remote sensing

MDPI

Supplementary Information for:

Short-term Ecogeomorphic Evolution of a Fluvial Delta from Hindcasting Intertidal Marsh-top Elevations (HIME)

Brittany C. Smith [1], Kevan B. Moffett [2,*], and David Mohrig [3]

[1] Princeton Hydro, 1108 Old York Road, PO Box 720, Ringoes, NJ, 08551, USA; xyzsmith@gmail.com
[2] School of the Environment, Washington State University, 14204 NE Salmon Creek Avenue, Vancouver, WA, 98686, USA; kevan.moffett@wsu.edu
[3] Department of Geological Sciences, The University of Texas at Austin, 2275 Speedway Stop C9000, Austin, TX, 78712 – 1722, USA; mohrig@jsg.utexas.edu
* Correspondence: e- kevan.moffett@wsu.edu

S1. Regression Model Results

S1.1. LIDAR data, processing, and HIME validation

S1.1.1. Details of converting LIDAR elevation data to an exposure probability map

The LIDAR survey [1] was flown by the National Center for Airborne Laser Mapping (NCALM) during local hours 9:03-13:56 on Jan 14 and hours 12:46-17:23 on Jan 15, 2009. The survey report noted low tide at 10:30 on Jan 14 and 11:20 on Jan 15 in Atchafalaya Bay (Rabbit Island). An Optech GEMINI Airborne Laser Terrain Mapper (ALTM) recorded return intensity data (1047 nm laser wavelength) with 12-bit dynamic range. The survey report noted a resolution of 4.5 points per square meter over land and much higher recovered point density over land than water. The planned overlap of the data from adjacent flight lines was 100%, 50% per side. Due to failure of automated calibration software over the very flat terrain, data were calibrated manually in two ways: by comparison among flight strips and by comparison to 954 ground GPS points surveyed over 1.3 kilometers of a nearby highway. Estimated vertical accuracy after calibration was 0.055 m. Points at the fringes of the scan lines, at angles greater than 4.0 degrees, were eliminated to limit propagation of small errors in pitch, roll, and scanner mirror angle measurements. TerraSolid's TerraScan software was used to remove vegetation and create a bare-earth dataset. Reported data were NAVD88 orthometric heights on NGS GEOID03. The regular pattern of high and low marsh surfaces in the LIDAR data (Figure S2c,d) corresponded to variability associated with the width of each flight path, and additional noise in the data resulted from signal reflection from the water and changes in signal over the time of the flight survey.

The LIDAR topographic survey was converted into an exposure probability map in five steps. First, the LIDAR data set was masked to remove submerged areas (apparent as water surface elevations) using a vectorized land outline created from an aerial photo taken in 2009 at a similar water level to that represented in the LIDAR survey. Second, mean local surface water level (MLW) above NAVD88 was calculated for each LIDAR pixel using the mean water level at the gage station, the surface water slope down-delta from the gage station, and the LIDAR pixel's distance from the delta apex. The distance was calculated as the distance along the channel from the delta apex to the northernmost tip of Pintail Island plus the straight line distance from the island tip to the pixel. This approach to calculating distance was justified for calculating the MLW in the channel around the island, which was the parameter required (not the cross-island gradient or flow path). Third, each MLW value was subtracted from each corresponding LIDAR point, converting the LIDAR data to land surface elevations above MLW. Fourth, the normal CDF of surface water level variations (F_Y) was also adjusted to MLW by subtracting the mean, so that the adjusted distribution had a mean of

0 and retained a standard deviation of 0.179. Fifth, for each value in the LIDAR-derived map of land surface elevation above MLW, the probability of non-exceedance by surface water flooding was calculated directly from this water level CDF. The resulting map is referred to as the "LIDAR 2009 exposure probability map" (Figure 3a) since the probability of non-exceedance is equivalent to the probability of exposure under the water level regime captured by the Camp Island gage period of record and the 2009 LIDAR topography acquisition.

S1.1.2. Results of HIME : LIDAR linear regression validation analysis for Pintail Island

Linear regression model (zero intercept): y ~ x

x = probability of exposure derived from 2009 LIDAR survey data [m NAVD88]

y = HIME probability of exposure, 2008-2010 timeframe, Pintail Island [m NAVD88]

```
Estimated Coefficients:
              Estimate       SE        tStat       pValue
        x1    0.98989     0.016226    61.007    2.2179e-20

    Number of observations:        17
    Error degrees of freedom:      16
    Root Mean Squared Error:       0.047
    Ordinary R-squared:            0.9630
    Adjusted R-squared:            0.9630
    Mean Absolute Error:           0.0350
    Mean Absolute Percent Error:   6.2%
```

S1.2. Results of regression models to predict WLD elevations from WLD geometric factors

Best-fit linear regression models to predict Wax Lake Delta marsh-top elevations (meters) from up to four contributing factors.

Results generated using MATLAB v.R2017a.

Linear regression results for each timeframe were generated using the code:

```
mdl = stepwiselm([factors], elevations, ...
    'constant', 'Upper', 'linear', 'Criterion', 'AIC');
ANOVA(mdl,'summary')
ANOVA(mdl)
```

Linear regression model: y ~ 1 + x1 + x2 + x3 + x4

Factors:

x1 = distance to delta apex (km)

x2 = distance to island apex (km)

x3 = distance to island edge (km), i.e., distance to channel

x4 = distance to island midline (km)

Results:

<u>Timeframe: 1993-1995</u>

```
Estimated Coefficients:
                       Estimate        SE         tStat       pValue
                       _________    __________    _______    __________

    (Intercept)          0.67015     0.0022028     304.22             0
    x1                  -0.10066    0.00042486    -236.93             0
    x2                 -0.020517    0.00055473    -36.985     9.054e-295
    x3                 -0.010835     0.0023764    -4.5595      5.141e-06
    x4                   0.02314     0.0017401     13.298     2.8446e-40

Number of observations: 42720, Error degrees of freedom: 42715
Root Mean Squared Error: 0.116
R-squared: 0.734,  Adjusted R-Squared 0.734
F-statistic vs. constant model: 2.95e+04, p-value = 0

ANOVA for fitted model
                    SumSq      DF       MeanSq       F      pValue
                    ______    _____    ________    _____    ______

        Total       2160.8    42719    0.050582
        Model       1586.8        4       396.7    29520      0
        Residual    574.01    42715    0.013438

ANOVA for model terms
                  SumSq      DF       MeanSq       F         pValue
                 _______    _____    ________    ______    __________

        x1        754.38        1      754.38     56137             0
        x2        18.382        1      18.382    1367.9    9.054e-295
        x3       0.27937        1     0.27937    20.789     5.141e-06
        x4        2.3765        1      2.3765    176.85    2.8446e-40
        Error     574.01    42715    0.013438
```

<u>Timeframe: 1996-1998</u>

```
Estimated Coefficients:
                       Estimate        SE         tStat       pValue
                       _________    __________    _______    ___________

    (Intercept)          0.68328      0.002115     323.06              0
    x1                 -0.096727    0.00041784    -231.49              0
    x2                 -0.017477    0.00054784    -31.901    7.5691e-221
```

```
        x3              -0.014094      0.0022179     -6.3546      2.1102e-10
        x4               0.021346       0.001657      12.883      6.5828e-38

    Number of observations: 44981, Error degrees of freedom: 44976
    Root Mean Squared Error: 0.117
    R-squared: 0.728,  Adjusted R-Squared 0.728
    F-statistic vs. constant model: 3e+04, p-value = 0

ANOVA for fitted model
                    SumSq      DF       MeanSq       F      pValue
                    ______    _____    ________    _____    ______

        Total       2255.7    44980    0.050149
        Model       1641.1        4      410.29    30027      0
        Residual    614.55    44976    0.013664

ANOVA for model terms
                  SumSq      DF       MeanSq        F          pValue
                 _______    _____    ________    ______    ___________

        x1        732.25        1      732.25     53590              0
        x2        13.906        1      13.906    1017.7    7.5691e-221
        x3       0.55176        1     0.55176     40.38     2.1102e-10
        x4        2.2677        1      2.2677    165.96     6.5828e-38
        Error     614.55    44976    0.013664
```

Timeframe: 1999-2001

```
Estimated Coefficients:
                       Estimate         SE         tStat        pValue
                       _________    __________    _______    ___________

        (Intercept)      0.73829     0.0021555     342.51              0
        x1             -0.096211    0.00042515     -226.3              0
        x2             -0.017972    0.00054783    -32.805    1.7932e-233
        x3             0.0053102     0.0021953     2.4189       0.015571
        x4              0.011535     0.0017296     6.6695     2.5948e-11

    Number of observations: 48529, Error degrees of freedom: 48524
    Root Mean Squared Error: 0.124
    R-squared: 0.684,  Adjusted R-Squared 0.684
    F-statistic vs. constant model: 2.63e+04, p-value = 0

ANOVA for fitted model
                    SumSq      DF       MeanSq       F      pValue
                    ______    _____    ________    _____    ______

        Total       2362.8    48528     0.04869
        Model       1616.5        4      404.11    26272      0
        Residual     746.4    48524    0.015382

ANOVA for model terms
                  SumSq       DF       MeanSq        F          pValue
                 ________    _____    ________    ______    ___________

        x1         787.75        1      787.75     51212              0
        x2         16.554        1      16.554    1076.2    1.7932e-233
        x3       0.090002        1    0.090002    5.8511       0.015571
        x4        0.68422        1     0.68422    44.482     2.5948e-11
        Error       746.4    48524    0.015382
```

Timeframe: 2002-2004

```
Estimated Coefficients:
                       Estimate         SE         tStat       pValue
                       _________    __________    _______    __________

        (Intercept)      0.88332     0.0024162     365.58             0
        x1              -0.11848    0.00046513    -254.73             0
```

```
        x2              -0.024671    0.00060448    -40.813             0
        x3              -0.027273     0.0025405    -10.735    7.4378e-27
        x4               0.023238     0.0019669     11.815    3.6252e-32

    Number of observations: 50044, Error degrees of freedom: 50039
    Root Mean Squared Error: 0.14
    R-squared: 0.733,  Adjusted R-Squared 0.733
    F-statistic vs. constant model: 3.43e+04, p-value = 0

ANOVA for fitted model
                    SumSq      DF        MeanSq       F      pValue
                    ______    _____    ________    _____    ______

        Total       3661.4    50043    0.073164
        Model         2683        4      670.75    34306      0
        Residual    978.35    50039    0.019552

ANOVA for model terms
                 SumSq      DF       MeanSq       F         pValue
                 ______    _____    ________    ______    __________

        x1       1268.6        1      1268.6     64886             0
        x2       32.568        1      32.568    1665.7             0
        x3       2.2533        1      2.2533    115.25    7.4378e-27
        x4       2.7291        1      2.7291    139.58    3.6252e-32
        Error    978.35    50039    0.019552
```

<u>Timeframe: 2005-2007</u>

```
Estimated Coefficients:
                      Estimate          SE         tStat       pValue
                     _________    __________    _______    __________

        (Intercept)     0.89265      0.002454     363.75             0
        x1             -0.11841     0.0004785    -247.47             0
        x2            -0.030325    0.00059775    -50.731             0
        x3            -0.020106     0.0024943    -8.0611    7.7152e-16
        x4             0.006853     0.0019467     3.5204    0.00043132

    Number of observations: 53719, Error degrees of freedom: 53714
    Root Mean Squared Error: 0.148
    R-squared: 0.738,  Adjusted R-Squared 0.738
    F-statistic vs. constant model: 3.78e+04, p-value = 0

ANOVA for fitted model
                    SumSq      DF        MeanSq       F      pValue
                    ______    _____    ________    _____    ______

        Total       4486.9    53718    0.083526
        Model       3311.4        4      827.86    37831      0
        Residual    1175.4    53714    0.021883

ANOVA for model terms
                   SumSq      DF       MeanSq       F         pValue
                 _______    _____    ________    ______    __________

        x1        1340.1        1      1340.1     61240             0
        x2        56.319        1      56.319    2573.6             0
        x3         1.422        1       1.422    64.981    7.7152e-16
        x4       0.27119        1     0.27119    12.393    0.00043132
        Error     1175.4    53714    0.021883
```

<u>Timeframe: 2008-2010</u>

```
    Estimated Coefficients:
                      Estimate          SE         tStat       pValue
                     _________    __________    _______    ___________

        (Intercept)     0.80925     0.0028549     283.46              0
```

x1	-0.10934	0.00055133	-198.32	0
x2	-0.020581	0.00071038	-28.972	6.3043e-183
x3	-0.02356	0.0031139	-7.5661	3.9154e-14
x4	0.066391	0.0024099	27.549	9.7406e-166

Number of observations: 46542, Error degrees of freedom: 46537
Root Mean Squared Error: 0.158
R-squared: 0.626, Adjusted R-Squared 0.626
F-statistic vs. constant model: 1.95e+04, p-value = 0

ANOVA for fitted model

	SumSq	DF	MeanSq	F	pValue
Total	3105.4	46541	0.066724		
Model	1944.2	4	486.05	19479	0
Residual	1161.2	46537	0.024953		

ANOVA for model terms

	SumSq	DF	MeanSq	F	pValue
x1	981.43	1	981.43	39331	0
x2	20.945	1	20.945	839.37	6.3043e-183
x3	1.4285	1	1.4285	57.246	3.9154e-14
x4	18.938	1	18.938	758.96	9.7406e-166
Error	1161.2	46537	0.024953		

<u>Timeframe: 2011-2013</u>

Estimated Coefficients:

	Estimate	SE	tStat	pValue
(Intercept)	0.78339	0.0023194	337.75	0
x1	-0.10621	0.00046588	-227.97	0
x2	-0.017908	0.00061135	-29.293	6.4484e-187
x3	0.0066117	0.0026177	2.5258	0.011547
x4	0.04947	0.0019173	25.802	9.1317e-146

Number of observations: 46385, Error degrees of freedom: 46380
Root Mean Squared Error: 0.134
R-squared: 0.701, Adjusted R-Squared 0.701
F-statistic vs. constant model: 2.72e+04, p-value = 0

ANOVA for fitted model

	SumSq	DF	MeanSq	F	pValue
Total	2802.5	46384	0.06042		
Model	1965.8	4	491.45	27241	0
Residual	836.73	46380	0.018041		
. Lack of fit	836.56	46375	0.018039	0.5317	0.90597
. Pure error	0.16964	5	0.033927		

ANOVA for model terms

	SumSq	DF	MeanSq	F	pValue
x1	937.55	1	937.55	51968	0
x2	15.481	1	15.481	858.09	6.4484e-187
x3	0.11509	1	0.11509	6.3796	0.011547
x4	12.01	1	12.01	665.72	9.1317e-146
Error	836.73	46380	0.018041		

2. Supplementary Tables

Table S1. Dates of Landsat imagery compiled for the study, and as divided into consecutive 3-year temporal subsets of images. *Dates used in method development and validation for Pintail Island case (and also 4-Jul-1999 and 17-Nov-2005 used for Pintail Island). All dates in table below used for WLD-wide study.

1993-1995	1996-1998	1999-2001	2002-2004	2005-2007	2008-2010	2011-2013
16-Jan-1993	9-Jan-1996	18-Feb-1999	25-Jan-2002*	1-Jan-2005	27-Feb-2008*	23-Mar-2011
17-Feb-1993	25-Jan-1996	22-Mar-1999	2-Feb-2002	17-Jan-2005*	30-Mar-2008*	24-Apr-2011
5-Mar-1993	13-Mar-1996	23-Apr-1999	10-Feb-2002*	18-Feb-2005	15-Apr-2008*	10-May-2011
22-Apr-1993	30-Apr-1996	5-Aug-1999*	18-Feb-2002	23-Apr-2005	1-May-2008*	26-May-2011
8-May-1993	16-May-1996	21-Aug-1999*	22-Mar-2002	25-May-2005	2-Jun-2008*	11-Jun-2011
9-Jun-1993	17-Jun-1996	6-Sep-1999*	9-May-2002	10-Jun-2005	22-Sep-2008*	27-Jun-2011
25-Jun-1993	19-Jul-1996	22-Sep-1999*	25-May-2002	12-Jul-2005	8-Oct-2008*	30-Aug-2011
27-Jul-1993	23-Oct-1996	24-Oct-1999*	18-Jun-2002*	13-Aug-2005	9-Nov-2008*	15-Sep-2011
12-Aug-1993	8-Nov-1996	9-Nov-1999*	28-Jul-2002	14-Sep-2005	25-Nov-2008*	1-Oct-2011
28-Aug-1993	10-Dec-1996	12-Jan-2000*	5-Aug-2002*	30-Sep-2005*	12-Jan-2009*	2-Nov-2011
29-Sep-1993	11-Jan-1997	29-Feb-2000*	8-Aug-2002*	16-Oct-2005*	1-Mar-2009*	24-Mar-2013
31-Oct-1993	3-May-1997	17-Apr-2000*	29-Aug-2002	5-Feb-2006*	20-May-2009*	29-Mar-2013
8-Mar-1994	4-Jun-1997	19-May-2000*	14-Sep-2002	10-Apr-2006*	8-Aug-2009*	13-Apr-2013
9-Apr-1994	6-Jul-1997	4-Jun-2000*	16-Oct-2002	12-May-2006	24-Aug-2009*	29-Apr-2013
25-Apr-1994	8-Sep-1997	20-Jun-2000*	17-Nov-2002	13-Jun-2006*	12-Nov-2009*	15-May-2013
11-May-1994	27-Nov-1997	24-Sep-2000*	4-Jan-2003	29-Jun-2006	16-Feb-2010*	16-Jun-2013
30-Jul-1994	29-Dec-1997	26-Oct-2000*	20-Jan-2003	31-Jul-2006	8-Jun-2010*	18-Jul-2013
15-Aug-1994	3-Mar-1998	27-Nov-2000*	10-Apr-2003	16-Aug-2006*	24-Jun-2010	3-Aug-2013
19-Nov-1994	4-Apr-1998	29-Dec-2000*	26-Apr-2003	1-Sep-2006*	10-Jul-2010*	4-Sep-2013
7-Feb-1995	20-Apr-1998	19-Mar-2001*	28-May-2003	17-Sep-2006	27-Aug-2010*	7-Nov-2013
12-Apr-1995	6-May-1998	20-Apr-2001	25-Sep-2003*	4-Nov-2006*	12-Sep-2010*	
28-Apr-1995	9-Jul-1998	6-May-2001	28-Nov-2003*	20-Nov-2006*	28-Sep-2010*	
17-Jul-1995	10-Aug-1998	22-May-2001	30-Dec-2003*	6-Dec-2006*	14-Oct-2010*	
2-Aug-1995	13-Oct-1998	9-Jul-2001	16-Feb-2004*	28-Mar-2007*	30-Oct-2010*	
18-Aug-1995		11-Sep-2001	4-Apr-2004*	29-Apr-2007*	1-Dec-2010*	
3-Sep-1995		27-Sep-2001	6-May-2004*	16-Jun-2007*		
5-Oct-1995		29-Oct-2001	22-May-2004*	2-Jul-2007*		
21-Oct-1995		30-Nov-2001	25-Jul-2004*	3-Aug-2007*		
6-Nov-1995			10-Aug-2004*	19-Aug-2007		
22-Nov-1995			11-Sep-2004*	4-Sep-2007*		
24-Dec-1995			27-Sep-2004*	20-Sep-2007*		
			13-Oct-2004*			
			29-Oct-2004*			
			16-Dec-2004 *			

Table S2. Dates of tropical storms and hurricanes passing within 200 km of Morgan City, LA, near the Wax Lake Delta, according to information at https://coast.noaa.gov/hurricanes/ (accessed 18-April-2020). For hurricanes, highest category rating while within 200 km of Morgan City is indicated.

Date	Type	Event
1942		*Wax Lake Delta Outlet Channel Constructed*
26-Aug-1992	Hurricane	Andrew – Category 4
16-Jan-1993		*Start of This Study's Period*
18-Jul-1997	Hurricane	Danny – Category 1
17-Sep-1998	Tropical Storm	Hermine
4-Jun-2011	Tropical Storm	Allison
4-Aug-2002	Tropical Storm	Bertha
23-Sep-2002	Hurricane	Isidore - Tropical Storm
3-Oct-2002	Hurricane	Lili – Category 3
28-Jun-2003	Tropical Storm	Bill
2-Sep-2004	Hurricane	Ivan – Tropical Storm
6-Oct-2004	Tropical Storm	Matthew
3-Jul-2005	Hurricane	Cindy – Category 1
29-Aug-2005	Hurricane	Katrina – Category 4
3-Aug-2008	Tropical Storm	Edouard
1-Sep-2008	Hurricane	Gustav – Category 2
2-Sep-2011	Tropical Storm	Lee 2011
20-Aug-2012	Hurricane	Isaac – Category 1
7-Jul-2019	Hurricane	Barry 2019 – Category 1
7-Nov-2013		*End of This Study's Period*

3. Supplementary Figures

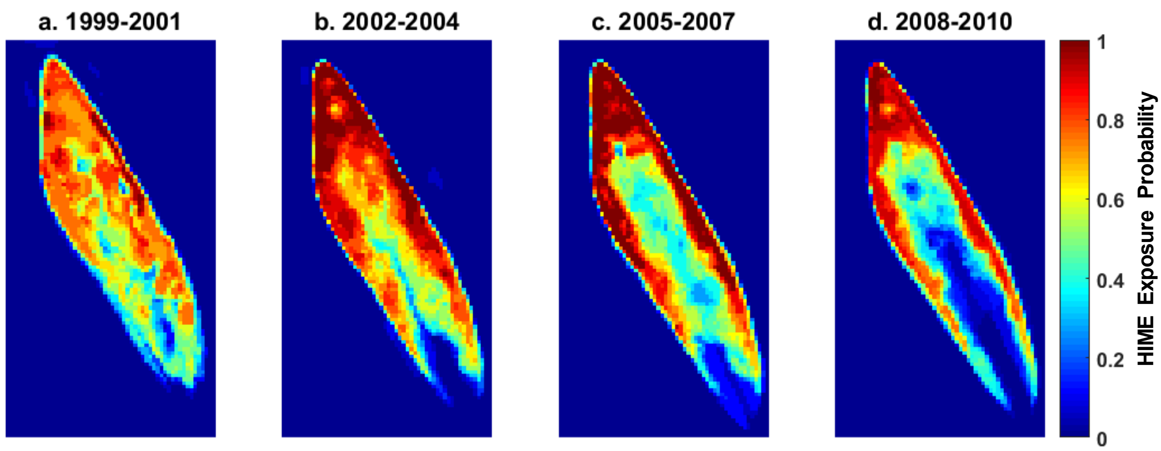

Figure S1. HIME raster exposure probability models for Pintail Island.

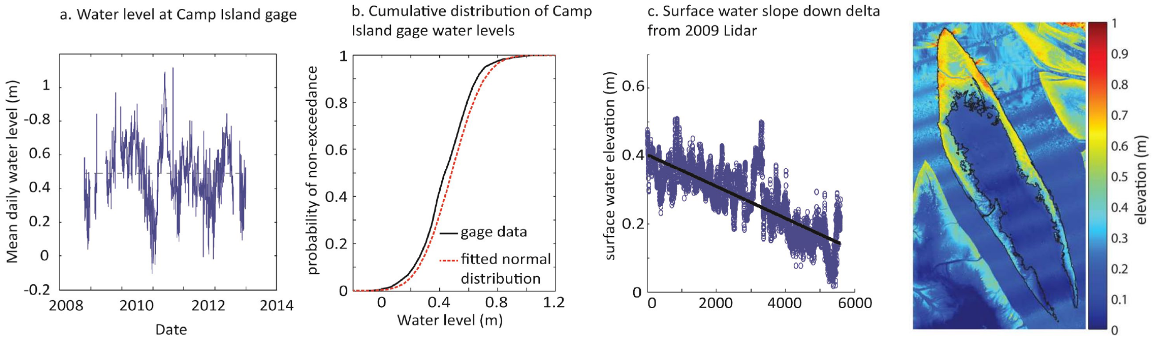

Figure S2. Surface water data and water level models used in study. a) Hydrograph of daily-average surface water level from USGS gage 073815925, located on Camp Island at the apex of the delta (29°32'24" N, 91°26'08" W; U.S. Geological Survey, 2014). Data with water level specified were only available for the period 10/15/2008-1/12/2014 at the time of the study. b) Empirical (dark solid line) and fitted normal (dashed red line) cumulative probability density functions of water level non-exceedance based on the data from (a). Fitted normal distribution has mean water level of 0.481 m (NAVD88; dashed line in (a)) and sigma = 0.179 m. c) Water surface transect (dots) down-delta derived from 2009 LIDAR data shown in (d) and fitted linear regression (dark line) indicating water surface slope of -4.7 E-5 (m/m), or water surface decrease of 4.7 cm/km. d) 2009 LIDAR data [1] illustrating surface water slope.

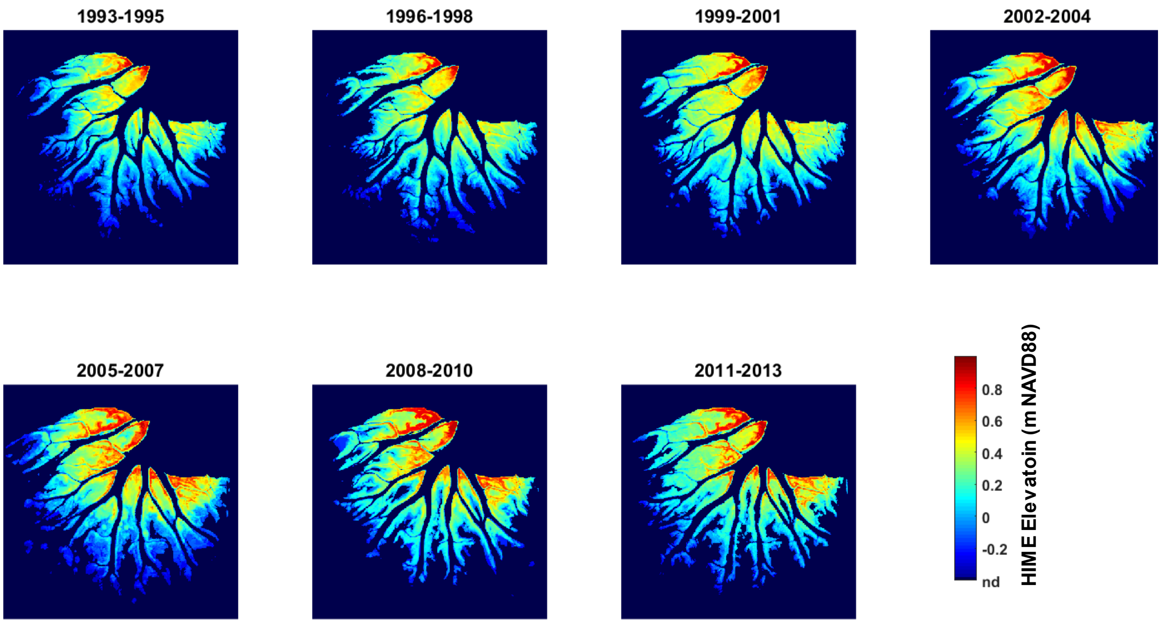

Figure S3. WLD HIME elevation maps.

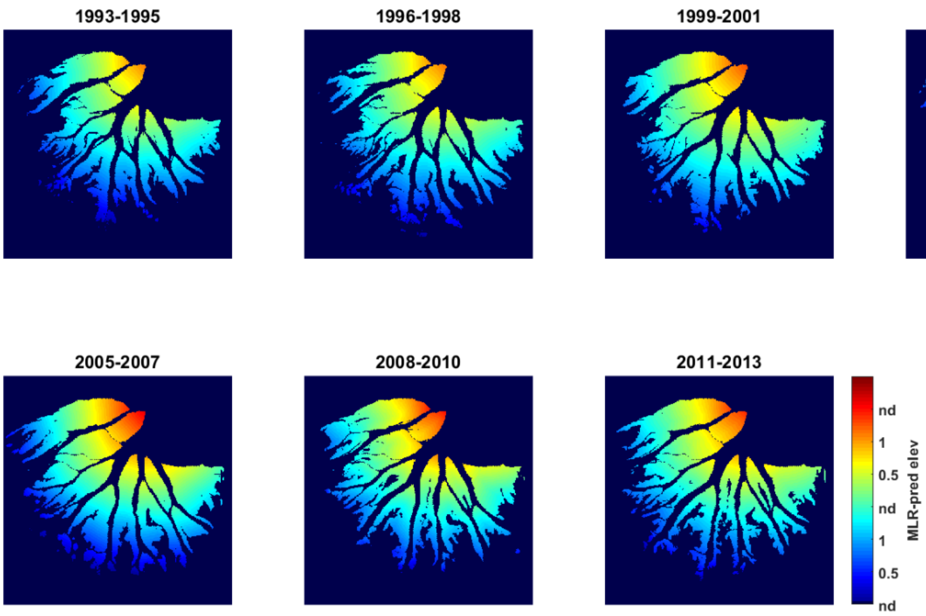

Figure S4. Elevation maps predicted by each timeframe's multiple linear regression model.

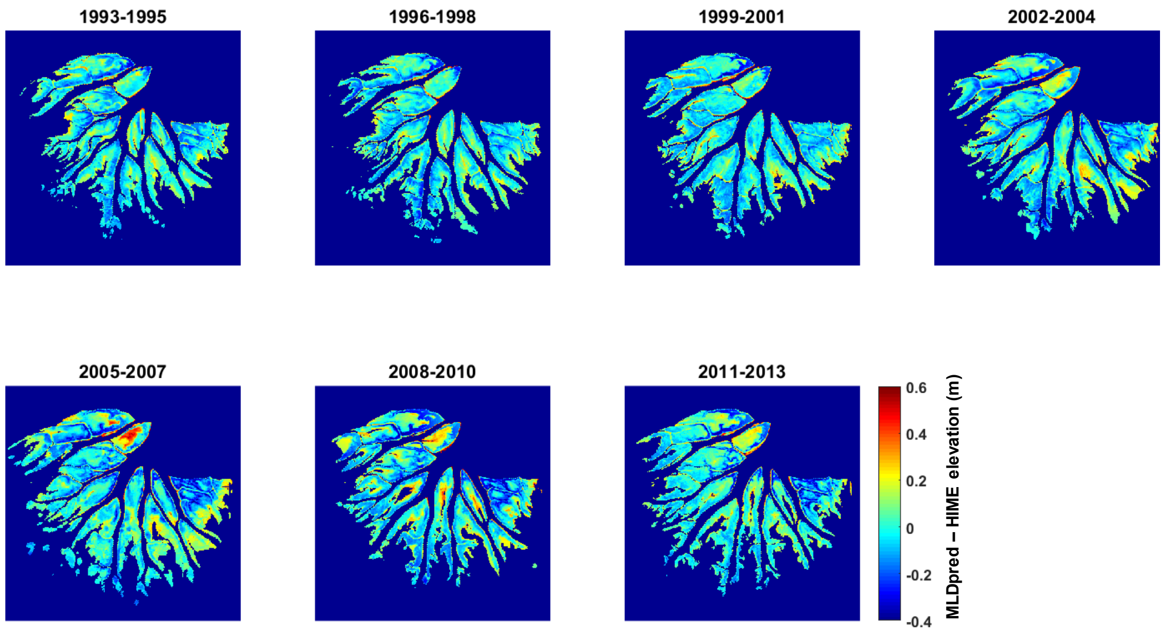

Figure S5. Mapped residuals of elevations predicted by each timeframe's multiple linear regression model minus the HIME-predicted elevation map for that timeframe.

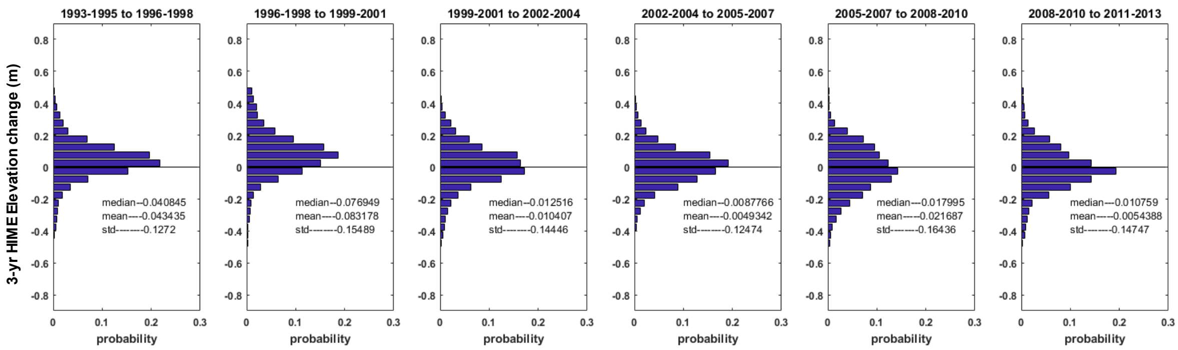

Figure S6. Histograms of magnitude of HIME elevation change between successive timeframes.

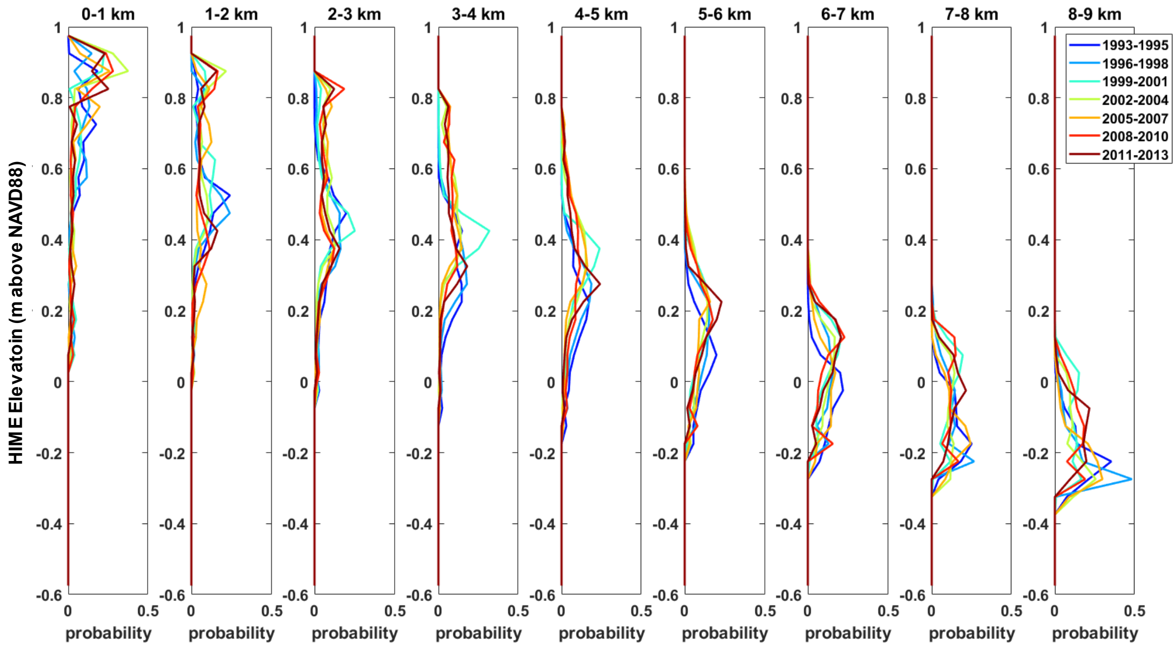

Figure S7. Elevation probability distributions through time within each 1km-band of distance from the delta apex.

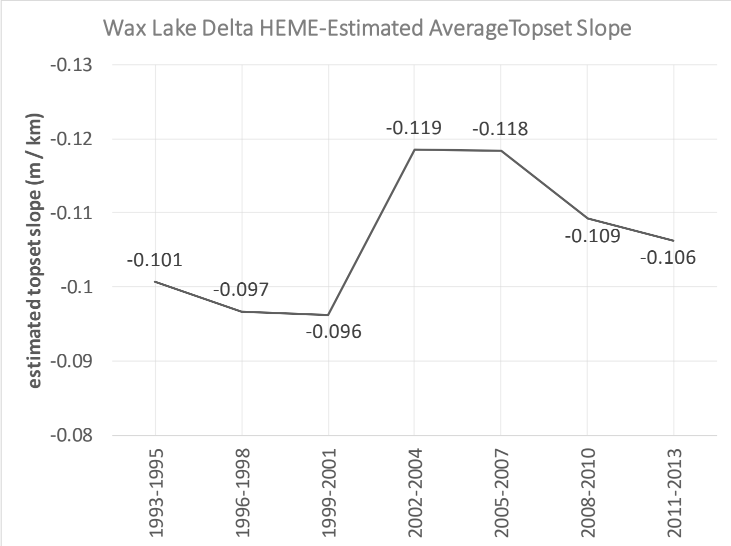

Figure S8. Progression of approximate WLD topset slope through time, as determined by coefficient of "distance to delta apex" factor in multiple linear regression model predicting WLD marsh-top elevations (see Table 1 of manuscript).

References

1. NCALM *Wax Lake Delta, Louisiana, USA 2009*; National Center for Airborne Laser Mapping, 2009; p. DOI: 10.5069/G95M63M8;