Potential influence of sea-level rise in controlling shoreline position on the French Mediterranean Coast

Cédric Brunel *, François Sabatier *

Aix Marseille Université, Université de Provence, 29, avenue Robert-Schuman, 13621 Aix-en-Provence Cedex 1, France
CEREGE, UMR 6635 CNRS, Centre Européen de Recherche et de l’Environnement, Eurpôle Méditerranéen de l’Arbois, 13545 Aix en Provence Cedex 4, France
UFR de Géographie UFR Géographie, Aix Marseille University, 29 av. R. Schumann, 13090 Aix en Provence, France

A R T I C L E  I N F O

Article history:
Accepted 14 May 2007
Available online 18 November 2008

Keywords:
Sea-level rise
Coastal erosion
Tide gauge
Shoreline evolution

A B S T R A C T

We analysed the rates of relative sea-level rise (RSLR) and the variations in shoreline position over more than a century on pocket-beaches in Provence and on open beaches of the Camargue (France). Our objective is to quantify the role of sea-level rise in the shoreline retreat, and evaluate this retreat in terms of future sea-level rise. The methodology did not use the classical Bruun rule but the principle of active flooding which combines the RSLR with the slope of the beach profile. This slope is averaged between the shoreline and the upper and lower part of the active profile. On the wave-dominated open-beaches of the Camargue, the sea-level rise between 1895 and 1977 yields a theoretical averaged retreat of −34.8 m along eroding beaches, but this value eventually represents only a small proportion (8%) of the total historical distance of shoreline retreat. On open-beaches exposed to the swell, (Camargue), rising sea level enhances the erosion, which is itself ultimately dependent on the action of the waves (longshore transport, cross-shore processes) and the sedimentary budget. In other words, sea-level rise is not the major cause of coastal erosion and does not represent the most severe risk along this type of shore. Moreover, the cross-shore processes of overwash “assist” the shoreline retreat by compensating for sea-level rise. On the other hand, since sea-level rise is one of the principal factors influencing shoreline retreat, the acceleration in sea-level rise predicted for 2100 will play an important role in the future position of the shoreline on pocket-beaches protected from wave action and with limited back-shore areas (i.e. the beaches of Provence). The width of the beaches is going to decrease significantly with the increasing risk of disappearance of some beaches. Indeed, if we integrate the low rates of long-term retreat, and taking account of the morphology of the back beach, then the pocket-beaches appear to be threatened by disappearance due to sea-level rise. Under these conditions, sea-level rise will have important socio-economic impacts on the pocket-beaches of Provence.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

Coastal environment managers are increasingly concerned by the current rise in sea level and its possible acceleration during the 21st century in relation to climate warming (Gornitz et al., 1982; IPCC, 2001; Nicholls and Stive, 2004) (Fig. 1). This phenomenon coincides with an unprecedented socio-economic development of the coastal fringe (Nicholls et al., 1990). Although the vulnerability of the some Mediterranean coasts to relative sea-level rise (RSLR) has already been studied (Jefic et al., 1992; Jimenez and Sanchez-Arcilla, 1997), recent scenarios for 2100 (IPCC, 2001) (Fig. 1) and sea-level measurements (Church and White, 2006) suggest an acceleration in sea-level rise. This enhances the importance of a new simulation of the impact of rising sea level on the shoreline position. In this paper, we investigate this long-term process on some typical beaches of the south of France, the open-beaches of Camargue and the pocket-beaches of Provence (Fig. 2). The Camargue is both a natural reserve and an area of polderized agriculture, where there are major issues linked to agriculture, tourism and ecological concerns, with coastal erosion being the main problem. Even though the population in this area is not as large as on other Mediterranean deltas such as the Nile, vulnerability to RSLR will mainly affect industrial and tourism activities. In Provence, the economic stakes of the coastal fringe are considerable and mainly related to the tourism industry. Indeed, seaside tourism in the area accounts for an annual turnover of 4.6 billion euros, that is to say, a fifth of the total sales turnover of the French tourism industry. Thus, the beaches of Provence represent an extremely important economic stake and their disappearance due to an acceleration of RSLR would be very prejudicial to the economy of the region.

It is difficult to take account of the “sea-level rise” parameter in quantifying shoreline evolution (Dubois, 2002). The most widespread method to achieve this aim is based on the Bruun rule (Bruun, 1962).
In his original publication, Bruun clearly stipulates that this principle only takes into account the effect of sea-level rise on the shoreline retreat and not the other processes controlling beach profiles (longshore and cross-shore sediment transport). However, this principle is applicable only to a restricted number of beaches (coasts without longshore sedimentary transport). Moreover, the mathematical equation proposed by Bruun is sometimes called into question (Pilkey et al., 1993; Thieler et al., 2000; Cooper and Pilkey, 2004) because it involves parameters (length and active depth of the profile) that are often difficult to evaluate. We do not discuss here whether Bruun’s principle should be used because this issue has recently been addressed in several contradictory articles, some of which note a satisfactory application of the principle (Kaplin and Selivanov, 1995; Nicholls and Stive, 2004; Zhang et al., 2004) while others debate its validity (Pilkey et al., 1993; Thieler et al., 2000; Cooper and Pilkey, 2004). In this article, on the other hand, we use a simple principle offlooding to determine the effect of the “sea-level rise” parameter in controlling shoreline retreat on the open-beaches of the Camargue and pocket-beaches of Provence (Fig. 2).

In the first place, these two types of coast show different sensitivities to sea-level rise. Indeed, the beaches of the Camargue seem particularly vulnerable to RSLR because of their gentle slope and the presence of lagoons that can be easily flooded. In contrast to the open-beaches of the Camargue, the pocket-beaches of Provence show steeper slopes. These pocket-beaches are protected laterally from storms by rock outcrops situated on either side, while the back beach is bounded by a scarp or a cliff above the upper foreshore. Because of their morphological characteristics, pocket-beaches are apparently less prone than the open-beaches of the Camargue to the problems of erosion brought about by RSLR.

In this paper, we firstly determine the rates of RSLR over the past century for the Camargue (tide gauge of Grau de la Dent) and the pocket-beaches of Provence (tide gauge of Endoume, Marseilles). These data are used to analyse the influence of sea-level rise on the shoreline position during the 20th century in the two studied areas. The comparison between the measured shoreline retreat and the calculated retreat (List et al., 1997; Leatherman et al., 2000) caused by the RSLR allows us to distinguish the impact of rising sea level from the many other factors (longshore and cross-shore sediment transport) that interact in the morphodynamics of the beaches. Lastly, based on past changes, and by integrating the geomorphology of the studied sites, we evaluate the risks of shoreline retreat linked to a rise in sea level for 2100 according to a scenario assuming a rise of +0.44 m (IPCC, 2001).

2. Presentation of the studied sites

All sites experience a microtidal regime (30 cm average tide range) and are essentially affected by waves and currents. Due to their geographical proximity, the sites are all subject to similar swell conditions. Waves come from two prevailing directions: from the SW (modal and fair-weather waves) and from the SE sector (storm waves). The annual return significant wave height is around 3.2 to 3.9 m, with an associated period of around 6.5 to 7.5 s. On the open-beaches of Camargue, the offshore waves coming onto the coast are weakly
refracted as they break, compared to the pocket-beaches of Provence where storms waves are reduced by at least 40% in the breaker zone.

2.1. The open and wave dominated beaches of Camargue

According to the classification of Galloway (1975), the Camargue (Rhône delta) is recognized as a wave-dominated delta. The coast is made up of approximately 90 km of sandy barred beaches extending from La Gracieuse spit to Espiguette spit (Fig. 3). The build-up of the Rhône delta plain began at around 7000 years BP, with the Holocene stabilisation of sea level, and took place in several stages summarized by Vella et al. (2005). Due to a natural decline in exceptional flood events and changes in land use in the catchment area (reforestation), the river sediment input to the sea has decreased significantly since the end of the Little Ice Age (Pont et al., 2002). From the 1950s and 1990s onwards, the construction of 78 hydroelectric dams has definitively blocked off most of the coarse load, thus decreasing even further the sediment flux in transit (IRS, 2000). On this delta, the river sand input to the littoral system shows a particular behaviour because the sand settles out on the prodeltaic lobe and does not contribute to the supply of the beaches to the west of the Grand Rhône mouth. The fluvial discharge of the Petit Rhône arms represent 10 to 15% of the Grand Rhône discharge and we consider that there is no sand input to the beaches as is evidenced by the bathymetric erosion on this area (Sabatier et al., 2009-this volume, 2006). Instead, the sediments are displaced by longshore currents towards the east (Suanez and Provansal, 1998; Sabatier and Suanez, 2003) (Fig. 3). Thus, the beaches on the western side of the Grand Rhône display a negative sediment budget during the 20th century, suggesting (very) little river sand input (Sabatier et al., 2009-this volume, 2006). To evaluate the impact of RSLR on the shoreline exposed to waves and not influenced by sediment input, we focus here on the beaches to the west of the Grand

Fig. 3. Distribution of littoral drift cells on the Camargue coast. Modified from Sabatier and Suanez (2003).

Fig. 4. Aerial view of the Rhône delta beaches. (Picture : Direction Régionale de l'Environnement du Languedoc-Roussillon).
Rhône mouth (Fig. 3). The shoreline began to take on its present-day shape from the beginning of the 18th century, forming a pattern of littoral drift cells (Sabatier and Suanez, 2003). According to the terminology of Wright and Short (1984), the beaches are of dissipative and longshore-bar-trough type, with an average grain size around 0.2 mm and a mean beach slope of around 1%. The delta plain and the coastal fringe seem to be very sensitive to RSLR because of the gentle slope and the low elevation of the major backshore lagoons (Fig. 4), which are submerged episodically during storm surges.

2.2. The pocket-beaches of Provence

Several tens of pocket-beaches are located along the rocky coast of Provence, between the Camargue and the Italian border, but only twenty-five of them satisfy the selection criteria for this study (Fig. 5): i) natural beach evolution without any anthropogenic action influencing the shoreline position (no dredging activities or coastal engineering developments, etc.) and ii) small-sized catchments areas with negligible fluvial inputs that do not influence the sediment budget of the beaches. For all these beaches, the more important fluvial sediment input comes from the Gapeau and the Pansard–Maravenne rivers (2000 m³/year), which are located more than 3 km away from the first beach studied. Moreover, there was no land-use change in the catchment areas throughout the investigated period. We thus assume no significant river or continental sediment input to the investigated pocket beaches at the time scale of 100 years. In addition, the selected beaches are bordered laterally by rocky points that extend sufficiently seaward (water depth of −8 to −10 m) to protect the beaches from storm waves, thus limiting the sediment outputs or inputs due to longshore drift. Consequently, this type of beach can be regarded as a relatively closed system, where sedimentary exchanges are little affected by the waves compared with open-beaches exposed to the swell, such as the open-beaches of the Camargue. The twenty-five pocket-beaches have profiles generally characterized by a poorly developed back-shore and foreshore (average width between 7 and 30 m) and by the presence of a cliff or an embankment behind the beach against which the sediments are banked up (Fig. 6). The submerged part of the beach is partially colonized by solid masses of Posidonia meadows between −2 and −10 m water depth. To a certain extent, this sea grass serves for damping the swell and forms an obstacle to the movement of sediments on the bottom. Eighteen of the selected beaches are made up of medium to coarse sands and the seven other beaches are composed of fine sands, which results in slopes varying from 1 to 3.6% (average 1.9%). To a first approximation, this slope seems to represent a natural protection against the RSLR.

3. Methods and data used

3.1. Tide gauge analysis

Two tide gauges on the French Mediterranean coast have been recording relative sea-level variations for more than a century (Fig. 2). Since 1905, the Compagnie du Salin du Midi, using a floating tide-gauge installed in the port of Grau de la Dent, has made measurements of sea level in the Rhone delta (Fig. 2). The height of the sea surface is recorded daily at 7 h. The data obtained by the tide-gauge at Endoume in Marseilles cover a longer period, since the first recordings date back to 1885. The measurements are carried out using a planimetric system fixed on the sea surface, which is defined as the reference datum. The tide-gauge is periodically recalibrated with respect to this datum. Both tide measurements (Grau de la Dent and Endoume) refer to the national French level (NGF). Despite the differences in the tools and methods of measurement used at both tide-gauge stations, it is relevant to make a comparison of the data (Suanez et al., 1997). The tide gauges are used here as a reference to evaluate the rate of sea-level rise for the open-beaches of Camargue (tide gauge of Grau de la Dent) and the pocket-beaches of Provence (tide gauge of Endoume–Marseilles). This analysis is based on the work of Suanez et al. (1997), who have already analysed the data from these two tide gauges. Nevertheless, we propose an update to 2005 since Suanez et al. (1997) only included data up to 1993.

3.2. Analysis of the historical shoreline changes

We investigated the long-term (1 century) relations between relative sea level and shoreline position. Old maps and aerial photographs were selected to cover the 20th century for the open-beaches of Camargue and the twenty-five pocket-beaches of Provence.
The oldest data were collected by the SHOM (Service Hydrographique de la Marine) engineers in 1895 (open-beaches of Camargue) and in 1896 (pocket-beaches of Provence), using the method of triangulation by means of a theodolite. The most recent survey are aerial photographs carried out by the IGN (Institut Géographique National) in 1977 (open-beaches of Camargue) and in 1998 (pocket-beaches of Provence). For the Camargue area, the period of study ends in 1977 because the hard engineering works built along the shore since the beginning of the 1980s locally modify the position of the shoreline (Sabatier et al., 2009-this volume, 2006), so the inclusion of later dates would have been likely to disturb the analysis.

The treatment of the aerial photographs is based on classical methods used in many studies (Dolan et al., 1991). The data from the 19th century and the aerial photographs from 1977 were scanned, digitalised and georeferenced in French metric Lambert III co-ordinates. The geometrical correction is made with ER Mapper© software from a reference document consisting of the BD-ortho 1998©. The BD-ortho 1998© is a very accurate aerial photograph georeferenced mosaic produced by IGN in 1998. The complete dataset was compiled in a Geographical Information System (MapInfo 6.5©) and then used to draw the shoreline position (instantaneous limit of the run-up) and calculate the distances of coastline retreat or advance.

According to the SHOM, the surveying techniques used during the 19th century are highly reliable, so the measuring precision is estimated at $+/-10$ m for the 1895 and 1896 data. The sighting of fixed points (landmarks or invariable features) visible on aerial photographs of 1977 (buildings, works, road crossings, etc.) enables us to define, after superposition, a margin of error of $+/-3.5$ m. For the 1998 shoreline position, the errors of the BD-ortho are estimated at $+/-0.50$ m by the IGN.

### 3.3. The flooding principle

To determine the impact of the sea-level rise on shoreline retreat, we did not adopt Bruun’s approach, because the concepts on which his rule is based show several shortcomings (Pilkey et al., 1993; Thieler et al., 2000; Dubois, 2002; Pilkey and Cooper, 2004; Davidson-Arnott, 2005). On the other hand, in spite of Davidson-Arnott (2005) criticisms against Bruun’s principle, this author nevertheless proposes to adapt the rule by: i) excluding the points currently called into question by Pilkey et al. (1993), Thieler et al. (2000), Cooper and Pilkey, (2004), ii) preserving the idea that if the sea level rises, then a shoreline retreat will be observed, iii) adding the dune-beach system into the sedimentary budget, and iv) considering the natural horizontal landward migration of this system in the case of a sea-level rise. Nevertheless, the conditions for application of the rule are not strictly satisfied on the studied sites. For example, on the open beaches of the Camargue, there is a significant longshore transport, while, on the pocket beaches of Provence, the presence of a rocky substrate on the back-shore can block the horizontal migration of the beach. For the above reasons, we could not use Bruun’s rule here because, if we had done so, this would imply we accepted all of the necessary conditions for its use (Davidson-Arnott, 2005).

Under these conditions, we considered it more advisable to make use of the geometrical relations of the beach profile (slope) and height of sea level, while basing our study on the flooding principle. Passive submersion implies that the sea-level rise is associated with submergence of the land behind the dune, generally lagoons and salt marshes, without any morphological modification of this area (Agrawala et al., 2004; Paskoff, 2004; Durand and Heurtefeux, 2005; Ericson et al., 2006). This approach does not take into account the fundamental processes involved in the retreat of sandy coasts. In fact, the shoreline retreat results in destruction of the dunes during storms, with some of the sand being projected behind the dunes (overwash), thus filling the salt-marshes or lagoons. Therefore, the shoreline retreat is accompanied by an increase in the elevation of the land behind the dune, which conditions the future position of the shoreline and compensates, at least partially, for the rise in sea level (Davidson-

---

### Table 1

Data used for the analysis of the long-term shoreline changes (SHOM: Services Hydrographiques et Océanographiques de la Marine; IGN: Institut Géographique National).

<table>
<thead>
<tr>
<th>Sites</th>
<th>Date</th>
<th>Type of document</th>
<th>Scale</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-beaches of Camargue</td>
<td>1895</td>
<td>Field survey and old maps</td>
<td>1:14,800</td>
<td>SHOM</td>
</tr>
<tr>
<td>Pocket beaches of Provence</td>
<td>1998</td>
<td>Aerial photographs, BD-ortho©</td>
<td>0.50 m resolution</td>
<td>IGN</td>
</tr>
</tbody>
</table>

---

Fig. 6. Ground photograph of the pocket beach of Notre Dame (Porquerolles Island). (Picture: F. Sabatier).
Arnott, 2005; Sabatier et al., 2005). Consequently, we have chosen to use the principle of dynamic - active submersion rather than passive submersion, assuming that the slope of the beach profile remains identical in time and migrates horizontally towards the land when the sea level rises (Fig. 7). The approach presented here has the major advantage of depending on simple parameters. It is based purely on the relationship between sea-level rise and the beach slope. These two parameters are clearly correlated since part of the beach is flooded when the sea level rises.

Nevertheless, the slope of the beach calls into question the morphodynamics of the studied area at the investigated time scale because the major issue is to determine an appropriate slope. Several options are possible, for example, Bruun (1962) proposes taking the slope from the top of the dune to the depth of closure and/or the limit of sand and mud. Since there are no continuous dunes on the Camargue coast, and because of the lack of data for 1895 and 1896, we do not take the top of the dune into account. Based on morphodynamics processes, we decided to adopt the average values of two different depths on the profile in order to obtain an accurate slope. The minimum and maximum slopes are taken as +/− boundaries. Firstly, the upper part of the active profile controlled by wave action is defined by the slope between the shoreline and the annual depth of closure. We selected the annual depth of closure, calculated by Sabatier et al.’s (2004) methodology, because the depth obtained is closed and seaward of the bars and the breaking zone. The values calculated are between −4 and −8 m depth on the open-beaches of Camargue and between −2 and −5 m depth on the pocket-beaches of Provence. Secondly, the lower part of the profile is defined between the shoreline and the limit of sand and mud on the open-beaches of Camargue (−10 to −20 m depth), and between the shoreline and the external limit of the bays on the pocket beaches (−4 to −8 m depth). The submarine slopes of the open-beaches of Camargue are measured on bathymetric maps established in 1974 and 1982, before the hard engineering developments during the 1980s (Sabatier et al., 2009-this volume, 2006) in order to use a natural slope, and on a bathymetric map based on 1993 data for the pocket-beaches of Provence. We do not consider the sand-mud limit on these beaches because this boundary is too deep (around −50 to −100 m) to play a significant role in the beach evolution. The presence of Posidonia, which can be regarded as a morphological limit of the beach profile, was regularly observed between the two selected depths, thus providing an additional argument for our choice of the value for the active slope of the profile.

The flooding principle defined above thus enables us to simulate the theoretical retreat of the past and future shorelines, being based on the slopes measured in the field and the sea-level rise recorded by tide-gauges during the 20th century or forecast using a RSLR of +44 cm for 2100. Nevertheless, on the open-beaches of Camargue, a subsidence of +1.1 mm/year (Suanez et al., 1997) is added to the proposed RSLR for 2100 in order to obtain a more realistic definition of the future relative sea level (total rise of +55 cm by 2100). This modification is not carried out for the pocket-beaches of Provence because there is no indication of vertical movements of the land at the investigated time scale. During the 20th century, to define the role of the sea-level rise forcing agent in controlling shoreline retreat, theoretical values are compared with the field measurements. Since we predict the shoreline position according to sea-level rise by using the active flooding principle, the results do not take account of erosional phenomena related to other forcings (such as gradient on the longshore sediment transport, off-shore sediment transport, etc.). The amounts of retreat derived from the active flooding principle are therefore minimum values, and the total retreat is potentially even more marked because of the action of other forcing agents on the profile. The validity and importance of the results obtained with this concept are discussed further below (see Section 5).

4. Results

4.1. RSLR since the beginning of the 20th century

In spite of a strong interannual variability, the tide-gauge readings at Grau de la Dent and Endoume–Marseilles show an upward trend over the century (Fig. 8). In Grau de la Dent, we measure a relative rise in sea level of 16 cm, which yields a trend of +2.2 mm/year by using a linear regression. In Marseilles, the total rise was 8 cm, which corresponds to a trend of +1.1 mm/year. While our results confirm previous studies on the rates of sea-level rise in the Camargue and Marseilles (Pirazzoli, 1986; Suanez et al., 1997), they also provide new and updated values. The relative secular rise in sea level is twice as fast in the Camargue as in Marseilles. Since the data from the Endoume–Marseilles tide-gauge are comparable with readings from the majority of Mediterranean sites considered as stable on a secular scale (Emery et al., 1988), the difference of 1.1 mm between the stations is attributed to negative movements of the ground on the coast of the Camargue, which are interpreted in terms of subsidence (Suanez et al., 1997).

4.2. Shoreline changes during the 20th century

The variations of the coastline of the open-beaches of Camargue between 1895 and 1977 (Fig. 9) allow us to distinguish the sectors undergoing erosion or sedimentary accretion confirming the littoral cell organisation described by Sabatier and Suanez (2003). The highest
Fig. 9. Displacement of the shoreline of the Camargue between 1895 and 1977. A: position of the profiles. B: measured displacement of the shoreline. C: retreat linked to the sea-level rise, as calculated using the flooding principle.
amounts of shoreline advance are recorded near the mouths of the Grand Rhone, with values of $+2300\ (\pm 10) \text{ m}$ as well as on the spits of Beauduc (+1200 m) (±10) and Espiguette (+1100 m) (±10) (Fig. 9). On the other hand, the beaches of Faraman, Saintes Maries-de-la-Mer and the Petite Camargue, which account for 70% of the coastline length, are subject to a major retreat of more than 250 (±10) and 500 (±10) m respectively and an average of about $-277\ (\pm 10) \text{ m}$.

Between 1896 and 1998, all the investigated pocket-beaches of Provence were undergoing erosion (Fig. 10). The shoreline of the 25 analysed pocket-beaches retreated by $-11\ (\pm 3.5) \text{ m}$ on average, but this varied from one beach to another, from $-4\ (\pm 3.5)$ to $-20\ (\pm 3.5)$ m. Various morphodynamic units can be distinguished: beaches of the coast of Le Lavandou with a weak retreat of $-7.3\ (\pm 3.5)$ m, beaches of Porquerolles with an average retreat of $-10\ (\pm 3.5)$ m, beaches of the Rade de Hyères with a stronger retreat of $-12\ (\pm 3.5)$ m, and, finally, beaches of the St Tropez peninsula with a retreat of $-15\ (\pm 3.5)$ m. The maximum retreat is measured on the beach of Léoube, in the northeastern part of the Rade de Hyères ($-20\ (\pm 3.5)$ m), whereas the nearby beaches have moved back by "only" $-8\ (\pm 3.5)$ and $-9\ (\pm 3.5)$ m (Pelegrin and Estagnole beaches). If we consider that the pocket-beaches are embanked and narrowing, the investigated beaches lost an average of 40% ($\pm 10\%$) of their surface area between 1896 and 1998.

4.3. Calculated shoreline changes during the 20th century by RSLR

Assuming a RSLR of $+0.17 \text{ m}$ between 1895 and 1977, as measured by the tide gauge at Grau de la Dent, the shoreline movements of the open-beaches of Camargue (as calculated by flooding) naturally exhibit a general theoretical retreat along all the coastline (Fig. 9). In the sectors undergoing long-term shoreline erosion (the beaches of Faraman, Saintes Maries-de-la-Mer and the Petite Camargue), the retreat by flooding amounts to an average of $-34.8\ (\pm 6) \text{ m}$. This calculated retreat varies between $-16\ (\pm 6) \text{ m}$ and $-60\ (\pm 6) \text{ m}$, reflecting the spatial variation of the measured slopes. These values are considerably smaller than the measured retreat and represent only 8% ($\pm 1.5\%$) on average of the shoreline erosion during the 20th century.

For the pocket-beaches of Provence, the flooding method yields an average shoreline retreat of $-6.4\ (\pm 1.5) \text{ m}$, between 1896 and 1998, assuming a sea-level rise of $+8 \text{ cm}$ over the same period (measured by the Endoume–Marseilles tide-gauge). The calculated minimum retreat is $-3.1\ (\pm 1.5) \text{ m}$ on the beach of Rayol, while the maximum retreat is $-10.3\ (\pm 1.5) \text{ m}$ for the northern beach of Cap Taillat (Fig. 10). These calculated values represent 60% of the total measured retreat.

4.4. Simulation of shoreline position in 2100 by RSLR

Given that the shoreline variations of the Camargue indicate some zones in accretion and others in erosion, we only evaluate the effect of sea-level rise on the retreat of the shoreline in those sectors undergoing retreat. On the long-term eroded beaches of the Camargue, the shoreline projection for 2100 results in a future average retreat of $-112\ (\pm 17) \text{ m}$, varying between $-52\ (\pm 17)$ and $-191\ (\pm 17) \text{ m}$.

On the pocket-beaches of Provence, the impact of the RSLR on the position of the shoreline by 2100 will result in an average retreat of $-20\ (\pm 2) \text{ m}$, with values varying between $-12\ (\pm 2)$ and $-41\ (\pm 2) \text{ m}$. Since most of the pocket-beaches are embanked (cliff or scarp above the back-shore), which limits the landward migration of the shoreline, the beach narrowing due to the RSLR will be about 40 ($\pm 10\%$) on average compared with the present situation (1998). Almost one quarter of the investigated pocket-beaches will lose at least 75 ($\pm 10\%$) % of their current surface-area by 2100.

5. Discussion

5.1. The role of the RSLR on the shoreline changes during the 20th century

If we consider only the rates of RSLR measured in the long term (+2.2 mm/year at Grau de la Dent and +1.1 mm/year at Endoume–Marseilles), it appears that the open-beaches of Camargue are more sensitive to sea-level rise than the pocket-beaches of Provence, since the sea level in the latter zone is rising twice as fast (Fig. 8). On the other hand, such a first approximation can be qualified by the geomorphological analysis of these two types of coast presented here.

Indeed, for the open-beaches of Camargue, in zones undergoing erosion, the measured average retreat is $-3.4\ (\pm 0.1) \text{ m/year}$ between 1895 and 1977, whereas the average retreat calculated from the RSLR is only $-0.4\ (\pm 0.07) \text{ m/year}$. Therefore, the relationship between the measured and the calculated retreat indicates that the RSLR could account for 8 ($\pm 1.5\%$) % of the total distance of shoreline retreat. Even if we take into account the margins of error, this percentage remains low, we show that RSLR has a minor influence on the shoreline retreat. Using the active flooding principle, the displacement of the shoreline indicates a contrary trend in the zones of accretion (Fig. 9), which reflects the large amount of longshore transport and the distribution of littoral cells (Sabatier and Suarez, 2003). The theoretical values of maximum retreat as a function of the sea-level rise are located in the Golfe de Beauduc, because the slopes in this sector are weakest, whereas the measured shoreline is advancing. This allows us to
highlight the dominant role of longshore inputs in controlling the long-term evolution of the coastline, in contrast to the influence of sea-level rise. The sandy inputs of the Rhone to the beaches not adjacent to the mouth play a very reduced role in the sedimentary budget of the investigated beaches. This is because the sands brought in by the Rhone are mainly stored at the mouth with a very weak redistribution towards the west, in accordance with the net longshore sediment transport (Fig. 3) (Sabatier et al., 2009-this volume, 2006). Moreover, the 20th century was characterized by a decrease in the sedimentary inputs, as well as the construction of dams that considerably reduce the sedimentary supply (Pont et al., 2002; Sabatier et al., 2009-this volume, 2006). In fact, sea-level rise enhances the retreat where the beaches are being eroded and reduces the advance of the shoreline on beaches that are accreting (mouth, spit and gulf). Thus, in order of increasing importance, the factors controlling shoreline retreat are as follow: (1) the gradient of longshore transport, (2) the weak redistribution of sandy inputs from the Rhone toward the beaches, and (3) the rise of sea level (Provansal and Sabatier, 2001; Sabatier and Provansal, 2002).

On the pocket beaches, the comparison between the measured ($-0.1$ (±0.03) m/year) and the calculated ($-0.06$ (±0.015) m/year) average retreat suggests that the sea-level rise plays an important role in the shoreline retreat (60%). This percentage varies between 50 and 70% if we include the margins of error. We infer that, in the long term, the presence of embayed beaches limits the wave erosion while reducing the sedimentary inputs and outputs. The pocket-beaches of Provence have suffered an average decrease of 40 (±10) % in their surface area between 1896 and 1998, so it is reasonable to consider they undergo significant erosion even at low rates of shoreline retreat ($-0.1$ (±0.03) m/year). Consequently, sea-level rise makes a significant contribution to the shoreline retreat and the narrowing of the pocket-beaches (Brunel and Sabatier, 2007).

5.2. The role of the RSLR on the shoreline position prediction for 2100

The morphodynamic characteristics of the open-beaches of Camargue offer a advantage of a flexible and natural defence faced with sea-level rise. Indeed, the profile can migrate landward in response to sea-level rise owing to the presence of sufficient available space behind the dunes occupied by lagoons and salt-marshes (Fig. 4). The shoreline retreat is accompanied by an increase in elevation of the delta plain caused by overwash processes. These natural mechanisms compensate, at least partially, for the rise in sea level (Sabatier et al., 2005). However, in the case of the open-beaches of Camargue, this evolution is locally disturbed by coastal defence works. On beaches with a seawall, there is no deposition of overwash and the vertical aggradation of the lagoons is blocked, thus preventing landward migration of the beach. This leads to the disappearance of the beach in front of the seawall following the sea-level rise, along with increased reflection against the structure (Suanez and Bruzzi, 1999; Samat et al., 2005; Sabatier et al., 2009-this volume, 2006). However, most of the hard engineering works consist of groynes rather than seawalls. Since the former structures do not block the cross-shore overwash processes, they allow, at least partially, the occurrence of natural processes. Regarding the sea-level rise, the beaches of the Camargue can potentially move back into a wide space of mobility. However, the values of retreat proposed here are much less than the values we can expect for 2100, because the “sea-level rise” factor is not responsible for controlling the position of the shoreline. The RSLR only exacerbates the shoreline retreat caused by the gradient of the longshore sediment transport. For the open-beaches of Camargue, the future challenge will be to evaluate the impact of climatic change on the sediment budget and on the longshore sediment transport.

On the pocket beaches, however, the presence of a break in the slope “blocking” the landward migration of the profile will lead to a significant reduction in the beach width. The acceleration in sea-level rise predicted for 2100 will play an important role in the future position of the shoreline for such beaches because of their narrowness (7 to 30 m in 1998) and the importance of sea level in controlling the shoreline position. Based on the principle of flooding, the average retreat of the beaches will be $-25$ (±2) m (Fig. 8) and the future wasting away of the beaches will be about $40$ (±10) % compared with 1998. Nevertheless, the simulations we propose for 2100 do not take into account the erosional phenomenon related to other forcing agents such as waves. Consequently, our results are minimum values, and the shoreline retreat is therefore likely to be even more marked. Assuming a sea-level rise of $+0.44$ mm/year, we can expect the disappearance of several pocket-beaches in Provence by 2100 (Brunel and Sabatier, 2007).

5.3. The active flooding concept under discussion

The active flooding principle used in this paper has the advantage of depending on simple parameters, making it possible to separate the “sea-level rise” factor from other processes controlling the beach profile (longshore and cross-shore sediment transport). This approach is evidently simplistic because beach morphodynamics is a function of nonlinear interactions and feedback effects between morphology and forcings (Stive and de Vriend, 1995). Lastly, this projection for 2100 does not incorporate any eventual modification of the storm regime, which could arise from the expected climatic change. Nevertheless, in spite of its empirical aspect, this method remains the only one able to evaluate the impact of sea-level rise on the shoreline retreat used by scientists (Durand and Heuverteux, 2005; Ferreira et al., 2006) and for coastal management developments (EPA, 2005). Consequently, our forecasts of shoreline retreat due to the acceleration in sea-level rise should be interpreted as an order of magnitude. Nevertheless, the important differences behaviour between open and pocket beaches to the RSLR do not invalidate our conclusions.

The principal criticism of the active flooding concept is that the slope of the profile is assumed to remain identical throughout the studied period. However, this concept can be realistic at the time scale investigated in this paper (Davidson-Arnott, 2005), even if the evolution of slope with time remains poorly understood. For example, Cowell et al. (1998) acknowledge that probably several hundred years would be required before the shoreline and shelf display significant morphological modifications. To address this crucial point concerning the principle of flooding, we adopt an average slope integrating several slopes related to geomorphological and sedimentological processes (see Section 3.3). In any case, even if we assume different slopes, we obtain coherent results for the open and pocket beaches. The shoreline retreat on open-beaches is weakly linked to the sea-level rise, in contrast to the pocket-beaches. This result could be integrated into coastal management practices. For example, the USGS (United States Geological Survey, Hammur-Klose and Thieler, 2001) is carrying out a cartography of the beaches vulnerable to sea-level rise by using an index based on six factors (geomorphology, coastal slope, relative sea-level rise rate, shoreline erosion/accretion rate, mean tide range, mean wave height) which include the slope of the shore and sea-level rise. In fact, the USGS implicitly uses the flooding principle but without varying the slope. Moreover, Hammur-Klose and Thieler (2001), incorporate these six factors into a vulnerability coefficient, in which each factor has the same weight in the final index. However, with a similar methodology, we show that the rise of sea level has a very different influence on the shoreline retreat according to the type of sandy coast. Hence, in the future, these results could be integrated into coastal zone management.

6. Conclusion

If we compare the open-beaches of the Camargue with the pocket-beaches of Provence, it appears – to a first approximation – that the
Camargue is in more danger from RSLR because the rates of sea-level rise there are twice as fast as in Provence (2.2 as against 1.1 mm/year, respectively), while the slopes are gentler (0.6% and 1.9% respectively) and the shoreline retreat is more marked. (−3.3 and −0.1 m/year respectively). Therefore, we provide evidence here that the RSLR has an enhanced influence on shoreline erosion on pocket-beaches compared with wave-dominated open-beaches. 

On the wave-dominated open-beaches of Camargue, the sea-level rise between 1895 and 1977 yields a theoretical averaged retreat of −34.8 (±6) m, but this value eventually represents only a small proportion (8 (±1.5)%) of the total distance of shoreline retreat. On open-beaches exposed to the swell, (Camargue), rising sea level enhances the erosion, which is itself ultimately dependent on the action of the waves (longshore transport, cross-shore processes) and the sedimentary budget. In other words, sea-level rise is not the major cause of coastal erosion and does not represent the most severe risk along this type of shore. Moreover, the cross-shore processes of overwash “assist” the shoreline retreat by compensating for sea-level rise. On the other hand, since sea-level rise is one of the principal factors influencing shoreline retreat, the acceleration in sea-level rise predicted for 2100 will play an important role in the future position of the shoreline on pocket-beaches protected from wave action and with limited back-shore areas (i.e. the beaches of Provence). The width of the beaches is going to decrease significantly with the increasing risk of disappearance of some beaches. Indeed, if we integrate the low rates of long-term retreat, and taking account of the morphology of the back beach, then the pocket-beaches appear to be threatened by disappearance due to sea-level rise. Under these conditions, sea-level rise will have important socio-economic impacts on the pocket-beaches of Provence.

To conclude, we should bear in mind the need to integrate coastal morphology and behaviour faced with the RSLR in order to estimate its impact on the past and future shoreline position. This is because the rate of sea-level rise and the beach slope cannot be sufficient factors in themselves. This analysis should enable politicians and environmental managers to make decisions with a fuller knowledge of the coastal processes.

Acknowledgements

This work is supported by an IGCP-UNESCO programme: Vulnerability and resilience assessment of coastal zones in Mediterranean and Black Sea areas related to the forecast sea-level rise for management purposes, and by LOICZ program (Land-Ocean Interaction In the Coastal Zone). At national level, this work received some financial support by CNRS programmes ORMÉ and RESYST and by French programs GICC-IMPLIT and Liteau-GIZCAN. Dr M.S.N. Carpenter translated an early version of the manuscript, and post-edited the English style of the final version. Thomas-Jules Fleury and Philippe Dussouillez (CEREGE) are acknowledged for their technical assistance on GIS.

References


Pose, J., Pirazzoli, P.A., 1989. Relative sea-level rise between 1895 and 1977 yields a theoretical averaged retreat of −34.8 (±6) m, but this value eventually represents only a small proportion (8 (±1.5)%) of the total distance of shoreline retreat. On open-beaches exposed to the swell, (Camargue), rising sea level enhances the erosion, which is itself ultimately dependent on the action of the waves (longshore transport, cross-shore processes) and the sedimentary budget. In other words, sea-level rise is not the major cause of coastal erosion and does not represent the most severe risk along this type of shore. Moreover, the cross-shore processes of overwash “assist” the shoreline retreat by compensating for sea-level rise. On the other hand, since sea-level rise is one of the principal factors influencing shoreline retreat, the acceleration in sea-level rise predicted for 2100 will play an important role in the future position of the shoreline on pocket-beaches protected from wave action and with limited back-shore areas (i.e. the beaches of Provence). The width of the beaches is going to decrease significantly with the increasing risk of disappearance of some beaches. Indeed, if we integrate the low rates of long-term retreat, and taking account of the morphology of the back beach, then the pocket-beaches appear to be threatened by disappearance due to sea-level rise. Under these conditions, sea-level rise will have important socio-economic impacts on the pocket-beaches of Provence.