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Transient and persistent shoreline change from a storm

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[1] There is disagreement as to whether shoreline position eventually recovers from large storms. In an earlier paper we showed that statistical modeling of historical shoreline data was improved by including large storms in the model via a transient storm function. Here we show that, at shorter timescales of months to years, modeling of the shoreline at Assateague Island, MD is improved by a storm model with both transient and persistent components. We find that the shoreline recovers from the storm rapidly, almost within a year, but that the recovery is only partial, despite anthropogenic reconstruction of a pre-existing berm. The long-term trend of a shoreline (whether erosive, accretive, or stationary) can thus be regarded as the cumulative persistent component of successive storms, although most long-term data sets are too temporally sparse to make such a parameterization more useful than a steady long-term rate. **Citation:** Anderson, T. R., L. N. Frazer, and C. H. Fletcher (2010), Transient and persistent shoreline change from a storm, *Geophys. Res. Lett.*, *37*, L08401, doi:10.1029/2009GL042252.

1. Introduction

[2] Coastal managers need to know how the shoreline is moving over long periods of time in order to plan development. *Douglas and Crowell* [2000] showed that post-storm shoreline positions can be outliers with respect to the trend, and that removing post-storm data can improve the apparent precision of trend estimates. However, removal of shoreline data inevitably introduces a degree of subjectivity. *Frazer et al.* [2009b] (paper 1) showed that including large storms as part of the shoreline model can improve long-term shoreline position prediction from sparsely sampled historical shoreline data, and that subjectivity in choice of which storms to model can be addressed by using an information criterion and by probability-weighted model averaging. In order to better understand how storms impact beaches, this study investigates shoreline response to a large storm on a time scale much shorter than that in paper 1. Here the time between most surveys is a few months.

[3] The US mid-Atlantic coast is subjected to intense tropical storms, which usually move quickly, impacting a given shoreline area for only a day, as well as mid-latitude storms known as "northeasters" which move more slowly, impacting a given shoreline area during several tidal cycles. Thus northeasters trap high-tide water, causing waves to reach higher portions of the shore. These large storm waves move sand from the dunes and berm to the offshore [*Short*, 1979]. Washover, aeolian transport and nearshore downwelling also remove sand and contribute to landward shoreline migration during a storm [*Niedoroda et al.*, 1984; *Kochel and Dolan*, 1986; *Leatherman*, 1979].

[4] In the intervals between storms, swell waves gradually move the offshore sand back onshore, and shoreline positions tend to recover from storms [*Birkemeier*, 1979; *Kriebel*, 1987; *Morton*, 1988; *Morton et al.*, 1994]. After a storm, the rate of shoreline change may return to its long-term trend [*Galgano and Douglas*, 2000; *Zhang et al.*, 2002a] over 5–15 years, depending on the magnitude of the storm. Historical shoreline data sets may span 150 years or more, but the data are temporally very sparse, so the details of shoreline recovery from a storm are not apparent. Here we model data in two dimensions (alongshore position and time) from Assateague Island, MD, containing a large storm. Our method is to transform the alongshore data into a sum of empirical orthogonal basis functions with time varying coefficients, then model the coefficients by the statistical methods of paper 1. Although the time window from March 1995 to September 2002 is relatively short, the data are relatively dense in time (24 surveys) and the behavior of the storm-influenced shoreline position is revealed in more detail. An onshore berm was leveled by the storm, and our model accounts for the effects of its replacement by coastal managers. Other forms of shoreline nourishment were used after the study interval.

2. Assateague Island

[5] Assateague Island is a barrier island along the coasts of Maryland and Virginia (Figure 1). Its Atlantic side consists of coastal dunes that seldom reach elevations above 2 meters, and its landward side is a low-elevation back barrier flat, sand and tidal wetland. Dominant waves have an average height of 1 m [*Schupp et al.*, 2007], and spring tides fluctuate between −1 and 3 m [*Field*, 1979]. Ocean City Inlet formed during a hurricane in 1933. Jetties constructed on both sides of the inlet in 1935 interrupted alongshore sediment transport from the north, causing severe coastal erosion south of the inlet [*Rosati and Ebersole*, 1996]. An ebb tidal delta subsequently formed and developed into a 300 m attachment bar connected to the shore about 650–950 m south of the inlet [*Schupp et al.*, 2007; *Rosati and Ebersole*, 1996] thus restoring a portion of the alongshore sediment transport [*Kraus*, 2000].

[6] In 1998, two large northeasters altered the study shoreline [*Ramsey et al.*, 1998]. On January 28, 1998, a low pressure system originating in Texas moved northeast, crossed the mouth of Chesapeake Bay and continued north with maximum wind gusts reaching almost 95 km/h and significant wave heights exceeding 7 m over an interval less than 24 hours. A few days later, on February 4, 1998, a

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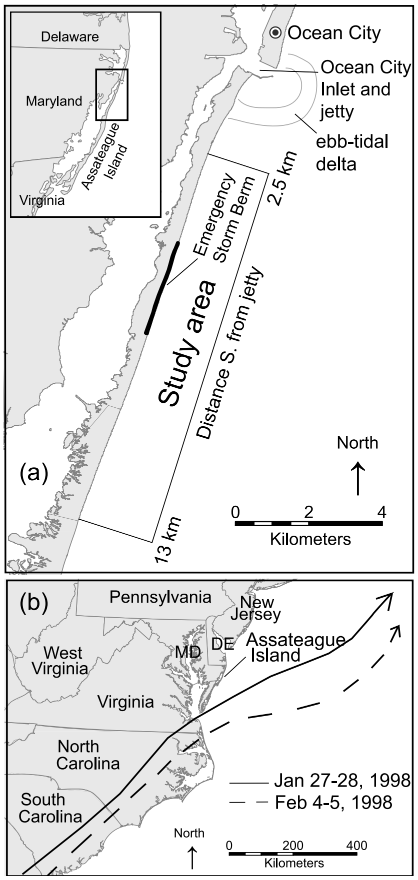

Figure 1. (a) Assateague Island, Maryland. (b) Tracks of the 1998 storms. See text for details. (This figure is drawn to be 1 column wide.)

stronger northeaster originating in the Gulf of Mexico crossed North Carolina and Virginia, and continued slowly north along the Atlantic Coast through February 6. This storm also produced significant wave heights exceeding 7 m, with maximum wind gusts near 95 km/h over a period greater than 24 hours. As the time interval between these two storms is much smaller than the interval between shoreline surveys, we model them as a single storm on February 4.

[7] The large waves generated by the two northeasters washed over portions of Assateague Island just south of the Ocean City Inlet. As a breach in the island was then considered a possibility, an onshore berm was constructed by the Assateague Island National Seashore North End Restoration Project (ASIS) and was completed 8 months after the storm. About 153,000 m^3 of sediment were deposited onto the beach 5–7.5 km south of Ocean City Inlet (National Park Service (NPS), Assateague Island National Seashore North End Restoration Project Timeline, available at www.nps.gov/asis/naturescience/upload/ProjectTimeline.pdf, 2006). (Prior accretion north of the jetties at Ocean City Inlet protected Ocean City from what might otherwise have been catastrophic erosion.)

3. Methods

[8] Shoreline positions for the years 1995 to 2003 have been collected by ASIS North End Restoration Project (www.nps.gov/asis/naturescience/resource-management-documents.htm), which used a kinematic GPS mounted on an ATV to map the high tide, high swash, wet/dry line four times a year. We used the Digital Shoreline Analysis System (DSAS) [*Thieler et al.*, 2005] to cast cross-shore transect lines 10 m apart in the alongshore direction. The result is a matrix $Y_{ij} = y(x_i, t_j)$ of shoreline positions in which the row index is alongshore distance and the column index is time. Each row of Y (a transect) is a time series of shoreline positions at one alongshore location, and each column of Y (a survey) is a snapshot of the shoreline position at a particular time. Columns were then anti-alias filtered and re-sampled to 50 m transect spacing.

[9] The traditional method of shoreline data analysis, called the single-transect method, models each transect independently, ignoring the lack of independence of the data at adjacent transects [*Fletcher et al.*, 2003]. We address the dependency issue as in *Frazer et al.* [2009a] and *Genz et al.* [2009] by the use of alongshore basis functions: We subtract the pre-storm survey temporally nearest to the storm, $y_{(0)}$, from all the columns of Y to obtain a matrix Z, find its singular value decomposition $Z = \sum_k \lambda_k u_{(k)} v_{(k)}^T$, then model each temporal coefficient $y_{(k)}(t_j) = \lambda_k v_{(k)}(t_j)$ as if it were a single transect. Our model for the data is thus

$$y(x,t) = y_{(0)} + \sum\nolimits_k u_{(k)}(x) y_{(k)}(t), \qquad (1)$$

in which the shoreline data mode $u_{(k)}(x)$ is the eigenvector of the matrix ZZ^T with eigenvalue λ_k^2. Only the first few modes are needed to model the data, but we modeled all temporal coefficients for completeness; the coefficients of modes higher than six were best modeled by noise.

[10] Paper 1 gives our method for fitting time models to the temporal coefficients. Here our most complex time model is

$$\begin{aligned} y(t) = {} & b + rt + n(t) \\ & + s_T e_+^{-\gamma(t-t_s)} + s_P H(t - t_s) \\ & + \nu\, e_+^{-\gamma(t-t_\nu)} \left(1 - e^{-\gamma(t-t_\nu)}\right) \\ & + a_c \cos(2\pi t) + a_s \sin(2\pi t). \end{aligned} \qquad (2)$$

The first line of equation (2) has the intercept, rate and noise terms; the second line has the transient and persistent parts of the storm function; the third line has the nourishment, and the fourth line has the seasonal component. The unit of time is years. In the storm function, t_s is the time of the storm, s_T is the amplitude of the storm transient, γ is the recovery rate, $H(t)$ is the unit step function, and s_P is the amplitude of the persistent component. The subscript "+" means that the storm transient $e_+^{-\gamma(t-t_s)}$ is zero prior to the storm. The shoreline displacement by the storm is the sum $s_T + s_P$. In the nourishment function, t_ν is the time of the nourishment, which was 8 months following the storm (NPS, project timeline, 2006), and ν is its amplitude. An information criterion (IC)—here the corrected Akaike Information Criterion (AICc)—is used to evaluate the likelihoods of models with various terms, and the model likelihoods are combined with prior model probabilities to generate model probabilities. Briefly, the posterior probability of the jth model is proportional to $\pi_j e^{-\mathrm{IC}_j/2}$, in which π_j is its prior probability, IC_j is its IC score, and $e^{-\mathrm{IC}_j/2}$ is its likelihood. The final model is a probability-weighted average over all candidate models. The covariance matrix of residuals, a modeling diagnostic, is given in Text S1 in the auxiliary material.[1]

[11] Here all models with non-zero prior probability are given equal prior probability. Models with zero prior probability (excluded models) are:

[12] 1. Models with no storm component, unless the model is only noise.

[13] 2. Models for which transient and persistent components have opposite signs: for example, a positive persistent component and negative transient component. For such models, the shoreline displacement $s_T + s_P$ is reasonable, but s_T and s_P may individually have unreasonably large amplitudes.

[14] 3. Models with a transient component whose recovery rate γ approaches zero. For such models the transient component is redundant, and only a persistent component is needed.

[15] Since all models not excluded are given the same prior probability, the model with the largest likelihood (lowest IC score) is the model with the largest posterior probability.

[16] In view of the decomposition into data modes, and the modeling of temporal coefficients, the transient and permanent components of the modeled storm are the respective mode sums

$$s_T(x,t) = \sum\nolimits_k s_T^{(k)} u_{(k)}(x) e_+^{-\gamma(t-t_s)}, \tag{3a}$$

shown in Figure 2c, and

$$s_P(x,t) = \sum\nolimits_k s_P^{(k)} u_{(k)}(x) H(t-t_s), \tag{3b}$$

shown in Figure 2d.

[17] To estimate errors we make an adiabatic approximation, assuming that errors in one modal coefficient are unrelated to those of other coefficients. For example, the variance in the estimate of the transient component amplitude is

$$\sigma_{s_T}^2(x) \approx \sum\nolimits_k \left(\sigma_{s_T}^{(k)}\right)^2 \left(u_{(k)}(x)\right)^2. \tag{4}$$

Calculation of quantities such as $\sigma_{s_T}^{(k)}$ includes model selection error and is given in the auxiliary material. In regard of errors, *Zhang et al.* [2002b] found that the variability of the high water line at Duck, North Carolina, is significantly lower during summer than in other seasons. To test for an effect on our results we grouped residuals (predicted position from a model average with no seasonal function, minus the data) by seasons and tested for differences in mean and variance, finding no significant difference at the 95% level of confidence. We also re-ran our computations using the seasonal uncertainties from our residuals and found that our results did not change in any significant way. Seasonal variation of uncertainty would probably have affected our analysis more if the data set had fewer surveys.

4. Results

[18] Figure 2 shows the analysis of shoreline data from Assateague Island, MD. Figure 2a is a 2D perspective plot of the original data, and Figure 2b is the complete model including all modes. Figure 2c shows the transient portion of the storm, and it can be seen that recovery is rapid, almost within 2 years for all portions of the beach. Figure 2d shows the persistent component of the storm, which is lower in amplitude than the transient component, i.e., it does not account for as much of the initial shoreline displacement as the transient part of the model. Areas of the largest persistent shoreline change correlate roughly with areas of shoreline where the island was overwashed by the storm 5–8 km south of the inlet. Figure 2e shows the modeled nourishment associated with the replaced onshore berm.

[19] The first six modes have more than 99% of the data variance, and the temporal coefficients of the remaining modes are best modeled by noise. The first mode has 90.7% of the data variance, the second mode 5.0% and the third mode 1.9%. (See auxiliary material for a table of modal contributions.) The temporal coefficient of the first mode is shown in Figure 2g, and the temporal coefficients of modes 2 and 3 are given in the auxiliary material. The first coefficient shows a strong storm signature with obvious transient and persistent components, and it is not surprising that the best model, i.e., the model with the largest posterior probability, is the model with rate, transient and persistent storm components. The probability-weighted average model, incorporating all possible models with likelihoods based on IC values, shows virtually no rate but a rapidly recovering transient storm component as well as a persistent component. There is also a small perturbation as a result of nourishment. The best model for the second mode coefficient (auxiliary material) has rate, transient storm, and nourishment. The best model for the third mode coefficient has no rate, but a transient storm component and a larger nourishment term.

[20] Figure 2h shows shoreline displacement at the first survey after the storm (February 11, 1998). The black dashed line is the actual horizontal landward change in shoreline position seen in the data. The blue line is the model displacement due to the storm. The green and red lines show the transient and persistent shoreline change due to the storm respectively.

5. Discussion and Conclusions

[21] The Assateague Island data suggest that storm-induced shoreline change can be modeled as the sum of a transient component that is recovered in a few years and a component that persists until sediment is mobilized by a subsequent storm. There is thus a suggestion that long-term shoreline change can be grossly modeled as the cumulative sum of persistent components from storms. Unfortunately, most historical shoreline data sets do not have the time resolution necessary to resolve the transient and persistent components, and it is probably better to model such data with a gradual trend (rate term) plus a sum of transients from

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL042252.

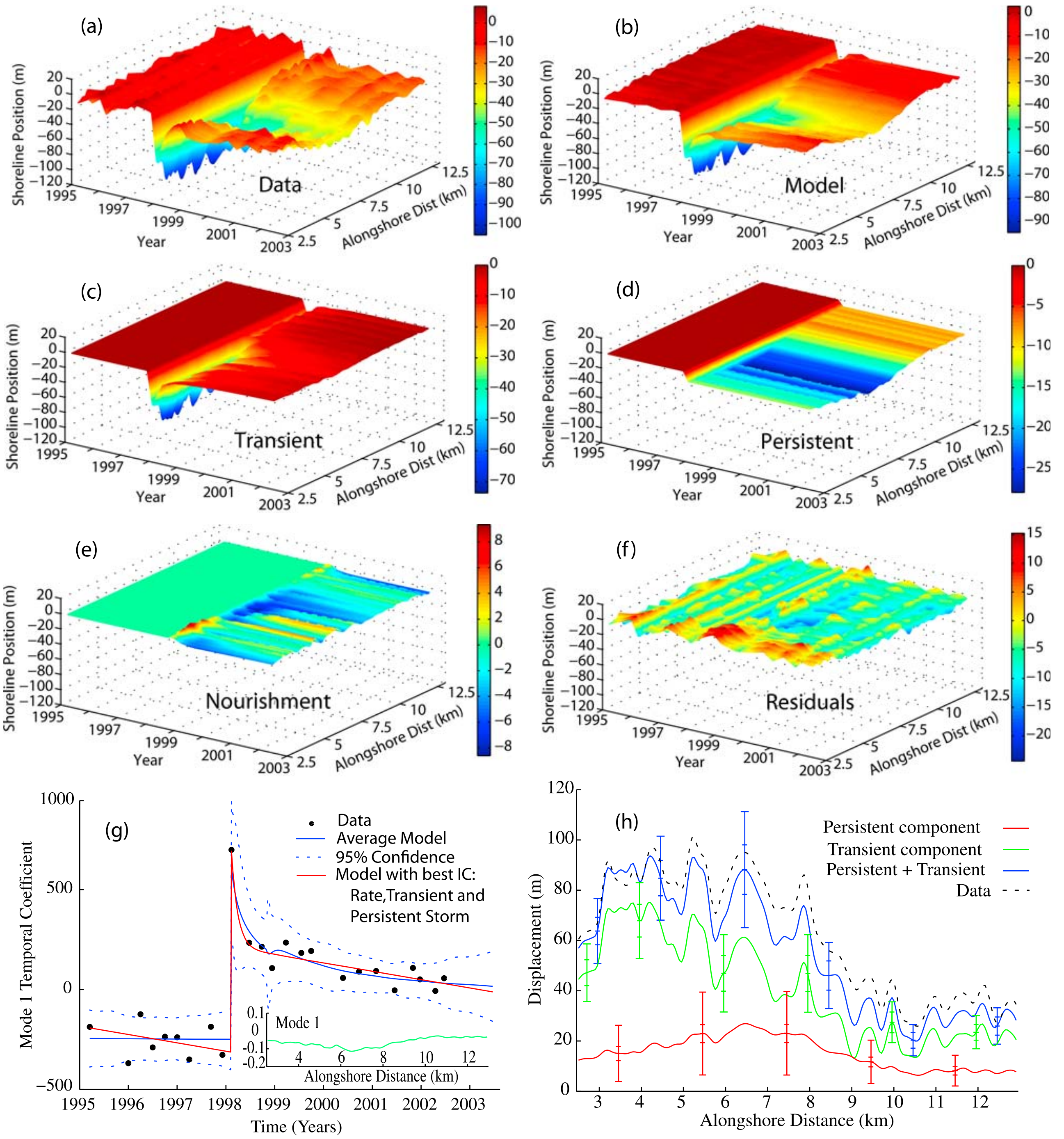

Figure 2. (a) Shoreline data from Assateague Island, Maryland. (b) Probability-weighted average model. (c) Transient component of storm related shoreline change. (d) Persistent component of storm-related shoreline change. (e) Nourishment component of model (see text). (f) Residuals = data − model prediction. (g) Temporal coefficient of the first shoreline data mode (filled circles), with best model (red) and probability-weighted average model (blue). (h) Transient and persistent parts of the storm; the transient part is evaluated at the time of the first post-storm survey for comparison with data. The dotted line (data) is the first post-storm survey minus the average of pre-storm surveys. On the error bars, the inner ticks are the standard error of the model-average computed using the method of paper 1, and the outer ticks include model selection error—see section E of Text S1 for details.

the larger storms, as in paper 1. Still, a transient-persistent analysis may be useful in shoreline management. For example, in areas where multi-decade data are not available, a transient-persistent analysis of recent, temporally dense data containing a storm might be used to generate a very coarse estimate of long-term rate as the persistent component from the storm divided by the expected time interval between such storms.

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