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Rapid Deterioration of a Salt Marsh in Venice Lagoon, Italy

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ABSTRACT

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From March 1993 until June 1995, various aspects of sediment dynamics and geomorphological change were measured in an eroding salt marsh in Venice Lagoon. Marsh edge retreat and changes in interior pond size were measured in relation to permanent stakes placed in the marsh. Short term sedimentation and vertical accretion on the marsh surface were measured as the deposition of material on filter papers and the accumulation of material over feldspar clay marker horizons, respectively. A sedimentation-erosion table was used to measure elevation change of the surface of the marsh and the eroding mudflat in front of the marsh. High wave energy caused by strong winds and a long fetch is leading to marsh edge retreat of 1.2–2.2 m yr^{-1} and the formation of new tidal channels which are cutting rapidly into the marsh. Short-term sedimentation was highly variable, ranging from 2.9 to 72.3 g $m^{-2}d^{-1}$, with the highest values occurring during strong storms. Vertical accretion on the marsh surface was high, averaging 2.3 cm yr^{-1}. This was reflected in high increases in marsh surface elevation which averaged 1.54 cm yr^{-1}. By contrast, the eroding marsh front lost elevation at 4.12 cm yr^{-1}. The high rate of accretion in the marsh is supported by material eroded from the marsh front and the lagoon bottom. Wave energy and the tidal prism in the lagoon have increased due to increased depth and fetch. Thus, this marsh is likely to deteriorate rapidly despite the high sediment input because of the high rates of lateral erosion. The most practible solution to this deterioration is reduction of wave energy by permeable barriers.

ADDITIONAL INDEX WORDS: *Mediterranean, Venice Lagoon, salt marsh, erosion, sea-level rise.*

INTRODUCTION

The survival of tidal marshes in coastal systems is dependent on a number of factors, including subsidence, vertical accretion, and wave energy. Eustatic sea level rise has been increasing at a rate of 1–2 mm yr^{-1} over the last century (GORNITZ *et al.*, 1982) and it will likely accelerate over the coming 100 years (WARWICK and ORLEMANS, 1990; WIGLEY and RAPER, 1992). In addition, subsidence due to a number of factors, has caused relative sea level rise (RSLR) to be much greater than the eustatic rate in a number of coastal systems. For example, in the Mississippi delta, RSLR is about 10 mm yr^{-1}, primarily due to regional subsidence (PENLAND and RAMSEY, 1990). For the Nile Delta, the rate of subsidence is as high as 5 mm yr^{-1} (STANLEY, 1988). In Venice Lagoon, ground water withdrawal from the 1940's to the late 1960's led to RSLR as high as 8 mm yr^{-1} (SESTINI, 1992).

If marshes are to survive rising water levels, they must be able to accrete at a rate such that surface elevation gain is sufficient to offset RSLR. A number of studies have shown that coastal marshes are able to accrete at a rate equal to the historical rate of eustatic sea level rise (1–2 mm yr^{-1}, GORNITZ *et al.*, 1982) and survive for long periods of time (REDFIELD, 1972; MCCAFFEY and THOMPSON, 1980; ORSON *et al.*, 1987). Marshes, however, are able to survive much higher rates of RSLR if there is sufficient sediment input and *in situ* organic soil formation. In the Mississippi Delta, for example, RSLR generally is between 8 and 12 mm yr^{-1} (PENLAND and RAMSEY, 1990). Tidal creek streamside levee marshes and those near sources of riverine sediments are able to accrete vertically at rates higher than RSLR while back marshes generally have accretion rates less than RSLR (BAUMANN *et al.*, 1984; HATTON *et al.*, 1983).

Marshes can also deteriorate due to high hydrodynamic energy. High wave energy on exposed marsh shores can lead to shoreline retreat and, at times, scour of the surface of the marsh (PETHICK, 1992). Wave energy can also lead to the enlargement of interior marsh ponds (STEVENSON *et al.*, 1985). An increased tidal prism due to increased water depth or higher sea level leads to the deepening and widening of tidal channels (PETHICK, 1992, 1993).

In this study, we investigated various aspects of sediment dynamics and geomorphological change in an eroding salt marsh in Venice Lagoon. In order to develop a better understanding of the processes taking place in this eroding marsh, we made a number of measurements of erosion, sediment de-

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position, and accretion. Specifically, the objectives were to measure: (1) horizontal retreat of the marsh front, (2) elongation and widening of tidal creeks, (3) short term sediment deposition, (4) vertical accretion, and (5) surface elevation change. These measurements provide information on both horizontal and vertical changes taking place at the study site. Short term sediment deposition provides information on the mechanisms of sediment delivery, such as storm events. Vertical accretion provides information about the thickness of accreted material, while surface elevation change measurements show whether the vertical accretion is leading to a gain in elevation. For example, if processes such as compaction, consolidation and subsidence are greater than vertical accretion, a marsh can show sediment accretion but actually loose elevation (*e.g.*, CAHOON *et al.* 1995b). These issues are discussed in more detail later.

Study Area

The Lagoon of Venice is a large (approximate area is 550 km^2), shallow coastal lagoon located along the Adriatic Sea in northeastern Italy (about 45°N, 12°E, Figure 1). The lagoon originated nearly 6,000 years ago when rising sea level flooded the upper Adriatic Wurmian paleoplain (GATTO and CARBOGNIN, 1981). Two barrier islands separate the lagoon from the sea and water is exchanged through three large inlets. Over the past five centuries, sediment dynamics of the lagoon have been greatly altered. The Brenta and Piave rivers formerly flowed into the lagoon and the lagoon, created by the Holocene transgression, filled to a large degree by sediments from rivers. The Venetians changed the courses of these rivers to prevent further infilling and the rivers presently flow into the sea to the south and north of the lagoon. Only a few rivers (the total discharge being 30 m^3 s^{-1}) presently discharge to the northern lagoon although there is considerable agricultural drainage into the lagoon (BENDORICCHIO *et al.*, 1993). Thus riverine sediment input to the lagoon has been almost completely eliminated. Long jetties constructed in the inlets have greatly reduced the import of coarse marine sediments into the lagoon. As a result of these alterations and erosion of bottom sediments, there is a net export of about one million m^3 yr^{-1} of sediments from the lagoon system (BETTINETTI *et al.*, 1995).

Most of the lagoon area is occupied by a large central waterbody (about 400 km^2) which is partially vegetated by macroalgae and seagrasses. The mean depth of the lagoon is 1.1 m and the tide range is 0.6–1 m, thus extensive tidal flats are exposed at low tide. There are extensive intertidal salt marshes, especially in the southwestern and northeastern portions of the lagoon. The dominant marsh species include *Limonium serotinum*, *Salicornia* sp. pl., *Halimione portulacoides* and *Spartina maritima* (a listing of plant species of the lagoon is given by GEHU *et al.*, 1984). These marshes are considered very important in Europe due to their aerial extent, high productivity, and habitat value (DIJKEMA, 1984). Salt marsh area in the lagoon, however, has fallen from about 12,000 ha at the beginning of the century to about 4,000 ha at present due to reclamation, erosion, pollution, and natural and human-induced subsidence (FAVARO, 1992; RUNCA *et al.*, 1993).

The study site is located on Punta Cane, one of the largest salt marsh islands (36 ha) in the southern lagoon in an area where there are still extensive salt marshes (Figure 1). The most widespread vegetation type in the study area is a salt marsh association, dominated by *Arthrocnemum fruticosum* and *Puccinellia palustris* with lesser occurrence of *Spartina maritima* and *Limonium serotinum*, which occurs at an elevation between 0.15 and 0.40 m above msl. There are a number of small ponds (10–20 cm deep, 3–5 m in diameter) scattered throughout the marsh. Seagrass beds of *Zostera marina* and *Z. noltii* are common in the zone in front of the island.

The front of the island is exposed to wave attack generated when winds blow over about 7.5 km of open lagoon. Because of this, waves are not fetch-limited and during storms large waves can be generated. In winter, storms with strong northeast winds up to 80–90 km h^{-1} or higher called Bora occur on average of about once a month and winds blow for 2–3 days. The Bora winds depress water levels in the northern Adriatic and Venice Lagoon so that the marshes are flooded less often and the mean water level can be 30 to 50 cm lower in the northern lagoon. Because of the lowered water level, waves generated by the Bora winds more often attack the marsh edge below the level of vegetation. During the spring and fall, southern winds as high as 50–60 km h^{-1} called the Scirocco lead to elevated water levels in the northern Adriatic and extensive flooding of marshes in Venice Lagoon. Waves generated during these periods often propagate into the marsh depositing suspended and floating material. We have observed thick racks of sea grasses and other debris 40–50 cm high deposited after storms. The strong wave activity is causing rapid frontal erosion along the exposed edge of the marsh vegetation at Punta Cane. In the first 3–5 m, the vegetation has been completely eroded away and bare mud is exposed. In addition, a number of tidal creeks are cutting into the marsh. The wave-caused erosion observed in our study is a continuation of conditions which have existed for many years. The edge of most of the exposed salt marshes in the southern lagoon are eroding and there has been an expansion of the tidal network over the past several decades (CONSORZIO VENEZIA NUOVA, 1993). By comparing official maps, CAVAZZONI and GOTTARDO (1983) calculated that between 1933 and 1970, these marshes retreated at a rate of 0.8–2.7 m yr^{-1}.

METHODS

A 50 × 50 m area was marked off with one side along the marsh edge, and duplicate, randomly-placed 4 × 4 m plots were established within this area for measurement of short-term sedimentation patterns, vertical accretion, and change in surface elevation. Hunters and fishers sometimes walk over the area, so the plots were fenced with barbed wire. A boardwalk was established within each plot to minimize local disturbance of the vegetation and substrate during measurements.

Short-term sedimentation was measured as the accumulation of material on 9 cm Whatmann ashless filters fixed to

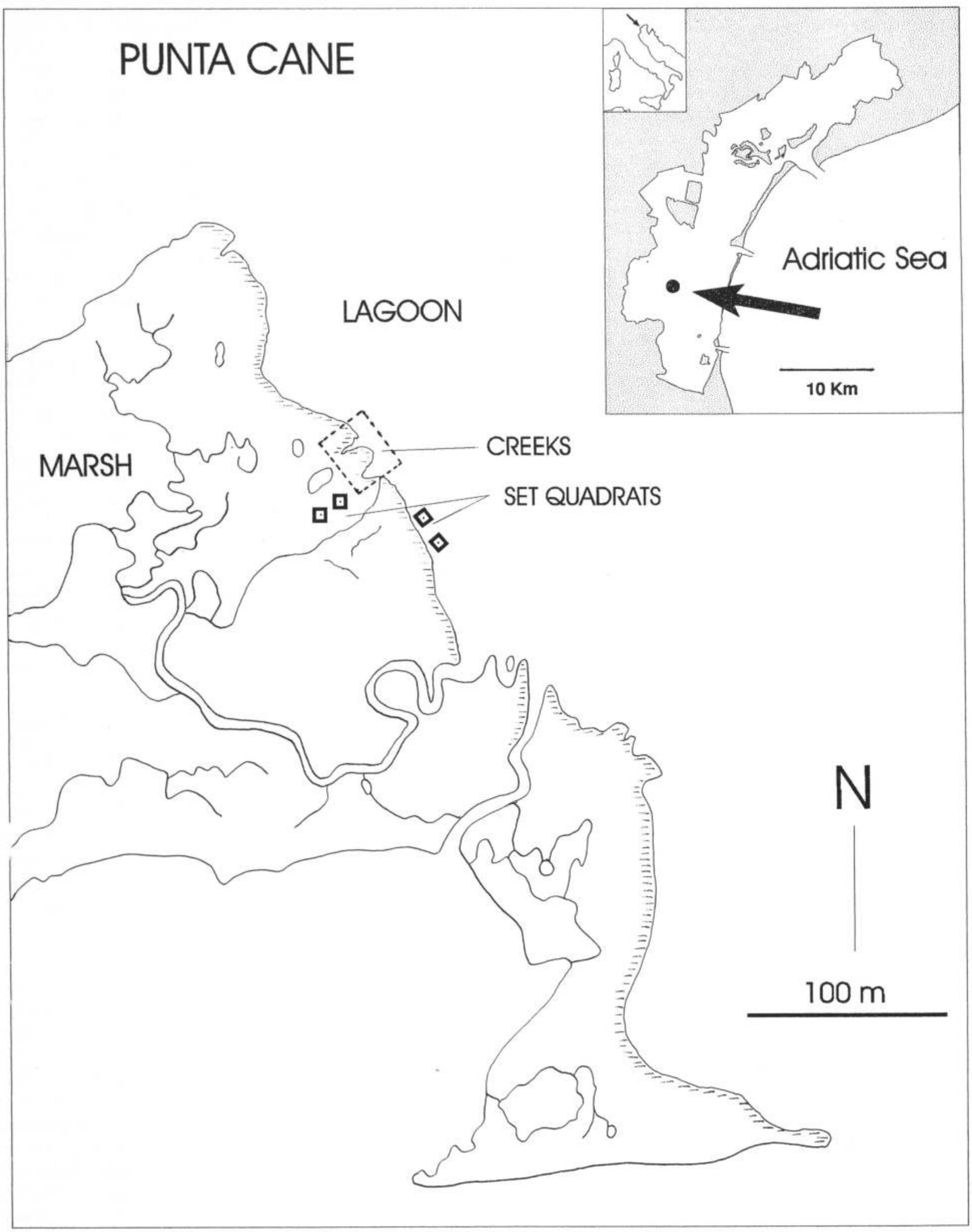

Figure 1. Map of the study area showing locations of the SET and marker horizon measurements and the location of the developing tidal creeks. The study site in the southern part of Venice Lagoon is characterized by numerous small marsh islands. The dashed area is shown in more detail in Figure 2.

inverted plastic petri dishes placed on the marsh surface (as described by REED, 1992) from March 1993 to June 1995. Three pre-weighed, numbered filters were placed in each plot, for a total of 6 filters, at various times throughout the study period and left in place for 2–4 weeks. Filters were collected in April (3 filters), October (4), and November (6) 1993; February (1), May (6) and August (6) 1994; and January (6) and April (6) 1995. At times, we encountered difficulties with filters, which were continuously moist, being eaten by small animals such as amphipods. In order to counter this, the filters were soaked in gasoline prior to being placed in the marsh, thus minimizing loss of filter material. Where parts of filters were lost, we estimated the percentage area lost and corrected for this. After collection, the filter papers were dried at 60°C for 48 hours, weighed to obtain total dry weight sedimentation. The filters were then combusted at 500°C for one hour and re-weighed; the loss on combustion was considered organic matter and the remainder was inorganic material. Because measurements are made on a short-term basis, the effect of particular types of events (such as storms, high river flow, rainfall, *etc*) can be determined.

Vertical accretion was measured as the accumulation of material over artificial marker horizons laid down on the marsh surface (CAHOON and TURNER, 1989). The marker horizons consist of 0.25 m^2 plots of white feldspar clay spread on the marsh surface to an approximate depth of 1 cm. Three horizons were randomly laid down in each plot for a total of six markers. The markers were set up in March, 1993 and sampled by coring in February and June 1994, and February and June 1995. Five measurements were made in each marker during each sampling date.

Surface elevation changes were measured using a sedimentation erosion table (SET) developed for high precision measurements of surface elevation changes in wetlands (BOUMANS and DAY, 1993). One SET station was established in each plot in March 1993 and surface elevation was measured in November 1993, February, June and October 1994, and January, April and June 1995. The SET has an accuracy of about 2.0 mm. An advantage of the SET is that once a station is established, it can be measured for many years. SET stations were also established about 4 m in front of the marsh in an intertidal area of active erosion. Bulk density of the top 5 cm of soil was measured from seven 2.5 cm diameter cores collected from undisturbed marsh in the immediate vicinity of the plots. The percentage water content of the cores was determined as weight loss upon drying for 48 hours at 70°C and percentage mineral and organic matter was determined from loss on ignition at 500°C for 2 hours.

Changes in the position of the edges of the marsh front, tidal channels and small pond were determined relative to reference markers placed at the beginning of the study (Figure 2). Ten stakes were placed, one each 10 m, along the vegetation edge and eroding front of the marsh substrate. At each tidal channel, two stakes were placed in line with the head of the channel so that both lengthening and widening of the channel could be measured. Finally, a number of stakes were placed around the edge of a small pond. Changes in the position of the marsh edge relative to the reference stakes were made during each field visit.

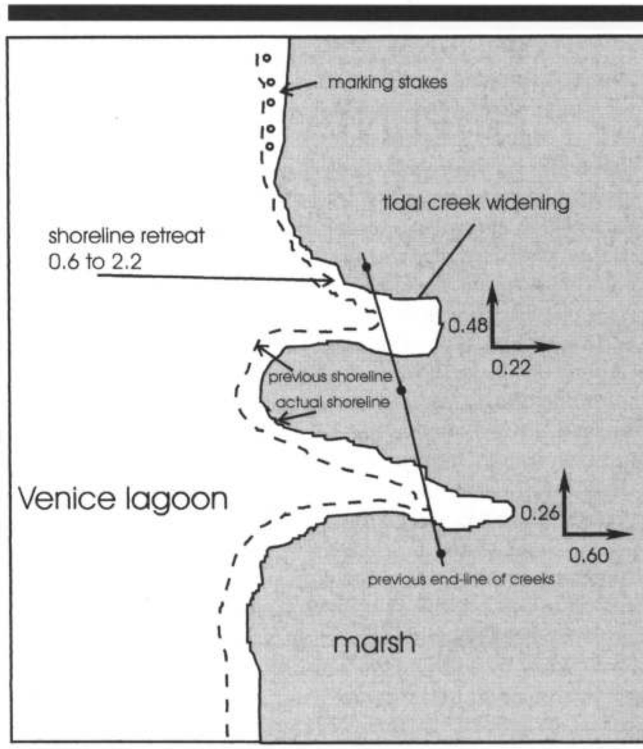

Figure 2. Rates of tidal creek widening and lengthening and shoreline retreat (all rates are expressed in m yr^{-1}). Open circles are stakes used to measure the rate of shoreline retreat and closed circles are stakes used to mark the original length and width of the tidal channels. See Figure 1 for scale.

For statistical analysis, short term sedimentation data were not normally distributed and they were log10 transformed. One-way ANOVA was used to test for differences among sampling intervals. Accretion data were also log10 transformed in a one-way ANOVA that was used to test the equality of the means. Differences between pairs of means were tested with a t-test. SET data were normally distributed and a t-test was used to compare the differences between means. A p value < 0.05 was considered significant.

RESULTS

The results indicate that the marsh edge is eroding rapidly and that the eroded material, along with material advected in from the lagoon, is being deposited on the marsh surface. The edge of the marsh is experiencing a relatively rapid retreat due to wave induced erosion (Figure 2). Over the two years of measurement, the vegetation edge retreated at a rate of 0.6–2.2 m yr^{-1}. The erosion of the marsh edge is proceeding in two phases. First, the above ground vegetation is eroded exposing an elevated intertidal bench about 2.5–5.0 m wide at approximately the level of the marsh surface, which is devoid of living plant material. The substrate is composed of relatively firm material with an organic content about 30%. Subsequently, this bench is eroded back along its seaward margin resulting in a sub-tidal elevation. Within our immediate study area, two new tidal channels are rapidly cutting

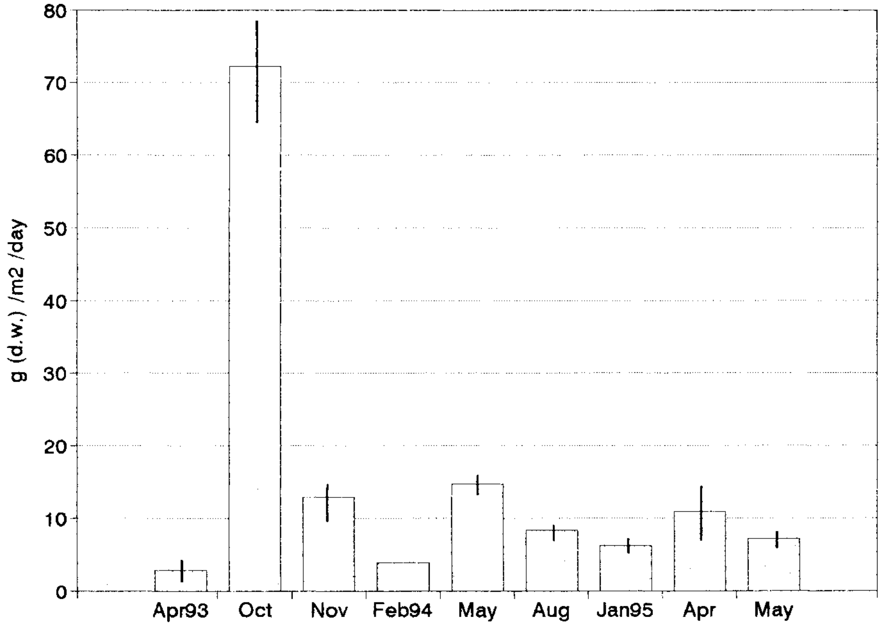

Figure 3. Short term sedimentation patterns at Punta Cane. Bars are means ± SE.

into the marsh. The two channels are lengthening at a rate of 0.2 and 0.6 m yr^{-1} and widening at a rate of 0.48 and 0.26 m yr^{-1}, respectively. We observed distinct depositional layers in the exposed vertical erosional surface on the edge of the developing tidal channel. Material of relatively recent origin, such as plastic sheeting, was buried 30–50 cm indicating that this marsh formed rapidly over the past several decades by vertical accretion. In contrast to the rapid changes at the marsh front, the small pond did not significantly change in width or depth during the two years of measurement.

The results of the short term sedimentation measurements reveal highly variable deposition rates with the highest values associated with storm events (Figure 3). Accumulation rates varied from 2.9 to 72.3 g $m^{-2}d^{-1}$ and averaged 15.5 g $m^{-2}d^{-1}$. The differences among trips was highly significant ($p < 0.01$). The highest rate of October, 1993, was associated with sustained Scirocco storms and high tides which occurred during the measurement period. During these storms, there were strong southerly winds of 60 km h^{-1} and the highest tides in the last 10 years. The material deposited on the filters had 27.7–32.4% organic matter.

The marsh is accreting rapidly, with the marker horizon data indicating a mean accretion rate of 2.32 cm yr^{-1} over the duration of the study. The depth of accreted material varied considerably over time and there were highly significant decreases ($p < 0.001$) from February to June 1994 and from January to July 1996 (Figure 4). All measurement were highly significantly different from each other ($p < 0.001$). A considerable portion of the accreted material was sea grass debris which we often observed on the marsh surface, especially after storms and high tides. The accretion cores taken in February 1994 and January 1995 contained considerable amounts of compacted sea grass leaves. The decomposition and compaction of these leaves is probably responsible for part of the decrease in the depth of the material over the marker measured in June 1994. The upper five cm of the soil had a relatively low bulk density of 0.26–0.58 g/cc (average 0.4), water content was 69.4 and organic matter 25.6%.

The surface elevation changes reflect the erosion and accretion patterns described above (Figure 4). The SET readings show that over the two year measurement period, the marsh surface increased by 1.54 cm yr^{-1} while the elevation of the eroding marsh front decreased by 4.12 cm yr^{-1}. Both of these changes were significant at $p < 0.001$. Temporally, surface elevation increased by almost 2.0 cm from November 1993 to February 1994 then decreased by about 0.8 cm in June 1994. A similar increase followed by a decrease occurred between October 1994 and March 1995. Both of these changes were highly significant ($p < 0.001$). These patterns of surface elevation change followed changes in the thickness of material over the marker horizons. These changes likely reflect sequential deposition followed by erosion or consolidation and decomposition of deposited material.

DISCUSSION

The patterns of morphological change at Punta Cane reflect changes in wave energy and relative sea level in Venice Lagoon, and are consistent with trends observed in other areas. During this century there has been a relative increase in water level due to eustatic sea level rise, subsidence, and deepening of the lagoon (CAVAZZONI and GOTTARDO, 1983; SESTINI, 1992). The background rate of geologic subsidence in Venice is presently 1.33 mm yr^{-1} (PIRAZZOLI, 1987), but between 1930 and 1970, RSLR was 24 cm, about half of which was due to ground water withdrawals (SESTINI, 1992; BON-

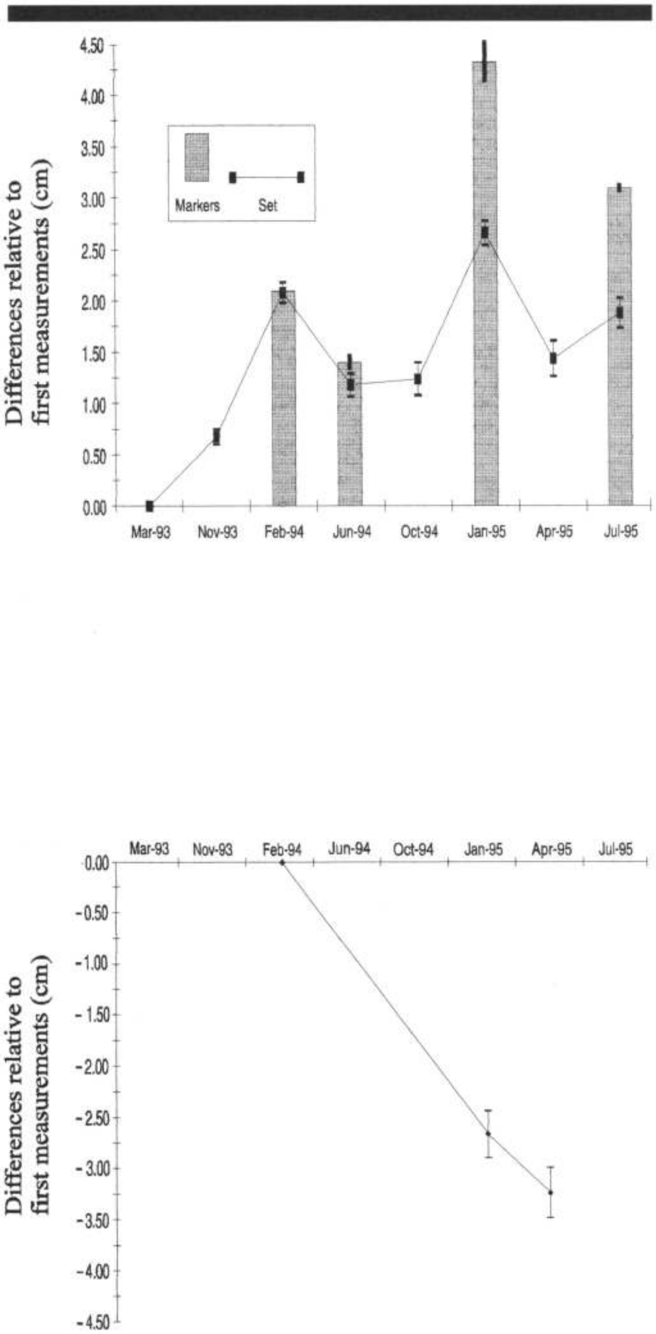

Figure 4. Accretion (measured by marker horizons) and surface elevation change (measured by SET) at Punta Cane. Values are means ± SE. Top panel is for the marsh, bottom panel is for the tidal flat.

DESAN *et al.*, 1995). The lagoon has deepened by up to 30 cm due both to the RSLR and erosion of the bottom due to longer fetch because of marsh retreat (CONSORZIO VENEZIA NUOVA, 1993). This has led to both greater wave energy and a larger tidal prism within the lagoon.

Although large-scale, infrequent events such as major river floods and hurricanes can have great effects on coastal ecosystems, higher frequency events such as storms are also important (REED, 1989). In Louisiana, the passage of seasonal cold fronts is responsible for much of the sediment deposition in coastal marshes (BAUMANN *et al.*, 1984; REED, 1989; BOUMANS and DAY, 1994). Similarly, STUMPF (1983) reported that strong storms were the most important mechanism leading to sediment deposition in a Delaware salt marsh.

Short-term sedimentation patterns were highly variable with peak rates over an order of magnitude greater than the lowest ones. This high variability resulted because most sediment deposition on the marsh surface was associated with high energy storm events, as has been reported for the Mississippi Delta, the Rhone delta, southeast England and other areas (STUMPF, 1983; BAUMANN *et al.*, 1984; REED, 1989; PETHICK, 1992; DAY *et al.*, 1995). The highest short-term sedimentation rates during the entire period of study occurred during the strong storms of October 1993. The rates of short term sedimentation were comparable to values reported elsewhere. BOUMANS and DAY, (1994) reported mean short-term sedimentation rates ranging from 0 to 11.9 g $m^{-2}d^{-1}$ at various sites in the Mississippi delta. The highest rates were near the coast and during storms while the lowest rates occurred in impounded marshes. REED (1989, 1992) reported short term sedimentation rates from 0 to 40 g $m^{-2}d^{-1}$ in Louisiana coastal marshes; sedimentation was higher near the coast and during winter frontal passages. In the Mississippi delta, short term sedimentation associated with Hurricane Andrew was as high as 130 g $m^{-2}d^{-1}$ (CAHOON *et al.*, 1995a). In the Rhone delta, short term sedimentation ranged from $<$ 1.0 to 95 g $m^{-2}d^{-1}$ with the highest values associated with a major Rhone River flood (DAY *et al.*, 1995).

The marsh retreat and SET data reveal a very dynamic marsh which is eroding along the margin but accreting very rapidly behind the erosional front. Such edge erosion is common for exposed marshes (WELLS, 1995). PETHICK (1992) reported similar results for several marshes in southeast England where over a two year study, the surface of the streamside marsh increased by 1.4 cm yr^{-1} and the mudflat in front of the marsh eroded by a similar amount. The material deposited on the marsh surface is derived from the eroding marsh front as well as the open lagoon, including both resuspended lagoon sediments and dislodged submerged aquatic vegetation. Similar findings have been reported from the Mississippi delta (BAUMANN *et al.*, 1984; REED, 1992; BOUMANS and DAY, 1994) and southeast England (PETHICK, 1992). The results for Punta Cane also showed a very dynamic marsh surface with increases in elevation and accretion followed by decreases. Pethick reported that the saltmarsh in southeastern England experienced erosion of about 0.5 cm during strong storms. HARTNALL (1986) reported seasonal changes in the surface elevation of a salt marsh at Lincolnshire, UK, of up to 3.0 cm yr^{-1} with increases in the summer and decreases in the winter. These changes were attributed to seasonal growth and decay of marsh vegetation as well as to sediment input. The highest rates of elevation gain were in areas with a high density of tidal channels. BAUMANN *et al.*, (1984) also reported erosion of the marsh surface in the Mississippi delta. SET results from other areas almost always show both increases and decreases in marsh surface elevation, sometimes greater than 1.0 cm over several months (CHILDERS *et al.*, 1993; CAHOON *et al.*, 1995a, b). These changes have been attributed to storm deposition, consolidation of deposited material, seasonal patterns of root growth and decomposition, and shrinking and swelling of the soil under different inundation patterns. At Punta Cane, storm deposition followed by decomposition is clearly taking place but the other aforementioned factors may be important also.

The rate of accretion at Punta Cane, which ranged from 1.1–2.3 cm yr^{-1} during the different sampling intervals, is similar to values reported from the Mississippi delta where there is a high rate of geological subsidence. CAHOON (1994) reported that vertical accretion in the Mississippi delta was 0.3 cm/yr in a brackish marsh far from the coast and about 1.0 cm yr^{-1} in a marsh near the coast. CAHOON and REED (1995) found accretion strongly related to duration of flooding in a Louisiana salt marsh. During a stormy, high water period, accretion was 3.6 cm/yr compared to 1.08 cm yr^{-1} during a normal period.

There is rapid shoreline retreat and the formation of new tidal channels at Punta Cane. Our measurement of shoreline retreat of 1.2–2.2 m yr^{-1} compare favorably with the longer term retreat rate of 0.8–2.7 m yr^{-1} measured for marshes in the southern Lagoon between 1993 and 1970 (CAVAZZONI and GOTTARDO, 1983). This reduction in marsh area is consistent with changes in the hydrodynamics and morphology of the lagoon. The lagoon has deepened due to RSLR and scour and, as a result, wave energy and the tidal prism have increased.

It is probable that the new tidal channels which are now forming will eventually cut entirely through the island. This is the expected result of increasing RSLR. Tidal channels serve to dissipate energy. In an equilibrium condition with sufficient marsh area, creek development is halted by dissipation of tidal energy and morphological restrictions on further creek bifurcation (PETHICK, 1992). With increasing wave and tidal energy associated with increased water levels, however, tidal channels tend to develop as long, straight creeks with few tributary junctions. If the marsh is large enough, these creeks end in an intricately branched network of small channels. PETHICK (1992) has clearly described these processes for marshes of the Norfolk coast in southeast England. At Punta Cane the marsh islands are probably not large enough to allow the formation of the branched network. This is evidenced by numerous long straight channels which cut through the marshes in southeastern Venice Lagoon and which have led to fragmentation of the marsh in that area. The marsh at Punta Cane is high and is strong enough to easily support being walked upon for the first 30–50 m. Further back, the marsh is lower with less bearing strength and has more ponds. When the tidal channels reach this zone they will probably cut much faster. Accelerated sea level rise will likely lead to more rapid deterioration of the marshes at Punta Cane and nearby areas in the southeastern lagoon (*e.g.*, PETHICK, 1993; WELLS, 1995).

The life cycle of the marsh is very rapid compared to some other areas where there has been a slow but sustained vertical adjustment to eustatic sea level rise of a few mm per year for up to several thousand years (REDFIELD, 1972; MACAFFREY and THOMPSON, 1980; ORSON *et al.*, 1987). By comparison, approximately the upper half meter of marsh which is located just behind the eroding edge at Punta Cane was formed over the past 30–50 years as evidenced by material of recent origin buried 30 to 40 cm below the surface. This is consistent with a RSLR of about 30 cm or more since 1930 (24 cm between 1930 and 1970 and about 7.0 cm since 1970, SESTINI, 1992; BONDESAN *et al.*, 1995). The marsh edge zone which we are studying will rapidly disappear over the next decade or so due to both shoreline retreat and tidal channel formation.

If no action is taken to prevent it, the marsh at Punta Cane will continue to erode, perhaps at an accelerating rate as RSLR and lagoon deepening continue to increase. We think that the only practicable way to reverse the present trend is to reduce wave energy along the marsh edge using permeable breakwaters or wave-stilling devices. Because they are permeable, they would not reduce sediment delivery to the marsh surface and would probably enhance accretion and revegetation in front of the marsh. Such breakwaters have been used successfully to establish marshes in The Netherlands and the Mississippi delta (SCHOOT and DE JONG, 1982; BOUMANS, 1994). It is possible that placement of such structures could be done in a way that waves are reduced and accretion is enhanced in both the immediate vicinity of the structure but also at some distance away in adjacent areas. Such action should be taken as part of a holistic management strategy for the entire lagoon. A number of elements of such an approach have been proposed including construction of salt marshes and tidal flats with dredge material, vegetative plantings, reintroduction of river inflow to the lagoon, and use of wetlands to reduce nutrient levels. PETHICK (1993) and DAY and TEMPLET (1989) have proposed such holistic management approaches for the southeastern coast of the UK and for the Mississippi delta, respectively.

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