Appendix H

Karen Terwilliger/TCI

Refuge beaches and dunes

Sea Level Affecting Marshes Model (SLAMM) Analysis

Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Nantucket NWR

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Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Nantucket NWR

Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 could be 50 to 140 cm. Pfeffer et al. (2008) suggests that 200 cm by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. Rising sea level may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat migration as salt marshes transgress landward and replace tidal freshwater and brackish marsh (Park et al. 1991).

In an effort to address the potential effects of sea level rise on United States national wildlife refuges, the U. S. Fish and Wildlife Service contracted the application of the SLAMM model for most Region 4 refuges. This analysis is designed to assist in the production of comprehensive conservation plans (CCPs) for each refuge along with other long-term management plans.

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 5.0) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al., 1991; Lee, J.K., R.A. Park, and P.W. Mausel. 1992; Park, R.A., J.K. Lee, and D. Canning 1993; Galbraith, H., R. Jones, R.A. Park, J.S. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2002; National Wildlife Federation et al., 2006; Glick, Clough, et al. 2007; Craft et al., 2009.

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site-specific data.
- **Overwash:** Barrier islands of under 500 meters width are assumed to undergo overwash during each 25-year time-step due to storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.

- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain.

SLAMM Version 5.0 is the latest version of the SLAMM Model, developed in 2006/2007 and based on SLAMM 4.0. SLAMM 5.0 provides the following refinements:

- The capability to simulate fixed levels of sea-level rise by 2100 in case IPCC estimates of sea-level rise prove to be too conservative;
- Additional model categories such as "Inland Shore," "Irregularly Flooded (Brackish) Marsh," and "Tidal Swamp."
- *Optional.* In a defined estuary, salt marsh, brackish marsh, and tidal fresh marsh can migrate based on changes in salinity, using a simple though geographically-realistic salt wedge model. This optional model was not used when creating results for Nantucket NWR.

Model results presented in this report were produced using SLAMM version 5.0.1 which was released in early 2008 based on only minor refinements to the original SLAMM 5.0 model. Specifically, the accretion rates for swamps were modified based on additional literature review. For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 5.0.1 technical documentation (Clough and Park, 2008). This document is available at http://warrenpinnacle.com/prof/SLAMM

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (CREM 2008).

Sea-Level Rise Scenarios

The primary set of eustatic (global) sea level rise scenarios used within SLAMM was derived from the work of the Intergovernmental Panel on Climate Change (IPCC 2001). SLAMM 5 was run using the following IPCC and fixed-rate scenarios:

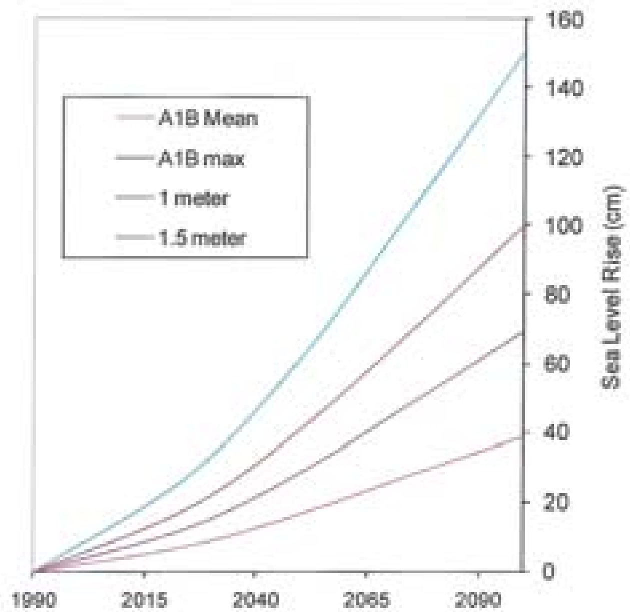
Scenario	Eustatic SLR by 2025 (cm)	Eustatic SLR by 2050 (cm)	Eustatic SLR by 2075 (cm)	Eustatic SLR by 2100 (cm)
A1B Mean	8	17	28	39
A1B Max	14	30	49	69
1 meter	13	28	48	100
1.5 meter	18	41	70	150

Recent literature (Chen et al., 2006, Monaghan et al., 2006) indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to dynamic changes in ice flow omitted within the IPCC report's calculations. A recent paper in the journal *Science* (Rahmstorf, 2007) suggests that, taking into account possible model error, a feasible range by 2100 might be 50 to 140 cm. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC

AR4 projected sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008)

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, 1½ meters of eustatic sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 1).

Figure 1: Summary of SLR Scenarios Utilized



Methods and Data Sources

LIDAR elevation data are unavailable for this National Wildlife Refuge (NWR). Elevation data used are based on National Elevation Data (NED). An examination of the NED metadata indicates that this digital elevation map (DEM) was derived from a 1972 survey (Fig. 2). The contour interval used to derive the DEM was ten feet. The majority of the refuge falls below the ten foot contour line meaning there is significant uncertainty as to dry land elevations at this site. Beach elevations were estimated as a function of tidal range, a procedure that is also subject to uncertainty.

Figure 2: Nantucket Excerpt from USGS Map.

The National Wetlands Inventory for Nantucket is based on a photo date of 1999. An examination of the NWI map overlaid on recent satellite photos indicates a land boundary shift of around 70 meters in places (Figure 3). Because beach elevations are estimated as a function of tide range, using the SLAMM elevation pre-processor, this disconnect between vertical NED data and horizontal beach location may not have a significant effect on model predictions. Dry land elevations are subject to more uncertainty.

Figure 3: Land boundary shift of nearly 70 meters indicated by white line

Converting the NWI survey into 30 meter cells indicates that the approximately twenty nine acre refuge (approved acquisition boundary including water) is primarily composed of the categories as shown below:

Dry Land	62.5%
Ocean Beach	26.6%
Open Ocean	10.9%

Based on the NWI coverage, there are no dikes or impounded wetlands within the Nantucket NWR.

The historic trend for sea level rise was estimated at 2.95 mm/year using the value of the closest station (8449130, Nantucket Island, MA). This measured rate is somewhat higher than the global average for the last 100 years (approximately 1.5-2.0 mm/year). Any effects of isostatic rebound that have affected this region for the last 100 years are measured within that historic trend and that same rate of isostatic rebound is projected forward into the next 100 years.

The tide range at this site was estimated at 1.089 meters using the closest NOAA oceanic gage (8449130, Nantucket Island, MA).

Figure 4: NOAA Gage Relevant to the Study Area.

Accretion rates in salt and brackish marshes are not relevant to this site as no marshes appear in the initial condition, nor in future predictions.

Modeled U.S. Fish and Wildlife Service refuge boundaries are based on Approved Acquisition Boundaries as published on the FWS "National Wildlife Refuge Data and Metadata" website. The modeling team were in contact with Eastern Massachusetts National Wildlife Refuge Complex biologist Stephanie Koch to ensure model parameters were consistent with local knowledge.

The cell-size used for this analysis was 30 meter by 30 meter cells. However, the SLAMM model does track partial conversion of cells based on elevation and slope. (Note that since the LiDAR data produce a more accurate DEM, only the elevations of wetlands classes lying outside of the LiDAR data (in the NED data) in Nantucket were overwritten as a function of the local tidal range using the SLAMM elevation pre-processor.)

SUMMARY OF SLAMM INPUT PARAMETERS FOR GREAT BAY

Description	Nantucket
DEM Source Date (yyyy)	1972
NWI_photo_date (yyyy)	1999
Direction_OffShore (N|S|E|W)	N
Historic_trend (mm/yr)	2.95
NAVD88_correction (MTL-NAVD88 in meters)	-0.09
Water Depth (m below MLW- N/A)	2
TideRangeOcean (meters: MHHW-MLLW)	1.089
TideRangeInland (meters)	1.089
Mean High Water Spring (m above MTL)	0.724
MHSW Inland (m above MTL)	0.724
Marsh Erosion (horz meters/year)	1.8
Swamp Erosion (horz meters/year)	1
TFlat Erosion (horz meters/year) [from 0.5]	0.5
Salt marsh vertical accretion (mm/yr) Final	3.78
Brackish March vert. accretion (mm/yr) Final	3.78
Tidal Fresh vertical accretion (mm/yr) Final	5.9
Beach/T.Flat Sedimentation Rate (mm/yr)	0.5
Frequency of Large Storms (yr/washover)	50
Use Elevation Preprocessor for Wetlands	TRUE

Results

Nantucket National Wildlife Refuge is predicted to show effects from sea level rise. The refuge is predicted to lose about one fifth of its dry land and half of its ocean beach in the most conservative scenario.

SLR by 2100 (m)	0.39	0.69	1	1.5
Dry Land	20%	33%	51%	71%
Ocean Beach	49%	57%	77%	89%

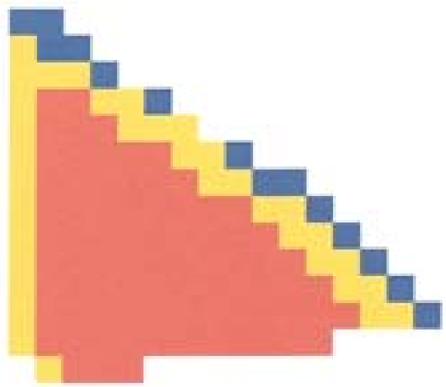
Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise

Maps of SLAMM input and output to follow will use the following legend:

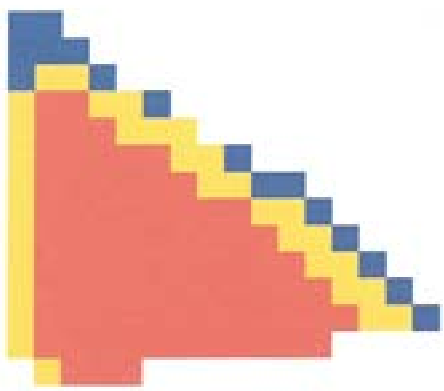
Nantucket
IPCC Scenario A1B-Mean, 0.39 M SLR Eustatic by 2100

Results in Acres

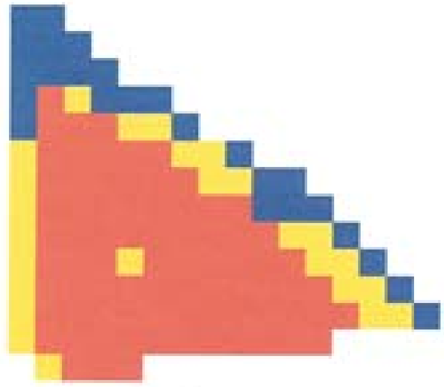
	Initial	2025	2050	2075	2100
Dry Land	17.8	17.5	16.7	15.7	14.3
Ocean Beach	7.6	6.9	6.2	4.8	3.8
Open Ocean	3.1	4.1	5.5	8.0	10.3
Total (incl. water)	**28.5**	**28.5**	**28.5**	**28.5**	**28.5**



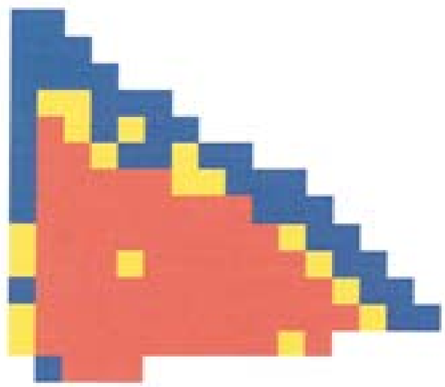
Nantucket, Initial Condition



Nantucket, 2025, Scenario A1B Mean



Nantucket, 2050, Scenario A1B Mean



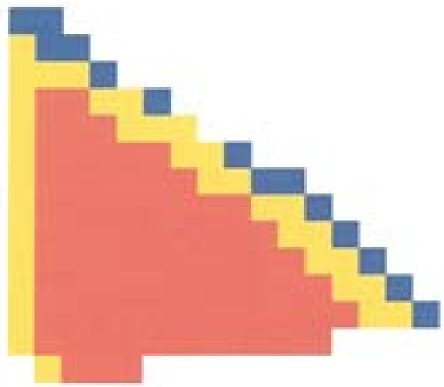
Nantucket, 2075, Scenario A1B Mean

Nantucket, 2100, Scenario A1B Mean

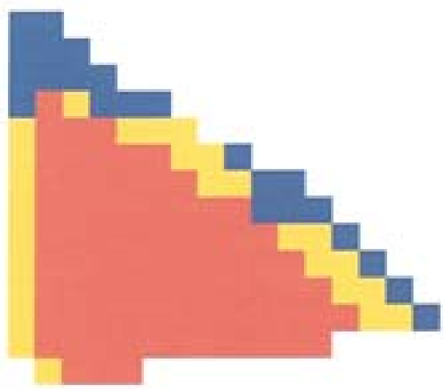
Nantucket
IPCC Scenario A1B-Max, 0.69 M SLR Eustatic by 2100

Results in Acres

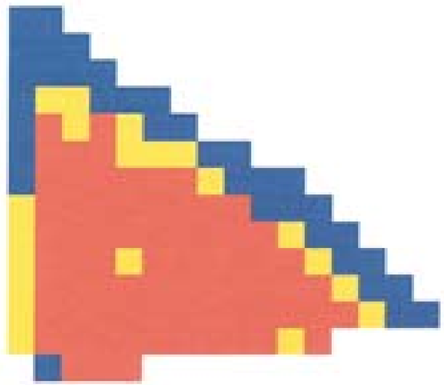
	Initial	2025	2050	2075	2100
Dry Land	17.8	17.3	16.0	13.8	11.9
Ocean Beach	7.6	6.6	5.1	3.9	3.2
Open Ocean	3.1	4.6	7.4	10.7	13.3
Total (incl. water)	**28.5**	**28.5**	**28.5**	**28.5**	**28.5**



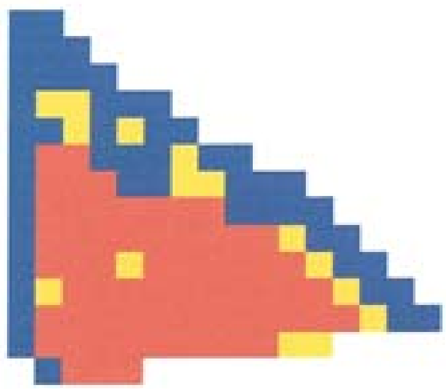
Nantucket, Initial Condition



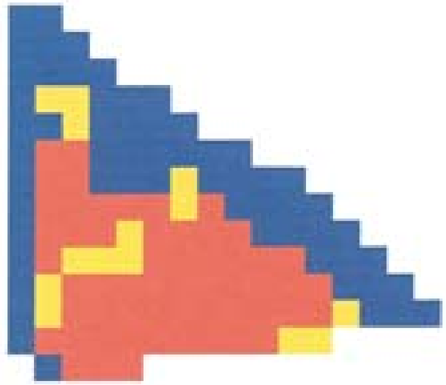
Nantucket, 2025, Scenario A1B Maximum



Nantucket, 2050, Scenario A1B Maximum



Nantucket, 2075, Scenario A1B Maximum

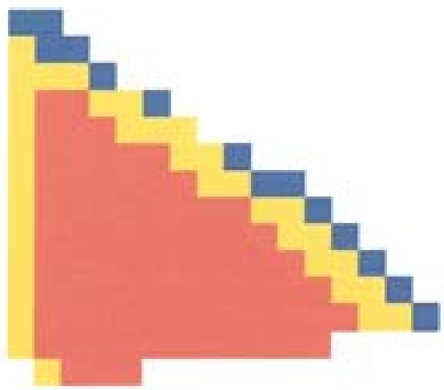


Nantucket, 2100, Scenario A1B Maximum

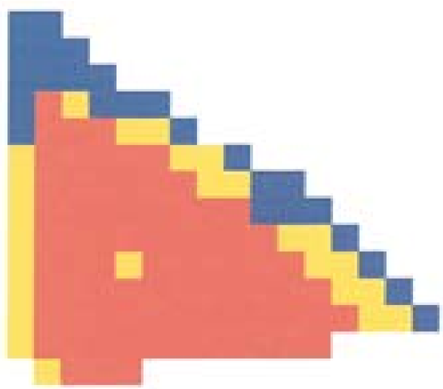
Nantucket
1 Meter Eustatic SLR by 2100

Results in Acres

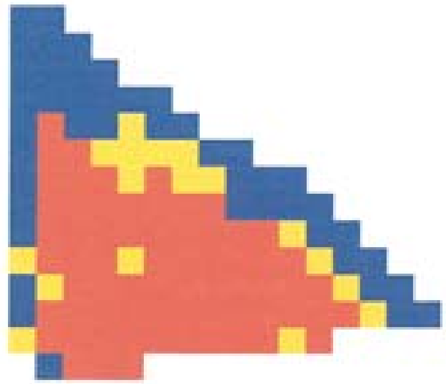
	Initial	2025	2050	2075	2100
Dry Land	17.8	17.0	15.1	12.3	8.8
Ocean Beach	7.6	6.2	3.6	1.9	1.7
Open Ocean	3.1	5.3	9.8	14.3	18.0
Total (incl. water)	**28.5**	**28.5**	**28.5**	**28.5**	**28.5**



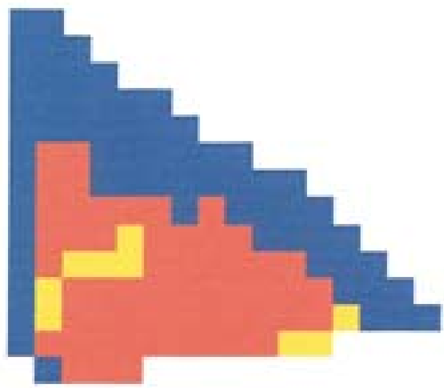
Nantucket, Initial Condition



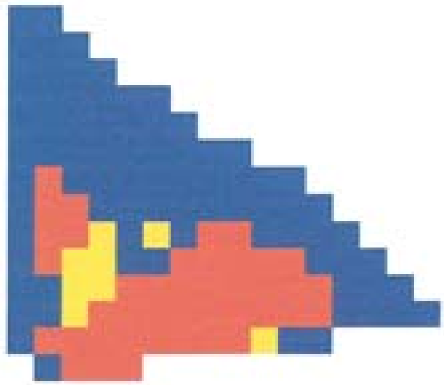
Nantucket, 2025, 1 meter



Nantucket, 2050, 1 meter



Nantucket, 2075, 1 meter

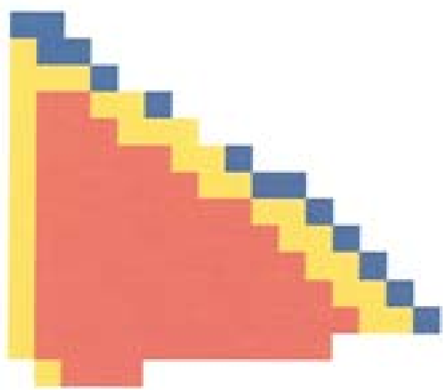


Nantucket, 2100, 1 meter

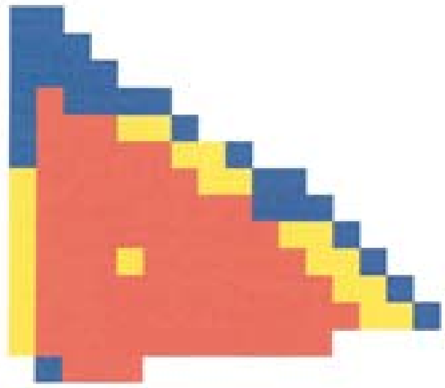
Nantucket
1.5 Meters Eustatic SLR by 2100

Results in Acres

	Initial	2025	2050	2075	2100
Dry Land	17.8	16.5	13.4	8.9	5.1
Ocean Beach	7.6	5.6	3.7	1.3	0.8
Open Ocean	3.1	6.3	11.4	18.3	22.2
Estuarine Beach	0.0	0.0	0.0	0.0	0.2
Estuarine Open Water	0.0	0.0	0.0	0.0	0.1
Total (incl. water)	**28.5**	**28.5**	**28.5**	**28.5**	**28.5**

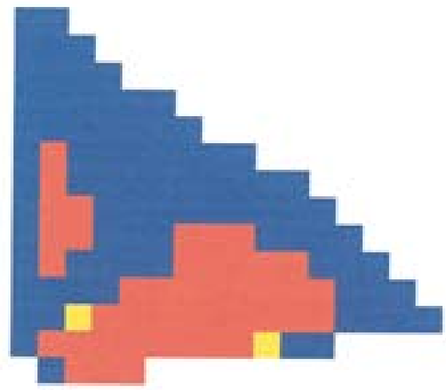


Nantucket, Initial Condition

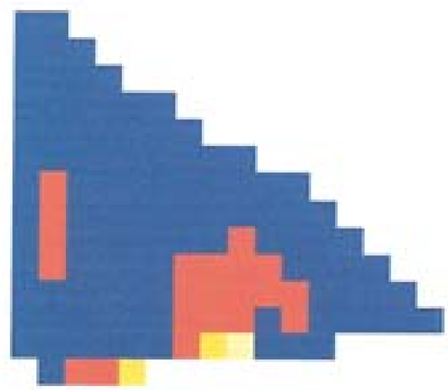


Nantucket, 2025, 1.5 meter

Nantucket, 2050, 1.5 meter



Nantucket, 2075, 1.5 meter



Nantucket, 2100, 1.5 meter

Discussion:

Model results for Nantucket NWR indicate that it is vulnerable to the effects of sea level rise under all scenarios. Vulnerability is relatively high due to the general susceptibility of ocean beaches to sea level rise and the large quantity of dry land that falls below the ten foot USGS contour.

Model results for this site are subject to considerable uncertainty. Dry land elevations are poorly characterized by the low-resolution NED (from 1972). Predicted dry-land loss rates would be refined with a higher vertical resolution dataset. Additionally, ocean beach erosion is difficult to precisely characterize with a relatively simple model. Finally, ocean beach elevations are estimated as a function of tidal range because elevation data have a low vertical resolution.

The SLAMM model does account for the local effects of isostatic rebound by taking into account the historical sea level rise for each site. The historical rate of land movement is predicted to continue through the year 2100 (i.e. the rate of isostatic rebound is assumed to remain constant).

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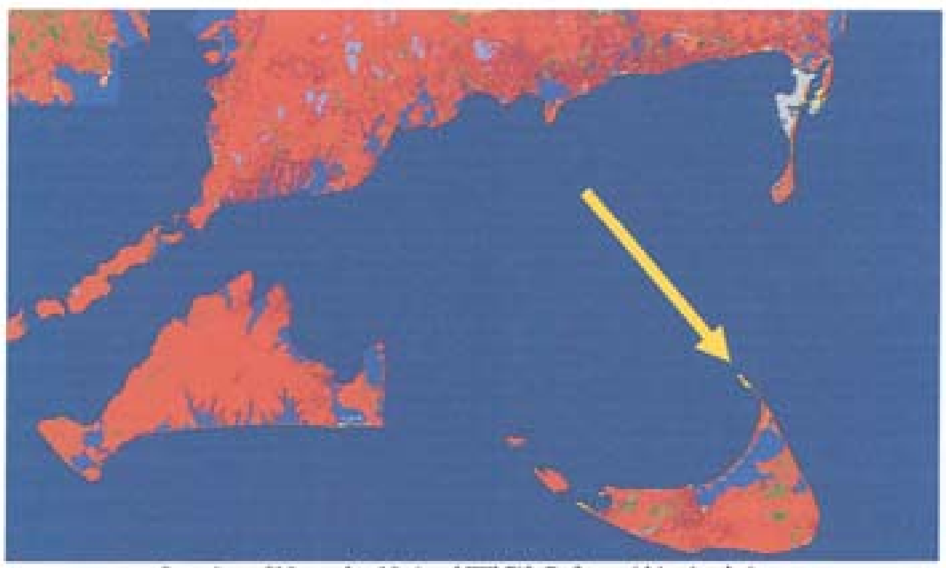
Appendix A: Contextual Results

The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated dry lands will convert to marshes or ocean beach depending on their proximity to open ocean.

For this reason, an area larger than the boundaries of the USFWS refuge was modeled. These results maps are presented here with the following caveats:

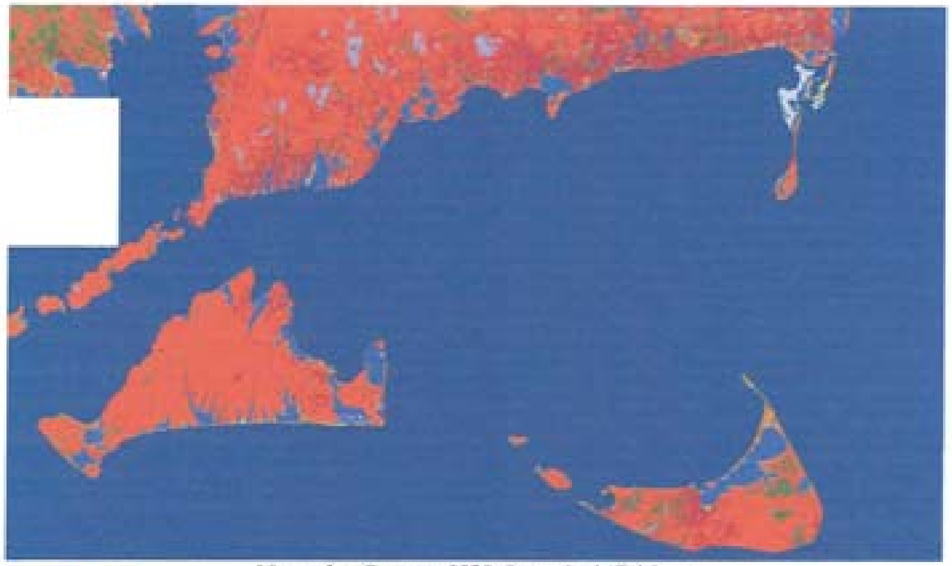
- Results were closely examined (quality assurance) within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to assess the probable location and effects of dikes for USFWS refuges, but this effort was not made for surrounding areas.



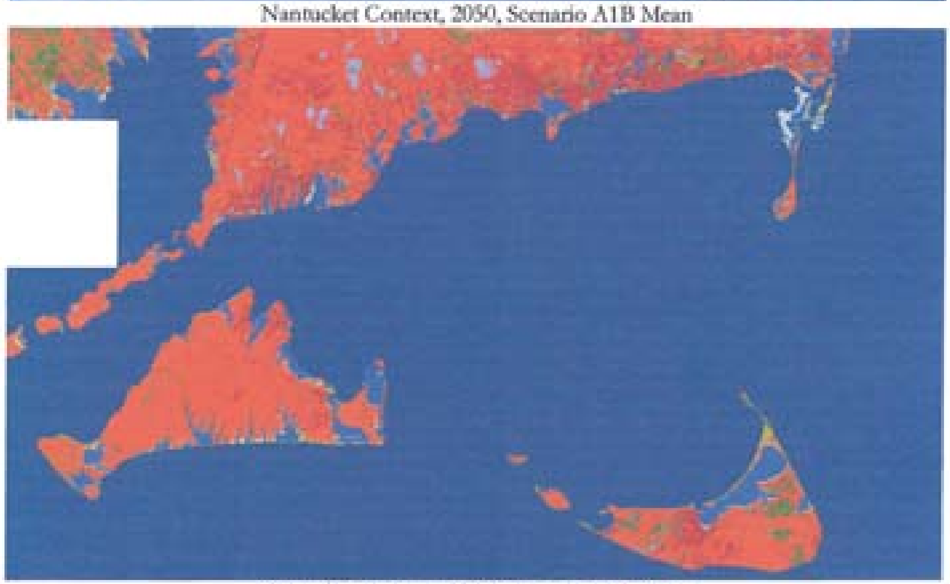
Location of Nantucket National Wildlife Refuge within simulation context

Nantucket Context, Initial Condition

Nantucket Context, 2025, Scenario A1B Mean

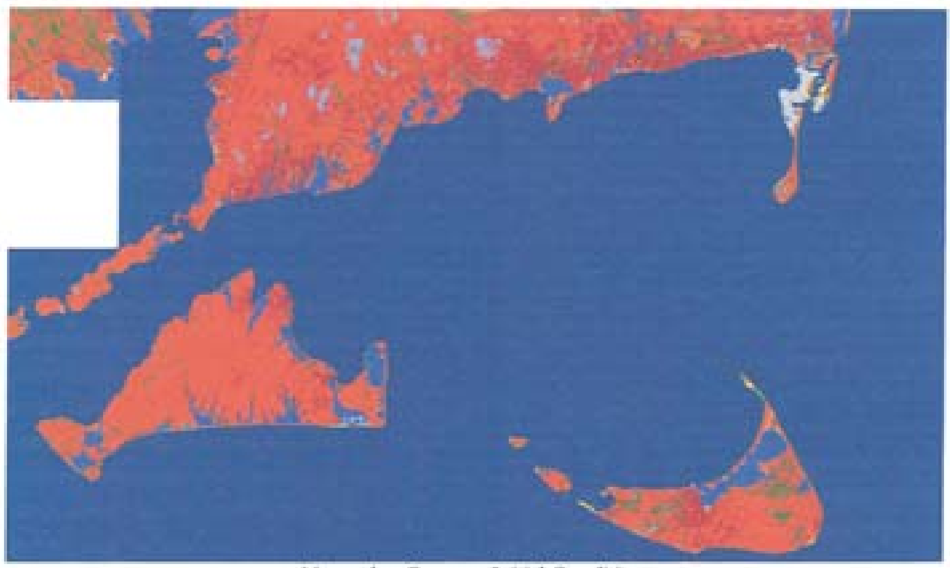


Nantucket Context, 2050, Scenario A1B Mean



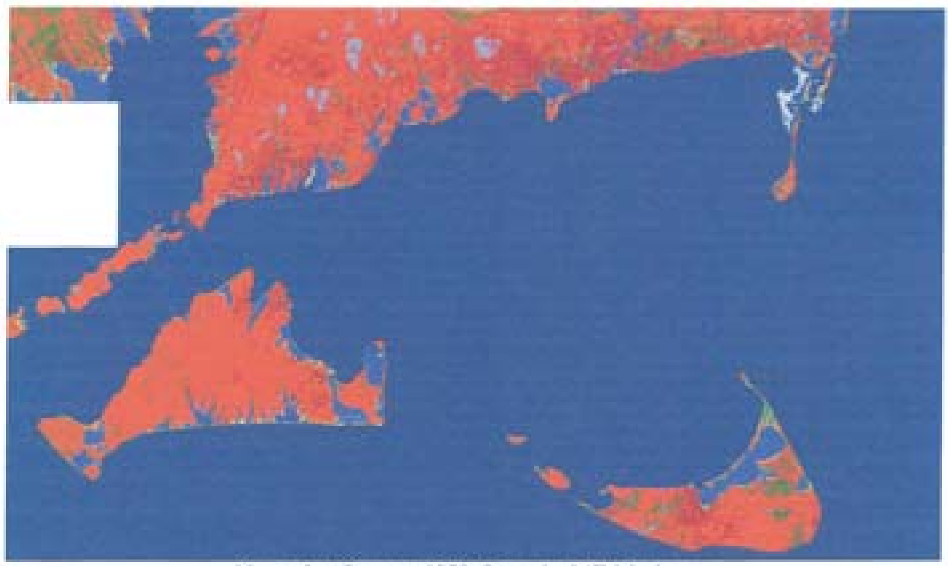
Nantucket Context, 2075, Scenario A1B Mean

Nantucket Context, 2100, Scenario A1B Mean

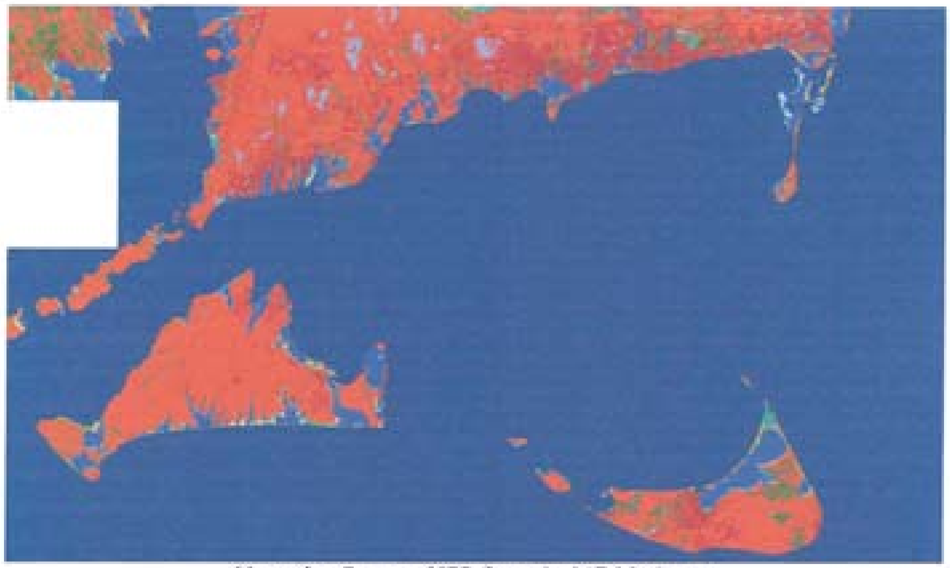


Nantucket Context, Initial Condition

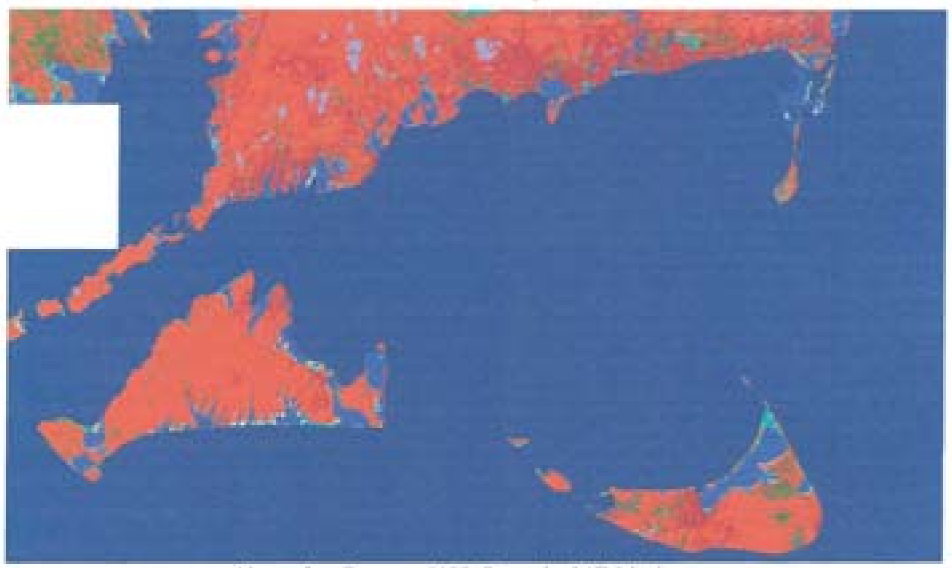
Nantucket Context, 2025, Scenario A1B Maximum



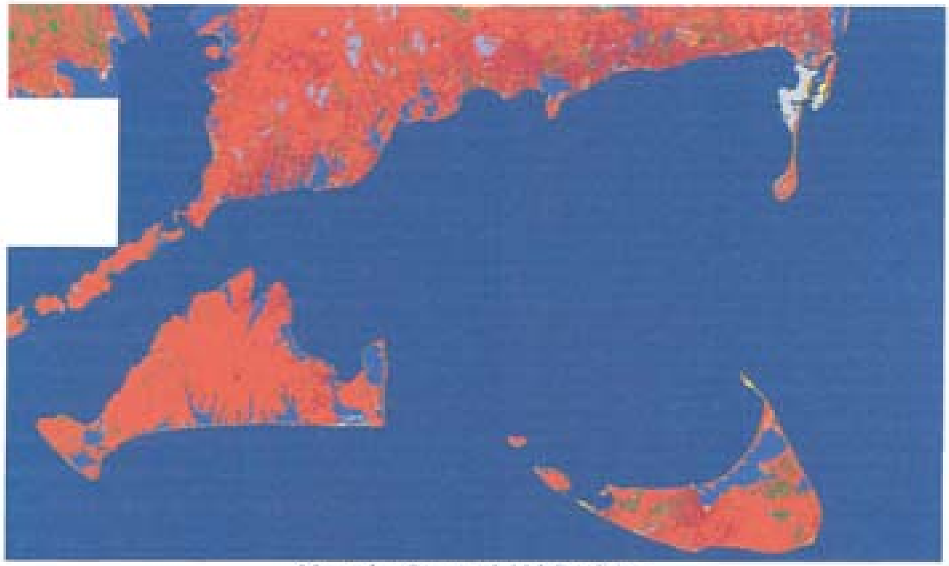
Nantucket Context, 2050, Scenario A1B Maximum



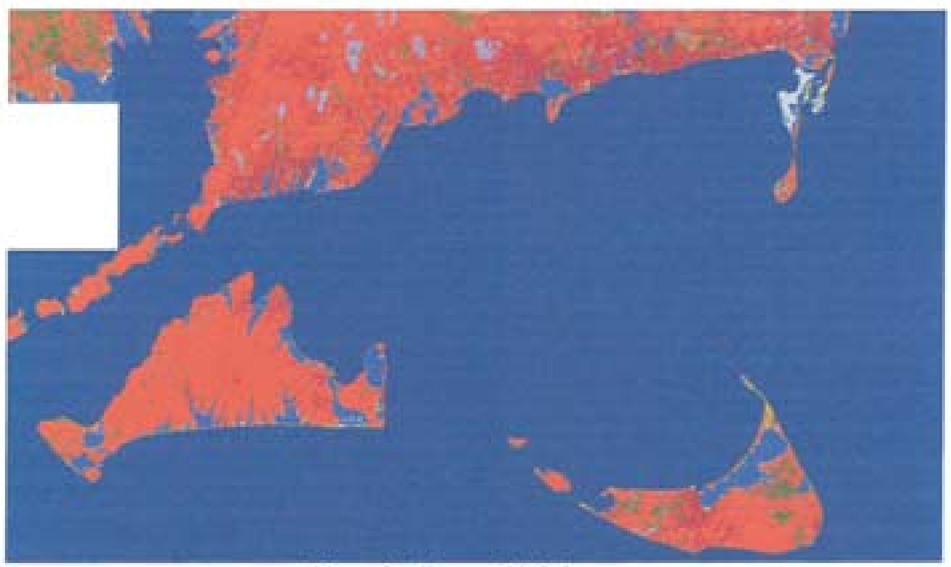
Nantucket Context, 2075, Scenario A1B Maximum



Nantucket Context, 2100, Scenario A1B Maximum

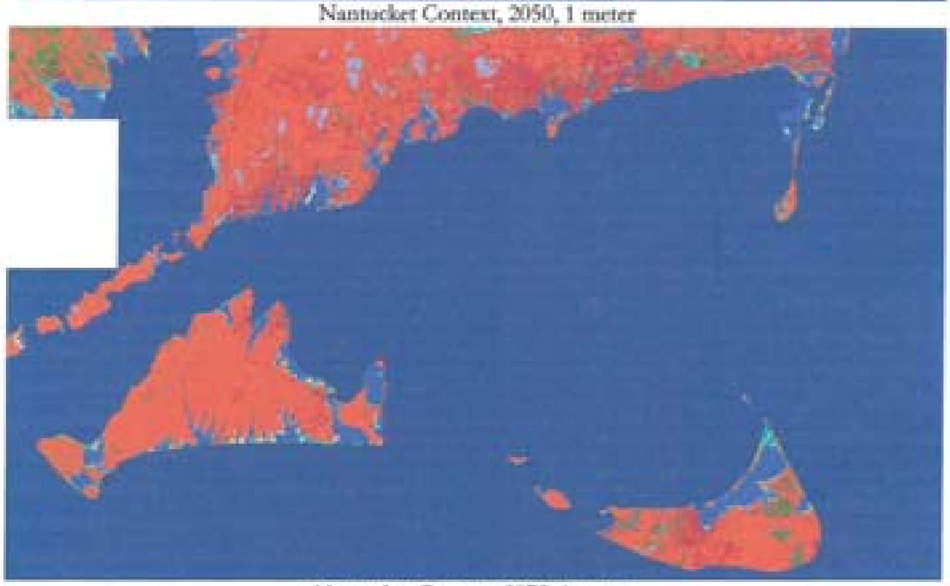


Nantucket Context, Initial Condition

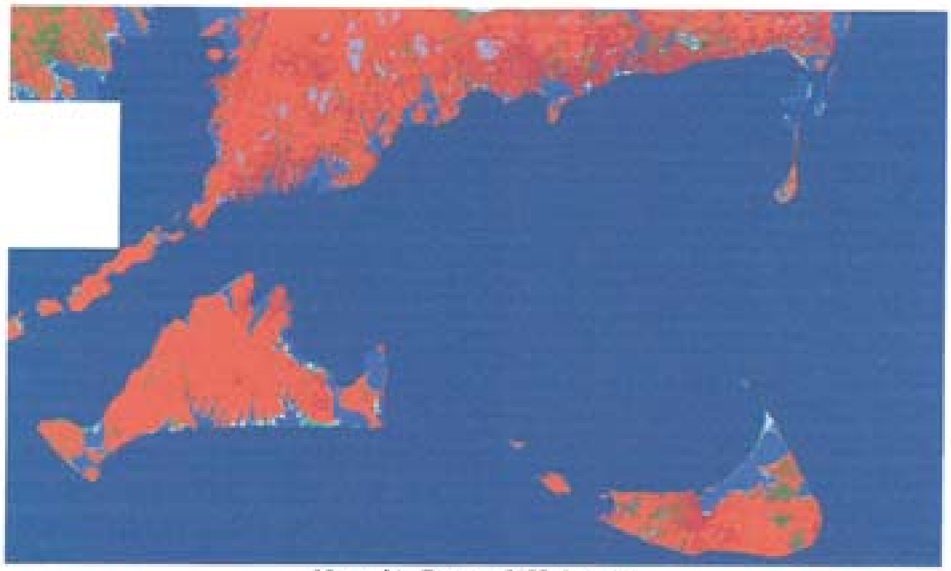


Nantucket Context, 2025, 1 meter

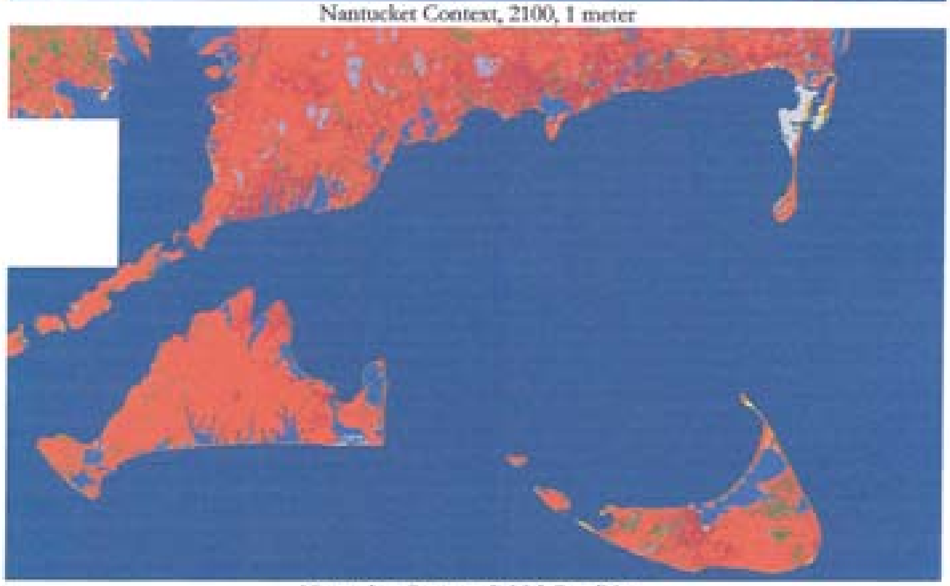
Nantucket Context, 2050, 1 meter



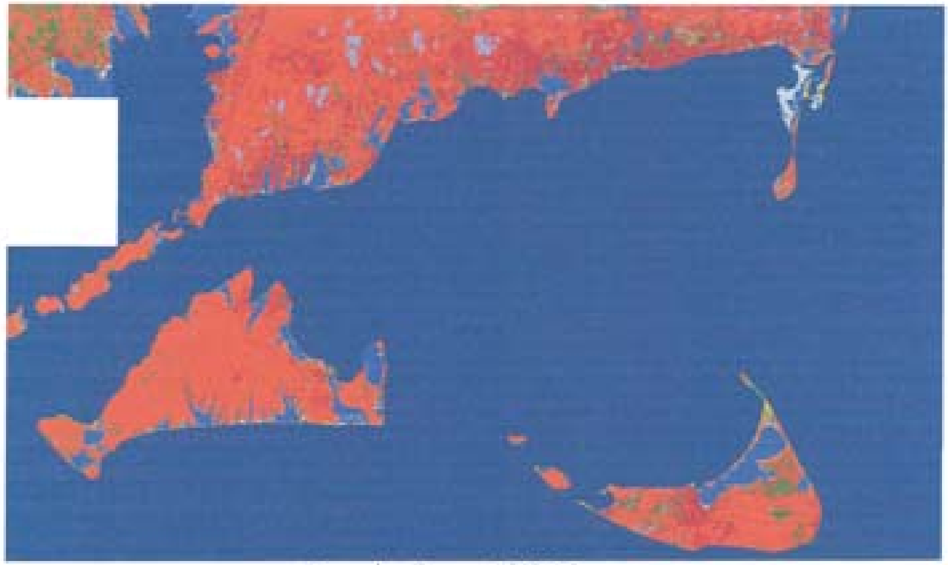
Nantucket Context, 2075, 1 meter



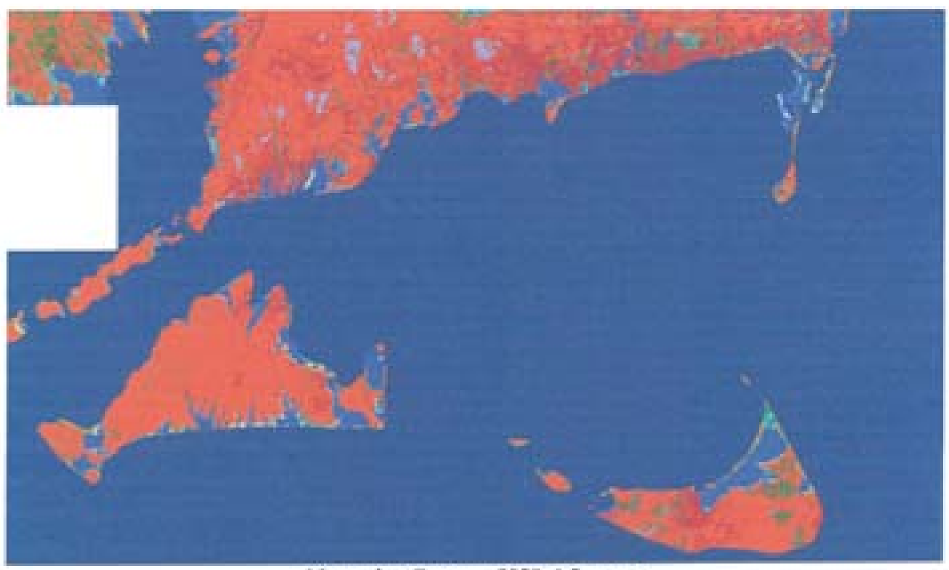
Nantucket Context, 2100, 1 meter



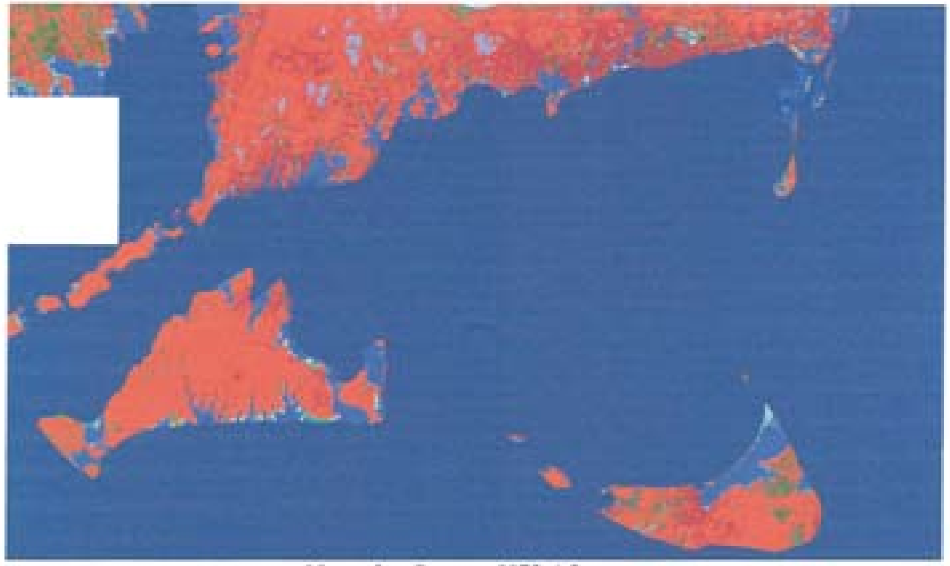
Nantucket Context, Initial Condition



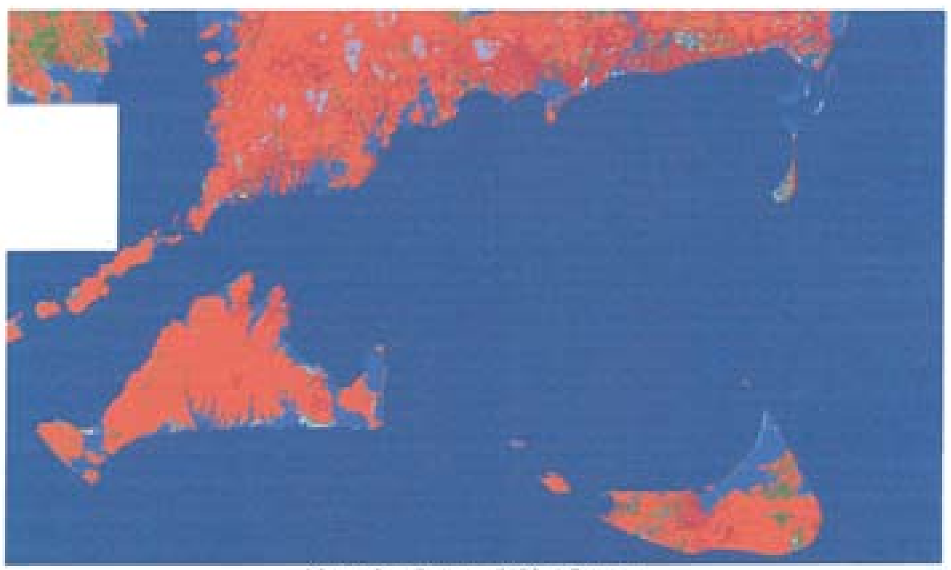
Nantucket Context, 2025, 1.5 meter



Nantucket Context, 2050, 1.5 meter



Nantucket Context, 2075, 1.5 meter



Nantucket Context, 2100, 1.5 meter