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The Influence of Wave-, Wind- and Tide-Forced Currents on Headland Sand Bypassing –
Study Case: Santa Catarina Island North Shore, Brazil

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ABSTRACT

Investigations of headland sand bypassing is still an under-reported subject in the literature. This paper aims to understand the contribution of currents forced by different mechanisms such as tides, winds (i.e. local wind acting over the ocean surface generating currents, without considering wave generation) and waves (as they approach/break on the coast) to headland sand bypassing. The study was carried out in an area comprising a series of seven headlands with varying wave exposure due to changes in shoreline orientation and increasing tidal influence close to a relatively large bay. This paper uses a calibrated and validated process-based model (Delft3D) to simulate a series of scenarios including spring and neap tides during flood and ebb conditions and a range of wind and wave scenarios that encompass both average and extreme conditions. The results indicate that waves are the main driving force for the headland bypassing as they transport sand at rates two orders of magnitude higher than tide- or wind-driven sediment transport. The tide-driven currents can only transport sediment during spring tides in locations where the currents are intensified. It is also demonstrated that the wave direction plays an important role in sediment transport. In exposed areas with larger headlands a combination of wave directions is required to first transport sediment offshore (out of the beach) and secondly to transport sediment alongshore and back to the next beach. Whereas in areas with little variation in wave direction exposure, the same oblique wave direction is responsible for the entire headland bypassing process. This is the first time the contribution of tide-, winds- and wave-generated sediment transport to headland bypassing have been studied.

Keywords: Numerical modelling; sediment transport; littoral drift; sediment transport forcing.

1. Introduction

Sand bypassing of headlands is of major interest to coastal researchers, engineers and managers because it is a component of longshore sand transport and can be very important for sediment budgets and their modulation. The process was conceptually described by Evans (1943), Short and Masselink (1999) and Smith (2001). Due to their economic importance, most bypassing studies have focused on man-made structures or inlets (Silvester, 1985; FitzGerald et al., 2000; FitzGerald and Pendleton, 2002; Cheung et al., 2007; Mariani, 2010; Eslami et al., 2010; Ab Razak et al., 2013; Garel et al., 2015). More recently studies have focused on understanding the process using GIS, field data and numerical modelling (Goodwin et al., 2013; Ribeiro et al., 2014; Duarte et al., 2014; Ab Razak, 2015; George et al., 2015; Vieira da Silva et al., 2016a, b). Despite the growing interest in headland sand bypassing, George et al. (2015) highlight that there is little information on processes, pathways and timing of sediment transport around headlands. .

Most of studies infer that the main driving force for headland sand bypassing is waves (i.e. Evans, 1943; Short and Masselink, 1999; Smith, 2001; Goodwin et al., 2013; Ab Razak, 2015). However, while the effect of winds and tidal currents has never been tested, they may also contribute to sediment transport around headlands. Masselink and Pattiaratchi (1998) described the importance of winds on low energy environments, while Lessa et al. (2001) suggest that tidal currents are important components of longshore sediment transport close to large embayments. Therefore, rather than assume winds and tidal currents have little influence, the present paper intends to quantify the importance of each driving force using a process-based model. The aim of the present paper is to: 1) understand the importance of each driving force (waves, tides and wind) on the bypassing process around both protected and exposed headlands under variable tidal influence; 2) identify the environmental conditions that allow the headland sand bypassing to occur; and 3) understand the conditions that generate the headland sediment bypassing in the study area.

2. Regional Settings

The study area is located on the north shore of Santa Catarina Island, southern Brazil (Fig. 1) and encompasses eight beaches (Santinho, Ingleses, Brava, Lagoinha, Ponta das Canas - Canasvieiras, Jurerê, Forte and Daniela) separated by headlands (Fig. 2). Santa Catarina coast is classified as rugged bedrock-controlled strandplain coast (Klein et al., 2010). FitzGerald et al. (2007) described it as having relatively narrow discontinuous coastal plain that is bordered by crystalline rocks and where exposed granitic plutons form numerous low-relief headlands that dominate this section of the coast.

Santa Catarina Island has a microtidal regime, with neap and spring tides ranging between 0.4 to 1.2 m, respectively. Truccolo et al. (2004) found that Santa Catarina State is influenced by storm surges that can reach up to 1 m. Winds are predominantly NE with stronger S winds associated with the passage of cold-front systems (Nobre et al., 1996; Truccolo, 2011).

Figure 1: Study area. A) General location in South America (dot); b) dataset location, numerical grid; c) transect locations (T) where the transport rates were integrated for every simulation.

Figure 2: Detail of the studied headlands. A)Santinho-Ingleses, B) Ingleses – Brava; C) Brava – Lagoinha and Lagoinha - Ponta das Canas – Canasvieiras; D) Ponta das Canas – Canasvieiras – Jurerê; E) Jurerê – Forte; F) Forte – Daniela. Aerial images source: Google Earth Image© 2017 TerraMetrics and Google Earth 2017 Image © 2017 CNES / Airbus.

According to Araújo et al. (2003), waves arrive mainly from S with peak periods of 12 s followed by waves from E with peak periods of 8 s while 30% of the time bimodal sea conditions occur. The wave height averages 1 to 1.5 m, with highest waves from S. The deepwater wave height and peak period can exceed 4 m and 12 s, respectively (Araújo et al., 2003). S swell prevails during austral autumn and winter (March to August), a predominance of E seas occurs during spring while during the summer (December to February) both sea and swell are present. The main wave, tide and wind conditions in the study area are summarized in Table 1.

Table 1: Summary of physical settings (Nobre et al., 1996; Araújo et al., 2003; Truccolo et al., 2004 and Truccolo, 2011).

Physical settings	Characteristic
Tides	0.4 - 1.2 m (neap-spring)
Storm surge	Up to 1m
Main wind direction	Northwest
Extreme wind direction	South
Main wave direction and period	South 12 s / East 8 s
Significant wave height	1 - 1.5 m
Extreme wave conditions	Up to 4 m / > 12 s

The north shore of Santa Catarina Island has an Relative Tide Range (RTR) of ~1 and is mainly wave-dominated, based on Masselink and Short (1993). However, as presented by Vieira da Silva et al. (2016b) when breaker wave height (H_b) is lower than 0.4 m it becomes tide-modified. This scenario usually does not occur at the exposed east-facing beaches in the study area but it is common along the protected north-facing area.

The beachface sediment is homogeneous, with an average diameter of 0.22 mm (Martins and Eichler, 1969; Horn Filho, 2006; Vieira da Silva et al., 2016a). Vieira da Silva et al. (2016b) found that the same size of sediment is transported around the headlands. Also a very similar (0.23 mm) median grain size was found by Vintem et al. (2006) in the Santinho-Ingleses dunefield. Porpilho et al. (2016) showed that the inner shelf has similar sediments together with patches of coarser sediments.

Beaches are classified as ‘sheltered reflective’ on the north coast while on the east the beaches are predominately ‘rip-dominated transverse bar and rip to rhythmic bar and beach’ (TBR-RBB) (Klein et al., 2016). The east-facing beaches are well exposed to waves, while the north and west-facing beaches receive only refracted/attenuated waves (H2, 2008; Vieira da Silva et al., 2016b). CPE (2010) observed the intensification of tidal currents between Lagoinha and Ponta das Canas headlands especially during flooding tide.

The dunefield between Santinho and Ingleses migrates northward and delivers approximately $10,000 \text{ m}^3 \text{ yr}^{-1}$ to Ingleses beach via headland over-passing (Boeyinga et al., 2010). Pinto et al. (2015) observed a reduction in the active dunefield over the last 60 years due to urbanization and increased vegetation coverage.

Vieira da Silva et al. (2016a) identified an anticlockwise sediment transport path in the study area and Vieira da Silva et al. (2016b) confirmed the sediment path that includes longshore sediment transport and headland sand bypassing. This paper further develops the previous studies by analysing the scenarios that generate sediment transport around the headlands and assessing the importance of tide-, wind- and wave-generated currents to headland bypassing.

3. Materials and Methods

This paper uses a process-based (Deflt3D) numerical modeling order to assess the contribution of waves, tide and wind to the headland sand bypassing as well as identifying the environmental conditions that favor bypassing. The model set-up is the same as presented by Vieira da Silva et al. (2016b) and included both Wave and Flow modules. The wave model used two nested numerical grids, the first (Regional) is a curvilinear grid covering an area of 410 x 240 km resulting in varying resolution from deep (10 x 6 km) to shallow water (1.7 x 1.7 km). A higher resolution (Local) grid covering an area of 50 x 95 km was nested on Regional grid and also gave resolution from 1.5 x 1.2 km offshore to 30 x 30 m at the study area. The Flow module was run with a very similar grid as Wave Local. The differences are: 1) the Flow grid is two lines/rows smaller than Wave Local, avoiding boundary instability; and 2) the Flow module was run in 3D mode with five sigma vertical layers. The higher resolution close to the shore (i.e. surf zone) and five sigma layers allowed a better representation surf zone dynamics, including cross-shore sediment transport (e.g. undertow currents, rip currents). The hard bottom (i.e. headlands) was mapped so no sediment transport will start over the headlands and no erosion of the headlands occurs.

The model was calibrated (waves, currents and water level) in three locations for approximately a month representing austral summer and validated for a month during winter period. Detailed error statistics for both calibration and validation periods is presented in Table 2. To further improve the accuracy of the model, the authors tested three sediment transport formulae (Bijker, 1967; 1971; van Rijn 1993; 2000; Soulsby, 1997) against measured data from a sediment trap experiment. The experiment was carried out at two locations around two headlands (total of four sampling locations). A total of 140 samples were obtained avoiding bottom disturbances by placing (recovering) the samplers at (from) the bottom by divers. A detailed description of the field measurements is presented by Vieira da Silva et al. (2016b). The authors concluded that the Bijker formulae (1967; 1971) provided

the best results in terms of sediment transport magnitude ($MAE = 1.36 \times 10^{-7} \text{ m}^3 \text{ m}^{-1} \text{ s}^{-1}$, $RMSE = 1.87 \times 10^{-7} \text{ m}^3 \text{ m}^{-1} \text{ s}^{-1}$, $R^2 = 0.6$). Therefore it was used by the authors as well as for the present study.

Table 2: Error statistics for significant wave height (H_s), Peak wave period (T_p), peak direction (Dir_p), water level (wl), currents in U and V direction. Root mean square error (RMSE), Mean Absolute Error (MAE), Bias (BIAS), Scatter Index (SI) and standard deviation of errors (std).

Cal/Val	Location	Error statistics	H_s	T_p	Dir_p	wl	U	V
Calibration	ST15	RMSE	0.24	1.03	18.78	0.11	0.05	0.13
		MAE	0.14	0.52	10.48	0.08	0.03	0.09
		BIAS	-0.14	-0.57	-10.78	-0.03	-0.02	-0.09
		SI	0.20	0.14	0.21	0.05	0.03	0.06
		std	0.19	0.86	15.38	0.10	0.05	0.09
	ST16	RMSE	0.13	0.96	34.67	0.10	0.07	0.05
		MAE	0.09	0.64	13.44	0.08	0.05	0.04
		BIAS	-0.07	-0.26	-0.31	-0.04	0.03	0.00
		SI	0.22	0.13	0.73	0.05	0.04	0.02
		std	0.11	0.92	34.67	0.09	0.06	0.05
	ST17	RMSE	0.25	0.55	41.87	0.10	0.14	0.11
		MAE	0.18	0.41	35.56	0.08	0.11	0.08
		BIAS	-0.14	-0.13	-36.78	-0.02	0.02	0.01
		SI	0.19	0.08	0.40	0.05	0.07	0.05
		std	0.21	0.54	20.01	0.10	0.14	0.11
Validation	ST15	RMSE	0.19	1.32	23.68	0.07	0.12	0.11
		MAE	0.13	0.84	16.97	0.06	0.11	0.09
		BIAS	-0.02	-0.47	-0.65	0.00	-0.10	0.02
		SI	0.13	0.14	0.23	0.04	0.06	0.05
		std	0.18	1.24	23.68	0.07	0.05	0.11
	ST16	RMSE	0.12	1.57	12.00	0.10	0.06	0.04
		MAE	0.08	0.65	8.50	0.07	0.04	0.03
		BIAS	-0.01	-0.29	1.00	0.00	0.00	0.00
		SI	0.24	0.19	0.27	0.05	0.03	0.02
		std	0.12	1.54	11.96	0.10	0.06	0.04
	ST17	RMSE	0.36	1.19	28.19	0.08	0.13	0.12
		MAE	0.29	0.74	23.62	0.06	0.10	0.09
		BIAS	-0.29	0.00	-17.22	0.00	-0.01	0.01
		SI	0.28	0.13	0.26	0.04	0.06	0.06
		std	0.22	1.19	22.33	0.08	0.13	0.12

A series of scenarios for waves, tides and local wind were simulated (Table 3) to identify which ones were capable of causing sediment transport around the headlands. To simplify the analysis we analyze the processes separately. The non-linearity effects between tides, wind and wave forcing are beyond the scope of this paper.

3.1 Tide Scenarios

The tide scenarios were obtained from a 29-day simulation including two neap and two spring tides forced using predicted tides from TPXO 7.2 model (Egbert et al., 1994; Egbert and Erofeeva, 2002 - see location of the tidal constants in Fig. 1). The sediment transport was obtained from the simulation for neap (or spring) tides for the day when the tidal amplitudes were minimal (or maximal). At each scenario (spring ebb, spring flood, neap ebb and neap flood) the instantaneous sediment transport was obtained when the maximum sediment transport occurs.

3.2 Wind Scenarios

To define the wind scenarios a NCEP Climate Forecast System Version 2 (CFSv2 - Saha et al., 2014) time-series (from 1979 to 2015) was analyzed (see location of the time-series in Fig. 1). First, the series was split into octants (N, NE, E, SE, S, SW, W and NW – Fig. 3a), the frequency of occurrence of each direction was calculated and the average and extreme were defined as the wind speed equivalent to the 50th and 95th percentile (Fig. 3b). Winds from W were not simulated since it occurs only 3.6% of the time. The simulated direction was defined as the central value for each direction bin (i.e. 0, 45, 90, 135, 180, 225, 315°). In order to analyze the effects of local winds generating currents in separate (without the effects of waves or water levels), the water level was set to zero and no waves were forced or generated during the simulations. No bottom changes were allowed during the simulation.

Each scenario was run for 5-10 days, including warm-up time to ensure the model is stable and the sediment transport is constant.

Figure 3: Wind scenarios selection. a) Percentage of occurrence per direction; b) Example (S winds) of cumulative distribution function of wind speed and definition of average and extreme scenarios.

3.3 Wave Scenarios

A Wave Watch III (WW3 - Tolman, 1991; 1997; 2009) time-series was analyzed to define the wave simulation scenarios. It consists of 36-year dataset of significant wave height, peak wave period and peak wave direction between 1979 and 2015 (see location of the time-series in Fig. 1). Similar to the method applied for selecting wind cases, the series was split into octants (N, NE, E, SE, S, SW, W and NW) and the frequency for each direction calculated (Fig. 4a). An average and an extreme scenario were defined for each direction corresponding to the 50th and 95th percentile of the wind magnitude, respectively (Fig. 4b). The associated peak wave period (T_p) for each selected H_s was defined according to Kamphuis (2010). Waves from SW, W, NW and N occur during less than 3% of the time and are likely to propagate offshore or arrive at the study area well attenuated, therefore these directions were not propagated. The wave direction for each scenario was defined as the central value of each

bin (i.e. 45, 90, 135, 180°). For all wave scenarios the water level and winds were set to zero (no winds or water level changes) and bottom changes were not allowed during the simulation. Each scenario was run for 5-10 days, including warm-up time to ensure the model is stable and the sediment transport is constant.

Figure 4: Wave scenarios selection. a) Percentage of occurrence per direction; b) Cumulative distribution function of wind speed and example (S winds) of average and extreme scenarios definition.

Table 3: Modelled scenarios. Tides: simulations of tides only; Winds: simulations considering local winds only (without wave forcing or generated in the model domain); Waves: simulations forced with waves only (no winds or tides were included).

#	Scenario	Tides	Wind	Waves
1	Flood Neap Tide	Flood Neap	-	-
2	Ebb Neap Tide	Ebb Neap	-	-
3	Flood Spring Tide	Flood Spring	-	-
4	Ebb Spring Tide	Ebb Spring	-	-
5	NW average wind	-	NW 5.2 m s ⁻¹	-
6	NW extreme wind	-	NW 9.8 m s ⁻¹	-
7	N average wind	-	N 6.4 m s ⁻¹	-
8	N extreme wind	-	N 9.9 m s ⁻¹	-
9	NE average wind	-	NE 6.4 m s ⁻¹	-
10	NE extreme wind	-	NE 10.1 m s ⁻¹	-
11	E average wind	-	E 5.8 m s ⁻¹	-
12	E extreme wind	-	E 9.8 m s ⁻¹	-

13	SE average wind	SE 5.6 m s ⁻¹	
14	SE extreme wind	SE 10.5 m s ⁻¹	
15	S average wind	S 7.2 m s ⁻¹	
16	S extreme wind	S 12.6 m s ⁻¹	
17	SW average wind	SW 7.4 m s ⁻¹	
18	SW extreme wind	SW 14.5 m s ⁻¹	
19	NE average wave		H _s 1.6 m / T _p 6.8 s
20	NE extreme wave		H _s 2.7 m / T _p 7.7 s
21	E average wave		H _s 1.6 m / T _p 7.8 s
12	E extreme wave		H _s 2.7 m / T _p 8.5 s
23	SE average wave		H _s 1.7 m / T _p 9.3 s
24	SE extreme wave		H _s 3.1 m / T _p 9.9 s
25	S average wave		H _s 2 m / T _p 10.6 s
26	S extreme wave		H _s 3.7 m / T _p 11.1 s

Overall, 26 scenarios encompassing a range of tides (four scenarios), winds (14 scenarios) and wave (eight scenarios) conditions were simulated and their characteristics are presented in Table 3. Vieira da Silva et al. (2016b) presented the sediment path for the region and, based on their results we defined representative transects (Fig. 1) where the sediment transport outputs were integrated. For each transect, the start and end point were defined where sediment transport occurs (i.e. the starting point is usually inland and final point where the sediment transport is insignificant). The instantaneous sediment transport results after model stabilization were interpolated from the numerical grid at every meter and further integrated to obtain the sediment transport for each transect. The model results are given in $\text{m}^3\text{m}^{-1}\text{s}^{-1}$ and were integrated for each transect (m^3s^{-1}) and simply multiplied by the number of seconds in a year (m^3yr^{-1}) to facilitate the interpretation of the results, as the aim of the present work is to analyse the importance of tides, wind-generated currents and waves on headland sand bypassing.

4. Results

This section presents the results of the modelling. It is divided in three sub-sections (tides, winds and waves) since each forcing present different orders of magnitude of sediment transport. Furthermore, the sediment transport rates were integrated along each transect presented in Fig. 1 and the transport rates are presented in m^3y^{-1} to facilitate interpretation. Figs. 5-7 present a summary of the sediment transport at each transect for all scenarios. Hollow squares refer to insignificant sediment transport ($<50 \text{ m}^3\text{yr}^{-1}$), a negative sign indicates sediment transport in the preferred sediment transport direction, i.e. an anticlockwise direction (towards the entrance of the bay – see Fig. 8a), whereas a positive sign indicates sediment transport in a clockwise direction (towards the exposed area – see Fig. 8c). The location of each transect (T) is presented in Fig. 1 and follows the anticlockwise sediment transport path of the region.

The tidal simulations (Fig. 5) indicate that during neap tides sediment transport does not exceed $50 \text{ m}^3 \text{y}^{-1}$ in the study area. While, during spring tides, the transport can reach $10^3 \text{ m}^3\text{y}^{-1}$ at the entrance of the North Bay (T20 and T23). It was also observed that tide-induced sediment transport at the northernmost portion of the Santa Catarina Island (T12) during spring ebb tides is a result of the water exiting the bay. The results indicate the anticlockwise direction of the transport during flood conditions (water entering the bay) while the clockwise transport occur during the ebb. The highest magnitude of the transport was observed in T23 during flood conditions ($4.03 \times 10^3 \text{ m}^3 \text{y}^{-1}$) while the maximum sediment transport during ebb conditions was observed in the same location with a much lower transport rate ($1.43 \times 10^3 \text{ m}^3 \text{y}^{-1}$).

Figure 5: Transport ($\text{m}^3 \text{yr}^{-1}$) during the tide scenario simulation per location (see Figure 1). + indicate sediment transport in clockwise direction (exiting bay); - indicate anticlockwise direction of sediment transport (towards the bay). Magnitudes lower than $50 \text{ m}^3 \text{y}^{-1}$ are not represented in the figure.

Fig. 6 presents the sediment transport modelling results for the wind simulation. The results indicate that wind-generated currents only induce sediment transport during extreme conditions with a maximum rate of $3.91 \times 10^3 \text{ m}^3 \text{y}^{-1}$ (anticlockwise) at T2 during extreme S winds. At this point (T2) the water mass is compressed between the headland and the small island, thereby intensifying the currents and consequently the sediment transport. At T16 the maximum transport ($1.74 \times 10^3 \text{ m}^3 \text{y}^{-1}$) occurs during extreme SW winds and is clockwise. This scenario generates currents moving out of the bay, which on reaching T16 are intensified by the presence of the headland between Ponta das Canas - Canasvieiras and Lagoinha beaches. At T20, extreme SW winds can induce the transport of approximately 100

$\text{m}^3 \text{y}^{-1}$ of sediment. Most of the wind-forced sediment transport higher than $50 \text{ m}^3 \text{y}^{-1}$ occurs in clockwise direction (extreme N at T12, extreme S at T16 and extreme SW at T16 and T20) however, the highest sediment transport occurs in anticlockwise direction (extreme S at T2). During extreme S and especially SW winds, T16 and T23 are influenced by the wind-generated clockwise currents as the wind reinforces the flow of water exiting from North Bay. During extreme N winds sediment is transported at T12 as a result of the eastward deflection (towards the ocean) of the wind-driven currents as they approach Santa Catarina Island. T2 has anticlockwise sediment transport as N (to the north) currents generated by extreme S and SW winds are compressed between the headland and the island, intensifying the sediment transport.

Figure 6: Transport ($\text{m}^3 \text{yr}^{-1}$) during wind scenario simulation per location (see Fig. 1). Av=Average; Ex=extreme; NW=Northwest; N=North; NE=Northeast, E=East, SE=Southeast; S=South and SW=Southwest. + indicate sediment transport in clockwise

direction (exiting bay); - indicate anticlockwise direction of sediment transport (towards the bay). Magnitudes lower than $50 \text{ m}^3 \text{ y}^{-1}$ are not represented in the figure.

Wave-induced sediment transport reaches $10^5 \text{ m}^3 \text{ y}^{-1}$, as shown in Fig. 7. The highest sediment transport rates are found during extreme easterly waves. T3 has the highest anticlockwise sediment transport rate ($4.56 \times 10^5 \text{ m}^3 \text{ y}^{-1}$) while the highest clockwise transport rate occurred at T11 ($4.64 \times 10^5 \text{ m}^3 \text{ y}^{-1}$).

Figure 7: Transport ($\text{m}^3 \text{ y}^{-1}$) during wave scenario simulation per location (see Fig. 1).

Av=Average; Ex=extreme; NE=Northeast, E=East, SE=Southeast and S=South. + indicate sediment transport in clockwise direction (exiting bay); - indicate anticlockwise direction of sediment transport (towards the bay). Magnitudes lower than $50 \text{ m}^3 \text{ y}^{-1}$ are not represented in the figure.

NE waves tend to transport sediment in a clockwise direction in the exposed area (T1 to T13) and in an anticlockwise direction in the protected area (T14 to T23). For average waves the exceptions are T5, located at the protected south portion of Ingleses beach, and T8 indicating the waves transport sand towards Brava-Ingleses headland and T12 because of wave obliquity at this point pushes sand towards Lagoinha beach. For extreme NE waves anticlockwise transport occurs in the exposed area (T4 and T6) due to a vortex formation generated by the presence of the island as well as the headland; this vortex widens during these conditions changing the direction of the transport in these locations. In the protected area, T17 and T19, an inversion of the sediment transport also occurs, however, at this point the magnitude of the transport is lowest for this scenario ($< 800 \text{ m}^3 \text{ y}^{-1}$).

E waves produced a general trend of anticlockwise transport sediment (towards the bay) in both the exposed and protected portions of the study area. Exceptions for average conditions are: T1, T7 and T11 that due their location in the northern portion of the beaches tend to transport sediment back along the beach; T2 and T17 are affected by the presence of small islands that increase the refraction and diffraction processes changing the wave direction and consequently the sediment transport at these points; and T19 where the sediment transport magnitude close to zero ($< 60 \text{ m}^3 \text{ y}^{-1}$). Extreme waves from E also produce anticlockwise sediment transport in the study area, however with higher rates than average conditions. Despite the higher transport rates during extreme scenarios, a difference between extreme and average E conditions is found in T2, where extreme waves transport sediment anticlockwise while average waves transport clockwise.

SE waves mainly affect the exposed portion of the study area. Average waves can transport sediment from T1 to T12 (from T13 the sediment transport rate is $< 55 \text{ m}^3 \text{ y}^{-1}$), extreme waves can transport sediment ($> 50 \text{ m}^3 \text{ y}^{-1}$) from T1 to T15. For both, Average and Extreme waves the sediment is mainly transported towards the bay (anticlockwise). Exceptions are T1

during average conditions, and T5 and T15 for extreme conditions. At T1 a sediment circulation cell is generated where sand is transported back to Santinho close to the headland and offshore (towards T2) at the end of the transect. During average conditions, the sediment can be more effectively transported close to the headland; on the other hand, during extreme conditions, the outer part of the circulation cell becomes stronger and transports more sand towards T2. At T5, wave diffraction generates a difference in wave height that results in a current moving from the middle of Ingleses to the south, consequently transporting sand in a clockwise direction. The maximum magnitude of sediment transport is found in T3 during extreme conditions, reaching $3.22 \times 10^5 \text{ m}^3 \text{ y}^{-1}$.

Waves from S are capable of transporting sediment only in exposed areas. The transport is limited to T1 to T4 during average conditions and from T1 to T13 during extreme conditions. However, it also can transport significant amounts of sediment, reaching $2.67 \times 10^5 \text{ m}^3 \text{ y}^{-1}$ during extreme conditions at T1.

5. Discussion

As in any numerical modelling exercise, assumptions and limitations have to be considered as the results are interpreted. The main assumptions and limitations are related to: 1) assumption that the nonlinearity effects between tides, winds and waves are small compared to the magnitude of each forcing separate which is the focus of this study; 2) despite of having tested different sediment transport equations against measured data (rarely done in numerical model applications), due to the nature of the field work carried out by Vieira da Silva et al. (2016b) it was not possible to measure the sediment transport during extreme events which can lead to some uncertainties during extreme events; 3) as the aim of this paper is to analyze scenarios to better understand the conditions that generate headland bypassing, some conditions such as bimodal wave cases were not considered; and 4) the results of wind

scenarios presented here are intended to understand the importance of winds only, without any other influence such as tides or waves that would normally be generated as the wind blows over the ocean's surface.

This section is divided into eight sub-sections covering the seven headlands (E to W) in the bypassing process, followed by a summary of the driving forces that generate headland sediment bypassing in the study area.

5.1. Santinho - Ingleses (T1 to T5)

This headland (Fig. 2a) was described by Vieira da Silva et al. (2016b) as the headland that has the most complex sediment transport pattern in the study area with both bypassing and overpassing. Dune sand overpasses the headland via a dunefield linking both beaches (Boeyinga et al., 2010; Pinto et al., 2015). Vieira da Silva et al. (2016b) found that the rates calculated by Boeyinga et al. (2010) and Pinto et al. (2015) for headland overpassing are two to three times higher than the net headland bypassing at this location. It was observed at T2 that extreme S and SW winds as well as waves from E, SE and S generate a northward current, which is intensified by the presence of the headland and small islands located 700-1000 m off the headland. These forces generate the northward migrating asymmetrical, catenary megaripples mapped by Porpilho et al. (2016). The authors also identify similar bedforms at T4, in this case migrating offshore (anticlockwise/eastward), driven by waves from NE (average) and E (extreme) that generate sediment transport in the same direction. The transport path at T3 occurs in anticlockwise direction, and is mainly driven by waves from E to S. Continuing its path, the sand transport is divided in two: 1) through the inner shelf (T6) driven by most wave conditions and 2) arrives at the southern end of Ingleses beach (T5), driven by waves from NE to E. The headland bypassing scheme presented here is similar to the model presented by Goodwin et al. (2013) for Byron Bay, Australia, where the

sand by-passes the prominent headland via the inner shelf and after passing the headland is pushed to the beach by NE (ENE in Australian case) and E (both cases) waves. Byron Bay and Ingleses are located at similar latitudes (difference of approximately one degree), both in the southern hemisphere and dominated by S waves.

5.2. Ingleses - Brava (T7-T9)

Ingleses - Brava headland (Fig. 2b) receives sediment from the inner shelf that has bypassed Santinho-Ingleses headland (Vieira da Silva et al., 2016b). This delivery, computed at T8, indicates that all simulated wave directions transported sediment toward the headland, except the S average scenario. Again, this pathway of sediment through the inner shelf is similar to that presented by Goodwin et al. (2013) for Byron Bay. Sediment is pushed back to Ingleses (T7) during NE and E wave conditions and pushed offshore during SE (average and extreme) and S (extreme) scenarios. The transport of sediment to Brava beach occurs during E and SE waves, during both average and extreme scenarios, and under S waves during extreme conditions; NE waves push it back offshore.

5.3. Brava - Lagoinha (T10-T14)

This headland (Fig. 2c) also receives sediment from the inner shelf (Vieira da Silva et al., 2016b), as computed for T10 (see Figs. 1, 8). Extreme waves from E through S as well as average waves from E and SE transport sediment clockwise towards Brava-Lagoinha headland. Average and extreme waves from NE also deliver sediment from the inner shelf to the headland (T13). At T11 sand is transported clockwise back to Brava during NE and E waves while SE and S waves transport sand anticlockwise towards the tip of the headland (Fig. 8C). At T12, tides can transport sediment during spring ebb conditions (clockwise), and extreme N winds are able to transport sand back to the tip of the headland. The waves transport sediment anticlockwise during most simulated scenarios, with the exception of

average S waves where no transport higher than $50 \text{ m}^3 \text{ y}^{-1}$ is observed. At T14 the sand is transported to the west towards Ponta das Canas headland. According to the model results presented here, this path is driven by waves from NE through SE. Headland sand bypassing around this headland does not follow a classic pulsating model, such as that of Short and Masselink (1999), but rather works as a continuous longshore sediment transport path.

5.4. Lagoinha-Ponta das Canas - Canasvieiras - (T14-T16)

At this headland (Fig. 2c) the tidal influence on sediment transport is close to zero (Fig. 5) and wind-driven currents are only capable of transporting sediment during extreme S or SW conditions in an anticlockwise direction (T16). Therefore, waves are the main driving force, following the classic model of pulsating headland sand bypassing with migratory spit development (Ponta das Canas spit) presented by Evans (1943), Short and Masselink (1999) and Smith (2001). The pulsating spit cycle controls the availability of sediment to the downdrift areas (Vieira da Silva et al., 2016a) and the sediment source for Ponta das Canas spit. The sand sources are both Lagoinha beach (T15) and wave-driven sand that travels through the inner shelf from the tip of Brava-Lagoinha headland (T14), as described by other authors (Evans, 1943; Short and Masselink, 1999; Smith; 2001; Ab Razak, 2015).

5.5. Ponta das Canas - Canasvieiras - Jurerê (T17-T18)

Sediment is transported from Ponta das Canas - Canasvieiras towards Jurerê (T17 – Fig. 2d) by average NE waves while the transport is in the opposite direction during extreme NE and E scenarios. However, average NE waves occur twice as frequently as extreme NE and E waves together, indicating a net transport anticlockwise. At the eastern end of Jurerê, Vieira da Silva et al. (2016a) also described a cyclic development of a minor migratory spit indicating an anticlockwise net sediment transport driven by average and extreme NE and extreme E waves. Tide and wind transport is negligible ($<50 \text{ m}^3 \text{ y}^{-1}$).

5.6. Jurerê - Forte (T19-T20)

Around this headland (Fig. 2e / T20) the tidal influence starts to become important and sediment can be transported towards the bay (anticlockwise) or towards the ocean (clockwise) during spring flood and ebb tides, respectively, with similar magnitudes (see Fig. 5), resulting in a net tide-induced sediment transport close to zero. Wind forcing can transport sediment only during extreme SW conditions at T20 in clockwise direction. At this headland, once again, the wave-induced sediment transport is the main driving force for headland bypassing. Almeida et al. (1991) indicate that the net sediment transport at Forte beach is towards the bay. At the western end of Jurerê (T19) the average NE waves drive the sediment towards Forte (anticlockwise) while (less frequent) extreme NE and E waves as well as average NE waves transport sediment to Forte (T20).

5.7. Forte - Daniela - North Bay (T21-T23)

Daniela spit (Fig. 2f) has the highest level of tide-induced sediment transport of the study area, especially at the SW end of the spit, towards the bay (T23) where transport rates during spring flood tides ($4 \times 10^3 \text{ m}^3 \text{ y}^{-1}$) are three times higher than during spring ebb tides ($1.4 \times 10^3 \text{ m}^3 \text{ y}^{-1}$), indicating a net tide-induced sediment transport towards the bay. Wind-driven currents do not transport sediment at this location (T21 to T23), and waves at this point can only transport sediment during NE conditions (both average and extreme) and extreme E waves, showing the importance of the wave direction and height in this protected part of the study area. These conditions are responsible for the development of Daniela spit as a result of the net sediment transport into the bay (Diehl, 1997). The author suggests that the source of sediment to Daniela spit is from the exposed beaches of Santa Catarina Island (i.e. Ingleses, Brava) as demonstrated here. Silveira et al. (2010) classified Daniela as being in dynamic

equilibrium with a shoreline seaward of its equilibrium position, indicating a positive sediment budget for the spit.

5.8. Headland bypassing overview

The present paper simulates the conditions that drive the headland bypassing and compared the amount of sand transported by different forcing (i.e. tidal-forced, wind-forced excluding waves, and wave-forced). Fig. 8 presents the conditions and magnitudes of sediment transport generated by different forcing mechanisms.

Figure 8: Overview of conditions that generate headland sand bypassing in anticlockwise (A) and clockwise directions (C). The arrows represent the sediment transport for anticlockwise (net) and the opposite of the authors suggestions for clockwise. Colours represent the magnitude of the sediment transport for each scenario in $\text{m}^3 \text{y}^{-1}$.

This is the first time the importance of each driving force has been tested and confirms the assumptions of several authors (Evans, 1943; Short and Masselink, 1999; Smith, 2001; Goodwin et al., 2013; Ab Razak, 2015) that waves are the main driving force for headland sand bypassing. The magnitude of sediment transport around headlands due to waves can reach $10^5 \text{ m}^3 \text{ y}^{-1}$, while wind-forced and tide-induced currents can transport sediment with two orders of magnitude lower than waves ($10^3 \text{ m}^3 \text{ y}^{-1}$). While waves decrease their sediment transport capacity as the area becomes more protected (towards T23), the tides can only transport sediment at the entrance of the bay (T20 and T23) where the entrance narrows and the tide-induced currents are stronger. A similar process of current intensification was described by Lessa et al. (2001) in NE Brazil. It was also observed that wind-forced currents can transport sediment during extreme conditions, especially for winds from N (T12), S (T2 and T16) and SW (T2, T16 and T20), similar to that described by Masselink and Pattiaratchi (1998) for a low energy coasts.

Fig. 8 demonstrates the importance of wave direction for headland sand bypassing. In the exposed areas (T1 to T12) waves from SE and E are the driving force, with E waves generating the highest transport rates from T1 to T17. This is because waves from the E lose less energy during wave refraction (when compared to the other directions). On the other hand, in the protected areas (T13 to T23), where there is little variation of wave direction a single oblique wave direction (NE) is responsible for the entire process.

6. Conclusions

This paper presented a numerical study assessing the importance of tides, winds and waves on sediment transport around headlands. The study was conducted on northern Santa Catarina Island, southern Brazil. Previous headland sediment bypassing studies have always assumed waves are the sole agent of transport and have not tested the influence of tides and winds.

This paper has, for the first time, separately tested each driving forcing to assess their role in the process. It was undertaken using a calibrated and validated numerical model and the results were used to understand the conditions that generate sediment transport around the headlands and along the beaches.

For the study area, tide-driven currents can only transport sediment during spring tides and in very specific locations where the currents are intensified and so is the sediment transport. Wind-driven currents are only capable of transporting sand during extreme wind conditions.

Waves were the main driving force for headland sediment bypassing. Waves transported sediment on the order of $10^5 \text{ m}^3 \text{ y}^{-1}$ while tides and winds result in the transport of up to $10^3 \text{ m}^3 \text{ y}^{-1}$ of sediment. The more exposed headlands had higher sediment transport, and while the magnitude of wave-induced sediment transport reduces as the coast becomes more protected, the wave-driven sediment transport always remained higher than tide- or wind-driven transport. For headland bypassing to occur, the right wave direction is also crucial, with the sand bypassing occurring in either direction at most headlands of the study area. The range of wave directions is, accordingly, important for the net balance for the whole system and its temporal variability may be the cause of the pulsating cycle of headland sand bypassing and spits development.

Depending of the degree of wave exposure and the headland size, a different combination of wave conditions are needed. Firstly the sediment has to be transported offshore, than a different wave angle would push sand back to the next beach. The simulation / measurements of sediment transport around headlands during bimodal wave cases would further develop the understanding of headland bypassing and the importance of wave directions to the process.

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Highlights

- Importance of different processes to headland sand bypassing were tested;
- Representative scenarios were modeled;
- Waves are the main driving force for headland bypassing;
- Wave-forced transport is two orders of magnitude higher than other forcing.