CoSMoS version 3.0 updates

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### CoSMoS 3.0 Southern California

<table>
<thead>
<tr>
<th>Phase I</th>
<th>Phase II</th>
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<tbody>
<tr>
<td>• Released December 2015</td>
<td>• November 2016</td>
</tr>
<tr>
<td>• 100 year coastal storm + 10 SLR scenarios</td>
<td>• 100-year, 20-year, 1-year, coastal storms &amp; background conditions + 10 SLR scenarios</td>
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<tr>
<td>• Long-term shoreline change</td>
<td>• Updates to long-term shoreline change models, including simulations for various coastal management scenarios</td>
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<tr>
<td>• Shoreline = static for flood simulations</td>
<td>• Flood simulations include long-term shoreline change</td>
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Downscaled (CaRD10) winds and SLPs (SIO)

**Global**
- WW3
- Simulates wave growth and propagation across entire Pacific basin
- Using GCM winds

**Tier I**
- Delft3D FLOW+WAVE
- Simulates tides, SS, SLAs, wave propagation and growth
- Using B.C.s and forcing from astronomic constituents, WW3 waves, GCM SSTs, and regionally downscaled SLPs and winds

**Tier II**
- Delft3D FLOW+WAVE
- Simulates tides, SS, SLAs, wave propagation and growth, fluvial discharge, and overland flow
- Using B.C.s and forcing from Tier I (water levels and waves), and regionally downscaled SLPs and winds

**Nearshore waves**
- Look-up-table relating nearshore waves at individual CSTs with offshore winds and deep water waves
- Using WW3 waves and GCM winds

**Long-term cliff & shoreline change**
- Newly developed models
- Using complete series of time-varying projected nearshore waves, SS, SLAs, and SLR

**Tier III**
- XBeach cross-shore
- Simulates water level variations, wave propagation, breaking, setup, and runup, and storm-related morphodynamic change
- Using B.C.s and forcing from Tier II (water levels and waves), and initial profiles reflecting long-term morphodynamic change

**Mapped outputs**
- Flood depths, extents and water levels
- Flood duration
- Maximum wave heights, currents
- Maximum wave runup

Identify storm events from TWL proxies (TWL = R+SLA+SS)

40 scenarios
Selection of Climate Scenario

2 emissions scenarios, 4 Global Climate Models

=> selected climate scenario RCP4.5 & the GFDL-ESM2M GCM (slightly higher waves compared to RCP8.5; GFDL able to reproduce historical wave climatology compared to observations offshore of San Diego)

[http://dx.doi.org/10.5066/F7D798G; Erikson et al. 2015]
Nearshore waves in southern California: hindcast, and modeled historical and 21st-century projected time series

- 3-hourly wave parameters (Hs, Tp, Dp, Dm, Tm) every ~100 m in the alongshore direction at the 10-m bathymetric contour for the southern California bight

- Hindcast: 1980-2010, SWAN forced by WIS waves and CaRD10 winds; reanalysis-forced product


- 21st-century: 2012-2100, GFDL-forced waves translated to the nearshore via the lookup table.

Identify storm events from TWL proxies (TWL = R+SLA+SS)


TWL: total water level
CST: cross-shore transect
GCM: global climate model
SST: sea surface temperatures
Dashed boxes represent observation or other model data
Identify storm events from TWL proxies (TWL = R+SLA+SS)

\[ R_{5\%} = 1.0 \left( 0.35 \beta_f (SWH \cdot L_o) \right) + \frac{SWH \cdot L_o (0.563 \beta_f^2 + 0.004)}{2} \]

\[ SS = C_0 + C_1 \cdot \ln(SWH) + C_2 [\Delta P / (\rho g)] \]

\[ SLA = C_0 + C_1 \cdot SSTA \]

Time-series used for long-term morphodynamic change modeling
(except runup which is calculated using site specific foreshore slopes)
CoSMoS-COAST

Numerically solves a coupled set of differential equations on a series of transects:

\[
\frac{\partial Y}{\partial t} = - \frac{K}{D_c} \frac{\partial Q}{\partial X} + C E^{1/2} \frac{\Delta E}{\tan \beta} - \frac{c \Delta S_{rel}}{\tan \beta} + \frac{V_{lt}}{t}
\]

Long-term due to unresolved processes, e.g. sediment supply (natural or anthropogenic)

\( Y = \) shoreline position  
  (cross-shore coordinate)

\( t = \) time

\( X = \) alongshore coordinate

\( Q = \) alongshore sediment transport rate

\( K = \) alongshore transport rate coefficient

\( D_c = \) Depth of closure

\( E = \) wave energy

\( C = \) equilibrium shoreline change magnitude parameter

\( \Delta E = E - aY - b = \) wave-shoreline disequilibrium

\( a, b = \) equilibrium shoreline change parameters

\( \Delta S_{rel} = \) relative sea-level rise rate

\( \beta = \) beach slope

\( c = \) Bruun coefficient

\( V_{lt} = \) long-term shoreline change rate due to sediment supply, unresolved processes, etc.

Model type:
- longshore + cross-shore + rate
- cross-shore + rate
- historical rate only
- no prediction (sea-wall, harbor, etc.)

Long-term shoreline change

\[
\frac{\partial Y}{\partial t} = -\frac{K}{D_c} \frac{\partial Q}{\partial X} + CE^{1/2} \frac{\partial E}{\partial X} - c\Delta S_{st} \frac{\partial \tan \beta}{\partial X} + \frac{V_{it}}{\tan \beta}
\]

long-term due to unresolved processes, e.g., sediment supply (natural or anthropogenic)

~4800 transects with ~100 m grid spacing
Data Assimilation

We use the *extended Kalman filter method* of Long & Plant 2012

- Auto-tunes model parameters for each transect to best fit the historical shoreline data
- We improved the method to handle sparse shoreline data and ensure that parameters are positive or negative.

Simulation output for a single transect at Del Mar Beach:
Simulation of shoreline in 2100 w/ 1.0 m of SLR ...

Long-term shoreline change

- Transect lines
- Initial shoreline (~1995)
- Final shoreline (2100)
- Final shoreline (2100) + potential seasonal erosion
- Non-erodible shoreline (sea-wall, infrastructure, etc.)
Simulation of shoreline in 2100 w/ 1.0 m of SLR ...

Results: 20-27% of beaches in Southern California may be completely eroded into existing infrastructure.
Cliff erosion, retreat, and sea level rise

Long-term cliff recession

Sea cliff retreat

Wave energy moves landward

Sea level rise

Diagram showing the effects of cliff erosion, retreat, and sea level rise on a coastal area.
2-D models


Soft rock: Walkden and Hall, 2005

1-D model ensemble

Hackney et al., 2011
Walkden and Dickson, 2008
Ruggiero et al., 2001

Energy flux (USGS)
Wave decay (USGS)
Profile slope (USGS)
Model forcing & inputs

Waves, water levels

1980 - 2100
Hindcast | Forecast

Vitoreuk et al., in revision
2-D model examples

YEAR: 2013

Elevation (m) vs. Cross-shore distance (m)

-10 0 10 20 30

20 m

250 m
1-D ensemble model example

1 m SLR historical retreat rate = 0.24 m/yr 1200 model runs

Cliff retreat distance (all models)

Cliff retreat distance (mean + uncert.)

Histogram of all models
Key differences between 2.0 and 3.0

- New 1-D model ensemble
- Beach behavior is different in new 2-D models
  - Large waves don’t cause as much erosion
  - Beach is more effective at protecting the cliff
- New SLR curves
Key assumptions, etc.

- Rock hardness implicit & constant?
- Profile shape controls cliff retreat?
- Beach protects cliff?
- Beach height keeps pace with SLR?
- Retreat rates are time-averaged?
- Short-term processes resolved?
- Dependent on historical behavior?
main sources of uncertainty & armoring

Historical cliff retreat rates
Ensemble model ‘spread’
Sea level rise
Statistical estimation of model coefficients

Hold the Line (used for flood maps)
Let it go
Coastal Management Scenarios

**Sandy Coast**
- Case 1: “hold the line” + no nourishment
- Case 2: “hold the line” + nourishment
- Case 3: no “hold the line” + no nourishment
- Case 4: no “hold the line” + nourishment

**Cliffs**
- Case 1 & Case 3

--- Flood simulations employ Case 1 ---
ΔR: cliff recession

ΔS: sandy shoreline change

ΔSLR

Long-term cliff & shoreline change

Tier III
• XBeach cross-shore

Initial shoreline
Non-erodible shoreline

Cliff top recession

arrow
Profile between bluff toe and top are translated by $\Delta R$
Volume (area in case of these one-line models) eroded is dispersed between the new toe position and depth of closure
1. profile assumed to be in ‘dynamic’ equilibrium
2. translate that section of the profile from the seaward end of the inner surf zone (ISZ) to a sub-aerial point that estimates the location of active tide, wave, and storm surge effects, or flood protection infrastructure by $\Delta S$ and SLR
3. volume change within active zone is applied seaward of ISZ
The **landward limit** of which a given profile is translated is defined by:

1. the active beach width, defined by vegetation lines digitized from aerial photography,
2. intersection of the foreshore slope and un-eroded (original) back-beach landward of the initial MHW line,
3. non-erodible line defined by existing infrastructure (identified from aerial images or available records), or
4. regionally-averaged active beach width (93m ± 76m, Southern California Bight).

The second criteria is included in an effort to account for very wide beaches that are heavily impacted by human activity (either by recreation or management) and lack vegetation or other discerning features that illuminate the active beach width.

- e.g. Venice Beach
  - *sans* criteria 2, the entire beach would be translated
ISZ: seaward end of inner surfzone
ABW: active beach width
NEL: non-erodible limit
Tier II (Delft3D FLOW + SWAN)

Tier III (XBeach)

Long-term cliff & shoreline change

Mapped outputs

Tier II
- Delft3D FLOW+WAVE

Tier III
- XBeach cross-shore
Merging Tiers II & III → flood map

Tier II high res. grids (harbors, lagoons, ...)

Tier III XBeach (open coast)

Combine results to get final flood maps

Digital Elevation Models (one for each SLR)

Tier II water levels (relative to NAVD88)

Tier III water levels (relative to NAVD88)

DEM (relative to NAVD88)
Flood map uncertainty ("potential")
Generated by raising and lowering flood elevation data by $\varepsilon$

$\varepsilon = \pm 0.50 \, m \pm 0.18 \, m + (4 \cdot 10^{-1} \, m/yr|\, - 6 \cdot 10^{-1} \, m/yr)$

**Model uncertainty**
$rms = 0.12m$
Area and number of storms validated against are small compared to the geographic extent of the study area and thus model error is increased

**Vertical accuracy of DEM**
$rms = 0.18 \, m$ in open terrain (Dewberry 2012)

**Vertical Land Motion**
Spatially variable attributed to tectonic movement of the San Andreas Fault System (Howell and others 2016)
Limitations, assumptions, and known issues

• First and foremost, these are models...
• Only evaluates response to one GCM and one RCP
• Pertaining to flood extents:
  – While CoSMoS includes estimates of fluvial discharge, the storms selected and modeled are based on coastal storm intensities (not riverine flooding per se)
  - Hydrographs are idealized and peak fluvial discharges are first-order estimates
  – Assumes max SWHs coincide with high spring tides and peak fluvial discharge occurs shortly after high tide
  – Flood depth and extents between modeled CSTs on the open coast are along-shore interpolations and are not exact representations of model outputs
  - Culverts or other manmade and natural underground pathways between coastal waters and land are not accounted for
Limitations, assumptions, and known issues

• Pertaining to sandy shoreline projections:

- Model evaluates 1-dimensional shoreline changes at a series of alongshore-spaced transects

- Model assumes a dynamic equilibrium beach profile; landward limit of beach profile evolution is estimated from a set of criteria; mass is not always conserved, esp. in cases with flood protection infrastructure

- Natural and anthropogenic sediment supply is estimated from sparse shoreline data
Limitations, assumptions, and known issues

• Pertaining to cliffs and bluffs projections:
  – are for the 2D model determined largely from the geometry of the coastal profiles (offshore slope, cliff face slope, beach slope, cliff toe elevation, etc.) rather than the geologic characteristics of the cliffs
  – are relative to mean long-term historic cliff retreat rates over the time period ~1930-2100 calculated by the USGS National Shoreline Assessment
  – are time-averaged and do NOT resolve individual cliff failure events
  – do not include the effects of rainfall or groundwater percolation, only wave impacts
Thanks for your time and interest!
Extra slides
Framework of scenario runs including summary of simulated time points
(each scenario uses data representative of the storm identified in the previous slide. But here, for the actual cosmos runs, a full tidal cycle is simulated with conditions representative of the pre-selected storm = ‘scenario’)

*1 Restart map files must have same IT as actual run (i.e. as the TierII scenario run).
*2 Start times differ based on time needed for specific model to stabilize.
*3 To attain maximum flooding extents we can end the simulation around Nov 06 2010 20:00 (4 hrs after peak at L.A.). However, to be consistent with previous CoSMoS runs that have been run for a full 25 hr time period and where we have evaluated Xbeach profile changes as well as duration of flooding, we need to run these simulations for a full tide cycle.
Results: Historical Shoreline change rates

These rates of accretion are not driven by natural sediment supply.
Shoreline Change

- Long-term simulations w/ standard numerical models are difficult (impossible?):
  - Morphologic time scales >> Hydrodynamic time scales

- We need to reduce the complexity & computational cost of long-term shoreline simulations
  - It is difficult (impossible) to explicitly account for all processes controlling shoreline evolution

- There are many sources of uncertainty in long-term shoreline predictions
  - sources of uncertainty: Chaotic behavior of climate, sea-level rise, wave climate, sediment supply, anthropogenic effects

- We have developed a new model to predict long-term shoreline change: CoSMoS-COAST
  - It is synthesized from many process-based models in the literature
  - It’s fast!
  - It uses data assimilation to auto-tune the models and increase reliability.
    However, “All models are wrong. Some models are useful.”

- We need more shoreline data
  - More shoreline data would improve performance of the model

- Many Beaches in California are anthropologically-controlled via nourishments
  - Shoreline prediction: The future beach state will be what we engineer it to be.
  - Still, the model may help answer many questions pertaining to the future of the coast
21st Century Scenario Summary for Southern California

<table>
<thead>
<tr>
<th></th>
<th>Avg</th>
<th>1yr</th>
<th>20yr</th>
<th>100yr</th>
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<tbody>
<tr>
<td>Wave height (m)</td>
<td>1.75</td>
<td>4.40</td>
<td>6.13</td>
<td>6.8</td>
</tr>
<tr>
<td>Wave period (s)</td>
<td>12</td>
<td>16</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Wave direction (deg)</td>
<td>286</td>
<td>284</td>
<td>292</td>
<td>287</td>
</tr>
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</table>
Example of modeled confluence of fluvial discharge & astronomic tides
**Deltares’ XBeach**

(Non)hydrostatic storm wave model

**Hydro:** depth $\ll$ lateral processes; vertical momentum = hydrostatic pressure

**Non-hydro:** fully-resolving micro-scale processes
• Infragravity wave example
What are infragravity (IG) waves?

- In shallower water: wave groups decay (because waves break)
- IG waves gain energy, propagate as free waves and reflect off the coast
- IG waves can dominate the spectrum in the nearshore
Shoreline Data:

- **5 shorelines** from USGS National Assessment of Shoreline Change
- **20 shorelines** extracted from LIDAR surveys
  (most are from SCRIPPS 2003 – 2009; most are south of Long Beach)
- **20 shorelines** from USGS field surveys
  (only in Santa Barbara area 2005 - present)
- **We need MORE!**
CoSMoS-COAST: Coastal One-line Assimilated Simulation Tool

Modifications to Long & Plant 2012 data-assimilation method:

**Original method:**

\[
\frac{dY}{dt} = CE^{1/2} (E - aY - b) + v_{lt}
\]

**Modified method:**

\[
\frac{dY}{dt} = -\frac{K_0 \exp(\sigma_k K_1)}{d} \frac{\partial Q}{\partial X} - C_0 \exp(\sigma_c C_1) E^{1/2} (E + a_0 \exp(\sigma_a a_1)Y - b_0 \exp(\sigma_b b_1)) + v_{lt} - \frac{c_0 \exp(\sigma_c c_1)}{\tan \beta} \frac{\partial S}{\partial t} + v_{lt}
\]

where,

\[
a = -a_0 \exp(\sigma_a a_1) \quad b = b_0 \exp(\sigma_b b_1) \quad C = -C_0 \exp(\sigma_c C_1) \quad c = c_0 \exp(\sigma_c c_1) \quad K = K_0 \exp(\sigma_k K_1)
\]

This modification ensure that coefficients \( K, b, c \) should be positive and \( C, a \) should be negative.

With out this constraint, models with limited data or poorly-initialized coefficients would often explode.
Cliff evolution models

“All models are wrong, but some are useful…”

…and each useful model is different.
general results
1) Construct the SLR curve (i.e., 93.1 cm for 2100)
2) Find the year that intersects for our scenarios, e.g., 0.25 m SLR= ~2045, 0.5 m SLR= ~2070, 0.75 m SLR= ~2085.
3) Then run the wave timeseries for that time period, e.g., 2010-2045 for 0.25 m SLR scenario, 2010-2085 for 0.75 m SLR
4) For all SLR scenarios above 93.1 cm, we will assume they are reached at 2100 (i.e., for 1 m, 1.25 m, 1.5 m, 1.75 m, 2 m, and 5 m), adjust the SLR curve accordingly and run the entire 21st century time-series for each
5) Run the above for all 4 management scenarios (nourishment off/on, hold the line off/on)