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Author
Druffel, Ellen M

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Banded Corals: Changes in Oceanic Carbon-14 During the Little Ice Age

Ellen M. Druffel

Summary. Radiocarbon analyses and stable isotope measurements are presented for two recent cores of banded corals from the Florida Straits. These values provide a record of variations in the ratio of carbon-14 to carbon-12 in the dissolved inorganic carbon in the surface waters of the Gulf Stream from A.D. 1642 to 1800. An increase in the carbon-14/carbon-12 ratio of 7 per mil for coral growth during the early 1700's was most likely induced by an increase in the carbon-14/carbon-12 ratio of 20 per mil in the atmospheric carbon dioxide that occurred at about 1700. The ratios of oxygen-18 to oxygen-16 in these coral bands show a small decrease of water temperature (~ 1°C) during the latter part of the Little Ice Age (1700 to 1725). These results support the hypothesis that the increase in atmospheric carbon-14 at about 1700, and possibly the temperature change as well, was caused by a decrease in solar activity (Maunder sunspot minimum).

Natural ^{14}C is produced in the stratosphere by the action of cosmic rays on ^{14}N. It is quickly oxidized to $^{14}CO_2$ and distributed into the troposphere, oceans, and land biota. During preindustrial times (before A.D. 1900), spatial variations in the ^{14}C content of the troposphere were minimal (±0.2 to 0.3 percent) (*1*). However, the world's surface oceans exhibited large variations in ^{14}C (±15 percent), due to a wide range of vertical mixing coefficients for near-surface waters. Regardless of these variations, the ^{14}C concentrations in the surface ocean have always been lower than those in the atmosphere (*2*). This depletion is maintained by the diffusion and advection of older subsurface waters into the surface layers of the oceans.

Secular variations in the atmospheric ^{14}C concentrations (*3*) have been recorded in tree rings for the past 8000 years (Fig. 1). The major trend in these data resembles a partial sine wave with a period of about 11,500 years. This variation is attributed to a gradual change in intensity of the magnetic dipole moment of the earth (*4*). A strong dipole moment decreases the flux of galactic cosmic rays that reaches the earth's stratosphere, resulting in a lower production of ^{14}C. Elasser *et al.* (*5*) determined that a 50 percent decrease of the geomagnetic field strength would increase the intensity of cosmic rays incident on the stratosphere by 10 percent (Fig. 1).

Superimposed on this major trend are minor fluctuations in the $^{14}C/^{12}C$ ratio with a period of about 200 years (Fig. 1). These fluctuations are most likely caused by variations in solar activity (*6, 7*). The galactic cosmic-ray flux responsible for ^{14}C production is modulated by changes in solar wind magnetic fields. As the intensity of the solar wind increases, more galactic cosmic rays are diverted from the earth's atmosphere, causing a decrease of the ^{14}C production. From tree ring analyses, De Vries (*8*) deduced two recent episodes of unusually high atmospheric ^{14}C concentration that occurred around A.D. 1500 (Spörer sunspot minimum) and A.D. 1700 (Maunder sunspot minimum). These periods of high ^{14}C were coincident with decreased solar activity (*9*). Stuiver and Quay (*10*) determined the increase in the atmospheric ^{14}C concentration that occurred around A.D. 1300 (Wolf sunspot minimum) (Fig. 2). These three periods of unusually high ^{14}C production were coincident, although not directly correlated (*11*), with recorded intervals of especially severe winters in Europe (*3*), a period known as the Little Ice Age. Whether the Little Ice Age was the direct result of low solar activity or whether this was a coincidence has not yet been resolved.

It is possible, although not probable, that the observed increase in the atmospheric ^{14}C concentrations during the Little Ice Age could also have been caused by decreased vertical mixing in the surface oceans or by large changes in the rate of CO_2 exchange between the air and the ocean. Neither of these changes is expected during periods of cooler average world temperature, such as that during the Little Ice Age. In order to eliminate these possibilities, however, it is necessary to acquire ^{14}C records for this period in the oceans. I show here that banded, hermatypic corals can be used as recorders of ^{14}C concentration in ocean waters during the Little Ice Age, just as tree rings are used to record ^{14}C concentrations in the atmosphere. The atmospheric ^{14}C record combined with the oceanic ^{14}C record may be used to determine the causal relationship and the timing of the ^{14}C variations observed in these two reservoirs during earlier times.

Corals as Oceanic Recorders

Hermatypic corals accrete aragonite, a crystalline form of calcium carbonate, with $^{14}C/^{12}C$ ratios equal to those in the dissolved inorganic carbon (DIOC) in the seawater at the time of coral ring formation (*12, 13*). As the world's surface oceans are saturated with respect to aragonite, hermatypic coral skeletons do not dissolve with time. Nor does arago-

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The author is assistant scientist in the Department of Chemistry, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543.

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nite exchange its carbonate with any other source of carbon. Once accreted, coralline aragonite retains a permanent and unaltered record of the $^{14}C/^{12}C$ ratio present in surface seawater during the past.

Corals also record evidence within their skeletons of significant ecological conditions and changes that occurred during their lifetimes. Wells (*14*) studied middle Devonian fossil corals and interpreted fine ridges on the surface of the coral epitheca to be daily growth bands. He found approximately 400 ridges (days) per annum, which agrees with astronomical expectations of the deceleration of the earth's period of rotation due to tidal friction.

The most conspicuous records contained within coral skeletons are annual density bands. These growth bands were first conclusively demonstrated as annual by Knutson *et al.* (*15*). The annual growth bands are primary skeletal characteristics that are exhibited as seasonal variations in the bulk density of the secreted skeleton (*16*). Many investigators have demonstrated the annual nature of density band pairs in hermatypic corals, using techniques such as alizarin staining, x-radiography, densiometry, autoradiography, and direct field observations (*15, 17, 18*).

Various radioisotopes, such as bomb-produced ^{14}C (*12, 13, 19, 20*), ^{90}Sr (*21*), and ^{228}Ra (*22*) have been used to corroborate the annual nature of growth bands in various corals. Seasonal variations in the $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios have been illustrated by Emiliani *et al.* (*23*), Fairbanks and Dodge (*24*), and Dunbar and Wellington (*25*). They concluded that corals accrete aragonite with a constant displacement of $^{18}O/^{16}O$ ratios from isotopic equilibrium with seawater and that these stable isotope ratios are records of changes in the seawater temperature.

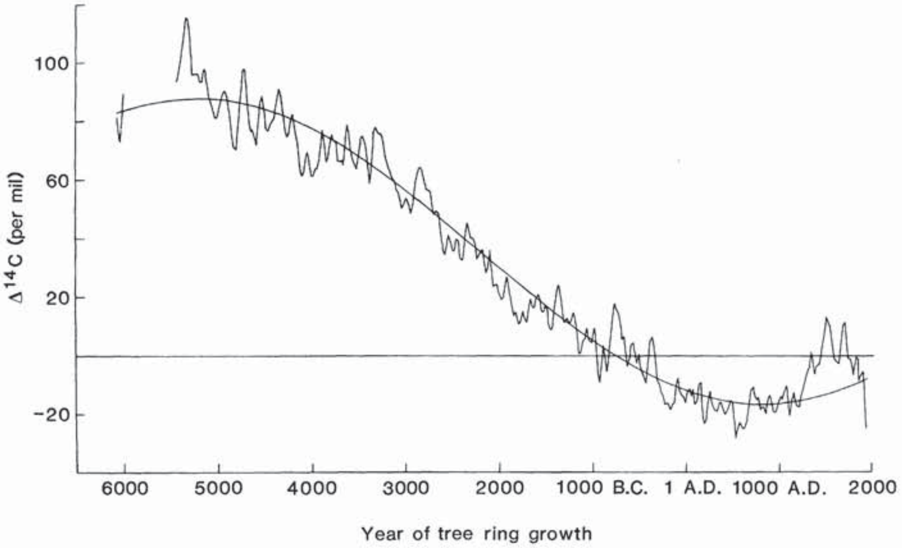


Fig. 1. The $\Delta^{14}C$ trend (see text for definition) in tree rings that grew from 6000 B.C. to A.D. 1950. The jagged line is a spline function fitted to the individual $\Delta^{14}C$ measurements obtained by Suess (*36*). A 200-year periodicity can be recognized by this fit and is believed to be the result of solar modulation of the cosmic-ray production of ^{14}C. The smooth curve is a best-fit sine wave (period, 11,500 years; amplitude, 50 per mil) corresponding to the $\Delta^{14}C$ changes caused by the change of the magnetic dipole moment of the earth (*4*).

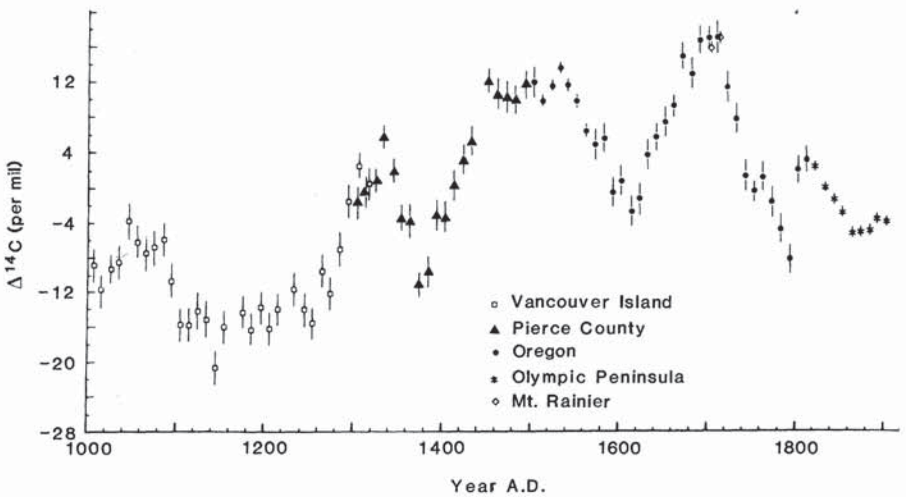


Fig. 2. Radiocarbon measurements of tree rings that grew from A.D. 1000 to 1910 (*10*). Notice the maximum rise of 20 per mil during the latter part of the Little Ice Age (1680 to 1750).

Sample Collection and Growth Analyses

Two coral cores (TRI and TRII) of *Montastrea annularis* were collected from The Rocks reef (24°57′N, 80°33′W) at a depth of 4 meters in the Florida Straits (Fig. 3). They were drilled and recovered by J. Harold Hudson (U.S. Geological Survey) and me. The Rocks reef is located 1 kilometer offshore from Plantation Key and lies on the fringes of the Florida Current (Fig. 3). The corals examined in this work were from an area that was constantly flushed by open ocean waters, specifically the Florida Current which is part of the Gulf Stream system. The cores were collected with a hydraulic drill, fitted with a diamond bit and core barrel. The corer was powered by a small hydraulic pump that was operated from aboard a small boat (*18, 26*).

Both coral cores were obtained from the same coral head at The Rocks reef. There is a partial void in both of these cores (around A.D. 1800) that represents the absence of no more than 5 years of coral growth (*27*).

Hudson *et al.* (*18*) used alizarin-staining techniques and x-radiography to depict annual density bands in *Montastrea annularis* from the Florida Straits. These investigators noticed that dense aragonitic bands accreted during the warm summer months of July through September and that thicker, less dense bands accreted during the cooler months of October through June. The most convincing evidence that these bands are annual is the presence of stress bands in the coral record. These bands form during unusually severe winters and are thicker than the annual dense bands of summer. These events, referred to locally as cold fronts, are the result of cold weather that originates in the northwest and passes over the reef in a southeastward direction. There is excellent correlation between the stress band record and all recorded cold fronts (late 1856, 1885, 1894, 1898, 1941, 1957, 1963, and 1969) (Fig. 4) (*18*).

Procedure

Coral slabs (4 millimeters thick) were cut along the vertical growth axes of both cores. Upon x-radiographic analyses (*18*) of the slabs, it was determined that TRI grew from A.D. 1642 to 1975 (Fig. 4) and TRII grew from A.D. 1692 to 1978. Subjection of these samples to x-ray diffraction analyses revealed pure aragonite and showed no traces of calcite. Each core was sectioned into samples that consisted of one to ten consecutive years of growth. Radiocarbon analyses were carried out at the La Jolla Radiocarbon Laboratory (*28*) on a total of 135 samples from both cores. Druffel and Linick (*12*) reported 65 of the results from TRI for the period 1800 to 1974. The ^{14}C measurements were carried out by standard gas proportional counting techniques (*12*).

All measurements were corrected for isotope fractionation (to a $\delta^{13}C$ relative to PDB-1 = −25.0 per mil) (*29*) and for decay since the time of formation (to A.D. 1950). The standard used was 95 percent of the net National Bureau of Standards oxalic acid count rate, corrected to $\delta^{13}C = -19.0$ per mil. All results are reported in terms of $\Delta^{14}C$, which is the deviation (per mil) from the activity of 19th-century wood:

$$\Delta^{14}C = \delta^{14}C - 2(\delta^{13}C + 25)\,(1 + \delta^{14}C/1000)$$

Stable isotope measurements ($\delta^{18}O$) (*29*) were performed by W. G. Mook at the University of Groningen on 79 coral samples from TRI for the period A.D. 1700 to 1790. Samples of coralline aragonite (10 milligrams) were baked (400°C) under vacuum to remove organic matter. They were acidified with 100 percent orthophosphoric acid, and the isotopes were measured on a V. G. Micromass 903 mass spectrometer. Results are reported with standard δ (per mil) notation relative to the PDB-1 standard. The precision for isotopic measurement of these samples was ±0.05 per mil for $\delta^{18}O$.

Results for Coral Growth from A.D. 1642 to 1800

The $\Delta^{14}C$ values for banded corals from TRI that had grown from A.D. 1642 to 1800 and all of those from TRII are listed in Table 1. Results for TRI for the period 1801 to 1974 are listed in (*12*).

The $\Delta^{14}C$ measurements of Florida coral that grew during preindustrial times are shown in Fig. 5. There are significant variations in the ^{14}C record for this period. The 15 $\Delta^{14}C$ values for coral that grew between A.D. 1642 and 1706 averaged −49 ± 4 per mil (Fig. 5a). There was a deviation from this average (to −43 ± 3 per mil) in a coral sample that grew from 1656 to 1660. The ^{14}C measurements of coral that grew after 1706 were significantly higher than −49 per mil. Of the 16 $\Delta^{14}C$ results for coral that grew from 1709 to 1740, almost 90 percent were higher than −49 per mil. A least-squares analysis of these 16 measurements reveals a significant slope; the fit of these data is shown in Fig. 5a. The ^{14}C concentrations increased rapidly from −49 to −42 per mil in a relatively short period (1706 to 1712). The values decreased slowly during subsequent years (1712 to 1750), from −42 to −49 per mil. The trends that are apparent in Fig. 5a are also shown to be statistically significant on the basis of a spline function (third-order polynomial) fitted to the $\Delta^{14}C$ data from Florida and Belize (*19*) corals (Fig. 6). Thus, it is apparent from these data that an increase in $\Delta^{14}C$ of 7 per mil had occurred in the surface waters of the Florida Current (Gulf Stream system) during the early 1700's. During

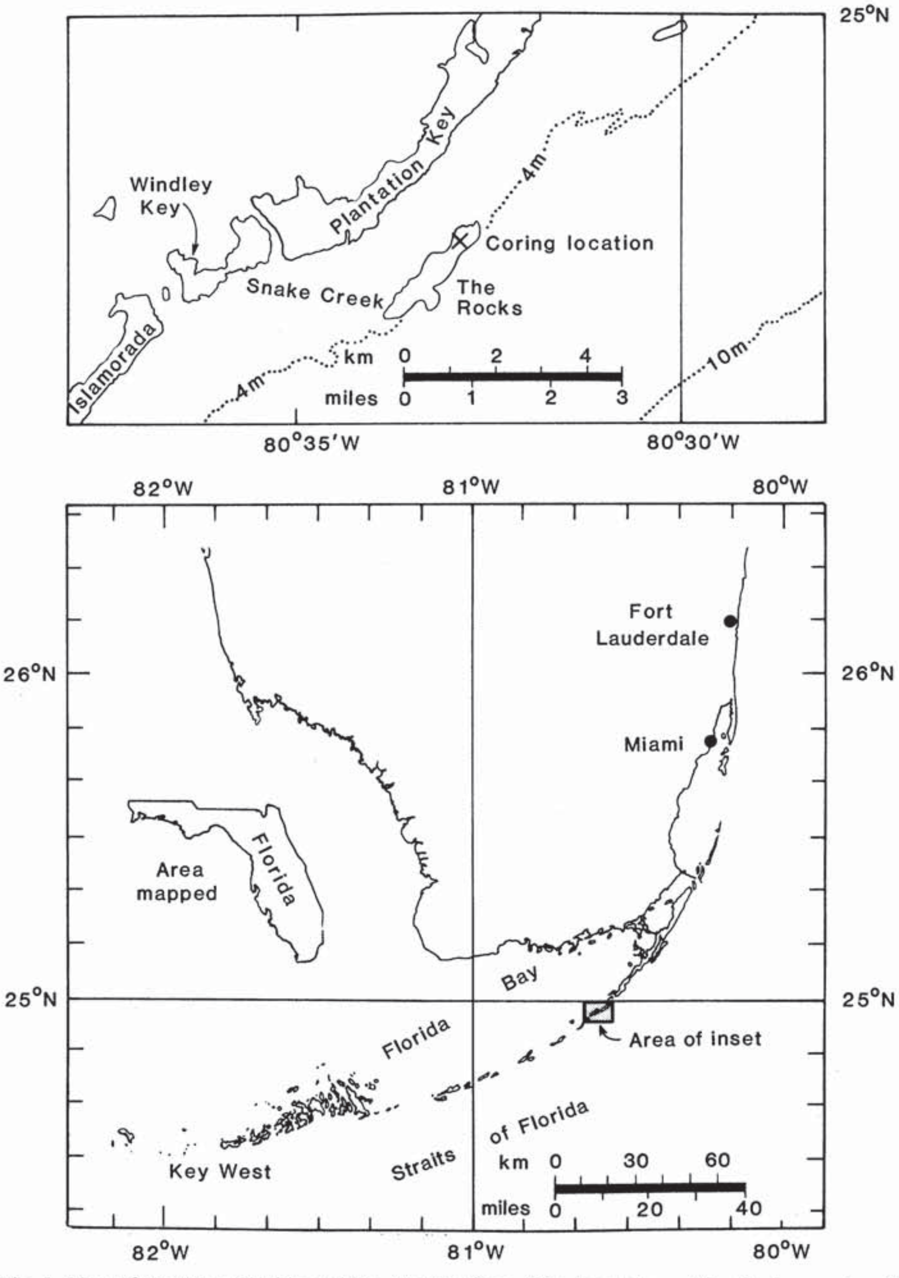


Fig. 3. Map of southern Florida and the Florida Keys. The inset shows The Rocks coral reef (24°57′N, 80°33′W). Both *Montastrea annularis* cores TRI and TRII were collected from the same coral colony at The Rocks at a depth of 4 meters. The Florida Current, a part of the Gulf Stream System, is located 4 kilometers south of the collection site. The major part of the reef water is supplied by the Florida Current.

the second half of the 18th century the ^{14}C concentrations remained unchanged; the average of 19 $\Delta^{14}C$ values is -49 ± 3 per mil.

The increase in ^{14}C in oceanic DIOC during the early 1700's was most likely the result of increased ^{14}C concentrations in the atmospheric CO_2 during that time. Figure 2 shows two ^{14}C maxima that were observed in tree rings from the early 16th and 18th centuries (*10*). These maxima, which coincide with the Little Ice Age, are almost certainly the result of decreased solar activity (*7*). As CO_2 is exchanged between the atmosphere and the surface ocean, an increase in the atmospheric $^{14}CO_2$ concentration would also appear in the DIOC of the surface ocean. There is a lag time of three to four decades between the onset of the increase in the atmosphere and that in the ocean (Fig. 7). Part of this delay can be attributed to the long residence time (10 to 15 years) for $^{14}CO_2$ in the atmosphere (*2, 12*). The ^{14}C increase in the atmosphere was about 20 per mil by the beginning of the 18th century, whereas the increase observed in corals during this time was only 7 per mil (Fig. 7). The attenuation of the ^{14}C peak in the surface ocean was caused by vertical exchange of older subsurface waters, which contain less ^{14}C, with surface waters (*2*). The isolation of subsurface waters from the atmosphere for extended periods of time causes ^{14}C to be lost as a result of in situ radioactive decay (*2*).

It is possible that the increase of $\Delta^{14}C$ in the surface waters of the Florida Straits during the Little Ice Age could also have been caused by a decrease in the rate of vertical exchange in the upper few hundred meters of the water column; this could have been caused by warmer surface water temperatures, which would not have been expected during an ice age. However, the $\delta^{18}O$ values from these banded corals (Fig. 8) indicate that the average temperature in Gulf Stream surface waters was slightly lower during the latter stage of the Little Ice Age (about 1700). A least-squares analysis of the $\delta^{18}O$ values reveals an overall decrease of 0.2 per mil from 1700 to 1790 (dashed line, Fig. 8), which corresponds to a warming of about 1°C (*24, 25*) from the latter part of the Little Ice Age to the end of the 18th century. A closer look at these data reveals a maximum $\delta^{18}O$ value of -4.0 per mil around 1725 and a sharp decrease to -4.4 per mil in the 1740's, which represents a rise in temperature of 2°C over this time period. There also appears to be a somewhat smaller maximum (-4.1 per mil) around 1760. These maxima (solid lines, Fig. 8) represent periods when the surrounding seawater was 1° to 2°C cooler than during the earlier periods. Cooler surface water temperatures during the early 1700's imply that there was an increase in vertical mixing between surface and subsurface waters, not decreased vertical mixing as would have been the case had changes in seawater temperature been the cause of the ^{14}C increase in the 1700's. An increase of the $^{14}C/^{12}C$ in the atmosphere due to the higher solubility

Table 1. Radiocarbon results for coral from the TRI core that grew during the period A.D. 1642 to 1800 and for coral from the TRII core that grew during the period A.D. 1642 to 1978. The $\delta^{13}C$ analyses were made on reburned acetylene gas. The errors are based only on counting statistics.

La Jolla sample No.	Core	Years	$\delta^{13}C$ (per mil)	$\Delta^{14}C$ (per mil)	La Jolla sample No.	Core	Years	$\delta^{13}C$ (per mil)	$\Delta^{14}C$ (per mil)
4432	TRI	1642 to 1645	−1.3	−50 ± 3	4794	TRII	1750 to 1752	−0.4	−48 ± 3
4409	TRI	1646 to 1655	−0.6	−46 ± 3	4231	TRI	1751 to 1755	−1.0	−43 ± 7
4404	TRI	1656 to 1660	−0.4	−43 ± 3	4777	TRII	1753 to 1755	0.1	−53 ± 4
4431	TRI	1661 to 1665	−0.7	−47 ± 3	4235	TRI	1756 to 1760	−0.5	−49 ± 4
4406	TRI	1666 to 1670	−0.4	−50 ± 4	4784	TRII	1759 to 1761	0.3	−49 ± 3
4430	TRI	1671 to 1675	−0.4	−49 ± 3	4770	TRII	1765 to 1767	0.0	−53 ± 4
4428	TRI	1691 to 1698	−0.8	−46 ± 3	4408	TRI	1766 to 1770	−0.8	−45 ± 6
4891	TRII	1694 to 1695	−1.6	−53 ± 4	4739	TRII	1768 to 1770	0.1	−50 ± 3
4831	TRII	1696 to 1697	−1.4	−49 ± 4	4775	TRII	1771 to 1773	0.3	−52 ± 4
4894	TRII	1698 to 1699	−1.3	−49 ± 5	4265	TRI	1771 to 1780	0.3	−43 ± 3
4832	TRII	1700 to 1701	−1.1	−41 ± 4	4782	TRII	1774 to 1776	0.2	−54 ± 3
4772	TRII	1702 to 1703	−0.7	−53 ± 3	4741	TRII	1777 to 1779	−0.8	−47 ± 4
4429	TRI	1699 to 1705	0.3	−46 ± 4	4737	TRII	1780 to 1782	−1.0	−45 ± 3
4780	TRII	1704 to 1706	−0.2	−56 ± 4	4197	TRI	1781 to 1785	−0.2	−46 ± 6
4793	TRII	1706 to 1707	−0.4	−46 ± 4	4912	TRII	1780 to 1785	0.3	−53 ± 3
4785	TRII	1708 to 1710	−0.1	−50 ± 3	4913	TRII	1782 to 1791	0.4	−53 ± 4
4892	TRII	1708 to 1710	−1.0	−41 ± 5	4738	TRII	1792 to 1794	−0.3	−49 ± 5
4284	TRI	1706 to 1715	−0.6	−32 ± 5	4786	TRII	1795 to 1797	−0.5	−53 ± 3
4830	TRII	1711 to 1713	−0.8	−41 ± 4	4742	TRII	1798 to 1800	−0.8	−50 ± 5
4238	TRI	1716 to 1720	−0.7	−44 ± 3	4893	TRII	1804 to 1806	−0.7	−47 ± 4
4890	TRII	1717 to 1719	−0.5	−44 ± 5	4889	TRII	1807 to 1809	−0.4	−45 ± 4
4778	TRII	1720 to 1722	−0.3	−43 ± 4	4740	TRII	1810 to 1812	0.6	−46 ± 4
4751	TRII	1723 to 1725	−0.4	−48 ± 4	4929	TRII	1876 to 1880	−0.1	−50 ± 5
4287	TRI	1721 to 1730	−0.1	−45 ± 3	4928	TRII	1881 to 1885	−0.5	−45 ± 5
4795	TRII	1726 to 1728	−0.3	−47 ± 4	4930	TRII	1906 to 1910	−1.0	−48 ± 4
4781	TRII	1729 to 1731	−0.2	−46 ± 4	4925	TRII	1920 to 1922	−0.4	−50 ± 4
4237	TRI	1731 to 1735	0.6	−46 ± 7	4927	TRII	1923 to 1925	−1.0	−53 ± 5
4750	TRII	1732 to 1734	0.5	−38 ± 3	4924	TRII	1930 to 1932	−0.3	−49 ± 3
4792	TRII	1735 to 1737	0.0	−40 ± 3	4926	TRII	1933 to 1935	−1.0	−54 ± 3
4282	TRI	1736 to 1740	−0.3	−45 ± 5	4911	TRII	1974	−0.4	154 ± 4
4773	TRII	1738 to 1740	0.2	−50 ± 4	4553	TRI	1975	−0.4	152 ± 8
4192	TRI	1741 to 1744	−0.2	−51 ± 7	4908	TRII	1975	−0.2	155 ± 5
4783	TRII	1741 to 1743	−0.8	−53 ± 3	4909	TRII	1976	−0.3	135 ± 4
4833	TRII	1744 to 1746	−1.1	−42 ± 8	4907	TRII	1977	−1.0	134 ± 4
4286	TRI	1746 to 1750	−0.3	−48 ± 7	4910	TRII	1978	−0.7	132 ± 4
4752	TRII	1747 to 1749	−0.3	−42 ± 4					

of CO_2 in surface waters cooled 1°C would be insignificant.

Most of the water in the Gulf Stream comes from the Sargasso Sea (*2*), a subtropical gyre in the North Atlantic that circulates in a clockwise (anticyclonic) direction. The circulation in the surface mixed layer is wind-driven (Ekman transport), and that in the deep water is a result of geostrophic forces. Ekman transport is convergent in a subtropical gyre, which forces water downward from the mixed layer. There is a complex process at work that selects only late winter water for actual net downward pumping, called Ekman pumping, into the geostrophic regime below (*30*). As the surface waters in the Gulf Stream were 1° to 2°C cooler during the early 1700's, it is probable that Sargasso Sea surface waters were also cooler during this period. It is likely that cooler surface water temperatures during the latter part of the Little Ice Age enhanced the downward penetration of waters in the Sargasso Sea during the late winter and perhaps induced prolonged convection that extended from early winter to spring.

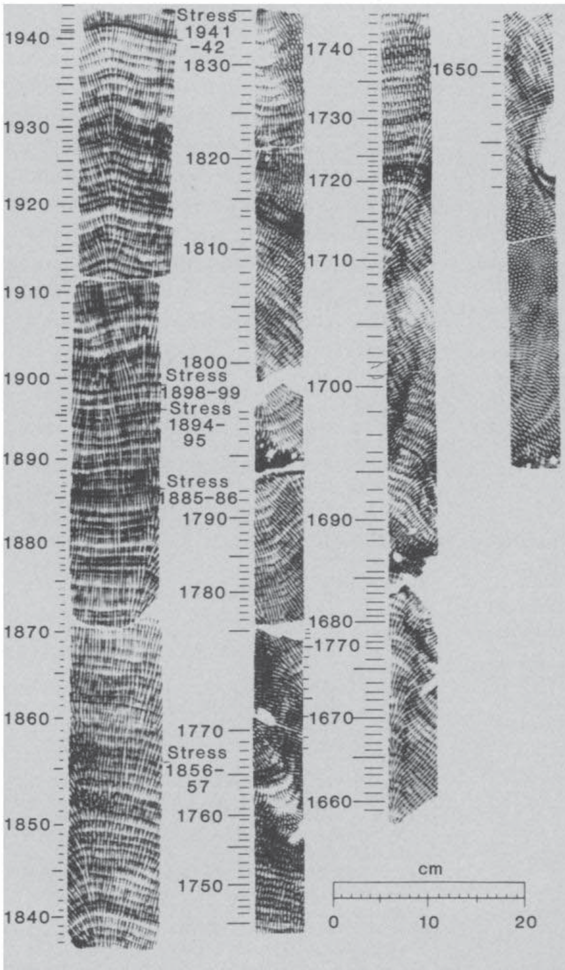
Results for Subsequent Coral Growth, A.D. 1800 to 1952

The ^{14}C concentrations in Florida coral that grew subsequent to 1800 also appear to reflect ^{14}C changes in the atmosphere. The $\Delta^{14}C$ measurements of Florida coral that grew during the 19th century (*12*) are shown in Fig. 5b. From 1800 to 1820, $\Delta^{14}C$ values remained unchanged from the previous 50-year period (-49 ± 5 per mil). However, further ^{14}C analyses since the publication of (*12*) reveal a significant decrease from about 1815 to 1865.

This decrease of 4 to 5 per mil in the $\Delta^{14}C$ of the surface ocean during the early and mid-1800's was coincident with a decrease of 9 per mil observed in the atmosphere (*10*) (Figs. 2 and 7). As was the case for the data from the early 1700's, the magnitude of the ^{14}C variation in the atmosphere was at least twice that in the surface ocean (Table 2). It is probable that the 4 to 5 per mil decrease observed in ocean waters was caused by declining atmospheric $^{14}CO_2$ concentrations. It is unlikely that this decrease was caused by enhanced vertical mixing in the upper layers of the ocean in view of preliminary $\delta^{18}O$ measurements which show a slight increase in the average surface water temperature from 1800 to 1900 (*31*).

A recent decrease in the ^{14}C concentration from A.D. 1900 to 1952, known as the Suess effect, has been noticed both in the atmosphere (*32*) and in the surface waters of the Gulf Stream (*12, 19*) and in the Peru Current (*20*). Concentrations of ^{14}C in the atmosphere decreased 20 to 25 per mil as a result of a dilution with ^{14}C-free CO_2 that results from the burning of fossil fuels (*33, 34*). The change in the surface waters of the Gulf Stream during this period (-12 per mil) (Fig. 6) was about half that in the atmosphere.

Table 2 lists data on the three variations in ^{14}C that were observed in the atmosphere and in the ocean from A.D. 1642 to 1952. The ratio of the observed variations (atmosphere/ocean) ranges from 1.7 to 2.8. The ratio predicted by the box-diffusion model of Oeschger *et al.* (*35*) for the Suess effect, a perturbation of the $^{14}C/^{12}C$ that was introduced



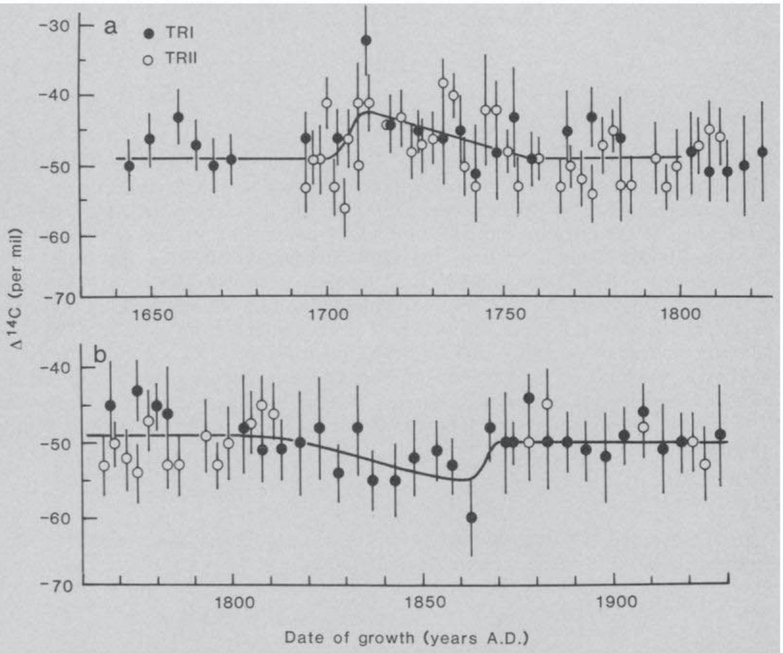


Fig. 4 (left). X-radiographs of the coral slabs from the core of *Montastrea annularis* (TRI) collected in June 1975. The top portion of this core is shown in (*12*). Dark, dense bands represent growth during warm-water months (July through September). Thus, TRI represents coral growth from A.D. 1642 to 1975. Thicker, denser layers, referred to as stress bands, formed during the unusually cold winters of late 1969, 1963, 1957 (*12*), 1941, 1898, 1894, 1885, and 1856. The correlation between these stress bands and the cold winters provides conclusive evidence that the density banding in this coral is indeed annual. Fig. 5 (right). (a) The $\Delta^{14}C$ measurements for *Montastrea annularis* (TRI and TRII) that grew in the Florida Straits from A.D. 1642 to 1830. Results from 1642 to 1710 and from 1751 to 1800 averaged -49 ± 4 per mil. Higher $\Delta^{14}C$ values were obtained for coral that grew from 1710 to 1750; a least-squares analysis of these data revealed a significant decrease from -42 per mil in 1710 to -49 per mil by 1750. This rise of 7 per mil during the first half of the 18th century is attributed to increased ^{14}C concentrations in atmospheric CO_2 (+20 per mil) during that time (Fig. 2). (b) The $\Delta^{14}C$ measurements for coral (TRI and TRII) that grew from A.D. 1760 to 1930. There is a noticeable decrease (-4 to -5 per mil) from 1820 to 1870. This decrease is attributed to decreased ^{14}C concentrations in atmospheric CO_2 (-9 per mil) during that time (Fig. 2).

initially into the atmosphere, is 2.5. The ratios listed in Table 2 are comparable, as the duration of each $^{14}C/^{12}C$ change is approximately the same (50 years). The agreement between the observed and calculated ratios is further evidence that the variations of ^{14}C observed in Florida corals during the Little Ice Age and during the mid-1800's were induced by changes of ^{14}C that occurred initially in the atmosphere. Had the ^{14}C variations originated in the ocean, for example, by the reduction or cessation of mixing between surface and subsurface waters, a ratio (atmosphere/ocean) of ≤ 1 would have been expected.

Conclusions

Analysis of the amplitude of the ^{14}C increase in the surface waters of the Florida Straits and that in atmospheric CO_2 during the Little Ice Age indicates that ^{14}C concentrations rose first in the atmosphere, probably as a result of reduced solar activity during the Maunder sunspot minimum. Analyses of the stable isotopic measurements ($\delta^{18}O$) of these corals show that slightly cooler surface water temperatures (by 1°C) were present in the Gulf Stream during the latter part of the Little Ice Age. This cooling suggests that ocean mixing patterns may have been different in the Gulf Stream during this period. A likely scenario may have included enhanced convection in the Sargasso Sea of late winter water (*30*) together with the downward penetration of cooler spring and early winter water into the geostrophic flow below.

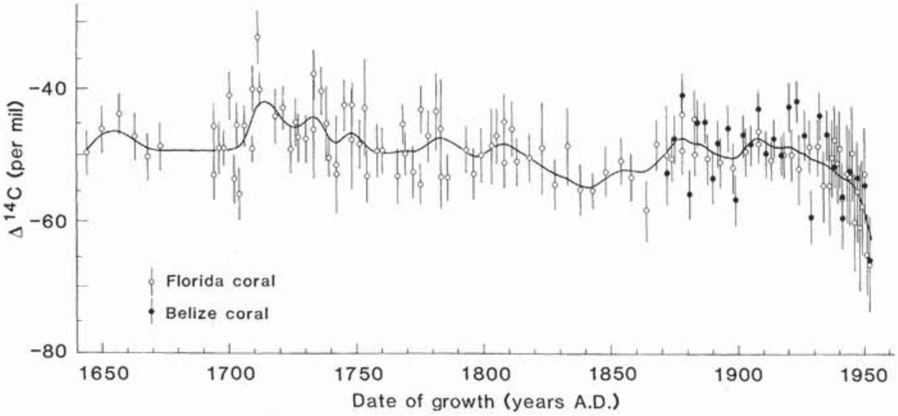
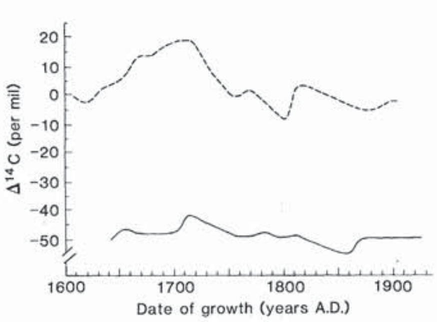


Fig. 6. Spline curve fit of $\Delta^{14}C$ measurements from two Gulf Stream corals (1642 to 1952) (*19*). Three long-term trends are apparent. (i) From 1710 to 1750, the effect of the Little Ice Age is seen as an increase in $\Delta^{14}C$ of 7 per mil and a subsequent decrease. This is most likely the result of increased ^{14}C concentrations in the atmosphere during this time (Fig. 2). (ii) From 1820 to 1870, there is a 4 to 5 per mil decrease in $\Delta^{14}C$, which may be the result of decreased ^{14}C concentrations in the atmosphere during the 19th century (Fig. 2). (iii) From 1900 to 1952, the Suess effect amounted to about −12 per mil in the Gulf Stream surface ocean waters (*12*). The Suess effect in the atmosphere was about −20 to −25 per mil. This is the result of the dilution of atmospheric ^{14}C concentrations with ^{14}C-free fossil fuel CO_2.



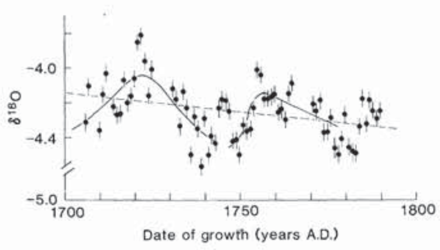


Fig. 7 (left). Average preanthropogenic ^{14}C concentrations in tree rings (dashed line) and coral rings (solid line) that grew from A.D. 1600 to 1900. The $\Delta^{14}C$ trend for trees is based on data from numerous areas in North America (*10, 34*). The $\Delta^{14}C$ trend for corals is a smoothed spline curve fitted to data from *Montastrea annularis* collected from Belize (Gulf of Honduras) (*19*) and the Florida Straits, both in the Gulf Stream system (see Fig. 6). Fig. 8 (right). Measurements of $\delta^{18}O$ for annual coral samples from the TRI core, relative to the PDB-1 standard. A least-squares fit of the individual measurements (dashed line) reveals a significant slope. In this way a 0.2 per mil decrease is recognized from 1700 to 1790. If one uses the calibration curve of Dunbar *et al.* (*37*), which portrays the $\delta^{18}O$ of coral accreted during periods of known temperature in the Gulf of Panama, this decrease represents an overall rise in seawater temperature of about 1°C from 1700 to 1790. There appear to be two maxima in this $\delta^{18}O$ record, around 1720 and 1760 (solid lines). These represent periods of lower seawater temperature.

Table 2. Observed $\Delta^{14}C$ changes in Florida coral and in trees as compared to those calculated by Oeschger *et al.* (*35*), using a box-diffusion model.

Time period (A.D.)	Variation of $\Delta^{14}C$ (per mil)		Ratio of atmospheric to surface ocean value
	Atmosphere	Surface ocean (Gulf Stream)	
		Observed	
1650 to 1710 (Little Ice Age or Maunder Minimum)	+20 (*10*)	+7*	2.8
1820 to 1870	−9 (*10*)	−4 to −5*	1.8 to 2.2
1900 to 1950 (Suess effect)	−20 to −25 (*10, 34*)	−11 to −12 (*12, 19*)	1.7 to 2.3
		Calculated	
1900 to 1950, Oeschger *et al.* (*35*)	−14.5	−5.7	2.5

*This study.

References and Notes

1. J. C. Lerman, W. G. Mook, J. C. Vogel, in *Radiocarbon Variations and Absolute Chronology*, I. Olsson, Ed. (Wiley, New York, 1970), pp. 275–302.
2. E. M. Druffel and H. E. Suess, *J. Geophys. Res.*, in press.
3. H. E. Suess, *Radiocarbon* **22**, 100 (1980).
4. V. Bucha, *Nature (London)* **213**, 1005 (1967).
5. W. Elasser, E. P. Ney, J. R. Winckler, *ibid.* **178**, 1226 (1956).
6. M. Stuiver, *J. Geophys. Res.* **66**, 273 (1961).
7. H. E. Suess, in *Radiocarbon Variations and Absolute Chronology*, I. Olsson, Ed. (Wiley, New York, 1970), pp. 595–605.
8. H. De Vries, *Proc. K. Ned. Akad. Wet. B* **61** (No. 2), 94 (1958).
9. M. Waldmeier, *The Sunspot Activity in the Years 1610–1960* (Schultess, Zurich, 1961); J. A. Eddy, *Science* **192**, 1189 (1976).
10. M. Stuiver and P. D. Quay, *Science* **207**, 11 (1980).
11. M. Stuiver, *Nature (London)* **286**, 868 (1980).
12. E. M. Druffel and T. W. Linick, *Geophys. Res. Lett.* **5**, 913 (1978).
13. Y. Nozaki, D. M. Rye, K. K. Turekian, R. E. Dodge, *ibid.*, p. 825.
14. J. W. Wells, *Nature (London)* **197**, 948 (1963).
15. D. W. Knutson, R. W. Buddemeier, S. V. Smith, *Science* **177**, 270 (1972).
16. R. W. Buddemeier, J. E. Maragos, D. W. Knutson, *J. Exp. Mar. Biol. Ecol.* **14**, 179 (1974).
17. I. G. MacIntyre and S. V. Smith, in *Proceedings of the Second International Symposium on Coral Reefs* (Great Barrier Reef Commission, Brisbane, 1974), vol. 2, pp. 277–287.

18. J. H. Hudson, E. A. Shinn, R. B. Halley, B. Lidz, *Geology* **4**, 361 (1976).
19. E. M. Druffel, *Radiocarbon* **22**, 363 (1980).
20. ______, *Geophys. Res. Lett.* **8**, 59 (1981).
21. J. F. Toggweiler, *Eos* **61**, 984 (1980).
22. W. S. Moore and S. Krishnaswami, in *Proceedings of the Second International Coral Reef Symposium* (Great Barrier Reef Commission, Brisbane, 1974), vol. 2, pp. 269–276.
23. C. Emiliani, J. H. Hudson, E. A. Shinn, R. Y. George, *Science* **202**, 627 (1978).
24. R. G. Fairbanks and R. E. Dodge, *Geochim. Cosmochim. Acta* **43**, 1009 (1979).
25. R. B. Dunbar and G. M. Wellington, *Nature (London)* **293**, 453 (1981).
26. I. G. MacIntyre, *Atoll Res. Bull.* **185**, 21 (1975).
27. J. H. Hudson, personal communication; R. W. Buddemeier, personal communication.
28. E. M. Druffel, thesis, University of California, San Diego (1980).
29. The carbon and oxygen isotopic ratios are defined as follows:

$$\delta^{13}\text{C} = \frac{{}^{13}\text{C}/{}^{12}\text{C}_{\text{sample}} - {}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}}{{}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}} \times 1000$$

relative to the Pee Dee belemnite standard (PDB-1).

$$\delta^{18}\text{O} = \frac{{}^{18}\text{O}/{}^{16}\text{O}_{\text{sample}} - {}^{18}\text{O}/{}^{16}\text{O}_{\text{standard}}}{{}^{18}\text{O}/{}^{16}\text{O}_{\text{standard}}} \times 1000$$

relative to the standard mean ocean water (SMOW).
30. H. Stommel, *Proc. Natl. Acad. Sci. U.S.A.* **76**, 3051 (1979).
31. W. G. Mook and E. M. Druffel, unpublished data.
32. H. E. Suess, in *Proceedings of the Conference on Nuclear Processes in Geological Settings* (Univ. of Chicago Press, Chicago, 1953), pp. 52–56.
33. M. Stuiver and P. D. Quay, *Earth. Planet. Sci. Lett.* **53**, 349 (1981); W. F. Cain and H. E. Suess, *J. Geophys. Res.* **81**, 3688 (1976).
34. P. P. Tans, thesis, Rijksuniversiteit en Groningen, Netherlands (1978).
35. H. Oeschger, U. Seigenthaler, U. Schlotterer, A. Gugelmann, *Tellus* **27**, 168 (1975).
36. H. E. Suess, personal communication.
37. R. B. Dunbar, G. M. Wellington, P. W. Glynn, E. M. Druffel, *Geol. Soc. Am. 93rd Annu. Meet. Abstr.* **12**, 417 (1980).
38. I thank J. H. Hudson and E. A. Shinn for providing this unique coral core. I am grateful to W. G. Mook for allowing me to publish part of his stable isotope data for this coral core. The technical expertise of S. Griffin, P. Yeager, D. Sullivan, C. Hutto, and T. Linick is greatly appreciated. I thank Drs. W. Mook, P. Williams, J. Reid, H. Oeschger, P. Brewer, W. Deuser, L. Keigwin, B. Michel, S. Rodriguez, B. Jenkins, P. Rhines, H. Suess, and H. Stommel for enlightening discussions. I also thank D. Berry, M. Harvey, and T. Velasquez for their help in preparing this manuscript. This article consists in part of a doctoral dissertation carried out under the direction of Professor Hans E. Suess and submitted to the Department of Chemistry, University of California, San Diego, in March 1980. Financial support from the National Science Foundation through grants EAR-78-15183 and OCE-79-17652 and from the Woods Hole Oceanographic Industries Program 4470 is gratefully acknowledged. This article is contribution 5047 from the Woods Hole Oceanographic Institution.

Theory and Observation in Cultural Transmission

L. L. Cavalli-Sforza, M. W. Feldman
K. H. Chen, S. M. Dornbusch

Summary. Cultural phenomena may show considerable stability over time and space. Transmission mechanisms responsible for their maintenance are worthy of theoretical and empirical inquiry; they are complex and each possible pathway has different effects on evolutionary stability of traits, as can be shown theoretically. A survey designed to evaluate the importance of some components of cultural transmission on a variety of traits showed that religion and politics are mostly determined in the family, a mode of transmission which guarantees high evolutionary stability and maintenance of high variation between and within groups.

The activities, values, and behavior of an individual that are acquired through instruction or imitation will be termed "cultural." Such phenomena are not exclusively human (*1*) but are most highly developed in our species. In attempting to construct a quantitative theory for the evolution of cultural traits we have found many concepts from the quantitative theory of biological evolution to be useful (*2*). It has often been suggested (*3*), though not widely appreciated, that the evolution of cultural phenomena can be viewed in a conceptual framework similar to that of biological evolution, but so far most analyses have been purely qualitative.

That the continuing process of evolution by random mutation and natural selection has produced the complexity and diversity of living systems is the cornerstone of interpretation in the biological sciences. Observed genetic variation is the result of interactions between the rules of genetic transmission, mutation, natural selection, and sampling, due to the finiteness of natural populations. Each of these phenomena can, in principle, be measured, and together they allow statistical prediction of the evolutionary trajectories of the genotypes in the population.

The cultural analog of mutation includes innovation as well as random change in the expression of traits (*2*). In fact, Galton (*4*), in explaining biological mutations ("sports" in domesticated plants and animals) compared them to technological innovations. Our concern here is not with the comparison of mutation and selection in biological and cultural situations, but with another ingredient in the process of evolution—transmission. Although well studied and quantified in biology, transmission is poorly understood in its cultural context. The study of quantitative aspects of cultural transmission can, we believe, create a foundation for the study of cultural evolution and, in the quantitative theoretical development upon which we have embarked, modeling of cultural transmission has a central place (*2*). To date quantitative studies of cultural transmission have been limited, although there already exist theories, such as mathematical epidemiology (*5*), which could augment the study of diffusion of innovations (*6*). In this article we suggest some of the possible applications of our general theory, in an empirical investigation of quantitative aspects of our general theory.

Models of Transmission

Cultural transmission is the process of acquisition of behaviors, attitudes, or technologies through imprinting, conditioning, imitation, active teaching and learning, or combinations of these. A quantitative theory of the evolution of a culturally transmitted trait requires modeling who transmits what to whom, the number of transmitters per receiver,

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L. L. Cavalli-Sforza is a professor in the Department of Genetics, Stanford University Medical School, Stanford, California 94305; M. W. Feldman is a professor in the Department of Biological Sciences, Stanford University; K. H. Chen is a professor in the Department of Mathematics, California State University, Long Beach 90840; and S. M. Dornbusch is Reed-Hodgson Professor of Human Biology in the Department of Sociology, Stanford University.

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