline structure, marked by the 10° and 14°C isotherms (and by the 33.4 and 33.8 isohalines), occur to depths below 200 m over the annual and interannual cycles. The estimated depth and temporal habitats of highest test production of *N. dutertrei* indicated by shading are based on the results of *Sautter and Thunell* [1991a, 1991b], and *Kincaid et al.* [2000].

Lin et al. (1997) found large down core fluctuations in $\delta^{18}O$ values of several species of planktonic foraminifera from ~50 year intervals in laminated sediments of the Cariaco Basin. While they found some interspecific variability due to habitat preferences, the large down core environmental changes were generally correlated. *Oppo and Fairbanks* [1989] found stronger down core correlations in the averages of $\delta^{18}O$ values than $\delta^{13}C$ averages from analysis of several size fractions of *Globigerinoides sacculifer* from cores of different latitudes. Their analysis also showed that the $\delta^{13}C$ signal was stronger between the same size classes from different cores than between different size classes from the same core and correlations were generally stronger in larger size fractions. They attributed the greater sensitivity of the carbon isotope to the different test sizes recording different environmental and intrinsic processes and emphasized the use of averaging measurements between size fractions to obtain reliable time series. We have taken a further step and averaged replicates within a limited size class of a single species. Although averaging values from different species and size fractions will result in a greater representation of the water column and the annual cycle, averaging measurements from one size fraction of a single species ensures a stronger down core signal from a particular habitat and season.

4.3 Interpretation of Interdecadal Variability

The magnitude of environmental change expected to affect the $\delta^{18}O_e$ over the interdecadal timescale can be estimated by comparing hydrographic measurements of temperature and salinity made by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program during 1949-1975 to those for 1977-1998 (Figure 10). These two periods bracket the basin-scale, interdecadal "regime shift" that occurred over the North Pacific and California Current in 1976-1977 [*Ebbesmeyer et al.*, 1991; *Mantua et al.*, 1997]. The difference in median temperature across the 1976-1977 transition in ocean climate ranges from 1.21°C at the surface to 0.24°C at 50 m (Figure 10), which is consistent with the analysis of *Roemmich and McGowan* [1995]. As can be seen in Figures 10a and 10b, temperature and salinity changes across the shift in climate regime are inversely correlated (warming accompanied by lowered salinity). The lighter values of $\delta^{18}O_e$ would be associated with a deepening of isopycnals, consistent with the seasonal and interannual changes in Figure 9. The regional warming (and freshening) after 1976 is consistent with the basin-wide changes in wind stress that altered the intensity of Ekman pumping in the eastern North Pacific [*Miller*, 1996].

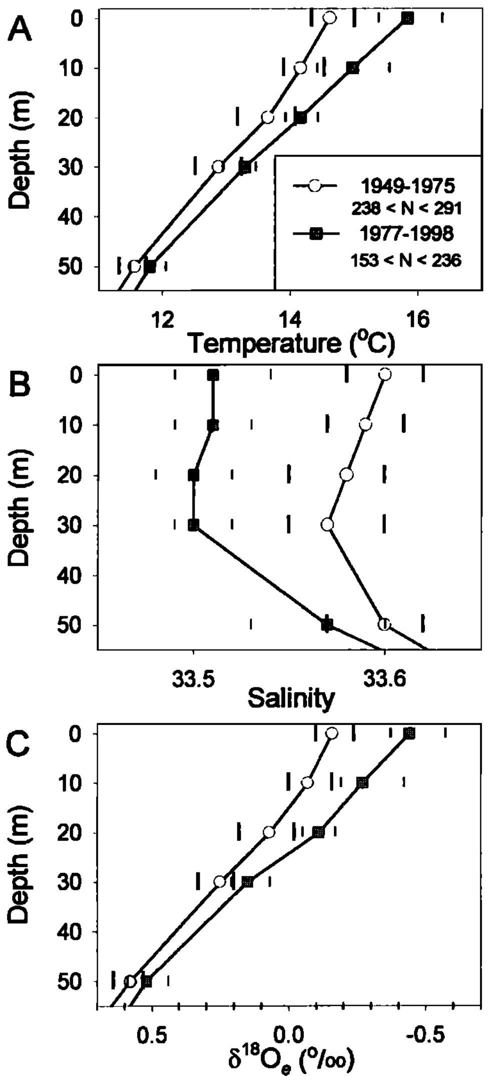

Figure 10. Comparison of (a) temperature, (b) salinity, and (c) calculated $\delta^{18}O$ of equilibrium calcite ($\delta^{18}O_e$) values in the upper 50 m from CalCOFI hydrographic data between the periods 1949-1975 and 1977-1998. Several hundred measurements were made around the Santa Barbara Basin lying within 34°-34°30' N and 119°30'-120°30' W (see Figure 1) across seasons and years in the denoted time periods. Shown are the median ± 95% error bars. The difference between time periods represents the interdecadal change that has taken place in the California Current in the last 50 years. The expected changes in $\delta^{18}O_e$ are calculated from the equation of *McCorckle et al.* [1990] with values of $\delta^{18}O_w$ ($\delta^{18}O$ composition of seawater) from the equation of *Spero and Lea* [1996]. The relative effects of temperature and salinity on derived $\delta^{18}O_e$ values are shown in Table 4.

The relative effects of temperature and salinity changes at depth on changes in $\delta^{18}O_e$ listed in Table 4 clearly indicate that temperature dominates the interdecadal signal. The difference in the median $\delta^{18}O_e$ across the two time periods ranges from 0.28‰ at the surface to 0.06‰ at 50 m, with a difference of 0.14‰ at the middle of the estimated depth habitat of *N. dutertrei* (25 m). The interdecadal change of 0.14‰ is of the same magnitude of our 95% precision limits in estimating the average $\delta^{18}O$ value of a 5 year interval from two measurements. A change of this magnitude would represent a moderate but significant interdecadal change in the time series of filtered $\delta^{18}O$ values in Figure 7b in which the largest peak to trough changes approach 0.25‰. Although uncertainties in habitat depth make it difficult to directly compare recent interdecadal changes to those of the past 1000 years, they appear to be of roughly the same magnitude. The change of 0.14‰ is also about one fourth of the range of interannual variability (0.55‰) estimated from Figure 9 and reported by *Thunell et al.* [1999]. Thus the relationship between the magnitudes of interdecadal to interannual variability mirrors that of interannual variability compared to the annual cycle, with the higher frequencies consistently associated with larger variances. The magnitude of interdecadal variability in $\delta^{18}O$ relative to the variability at higher frequencies and the signal to noise ratios confirms the importance of averaging replicate measurements to suppress noise within the intervals. Since a given 5 year interval may be affected by anomalous test fluxes from one or two particular years or machine error, we consider the smoothed high-frequency record (Figure 7b) to be the most representative of environmental change.

4.4 Variability in Ocean Climate of the California Current

We interpret the record of variability in Figure 7b as the interdecadal fluctuation in the character of the late summer-fall habitat of *N. dutertrei* at depths between roughly 10 and 50 m. According to the preceding discussion, these interdecadal fluctuations suggest changes in the state of the regional ocean climate of the California Current between periods of higher temperatures, greater stability, and generally deeper isotherms relative to periods of opposing conditions dominated by a shoaling thermocline and lower temperatures (of roughly 1°C). Observations and modeling of the interdecadal climate shifts of the past 50 years [*Graham*, 1994; *Miller et al.*, 1994, *Minobe*, 1997; *McGowan et al.*, 1998] further suggest that the temporal variability of Figure 7b was likely associated with large-scale changes in the geographic distribution of near-surface ocean temperatures throughout the North Pacific that follow an ENSO-like pattern. The interdecadal changes are characterized by alternations between states of a "thermal dipole" in which the eastern boundary at midlatitudes is warmer, while the central and western Pacific is cooler, and vice-versa [*Zhang et al.*, 1997]. The spatial patterns in temperature appear to be largely driven by basin-scale changes in wind stress with little relationship to local wind fields [*Latif and Barnett*, 1994; *Miller et al.*, 1994; *Roemmich and McGowan*, 1995; *Miller*, 1996;] and reflect a strong link between the ocean climate of the California Current system and the basin-scale climate of the North Pacific.

The broad peaks around the 57, 73, and 90 year periods in the power spectrum (Figure 8) are similar to the timescales of interdecadal change described by other authors from proxy records of the Santa Barbara Basin. *Baumgartner et al.* [1992] found peaks in fish scale deposition of sardines and anchovies around 55, 75, and 100 years. *Pisias'* [1978] analysis of radiolarian faunal from an 8000 year record from the Santa Barbara Basin revealed several spectral peaks (84, 89, and 104 years) near our broad peak at 90 years. His 25 year sampling interval would not be expected to resolve shorter periods. A time series of varve thickness from these sediments analyzed by maximum entropy spectral technique revealed a broad peak centered around 76 years, while an analysis of this series by empirical orthogonal functions (EOFs) revealed periods of ~58

Table 4. Summary of the Median Differences in Temperature, Salinity, and $\delta^{18}O_e$ Values Between 1949-1975 and 1977-1998 (from Figure 10) and the Relative Contributions of Temperature and Salinity to $\delta^{18}O_e$[a]

	Differences Between Periods			Effect of Difference on $\delta^{18}O_e$	
Depth, m	Temperature, °C	Salinity, psu	$\delta^{18}O_e$, ‰	Temperature, °C	Salinity, psu
0	1.21	0.09	0.28	0.28	0.03
10	0.82	0.08	0.20	0.19	0.03
20	0.59	0.08	0.18	0.14	0.03
30	0.41	0.07	0.09	0.10	0.03
50	0.24	0.03	0.06	0.06	0.01

[a] The relative effects of temperature and salinity on $\delta^{18}O_e$ are shown assuming that 1°C changes $\delta^{18}O_e$ by 0.23‰ and 1 psu changes $\delta^{18}O_e$ by 0.04‰ in the California Current [*Spero and Lea*, 1996].

and ~100 years [*Biondi et al.*, 1997]. It is not clear whether the broad spectral peak centered at the 76 year period is a combination of the two distinct EOFs or is an independent spectral peak.

Although relevant instrumental records lack the degrees of freedom necessary to describe persistent interdecadal variability, they show periods of variability consistent with the patterns presented in this paper. Records of wind stress, air and sea surface temperatures, atmospheric pressure, and fishery catches from the eastern North Pacific contain variability indicating periods of 50-75 years that are temporally coherent with one another [*Ware*, 1995; *MacCall*, 1996; *Minobe*, 1997; *Mantua et al.*, 1997]. The combination of the warm period centered around 1850-1860 A.D. and the subsequent cooling around 1870 (Figures 4a and 7b) is also consistent with the change in San Diego air temperature records as well as anomalous appearance and disappearance of tropical forms of fish and invertebrate fauna off California during these periods [*Hubbs*, 1948]. We believe that the interdecadal isotopic variability in Figure 7 may reflect an aspect of the Pacific Decadal Oscillation (PDO) identified by *Mantua et al.* [1997] which exhibits a period of roughly 55 years over the span from 1925 through 2000.

The low-frequency variability of the oxygen isotope series presented in Figure 7c exhibits features similar to other records of climate change extending over the last 1000 years. Underlying the interdecadal-scale variability, an anomalously warm coastal ocean persisted at the multicentennial-scale from roughly 1200 to 1450 A.D. This coincides with the age generally assigned to the "Medieval Warm Period" [*Lamb*, 1977; *Crowley and North*, 1996], although dates vary around the globe by region and the type of proxy record. The period of positive anomalies in the low-frequency series of $\delta^{18}O$ from *N. dutertrei* that continues from ~1450 to ~1800 A.D. is consistent with the dates associated with the cooling and neoglaciation of the "Little Ice Age" (LIA) in both the Southern and Northern Hemispheres [*Grove*, 1988; *Crowley and North*, 1996]. *Keigwin's* [1996] $\delta^{18}O$ analysis of *Globigerina ruber* using ~50 year sampling intervals from two box cores recovered from the Bermuda Rise also indicates multicentennial-scale changes in ocean temperatures associated with the LIA and Medieval Warm Period. Summer temperature records reconstructed from tree rings from the Sierra Nevada mountains in eastern California show centennial-scale trends, similar to those seen in Figure 7C, underlying decadal and interdecadal changes [*LaMarche*, 1974; *Graumlich*, 1993]. Likewise, faunal-based proxies from planktonic foraminifera [*Kipp and Towner*, 1975] and radiolarians [*Pisias*, 1978] analyzed using 25 year sampling intervals from Santa Barbara Basin sediments show centennial-scale changes corresponding to the aforementioned patterns. However, the 25 year intervals do not resolve the importance of the interdecadal fluctuations found here.

Despite the common centennial-scale trends, the nature of the strong interdecadal fluctuations found here differ from the nature of variability found in continuous high-resolution records from other regions where centennial-scale changes play a larger role. Ice cores collected from the Quelccaya summit in Peru reveal anomalously cool conditions for a period of several centuries throughout the LIA [*Thompson et al.*, 1986]. While there is considerable decadal variability throughout the 1000 year ice core record, there are no periods of positive anomalies during the LIA relative to the 1000 year mean. By contrast, the range of most of the interdecadal fluctuations throughout the 900 year record (Figure 7b) extends over the total spread of isotopic values in the series. In the varved sediments of the Cariaco Basin, Venezuela, centennial-scale variability in the abundance of *G. bulloides* is more important than the interdecadal variability present in a core spanning eight centuries [*Black et al.*, 1999]. Although our records do not resolve subdecadal and decadal-scale (10-15 year periods) fluctuations, we have shown that interdecadal variability is a dominant mode of thermal variability in the California Current relative to longer centennial-scale changes. We attribute these dominant interdecadal changes in the California Current to basin-wide alternation in the midlatitude ocean-atmosphere dynamics of the North Pacific producing the alternation in the thermal dipole as described by *Miller et al.* [1994], *Graham et al.* [1994], and *Miller* [1996].

The comparatively weak low-frequency variability in Figure 7c forms a baseline over which the interdecadal variability is superimposed. This centennial-scale baseline reflects longer-term tendencies toward one or the other regime of the coastal ocean climate, which would either reinforce or weaken the interdecadal-scale regime states. Accordingly, the Medieval Warm Period would have been a time in which interdecadal regimes characterized by deepened isotherms, higher stability, and warmer upper ocean temperatures off California were enhanced. During the interval of the Little Ice Age, interdecadal conditions of shoaling isotherms, decreased stability, and cooler temperatures would have been strengthened. The long-term ocean warming and cooling of the California Current region appears to be in phase with the warming and cooling of the midlatitude North Atlantic described by *Keigwin* [1996]. The question now remains whether the midlatitude central North Pacific and the coastal ocean off California are out of phase over the multicentennial timescale as we believe occurs at interdecadal timescales.

5. Conclusions

This is the first study to resolve both interdecadal and multicentennial-scale fluctuations in ocean climate from the isotopic signatures of planktonic foraminifera and, as such, is an important advance in the study of the interaction between these two timescales and in constructing high-resolution time series of this nature. We have examined the sources of isotopic variability from several size classes and species of planktonic foraminifera from the varved sediments of the Santa Barbara Basin. Replicate measurements on pooled tests within intervals reveal down core signal to noise ratios between 1.1 and 3.0 depending on species and size class. The noise is variability among measurements within a 5-year sampling interval and is attributed to analytical error as well as environmental variability associated with differences in depth, season, and year. Replicate measurements are necessary to reduce noise to acceptable levels relative to the down core signal. The choice of species and size fraction largely affects the down core signal to noise ratios and hence the clarity of the environmental signal that can be obtained.

We present a robust isotopic series from *N. dutertrei* that spans a 900 year period based on two to four measurements of pooled tests taken from the 5 year intervals. The major share of down core variability lies within interdecadal timescales. These interdecadal changes have broad spectral peaks centered around 57, 73, and 90 years, which are consistent with the spectra of other proxy time series from the Santa Barbara Basin. Oceanographic sampling over the past 50 years indicates that the effect of temperature on predicted $\delta^{18}O$ equilibrium calcite values is several times greater than the effect of salinity in the waters over the Santa Barbara Basin on seasonal, interannual, and interdecadal timescales. Thus the isotopic record primarily reflects changes in upper ocean temperature. The recent climate shift that occurred over the North Pacific in the mid-1970s produced thermal changes on a scale roughly comparable to the interdecadal fluctuations of the past 1000 years in the California Current. We also find centennial-scale changes that are consistent with global temperature changes associated with the Medieval Warm Period and the Little Ice Age. The persistent large interdecadal fluctuations in upper ocean temperature are superimposed on these longer-period changes and conceal to some degree this lower-amplitude multicentury variability.

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