# Signatures of sea level changes on tidal geomorphology: Experiments on network incision and retreat

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[1] How do tidal networks respond to changes in relative mean sea level (RMSL)? The question on whether the morphological features of a tidal landscape retain signatures of past environmental forcings, or are in equilibrium with current ones, is critical to our prediction of the fate of residual tidal landforms. In the case of tidal networks, the issue is quite relevant owing to their fundamental role on landscape eco-morphodynamic evolution. Here we explore the response of tidal networks to cyclic variations in RMSL triggering tidal prism changes on the basis of laboratory experiments carried out in a synthetic lagoonal environment. A decrease in the tidal prism leads to network retreat and contraction of channel cross sections. Conversely, an increase in the tidal prism promotes network re-incision and re-expansion of channel cross sections: Network retreat and expansion tend to occur within the same planar blueprint. Our results show that the drainage density of tidal channels is linearly related to the landscape-forming prism, although this relation is speculated to hold with reasonable approximation as a statistical tendency rather than as a pointwise, instantaneous adaptation. Changes in tidal prism rapidly influence network efficiency in draining the intertidal platform and the related transport of water, sediments, nutrients and pollutants. This bears important consequences for quantitative predictions of the long-term ecomorphological adaptation of the tidal landscape to RMSL changes. **Citation:** Stefanon, L., L. Carniello, A. D'Alpaos, and A. Rinaldo (2012), Signatures of sea level changes on tidal geomorphology: Experiments on network incision and retreat, *Geophys. Res. Lett.*, *39*, L12402, doi:10.1029/2012GL051953.

## 1. Introduction

[2] Whether or not the morphological features of a given landscape retain signatures of past climates is a classical and fascinating question in geomorphology [e.g., *Leopold et al.*, 1964; *Rinaldo et al.*, 1995]. Within tidal landscapes, improving our understanding of network dynamics in response to variations in relative mean sea level (RMSL) is theoretically and practically relevant for the key role exerted by tidal networks on the eco-morphodynamic evolution of tidal systems [e.g., *Fagherazzi and Overeem*, 2007; *de Swart and Zimmerman*, 2009; *Fagherazzi et al.*, 2012]. Despite their importance in landscape evolution, tidal networks have received less attention when compared to their fluvial counterparts [e.g., *Howard et al.*, 1994] particularly in terms of the chief processes governing their initiation and evolution, and their response to variations in external forcings [e.g., *Rigon et al.*, 1994; *Rinaldo et al.*, 1995]. Recently, several mathematical models have been developed to describe the morphogenesis and development of tidal networks [e.g., *Fagherazzi and Sun*, 2004; *D'Alpaos et al.*, 2005; *Marciano et al.*, 2005; *Kirwan and Murray*, 2007; *Temmerman et al.*, 2007]. These models deepen our understanding of tidal network growth, otherwise analyzed solely on the basis of field observations and related conceptual models [e.g., *Redfield*, 1965; *Allen*, 1997; *Perillo et al.*, 2005; *Hood*, 2006; *D'Alpaos et al.*, 2007b; *Hughes et al.*, 2009]. In two cases tidal network initiation and development have been addressed with physical models [*Stefanon et al.*, 2010; *Vlaswinkel and Cantelli*, 2011]. These studies showed that laboratory experiments can successfully model tidal network dynamics. Although tidal network response to RMSL changes has been addressed by conceptual [e.g., *Allen*, 1997] and numerical models [*D'Alpaos et al.*, 2007a; *Kirwan and Murray*, 2007], the effects of cyclic variations in RMSL on the characteristics and structure of tidal networks remain poorly understood, and the possibility of detecting signatures of past conditions imprinted on the landscape justifies analyses of the type proposed herein.

[3] Here we analyze tidal network response to changes in the tidal prism (i.e., the total volume of water exchanged through the inlet between low water slack and the following high water slack), triggered by RMSL changes, on the basis of laboratory experiments [*Stefanon et al.*, 2010] over timescales which would preclude network monitoring through field observations. The use of a controlled laboratory environment provides also the distinct advantage of isolating the effects of RMSL changes on landscape evolution, among those of the other physical and biological processes which, acting over overlapping spatial and temporal scales [e.g., *Rinaldo et al.*, 1999a, 1999b; *Feola et al.*, 2005; *Mudd*, 2011], shape the tidal landscape. Our results can be used to benchmark mathematical models which, to various degrees, conceptualize and simplify the actual governing processes.

## 2. Methods

[4] Our laboratory investigations were carried out in a synthetic lagoonal system, subjected to a prescribed tidal forcing generated within an adjoining basin representing the

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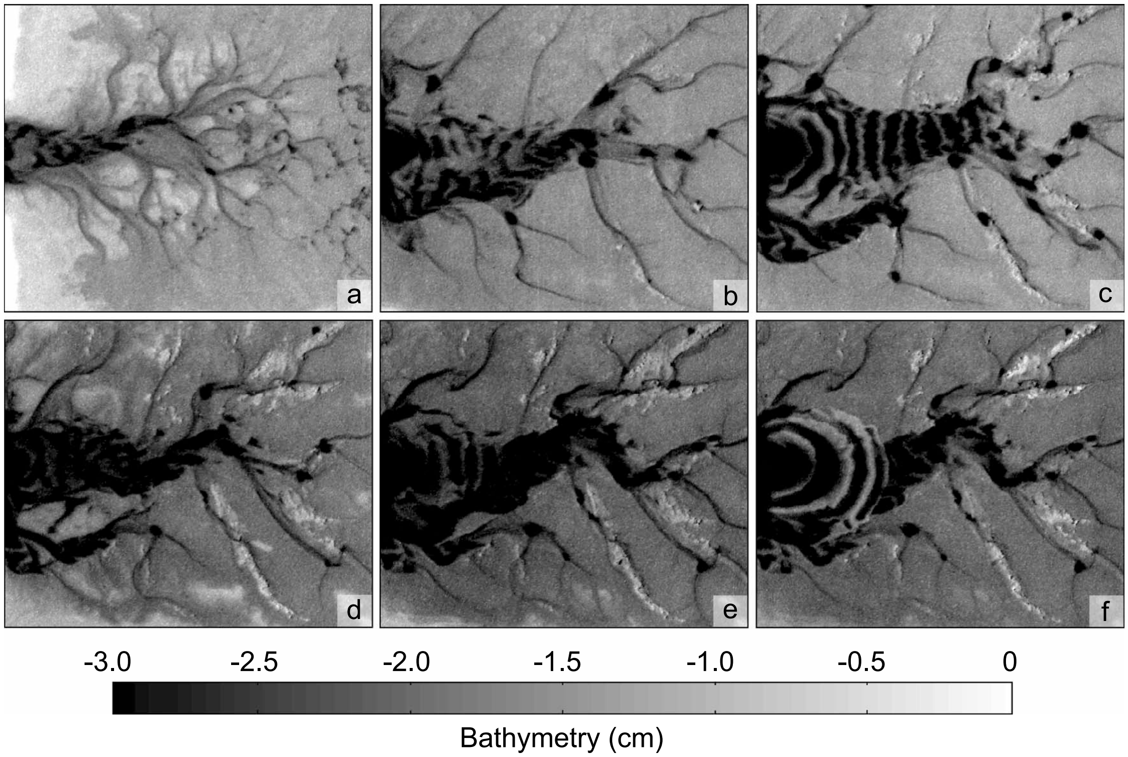


**Figure 1.** Distribution of bottom elevations for different network configurations during the experiment: (a) 133 cycles; (b) 1,752 cycles; (c) 9,351 cycles; (d) 9,631 cycles; (e) 11,355 cycles; (f) 12,459 cycles. Elevations are referred to the initial RMSL.

sea (see *Stefanon et al.* [2010] and the auxiliary material for a detailed description of the apparatus).[1] The tide propagates through a central inlet thus promoting the mobilization of cohesionless plastic grains (sediment density $\rho_s$ = 1041 kg/m$^3$ and median grain size $d_{50}$ = 0.8 mm) and the development of a channel network which cuts through the lagoonal basin. Due to lack of external sediment supply and absence of vegetation, the experimental lagoon is purely erosive. The sediments are invariably exported seawards, the lagoonal bottom progressively deepens with respect to RMSL, and the tidal prism, *P*, increases until equilibrium conditions occur [*Stefanon et al.*, 2010]. As a consequence, we simulate a decreases in *P* by decreasing RMSL, whereas an increase in *P* can be simulated by increasing RMSL, but it also implicitly occurs because of the erosive character of the experimental setting.

[5] The synthetic network structures are analyzed on the basis of two indicators of dynamics and morphology: tidal prism, *P*, and drainage density, *D.* The tidal prism is computed as $P = \int_S [H - \max(z, h)]dS$ where *S* is the area of the basin, *H* and *h* are the local maximum and minimum tidal levels, and *z* is the local bed elevation. The drainage density is addressed here following the approach proposed by *Marani et al.* [2003] that relies on the statistics of the unchanneled flow lengths, $\ell$ (i.e., flow-path lengths from any unchanneled site to the nearest channel). Such lengths are determined on the basis of drainage directions defined by time-averaged hydrodynamic gradients [*Rinaldo et al.*, 1999a]. While the classical Hortonian drainage density (total channelized length divided by the watershed area) is a poorly distinctive measure of how the catchment is dissected by the channel network, the drainage density computed as the inverse of the mean flow distance from any unchanneled point to the nearest tidal channel indicates how efficiently the network drains (feeds) its catchment during ebb (flood) [*Tucker et al.*, 2001; *Marani et al.*, 2003].

## 3. Experimental Results

[6] We started the experiment by forcing an initially flat topography (average elevation equal to RMSL) with a sinusoidal tide (amplitude of 1 cm and period of 8 minutes) whose characteristics were kept constant throughout the whole experiment. The experiment lasted about 13,000 cycles. A network of channels rapidly started to develop cutting through the undissected basin (Figure 1a). Small amplitude roughness in the initial topography favoured local flow concentration, which promoted incision. This early incision caused further flow concentration which lead to a positive feedback promoting the formation of the tidal network [e.g., *Fagherazzi and Furbish*, 2001]. Simultaneously, we observed the formation of a mild bottom slope towards the inlet, a decrease in bottom elevations, and an increase in the flowing tidal prism. A better defined network formed, which developed through: (i) channel elongation via headward growth; (ii) increase in the degree of incision and sinuosity as the channels aged; and (iii) formation of new tributaries (Figure 1b). After 9,351 cycles (Figure 1c) network configuration was rather stable and the tidal prism reached its maximum equilibrium value, attained when

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL051953.

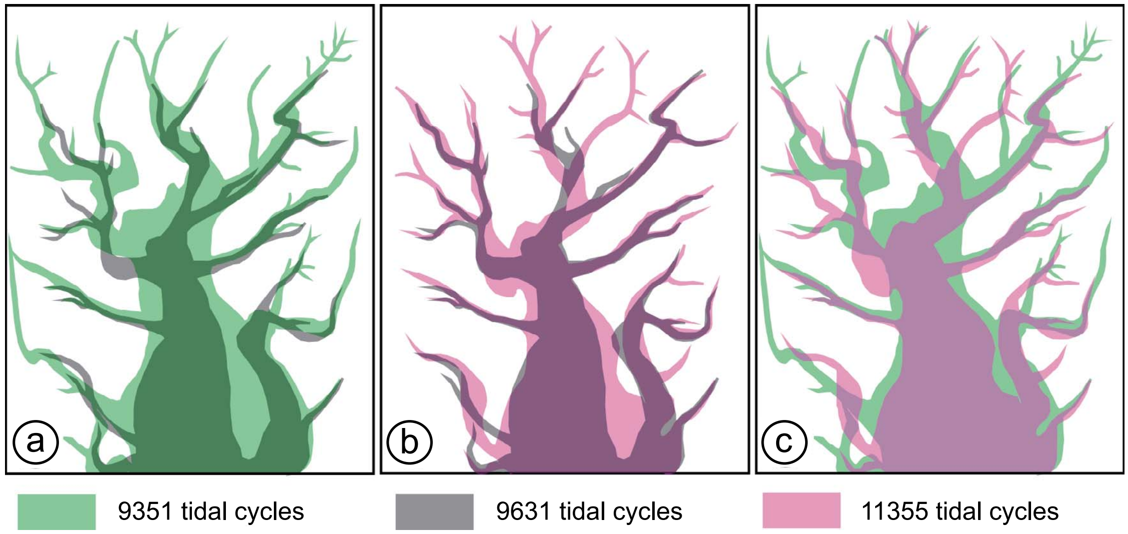


**Figure 2.** Overlap of relevant network configurations obtained during the experiment of RMSL changes in order to highlight differences in structure.

bottom elevations were everywhere lower than the minimum tidal level. We therefore reduced RMSL (1 mm per tidal cycle for an overall variation of 1.0 cm) to analyze the influence of such a decrease on network structure and cross-sectional geometry. Large portions of the shallows were characterized by drying processes during ebb. The decrease in RMSL led to a strong reduction in *P* and produced a rapid retreat of the network, clearly visible after about 100 cycles. All the channels experienced a contraction of their cross-sectional areas. After 9,631 cycles the network was characterized by a well-defined structure and by the presence of more pronounced bends (Figure 1d). The reduction in the water depth over the basin enhanced erosion processes on the shallows and within the network, thus leading to a progressive increase in *P*. Due to the ongoing increase in *P*, the central channel widened and deepened, and the channels cutting through the rest of the basin became progressively more defined and wider (Figure 1e). Some of the channels expanded out of their previous configuration and new tributaries formed. Network evolution proceeded with features analogous to those described in the first phase of the experiment until a new stable configuration was reached (after 11,355 cycles). We therefore increased RMSL (1 mm per tidal cycle for an overall variation of 1.0 cm) and observed that, except for negligible local effects, network structure did not experience any significant variation (Figure 1f).

## 4. Discussion

[7] The laboratory experiments presented herein support the description of network evolution and dynamics addressed by conceptual [e.g., *Allen*, 1997] and numerical models [*D'Alpaos et al.*, 2007a; *Kirwan and Murray*, 2007], and deepen our understanding of the effects of cyclic changes triggered by RMSL variations. The latter in fact, cannot be observed directly in nature owing to the long timescales involved, and have only been addressed so far on the basis of numerical experiments [*D'Alpaos et al.*, 2007a].

[8] When the tidal prism, *P*, decreases as a consequence of the reduction in RMSL (Figures 2a, 3a, and 3b), channel cross sections shrink and some of the channels infill with sediments eroded from the adjacent unchanneled areas, thus producing network contraction. Conversely, when *P* increases due to the erosion of the lagoonal bottom (Figures 3a and 3b), channel cross sections enlarge and the network re-expand (Figures 2b and 3d). In general, contractions and expansions tend to occur within the same planar configuration and the network re-expands cutting over the vestiges of old channels. However, in some cases, network re-extension through headward growth and initiation of new tributaries follows paths that do not overlap the old ones (Figure 2c). Interestingly, in almost all cases the network tends to evolve by re-occupying formerly channeled landscape portions (although with different new incisions), abandoned during the contraction phase, thus tending to recover the pre-contraction drainage efficiency, as we clarify in the following. This supports the "sediment poor" scenario modelled by *D'Alpaos et al.* [2007a] in which the lack of sediment prevents major modifications of the platform and cyclic network retreats and re-expansions occur.

[9] The sharp reduction in the RMSL immediately affects the tidal prism, *P* (note the sharp decrease in *P*, between 9,351 and 9,631 cycles, in Figures 3b and 3e) leading to a contraction of the network (Figure 3d) and a decrease in drainage density, *D* (Figures 3c and 3e). However, we observe that the drainage density is still decreasing (from 9,351 to 9,474 cycles, Figure 3c) when the tidal prism begins to increase again (at 9,361 cycles, Figure 3b) because of an increase in the bottom shear stress promoting erosion (Figure 3a). Although the characteristic timescales of *P* and *D*-adjustment to perturbations are of the same order of magnitude, the timescale characterizing variations in *D* seems longer than the timescale describing variations in *P*, which immediately responds to RMSL changes. Interestingly, when the tidal prism and the drainage density begin to increase (after 9,361 and 9,474 cycles, respectively, Figures 3b and 3c) both quantities tend to their

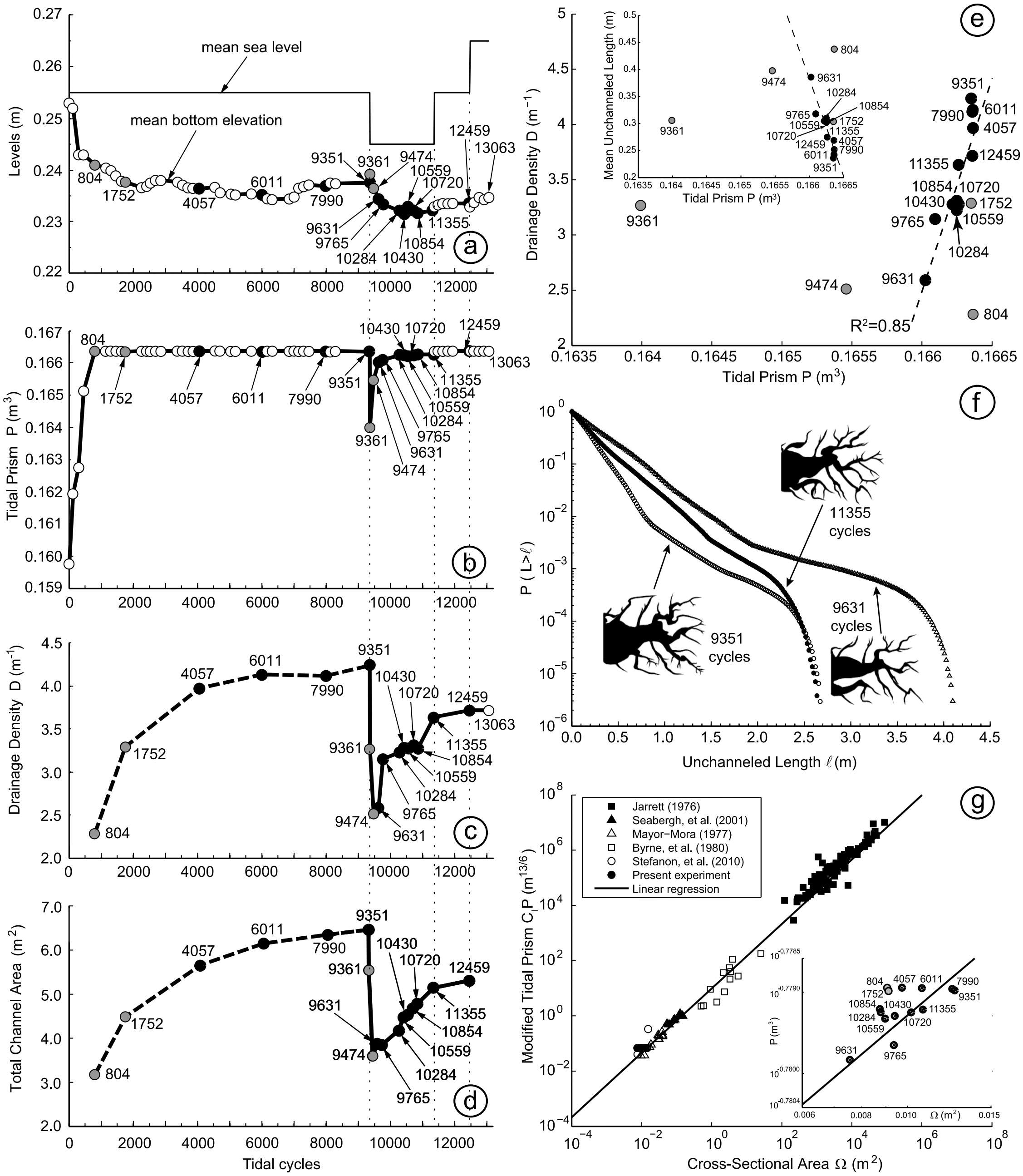


**Figure 3.** Temporal evolution of (a) mean bottom elevation and mean sea level, (b) tidal prism, (c) drainage density, and (d) total channeled area. Solid (black and/or grey) circles represent network configurations reported also in Figures 3e and 3g. Black circles represent configurations characterized by equilibrium or near-equilibrium conditions in terms of $P$ and $D$; grey circles represent non-equilibrium conditions close to perturbations in the forcings. (e) Tidal prism vs drainage density (the linear regression of the black circles is also shown, $R^2$ = 0.85). Inset: tidal prism vs mean unchanneled length. (f) Probability distribution of unchanneled lengths for three network configurations. (g) Tidal prism-channel area relationship for a number of natural and synthetic cross sections. Inset: detail of the relationship for the present experimental data.

pre-contraction values which, however, cannot completely re-establish due to the further step increase in RMSL imposed at 11,355 cycles (Figure 3a). This leads to a sharp increase in $P$ (which reaches its maximum value) and decrease in the bottom shear stress, and to the consequent vanishing of bottom erosion which actually freezes the network structure (note that the 11,355 point does not overlap the 9,351 point which is characterized by a higher drainage density).

[10] Our experiments suggest the existence of a relationship between the landscape-forming tidal prism, $P$, and the drainage density, $D$ (Figure 3e). Such a relationship seems to be well approximated by a linear trend, although this is speculated to hold with reasonable approximation as a

statistical tendency rather than as a pointwise (new channels develop in the re-expansion phase), instantaneous (a lag exists between *P* and *D*-changes) equivalence. This result qualitatively agrees with findings by *Marani et al.* [2003] for a number of actual salt-marsh watersheds of different size, whereas here we address ontogeny, i.e., the case of the same tidal basin at different stages of its evolution. Moreover, the larger variability displayed by the mean unchanneled length for the salt-marsh watersheds considered by *Marani et al.* [2003] suggests the presence of various overlapping bio-geomorphic processes (i.e., vegetation and microphytobenthos growth, sediment cohesion, minerogenic and organogenic sediment supply) which, at present, cannot be reproduced in laboratory experiments (growing alfalfa and using cohesive sediments are, however, underway).

[11] Our findings are also reinforced by the probability distributions of unchanneled lengths for three characteristic stages of the network development which, in analogy with natural tidal networks, display an exponential character (Figure 3f). The probability distributions characterizing network configurations before the contraction phase and after the re-expansion phase tend to overlap and the mean unchanneled length (i.e., the slope of the semilog plot) at the end of the re-expansion phase tends to recover the pre-contraction value.

[12] Decreasing or increasing tidal prisms promote not only channel network retreat or expansion (Figure 3d) but also shrinking or enlargement of channel cross-sectional areas (Figure 3g). It also emerges that the inlet cross-sectional area, $\Omega$, and the flowing tidal prism, *P*, follow the O'Brien-Jarrett-Marchi "law" [e.g., *D'Alpaos et al.*, 2009], an empirical relationship [*O'Brien*, 1969; *Jarrett*, 1976] substantiated from a theoretical point of view [e.g., *Marchi*, 1990], embodying complex and site-specific feedbacks among tidal channel geometries and tidal flows which occur both in inlet and sheltered channel sections [e.g., *Friedrichs*, 1995; *Rinaldo et al.*, 1999b; *D'Alpaos et al.*, 2010].

[13] Most models, both conceptual and numerical, describing the morphodynamic evolution of tidal channels cutting through vegetated or unvegetated platforms [e.g., *Redfield*, 1965; *Allen*, 1997; *Hood*, 2006; *Kirwan and Murray*, 2007; *Temmerman et al.*, 2007; *Hughes et al.*, 2009], account for the possible supply of sediments (e.g., from rivers or from the sea) whereas our experimental apparatus can reproduce only purely erosive settings. Some studies suggest tidal-channel development to be the result of depositional rather then erosional processes [e.g., *Redfield*, 1965; *Hood*, 2006], whereas others consider erosion as the dominant process [e.g., *Fagherazzi and Sun*, 2004; *Perillo et al.*, 2005; *D'Alpaos et al.*, 2005, 2007b; *Vlaswinkel and Cantelli*, 2011]. In the erosional scenario, differential erosion drives the evolution: Network configuration is driven by local excess in the bed shear stress compared to the critical threshold for sediment motion, as modelled in this experimental context. In the depositional scenario, channels form due to differential deposition driven by gradients of stream power. We suggest that these two apparently distinct processes of network formation can be seen as the result of the same morphodynamic feedback shaping the channel network which is fully captured by our experiments. In both cases, in fact, the spatial distribution of the bed shear stress is a critical process controlling either differential erosion or differential deposition.

[14] Although our experimental approach better simulates networks developing over sandy tidal flats and does not consider relevant processes for tidal landscape formation (related say to halophytic vegetation and microphytobenthos growth and zonation, sediment supply, or sediment cohesion), our experimental network configurations are similar in distinctive statistics and metrics to natural ones. This suggests that our experiments capture the fundamental processes driving network dynamics and are important for a variety of real-life tidal contexts.

## 5. Conclusions

[15] We have analyzed tidal network dynamics in response to changes in the landscape-forming tidal prism, triggered by RMSL variations. Our results show that changes in RMSL immediately affect the tidal prism, and the tidal prism rapidly and strongly influences channel cross-sectional areas, network structure and its drainage density as a measure of network efficiency in draining the landscape. Substantially reversible patterns of network contraction and re-expansion seem to occur that can result in the disappearance of the signatures of past climates: Changes in RMSL could be therefore reflected in network structure and efficiency as they occur. This seems to suggest that processes linked to network form and function such as transport of water, sediment, nutrients and pollutants, are minimally influenced by past RMSLs. A notable diversity emerges among tidal and fluvial landscapes. One, in fact, would superficially be induced to think that cyclic climate forcings (RMSL in this case, a threshold for erosion in *Rinaldo et al.* [1995]) would be facing similar memory effects in geomorphic signatures of past climates. In the case at hand, the lack of sediment supply from the outside should be parallel to the case where no net tectonic uplift operates. Whereas in fluvial landscapes this leads to a pronounced memory effect (different re-occupation of previously incised channels, hysteretic drainage densities), a much more pronounced adaptation to the current climate seems to be operating in the tidal landscape. Whether the lack of memory effects is an artifact of the current experiment or is possibly due to hysteretic behaviour deserves to be further investigated through new experiments. Further experimental work could also possibly address the study of the evolution of topographic concavity in cyclic RMSL forcings. Thus we believe that our results bear significant practical implications on the predictability of the long-term eco-morphodynamics of tidal systems and may help refining our understanding of tidal network dynamics in response to changes in RMSL and of the extent of the imprinting of such changes in the landscape.

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## References

Allen, J. R. L. (1997), Simulation models of salt-marsh morphodynamics: Some implications for high-intertidal sediment couplets related to sea-level change, *Sediment. Geol.*, *113*, 211–223.

D'Alpaos, A., S. Lanzoni, M. Marani, S. Fagherazzi, and A. Rinaldo (2005), Tidal network ontogeny: Channel initiation and early development, *J. Geophys. Res.*, *110*, F02001, doi:10.1029/2004JF000182.

D'Alpaos, A., S. Lanzoni, M. Marani, and A. Rinaldo (2007a), Landscape evolution in tidal embayments: Modeling the interplay of erosion, sedimentation, and vegetation dynamics, *J. Geophys. Res.*, *112*, F01008, doi:10.1029/2006JF000537.

D'Alpaos, A., S. Lanzoni, M. Marani, A. Bonometto, G. Cecconi, and A. Rinaldo (2007b), Spontaneous tidal network formation within a constructed salt marsh: Observations and morphodynamic modelling, *Geomorphology*, *91*, 186–197, doi:10.1016/j.geomorph.2007.04.013.

D'Alpaos, A., S. Lanzoni, M. Marani, and A. Rinaldo (2009), On the O'Brien-Jarrett-Marchi law,*Rend. Lincei Sci. Fis. Nat.*, *20*, 225–236, doi:10.1007/s12210-009-0052-x.

D'Alpaos, A., S. Lanzoni, M. Marani, and A. Rinaldo (2010), On the tidal prism-channel area relations, *J. Geophys. Res.*, *115*, F01003, doi:10.1029/2008JF001243.

de Swart, H., and J. Zimmerman (2009), Morphodynamics of tidal inlet systems, *Annu. Rev. Fluid Mech.*, *41*, 203–229, doi:10.1146/annurev.fluid.010908.165159.

Fagherazzi, S., and D. J. Furbish (2001), On the shape and widening of salt-marsh creeks, *J. Geophys. Res.*, *106*(C1), 991–1003.

Fagherazzi, S., and I. Overeem (2007), Models of deltaic and inner continental shelf landform evolution, *Annu. Rev. Earth Planet. Sci.*, *35*, 685–715, doi:10.1146/annurev.earth.35.031306.140128.

Fagherazzi, S., and T. Sun (2004), A stochastic model for the formation of channel networks in tidal marshes, *Geophys. Res. Lett.*, *31*, L21503, doi:10.1029/2004GL020965.

Fagherazzi, S., et al. (2012), Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors, *Rev. Geophys.*, *50*, RG1002, doi:10.1029/2011RG000359.

Feola, A., E. Belluco, A. D'Alpaos, S. Lanzoni, M. Marani, and A. Rinaldo (2005), A geomorphic study of lagoonal landforms, *Water Resour. Res.*, *41*, W06019, doi:10.1029/2004WR003811.

Friedrichs, C. T. (1995), Stability shear stress and equilibrium cross-sectional geometry of sheltered tidal channels, *J. Coastal Res.*, *11*, 1062–1074.

Hood, W. G. (2006), A conceptual model of depositional, rather than erosional, tidal channel development in the rapidly prograding Skagit River delta (Washington, USA), *Earth Surf. Processes Landforms*, *31*, 1824–1838, doi:10.1002/esp.1381.

Howard, A., W. Dietrich, and M. Seidl (1994), Modeling fluvial erosion on regional to continental scales, *J. Geophys. Res.*, *99*(B7), 13,971–13,986.

Hughes, Z. J., D. M. FitzGerald, C. A. Wilson, S. C. Pennings, K. Wie;ski, and A. Mahadevan (2009), Rapid headward erosion of marsh creeks in response to relative sea level rise, *Geophys. Res. Lett.*, *36*, L03602, doi:10.1029/2008GL036000.

Jarrett, J. T. (1976), Tidal prism-inlet area relationships: CERC-WES general investigation of inlets, *Tech. Rep. 3*, U.S. Army Coastal Eng. Res. Cent., Fort Belvoir, Va.

Kirwan, M., and B. Murray (2007), A coupled geomorphic and ecological model of tidal marsh evolution, *Proc. Natl. Acad. Sci. U. S. A.*, *104*(15), 6118–6122, doi:10.1073/pnas.0700958104.

Leopold, L. B., M. G. Wolman, and J. P. Miller (1964), *Fluvial Processes in Geomorphology*, W. H. Freeman, New York.

Marani, M., E. Belluco, A. D'Alpaos, A. Defina, S. Lanzoni, and A. Rinaldo (2003), On the drainage density of tidal networks, *Water Resour. Res.*, *39*(2), 1040, doi:10.1029/2001WR001051.

Marchi, E. (1990), Sulla stabilità delle bocche lagunari a marea, *Rend. Fis. Mat. Accad. Lincei*, *1*(2), 137–150, doi:10.1007/BF03001888.

Marciano, R., Z. B. Wang, A. Hibma, H. J. de Vriend, and A. Defina (2005), Modeling of channel patterns in short tidal basins, *J. Geophys. Res.*, *110*, F01001, doi:10.1029/2003JF000092.

Mudd, S. (2011), The life and death of salt marshes in response to anthropogenic disturbance of sediment supply, *Geology*, *39*(5), 511–512, doi:10.1130/focus052011.1.

O'Brien, M. P. (1969), Equilibrium flow areas of inlets in sandy coasts, *J. Waterw. Harbors Coastal Eng. Div. ASCE*, *95*, 43–52.

Perillo, G., D. Minkoff, and M. Piccolo (2005), Novel mechanism of stream formation in coastal wetlands by crab-fish-groundwater interaction, *Geo Mar. Lett.*, *25*, 214–220, doi:10.1007/S00367-005-0209-2.

Redfield, A. C. (1965), Ontogeny of a salt marsh estuary, *Science*, *147*(3653), 50–55.

Rigon, R., A. Rinaldo, and I. Rodriguez-Iturbe (1994), On landscape self organization, *J. Geophys. Res.*, *99*, 11,971–11,993.

Rinaldo, A., W. E. Dietrich, G. Vogel, R. Rigon, and I. Rodriguez-Iturbe (1995), Geomorphological signatures of varying climate, *Nature*, *374*, 632–636, doi:10.1038/374632a0.

Rinaldo, A., S. Fagherazzi, S. Lanzoni, M. Marani, and W. E. Dietrich (1999a), Tidal networks: 2. Watershed delineation and comparative network morphology, *Water Resour. Res.*, *35*(12), 3905–3917.

Rinaldo, A., S. Fagherazzi, S. Lanzoni, M. Marani, and W. E. Dietrich (1999b), Tidal networks: 3. Landscape-forming discharges and studies in empirical geomorphic relationships, *Water Resour. Res.*, *35*(12), 3919–3929.

Stefanon, L., L. Carniello, A. D'Alpaos, and S. Lanzoni (2010), Experimental analysis of tidal network growth and development, *Cont. Shelf Res.*, *30*, 950–962, doi:10.1016/j.csr.2009.08.018.

Temmerman, S., T. J. Bouma, J. Van de Koppel, D. Van der Wal, M. B. De Vries, and P. M. J. Herman (2007), Vegetation causes channel erosion in a tidal landscape, *Geology*, *35*(7), 631–634, doi:10.1130/G23502A.1.

Tucker, G. E., F. Catani, A. Rinaldo, and R. L. Bras (2001), Statistical analysis of drainage density from digital terrain data, *Geomorphology*, *36*(3–4), 187–202.

Vlaswinkel, B., and A. Cantelli (2011), Geometric characteristics and evolution of a tidal channel network in experimental setting, *Earth Surf. Processes Landforms*, *36*(6), 739–752.