RESTORING COASTAL ECOSYSTEMS AND ABRUPT CLIMATE CHANGE

AN EDITORIAL ESSAY

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Consensus exists that U.S. coastal ecosystems are severely degraded due to a variety of human factors requiring large financial expenditures to restore and manage (National Research Council, 2000). Yet, even as public controversy surrounds human factors in ecosystem degradation in the Gulf of Mexico (Ferber, 2004), Chesapeake Bay (Ernst, 2003; Thompson, 2004), and elsewhere, there is growing evidence that long-term coastal ecosystem management and restoration efforts should integrate abrupt climate change, including human-induced change, into research and modeling programs. Abrupt climate change[1] is a form of climate variability involving a shift in climate across a threshold at a rate exceeding that of the cause (National Research Council, 2002), such as the Younger Dryas climate cooling that began and ended in a few decades during the last deglacial period ∼12.8–11.6 thousand years ago. Abrupt climate changes, however, also punctuate the Holocene interglacial period at various spatial and temporal scales in the form of low-frequency, sometimes quasi-oscillatory decadal and multi-decadal variability. These types of climate variability include large shifts during the past few centuries complicated by recent anthropogenic influence on climate. The importance of decadal climate change due to the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) in the Pacific (Trenberth and Hurrell, 1994; Mantua et al., 1997), and the North Atlantic Oscillation (NAO) in the North Atlantic (Beaugrand et al., 2002; Drinkwater et al., 2003) is now widely recognized for oceanic ecosystem functioning (McGowan et al., 1998) and fisheries management (Botsford et al., 1997).

Conversely, the role of climate variability in coastal ecosystem functioning is usually not taken into account in coastal systems management, despite the fact that coastal restoration and water management projects, some having estimated costs in billions of dollars,[2] will take decades or longer to implement. Here we briefly summarize emerging evidence for climate forcing of coastal ecosystem parameters such as precipitation, river discharge, water quality, salinity, turbidity, faunal and phytoplankton dynamics, dissolved oxygen, and other ecosystem processes. Future sea-level change resulting from complex processes of ice-sheet dynamics and ocean

Climatic Change (2006) 74: 369–376
DOI: 10.1007/s10584-005-9029-7

thermal expansion and complicated by local geological, geomorphological, and climatological factors, poses an additional threat to many low-lying coastal regions. Sea-level change involves large uncertainties and longer timescales and, although it is beyond the scope of this paper, we acknowledge it can potentially complicate long-term coastal ecosystem response to climate variability.

Evidence for climate forcing of coastal ecosystems comes from three lines of research (see Figure 1). First, monitoring records extending back decades or longer, when compared to climate indices such as ENSO, PDO, and NAO, suggest that large-scale climatic teleconnections influence a range of coastal and adjacent oceanic and terrestrial systems. For example, climate impacts on snow cover, precipitation, streamflow, and aquatic ecosystems in the western U.S. are clearly coupled

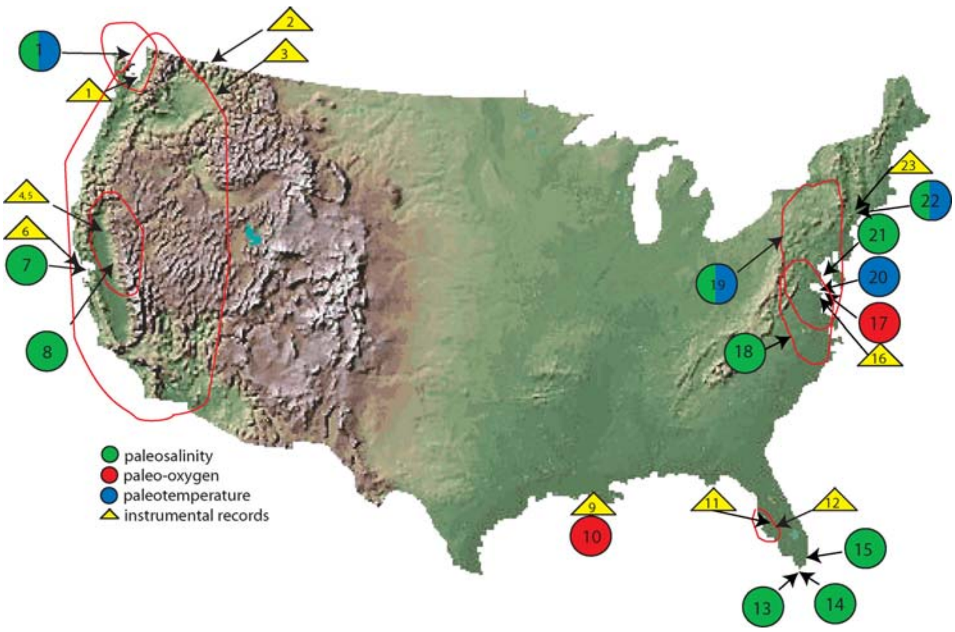

Figure 1. Map summarizing studies on the impacts of decadal-centennial climate on coastal ecosystems. Circles are paleoclimate records of salinity/precipitation, temperature, and oxygen triangles are instrumental records. Triangles are regional instrumental records of rainfall, stream discharge and climate indices; some studies also involve model simulations. Outlines show regional studies. Numbers in symbols keyed to references cited: 1. Whitfield et al. (2003), 2. Cayan et al. (1998), 3. Cayan and Peterson (1989), 4. Dettinger et al. (2004), 5. Knowles and Cayan (2004), 6. Lehman (2004), 7. Stahle et al. (2001), 8. Ingram and Ingle (1996), 9. Justic et al. (2003); 10. Rabalais et al. (2002), 11. Schmidt et al. (2001), 12. Lipp et al. (2001), 13. Swart et al. (1999), 14. Cronin et al. (2002), 15. Swart et al. (1996), 16. Harding and Perry (1997), 17. Karlsen et al. (2000), 18. Stahle et al. (1998), 19. Cook (2003), 20. Cronin et al. (2003), 21. Cronin et al. (2000), 22. Varekamp et al. (2003), 23. Howarth et al. (2000). Several studies are continent-wide or larger in scale (e.g., Cook et al., 1999; Woodhouse and Overpeck, 1998; Enfield et al., 2001). Base map from USGS National Elevation Dataset.

with ENSO and the PDO (Cayan and Peterson, 1989; Cayan et al., 1998); the shift in PDO in the late 1970s is now linked to ecosystem changes such as carbon production in San Francisco Bay (Lehman, 2004). Climate variability since the 1950s has also influenced Mississippi River discharge, contributing about 20% of variance to the size of the Gulf of Mexico "dead zone", although factoring out the contribution from land-use changes remains a challenge (Justic et al., 2003a,b). Decadal-scale climate-driven phytoplankton variability in Chesapeake Bay during the past 50 years is also superimposed on human-induced changes due to nutrient influx, population growth and other factors (Harding and Perry, 1997). In the Tampa Bay watershed, Florida, ENSO-driven winter rainfall and streamflow (Schmidt et al., 2001) are responsible for varying river discharge, which in turn strongly influences fecal coliform levels in the region (Lipp et al., 2001). On the continental scale, the quasi-cyclic (∼65–70 yrs) Atlantic Multidecadal Oscillation (AMO) and the PDO influence decadal variability in precipitation and discharge, which dramatically influence nutrient and sediment fluxes into U.S. coastal waters (Enfield et al., 2001; McCabe et al., 2004).

Second, significant climate influence on coastal ecosystems both during and prior to the development of monitoring programs comes from paleoclimate records from sediments, tree rings, and corals. In water-stressed California, tree-ring records allow partitioning of historical salinity extremes in San Francisco Bay that are caused by climatic variability from those caused by fresh-water diversion (Stahle et al., 2001). In Florida and Biscayne Bays, where salinity extremes caused by canal construction and water diversion in the Everglades are believed to affect many aquatic species, ENSO- and PDO-related rainfall variability, itself influenced by the phase of the AMO, is at least partially responsible for historical salinity extremes (Swart et al., 1996, 1999; Cronin et al., 2002). In Chesapeake Bay, sediment records show that hypoxia driven by 20th century agricultural nutrient influx was exacerbated by a change from drought conditions during the 1960s, the strongest in the eastern U.S. in centuries, to wetter and warmer conditions during the 1970s (Karlsen et al., 2000; Cronin et al., 2003, 2005). This well documented climatic shift in eastern North America coincides with an unusually large shift towards the positive phase of the NAO across the North Atlantic.

Pre-historical sediment records of the Medieval Warm Period (MWP, 9–14 centuries) and the Little Ice Age (LIA, 15–19 centuries) also show temperature and precipitation extremes indicative of regional climate variability. Examples include a warm and wet MWP and a cool and dry LIA in the Long Island Sound region of New York (Varekamp et al., 2003), salinity variability of 15 to 28 ppt in parts of San Francisco Bay during the LIA and MWP (Ingram and Ingle, 1996), and multi-decadal salinity and temperature variability in Chesapeake Bay during the past 2 millennia related to the NAO (Cronin et al., 2000). In some cases, sediment records of abrupt climatic change are corroborated by tree-ring records, such as those showing alternating periods of multi-decadal droughts and wet intervals in California (Stahle et al., 2001) and in the eastern United States (Stahle et al., 1998;

Cook et al., 1999; Cook, 2003). These and other studies demonstrate that, prior to any land clearance, water diversion or influx of anthropogenic nutrients, abrupt climatic shifts lasting decades or longer caused large changes in coastal ecosystems exceeding those observed in instrumental records. Although continental-scale correlations of short-term climate events are limited to tree-ring records of the more severe anomalies (Woodhouse and Overpeck, 1998; Stahle et al., 2000), and the ultimate causes of many regional events are unclear, abrupt climate transitions are nonetheless an inherent part of coastal ecosystem variability.

Third, improved climate model simulations also show that coastal ecosystems respond to natural climate variability, which itself has been perturbed by greenhouse gases. One example is the "end-to-end" assessment of future climate changes in the western U. S. under the "business as usual" atmospheric CO_2 scenario (Barnett et al., 2004), which concludes that human-induced climate change already is affecting hydrological budgets, and even greater changes are expected in the next few decades (Dettinger et al., 2004). By coupling climate, hydrologic, and estuarine models, researchers have been able to simulate the response of precipitation, Sierra Nevada snowpack, streamflow, and estuarine salinity in California and San Francisco Bay to climate variability (Knowles and Cayan, 2004). Model simulations of Mississippi River discharge also show that a 30% reduction in nitrogen influx, a target recommended to reduce the Gulf of Mexico dead zone to less than 5000 km^2 (Rabalais et al., 2002), may not be sufficient to reach desired goals (Justic et al., 2003a; Scavia et al., 2003). Another example is the modeled response of Chesapeake Bay salinity to future climate-induced variability of precipitation and Susquehanna streamflow (Najjar, 1999; Gibson and Najjar, 2000), which shows that a 10% increase in precipitation might translate into a 30% increase in stream flow. Model predictions such as these serve as guidelines for understanding future ecosystem response at decadal timescales most relevant to long-term restoration goals.

Progress notwithstanding, the complexities of ecosystem response to climatic forcing, especially in the context of local and regional ecosystem disturbance, raises formidable practical challenges (Stenseth et al., 2002). Perhaps the most complicated aspect of restoration pertains to spatial and temporal scales. Many of the Nation's programs designed to restore the health of critical coastal ecosystems such as San Francisco, Chesapeake, Florida and Tampa Bays, and the Gulf of Mexico continental shelf, are aimed at long-term objectives requiring decades to achieve. Conversely, local and regional hydrodynamic, ecosystem and other models, such as those designed to simulate the response of physical, chemical and biological systems to managed changes in sediment and nutrient input, fresh-water discharge, and land-use, are tested with rigorous calibration and validation procedures, but using calibration data sets limited to only a few years, although in some cases century-scale and longer instrumental data are available having great potential for calibration efforts.[3] While these models often produce impressive simulations of short-term (daily to interannual) hydrological variability, useful for short-term decision-making, with some exceptions, it is unclear how well they might simulate responses to climatic extremes on the scale of past and predicted changes outside their calibration range.

At large spatial scales, such as general circulation climate model simulations of 21st century global changes in river runoff due to anthropogenic greenhouse gas forcing, a consistent picture of future runoff trends does not emerge (Wolock and McCabe, 1999). Scale-related uncertainty in models means that assessment of long-term climate impact on coastal ecosystems has, with exceptions, been limited to discussion of potential rather than specific, quantifiable changes (Scavia et al., 2002). Even attempts to forecast coastal ecosystem response to climate through improved monitoring and calibration programs lack long time series to evaluate fully the physical and biological response of ecosystems to large climate shifts (Valette-Silver and Scavia, 2003).

Regional climate changes can be abrupt and large in scale, but their impacts might be anticipated if a new adaptive management paradigm is adopted. It would be highly advantageous for ecosystem restoration programs to routinely integrate past and predicted extremes in climate derived from instruments, paleoclimatology, and climate models into coastal ecosystem research, modeling and management. Towards this end, promising efforts include the CALFED San Francisco Bay-Delta Restoration Program (CALFED, 2003), the Georgia Basin-Puget Sound Research Conference (Whitfield et al., 2003), adaptive management of the Mississippi River-Gulf of Mexico system (Rabalais et al., 2002) and eutrophication in the Hudson River Estuary (Howarth et al., 2000). Understanding the impacts of abrupt climate shifts, whatever their causes, would not only increase the likelihood of success in restoring these and other altered ecosystems located in heavily populated areas, but it would also aid in adaptive management of the 22 estuaries in EPA's U.S. National Estuary Program, the 26 in NOAA's National Estuary Reserve Program, and other less impaired and unmanaged systems.

Acknowledgements

We are grateful to T. Armstrong, E. Dettman, J. Kiddon, J. Repetski, D. Scavia, A. Torres, D. Willard, and L. Wingard for critical reviews. We are especially appreciative to colleagues too numerous to mention from the research and managerial communities who freely shared their knowledge, facts and figures about coastal ecosystem modeling, management, and history. This paper is Contribution No. AED-05-012 of the Atlantic Ecology Division, National Health and Environmental Effects Research Laboratory, Office of Research and Development, USEPA. Although the research described in this paper has been funded in part by the U.S. Environmental Protection Agency, it has not been subjected to Agency review. Therefore, it does not necessarily reflect the views of the agency.

Notes

[1] The term “change” is used here informally to refer to shifts in climate due to either natural or anthropogenic forcing, or both, and thus does not strictly follow the commonly used convention distinguishing human-induced “change” from natural “variability”.

[2] It is difficult to quantify dollar costs for coastal ecosystem restoration and management or water quality improvement plans. Large programs include the Comprehensive Everglades Restoration Program (CERP), the CALFED-Bay-Delta Program in California, the Comprehensive Conservation and Management Plan for Tampa Bay, the Long Island Sound Study Program, the Chesapeake Bay Program, the Gulf of Mexico Program and Louisiana plan called “Coast 2050” (also called Louisiana Coastal Area (LCA)). See http://www.asiwpca.org/ for Clean Water State Revolving cost estimates.

[3] Calibration timescales for models used in water quality and ecosystem management vary widely depending on modeling goals and available monitoring data. Chesapeake Bay hydrodynamic and watershed models, Everglades and Florida Bay hydrodynamic, water quality, and landscape-trophic level models, Biscayne Bay hydrodynamic and ecosystem models incorporate between 1 and 20 years of calibration for simulation of annual, seasonal, and shorter timescales.

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(Received 18 January 2005; in revised form 4 November 2005)