Exploring the morphodynamic response of coastal barriers to sea-level rise along the Texas Gulf Coast

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Colorado School of Mines
Thursday September 20th 2018
Texas coastal communities benefit from: *Over 80% coverage* from coastal barriers across a coastline which spans **590 km**!
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*The global coast has ~7% coverage too!*

### Texas Coast: VITAL STATISTICS

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal range</td>
<td>&lt; 1m</td>
</tr>
<tr>
<td>Sig. Wave</td>
<td>0.9 to 2.1 m @ SE direction</td>
</tr>
<tr>
<td>Shoreline disp.$^2$</td>
<td>$p_{10}, p_{50}, p_{90}$: -4.6, -0.9, 1.6 m yr$^{-1}$</td>
</tr>
<tr>
<td>RSLR</td>
<td>2 to 6 mm yr$^{-1}$</td>
</tr>
<tr>
<td>Barrier Height</td>
<td>&lt;1 m to &gt;5 m</td>
</tr>
<tr>
<td>Barrier Width</td>
<td>&lt;300 m to &gt;8000 m</td>
</tr>
</tbody>
</table>

Three key regions of interest:
1) Follets Island
2) Mustang Island
3) North Padre Island
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**Follets Island:** sensitive canary
- Flanks a *major deltaic headland*
- Retreating landward > 2m yr\(^{-1}\)
- Low, narrow

**Mustang Island:** stable and stout
- Updrift of “longshore convergence zone”
- Retreating landward < 1m yr\(^{-1}\)
- Tall, wide

**North Padre Island:** modestly prograding
- Within “longshore convergence zone”
- Slightly prograding 0.03 m yr\(^{-1}\)
- Very tall and wide
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Big question:

What is the **long-term trajectory** of Texas’ coastal barriers?

*Over 80% coverage* from coastal barriers forming a coastline which spans **590 km**!
Communicating coastal change:

**Example:** “bath tub” model of Follets Is., TX

Extrapolation from historical rates and Inundation (bath tub) models:
are dangerously inadequate!

**Benefit:** Very easy to understand and communicate

Coastal barriers are dynamic landforms:
→ rarely drown in place!
  barriers respond to SLR
→ extrapolation!
  SLR is accelerating

https://coast.noaa.gov/slr/
**Big question:**

What is the **long-term trajectory** of Texas’ coastal barriers?

**Reasonable response:**

Use a **process-based** model to **estimate barrier response** to anticipated sea-level rise along the Texas coast.
Reduced / intermediate complexity modeling:

**Task:** simplify Texas’ coastal barrier morphology into *characteristic scales* and physical processes into *parameterized expressions* which resolve fundamental barrier responses to sea-level rise.
Reducing a barrier to *characteristic scales*
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Conceptual figure: *high vertical exaggeration!*

Lorenzo-Trueba and Ashton (2014)
Reducing a barrier to characteristic scales

What is closure depth, $D_c$?

Deep water waves

Waves “feel bottom”, steepen & break

Wave energy decreases with depth.
As waves shoal (enter shallow water), beyond $D_c$, waves move sediment

Conceptual figure: high vertical exaggeration!

Lorenzo-Trubea and Ashton (2014)
Galveston: fair weather waves
Galveston: *not-so-fair* weather waves

Hurricane Ike, 2008
**Significant** wave class:

\[ D_c \sim \text{wave energy & time} \]

*morphologically significant

Ortiz and Ashton, JGR Earth Surface, 2016
Reduced complexity process representation in *Barrier Sections*:

1) Passive flooding during RLSR:  
2) Shoreface sediment fluxes:  
3) Net longshore sediment flux  
4) Overwash sediment transport  

Note: every single process terminates at $D_c$!

**Conceptual figure**: high vertical exaggeration!

Reduced complexity process representation in *Barrier Sections*:

1) Passive flooding during relative sea-level rise:

![Passive flooding diagram](image)

### Passive flooding drives:

1) Inundation of barrier ($\downarrow H$)
2) Depth of closure ($D_c$) translates
3) Barrier shoreface steepens ($\uparrow \alpha_i$)

Relative sea-level rise (RSLR) is spatially variable, and includes local subsidence.

**Conceptual figure:** *high vertical exaggeration!*

Lorenzo-Trueba and Ashton (2014), Ashton and Lorenzo-Trueba (2015), Swanson et al., (in prep.)
Reduced complexity process representation in *Barrier Sections*:

2) Shoreface sediment fluxes:

Local wave climate drives shoreface toward equilibrium slope:

\[ Q_{sf} = k (\alpha_e - \alpha_i) \]

\[ K \sim \frac{\text{wave energy}}{\text{grainsize}} \]

Under-steepened \((\alpha_i < \alpha_e)\)

*Onshore directed sediment flux*

Over-steepened \((\alpha_i > \alpha_e)\)

*Offshore directed sediment flux*

If wave climate is unchanging, shorefaces trend toward “equilibrium profiles”, which have slopes that depend on wave energy and grainsize.

*Example*: under-steepened shoreface = onshore flux

Cross-shore fluxes attempt to maintain an equilibrium slope!
**Shoreface response rate**

Local wave class

Grainsize: always fine sand or finer!

- **Upper coast**
  - ~ 80 μm

- **Central**
  - ~ 120 μm

- **Lower coast**
  - ~ 150 μm

**Gradual increase in grainsize...**

- **Abrupt wave climate**
  - Increase, fine grain size
  - Significantly coarser broader shoreface

- **Tranquil wave climate**
  - Very fine grained

**Significantly coarser**

- **Similar wave climate**

Swanson et al., in prep.
Reduced complexity process representation in *Barrier Sections*:

3) Net longshore sediment flux

Longshore sediment flux is **assumed**:
1) Driven by:
   a) shoreline curvature
   b) wave height
2) remove subaerial barrier
3) linear with shoreface depth
4) **vary significantly** along the TX coast

**Conceptual figure:** *high vertical exaggeration!*

Reduced complexity process representation in *Barrier Sections*:

3) Net longshore sediment flux

**Net accumulation:**
Barrier shoreface steepens (↑ $\alpha_i$) → Helps to prograde barrier

**Net erosion:**
Barrier shoreface relaxes (↓ $\alpha_i$) → Helps barrier retreat

*Conceptual figure: high vertical exaggeration!*

Reduced complexity process representation in **Barrier Sections:**

**Overwash: a threshold process:**

- If $H < H_e$, Overwash **aggrades** barrier
- If $W < W_e$, Overwash **widens** barrier

**Modern transgressive barriers:**

Overwash attempts to maintain an equilibrium subaerial barrier volume!

$$Q_{ow} \sim (H_e - H)W + (W_e - W)H$$

**Conceptual figure:** *high vertical exaggeration!*

Reduced complexity process representation in *Barrier Sections*:

4) **Overwash sediment transport**

Overwash is a *threshold process*:

\[ \text{if } H < H_e \]

Overwash *aggrades* barrier

\[ \text{if } W > W_e \]

Barrier

Overwash attempts to maintain an equilibrium subaerial barrier volume!

\[ Q_{ow} \sim (H_e - H)W + (W_e - W)H \]

Conceptual figure: *high vertical exaggeration!*

Overwash is limited to be less than a maximum value: \( Q_{max} \).

\( Q_{max} \) is a very important *GLOBAL parameter*, so we will explore sensitivity in upcoming results. Reasonable values span 0 to 100 m\(^2\) yr\(^{-1}\)
**Barrier failure during sea-level rise:**

**Width drowning:**
- Initial width: 350 m
- Initial height: 3 m
- RSLR: 2 mm yr\(^{-1}\)

**Height drowning:**
- Initial width: 2 km
- Initial height: 3 m
- RSLR: 10 mm yr\(^{-1}\)

**Width drowning:**
- shoreface response rate is too low to keep all sediment!

- Gulf / Bay
- Barrier
- Antecedent

1) SLR increases \(\alpha\)
2) Drives offshore flux
3) Height↓ and Width↓
4) Overwash threshold broken

**Height drowning:**
- Maximum overwash \(Q_{ow_{max}}\)
- is too low to keep up with SLR!
Connecting coastal barrier sections:
**Connecting** coastal barrier sections:

Individual barrier sections have **local morphodynamic parameters**.

Barrier sections communicate via longshore sediment flux.

**Conceptual figure**: high vertical exaggeration!

Connecting coastal barrier sections:

**Shoreline**

**Big assumptions:**

1. Barrier sediment composition is sand
2. Inlets/jetties allow longshore bypass
3. Seawalls prevent shoreline displacement
4. Wave climate is unchanging
5. Fluvial contributions are steady
6. No further human modification
7. No geomorphic clearing events

Ashton and Lorenzo-Trueba (2015)
**Connecting** coastal barrier sections:

Individual barrier sections have local morphodynamic parameters. Barrier sections communicate via longshore sediment flux.

**Model execution:**

1. Initial condition: modern coast
2. Timestep: 1 day
3. Run time: 500 yr (or until barrier failure)
4. **EXPLORE!**
   1. Sea-level rise (0 to 10 mm yr\(^{-1}\))
   2. Maximum overwash (0 to 100 m\(^2\) yr\(^{-1}\))

Ashton and Lorenzo-Trueba (2015)
Post-processing: Monitor three key regions

Low, med., high cases:

**Low**: $\text{SLR} \approx 3 \text{ mm yr}^{-1}$, $Q_{ow\max} \approx 30 \text{ m}^2 \text{ yr}^{-1}$
- Recent rates of SLR (eustatic)
- Reasonable overwash given multi-century record (Odezulu et al., 2018)

**Medium**: $\text{SLR} \approx 5 \text{ mm yr}^{-1}$, $Q_{ow\max} \approx 50 \text{ m}^2 \text{ yr}^{-1}$
- Upper limit of IPCC “500-700 ppm” (~5 mm yr$^{-1}$ over 500 yr)
- Overwash: reasonable given radiometrically derived overwash rates (Odezulu, Anderson, and Swanson, In Prep)

**High**: $\text{SLR} = 10 \text{ mm yr}^{-1}$, $Q_{ow\max} = 100 \text{ m}^2 \text{ yr}^{-1}$
- Upper-estimate of IPCC “>700 ppm” (~13 mm yr$^{-1}$ over 500 yr)
- Unprecedented rates of overwash

**Concept**: higher rates of SLR correlate to higher rates of overwash

*Post-processing: Monitor three key regions*

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*Post-processing: Monitor three key regions*
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**Follets Island**
- A sensitive canary of the coast
- Updrift of major deltaic headland
- Elevation (MHHW): $H = 1.7 \text{ m}$, $W = 610 \text{ m}$

**Mustang Island**
- A stout, stable barrier
- Updrift of “longshore convergence zone”
- Elevation (MHHW): $H = 3.4 \text{ m}$, $W = 1700 \text{ m}$

**North Padre Island**
- Modestly prograding
- In “longshore convergence zone”
- Elevation (MHHW): $H = 3.9 \text{ m}$, $W = 2100 \text{ m}$

Swanson et al., in prep.
Follets Island: Dip sections

Simulation stats:
Low: 470 yr / ~1.3 m SLR
Med.: 380 yr / ~1.9 m SLR
High: 250 yr / ~2.5 m SLR

Follets Island exhibits strong landward retreat (always!)

Swanson et al., in prep.
Follets Island: \textit{Low case}

Notable barrier responses:
1) Slow retreat, then accelerated retreat!
2) Subaerial barrier shrinks, then stabilizes
3) Constant overwash by height
   Overwash by width by \textasciitilde180 yrs.
4) Strong retreat reduces longshore flux

Swanson et al., in prep.
Follets Island: *Low and mid. cases*

**Notable barrier responses:**
1) Overwash by width at ~ 170 yrs
2) Faster and further retreat

Swanson et al., in prep.
Follets Island: *Low, mid., and high cases*

**Notable barrier responses:**

1) Largest and fastest retreat
2) Overwash by width at 100 yrs
3) Strong retreat redirects longshore transport.
4) Increases in SLR and $Q_{ow_{max}}$ vastly accelerate barrier behavior!

Swanson et al., in prep.
Follets Island: *Mean annual rates of change*

Mean annual shoreline disp.

Historical shoreline disp. rates:

\[ p_{10} \sim -3.3 \text{ m yr}^{-1} \]
\[ p_{50} \sim -2.5 \text{ m yr}^{-1} \]
\[ p_{90} \sim 0.4 \text{ m yr}^{-1} \]

Swanson et al., in prep.

Extrapolation from historical records may severely under-estimate responses!
Mustang Island: *Dip sections*

**Simulation stats:**
- Low: 470 yr / ~1.3 m SLR
- Med.: 380 yr / ~1.9 m SLR
- High: 250 yr / ~2.5 m SLR

Mustang exhibits significant progradation on marine deposits → History of retreat recreated by high SLR and overwash rates

Swanson et al., in prep.
**Mustang Island: Low case**

**Notable barrier responses:**
1) Fast progradation, then slower!
2) Subaerial barrier shrinks, then stabilizes
3) Overwash by height by ~ 300 yrs
4) Overwash slows progradation + stabilizes barrier vol.

Swanson et al., in prep.
Mustang Island: *Low and mid. cases*

Notable barrier responses:

1) Overwash by height at 220 yrs
   Nearly halts barrier progradation
**Mustang Island: Low, mid., and high cases**

1) Overwash by height at 110 yrs and high SLR causes a progradational barrier to retreat!

**Notable barrier responses:**

- Subaerial Vol. % change
- Net shoreline displacement m
- Critical barrier ratio
- Width
- Eq. Width
- Height
- Eq. Height
- Total overwash cum. Sed. Flux
- Longshore cum. Sed. Flux

Swanson et al., in prep.
Mustang Island: *Mean annual rates of change*

Although progradation has occurred for ~500 yrs within the central Texas region, this isn’t reflected in shoreline surveys.

Historical shoreline disp. rates:
- $p_{10} \sim -1.2\ \text{m yr}^{-1}$
- $p_{50} \sim -0.5\ \text{m yr}^{-1}$
- $p_{90} \sim 0.5\ \text{m yr}^{-1}$

*Swanson et al., in prep.*
Like Mustang, N. Padre exhibits significant progradation → History of retreat recreated by high SLR and overwash rates

Swanson et al., in prep.
N. Padre Island: *Low case*

**Notable barrier responses:**
1) Fast progradation, then slower!
2) Subaerial barrier shrinks, then stabilizes
3) Overwash by height by ~ 425 yrs
4) Overwash slows progradation + stabilizes barrier vol.

Swanson et al., in prep.
N. Padre Island: *Low and mid. cases*

Notable barrier responses:

1) Overwash by height at 310 yrs
   Nearly halts barrier progradation

Swanson et al., in prep.
N. Padre Island: *Low, mid., and high cases*

Notable barrier responses:
1) Overwash by height at 175 yrs and high SLR causes a transition: progradation to retreat!

Swanson et al., in prep.
N. Padre Island: *Mean annual rates of change*

Although progradation has occurred for ~ 500 yr within the central Texas region, this isn’t reflected in shoreline surveys.

Historical shoreline disp. rates:

\[ p_{10} \sim -0.75 \text{ m yr}^{-1} \]
\[ p_{50} \sim -0.03 \text{ m yr}^{-1} \]
\[ p_{90} \sim 0.5 \text{ m yr}^{-1} \]

Paine et al., JCR, 2016

Swanson et al., in prep.
When, how, and where do barriers fail?

+’s indicate: min, med., and max scenarios

Swanson et al., in prep.
Where do barriers fail?

Clustering of failures:
The upper Texas coast
Low barriers of various width
Low response rate (K)

Swanson et al., in prep.
**Why do barriers fail?**

**Matagord Peninsula:** *Failure by width-drowning*

1) *minimal input* from Colorado/Brazos
2) Within low $Q_{ow_{max}}$:
   - Width reduction by:
     1) Longshore transport
     2) Overwash due to low H

---

*Swanson et al., in prep.*
Why do barriers fail?

Upper Galveston: Failure by **height-drowning**

1) No fluvial source
2) Wide (~2.2 km), Low (~2.2 m)
3) low overwash rates cannot keep up with: RSLR (subsidence = 3.4 mm yr⁻¹)
**Why do barriers fail?**

**Follets Island – Height drowning**
1) low H (~1.7 m), modest width (~0.6 km)
2) low overwash rates cannot keep up with: RSLR (subsidence = 1.2 mm yr\(^{-1}\))

**Follets Island – Width drowning**
1) low H (~1.7 m), modest width (~0.6 km)
2) low shoreface response rate (K)

*Sediment loss to the shelf during SLR!*

Swanson et al., in prep.
**Why do barriers fail?**

Lower Galveston: *Failure by width-drowning*

1) Follets retreats into Christmas Bay
2) too wide (~1.2 km) to retreat
3) relative change in shoreline position → drives longshore fluxes to Follets

*Swanson et al., in prep.*
**Conceptual summary**

1. **Sea-level increases**
   - Barrier scales diminish

2. **Overwash becomes frequent**

3. **Overwash is sourced from shoreface**
   - 1) retreat rates *increase*
   - 2) progradation rates *decrease*
   - 3) barrier volume *stabilizes*

4. **Longshore transport system is modified**

**Retreating barriers:**

- Longshore transport system is redirected.
- Sediment removed from shoreface.
- Overwash deposits.

Map view

*Swanson et al., in prep.*
Conceptual summary

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Prograding barriers:

- Map view
  Swanson et al., in prep.
Conclusions:

• Texas’ long-term barrier trajectory is set by initial scales and location within Texas’ longshore transport system
• Range of forecasts capture:
  • Historical behavior
  • late Holocene architecture
• Barrier responses to sea-level rise modify longshore transport
• Future work:
  • Use coastal barrier model to forward model:
    • stratigraphic architecture (constrain shoreline controls)
  • Open-source-it! Open framework for coastal barriers
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  - Open framework for coastal barrier modeling.
Thank you! A special thanks to Dr. Hongbo Ma! (Rice U.)
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