THE RECENT STORM RECORD IN THE SOUTHWESTERN SPANISH COAST: CLIMATIC PERIODICITY AND GEOLOGICAL IMPLICATIONS

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ABSTRACT

This work compares the geomorphic evolution of the Huelva coast (SW Spain), some climatic-oceanographic data of the Cádiz Gulf and its recent storm record, covering the last four decades (1956-1996). An interesting correlation was found between the southwestern wind periodicity, the number of storm periods and the beach ridges observed in the main spits (El Rompido and Doñana). The spectral analysis of the wind time series permits to establish two most probable levels of periodicity: 6 years and 9-10 years. Both periods coincide with the storm record and the creation of new beach ridges after a high-energy period.

KEY WORDS

storm, climatic periodicity, shoreline geomorphology, SW Spain

INTRODUCTION

In the short-term analysis of coastal morphodynamics, the storm-induced damages must be considered. Storms cause a high variability in the beach-nearshore profiles (Lee *et al.*, 1998), with differential effects over successive sectors of the same coast with different hydrodynamic features (Ballesta *et al.*, 1998; Rodríguez-Ramírez *et al.*, 2000). These events increase the coastal erosion and move sand rapidly offshore, while lower energetic conditions may cause gradual beach accretion (Komar, 1976). Consequently, managers need tools (i.e., event periodicity, sediment transport, modelling approach) to evaluate the possible consequences (Ahyerre *et al.*, 1998; Gönnert, 1999; Williams & Rose, 2001).

The littoral of the Huelva province (SW Spain) is an important tourist area, being visited by more than one million people between May and September. This “sun and beach” tourism needs a continuous management during the winter months. In these months, storms cause periodically considerable property damages over fisheries, harbours, private vacation homes or public earth-works. Causes of this periodicity have not been studied, but may be initially related with climate variables, i.e. the NAO (North Atlantic Oscillation Index; Hurrell, 1996). The NAO is an index representing the differences of atmospheric pressure at sea level between the Azores and Iceland (Kutzbach, 1970; Wallace & Gutzler, 1981). Positive values are associated with low cyclone activity in southern Europe and conversely (Rodwell *et al.*, 1999).

In this paper, we analyse the storm record on the Huelva littoral during the last four decades (1956-1996), delimiting the effects in beaches and spits. Results are compared with a statistical study of the dominant winds and other climatic-oceanographic features, in order to establish the periodicity of these events. Conclusions may be interesting for the short-term, geological analysis of waste prograding phases.

STUDY AREA

The Huelva coast is composed by large sandy beaches (145 km long), only interrupted by the presence of estuarine mouths (Fig. 1: Guadiana, Piedras, Tinto-Odiel and Guadalquivir rivers). The littoral morphology of this area is mainly linked to five

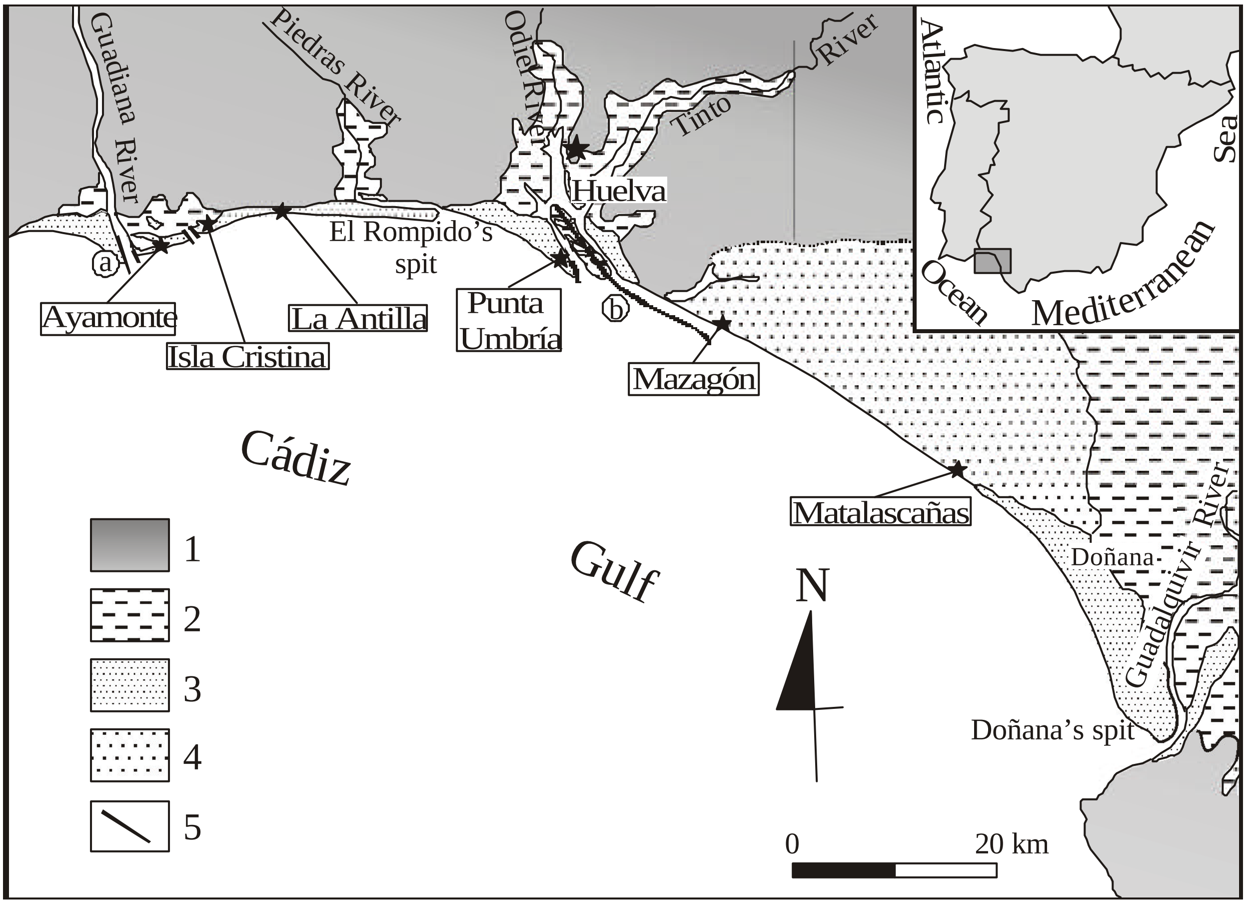


Figure 1.- Location map, including the main tourist beaches, spits and groynes. 1: Plio-Pleistocene substrate; 2: Salt marshes; 3: Spits; 4: Stabilised sandy formations. Main groynes. a: Vila Real do Santo Antonio; b: Huelva.

morphodynamic factors: tidal regime, wave action, coastal drift currents, fluvial dynamics and artificial groynes. The tidal regime is mesotidal (Davies, 1964) or high mesotidal (Hayes, 1979), with a mean range of approximately 2 m (Borrego & Pendón, 1989). Wave energy is medium, because 75 % of the waves do not exceed 0.5 m in height (CEDEX, 1991). This factor has an important seasonal variability and is higher during the winter storms (December-January).

The coastal drift currents have the greatest effects on the sediment redistribution of this littoral. The net sediment flow is oriented toward the east, with an high annual transport of sediment (180,000 to 300,000 m^3) in this direction (CEEPYC, 1979; Cuena, 1991). This transport is particularly important in the morphological variations of the shoreline owing to the orientation of this coastal sector, open to the southwestern. These conditions favour the development of broad littoral lowlands, usually sheltered by spits (El Rompido, Doñana), where tidal flats and fresh-water marshes extend several kilometres inland.

Two rivers (Guadiana and Guadalquivir) are the main sediment source of the Huelva littoral, with a mean discharge of 144 m^{3}s^{-1} and 185 m^{3}s^{-1}, respectively (Vanney, 1970). The remainder rivers (Piedras, Tinto and Odiel) have very limited flows, with a scarce importance in the sedimentary dynamics of the southwestern Spanish coast. In addition, the sediment transport capacity of these five rivers has decreased since 1960, with the construction of 65 dams regulating over 75 % of the flow (Ojeda, 1988).

This coast is heavily "defended" with modern protective groynes, causing either total (Vila Real do Santo Antonio, Huelva) or partial (Isla Cristina, Punta Umbria) obstacles to the sedimentary fluxes. Consequently, two sedimentary units (Ayamonte-Punta Umbría and Mazagón-Doñana) may be delimited in this human-altered area, directly related with the effects of the main groynes (Ojeda, 1989). Each unit includes two different zones: a) beaches affected by erosive processes (Ayamonte, Isla Cristina, La Antilla, Punta Umbría, Mazagón, Matalascañas); and b) prograding spits (El Rompido, Doñana).

METHODOLOGY

Two daily journals (Odiel and ABC) provided the historical record of storm conditions and their economic effects. Tidal coefficients (rate between the measured height tide and the mean height tide) and

Years	Date	Tidal coefficient	MWS	MWH	Years	Date	Tidal coefficient	MWS	MWH
1962-1963	63Jan24	69 - 74			**1989-1990**	89Dec03	51 - 73		
	63Jan25	78 - 82	up to 10	nd		89Dec04	47 - 68		
	63Feb19	38 - 40				89Dec05	46 - 63	up to 10	up to 6
						89Dec20	36 - 50		
1969-1970	70Jan11	94 - 95				89Dec24	43 - 49		
	70Jan12	87 - 90	up to 10	nd		89Dec27	63 - 72		
	70Jan13	77 - 82							
					1995-1996	95Dec31	47 - 53		
1972-1973	72Dec27	56 - 61				96Jan01	52 - 61		
	73Jan12	60 - 63	nd	6 to 7		96Jan02	59 - 62		
						96Jan03	62 - 68		
1978-1979	79Jan26	84 - 90				96Jan04	66 - 71		
	79Jan31	96 - 101				96Jan05	68 - 79		
	79Feb01	83 - 90				96Jan06	69 - 83		
	79Feb10	72 - 76	nd	up to 5		96Jan16	53 - 68		
	79Mar18	72 - 76				96Jan21	103 - 116	up to 8	nd
						96Jan22	101 - 118		
1981-1982	81Dec10	99 - 102				96Jan23	96 - 114		
	81Dec11	103 - 104				96Jan24	84 - 105		
	81Dec12	100 - 102				96Jan25	70 - 92		
	81Dec27	76 - 76				96Jan26	61 - 76		
	81Dec28	72 - 76	nd	up to 5		96Feb02	60 - 68		
	82Jan11	95 - 97				96Feb03	66 - 75		
	82Jan12	88 - 92				96Feb18	99 - 107		
	82Jan13	79 - 84				96Feb19	105 - 116		
1987-1988	87Dec04	78 - 79			**1998-1999**	98Dec31	87 - 90		
	87Dec09	53 - 56	8	7 to 8		99Jan12	35 - 46	up to 11	up to 5
	87Dec14	45 - 48				99Jan22	72 - 90		
	87Dec16	59 - 63							

Table I.- Storm period record (1956-2000) in the Huelva littoral. MWS: maximum wind speed; MWH: maximum wave height.

wave heights were recovered from the Huelva harbour archives, whereas the wind speeds were supplied by the Spanish National Institute of Meteorology at the Huelva station (period 1961-1996). Data were normalised to standard scales (Tab. I: Beaufort for winds and Douglas for waves).

The time series of wind speeds were studied, calculating the periodicity diagram of the main wind directions with the application of the Fourier transformation to the autumn-winter data. This mathematical algorithm permits to establish the most probable periodicity in the analysis of time series. In a further step, this wind datasheet was related by spectral, bivariate analysis with the NAO values. For this purpose, the popular coherence C (p) between X and Y was used, measuring the degree to which X and Y are jointly influenced by cycles of frequency “w” (Hamilton, 1994).

RESULTS AND DISCUSSION

Storms: periodicity and conditions

Between 1956 and 1996, eight winter storm periods were identified in the southwestern Spanish coast (Tab. 1): 1962-1963, 1969-1970, 1972-1973, 1978-1979, 1981-1982, 1987-1988, 1989-1990 and 1995-1996. In most cases, these high-energy periods are concentrated in two months (December and January), although isolated storms are recorded on February-March (1963, 1979, 1996). An additional periodicity may be inferred in the fairweather conditions, i.e., the intervals separating two consecutive storm periods (Lee *et al.*, 1998). After the first storm period (1962-1963), a long interval (6-7 years) was found until the next period, being followed by a shorter cycle (2-3 years).

Each storm period includes one to four storm families (1-7 days), being separated by 2-40 quieter days. An analysis of the individual storm features indicates a direct relation between the direction and

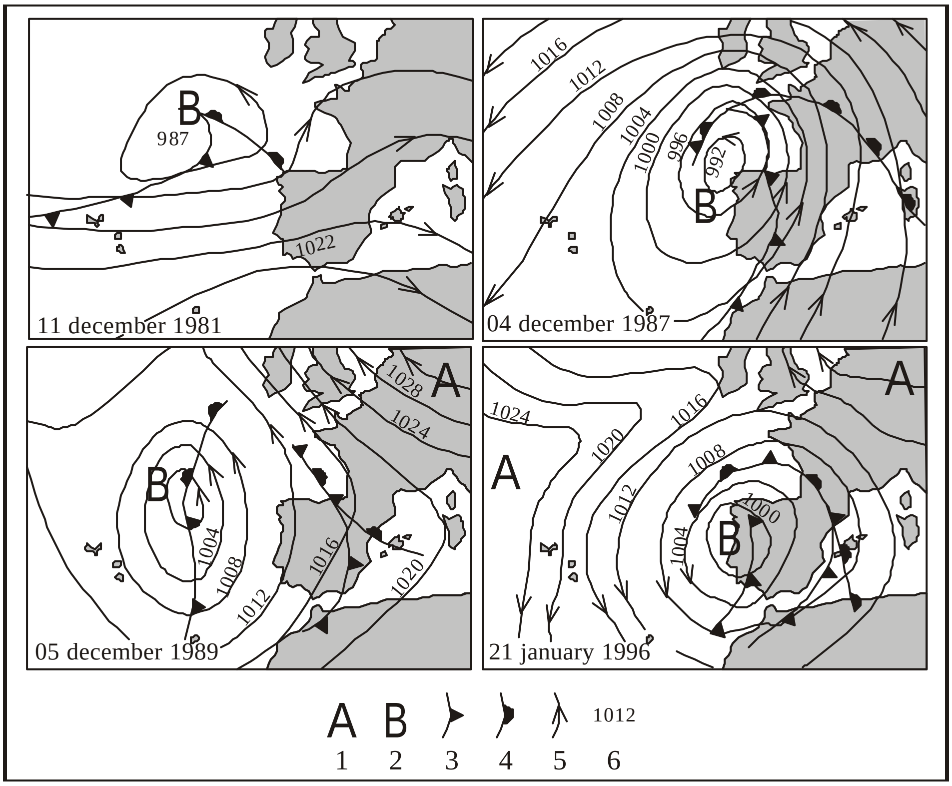


Figure 2.- Meteorological maps of four storm days cited in this work. 1: anticyclone, high pressure; 2: cyclone, low pressure; 3: cold front ; 4: hot front; 5: wind direction; 6: atmospheric pressure (in Mb).

speed of the prevailing winds and the causes of these events. In all cases, these winds come from the third quadrant (Fig. 2), with high to very high speed values (8-12) in the Beaufort scale (Tab. I). Consequently, a more detailed study of the third quadrant velocities is need in order to establish the periodicity of the storm-wind interrelation (see below).

Single storms are also characterised by the wave height, a partially wind-induced variable. In these events, high values (5-7 in the Douglas scale) were found, coinciding with very variable values of the tidal coefficient. This coefficient do not shows a predictable behaviour during the storms, with a wide range in the measured data (35-118).

Wind, waves and sediments

The southwestern winds are dominant in the area studied (Fig. 3), being selected for a detailed analysis. In autumn-winter, these third quadrant winds have a mean velocity of 16 km h^{-1} and a frequency of the 35 % of the days. These seasons present very heterogeneous values, being related with the cyclone activity. Intervals of very high cyclone activities (Fig. 4, A: 1963-1964, 1969-1970, 1974-1979, 1984-1986, 1995-1996) are characterised by their intermittence, with very mild wind regimes or even calms until the following cyclone. In these cyclone periods, the annual mean values of wave heights were 1.2 m, although storm conditions (gusts up to 90 km h^{-1}) may induce wave heights up to 6-7 m, always in winter (1974-1979: 10 days; 1984-1986: 2 days; 1996: 1 day). During a single storm, these winds generate sea-type waves, which are responsible of a strong erosion in the littoral beaches. In the post-storm spring-summer, high volumes of the sediment eroded were transported toward the coast, causing the progradation of the littoral spits with a new beach ridge (Tab. II).

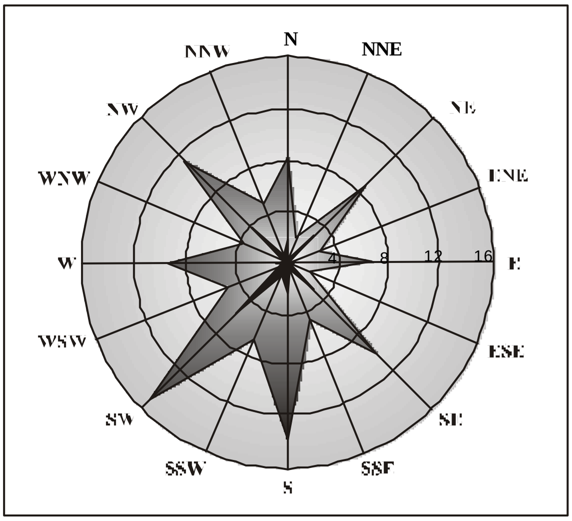


Figure 3.- Annual analysis of the wind (1960-1996 period): mean speed (external, grey rays, in km h^{-1}) and frequency (internal, black rays, in mean number of days by month).

Years (Winter)	Storm periods	Beach ridges	
		El Rompido	Doñana
1956-1969	1 (1962-1963)	1	1
1970-1977	2 (1969-1970; 1972-1973)	2	3
1978-1980	1 (1979-1980)	1	1
1981-1984	1 (1981-1982)	1	1
1985-1990	2 (1987-1988; 1989-1990)	2	2
1991-1996	1 (1995-1996)	1	1
1997-2000	1 (1998-1999)	1	1

Table II.- Correlation between the storm periods and the number of beach ridges observed in the two spits analysed (data from Rodríguez-Ramírez et al., 2000)

In contrast, calmer periods (1961-1962, 1971-1972, 1983, 1988, 1992, 1995) are intercalated between these energetic years, with lower mean wave heights (0.6-0.7 m). In these periods, progradation is very scarce or null and a swale is observed in the littoral spits (Rodríguez-Ramírez *et al.*, 2000).

Wind periodicity, storm record and NAO

The application of the Fourier transformation to the time series of autumn-winter wind speeds permits to distinguish two more probabilistic frequencies (Fig. 4, C: 6 years and 9-10 years), which are also found in the storm series. In most cases, a 9-year post-storm period contains two storms (period-2 and period-3), being situated at 6-7 and 9-10 years after the period-1, respectively. This initial coincidence would indicate a possible statistical interrelationship between both variables, but the small record of recent storm periods registered only permits a first approximation.

This hypothesis was tested in the period 1996-2000, by analysing the new record of storm periods. A high-energy period (1998-1999) happened in agreement with the hypothetical storm sequence, which predict new storms in 1995 (period-2) and 1997-1998 (period-3) after 1989 (period-1). In this hypothetical 9-year sequence, the following storm period will be between 2004 and 2005, although a new positive date do not indicates the total confirmation of the initial hypothesis. We will need 20-30 storm periods (a century, at least) for an adequate, statistical testing of this correlation.

This possible periodicity may be related with cyclical changes of the cyclone regime, which are expressed in the NAO values (Fig. 4, B). In the analysis of the wind-NAO spectral series, the 3-year frequency shows the higher probabilities (Fig. 4, D), indicating some degree of common behaviour between these two variables. This frequency is in agreement with the two main frequencies (6 and 9-10 years) obtained for the

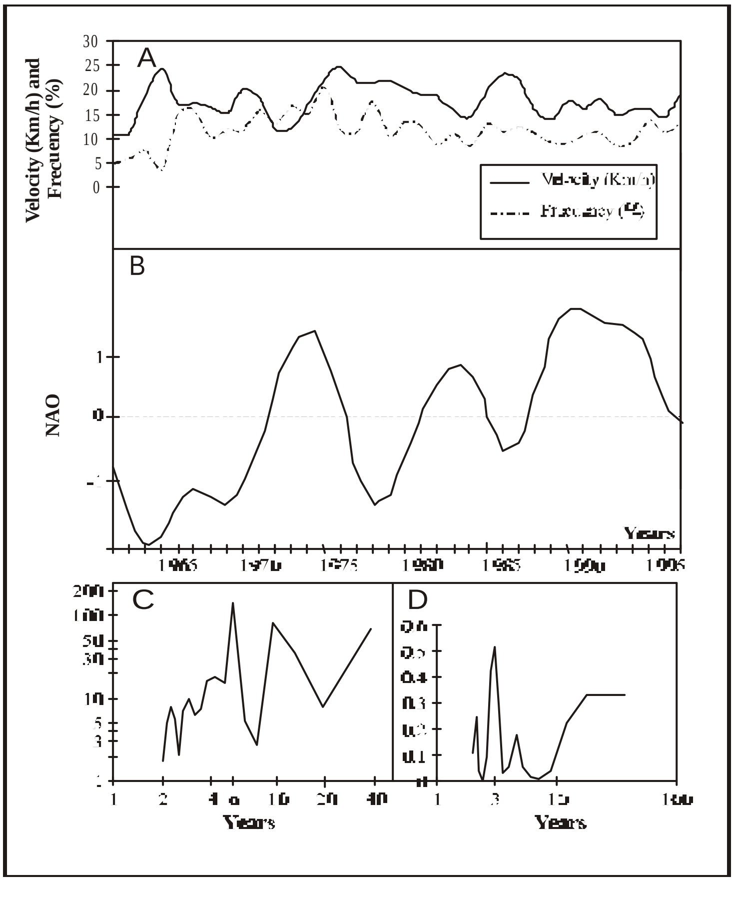


Figure 4.- A: Velocity and frequency of the third quadrant winds (period 1961-1996); B: NAO record; C: Periodicity diagram of the third quadrant wind speeds; D: Coherence values between NAO and wind speeds (X-axis in log scale).

wind series. Moreover, an additional coincidence was found by contrasting the evolution of the NAO values and the storm record. Except for the 1989-1990 winter, the remaining storm periods were characterised by negative values of the NAO index, indicating an possible relation between storms and high cyclone phases. In the future, the NAO values collected during a storm periods will may be even positive, due to the increasing tendency of this variable in the last decades.

Geological implications

Hierarchies of prograding phases have been established on a world-wide scale in coastal formations (Vail *et al.*, 1977; Posamentier *et al.*, 1988). These phases are denominated “P”, “h” and “c”, and all are cyclical. “P” cycles (4500 years approximately) define the greatest eustatic variations with major progradation bodies, caused by neoglacial event (Denton & Karlen, 1973) and global cooling (Curray *et al.*, 1969). The “h” cycles (2260-960 years) produce minor progradation and may be linked with changes in the circulation of deep-ocean currents and/or internal readjustments in the global hydrodynamic characteristics in ice-thawing intervals (Ruddiman and McIntyre, 1981). Finally, the “c” cycles (500-50 years) create brief still stands, terraces and other features with attendant sets of very small progradation bodies within the larger “P” and “h” cycles. Double-Hale solar cycles have similar periods and there may be a causal relationship (Fairbridge and Hillaire-Marcel, 1977).

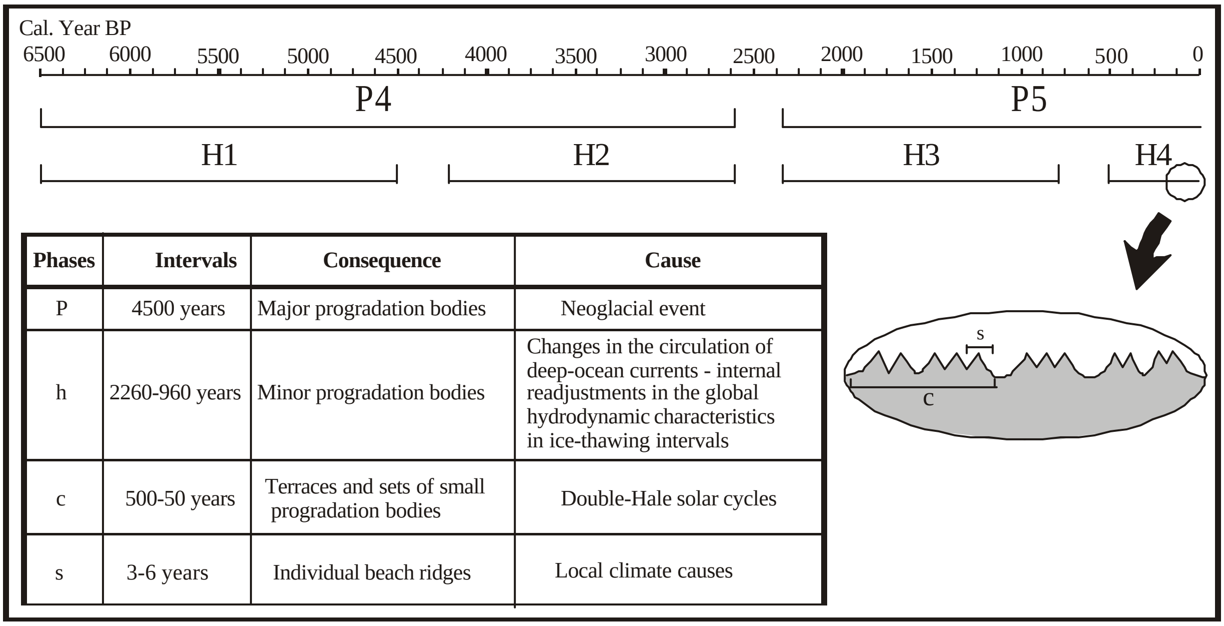
In the Cádiz Gulf, these phases have been defined in the last years (Fig. 5), being represented by a succession of beach-ridges in the littoral spits (Dabrio *et al.*, 1986; Zazo *et al.*, 1994; Rodríguez-Ramírez, 1996; Rodríguez-Ramírez *et al.*, 1996). In the Doñana spit, the “c” cycles shows a periodicity of 100 years and are related with climatic fluctuations (Zazo *et al.*, 1994; Lario, 1996). These cycles are composed by smaller units, created during shorter phases but not defined at present.

In this paper, we propose the creation of a new phase denominated “s” (short-term) in this area, including the beach ridges originated by response to periodical storms. The extension of this phase in other local studies will involve:

a) A detailed study of the regional/local factors (direction and speeds of winds, regional indexes of low-high pressures, waves, tides, sediments). For example, this phase has been registered either in microtidal and mesotidal areas (Bowman & Goldsmith, 1983; Orford & Carter, 1985) and sandy and/or gravel coasts (Orford & Carter, 1984);

b) An interrelation between these variables and the storm record. This step needs a prolonged storm record (a century, probably; Gonnert, 1999) for an adequate treatment of the historical data.

c) A comparative response to storms events in the different stretches of the same coast, with special attention to the spit progradation-retrogradation expressed in the number of storm-induced beach ridges and the following post-storm swales (i.e., Zazo *et al.*, 1994).



Phases	Intervals	Consequence	Cause
P	4500 years	Major progradation bodies	Neoglacial event
h	2260-960 years	Minor progradation bodies	Changes in the circulation of deep-ocean currents - internal readjustments in the global hydrodynamic characteristics in ice-thawing intervals
c	500-50 years	Terraces and sets of small progradation bodies	Double-Hale solar cycles
s	3-6 years	Individual beach ridges	Local climate causes

Figure 5.- Prograding phases of the Huelva littoral, including the new phase defined: intervals, consequences and causes (partly modified from Zazo et al., 1994)

CONCLUSIONS

(1) In the last forty years (1956-1996), the analysis of the storm periods suffered by the Huelva littoral (SW Spain) indicates a concentration in the winter months (December-January) and a statistical behaviour similar to the third quadrant wind speeds. After the first storm period registered (1962-1963), two new high-energy periods are probably found in the following 10-year intervals: period-2, at 6 years, and period-3, at 9-10 years. The first test of this hypothesis was positive in the 1997-2000 period.

(2) Each high-energy period induces the generation of new beach-ridges at littoral spits during the post-storm period. The number of these sedimentary beds coincides closely with the storm-periods included in each interval studied by aerial photographs, whereas the intermediate swales are characteristic of fairweather conditions.

(3) This study permits to delimit a new prograding phase (s), directed related with regional conditions (cyclones, wind speeds, waves, tidal range, sedimentary regime).

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