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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea-level rise (SLR). The Intergovernmental 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 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat "migration" as salt marshes transgress landward and replace tidal freshwater and irregularly-flooded 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 many coastal 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 6) 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 et al. 1992; Park et al. 1993; Galbraith et al. 2002; National Wildlife Federation & Florida Wildlife Federation 2006; Glick et al. 2007; Craft et al. 2009). The first phase of this work was completed using SLAMM 5, while the second phase simulations were run with SLAMM 6.

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 specified interval for large 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 or can be specified to respond to feedbacks such as frequency of flooding.

SLAMM Version 6.0 was developed in 2008/2009 and is based on SLAMM 5. SLAMM 6.0 provides backwards compatibility to SLAMM 5, that is, SLAMM 5 results can be replicated in SLAMM 6. However, SLAMM 6 also provides several optional capabilities.

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback will be used in USFWS simulations, but only where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations.
- Integrated Elevation Analysis: SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.
- Flexible Elevation Ranges for land categories: If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations, the use of values outside of SLAMM defaults is rarely utilized. If such a change is made, the change and the reason for it are fully documented within the model application reports.
- Many other graphic user interface and memory management improvements are also part of the new version including an updated *Technical Documentation*, and context sensitive help files.

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough et al. 2010). 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 (Council for Regulatory Environmental Modeling 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

Forecast simulations used scenario A1B from the Special Report on Emissions Scenarios (SRES) – mean and maximum estimates. The A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy sources will be balanced across all sources. Under the A1B scenario, the IPCC WGI

Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 to 0.48 meters of sea level rise by 2090-2099 "excluding future rapid dynamical changes in ice flow." The A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 meters of global sea level rise by 2100. A1B-maximum predicts 0.69 meters of global SLR by 2100.

The latest 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 the 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 of 50 to 140 cm. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf 2009). Pfeffer et al. (2008) suggests that 2 meters by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. 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." (Clark 2009) A recent paper by Grinsted et al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario..." Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

To allow for flexibility when interpreting the results, SLAMM was also run assuming 1 meter, $1\frac{1}{2}$ meters, and 2 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

Key West NWR is located in the Southern Gulf of Mexico adjacent to Great White Heron NWR, as shown in Figure 2. Great White Heron NWR was recently modeled using SLAMM6 by the Gulf of Mexico Alliance through a grant from the Gulf of Mexico Foundation, Inc. to support the Habitat Conservation and Restoration Priority Issue Team, a part of the Governor's Gulf of Mexico Alliance. The application of SLAMM to Great White Heron NWR included model hindcasting (calibration) and elevation uncertainty analysis. Because of their close proximity, this SLAMM analysis of Key West NWR was carried out using the model calibrated to Great White Heron NWR as well as information learned about the Florida Keys through that implementation of the SLAMM model.



Figure 2. Key West National Wildlife Refuge study area (boundary shown in red). It is adjacent to Great White Heron NWR and National Key Deer NWR

Elevation data utilized were 1971 1/3-Arc Second National Elevation Dataset data (contour) data. However, the entire refuge is located below the lowest contour of these five-foot contour data. Because LiDAR data were not available for this site, the elevation pre-processor module of SLAMM was used to assign elevations for wetlands as a function of the local tide range. For a more in-depth description of the elevation preprocessor, see the SLAMM 6 technical documentation (Clough et al.

2010). This process causes additional uncertainty in model results as covered in the *Discussion* section below.

The National Wetlands Inventory for the study area was fairly recently updated and is based on 2009 photography. Converting the NWI survey into 10 meter cells indicated that the approximately 128,048 acres of the refuge included in this study (approved acquisition boundary including water) are composed of the following categories:

Land cover type	Area (acres)	Percentage (%)
Open Ocean	76,569	60
Estuarine Open Water	27,005	21
Tidal Flat	21,742	17
Mangrove	2,372	2
Irregularly Flooded Marsh	117	< 1
Regularly Flooded Marsh	89	< 1
Estuarine Beach	86	< 1
Ocean Beach	68	< 1
Total (incl. water)	128,048	100

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Table L. Land-cover	categories and tr	ieir adundance Key	V WEST INWK ACCOR	ling to the 2004 in will laver
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According to the National Wetland Inventory, there were no impounded or diked areas within Key West NWR.

The closest tidal NOAA tidal gauge station to Key West NWR is located at Key West (gauge #8724580), as presented in Figure 4.

The historic trend for sea level rise was estimated to be 2.24 mm/year. This rate was measured at Key West NOAA gauge #8724580 and is only slightly higher than the global average for the last 100 years (approximately 1.5-2.0 mm/year). Within SLAMM relative sea level change is estimated as the sum of the historic eustatic trend, the site-specific rate of change of elevation due to subsidence, and the accelerated rise depending on the scenario chosen (IPCC 2001; Titus et al. 1991).

Two values of great diurnal tide range (GT) were applied to Key West NWR. The Western portion of the refuge (subsite 1 shown in Figure 3) was assigned a GT of 0.51 m. The Eastern side (subsite 2) was assigned a GT of 0.55 m, reflecting the average of the stations on the eastern half of the refuge shown in Figure 4.



Figure 3. Input Subsites



Figure 4. Great Diurnal Tide values(m) taken from Key West NOAA Gauge #8724580 (green balloon), NOAA tide predictions (pink balloons), and USGS tide data (red and black balloons)

The "salt elevation" parameter within SLAMM designates the boundary between coastal wetlands and dry lands or fresh water wetlands. An estimate of this elevation may be derived by examining historical tide gauge data to determine how frequently different elevations are flooded with ocean water. For this application, the salt boundary was defined as the elevation above which inundation is predicted less than once each thirty days. This elevation was derived using data from the gauge at Key West. Based on this frequency-of-inundation analysis SLAMM mean high water spring (MHWS) was estimated at 180% of MHHW. This resulted in the salt elevation parameter being set to 0.459 m above MTL for subsite 1 and 0.496 m above MTL for subsite 2.

Accretion rates for mangrove were set to 3.3 mm/year based on the results of a study performed using Cesium-137 dating in nearby Lignumvitae Key and Plantation Key (Callaway et al. 1997). The Callaway study makes a distinction between red mangrove, which grows along the lowest edges of the wetland, and black mangrove, which grows in the interior of mangrove swamps. Red mangroves are found to have higher average accretion rate than black mangrove. SLAMM does not make a distinction between black and red mangrove, so the average of red and black mangrove accretion rates was used to produce a rate of 3.3 mm/year.

Changes were made to calibrate SLAMM when applying it to neighboring Great White Heron NWR. Beach sedimentation rates were increased from the SLAMM default of 0.5 mm/year to 1 mm/year and tidal flat erosion rates reduced from 0.5 mm/year to 0.1 mm/year. This change improved model results after initial hindcast calibrations predicted more beach loss than was observed at Great White Heron NWR.

In addition, an analysis of wetland elevations in Great White Heron NWR using current LiDAR data indicated mangroves at this site were found to inhabit an elevation range below mean-tide level. For example, the 5th percentile of elevation (in half-tide units, or HTU) for mangrove was -0.63, as opposed to the model default minimum elevation of 0 (mean tide level). When applied to Great White Heron the minimum elevation within the model was changed to -0.63 HTU to reflect the range of mangroves observed at that site. Because of its proximity to Great White Heron NWR, the same modification of the SLAMM conceptual model was made for application to Key West NWR.

The MTL to NAVD88 correction was set to -0.270 m, which was derived using data from the Key West NOAA gauge #8724580.

The cell-size used for this analysis was 10 meter by 10 meter cells. SLAMM will also track partial conversion of cells based on elevation and slope.

Description	Subsite 1	Subsite 2
NWI Photo Date (YYYY)	2009	2009
DEM Date (YYYY)	1971	1971
Direction Offshore [n,s,e,w]	South	South
Historic Trend (mm/yr)	2.24	2.24
MTL-NAVD88 (m)	-0.27	-0.27
GT Great Diurnal Tide Range (m)	0.51	0.551
Salt Elev. (m above MTL)	0.459	0.496
Marsh Erosion (horz. m /yr)	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1
T.Flat Erosion (horz. m /yr)	0.1	0.1
RegFlood Marsh Accr (mm/yr)	3.9	3.9
IrregFlood Marsh Accr (mm/yr)	4.7	4.7
Tidal-Fresh Marsh Accr (mm/yr)	5.9	5.9
Inland-Fresh Marsh Accr (mm/yr)	0	0
Mangrove Accr (mm/yr)	3.3	3.3
Tidal Swamp Accr (mm/yr)	0	0
Swamp Accretion (mm/yr)	0	0
Beach Sed. Rate (mm/yr)	1	1
Freq. Overwash (years)	4	4
Use Elev Pre-processor [True,False]	TRUE	TRUE

Table 2. Summary of SLAMM Parameters applied to Key West NWR

Results

SLAMM simulations predict Key West NWR will be severely impacted under all the SLR scenarios tested.

Table 3 presents the predicted loss of each wetland category by 2100 for each of the five SLR scenarios examined. 17% of the area of Key West NWR is composed of tidal flat. Tidal flat is predicted to completely inundated by 2100 under every SLR scenario examined. Mangroves are the second-most common land cover type in the refuge and at 1 meter of SLR by 2100, a level that some scientists consider to be the "most likely" scenario", 99% of the refuge mangroves are predicted to be lost. Conversely, under the A1B mean scenario (0.39 m SLR by 2100), only 19% of the mangroves in the refuge are predicted to be lost. In addition, all of the irregularly-flooded marsh appears resilient to the A1B mean scenario but nearly 75% is predicted to be lost by 2100 under the A1B max scenario (0.69 m SLR by 2100).

At of SLR rates of 1 m by 2100 and higher, the entire refuge is predicted to convert to open water.

Land an and a second	Loss Rates by 2100 for different SLR scenarios							
Land cover category	0.39 m	0.69 m	1 m	1.5 m	2 m			
Tidal Flat	100%	100%	100%	100%	100%			
Mangrove	19%	64%	99%	100%	100%			
Irregularly Flooded Marsh	0%	74%	100%	100%	100%			
Regularly Flooded Marsh	22%	99%	98%	100%	100%			
Estuarine Beach	-34% (gain)	67%	100%	100%	100%			
Ocean Beach	91%	100%	100%	100%	100%			

Table 3. Predicted Loss Rates of Land Categories by 2100 Given Simulated Scenarios of Eustatic Sea Level Rise.

Key West NWR IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

		Initial	2025	2050	2075	2100
Open Ocean	Open Ocean	76569	76573	76600	76617	76631
	Estuarine Open Water	27005	31073	43233	48471	49157
	Tidal Flat	21742	17679	5563	515	36
	Mangrove	2372	2370	2252	2086	1917
	Irregularly Flooded Marsh	117	117	117	117	117
	Regularly Flooded Marsh	89	89	76	74	69
	Estuarine Beach	86	84	171	148	116
	Ocean Beach	68	64	37	20	6

Results in Acres



Key West NWR, Initial Condition



Key West NWR, 2025, Scenario A1B Mean



Key West NWR, 2050, Scenario A1B Mean



Key West NWR, 2075, Scenario A1B Mean



Key West NWR, 2100, Scenario A1B Mean

Key West NWR IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

	Results in Acres					
		Initial	2025	2050	2075	2100
Open Ocean	Open Ocean	76569	76577	76613	76637	76637
	Estuarine Open Water	27005	34723	48575	49783	50447
	Tidal Flat	21742	14074	610	78	63
	Mangrove	2372	2328	1912	1367	842
	Irregularly Flooded Marsh	117	117	104	69	30
	Regularly Flooded Marsh	89	88	62	29	1
	Estuarine Beach	86	81	148	85	28
	Ocean Beach	68	60	24	0	0
	Total (incl. water)	128048	128048	128048	128048	128048

Key West NWR, Initial Condition



Key West NWR, 2025, Scenario A1B Maximum



Key West NWR, 2050, Scenario A1B Maximum



Key West NWR, 2075, Scenario A1B Maximum



Key West NWR, 2100, Scenario A1B Maximum

Key West NWR 1 m eustatic SLR by 2100

	Results in Acres					
		Initial	2025	2050	2075	2100
Open Ocean	Open Ocean	76569	76581	76628	76637	76637
	Estuarine Open Water	27005	38765	49583	50586	51368
	Tidal Flat	21742	10142	74	64	8
	Mangrove	2372	2231	1534	727	32
	Irregularly Flooded Marsh	117	113	70	2	0
	Regularly Flooded Marsh	89	83	36	0	2
	Estuarine Beach	86	77	115	32	0
	Ocean Beach	68	56	9	0	0

Key West NWR, Initial Condition



Key West NWR, 2025, 1 m



Key West NWR, 2050, 1 m



Key West NWR, 2075, 1 m



Key West NWR, 2100, 1 m

Key West NWR 1.5 m eustatic SLR by

Results in Acres Initial Open Ocean Estuarine Open Water Tidal Flat Mangrove Irregularly Flooded Marsh Regularly Flooded Marsh Estuarine Beach Ocean Beach Total (incl. water)



Key West NWR, Initial Condition



Key West NWR, 2025, 1.5 m



Key West NWR, 2050, 1.5 m



Key West NWR, 2075, 1.5 m



Key West NWR, 2100, 1.5 m

Key West NWR 2 m eustatic SLR by 2100

		Initial	2025	2050	2075	2100
Open Ocean	Open Ocean	76569	76596	76637	76637	76637
	Estuarine Open Water	27005	48393	50831	51399	51411
	Tidal Flat	21742	915	108	12	0
	Mangrove	2372	1894	447	0	0
	Irregularly Flooded Marsh	117	83	0	0	0
	Regularly Flooded Marsh	89	59	0	0	0
	Estuarine Beach	86	66	25	0	0
	Ocean Beach	68	41	0	0	0
	Total (incl. water)	128048	128048	128048	128048	128048

Results in Acres



Key West NWR, Initial Condition



Key West NWR, 2025, 2 m



Key West NWR, 2050, 2 m



Key West NWR, 2075, 2 m



Key West NWR, 2100, 2 m

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Discussion

The application of SLAMM to Key West NWR indicates the effects of sea-level rise on this refuge will be severe. The refuge is "microtidal" in nature, with an average range of tide around 0.5 m (1.5-1.7 feet). This means that wetlands for this site are predicted to occupy a narrow elevation range and be more prone to adverse effects from SLR. In addition, the majority of the land in the reserve is tidal flat which has a limited elevation range.

An important source of model uncertainty is the accretion rate for vegetation. The accretion rate for mangroves in Key West NWR was assumed to be 3.3 mm/yr based on a study of mangroves in Lignumvitae and Plantation Keys which lie approximately 100 miles west of the refuge (Callaway et al 1997). Since this rate of accretion is lower than the lowest SLR scenario (0.39 m by 2100) some mangroves in Key West NWR are predicted to be lost under every SLR scenario examined.

The best available elevation data for this site were derived from five foot USGS contours created in 1971. Estimates of land elevations below the five foot contour are quite uncertain. The SLAMM pre-processor was utilized to estimate elevation ranges for all of the wetlands at this site as a function of tide range and known relationships between wetland types and tide ranges. However, wetland elevations were assumed to be uniformly distributed over their feasible vertical elevation ranges or "tidal frames"—an assumption that may not reflect reality. If wetlands elevations are actually clustered high in the tidal frame they would be less vulnerable to SLR. If wetlands are towards the bottom, they would be more vulnerable. LiDAR data for the site would assist in reducing model uncertainty in this manner. However, given the short height of the tidal frame (low tidal elevation range), wetlands are likely to be overwhelmed by most scenarios of eustatic SLR regardless of their initial condition elevations.

Although somewhat uncertain, model results shed some light on the potential timing of land loss in Key West NWR. Under the A1B mean scenario, 98% of the tidal flat is predicted to be lost by 2075, whereas under the 2m scenario 96% is predicted to be lost by 2025. Under the 1 m scenario, which some scientists consider the "most probable", the majority of the refuge is predicted to be inundated by 2075 with less than half of the original mangrove and beach still remaining.

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