Contrasting styles of swell-driven coastal erosion: examples from KwaZulu-Natal, South Africa

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Abstract – During 2006–2007, the KwaZulu-Natal coast of South Africa was exposed to several large swell events ($H_o > 3$ m), near the peak of the lunar nodal cycle, causing shoreline recession. The largest swell ($H_s = 8.5$ m) struck the coast on the March equinox (18th–20th) and generated a strong storm-return flow. Observations made before, during and after record dramatic coastal erosion (shoreline recession of up to 40 m and substantial property damage). This swell event removed the semi-continuous nearshore bar system and 'conditioned' the coast such that lesser subsequent swell events accomplished much greater amounts of coastal erosion than expected (up to 100 m at certain erosion hotspots) because waves reached the coast without significant energy dissipation. Subsequent bar generation rebuilt the inshore bars within six months. The styles of erosion during the March '07 event and other 2007 swells were markedly different. Lesser swells are focused by headlands and result in megarip development and activation of erosion hotspots. The March '07 event still-water level was raised (equinoctial spring high tide and a storm surge of 0.33–0.45 m) to a level that rendered most headlands (and erosion hotspots) ineffective and resulted in laterally extensive erosion of soft shorelines. Results record cumulative effects of successive swell events on coastal behaviour that proved to be critical in enabling erosion to proceed at rapid rates after the coast had been initially destabilized. Unlike hurricanes and tsunamis, surges associated with swell events are relatively minor and therefore extensive erosion is linked with high lunar tides. There is circumstantial evidence that swell-induced erosion follows the broad 18.6 yr lunar nodal tidal cycle when the chances of large swells coinciding with high water levels are increased.

Keywords: coastal erosion, megarip, high swell, disequilibrium coastline, storm-return flow.

1. Introduction

Most of the world's coastlines are eroding, and typical erosion rates for soft coastlines vary from 0.3 m to 1.0 m per year (Pilkey & Cooper, 2004). The drivers of coastal erosion are complex and include large magnitude events (large swells, tsunamis and storms), sea level rise, sediment scarcity, human activities and antecedent conditions. All of these factors vary in time and space and may interact via feedback relationships. Understanding the role of specific drivers of coastal erosion is, however, important in the global context of climate change. Storms (particularly hurricanes) are often cited as important drivers of coastal erosion (e.g. Dolan & Hayden, 1981), as surges associated with low pressure systems cause water levels to be especially elevated and enable waves to reach back-beach areas.

Many of the world's open ocean coasts experience large swells generated by distant storms in addition to storm waves. These differ from storms in that the waves tend to be larger, of longer period and are not always accompanied by a tidal surge. Storm frequency, size and duration can be related to local synoptic, regional and global drivers. For example, the effects of El Niño on storms have been noted in California (Ruggiero *et al.* 2001; Allan & Komar, 2002; Sallenger *et al.* 2002; Bromirski *et al.* 2004) and in Australia (Phinn & Hastings, 1995; Hemer *et al.* 2008).

During the period 2006–2007 a number of large swell events occurred on the KwaZulu-Natal Coast (KZN) coast of South Africa (Fig. 1). Several of these swells coincided with spring and equinox tides and resulted in shoreline recession. The most dramatic effects were associated with a large swell on the March equinox (18th–20th), which had an 8.5 m significant shallow water wave height (H_s) and a maximum swell height of 14 m (H_{max}) (M. Rossouw, CSIR, pers. comm.). The

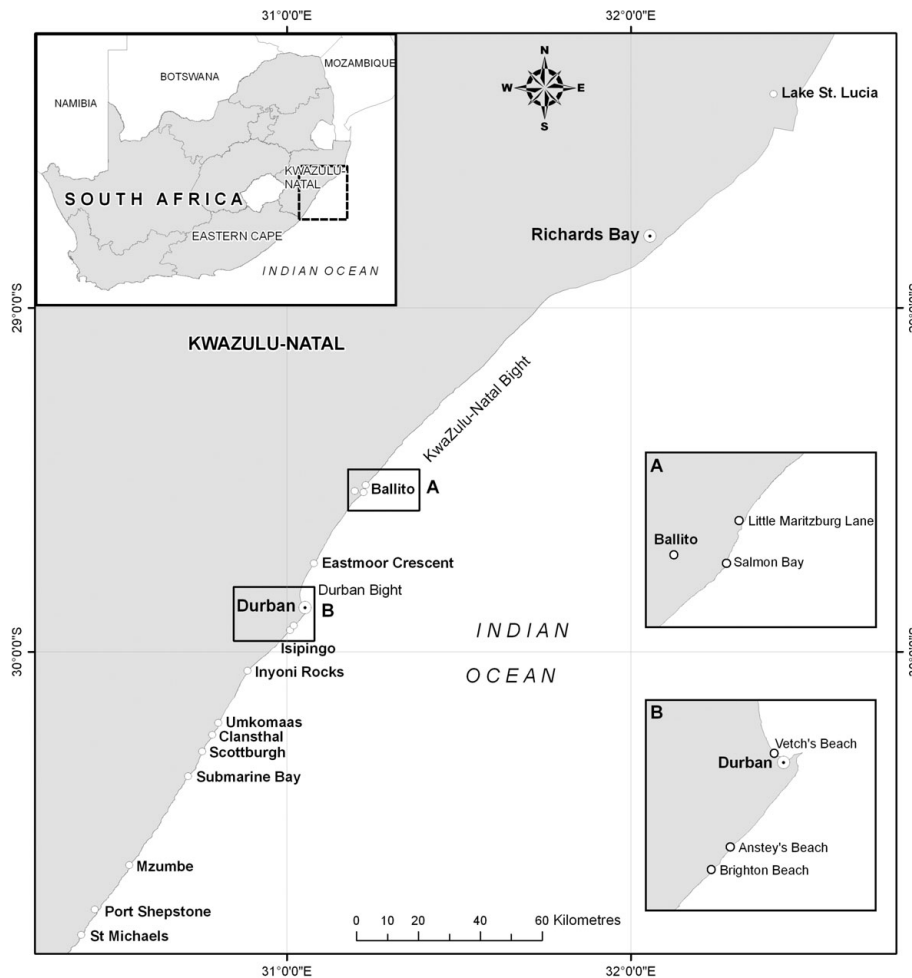*Author for correspondence: asconsulting@telkomsa.net
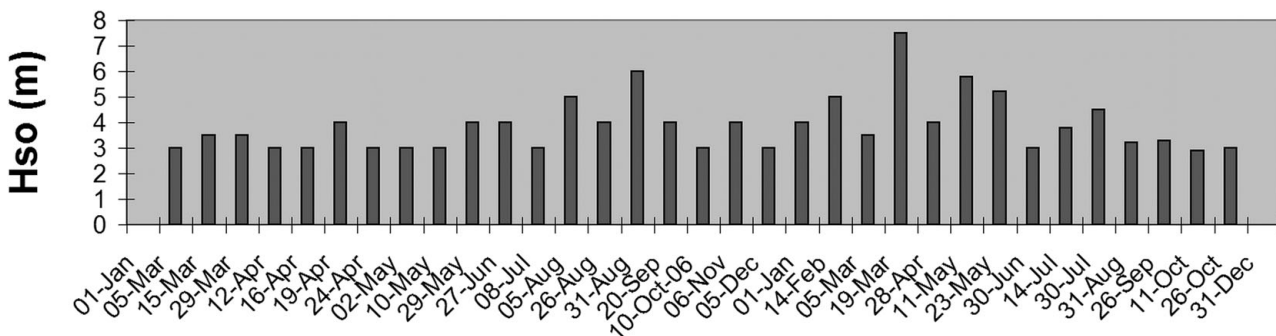
Figure 1. Location map.

Figure 2. Significant 2006–2007 swell events ($H_{so} > 3$ m) for the KwaZulu-Natal Bight area.

temporal and spatial patterns of coastal response to this and other swell events were highly variable.

We describe the morphodynamics of a series of swell events with attention to water levels, wave heights and erosion patterns revealed by a combination of visual observations, in most cases, and field measurements (Fig. 2). The aim of this paper is to document the impacts of the 2006–2007 Erosion Event on the KZN coast of South Africa (Fig. 1). The swell that struck on the March equinox was particularly damaging but this cannot be seen in isolation, and observations made before, during and after this event provide insights into the overall coastal morphodynamics. Unless otherwise stated, the highest significant offshore swell (H_o)

values were obtained from satellite altimetry (http://las. aviso.oceanobs.com/las/servlets/dataset?catitem = 2) for the centre of the KwaZulu-Natal Bight (Fig. 1). Tidal data were obtained directly from the Hydrographer SA Navy. Coastal elevations are given according to Chart Datum (CD), which for the Durban area is mean sea level (msl), plus 0.9 m.

2. Physical setting

The KZN coastline is generally eroding in the long-term (Cooper, 1991a,b, 1994) at rates comparable with global values. This ongoing coastal erosion is attributed to various global and regional factors, including coastal

Table 1. 2006 erosion episodes at Eastmoor Crescent, Durban

Date dd/mo/yr	Erosion	H_O	Tide state	Tidal height (m)	Comment
5/03/06	None	3		na	
15/03/06	EHS	3.5	Springs	n/a (predicted 2.18)	Equinox
19/03/06	EHS (very strong)			na	
29/03/06	EHS	3.2	Springs	n/a (predicted 2.16)	Swell peaked 28/03
7/09/06	?EHS	2.5	Springs	2.23	
26/09/06	EHS	3.3	After springs	1.58	Equinox
7/10/06	EHS	3	Springs	2.3	Lunar Nodal Cycle
10/11/06	Minor erosion	2.5	Neaps	1.54	

EHS – erosion hotspots

and terrestrial land use changes, river sand mining and dam construction (Garland & Moleko, 2000). In many places coastal development has been allowed on the primary dunes and even in some instances, on the back-beach, closing off this natural source of sand.

KZN has a high-energy coastline with coarse-grained, sandy reflective to intermediate beaches (Cooper, 1991a). On the intermediate beaches that characterize the study area, the nearshore zone is typified by semi-continuous, shore-parallel nearshore bars. Swell data from the South African Data Centre for Oceanography, compiled from voluntary observation ships, for the area 29–30° S and 31–33° E, indicate that this coast is dominated (40 % of the year) by large amplitude southerly swells (Begg, 1978; Rossouw, 1984), mostly generated by eastward moving cold fronts with low pressure centres passing to the south of southern Africa. Large swells ($H_{max} = 8$ –10 m and periods of 11–17 s) are commonly recorded during mid-winter storms in the KwaZulu-Natal Bight (Ematek, 1992). Swells associated with such storms generally approach from the south and southwest (Hydrographic Research Unit, 1968), but once on the shallower continental shelf (< 100 m deep) are refracted and make landfall from a more SSE direction. The KZN coast is also impacted by easterly to SE swells associated with tropical cyclones (hurricanes) and cut-off low (COL) storms. Although less frequent in occurrence, tropical cyclones have been responsible for damaging large swells; for example, Tropical Storm Imboa (February, 1984) produced 9 m (H_s) swells in the Richards Bay area (M. Rossouw, CSIR, pers. comm.). An example of a swell associated with a COL was that which struck on the March equinox (2007). Moes & Rossouw (2008) have indicated an average H_s of 1.8 m for Durban, diminishing northward to 1.5 m at Richards Bay (Fig. 1). Durban and Richards Bay have average spring tidal ranges of 1.8 and 1.84 m, respectively, with maximum tidal heights of 2.3 and 2.47 m, respectively.

The KZN coast comprises a number of headland-bound bays containing sandy beaches (Cooper 1991a,b, 1994), some of which form barriers across river mouths (Cooper, 2001). Beach rotation (see Short, 2002) is a feature of the headland-bound bays. A continuous sand beach in the form of a 20 km long zeta bay extends through the Durban Bight (Fig. 1). Most of the beaches are backed by steep coastal dunes, although some are backed by rock outcrop. Dunes commonly reach heights of 30–60 m, and are often compound features, varying in age from Late Pleistocene to Holocene (Tinley, 1971). Coastal development, especially over the last fifteen years, has covered large parts of the coastal dune cordon and any bare sand patches have been planted and stabilized, often with alien vegetation.

3. Tidal-driven erosion events of 2006

A number of large swell (H_s > 3 m) events occurred during 2006. Three of these were associated with the equinoctial and lunar nodal cycle (LNC) peaks. Erosion associated with such events was confined to isolated sandy coastal stretches along the KwaZulu-Natal coastline (Richard's Bay, Salmon Bay, Eastmoor Crescent & Vetch's Beach, Submarine Bay and St Michaels-On-Sea; Fig. 1). These locations are erosion hotspots (EHS), as described elsewhere (List, Farris & Sullivan, 2003; McNinch, 2004), that respond readily to large wave events. One of the best observed examples is the highly reflective Eastmoor Crescent Beach, Durban, which is located at the north end of a log-spiral bay (Fig. 1). Gardens of houses built in the dunes were undercut and infrastructure was threatened as the high water line (HWL) receded by 30 m during the equinoctial and LNC erosion events in 2006. This erosion was primarily tide-driven, but the occurrence of large swells, during or prior to these high tides, played a role (Table 1).

Erosion during 2006 was caused by the development of a megarip (see Short, 1999) which formed a cusp 60–100 m wide. Shoreward head-cutting megarip currents caused the formation of a steep erosion sand scarp. This beach is normally typified by symmetrical longshore sandwaves (see Thevenot & Kraus, 1995) with wavelengths of ± 300 m. One such sandwave grew larger, asymmetrical and mobile, EHS activity took place in the trough that preceded it, and it moved progressively northward, driven by the northerly longshore drift.

4. Decaying cyclone swell erosion morphodynamics

Oceanographic conditions in early 2007, prior to the March '07 event, were dominated by swells ($H_{so} =$ 2 to 5.5 m; see Table 2) produced by decaying tropical

Table 2. Decaying cyclonic swells that preceded the March (2007) swell

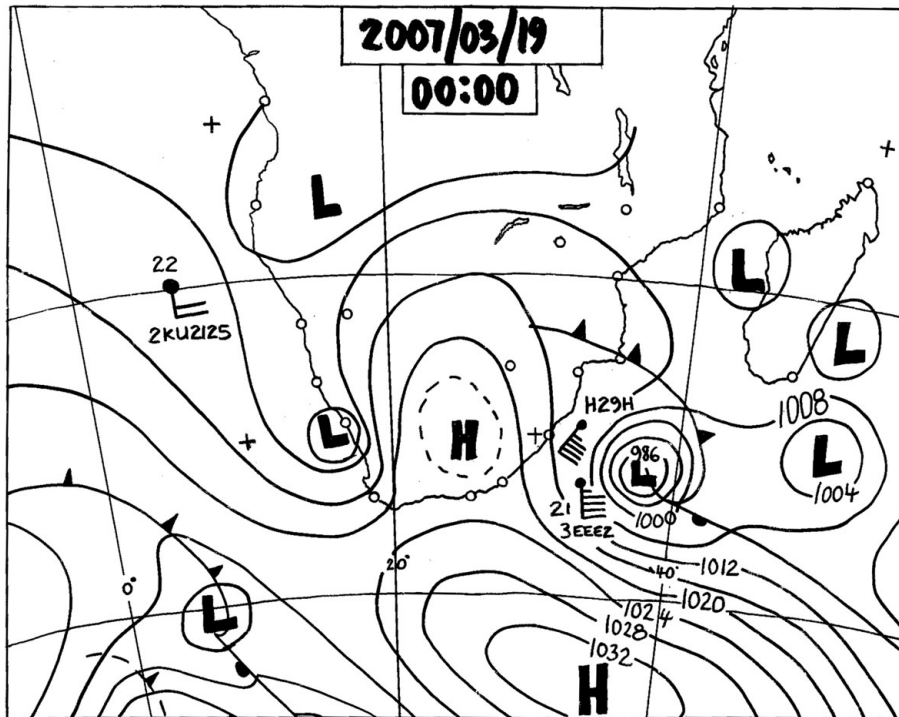| Date	Erosion	H_O	Tide	Tidal height (m)	Comment
14/02/07	None reported	5.0	Before springs	1.96	Ex-Cylone Favio Swell
1–5/03/07	EHS	3.5	Springs	1.66 to 2.11	Ex-Cyclone Gamede Swell

Figure 3. Synoptic chart showing the *Cut-Off Low* weather system responsible for the storm that produce the large swell on March '07 swell (source: South African Weather Service).

cyclones (hurricanes). Two late-season Indian Ocean tropical cyclones (Favio and Gamede) moved west towards Madagascar, and then turned south, weakening into extra-tropical lows as they did so. Both were blocked by high pressure systems, remained stationary and generated sizeable swell that persisted for several days, pounding the KZN coastline. Swell from ex-tropical cyclone Favio peaked four days before spring tides, while that from ex-tropical cyclone Gamede coincided with a spring-high tide (Table 2). These events activated some EHS and opened isolated estuaries, notably that of Lake St Lucia which had been closed for five years prior to this (Zaloumis, 2007).

5. March 2007 swell morphodynamics

The March 2007 swell was generated by an intense cut-off low (COL) pressure system (Fig. 3; Table 3), which remained semi-stationary some 500–700 km southeast of the KZN coastline, between the 18th and 20th March 2007. The swell peaked early on 19th March; data from the Richards Bay (Fig. 1) wave rider buoy gave an H_{max} of 14 m and an H_s of 8.5 m, a period of 16 seconds and a southeasterly direction (Rossouw, pers. comm). The swell peak struck twenty-four hours before the equinox

Table 3. Data from the March (2007) swell, measured at Durban

Date	Erosion	H_O(m)	*Tide predicted	*Tide measured	Surge
17/03/07	No erosion	2	1.98	2.15	0.17
18/03/07	No erosion	3–4 SE	2.12	2.34	0.22
19/03/07	Lateral erosion	Hs: 8.5 SE	2.24	2.57	0.33
20/03/07	Lateral erosion	5.5	2.28	2.73	0.45
21/03/07	No data	3.	2.25	2.58	0.33
22/03/07	No data	2.5	2.13	2.32	0.19
23/03/07	No data	2.5	1.95	2.04	0.09

*Note all tidal heights are CD.

(Smith *et al.* 2007; Guastella & Rossouw, 2009), which was boosted by a storm surge (Table 3).

The March '07 swell impact, boosted by the unusually high spring tides and storm surge, resulted in the inundation of coastal areas that seldom experience it and caused widespread coastal erosion from southern Mozambique (Smith *et al.* 2007) to the Eastern Cape (Anderson & Mead, 2009). Hinterland penetration was generally low due to the steep nature of the coastline; however, seawater surged 2 km into the Richards Bay Harbour. Estuary barriers were overwashed and washover fans 100–300 m wide created, comparable to a weak category 3 Caribbean hurricane (Morton & Sallenger, 2003). Offshore the nearshore (surf) bars
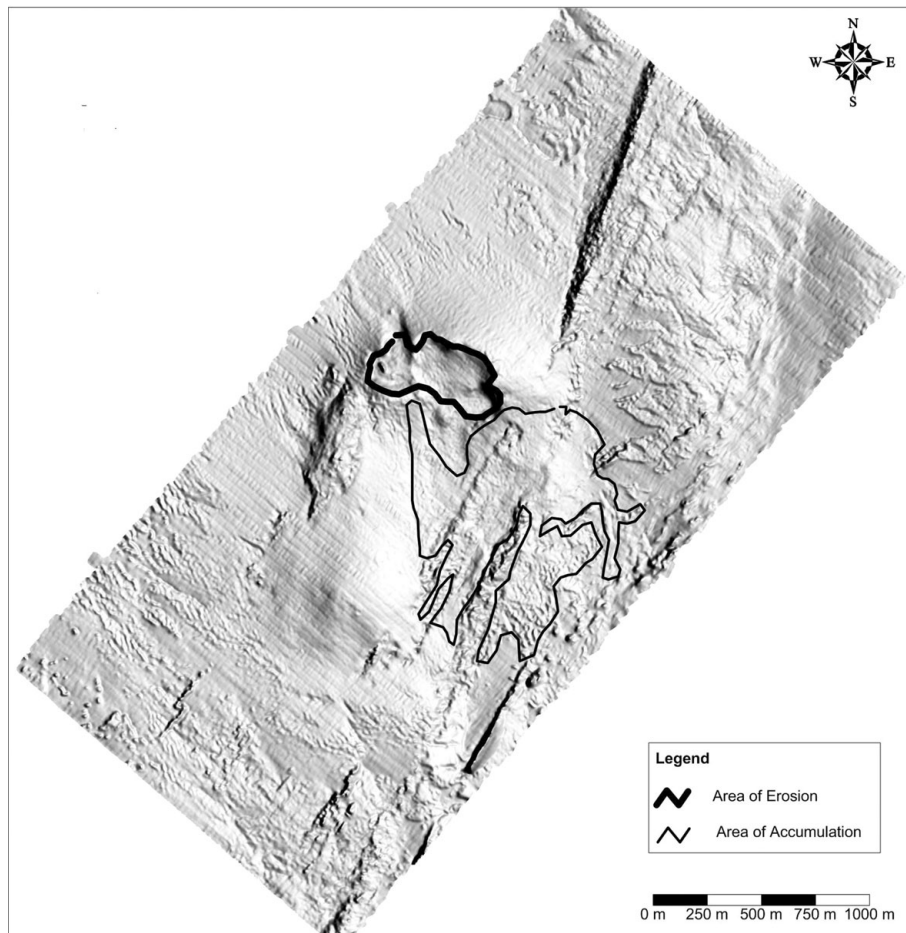
Figure 4. Multibeam image of the Richards Bay offshore dredge dump site showing scouring and deposition.

were destroyed and sediment moved beyond the depth of closure. Dunes, beach, nearshore and inner-shelf sands were eroded.

5.a. March 2007 swell impacts

5.a.1. Richards Bay

Richards Bay (Fig. 1) underwent coastal erosion, associated with coastal dune undermining, and the HWL retreated by up to 30 m. Shelf sediment at the Richards Bay dredge dump site, located at −20 m CD and 3 km from the coast, had built up to −11 m CD prior to this event (January, 2006 survey). A subsequent survey (July, 2007) noted that this feature had been lowered to −14 m. Although this survey may include effects from subsequent swells (Fig. 2), it is likely that most of it was related to the March '07 swell. Five hundred thousand cubic metres of sediment was eroded and transported 200 to 700 m further offshore and deposited at depths of about −21 m CD (P. Van den Bossche, M. R. Machutchon & P. J. Ramsay, unpub. report no. 2007–011, Marine Geosolutions (Pty) Ltd, 2008)(Fig. 4). This amount of erosion is equivalent to the Richards Bay annual longshore drift volume (see Schoonees, 2000). This evidence proves the existence of a return flow associated with the March '07 swell event, as is to be expected with an event of this

magnitude (see Thornton, Humiston & Birkemeier, 1996; Gallagher, Elgar & Guza, 1998).

5.a.2. Ballito

The Ballito coastline projects into the Indian Ocean (Fig. 1) and comprises a number of short topographically bound beaches bracketed by rocky headlands, associated with wave-cut platforms. The March '07 swell caused the HWL to retreat by 5 to 50 m. Dunes were undercut and structures erected on them were damaged. In the rocky areas a boulder storm beach deposit was formed on the landward side of the wave-cut platform (Fig. 5). Old coastal defences were exposed and existing seawalls failed (Fig. 6).

The zone between the measured tidal height (2.73 m CD) and the erosion line (± 4.5 m CD), at the height of the swell, represents rapid water level changes due to the pulsed arrival of wave sets. Wave run-up inundation levels reached 11.6 m CD, but in general this did not result in scour, unless focused by badly placed infrastructure. Erosion was generally laterally persistent and greatest on the southern lee of high headlands (Mather, 2007; Smith et al. 2007). The higher the blocking headland the greater the observed run-up (Fig. 7). Substrate also played a key role and damage was greatest where structures had been built
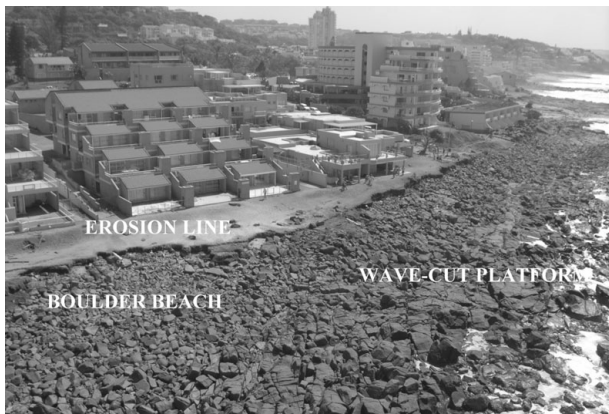
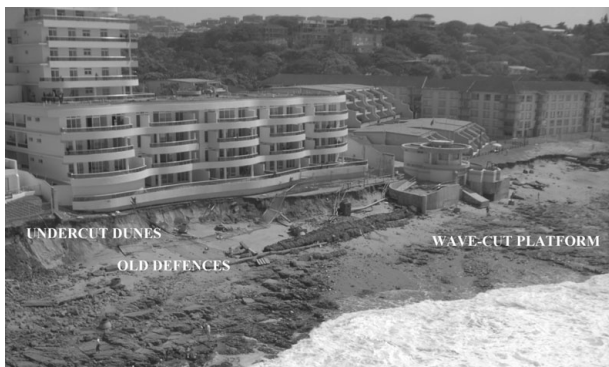Figure 5. Ballito rocky coastline following the March '07 swell event.

Figure 6. Ballito: multi-storey block founded on the dune cordon and located within the 5 m amsl contour.

Figure 7. Ballito: headland induced erosion (with anthropogenic component), note the greater erosion on the southern side (left of image).

on sand (Fig. 6), especially within the 5 m amsl contour (5.9 m CD), and particularly where bedrock is shallow (Smith *et al.* 2007). Wave-cut platforms amplified erosion.

The seabed in the vicinity of the wreck *Fame* (a common SCUBA destination some 350 m off Salmon Bay, Ballito; Fig. 1) deepened from −18.3 to −25.0 m CD between December 2005 and February 2006 (Table 4). This indicates a gradual loss of sand to at least February (2006). By late 2008 it had built up significantly to −10 m CD. Onshore, Salmon Bay lost

Table 4. Changing bathymetry off Salmon Bay (2005–2008)

Date	Depth (m)
October (2005)	−19.1
December (2005)	−18.3
February (2006)	−25.0
Late 2008	−10

some dune buffer (HWL retreated 10 m) during the March '07 swell. Simple calculations suggest that a minimum of 1.5×10^6 m^3 sediment may have been removed from the Salmon Bay coastline and deposited 350 m offshore at depths of at least −20 m CD. SCUBA ground truthing (late in 2008) still showed that the nearshore and shallow inner shelf (5–15 m deep) were littered with building and infrastructure rubble.

The soft coastline at Little Maritzburg Lane (Fig. 1) experienced severe erosion. This was due to a rocky point (surfer's point) to the south bypassing much of the wave energy northwards and focusing it on the soft coastline at the end of the rocky point.

5.a.3. Durban

During the March '07 swell event the HWL receded 5 to 35 m in a few hours (Smith *et al.* 2007); wave run-up was surveyed at 4.9–10.9 m CD (Mather, 2007). The higher run-ups were on the exposed Anstey's and Brighton beaches, whereas the more protected parts of the Durban Bight experienced lower run-ups. At 650 to 800 m off the southern exposed beaches, seaward of a very high point near Isipingo (Fig. 1), erosion was detected at depths of −18 to −22 m CD (P. J. Ramsay & P. Van den Bossche, unpub. report 2008–007, Marine Geosolutions (Pty) Ltd, 2008).

Four million cubic metres ($\sim$40 m^3 per metre of coastline) of sand were stripped from the Durban beaches during this large swell (Mather, 2008) (Fig. 1). This volume is eight times the annual longshore drift (see Schoonees, 2000). Extrapolation from these measurements suggests that 2.5×10^7 m^3 of sand could have been lost from the total KZN coast in 48 hours (Smith *et al.* 2007). The lower wave run-up in the central Durban beaches (between Vetch's and Eastmoor beaches) damaged urban beachfront structures, especially glass doors and windows. In contrast, on the exposed southern beaches, water-loffel retaining systems and concrete seawalls failed. When seawalls did hold the line, some were overtopped and excavated from behind and failed to stop the erosion. In general they induced intense scouring, especially at their ends, amplifying the swell damage.

5.a.4. KZN South Coast

The KZN South Coast was less severely impacted. Here a coastal zone called the Admiralty Reserve, which extends from the HWL inland for 47 m is present. The removal of vegetation and building is prohibited

Figure 8. Inyoni Rocks: note the wide northern beach on June, 2006 (left image), whereas by July, 2007 (right image) the northern beach has thinned and sediment has built up on the southern point. The July, 2007 image was captured prior to peak erosion; note the lack of surf bars.

in this zone, but in places where this restriction has been relaxed, swell damage was experienced. In areas of vegetated coastal dunes, run-up never exceeded 4.9 to 5.9 m CD, and was often less.

6. Winter 2007 swell morphodynamics

There was a gap of just over a month between the March '07 large swell event and the onset of the Winter '07 erosion cycle. During this time there were no large (> 3 m) swells (Fig. 2). Winter erosion is driven by seasonally enhanced south-to-north littoral drift, driven by the stronger winter swell regime. This generally results in beach thinning in the southern parts of topographically bound beaches, accompanied by deposition on the southern lee of northern headlands (Fig. 8).

Winter '07 erosion was restricted to erosion hotspots and built upon that already accomplished by the March '07 swell. It was driven by a series of eight large swell events ($H_s \geq 3$ m) and several minor ones which struck over a period of four months (Fig. 9). Ten swells coincided with spring tides and six with neaps (Table 5). It commenced with a 4 m swell on April 29th (Fig. 9) which maintained a 3 m height through the spring tidal cycle. This was followed by two large swells (> 5 m)

on the 11th and 23rd May, both of which occurred on neap tide (Table 5). Minor EHS erosion was associated with these events, but against the backdrop of the March '07 erosion, mostly went unnoticed at the time. From this point to the end of August, chronic coastal erosion occurred at some EHS localities: Little Maritzburg Lane (Ballito), Eastmoor Crescent, (Durban), Inyoni Rocks (Durban), Submarine Bay, Clansthal, Scottburgh and Mzumbe. This occurred on all spring high tides, and several neap high tides; most damage to infrastructure occurred at Inyoni Rocks and Submarine Bay (Table 5) where the HWL retreat was greatest. With the exception of Eastmoor Crescent, all these localities are within topographically bound beaches, associated with megarip currents. Although this style of winter erosion is normal for this coast, following the March '07 event it was extreme. A similar pattern was recorded from California during the 1996– 1997 El Niño season (Sallenger *et al.* 2002) and this was also related to megarip current activity (Thornton, MacMahan & Sallenger, 2007). Dramatic erosion took place on July 30th when a swell ($H_o = 4.5$ m), again coinciding with spring tides, struck the coast (Table 5). At its peak, winter erosion occurred during neap tides and even during low swells; however, the greatest impact was during high swells and spring tides. The

Table 5. Submarine Bay* Winter erosion schedule

Date (DD/MO/YR)	Erosion	H_o (m)	Tidal height	Wind speed variation (m/s)	Wind speed (avg) m/s	Wind variation	Storm type†
							No surf bars
7–12/05/07	E	1.9 to 5.4 SW	1.43 to 1.65	na	na	NE	Strong HP over E of country, CF to S, strong PG
23/05/07		5.2 SE	1.73	1.8–8.2	4.7	SW–S	Fresh SSW, Cold front followed by strong HP
01/06/07	E	1.9	1.74	0.7–9.6	3.8	SE–NE	Fresh NE, CF followed by ridging high
08/06/07		2.2	1.68	2.9–5.6	3.7	SW–SSE	Mod SSE, funny COL
15/06/07	E	2.1	1.93	1.4–4.1	2.7	WSW–NE	Mod NE, CF followed by high
22/06/07	D	2.2	1.54	0.8–6.7	3.7	var–NE	Mod NNE, probably CF followed by high
30/06/07	E	3	1.97 (0.144 surge)	0.7–4.4	2.7	SSW–NE	Var–NE, CF, COL SE of KZN
07/07/07	E: 2 m	1.6	1.68	0.9–3.9	3.0	SW–NE	Var–NE, no charts
14/07/07	E: 4.5 m	3.8 SW	na	0.9–5.1	3.1	SSW–NE	Mod NE, CF
20/07/07	E1 m	2.1	1.55	1.6–5.1	2.9	var–NE	Mod NE, CF strong S of country
21/07/07	E	2.2	1.56	1.9–9.1	4.9	SSW–SSE	Strong S, CF
30/07/07	E: 6–10 m	4.5 SW	1.88 (-0.12 surge)	1.8–4.0	3.1	SW–ENE–S	Mod var, CF, S swells
07/08/14	E	2.5	1.42	0.8–7.7	4.9	SSW–S	Mod S, CL followed by CF
15/08/07	none	2.2	2.24 (0.22 surge)	3.8–13.3	6.9		Strong S, CF, S swells
29/08/07	E	3.2 SW	2.29	1.3–6.5	4.7	N–NE	Str SW 27–28, fresh NE 29–30, COL
30/08/07	E	3.2	2.3	1.0–5.5	3.4	SW–NE	Mod NE, after COL
							Surf bars reformed
11/09/07		2.4	2.19	0.5–8.5	5.3	N–NNE	Fresh NNE, str CF S of KZN
26/09/07		3.3	2.21	5.8–14.6	9.4	NNE–NE	Strong NNE, CF followed by ridging high
11/10/07		2.9	2.1	1.2–8.2	4.6	SSW–NE	Fresh NNE, no charts
26/10/07		3	2.34	2.1–11.7	7.1	N–NE	Strong NE, CF/COL? Ridging high
10/11/07		2.4	2.03	3.1–11.8	7.8	S–SSW	Strong SSW, CF
24/11/07		2.1	2.16	3.5–8.5	5.6	S–SSW	Fresh SSW, not much, CL
24/12/07		2.3	1.94	1.6–5.7	4.0	NE–S–SE–NNE	Var E, CF ridging high

*This is based on observations at Submarine Bay (R. Osborne, pers. comm.) but there is good agreement with Ballito, Eastmoor Crescent and Inyoni Rocks.
†CF – cold front; CL – coastal low; COL – cut-off low; HP – high pressure.
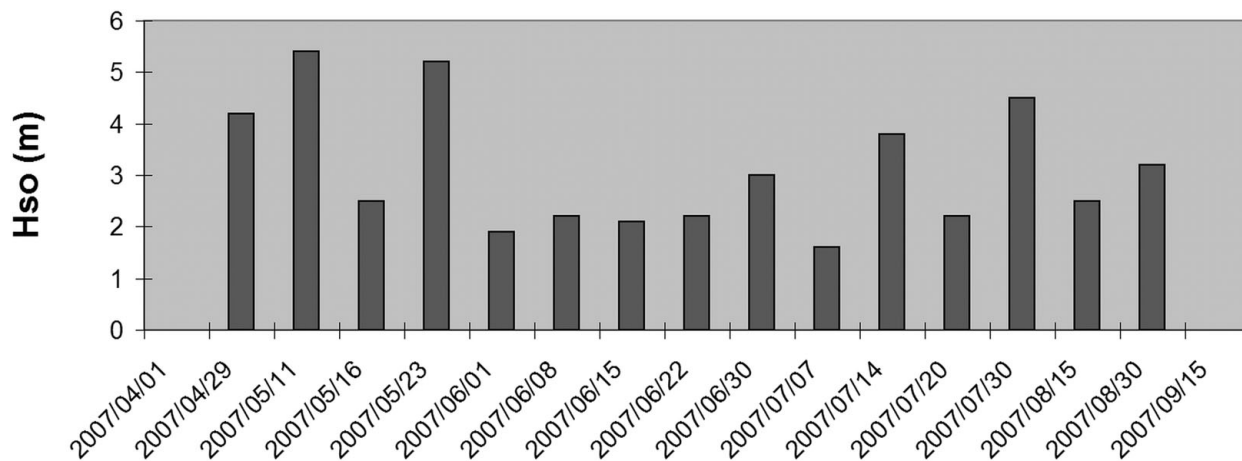
Figure 9. Significant open ocean swells during the May to August (2007) Winter Erosion cycle.

Figure 10. EHS at Inyoni Rocks, Amanzimtoti, June (2006: left) and July (2007: right) (Source: Independent Newspapers). The 2007 erosion had not yet peaked and but for an intervention strategy the shoreline may have receded further. Note the absence of a nearshore bar and suspended sediment in the nearshore surf zone on the right.

final erosion episode occurred on 30th August when a swell ($H_o = 3.2$ m) coincided with a very high spring tide (2.3 m CD) (Table 5). This event marked the end of the prolonged phase of EHS activity that commenced in late April 2007.

HWL retreat values of 0.6 to 10 m per day were achieved at certain erosion hotspots during single events, but these totaled to give cumulative retreat values of 40 to 100 m (Fig. 10). Although these figures may not seem high for seasonal events, as some beaches in SE Australia are known to normally oscillate by as much as 100 m, with a recovery time of 2–5 years (Thom & Hall, 1991; Short, Tremanis & Turner, 2001), they are equal to, and in some cases exceed, the KZN coast maximum historic EHS HWL variation (Table 7). In some instances, only dump rock intervention prevented the Winter '07 erosion from reaching its natural peak. Analyses of the low-lying terrestrial topography of both Inyoni Rocks and Submarine Bay suggest that a further 30 to 50 m of

erosion could have taken place if no intervention had been undertaken.

7. Coastal recovery

A new nearshore bar system (surf bars) was developed by early September 2007. As the quality of the surf improved, this event was well observed by the large local surfing community. Following this, a large swell ($H_o = 3.3$ m) struck on the September equinox (Table 6), but produced little notable erosion, even though it was comparable to, and in fact slightly higher than the 31st August '07 swell (the last major erosive event). Only one significant event was recorded (at Submarine Bay), the significance of which is still being assessed. For the remainder of 2007, swells of a size that had previously been associated with erosion were linked with non-erosion and even deposition (Table 6). By February (2008), most EHS localities and laterally eroded beaches had been restored to at least 60 %

Table 6. *The largest swells of the 2007 summer season*

Date	Erosion	H_O	Tidal state	Tidal height	Comment
11/09/07	No erosion	2.4	Springs	2.08	Coast defended/ Surf bars reformed
26/09/07	No erosion	3.3	Springs	2.28	Parameters > August Swell
11/10/07	No erosion	2.9	Springs	2.04	This combination experienced erosion during winter
26/10/07	No erosion	3	Springs	2.24	Parameters ∼ August Swell
10/11/07	No erosion	2.4	Springs	1.95	This combination experienced erosion during winter
10/11/07	No erosion	2.4	Springs	1.95	This combination experienced erosion during winter
24/11/07	No erosion	2.1	Springs	2.11	Equivalent to winter erosion forming events
09/12/07	No erosion	2.5	Springs	1.87	Strong deposition (D: 20 m)
24/12/07	No erosion	2.3	Springs	1.98	This combination experienced erosion during winter

of their pre-March '07 erosion width. Pristine coastal dunes which had been impacted, had re-vegetated to some degree and in some instances new fore-dunes had established. In urban areas the coastal dune cordons have been impacted by development, to the point where they are dysfunctional and incapable of acting as either a swell defence or sediment source (Mather, 2007; Smith *et al.* 2007). These had to be repaired artificially using four-ton geo-textile sandbags. Although the KZN coastline appears to have re-equilibrated, the sand loss in some urbanized coasts has resulted in the new HWL being 5 to 10 m landward of the pre-March '07 position.

8. Discussion

The distinctive characteristics of the March '07 swell event were its swell size ($H_s = 8.5$ m) and that it peaked less than 24 hours before the March equinox (coinciding with the joint highest tide of the year) which occurred near the top of the LNC. The proximity to the storm of origin (Fig. 3) resulted in a storm surge (0.33 to 0.45 m), and this together with the swell being disordered, as a result of the storm centre being only 450 km away (Smith *et al.* 2007), meant that the wave sets were closely spaced and there was insufficient time between wave land-falls for water to drain away completely under gravity. Consequently, wave energy could not be dissipated in the surf zone as has been noted elsewhere (Cooper *et al.* 2004). On most of the KZN coast, dunes and a steep hinterland prevented inland penetration and consequently sediment could only be moved alongshore or offshore (Morton & Sallenger, 2003), except at estuary barriers where overwash occurred. Thus a storm surge hydraulic head was established which gave rise to a strong return flow.

Subsequent EHS activity under moderate swell conditions is attributed to the March '07 swell having left the coast in a state of disequilibrium. Nearshore bars had been destroyed or the sand moved too far offshore by the return bottom current to be effective (see Backstrom, Jackson & Cooper, 2009). Offshore evidence from Richards Bay, Durban and Salmon Bay supports this. As the rising swell limb was very steep, offshore sediment transport probably took place early in the March '07 swell event following a process of episodic net offshore bar migration (see Ruessink, Pape & Turner, 2008). During subsequent smaller swell events, the lack of a nearshore bar system reduced the

frictional effect of incoming swell and resulted in waves breaking closer to shore, with higher energies due to reduced energy dissipation. This process has been recorded from the Australian Gold Coast (Castelle, Le Corre & Tomlinson, 2008). Consequently, following the large March '07 swell event, smaller swells with heights not normally associated with coastal erosion drove the megarip currents and EHS erosion. Between the swells on the 30th August ($H_o = 3.2$ m) and the 26th September equinox ($H_o = 3.3$ m), no major swell occurred and the nearshore (surf) bars were able to reform, restricting further erosion. This event was near-synchronous along the coast and marked the end of a six-month period of coastal disequilibrium triggered by the March '07 large swell event.

Storm-return flow events, such as that driven by March '07 swell, offer a mechanism by which sediment can be exported from the coast and nearshore zone to the inner shelf and beyond (Elliot, 1986; Tucker & Wright, 1990; Finkl, 2004; Backstrom, Jackson & Cooper, 2009). It is known that sediment was moved to depths of at least -18 to -22 m CD during the March '07 event. Sediment build-ups on the landward side of shore-parallel, aeolianite reefs, at depths up to -60 m CD in KZN are known (Flemming, 1981). Additional evidence that sediment passes offshore from the nearshore zone is shown by the presence of the shoreface-connected ridge fields on this coast (Bosman, Smith & Uken, 2008).

While large swell events commonly move sediment into the longshore drift via megarip-currents, severe events such as the March '07 swell move it from the nearshore zone onto the shelf. The size of the swell is undoubtedly important in shifting the focus of wave breaking and imparting excess energy to the shoreline, but the enhanced water levels associated with barometric surge, extreme astronomical tides, storm surges and wave set-up are also responsible for coastal erosion. Unlike elsewhere (Cooper *et al.* 2004; Backstrom, Jackson & Cooper, 2009), the Winter '07 erosion was not wind dependent (Table 5).

Not all coastal stretches underwent erosion during the March '07 event. Several erosion hotspots which had been active during 2006, such as Eastmoor Crescent (Durban), Inyoni Rocks (South Durban) and Submarine Bay (KZN South Coast)(Fig. 1), underwent little or no erosion during the March '07 event. All of these areas had wide sandy beaches at the time

Table 7. Cumulative (2006–07) high-water mark changes compared to known long-term values
(1937–8: Cooper, 1991a,b, 1994)

Location	2007 erosion (m)	Envelope of mobility (m)	Ratio: 2007 erosion/erosion envelope	*Erosion event
Richards Bay	±30	25	120%	LNC, MS, WE
Little Martizburg Lane	±25	40	62.5%	LNC, MS, WE
Eastmoor Crescent	±30	48	62.5%	EQ, LNC, WE
Vetch's Beach	±10	+50	20%	EQ, LNC, WE
Ansteys Beach	±30	18	160%	MS, WE
Brighton Beach	±35	55	63%	MS, WE
Inyoni Rocks	±100	38	263%	MS, WE
Umkomaas	±65	65	100%	MS
Clansthal	±15–30	53	28–54.5%	MS, WE
Scottburgh	±40–50	52	80–96%	MS, WE
Submarine Bay	±75	57	131.5%	LNC, WE
Umzumbe	±40	75	53%	MS, WE
Mtwalume	±40	55	73%	MS, WE

*EQ – equinoxes (2006), LNC – lunar nodal cycle (2006), MS – March swell (2007) and WE –
winter erosion (2007).

the March '07 swell hit, reducing the impact; this effect has been noted elsewhere (Sallenger *et al.* 2002). Some relatively minor erosion took place, but the catastrophic destruction anticipated at Eastmoor Crescent, considering its recent history, did not take place.

The contrasting styles of swell-driven coastal erosion between the March '07 and the Winter '07 swell events may be explained in terms of water-level dynamics and geomorphology (Loureiro, Ferreira & Cooper, 2009). During the March '07 swell, the very high water levels flooded some points and headlands, removing their topographic effect (Thornton, MacMahan & Sallenger, 2007); consequently, megarip EHS activity, itself geomorphologically controlled (Shand, Hesp & Shepherd, 2004), was weakened or absent except in the case of very high relief headlands. As a result, the coast responded with lateral (alongshore) erosion as opposed to EHS activity during the March '07 swell.

Recurrence interval estimates of the March '07 swell event range from 20 years (based on the historic record: Guastella *et al.* 2008), 35 years (based on wave height) to 500 years (base on coincidence of tide and storm: A. Theron & J. Rossouw, unpub. data, 2008: http://researchspace.csir.co.za/dspace/bitstream/10204/2561/1/Theron_2008.pdf). If the cumulative erosion recorded during 2006–2007 is compared to the long-term (1937–1983) HWL fluctuations (Cooper, 1991a,b, 1994), the greatest erosion corresponds to the areas with the largest historic envelopes of mobility (Table 7). (Due to the sampling intervals, varying from years to decades, these figures for envelopes of mobility have to be considered as minimums.) Indeed, many 2006–2007 HWL retreat values are similar to the known envelope of mobility values, indicating that such erosion events are not uncommon in the long-term.

However, at some locations the 2006–2007 erosion far exceeded the historic envelope of mobility, suggesting it to be a more unusual event. At Ballito, shell middens, which were active until the 1920s (L. van Schalkweg, pers. comm.), were exposed and partly eroded by wave action during March 2007, suggesting a longer interval since previous erosion of this magnitude.

Parts of the coast have been heavily urbanized during the last twenty years, perched swamps drained and coastal dunes made dysfunctional; consequently, the coastal erosion response was exacerbated by poor urban planning. All instances of 2006–2007 erosion which exceeded that of the envelope of mobility (Table 7) took place on highly urbanized coastlines. In contrast, natural coastline reaches recovered within a year, suggesting that the historic envelope of mobility is sufficient to accommodate such erosion events. In rocky coastal areas it was also noted that the wave-cut platform was only partially exposed, with part remaining buried under dune sand or drained swampland (Fig. 4). This suggests that the wave-cut platform-forming swell event is larger still.

There is some evidence that EHS activity is episodic on the KwaZulu-Natal coast. At Eastmoor Crescent, a similar scale of erosion to that of 2006–2007 was recorded in 1970 and 1989; both occurred near previous LNC peaks (Fig. 11). Further, it is known that between July 1987 and June 1988, a period which straddles the previous LNC peak, the annual sediment loss from Durban's beaches was three times the annual average. At Submarine Bay, comparable erosion was recorded in 1991 (R. Osborne, pers. comm.) and unsubstantiated anecdotal information suggests that similar erosion occurred in the early 1940s.

The LNC is known to modulate tidal amplitude by 3–5 % (Gratiot *et al.* 2008; Oost *et al.* 1993). On swell-dominated coasts with narrow shelves, such as those of KwaZulu-Natal (4 to 47 km wide), tides are a particularly important mechanism for creating elevated water levels and thus in transferring increased wave energy to the back-beach where shoreline erosion is accomplished. A long period of stability (no major storms in 20 years), together with ignorance and greed, contributed to construction in inappropriate locations as landowners presumed them to lie outside the active
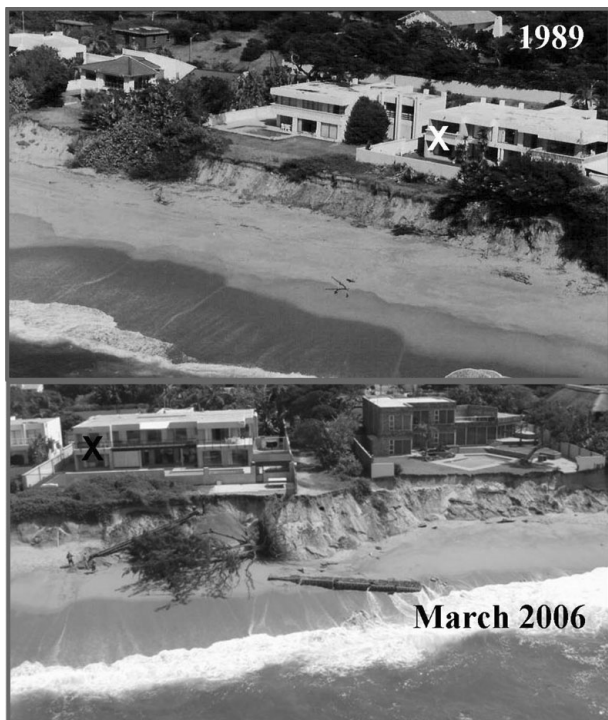
Figure 11. Eastmoor Crescent, Durban: erosion from 1989 (top) and 2006 (bottom).

coastal zone. Unwise development has undoubtedly increased the notoriety of the March '07 swell event.

According to Elsner, Kossin & Jagger (2008), cyclone numbers in the South Indian Ocean are unchanged (although storms are increasing in intensity); however, data posted online (Hurricane Alley Inc.), when plotted, suggest that there is an increase in storm numbers. At Richards Bay the intensity of swell exceedance events has remained fairly constant, but there has been an overall increase in number of exceedances since 1979 (Guastella & Rossouw, 2009). With the increase in the westerly winds between 30 and 60° S (Böning *et al.* 2008), significant wave heights are also likely to increase. Theron (2007) has calculated that 10 % stronger winds would give wave height increases of 26 %, with coastal sediment transport rates increasing by 40 % to 100 %. This, coupled with rising sea level, means that the probability of occurrence of high water levels and large swells will increase and that EHS erosion and higher-swell-driven widespread erosion events of the scale experienced in March 2006–2007 will become more common.

9. Conclusions

The 2006–2007 period was marked by contrasting styles of coastal erosion along the KwaZulu-Natal coastline of southern Africa. Landfall of large ocean swells ($H_{so} > 3$ m, but < 5.5 m) associated with the unusually high spring tides, leading up to and just after the lunar nodal cycle of 2006, caused erosion at isolated erosion hotspots. In contrast, the large March '07 swell ($H_s = 8.5$ m) produced widespread, lateral (alongshore) coastal, nearshore and shelf erosion.

The contrasting styles of swell-driven coastal erosion between the March '07 and the Winter '07 erosion events may be explained in terms of water-level dynamics and geomorphology. The March '07 large swell-driven megarip currents moved eroded coastal sediment onto the shelf, eroded the nearshore (surf) bars and triggered six months of coastal disequilibrium. In contrast, the Winter '07 erosion moved sediment into the longshore drift and ultimately rebuilt the nearshore bars.

The March '07 coastal erosion was an exceptional event that required the co-existence of a large swell, a storm surge and very high astronomical tides. Swell direction and not wind direction was a factor in coastal erosion. The steep nature of the coastline was responsible for the generation of a strong storm return flow, active to at least −20 m CD. Coastal surge penetration was low due to the steep hinterland, but washover fans 100–300 m long developed in estuaries.

Winter '07 erosion was anomalously severe due to the lack of nearshore bars to dissipate wave energy; consequently, this energy reached the coast and strongly drove the megarip current cells driving the EHS localities. EHS activity continued from the end of April to the end of August, amplified by very high tides and high swells ($H_o > 3$ m, but < 5.5 m), but at its peak also took place during low swells ($H_o \sim 2$ m) and on neap tides.

The nearshore bars had been replaced and coastal erosion had ceased by the end of September, 2007. The natural coastline recovered (at least 60 %) within a year. The recurrence interval of the 2006–2007 erosion season is unknown, but all coastal erosion was contained within the HWL envelope of mobility, with the exception of that at highly modified urbanized coasts. Unwise urbanization was a key contributor to the 2006–2007 coastal erosion, making it look much worse than it was. The fact that the coastline recovered quickly suggests this event to have been significant but not extreme.

There is some evidence that erosion events are cyclic on this coast, possibly controlled by the lunar nodal cycle. With the rising sea levels and stronger winds forecast for global warming, erosion such as this is likely to increase along the KwaZulu-Natal coast.

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