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The potential impacts of climate change on the mid-Atlantic coastal region

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ABSTRACT: This paper assesses the potential impacts of climate change on the mid-Atlantic coastal (MAC) region of the United States. In order of increasing uncertainty, it is projected that sea level, temperature and streamflow will increase in the MAC region in response to higher levels of atmospheric CO_2. A case study for Delaware based on digital elevation models suggests that, by the end of the 21st century, 1.6% of its land area and 21% of its wetlands will be lost to an encroaching sea. Sea-level rise will also result in higher storm surges, causing 100 yr floods to occur 3 or 4 times more frequently by the end of the 21st century. Increased accretion in coastal wetlands, however, which may occur in response to increases in CO_2, temperature, and streamflow, could mitigate some of the flooding effect of sea-level rise. Warming alone will result in northward displacements of some mobile estuarine species and will exacerbate the already low summer oxygen levels in mid-Atlantic estuaries because of increased oxygen demand and decreased oxygen solubility. Streamflow increases could substantially degrade water quality, with significant negative consequences for submerged aquatic vegetation and birds. Though climate change may have some positive impacts on the MAC region, such as increased coastal tourism due to warming and some ecological benefits from less-frequent harsh winters, most impacts are expected to be negative. Policies designed to minimize adverse ecological impacts of human activities on coastal ecosystems in the mid-Atlantic, such as decreases in nutrient loading of watersheds, could help mitigate some of the risks associated with future climate variability and change in this region.

KEY WORDS: Climate change impacts · Coastal regions · Sea-level rise

1. INTRODUCTION

Impacts of climate change on coastal regions will have a regional signature that depends on the local climate change and the local geomorphological, biogeochemical, ecological and social factors that affect the sensitivity to climate. Here we present an assessment of the potential impacts of climate change on one of the most populated and ecologically important areas of the United States, the mid-Atlantic coastal (MAC) region,

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as part of a ‘National Assessment’ process mandated by the US Global Change Research Program (Fisher et al. 2000, in this issue). For this assessment, the MAC region extends from central New Jersey (near Toms River) to central North Carolina (near Cape Lookout), and includes several large estuaries: Delaware Bay, Chesapeake Bay and Albemarle-Pamlico Sound (see Polsky et al. [2000, in this issue] for a map of the region). Our assessment is based partly on output from coupled ocean-atmosphere models developed at the Hadley Centre for Climate Prediction and Research and the Canadian Climate Centre (CCC) (Polsky et al. 2000). These models were run in a transient mode from the middle of the 19th century to the end of the 21st century with gradual increases in greenhouse gases (1% yr^{-1} CO_2 equivalent) and sulfate aerosols (the ‘IS92a’ scenario, Houghton et al. 1996). For more details on the models, see Johns et al. (1997), Mitchell et al. (1995), Mitchell & Johns (1997), Boer et al. (1984, 1992, 2000a,b), Flato et al. (2000) and McFarlane et al. (1992). Following National Assessment guidelines, we base our assessment on output from these models averaged over 10 yr periods centered on 2030 and 2095, referenced to the climate of the 10 yr period centered on 1990, except where noted.

The remainder of the paper is organized as follows: First we summarize how climate change is likely to affect the physical environment in the MAC region. We not only consider how sea level will change, but atmospheric CO_2, temperature, precipitation and streamflow. Then we discuss the possible ecological and societal responses to such changes. We conclude by identifying priorities for climate-change research in the MAC region.

2. CLIMATE-RELATED CHANGES IN THE PHYSICAL STATE OF THE MAC REGION

2.1. Atmospheric CO_2 concentration

Of the possible global changes in the physical environment of coastal regions, a rise in atmospheric CO_2 is the most likely (Table 1). Though there is active debate about the necessity and feasibility of reducing CO_2 emissions, the long lifetime of CO_2 in the atmosphere means that CO_2 levels will likely rise even in the face of the most stringent emission reductions (Houghton et al. 1996). The best estimate is that atmospheric CO_2 concentration will be approximately double its 1990 value by 2095.

2.2. Sea-level rise and coastal flooding

Sea-level variations on time scales of a decade or more have 2 components: a global component that reflects thermal expansion of the ocean and glacial melting (eustatic sea-level rise) and a local component that reflects vertical land movements (resulting, for example, from regional tectonics, post-glacial isostatic adjustment, compaction and surface subsidence). The sum of the 2 components is known as relative sea-level rise (RSLR), which, over the past 100 yr, has been measured mainly from tide gauges. By avoiding regions of significant tectonic sea-level rise impacts and by accounting for post-glacial isostatic adjustment, Douglas (1991) estimated a eustatic sea-level rise of 1.8 ± 0.1 mm yr^{-1} between 1880 and 1980. By considering other studies, Warrick et al. (1996) gave a range of 1.0

Table 1. Mid-Atlantic coastal (MAC) region climate projections for 2030 and 2095 with respect to 1990

Parameter	2030 Mean	2030 Range	2095 Mean	2095 Range	Reliability of mean prediction
CO_2 (%)[a]	+25	+20 to +30	+92	+52 to +118	Very high
(ppm)	+90	+70 to +105	+325	+185 to +420	
Sea level (cm)[b]	+19	+11 to +31	+66	+39 to +102	High
Temperature (°C)[c]	+1.3	+1.0 to +1.5	+4.0	+2.7 to +5.3	High
Precipitation (%)[c]	+4	–1 to +8	+15	+6 to +24	Medium
Streamflow (%)[d]	+2	–2 to +6	+11	–4 to +27	Low

[a] Mean reflects IS92a and range reflects IS92d and IS92f CO_2 emission scenarios; see Fig. 5b from technical summary of Houghton et al. (1996). 1990 CO_2 concentration was 355 ppm

[b] Low, middle and high projections of Warrick et al. (1996) for IS92a scenario with varying aerosols (see their Fig. 7.7), plus a local component of 2 mm yr^{-1}

[c] Range is given by Hadley Centre and Canadian Climate Centre (CCC) models for the mid-Atlantic region (Polsky et al. 2000). Mean is average of 2 models. Changes are with respect to 1983–1994 model output

[d] For the Susquehanna River Basin, using a water balance model forced with the CCC and Hadley output (Neff et al. 2000)

Note

In the published article the temperature data in Table 1 were incorrect. These data have been corrected here

to 2.5 mm yr^{-1} for eustatic sea-level rise over the past century. In the mid-Atlantic region, RSLR is between 3 and 4 mm yr^{-1} (Titus & Narayanan 1995), suggesting a local component of RSLR of about 2 mm yr^{-1}, which may be due to variations in the accumulations of Holocene sediments and their subsequent compaction (Psuty 1992, Nicholls & Leatherman 1996), regional differential crustal warping (Walker & Coleman 1987) and possibly removal of groundwater by humans (Leatherman et al. 1995). Kearney & Stevenson (1991) noted that around Chesapeake Bay, relatively rapid RSLR during the 19th century contrasts with slower RSLR during the 17th and 18th centuries, a period of cooler global conditions. They also note that 19th-century global warming and eustasy are insufficient to account for the magnitude of the recent acceleration in RSLR around Chesapeake Bay. The effects of groundwater withdrawals and recent alterations in sediment loading need to be evaluated to fully understand local changes (Kearney & Stevenson 1991).

The rate of eustatic sea-level rise is likely to increase in the future because of CO_2-induced warming, which will cause expansion of the ocean and possibly glacial melting. The best estimate of Warrick et al. (1996) is that, by 2030 and 2095, global sea level will be about 11 and 45 cm higher, respectively, than in 1990. Adding in a local RSLR of 2 mm yr^{-1}, these figures increase to 19 and 66 cm, respectively, for MAC waters (Table 1). For the MAC region, therefore, global climate change, as opposed to local effects, is predicted to account for about 60 and 70% of the sea-level change from 1990 to 2030 and 2095, respectively.

How much land will be lost as a result of sea-level rise in the MAC region? We are currently using digital elevation models (DEMs) to assess this and here we present the results for Delaware. A simple inundation model was used in which all land with an elevation less than 61 cm is assumed to be flooded.[1] We acquired DEMs in 7.5 min maps with a horizontal resolution of 30 m from the United States Geological Survey (USGS, detailed information on the data set is available from USGS 1999a). We estimate that 91 km^2 (22000 acres) would be inundated, or about 1.6% of the total land area of the Delaware (Fig. 1). There are 2 factors that make this calculation an underestimate. First, the DEMs are derived by digitizing topographic maps with coarse contour intervals, normally around 10 ft (3 m), using linear interpolation to fill in values between contour lines. Because shorelines in the MAC region are typically concave-up (i.e. the slope increases in the inland direction), the DEMs underestimate the amount of low-lying land nearshore. Second, we have completely ignored erosion at the shoreface, which will increase the amount of inundation (Bruun 1988). Other factors that could bias our calculation, such as the delivery of sediment from rivers

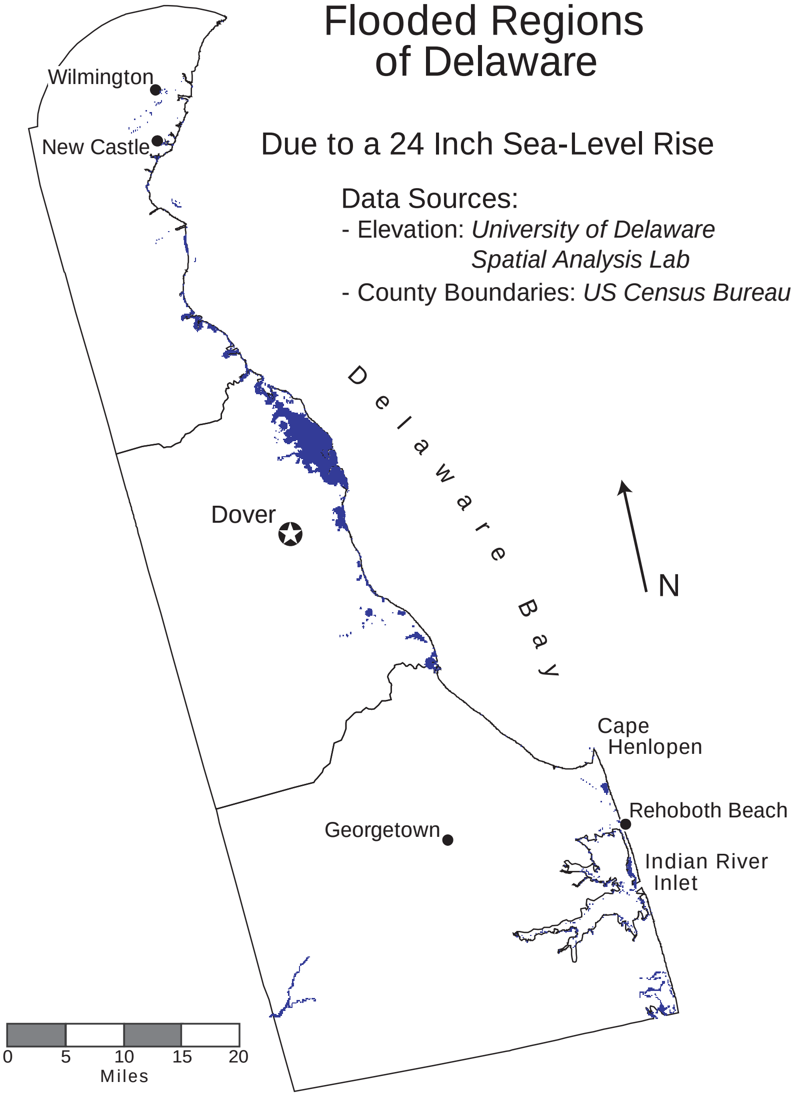

Fig. 1. Inundation of the shoreline of Delaware due to a rise in sea level of 61 cm (2 ft). See text for details of calculation

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[1] The DEMs give elevation in integral feet. A value of 1 ft, for example, is assumed to represent land between sea level and 1 ft above sea level. For the calculation, we chose a sea-level rise of 2 ft (61 cm), which is the value closest to 66 cm, the projected rise for 2095

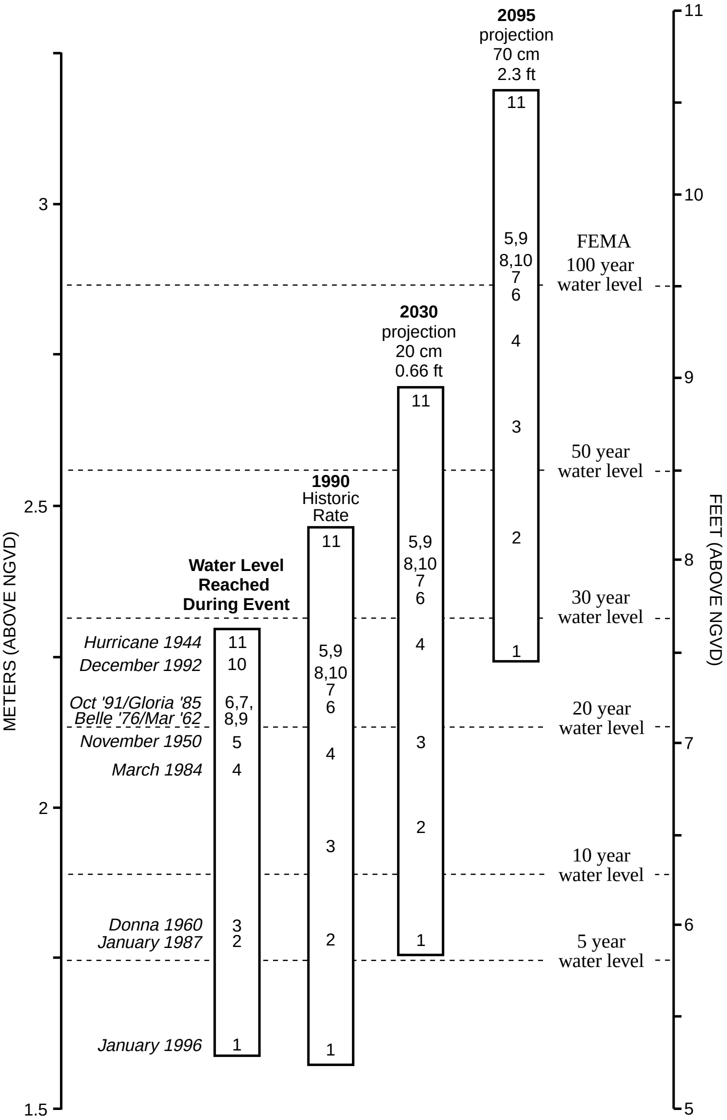

Fig. 2. Impact of sea-level rise on storm-surge-level recurrence intervals at Atlantic City, New Jersey. Recurrence-interval values (horizontal lines) are current Federal Emergency Management Agency (FEMA) determinations for Atlantic City. The vertical axis is height above the fixed elevation known as the National Geodetic Vertical Datum (NGVD). The first column on the left is the storm-surge level achieved during the specific event. Each event has a corresponding number repeated in the remaining columns. The second column shows the flood levels these storms would have produced had they occurred in 1990, using a sea-level rise of 3.85 mm yr^{-1}. The third and fourth columns show the expected flood level of these storms given a sea-level increase of 20 cm and 70 cm, the best estimates for 2030 and 2095, respectively

and organic matter accumulation in the root zone of marshes, are taken up in a later section.

Storm-surge levels will be affected by sea-level rise, even if the frequency and intensity of storms do not change. To illustrate this, past storm events in Atlantic City, NJ, are adjusted to the 1990 sea level and projected to 2030 and 2095 (Fig. 2). Consider the 1962 storm, which had a probability slightly greater than 1-in-20 yr. If that storm had occurred in 1990, its flood level would have been 11 cm higher, assuming a 3.85 mm yr^{-1} rate of sea-level rise, the average over the past 85 yr (Psuty & Collins 1996). Such a flood has nearly a 1-in-30 yr probability. If the storm were to occur in 2030, when sea level is expected to be about 20 cm higher than in 1990, it would produce a flood considered to have a 1-in-40 yr probability. For 2095, when sea level is expected to be about 70 cm higher than in 1990, it would produce a flood considered to have a 1-in-120 yr probability. These calculations suggest that coastal flooding due to storms will be much more severe by the end of the 21st century than they are today.

2.3. Temperature

The prediction of rising air temperature in the MAC region is less certain than the sea-level rise prediction because regional responses of climate are harder to predict and the cooling impact of aerosols may offset the CO_2-induced warming. This cooling impact is likely to be significant in the mid-Atlantic region because of its high industrial activity, though the implementation of new environmental regulations would reduce the impact. Uncertainties are reflected in the range of the predictions of the 2 climate models used for the National Assessment (Table 1; see also Polsky et al. 2000).

How will MAC water temperatures respond? Using data from the Chesapeake Bay Program, we computed monthly mean temperature from 1949 to 1994 in 23 regions of the main-stem Chesapeake Bay, using techniques described by Gibson & Najjar (unpubl.). We found Bay temperature to be highly correlated (r^2 from 0.68 to 0.93) with the estimation of mean surface air temperature over the Susquehanna River Basin (Najjar 1999). The slopes of the linear fits vary from 0.99 in shallow waters to 0.68 in deep waters, showing that water temperatures in Chesapeake Bay, and probably in most estuaries and coastal bays in the region, closely track air temperature. This suggests that the warming of surface air masses in the northeastern US will be tracked by nearshore MAC waters. During the summer, water temperatures in shallow areas may increase less than air temperatures as a result of evaporative cooling. In deeper, less-restricted MAC waters, the temperature change is likely to be smaller because of the greater volume to be heated and the larger influence of ocean circulation and mixing (Williams & Godshall 1977).

2.4. Precipitation

The 2 National Assessment models predict increases in mean precipitation over the northeastern US by 2095 (Table 1). Such predictions are supported by other climate model studies in the mid-Atlantic (Hodny 1992, Crane & Hewitson 1998, Najjar 1999). Estimates of the magnitude and seasonal timing of the precipitation increase vary considerably among models, suggesting significant uncertainty in these predictions. The combined effect of higher sea level and more precipitation would very likely result in greater coastal flooding.

2.5. Streamflow

Streamflow into coastal waters, which responds to air temperature and precipitation, is an extremely important driver of variability in mid-Atlantic estuaries. Neff et al. (2000, in this issue) showed that very different changes in streamflow are predicted by a water balance model when forced by the output of the 2 National Assessment climate models; this is because of the counteracting effects of increasing temperature and precipitation (Table 1). Three published studies on the response of mid-Atlantic streamflow to a doubling of atmospheric CO_2 reinforce this uncertainty (McCabe & Ayers 1989, Moore et al. 1997, Najjar 1999). In the future, other factors may also affect the amount of streamflow into coastal waters. Elevated CO_2 may decrease evapotranspiration on land, thereby increasing streamflow (Wigley & Jones 1985). Increased urbanization will increase the fraction of land that is impervious to water infiltration, resulting in increased runoff and streamflow (DeWalle et al. unpubl.). The combined uncertainty of the effects of precipitation, temperature, CO_2, and urbanization on streamflow makes prediction extremely uncertain.

3. ECOLOGICAL RESPONSES

3.1. Coastal wetlands

Coastal wetlands include wetland forests, saltwater marshes and freshwater marshes. These wetlands serve several important functions: wildlife habitats; spawning grounds; filtration systems for excess nutrients (from agricultural runoff and acid rain), heavy metals, and organic toxic substances (e.g. pesticides); and recreational open space. Sea-level rise is likely to be the most important climate-related impact on coastal wetlands. To evaluate the potential for this impact, we return to the Delaware case study (Fig. 1). To characterize land-use, we use maps from the Multi-Resolution Land Characteristics (MRLC) Consortium, which are based on Landsat Thematic Mapper data (USGS 1999b). The data are available at the same resolution as the DEMs described earlier and are based on the land use characteristics of 1993. We find that most of the affected area is wetlands—95% marsh and 1% forest—and estimate that 21% of all marsh land in Delaware will be flooded.

The potential for future horizontal migration inland by wetland plant species is limited primarily by human barriers, such as urban and suburban development and the construction of seawalls and bulkheads. Less than 1% of the affected area in Fig. 1 is currently developed, suggesting that future horizontal migration may be possible in Delaware if urbanization is controlled. However, direct anthropogenic modifications, including causeway construction, which alters tidal flushing, and creation and maintenance of mosquito ditches, can alter salt marsh vegetation patterns and processes (Niering & Warren 1980).

Wetlands can accrete vertically, depending on the availability of sediment and the rate of organic matter accumulation within the root zone, potentially reducing the flooding effect of sea-level-rise. The amount of land lost for a given length of shoreline will be a reflection of the deficit of sediment and organic matter inputs with respect to the increased volume of water associated with sea-level rise. As noted earlier, Chesapeake Bay salt marshes currently do not receive sufficient sediment and organic matter to keep up with current rates of sea-level rise (Stevenson et al. 1988, Kearney & Stevenson 1991). It seems likely that the current imbalance will grow in the future because sea-level rise rates are projected to increase and because the decreasing trend in sediment yields of major mid-Atlantic rivers over the past few decades is likely to continue. The latter is largely a result of farmland abandonment, dam construction and reduced soil erosion (Trimble 1974, Meade 1982).

Because of the importance of sediment inputs, MAC wetlands will not respond uniformly to sea-level rise. Thus, those wetlands lacking inputs of riverine sediments will be most vulnerable to sea-level rise. These wetlands include microtidal marshes of the Chesapeake Bay, extensive non-tidal wetlands of the Albermarle-Pamlico Peninsula (Moorhead & Brinson 1995), and upland and marsh islands in Chesapeake Bay. Wray et al. (1995) noted that upland islands along the main stem of Chesapeake Bay are rapidly eroding, due to wave action against low silt/clay cliffs, and are expected to totally disappear in fewer than 20 yr. Marsh islands in Chesapeake Bay are shrinking due to perimeter edge erosion and interior marsh loss, and are likely to be greatly reduced in size or totally lost in the coming century (Wray et al. 1995).

On the other end of the spectrum are tidal freshwater marshes, which receive large influxes of riverine sediments, and so are likely to be less vulnerable to sea-level rise than their saltwater counterparts. However, horizontal migration of these wetlands will be limited by the steep valley slopes that characterize the upper reaches of such river systems, and up-river migration will be limited by increasingly narrow channels. Conversely, an increase in freshwater flow would shift tidal freshwater wetlands downstream, potentially increasing their area.

Climate-related changes in the environment may affect the material balance in wetlands, thereby affecting the degree of flooding due to sea-level rise. This could happen in at least 3 ways. First, carbon storage in wetlands may be altered by elevated CO_2. A Maryland salt marsh exposed to experimentally doubled levels of CO_2 (with respect to ambient) since 1987 has responded with an increase in carbon storage, mainly below ground (Drake et al. 1996). Because the marsh in this study is isolated from a number of geophysical and biogeochemical processes that affect soil aggregation on regional scales, it is uncertain whether these results can be applied regionally. Second, regional warming may influence carbon storage in marsh sediments. A trend for higher levels of soil organic matter in Gulf-of-Mexico marshes compared to northern marshes (Callaway et al. 1996) suggested that the net effect of regional warming will be to increase accretion rates. Also, the effect of elevated CO_2 on net ecosystem production increases with temperature by about 2% $°C^{-1}$ (Drake et al. 1996). Third, and last, if streamflow and streamflow variability increase [as a result of increases in precipitation and precipitation variability (Table 1)], then riverine inputs of sediments to marshes would likely increase.

Thus, all 3 of these climate-related changes (CO_2, temperature and hydrology) have the potential to reduce some of the flooding effect of sea-level rise in coastal wetlands. Quantifying these effects, however, is extremely difficult. With regard to the impacts of hydrology, they are difficult to quantify mainly because of the uncertainty in the precipitation predictions. With regard to organic matter accumulation rates, very little is known about their theoretical maximum upper limits and to what extent accretion results in an increase in surface elevation. For example, Bricker-Urso et al. (1989) suggested a maximum theoretical accretion rate of 16 mm yr^{-1}, a rate that exceeds even the highest projections for the mid-Atlantic, but Cahoon et al. (1995) found that surface elevation changes in microtidal marshes in the southeastern US were significantly less than vertical accretion rates. Clearly, more work is needed on the potential for increased accretion in the root zone as a function of CO_2 and temperature increases, particularly in the context of local elevation changes due to subsurface subsidence.

In addition to RSLR and resulting changes in vegetation patterns, elevated CO_2 in the marsh study described above significantly increased the density of C3 species (e.g. sedge *Scirpus olneyi)* at the expense of C4 species (e.g. grasses *Spartina patens* and *Distichlis spicata*) (Drake et al. 1996). Thus, elevated CO_2 may change plant species composition in coastal marshes. The cumulative consequences of such changes on ecosystem functioning are uncertain.

3.2. Coastal bays and estuaries

3.2.1. Salinity

As sea level rises, the ocean will encroach landward and estuarine salinity will increase. Hull & Titus (1986) suggest that such a salinity change could have significant negative impacts on drinking water quality and estuarine ecosystems in and around Delaware Bay during the 21st century. They used a 1-dimensional numerical model to evaluate the impact of a 73 cm sea-level rise (expected near the end of the 21st century, Table 1) on salinity above a 1965 baseline. The maximum 30 d average chloride concentration increased from 135 to 305 mg l^{-1} (average seawater is about 20 000 mg l^{-1}) at one location in the upper Bay. The salt front (a rapid change in salinity in the horizontal direction, which is indicated by a chloride concentration of 250 mg l^{-1} in this Bay) was predicted to move upstream by 11 km.

In addition to sea-level variations, streamflow affects estuarine salinity on interannual timescales. Drought conditions in late 1964 caused the Delaware Bay salt front to advance up to 50 km upstream with respect to its average position (Hull & Titus 1986). To investigate streamflow impacts on Chesapeake Bay salinity, Gibson & Najjar (unpubl.) developed an autoregressive statistical model with monthly resolution. They found that annual mean salinity decreases by 0.8% in the upper Bay to 0.1% in the lower Bay for every 1% increase in annual mean streamflow. We applied the Gibson & Najjar (unpubl.) model to the streamflow projections by Neff et al. (2000), which were derived using output from the National Assessment climate models. For the CCC model, the mid-Bay salt front is projected to migrate upstream by 3 km (0.94% of the Bay's length) by 2030 and 7 km (2.2% of the Bay's length) by 2095. For the Hadley model, the mid-Bay salt front is projected to migrate downstream by 11 km (3.4% of the Bay's length) by 2030 and 48 km (15% of the Bay's length) by 2095. Clearly, streamflow changes could either offset or compound the effects of sea-level rise on the salinity of MAC waters.

3.2.2. Water quality, plankton and submerged aquatic vegetation

Current water-quality conditions in mid-Atlantic estuaries are typically poor. According to NOAA (1997a,b) and US EPA (1998), mid-Atlantic estuaries are generally characterized as high in chlorophyll concentration (a measure of phytoplankton abundance), nutrients and turbidity, and low in submerged aquatic vegetation (SAV) and dissolved oxygen. A significant increase of phytoplankton biomass has occurred during the last 40 to 50 yr in MAC waters; the increase in Chesapeake Bay has been particularly well documented (Harding & Perry 1997). Nuisance algae are reported for half of the mid-Atlantic estuaries and toxic algal blooms have had resource impacts in 4 bays, 3 of which are in North Carolina (NOAA 1997a,b). US EPA (1998) identified Chesapeake Bay as the most hypoxic estuary in the region, with low dissolved oxygen levels associated with stratification and nutrient overenrichment.

How will climate change influence mid-Atlantic estuarine water quality, plankton, and SAV? The single most important climatic influence on estuarine water quality is streamflow. For several reasons, water quality degrades as streamflow increases (Hurley 1991). First, the vertical stability of the water column increases as fresher water overrides denser saltier water, decreasing the ability of winds and tides to vertically mix water, thereby decreasing the replenishment of oxygen from the atmosphere to deeper waters of the estuary. Second, nutrient inputs from associated watersheds increase, increasing plankton production and the rain of organic debris to deeper levels, causing additional oxygen consumption as bacteria and other fauna degrade the debris. Third, increased particle loads in shallow areas may hinder filter feeding by invertebrates and cause water clarity and photosynthesis by SAV to decrease. Fourth, increased nutrient loading (and warming) stimulates growth in epiphytic algae on the blades of the SAV, reducing the light available to the SAV. Losses in SAV and their physical buffering of wave action along shorelines can contribute to increases in coastal erosion, which may further decrease water clarity.

Because of its impact on mid-Atlantic fisheries, the degree of anoxia in Chesapeake Bay is an important water-quality indicator. Seliger & Boggs (1988) found that summertime anoxic volume in Chesapeake Bay in recent decades was highly correlated with April-May flow of the Susquehanna River, a major source of fresh water to the Bay. Their analysis suggests that a 10% increase in flow results in a 26% increase in summertime anoxic volume. The fact that anoxia depends on the timing, as well as the magnitude, of streamflow makes prediction under climate change difficult. Table 2 highlights this point by summarizing how climate-induced changes in streamflow may change Chesapeake Bay anoxia in the future. In addition to the 2 National Assessment models, results from 2 regional climate models are used. The results show that anoxia changes could be very large but the direction of the change varies among the different climate models. Walker et al. (2000) documented how anthropogenic activity has dramatically altered the relationship between nutrient flux and streamflow during the last century. They suggested that the relationship between Chesapeake Bay anoxia and streamflow documented by Seliger & Boggs (1988) was much stronger in the past few decades than it was in previous centuries. If nutrient loads to the coast continue to increase as coastal populations grow, it seems that anoxia will become even more sensitive to streamflow in many mid-Atlantic estuaries.

Table 2. Change in April-May flow of the Susquehanna River and Chesapeake Bay summertime anoxic volume estimated from climate model output. CCC = Canadian Climate Centre

Change	Hadley 2030	CCC 2030	Hadley 2095	CCC 2095	Nested model[a] $2 \times CO_2$	Empirical downscaling[b] $2 \times CO_2$
April-May flow (%)[c]	+12	−4	+4	−25	+43	−0.2
Anoxic volume (%)[d]	+31	−10	+10	−65	+112	−0.5

[a] Details of these models are given in Crane & Hewitson (1998) and Najjar (1999)

[b] See Crane & Hewitson (1998) for details of precipitation calculation. Temperature taken from Hadley 2095

[c] Computed from water balance model of Najjar (1999). Also see Neff et al. (2000)

[d] Uses linear relationship of Seliger & Boggs (1988)

The oxygenation of estuarine waters will be affected by warming. For each °C that water warms, oxygen solubility (the capacity to dissolve oxygen) decreases by about 2%. Changes in oxygen concentration also depend on biotic factors. Higher temperature increases bacterial production and raises the metabolism of cold-blooded aquatic animals (invertebrates, amphibians, fish and reptiles), thereby increasing the metabolic need for oxygen. Thus, warming will increase anoxia in MAC waters, but the magnitude of the effect is not known.

Increases in water temperature are likely to have important effects on phytoplankton species composition, their geographic range, and grazing rates of their zooplankton and benthic filter- feeding predators. Several species of toxic phytoplankton enjoy wider distribution during warmer periods (Tester 1996). Keller et al. (1999) demonstrated that increases in winter temperature can result in increased cropping of phytoplankton by zooplankton in the water column, reducing the supply of detrital material for benthic organisms. This could negatively impact benthic food chains, but have a positive effect on the oxygenation of bottom waters.

3.3. Fish and shellfish

Variations in the abundance of many fish and shellfish are correlated with environmental conditions during early larval stages that affect natural mortality. Such variations subsequently affect variations in fishing mortality. H. Austin & R. Wood (Virginia Institute of Marine Sciences, pers. comm.) summarized fluctuations in recruitment patterns of Chesapeake Bay fish in relation to variations in weather and climate during the past several decades. Recruitment success in anadromous species was associated with variations in river discharge, whereas recruitment in bay-spawned species was influenced by wind, river discharge and temperature. Shallow-water spawners were sensitive to variability in precipitation and sea level during critical periods. Recruitment in many shelf-spawned species was associated with variability in winds on the coastal shelf. Thus, a combination of heavy fishing pressure and a series of climatically unfavorable years for recruitment can result in dramatic reductions in the abundance of valued fish stocks.

There is a historical basis for expecting warming to have significant impacts on estuarine and marine fish and shellfish in the mid-Atlantic. For example, Murawski (1993) found that marine temperature variation on the North American east coast explained changes in the north-south distribution of 12 of 36 species of fish. On the west coast from the early 1930s to the mid 1990s, annual mean shoreline temperature increased by 0.75°C, while abundances of 63% of northern species of rocky intertidal invertebrates decreased and 89% of southern species increased (Barry et al. 1995). Species whose southern range ends in the MAC region, such as the soft clam *Mya arenaria* in Chesapeake Bay, may be eliminated if water temperatures reach levels that are lethal or that inhibit successful reproduction. Such losses could initially reduce local estuarine diversity because species are often more readily eliminated from an estuarine environment than replaced (Kennedy 1990). On the other hand, a positive impact of warming might be less frequent severe winters, like the severe winters of 1977 and 1981, which are thought to have resulted in low blue crab *Callinectes sapidus* catches in the Delaware estuary (US EPA 1998).

Parasitic and predatory relationships among organisms in MAC waters are also sensitive to temperature. The parasite that causes Dermo disease in eastern oysters *Crassostrea virginica* was restricted to locations south of Delaware Bay before 1990. Since then, a rapid range expansion of this parasite to the north has occurred in association with warmer winters (Cook et al. 1998). Links between climate change and other marine diseases have been reviewed by Harvell et al. (1999). Experiments in Oregon have shown that small changes in sublethal temperatures interfere with the controlling effect of a starfish on its mussel prey, thereby potentially altering species compositions and dynamics of the intertidal community (Sanford 1999). Thus small, nonlethal temperature changes can indirectly cause large ecological changes.

The interactions between higher temperatures and depleted oxygen noted earlier could constrict the available habitat for a variety of species along the North American east coast, including striped bass *Morone saxatilis* in Chesapeake Bay, an important spawning center for this species (Coutant 1990). Laboratory studies have shown that organisms under stress pay a metabolic cost in the form of a continued expenditure of energy that may preclude survival if the stress does not abate (e.g. Parsons 1990). Examples of this in Chesapeake bay are shellfish mortalities that have occurred due to low-oxygen conditions (Officer et al. 1984, Seliger et al. 1985).

Climate-related salinity changes also could affect mid-Atlantic estuarine ecosystems. Sea-level rise will enable mobile estuarine species to migrate upstream, where potential impacts from pollution and other human influences will be greater. Higher salinities could result in the invasion of salinity-tolerant pests, such as 2 lethal oyster diseases and 2 species of predatory snails of eastern oysters that are inhibited by salinities below about 12 and 20, respectively (Kennedy & Breisch 1981). During the mid-1980s, for example, low riverine flows resulting from low precipitation over the watersheds of mid-Atlantic states caused estuarine salinities to be higher than normal. Oyster diseases responded positively to these saltier waters and decimated the oyster population in much of the region (US EPA 1998). The predicted increases in streamflow (Table 1), on the other hand, may benefit oysters by making estuarine waters fresher and a poorer environment for disease. But if precipitation variability increases as predicted (Table 1), oysters and organisms with similar salinity thresholds may suffer. For example, the tremendous freshening of Chesapeake Bay associated with Tropical Storm Agnes in 1972 caused massive oyster mortality (Leatherman et al. 1995).

3.4. Birds

The bays and estuaries of the mid-Atlantic region provide important habitat for a variety of resident and migratory birds including the osprey, bald eagle, 6 species of colonially nesting waders (such as the great blue heron and snowy egret), and dozens of shorebird and waterfowl species. Chesapeake and Delaware Bays harbor the largest concentrations of migratory shorebirds in the western hemisphere. Approximately 70% of the entire North American population of the red knot *Calidris canutus* is in Delaware Bay at one time (Sutton et al. 1996). Chesapeake Bay is also used by nearly 1 million ducks, geese and swans to feed and rest during the winter months and thousands more use it as a migration stopover point. MAC birds utilize a diversity of wetland habitats within the region for feeding, consuming fish, amphibians, invertebrates, and SAV. Habitat loss and the effects of contaminants and declines in water quality on food resources have caused population declines of many of these species (Funderbunk et al. 1991). Changes in water temperature and quality under climate change will have mostly indirect effects on these species, primarily through changes in the distribution and abundance of food resources.

Waterfowl use of Chesapeake Bay has changed tremendously in the last 50 yr. Wintering population sizes of most duck species have declined steadily since the 1950s, while population sizes of Canada geese and snow geese have increased (Perry & Deller 1996). Most of these changes are attributed to changes in waterfowl food resources in and around the Bay, particularly the widespread decline of SAV (Perry & Deller 1996). Projections of warming Bay waters, possible streamflow increases, and increasing coastal populations suggest that water quality and therefore SAV will continue to decline, leading to further declines in SAV-dependent waterfowl. Diving ducks and many other birds could also be negatively impacted by the anoxia-induced declines in shellfish noted earlier.

Factors outside the mid-Atlantic will likely play a role as well. For example, Sorenson et al. (1998, unpubl.) used the warmer and drier projections for the prairie pothole region of the north-central US and south-central Canada (the continent's 'duck factory') to infer that the number of pothole wetlands and, correspondingly, the number of ducks breeding in the region would be reduced. In turn, this could reduce waterfowl abundance in MAC waters because many of the ducks that winter there breed in the pothole region. Band recovery data for one of the most abundant ducks, the canvasback *Aythya valisineria*, show that approximately 40% (346/875) of canvasbacks breeding in the prairie pothole region winter in the Atlantic Flyway. Ninety-one percent (316/346) of the Atlantic Flyway population are found in MAC waters, 75% (236/316) of these on Chesapeake Bay. Declines in breeding population sizes of ducks in Prairie Canada ranging from 19 to 39% and 7 to 70% are projected for the 2030s and 2090s, respectively (Sorenson et al. unpubl. data). Declining breeding population sizes and fewer young produced under increasing drought conditions on the prairies coupled with likely declines in wintering habitat quality due to climate change bode poorly for future duck populations on MAC waters.

4. SOCIETAL RESPONSES

The coastal areas of the mid-Atlantic region have aesthetic and economic values. The shore is a tourist destination, inviting investment in facilities to serve the tourist population. For many coastal areas, visitors and temporary residents exceed the resident population by an order of magnitude or more. The annual flux of visitors to the coast is concentrated during the peak summer holiday but extends to the shoulder seasons in late spring and early fall, as well as weekends and holidays.

American society has, in general, subsidized coastal development with federal activities such as shoreline protection, beach replenishment, federal disaster assistance, and the National Flood Insurance Program (NFIP). Coastal counties of 4 mid-Atlantic states (New Jersey, Delaware, Maryland, Virginia) had 177 758 NFIP policies in effect with $21 billion in coverage from 1978 to 1998 (H. John Heinz III Center for Science, Economics and the Environment 1999). During that time, $81 million in premium revenues were collected and $327 million were paid in 46 670 thousand claims, $138 million (42%) of which were repetitive. The Coastal Zone Management Act of 1972, in cooperation with state coastal agencies, provides measures to control development, and NFIP has strengthened regulations regarding the elevation of new or reconstructed buildings. However, NFIP regulations are enforced poorly in many areas. Furthermore, federal declarations of emergency, which make people eligible for financial assistance after storms, may only serve to encourage development.

4.1. Potential impacts

The potential impacts on development and use in the MAC region are positive and negative. On the positive side, a warming of several °C (Table 1) would significantly extend the season of coastal recreation, giving seasons to the northerly areas that are as long as those now occurring in North Carolina and Virginia. On the negative side, there appear to be greater risks. Although the MAC region is not particularly vulnerable to hurricanes (with the exception of the Outer Banks of North Carolina), September is the most common period of direct hits (Jarrell et al. 1992). Thus, an extension of the tourist season would result in a greater number of people potentially affected by hurricanes. The threats to the coasts from sea-level rise include long-term and sometimes subtle threats from coastal inundation and erosion. Immediate threats may occur from storms and tidal surges either greater in frequency and severity than in the past or imposed on higher water levels (Fig. 2). Wetlands loss due to sea-level rise and increased anoxia and habitat squeeze due to warming would negatively affect waterfowl hunting and sport and commercial fishing. If warming increases toxic algal blooms, decreased coastal tourism and fishing would likely result.

4.2. Management and adaptation options

Sea-level rise poses an important challenge to desirable coastal environments and beach-front developments. In estuaries, it is likely that protection from submergence will be accepted only for socially significant locations, and values of land development will largely determine areas to be protected by dikes or walls. Dry land will yield to wetlands and water where economic or cultural importance, or both, are not established. In Chesapeake Bay, with its numerous small cliffs, sea-level rise will directly increase erosion rates if other changes (e.g. increased bulkheading) do not occur. Response strategies will vary from state to state. North Carolina prohibits armoring of the open shoreline, while other states allow a wider range of responses. Titus (1998) documented rapidly increasing armoring of Maryland's bay shores. Some communities will identify ecologically important areas and protect them, as is being tried in parts of the Blackwater Refuge in Maryland. Both protection and abandonment will exact a cost from society that will increase through time.

In general, we anticipate that in the ocean coastal areas, society will continue to support structural approaches such as beach replenishment, groins, and sea walls to maintain the status quo. Titus et al. (1985) estimated that the costs of maintaining the beachfront should be negligible over the next 40 yr, given the large amount of revenue that local tourism generates. Their calculations were based on sea-level rise scenarios close to the middle and high projections shown in Table 1. From these scenarios, sand requirements and their associated costs were computed. More recent studies using similar methods support the economic benefit of beach nourishment in Delaware (Faucett Associates 1998, Parsons & Powell 1998). Nevertheless, Delaware has taken the stance of allowing strategic retreat for state-owned coastal lands. An emerging policy of beach replenishment in New Jersey has a potential cost of \$60 million mile^{-1} and a 50 yr total cost of \$9 billion (Grunwald 1999).

There are important legal dimensions to the process of beach retreat in coastal areas (Titus 1998). For example, if individual landowners are allowed to build seawalls to protect against beach erosion, the publicly accessible margin between high and low tide may eventually disappear. Titus (1998) argued for a rolling easement concept that would maintain public access to tidal lands as shorelines retreat, even beneath buildings raised above regulation flood levels. Acceptance of such a policy would require legislative action. Some degree of beach replenishment and shoreline hardening might be necessary to make such a policy seem less threatening to private property in the short run.

Inland flood losses and flood control investments in the US have increased with time. Settlement history and the development of federally subsidized transport systems and flood mitigation measures have encouraged floodplain occupancy. It has taken a century for US flood control policy to begin moving from structural approaches to non-structural approaches. Only in the last decade has there been serious consideration of relocating flood-prone communities and abandoning breached levees to re-establish normal river-floodplain relations. On the mid-Atlantic coast, if not elsewhere, one can foresee coastal management repeating the inland floodplain experience: federal subsidies for occupation of dynamic and sometimes hazardous coastal zones; structural answers to control coastal hazards and the impact of sea-level rise; and ever-increasing vulnerability with losses increasing along with investments in protection.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Informed speculation on how climate change may affect the mid-Atlantic coastal region can be based on information about past climate impacts on the region and climate model projections. Sea level, temperature, storminess and streamflow have had profound effects on the MAC region. Climate change has caused a progressive and significant increase in sea level over the past century, eroding shores and increasing storm-related coastal flooding. Temperature variations have affected coastal ecosystems and fisheries by changing parasite-host relationships, and may also affect predator-prey relationships among other things. Streamflow variations have effectively dictated the seasonal and interannual variations in estuarine water quality. Past experience strongly suggests that mid-Atlantic climate change will significantly impact coastal waters. Table 3 presents a qualitative summary of what the impacts might be and how certain the predictions are. The ecological, and hence societal, impacts are largely negative. The only positive societal benefit is the potential for increased coastal tourism due to the warmer climate. Table 3 also presents the potential impacts on the MAC region of future population growth. These impacts tend to be in the same direction as the climate change impacts.

The high human population density of the MAC region has increased the sensitivity of the region to climate variability. For example, coastal inundation due to sea-level rise is exacerbated by human activities that reduce the supply of sediment, such as dam building and bulkheading. Coastal anoxia has probably always been sensitive to streamflow in many mid-Atlantic estuaries, like Chesapeake Bay (Cooper & Brush 1991), but nutrient inputs due to human activity have probably heightened this sensitivity (Walker et al. 2000). Thus, climatic and human influences act synergistically on the MAC region. We speculate that climate may indirectly impact the MAC region in the future through warming-induced human migration to the coast. This could compound effects on water quality and sea-level rise, as suggested in Fig. 3. One management implication of our study, therefore, is that policies designed to reduce adverse environmental impacts of local human activities could help mitigate some of the risks associated with climate-change.

The capability of predicting the environmental impacts of future climate change on the MAC region is influenced by 2 factors: (1) our ability to predict how the regional climate will change and (2) our understanding of the sensitivity of the region to climate change. Predictions for sea-level rise and temperature change have much greater certainty than predictions for other aspects of climate variability. There is a large body of work published on global sea-level rise (Warrick et al. 1996, and references therein), and on RSLR in Chesapeake Bay and its likely consequences (Kearney & Stevenson 1991, Downs et al. 1994, Wray et al. 1995). There is substantially greater uncertainty concerning past and future changes in extreme weather events, variability in regional precipitation, and streamflow, all of which have the potential for substantial impacts in the coastal zone. More research is clearly needed in these areas.

Though there is abundant evidence that ecosystems in the MAC region are sensitive to climate, the mechanisms are not well understood; this makes prediction of the impacts of climate change unreliable, even if the future climate could be predicted with certainty. We recommend a 4-pronged approach to understanding the sensitivity of MAC ecosystems to climate, and to help distinguish between effects of climate variability and other anthropogenic components of change: (1) increased monitoring and historical data analysis; (2) experimental manipulation of the environment (temperature, salinity, CO_2, etc.) in the laboratory and field to test specific hypothesis concerning ecosystem sensitivity; (3) measurement and analysis of paleo-climate variability (from caves, tree rings, marine sediment cores, etc.) to increase our understanding of decadal-scale changes in regional climate, in the context of larger spatial-scale variability in the northern hemisphere during the Holocene; and (4) numerical modeling of the impact of climate on physical, chemical and biological processes.

There are a number of important unknowns with regard to the societal impacts of climate change in the MAC region. Research attempting to quantify the effect of increased temperatures on human migration to the coast would be extremely helpful. Mapping is

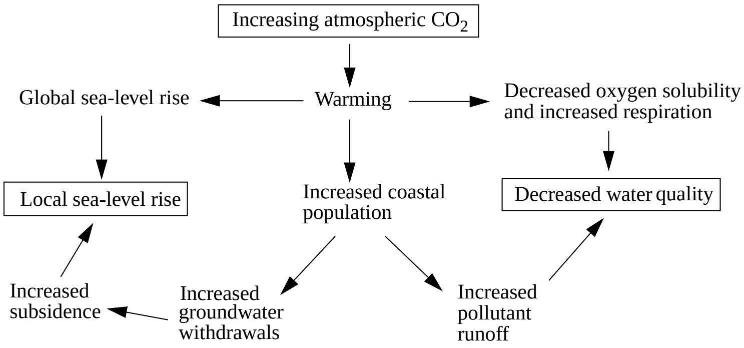

Fig. 3. Schematic showing possible synergistic impacts of climate change and coastal development on sea-level rise and water quality

Table 3. Summary of potential impacts of climate and population change on the mid-Atlantic coastal region. SAV: Submerged aquatic vegetation

Best estimate of change	Impact if significant change occurs					
	Wetlands	Water quality	SAV	Fish and shellfish	Birds	Society
Near certain CO_2 increase	Possible increase in accretion	Slight pH decrease	Small	Small (calicification decrease?)	None	None
Very likely sea level increase	Likely flooding	Very likely higher turbidity	Likely decrease due to increased turbidity	Possible species distribution changes due to salinity changes; possible oyster disease increase	Likely loss of intertidal habitat and decrease in food for SAV-dependent species	Very likely increased costs of coastal flooding
Likely temperature increase	Possible increase in accretion	Possible increase in anoxia and nuisance blooms; possible phytoplankton decreases	Likely species distribution changes	Likely species distribution changes; likely oyster disease increase	Possible species-distribution changes	Likely increased tourism and possible migration to the coast
Possible precipitation and streamflow increase	Possible increase in accretion due to increased sediment input	Very likely increase in turbidity and anoxia	Very likely decrease due to increased turbidity and nutrients	Likely decrease due to decreased water quality; possible species-distribution changes due to salinity changes; possible oyster disease decrease	Likely decrease in food for SAV-dependent species	Possible increased costs of coastal flooding; likely decrease in recreational and commercial fishing
Very likely population increase	Decrease in area due to: human development, decreased sediment supply (due to dams), and increased groundwater withdrawals	Likely increase in toxic substances, nutrients and anoxia. possible turbidity decrease due to dams and bulkheads	Likely decrease due to water-quality decrease, but possible increase due to lower turbidity	Likely decrease due to water-quality decrease and overfishing	Likely decrease in food for SAV-dependent species	Increased tourism

needed of coastal regions that are most economically vulnerable to climate change, particularly to sea-level rise. Finally, research into the long-term costs and benefits of federal subsidies and shoreline protection methods would be most helpful in guiding future public policy for the mid-Atlantic coastal region.

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