por flux of this magnitude would reduce the apparent residence time from 6 years to 30 days. For comparison, we can use Junge's relationship (*25*) between residence time and sample variance to obtain an independent estimate of atmospheric residence time. From our Enewetak data, the residence time of PCB (Aroclor 1242) is calculated to be 189 days. This relatively short residence time further suggests that rainout is not the only removal mechanism for organics in the marine atmosphere.

The data presented here confirm the presence of selected organic pollutants in the atmosphere of remote marine regions and provide a baseline against which future pollutants may be measured. Work is continuing in our laboratory to identify several other unknown compounds in our samples and to estimate the flux of these pollutants across the air-sea interface. In particular, better measurements of the rate of gas exchange of some pollutants are required to obtain an accurate estimate of the transfer of organic pollutants to the ocean. Additional measurements of organic pollutants are also required in the mid- to high-latitude regions if we are to obtain a realistic picture of the distribution of organic pollutants in the marine atmosphere.

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Annual Growth Increments in Shells of *Spisula solidissima* Record Marine Temperature Variability

Abstract. *Systematic variations in annual growth increments, formed over a 16-year period in shells of the marine bivalve mollusc* Spisula solidissima, *reveal more growth in some years than others. Favorable years are indicated by larger than expected annual growth increments and successful recruitment of juveniles. Variations in the size of growth increments correlate negatively with sea surface temperatures. The results suggest that the annual growth increments in the shells of certain molluscs record changes in the marine environment and may be useful monitors of pollution and indicators of paleotemperatures.*

Many species of bivalve molluscs have been reported to contain annual growth increments in their shells (*1*) analogous to tree rings (*2*) or annual growth bands in corals (*3*). Methods borrowed from dendrochronology can be used to assess systematic variations in the size of these increments. Such variations suggest that fluctuations in environmental favorability for growth occurred during certain years. The bivalve shell may thus be considered a recorder of conditions in the marine environment.

I explored the relative value of using annual increments of shell growth in bivalves as environmental indices by examining populations of *Spisula solidissima*, the Atlantic surf clam, collected along the New Jersey coast. For two consecutive years, April 1977 through March 1979, specimens were collected every other week or, during winter, once a month. Examination throughout the year of the growing shell margins of these clams demonstrated the existence of annual increments of shell growth in this species (*4*), confirming the results of an earlier investigation involving marked and recovered clams (*5*). One growth increment, GI-1 (Fig. 1), forms each year in late summer to fall when water temperatures are highest and the animals spawn (*6*). Throughout the remainder of the year, the other growth increment, GI-2 (Fig. 1), is deposited.

Age and growth rate for any surf clam can be determined by measuring successive shell heights of the annual growth increments in a cross section of the shell (*4–6*). These measurements provide a relative indication of how much an individual grew in a given year. Caddy and Billard (*7*) have shown that shell growth for inshore surf clams is best described by a von Bertalanffy curve [described in (*7*)] which predicts a slowing of growth rate with size and age. Their study and that of others (*5*) suggest that inshore

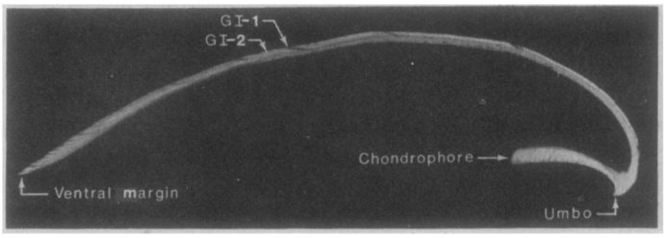

Fig. 1. Radial cross section of surf clam shell. Growth increment GI-1, the thin dark increment, forms annually in the late summer to fall while GI-2, the wider, opaque, white increment, forms during the remainder of the year. The distance between the umbo and the contact of GI-1 with the external shell surface is the shell height for any given year. The difference between successive shell heights is used as the measure of the annual growth increment in shell size. Shell height is 125 mm.

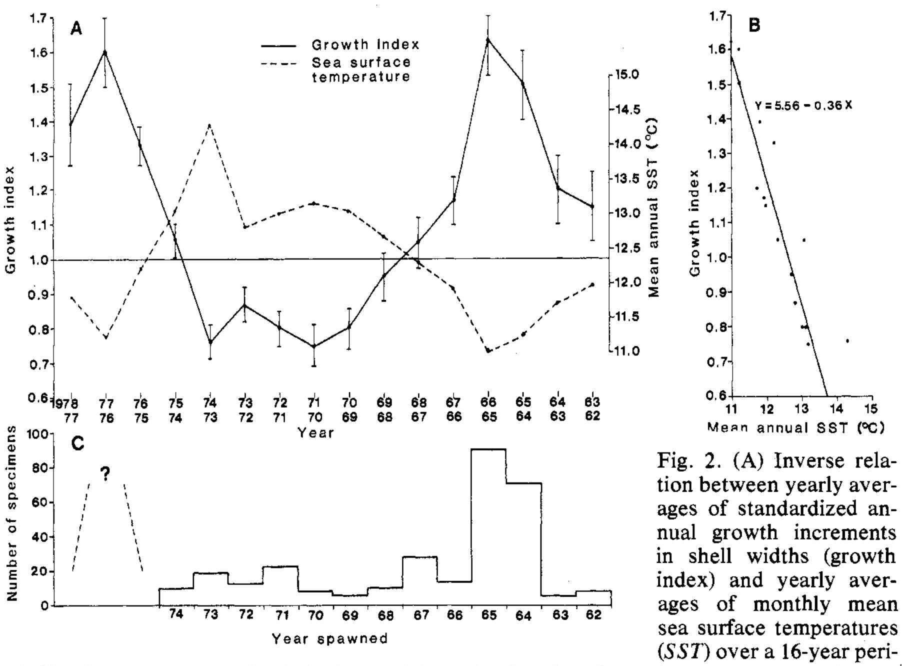

Fig. 2. (A) Inverse relation between yearly averages of standardized annual growth increments in shell widths (growth index) and yearly averages of monthly mean sea surface temperatures (*SST*) over a 16-year period. Yearly measurements begin in August (about the time GI-1 formation starts) and end in July so that record extends from August 1962 through July 1978. Vertical bars indicate 95 percent confidence intervals. (B) Least-squares regression line showing relation between standardized annual shell growth increments and marine temperatures. (C) Histogram of year in which all surf clams used in this study were spawned (*12*).

clams can attain ages of 15 to 17 years, while larger, offshore individuals live up to 25 to 30 years (*6*). The shells of these bivalves provide more or less continuous growth records for these periods.

The exponential rate of change in successive yearly shell heights throughout the life of an inshore surf clam is calculated as the first derivative of the von Bertalanffy growth curve (*8*) with respect to time

$$dy/dt = ae^{-kt}$$

where t represents time in years, y is shell height, e is the base of the natural logarithms, k is a constant determined by curve fitting, and $a = k \times y_\infty$ where y_∞ equals maximum shell height. This equation matches that commonly used for standardizing data on the widths of tree rings, though a constant is often added on long tree ring records (*2*). The exponential decrease in the widths of tree rings throughout a tree's life obeys the same law as the decrease in heights of growth increments in surf clam shells. Yet, as with trees, the bivalve data seldom describe a smooth decay curve. Particular years have anomalously wide or narrow increments relative to the predicted curve, indicating that certain years were better or worse than average for growth.

To ascertain whether there was a systematic variation in the size of the annual growth increments among a population of surf clams, I subjected 303 inshore surf clams, living less than 5 km from shore and above the thermocline, to a standardization analysis of the type used on tree ring widths (*9*). The results of this analysis (Fig. 2A) indicate that certain years were statistically better (growth index > 1.0) or worse (growth index < 1.0) than average for growth.

New information (*6*) on recruitment of juveniles also suggests that certain years are more "favorable" than others. When the age of each clam is determined by counts of the total number of annual growth increments in the shell, and the time that the clam was collected is known, it is possible to create a histogram indicating the number of specimens in the sample spawned in each year (Fig. 2C). It appears from this analysis that particular years were also better than others for successful recruitment of *S. solidissima*. Loesch and Ropes (*10*) and Franz (*11*) have suggested that *S. solidissima* experiences episodic recruitment. Although many more samples are needed to adequately document recruitment history patterns, my findings suggest that good growth years are also good recruitment years (*12*).

Several workers (*13*) have observed that not all years are equally favorable for bivalve growth. My results indicate that annual growth increments in shells successfully record these variations. Environmental variables could be responsible for these vicissitudes since many environmental factors, which vary from year to year, such as temperature (*14*), food supply (*15*), food quality (*16*), and oxygen supply (*17*), are known to influence growth. However, only sea surface temperatures had been recorded in enough detail near the study area to permit a time-series comparison with the growth record of *S. solidissima*. The sea surface temperature curve (Fig. 2A) represents 12-month averages of monthly mean sea surface temperatures taken in the region where the surf clams were collected (*18*).

Only inshore clams living above the thermocline were considered in this study. Shell growth records could be extended back 25 to 30 years if the larger, offshore clams, which live at greater depths and below the thermocline, could be used. However, sea surface temperatures would no longer accurately reflect the year-round bottom temperatures that these clams experience, and adequate time-series bottom temperatures were unavailable.

When the average growth indices of the 16-year record are compared with the sea surface temperature curve (Fig. 2, A and B), the most striking feature is the inverse correlation ($r = -.9$; $P < .01$) between the two (*19*). This is particularly noticeable when comparing those years that deviate most dramatically from the mean such as 1965 to 1966 and 1975 to 1977. It is not clear why cool years are more conducive to growth and recruitment in *S. solidissima* than warm years. It would seem that either temperature influences growth rate directly, or it does so indirectly through other factors such as availability of food, nutrients, or oxygen.

The systematic variation in size of annual growth increments in the shells of *S. solidissima* provides a record of marine environmental variability that is inversely correlated with temperature. Such a climatic record in the bivalve shell could be important in monitoring the effect of changes in marine conditions due, perhaps, to thermal pollution. Fossil shells may also be useful as paleoecologic indicators of past temperature regimes (Fig. 2B). If the periodicity of repeating shell structures is adequately documented, this growth record may be extended many years through examination of longer lived bivalve species (*20*).

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9. All specimens were captured alive so that each annual growth increment of the shell could be assigned to a specific calendar year. The shell height for each year of growth of each specimen was measured on shells sectioned radially (4148 measurements). The change in shell height for every year of growth (annual growth increment size) for each specimen was calculated as the difference between successive shell heights. An exponential decay curve was fitted to these data by a least-squares regression on the logarithmically transformed data. In all cases a correlation coefficient $r > .9$ was obtained. The yearly changes in shell height measured were converted to standardized indices (Fig. 2A) by dividing each by the expected growth. This division removes the ontogenetic growth trend and scales the variance so that it remains constant throughout the series, thus yielding standardized yearly indices that can be compared between individuals of any size (age).
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19. Pearson product-moment correlation coefficient: $r = -.91$, $P < .01$. The zeroth-order serial correlation coefficient (no lag in years): $r = -.93$, $P < .01$. Higher order coefficients were not significant. Correlations between growth and maximum, minimum, and standard deviation of monthly sea surface temperatures were also not significant.
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Relative Humidity: Important Modifier of Pollutant Uptake by Plants

Abstract. *Laboratory measurements of foliar uptake of sulfur dioxide and ozone by red kidney beans demonstrated a strong effect of relative humidity on internal pollutant dose. Foliar uptake was enhanced two- to threefold for sulfur dioxide and three- to fourfold for ozone by an increase in relative humidity from 35 to 75 percent. For the same exposure concentration, vegetation growing in humid areas (such as the eastern United States) may experience a significantly greater internal flux of pollutants than that in more arid regions.*

Plant susceptibility to air pollution stress is strongly influenced by environmental variables including air temperature, wind speed, light intensity, soil fertility, and soil and atmospheric moisture levels (*1-4*). The supply of moisture to vegetation both before and during exposure has been recognized for many years as one of the the most important of these variables (*5-11*). Conditions that minimize plant moisture stress, such as high soil moisture and high atmospheric humidity, generally increase plant susceptibility to foliar injury by air pollutants. Subtle pollutant effects on physiological processes, such as photosynthesis and transpiration, may also be enhanced by high humidity (*12*).

Although regional differences in average annual humidity have been implicated in the greater sensitivity of vegetation to air pollution in the humid eastern United States (*9, 13*), the physiological mode by which this environmental variable controls pollutant-plant interactions is not well understood. Mechanistically, vegetation may react to increased humidity by (i) enhanced uptake of pollutants, (ii) greater physiological sensitivity to the same level of pollutant uptake, or (iii) a combination of (i) and (ii).

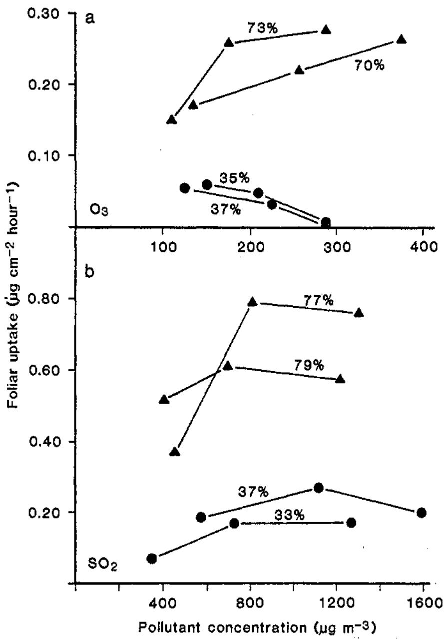

Fig. 1. Foliar uptake of O_3 (a) and SO_2 (b) as influenced by relative humidity and pollutant concentration. Results shown represent two exposures (ten plants each) at each humidity and pollutant combination.

Laboratory experiments were performed to determine the basis for humidity-induced variations in plant sensitivity to SO_2 and O_3. Eight groups of ten greenhouse-grown bush beans, *Phaseolus vulgaris* (Bush Blue Lake variety 274), were exposed in open gas-exchange chambers (*14*) to three concentrations of SO_2 (range, 350 to 1550 μg m^{-3}) or O_3 (range, 100 to 375 μg m^{-3}). Pollutant concentrations were maintained for 1 hour before measurement of uptake and progression to the next higher concentration. Relative humidity was held at 35 ± 2 or 75 ± 5 percent in two replicate chambers for each of the two pollutant series. Concurrent measures of both total pollutant flux and CO_2 assimilation (photosynthesis) were determined from mass balance calculations based on concentrations of gas entering and leaving the chambers. To determine physiological uptake, total flux calculations were corrected for adsorptive loss to both chamber walls and external leaf surfaces (*14*).

The effects of a 40 percent increase in humidity on uptake of both SO_2 and O_3 were pronounced at all gas concentrations (Fig. 1). Average SO_2 uptake was enhanced approximately 250 percent, and O_3 uptake was increased 400 percent. Maximum O_3 uptake (0.28 μg cm^{-2} hour^{-1}) occurred at a concentration of 150 μg m^{-3} (0.079 ppm); the corresponding maximum for SO_2 (0.80 μg cm^{-2} hour^{-1}) occurred at 800 μg m^{-3} (0.31 ppm). Uptake of both SO_2 and O_3 increased with the initial increase in exposure concentration in all treatments except O_3 at low relative humidity. With the latter treatment O_3 uptake decreased as the O_3 concentration increased. As pollutant concentrations increased further, uptake did not increase proportionally, but actually declined in all treatments except O_3 at high relative humidity.

Nonproportional uptake with increas-

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