Climatic variability in the eastern United States over the past millennium from Chesapeake Bay sediments

T. Cronin
D. Willard
A. Karlsen
S. Ishman
S. Verardo
J. McGeehin

U.S. Geological Survey, Reston, Virginia 20192, USA

R. Kerhin*
Maryland Geological Survey, Baltimore, Maryland 21218, USA

C. Holmes
U.S. Geological Survey, St. Petersburg, Florida 33701, USA

S. Colman
U.S. Geological Survey, Woods Hole, Massachusetts 02543, USA

A. Zimmerman
Virginia Institute of Marine Science, Gloucester Point, Virginia 23062, USA

ABSTRACT
Salinity oscillations caused by multidecadal climatic variability had major impacts on the Chesapeake Bay estuarine ecosystem during the past 1000 yr. Microfossils from sediments dated by radiometry (14C, 137Cs, 210Pb) and pollen stratigraphy indicate that salinity in mesohaline regions oscillated 10–15 ppt during periods of extreme drought (low fresh-water discharge) and wet climate (high discharge). During the past 500 yr, 14 wet-dry cycles occurred, including sixteenth and early seventeenth century megadroughts that exceeded twentieth century droughts in their severity. These droughts correspond to extremely dry climate also recorded in North American tree-ring records and by early colonists. Wet periods occurred every ~60–70 yr, began abruptly, lasted ~20 yr, and had mean annual rainfall ~25%–30% and fresh-water discharge ~40%–50% greater than during droughts. A shift toward wetter regional climate occurred in the early nineteenth century, lowering salinity and compounding the effects of agricultural land clearance on bay ecosystems.

Keywords: Holocene climate, benthic foraminifera, Chesapeake Bay, estuarine ecosystem, eastern U.S. precipitation, eastern U.S. climate.

INTRODUCTION
Twentieth century climatic variability is caused by ocean-atmosphere interactions (Latif and Barnett, 1994; Woodhouse and Overpeck, 1998), solar variability (Crowley and Kim, 1996; Lean and Rind, 1998), volcanic processes (Robock and Mao, 1995), climatological “noise,” anthropogenic perturbations to Earth’s atmosphere, or a combination of factors (Rind and Overpeck, 1993). Because instrumental records rarely exceed 100 yr, paleoclimate reconstructions can establish which factors are most important over multidecadal time scales, distinguish anthropogenic and natural causes, and test climate-model simulations of decadal- and centennial-scale variability (Latif, 1998). Paleoclimatic records from polar and tropical regions suggest that decadal- and centennial-scale climate changes are characteristic of the past millennium, a period that includes the Medieval Warm Period (ninth through fourteenth centuries) and the Little Ice Age (fifteenth through nineteenth centuries) (Hughes and Diaz, 1994; Overpeck et al., 1997).

Yet, except for tree-ring records (i.e., Cook and Jacoby, 1983; Stahle et al., 1998), multicentury records are sparse from most of the United States, and the ecological impacts of Holocene climate variability remain poorly known.

We investigated the past millennium of paleoclimatic history of the mid-Atlantic region preserved in the sedimentary record of Chesapeake Bay. Chesapeake Bay, the largest estuary in the United States, is a 320-km-long, 20–40-km-wide, 6500 km2 drowned river valley (average and maximum depths of 8.5 m and 53 m, respectively) inundated by the late Quaternary sea-level rise ca. 6–8 ka (Colman and Mixon, 1988). The bay’s thick Holocene section (Colman and Halka, 1989) contains micropaleontological and geochemical evidence for changes in fresh-water and sediment inflow, salinity, dissolved oxygen, and temperature (Cronin et al., 1999a). Its record of decadal- and centennial-scale variability holds promise for understanding impacts of past and climate change.

Figure 1. Cores in Chesapeake Bay. Sites PTMC-3, PRCK-3, AZM-3 are located in main channel, and PTXT-2 is near Patuxent River mouth. Paleosalinity estimates are based on percentage of Elphidium in Holocene sediments using salinity model in Figure 2. Ages are based on radiometric dating and pollen stratigraphy; sedimentation at PRCK-3 was irregular. Shallow-water sites (PTXT-2, AZM-3) were more sensitive to salinity variability than deeper water sites (PRCK-3, PTMC-3).

*Deceased.

Data Repository item 20004 contains additional material related to this article.
MATERIAL AND METHODS

We studied cores across a salinity gradient of <10–22 ppt in the mesohaline bay (Fig. 1; Table 1). Chesapeake Bay salinity is influenced by seasonal and annual fresh-water discharge, which is largely a function of precipitation in the watershed (Najjar, 1999; Cronin et al., 1999a). Monitoring records in the bay just off the Potomac River, for example, show that minimum and maximum wet-season salinities from 1984 to 1997 were 10 and 18 ppt, respectively; dry-season minima and maxima were 17 and 22 ppt, respectively. Post-1950 data show that interdecadal midbay surface-water salinity extremes ranged from minima of 15–16 ppt during the dry 1960s to minima of <5–7 ppt during the wet 1970s. Thus, this region is sensitive to both short- and long-term fresh-water discharge variability and is well suited to record climatically driven salinity oscillations.

Lithologic and X-ray radiograph studies show that sediments in the midbay consist mostly of fine-grained organic-rich mud and fine sand (Kerhin et al., 1998). Sediment-accumulation rates and age models were obtained by using pollen stratigraphy and radiometric dating. Prior studies (Brush et al., 1982; Brush, 1989; Cooper and Brush, 1991) provide a framework for post-colonial pollen stratigraphy. Two events are especially useful markers: the appearance of abundant (>10% of the total assemblage) Ambrosia (ragweed) between ca. A.D. 1800 and 1850 (the agricultural horizon) and the disappearance of Castanea dentata (chestnut) ca. 1930. We converted 214C dates on shells into calendar years using the model of Stuiver and Reimer (1993). Ages for sediments deposited over the past century at sites PTXT-2 and PTMC-3 were obtained from short-lived radioisotopes 137Cs and 210Pb. A 137Cs spike at 30 cm (ca. 1963) in PTXT-2-G-4, 27 cm in PTMC-3-P-2, and 56 cm in AZM-3 is corroborated by 210Pb profiles. Errors associated with each dating method are ~±20 yr for the agricultural horizon, ~±5 yr for the 137Cs spike, ~±5–20 yr for the 210Pb profile, and ±62–145 yr for radiocarbon dates. Age and core site data are available from the GSA data repository (see footnote 1). From dated horizons, we computed calendar-year age models that are corroborated by instrumental and tree-ring records (see following).

We used the benthic foraminifer Elphidium and several ostracode species to trace salinity variability (Ellison and Nichols, 1976; Cronin et al., 1999b). A linear model to calculate paleosalinity from the relative frequencies of Elphidium on the basis of its frequencies in surface sediment is expressed as S = (0.181 X P) + 10.66 (r2 = 0.66), where S = salinity and P = percentage of Elphidium for salinity between 10 and 20 ppt (Fig. 2A). For P values >45%, the model extrapolates salinity on the basis of populations from the lower bay where Elphidium is more abundant (P = ~50%–85%) of the total foraminifer assemblage) at salinities of 20–30 ppt (Ellison and Nichols, 1976). At salinities below ~10 ppt, Elphidium is absent (P = 0%). Other environmental factors (i.e., dissolved oxygen, substrate) account for the rest of the variability in Elphidium abundance.

To cross-check this model, we compared paleosalinity trends from core PTXT-2-P-5 to instrumental records of Washington, D.C., rainfall and Potomac River discharge for the past 175 and 90 yr, respectively (Fig. 2B). For downcore analyses, ~100 foraminifers were isolated from 40–60 g at 2 cm spacing. Confidence intervals for 100 individuals are ±5% to 9%, depending on the species’ relative frequency; thus, temporal changes in relative frequencies of 10% to >80% are statistically significant (Buzas, 1990). Although the earliest rainfall records may not be accurate, the decadal trends revealed by the Elphidium record still generally match Washington rainfall and Potomac River discharge. Three periods of reduced salinity (W1–W3) correspond to periods of greater than average discharge and rainfall (1860–1910, 1930–1950s, and post-1970). Dry periods (D1, D2) during the 1930s and 1960s cor-

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1GSA Data Repository item 20004, Table 1. Site and geochronologic data for Chesapeake Bay cores, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm.
respond to times of high bay salinity. Similar but
damped patterns are evident at the other sites (Fig. 1). A salinity excursion of 10–15 ppt (i.e.,
W1 and W2) equals an increase in annual
Potomac River discharge of ~2000–4000 cubic
feet per second (cf) (35.315 ft^3 = 1 m^3) (25%–
50%) over dry periods, and a corresponding
7–10 in/yr (18–25 cm/yr, 20%–30%) increase in
rainfall. These foram-based paleosalinity varia-
tions are quantitatively similar to those measured
over the past 50 yr from this region.

PAST MILLENNIUM OF CLIMATE
VARIABILITY
Reconstructed salinity for the past millennium
reveals several first-order trends (Fig. 1). First,
over centuries, it is possible to trace a north to
south and shallow to deep salinity gradient, as
measured by the percentage of Elphidium. Farther
south and deeper water core sites have on average
greater proportions of Elphidium and thus higher
estimated salinity. The shallowest site (site
PTXT-2, 12 m water depth) was the most sensitive
to decadal salinity variability; the deepest and most
oceanward site (PTMC-3) was the least sensitive.
This pattern reflects the influence of saline Atlantic
water in the deep channel, even during wet
periods, and the greater sensitivity of shallower re-
gions to changes in fresh-water flow. Second, pre-
eighteenth century salinity was on average several
parts per thousand higher than salinity during the
past two centuries; all cores show evidence for low
salinity fell by ~10–15 ppt. Conversely, dry inter-
vals are prolonged periods of

MEGADROUGHTS IN THE EASTERN
UNITED STATES
It is useful to compare the Chesapeake Bay
salinity record to other climatic records for North
America. Figure 3 compares the PTXT-2 salinity
record to the Palmer Hydrological Drought Index
(PHPDI) for July reconstructed from tree rings from
southern Virginia and northeastern North
Carolina (Stahle et al., 1998). The PHPDI record
was smoothed for easier comparison to the sedi-
mentary record. Although a precise correlation
between paleosalinity and PHPDI is difficult to
achieve because of dating error, there are note-
worthy similarities between the two records.
First, there is strong evidence that sustained
droughts during the middle to late sixteenth and
early seventeenth century were more severe than
twentieth century droughts. Events D14, D13,
D12, and D11 represent sixteenth and early
seventeenth century periods of high salinity
comprising 30% to >50% of the assemblage.

Large-scale fluctuations in salinity are also
indicated by ostracode assemblages. Cythero-
morpha newportensis (salinity range ~>16–32
ppt) oscillated approximately in phase with El-
phidium. During droughts, marine species (Pro-
tocytheretta edwardsi, Actinocytheris capitans,
Pellucistoma magniventra) inhabited mid-Chesa-
peake Bay, reflecting diminished fresh-water in-
flux; by the late 1700s, the brackish-water
species Perissocytheridea brachyformia (<15 ppt)
composed 30% to >50% of the assemblage.

Figure 3. Comparison of 500 yr salinity record at PTXT-2-P-5 to nine point smoothed

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English colonists during the 1560s, ca. 1587–1589, and ca. 1606–1612 (Stahle et al., 1998).

Second, from the late seventeenth until the early nineteenth century, more frequent lower amplitude salinity excursions (W11–W4) signify periods of high regional precipitation and PHDI values usually <0. Stahle et al. (1988; see also Stahle and Cleaveland, 1992) found progressively higher PHDI values after A.D. 1750 in bald cypress records from the southeastern United States.

Third, Chesapeake and tree-ring records indicate that a climatic transition occurred about 1825–1840 when a prolonged low-salinity phase began (W3), and PHDI values exceeded 1 for much of the period 1825–1910 (Stahle et al., 1998). On the basis of 74 tree ring records from the eastern United States, Cook and Mayes (1987) inferred a major atmospheric reorganization about 1836 that apparently initiated this period of wet climate. They also showed that the period 1836–1879 was characterized by high tree growth in mid-Atlantic regions, also consistent with greater mean annual precipitation and low bay salinity. Thus, although land-use changes influenced parts of Chesapeake Bay (Cooper and Brush, 1991), paleosalinity and tree-ring records suggest that during the nineteenth century Chesapeake Bay was also influenced by continental-scale climatic changes.

Although it is premature to link variability in Chesapeake salinity and eastern U.S. precipitation directly to specific causes, the patterns suggest “teleconnections” that can, at least conceptually, be related to decadal-scale climatological processes operating today. For example, a positive Pacific North America atmospheric pattern causes meridional mid-tropospheric flow in the eastern United States when the polar front and jet stream are pushed farther south than usual and the eastern U.S. coast has greater spring precipitation (Yarnal and Leathers, 1988; Henderson and Vega, 1996). Sixteenth and seventeenth century droughts might represent the opposite situation (negative Pacific North America pattern), in which zonal flow reduces precipitation in the watershed. Teleconnections to the North Atlantic oscillation (Hurrell, 1995) may also influence the northern part of the watershed when positive values correlate with increased precipitation (Vega et al., 1998). Simulated (Delworth et al., 1993) and observed (Kushnir, 1994) variability in North Atlantic Ocean sea-surface temperature, with spectral peaks at 40–80 yr, is similar to the 60–70 yr frequency of Chesapeake Bay wet periods. Because the Pacific North America and North Atlantic oscillation are linked to wind-driven oceanic circulation in subtropical gyres and/or thermohaline circulation (Latif, 1998), climate variability in the Chesapeake region may ultimately be linked to oceanic factors, although this hypothesis needs to be tested. Estimates of past precipitation and river discharge changes based on paleosalinity reconstructions are roughly comparable to increases in Susquehanna River basin rainfall and discharge due to doubling of atmospheric CO₂, as predicted by regional climate (Crane and Hewitson 1998) and hydrological models (Najjar, 1999).

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