Abstract

Sea level change is generally taken to indicate climate change, and may be more nearly global than what we perceive to be climate change. Close to the beach, even a small sea level change (such as 1–3 m) produces important changes in local depositional conditions. This effect can be deduced from a study of properly selected beach deposits.

Various measures of beach-sand grain size indicate conditions of deposition. The best of these parameters is the kurtosis; it is a reliable indicator of surf-zone wave energy density. An abrupt energy-level shift, after centuries with little change, indicates sea level rise or drop. Kurtosis, within stated limits, shows this.

Beach ridge systems (successive, distinct old beach deposits) span the last several thousand years. A sequence of sand samples across such a deposit provides grain-size evidence for alternating high and low sea level. Changes were 1 to 3 m vertically, and took place at rates of about 1 cm yr⁻¹. There were at least seven such events in the last 3000 years.

The two most recent changes were the drop and subsequent rise that marked the Little Ice Age (starting about 1200 A.D.). One cannot say, from these data, that the planet has come fully out of the Little Ice Age. Predictions about what sea level will do in the near future should be based on the many small changes (1 to 3 m) in the last few thousand years, rather than on the arbitrary, fictitious, and unrealistic absolute sea level that appears to underlie various popular forecasts.

1. Introduction

Points to be discussed include the following:
1. The beach-sand grain-size parameter, kurtosis, is an excellent index (inverted) to surf-zone wave energy levels.
2. Many beach ridge plains (sequences of old beaches) were deposited more or less continuously across the most recent thousand years, or few thousands of years; each ridge was the beach at one time.
3. Each ridge typically represents some decades of deposition, but does not indicate erosion (which does not produce a beach ridge).
4. If such ridges are sampled systematically, old to young, a history of grain-size parameters (including kurtosis) is obtained.
5. Where dates are available, this history shows centuries of high kurtosis, then centuries of low kurtosis, etc., in an orderly sequence.
6. Kurtosis changes little except at intervals of centuries, so the indicated changes in surf-zone wave energy must represent sea level events, and not storms.
7. The method succeeds in part because data points are only decades apart, hence closer together in time than changes in sea level (centuries apart).
8. The Little Ice Age (1200–1800 A.D.) shows up clearly in the data.
9. The latest interval in the data, marked by continuous sea level rise, represents warming from the Little Ice Age.
10. There is no absolute sea level through time. The concept of absolute position appears to underlie various forecasts that sea level must rise significantly in the near future. These forecasts assume that only anthropogenic changes are taking place, or are about to take place, and that without human influence there will be no change. A recent book (Crowley and North 1991) emphasizes the importance of using the record, longer than the instrumental record of the latest century, as a base for making projections into the future. Longer-than-instrumental datasets show clearly that other changes have been taking place, and therefore one cannot know in advance how the system will react during the interval of increased anthropomorphic influences: some other factor may be more important.

2. Background

Mature beach sands, not too close to major river deltas where subsidence may mask sea level effects, have grain-size measures that tend to indicate the surf-zone wave energy level (Tanner 1991b). The mean size may not be useful because it may reflect availability; the standard deviation and the skewness are better.

The grain-size kurtosis (based on the fourth moment) is the best of the four; it commonly correlates well with the wave energy level. These statements refer to straight or nearly straight quartz sand beaches, under low-to-moderate wave-energy regimes, and must not be extrapolated to other materials and conditions.

Kurtosis values close to 3 (the Gaussian value) are typical of high wave-energy sand beaches. Low-to-moderate energy beaches have kurtosis values that
are much higher: 4, 6, 8, or even more. These results have been obtained from work on many beaches, some of it summarized in the following.

The variability of the kurtosis (standard deviation of \( K \)) tends to be low on high-energy beaches, and high on low-energy beaches. A value of \( K \) close to 3 means high wave energy; because the standard deviation of such \( K \) values typically is also low, the wave energy was consistently high. On the other hand, low-energy beach sands commonly have high values of \( K \), and much variation in those values; the variation reflects changes in the energy level on a short-term basis. This is because storms are markedly different from average conditions on a low-energy beach, but not so different on a high-energy beach.

As the mean energy level goes down, settling of sediment from the water column may increase in importance (kurtosis values of 10, 20, or more).

3. Kurtosis: \( F_n (E) \)

Kurtosis from a long series of beach samples taken in 1978 and 1979 from Captiva and Sanibel islands, Florida (Silberman 1979), from one tip to the other, matches the systematic change in wave energy levels from one end of the study area to the other (Fig. 1). At the north end, where the beach faces the open Gulf of Mexico and waves are relatively large, the kurtosis is low (close to 3); at the south end, where the beach has a markedly different orientation and is protected, and where waves are very small, kurtosis is high (6 or more).

Forty-four beach-sand samples were collected on one day (12 March 1974) from the lower beach of Dog Island, Florida, from one tip to the other (Emmerling 1975; for location, see inset in Fig. 1). The first four moment measures show systematic changes along this strip. On the open beach facing the Gulf of Mexico (but not at the tips where wave refraction is severe), at the place where the surf-zone wave energy level is high, the kurtosis is low, and where wave energy is low, kurtosis is high. A plot of \( 1/kurtosis \) matches a plot of wave energy, except at the recurved tips.

Rizk (1985) studied beach-sand granulometry on Alligator Spit, southwest of Tallahassee, at the end of a 9-year interval during which there were no hurricanes in his study area. He analyzed beach sands collected during the spring (high-energy season) and during the summer (low-energy season) (Fig. 2). Rizk and Demirpolat (1986) restudied the same traverses after the passage of each of two hurricanes (Elena and Kate, 1985). This work provided data from three different energy levels:

- a) under fair-weather seasonally low energy conditions,
- b) under fair-weather seasonally higher energy conditions, and shortly after the passage of each of two hurricanes (Fig. 2). The mean value of the kurtosis, for 15 beach samples, was 3.71 (standard deviation of \( K \), 1.17) for fair-weather low-energy conditions. For the fair-weather higher-energy conditions, mean \( K \) was 3.45 (standard deviation of \( K \), 0.76).

Samples taken shortly after each of the two hurricanes had mean \( K \) of 3.32 (standard deviation of \( K \), 0.54). Rizk (1985) concluded that the higher-order moments are more sensitive than lower-order moments, and Rizk and Demirpolat (1986) noted that major storms tend to homogenize the beach sand by cross-beach mixing, because of much higher wave energy in a storm. In tabular form (mean \( K \) first, its standard deviation second):

<table>
<thead>
<tr>
<th></th>
<th>Mean ( K )</th>
<th>Standard Deviation of ( K )</th>
</tr>
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<tbody>
<tr>
<td>Fair weather, low energy</td>
<td>3.71</td>
<td>(1.17)</td>
</tr>
<tr>
<td>Fair weather, higher energy</td>
<td>3.45</td>
<td>(0.76)</td>
</tr>
<tr>
<td>Early poststorm</td>
<td>3.32</td>
<td>(0.54)</td>
</tr>
</tbody>
</table>
A long, narrow, sandy peninsula separates the Gulf of Mexico from the southern end of Laguna Madre, near the Boca Chica locality east of Brownsville, Texas (Tanner and Demirpolat 1988; but the numbers given here were not included in the published report). Two modern beach samples from the lagoon side had a kurtosis of 4.11, and 10 adjacent but slightly older lagoon beach samples (for comparison) had kurtosis values of 4.2 and higher. On the open Gulf of Mexico beach, kurtosis was 3.39.

As a general rule, with the exceptions noted above, kurtosis is an inverse function of surf-zone wave-energy density.

4. Long-term changes

When sea level rises a small amount, such as 1 to 3 m, even with constant wave climate, the wave energy level in the surf zone increases. This is because the bottom profile, running from the beach out to sea, is gently concave upward. Therefore, after a small rise in sea level, the water at (for example) 100 m from the shore is deeper than it was at 100 m from the previous shore, prior to the rise. With slightly deeper water, inshore, there is less energy drain from shoaling waves to the bottom, and more energy is left for the breakers.

When sea level drops a small amount, the surf-zone wave-energy density decreases a little bit. These small changes show up in the grain-size parameters.

A hurricane passes in a day or two, and the effects on beach sand are removed in a few weeks or months. But the effects of a sea level change cannot be eliminated so quickly. A study of 150 years of migration of Johnson Shoal, toward Cayo Costa Island on the lower west coast of Florida, showed that this natural sand body has not been removed by wave action, and will not be removed for some time yet (Tanner 1990a). During the history of migration, the transverse bottom profile has been unusually shallow, and the wave-energy density on the beach landward of the shoal has been reduced greatly. It should be clear that a large change in the bottom profile will be more difficult to modify than a small relocation of beach sand during a storm. Therefore, it is thought that a small sea level change in a low-to-moderate energy area can influence the bottom profile, the surf-zone wave-energy density, and, hence, the grain-size characteristics of beach sand for two or more centuries.

This means that the relationship between $1/K$ and wave-energy density, given above, will persist for relatively long time intervals, and that a properly chosen sequence of beach sand samples, constituting a time series, might show evidence of sea level change(s).

5. St. Vincent beach ridges

St. Vincent Island, on the Gulf of Mexico coast southwest of Tallahassee (Fig. 3), has been a laboratory for the coastal sedimentology program at Florida State University (Tanner 1974). There are about 180 beach ridges on the island, spanning an interval across the most recent 3000–3500 years. Wave-
energy density in the surf on the ocean side is ideal for using the granulometric method outlined here; breaker heights average a few tens of centimeters (moderate energy). Each beach ridge was the beach at the time of deposition. Individual ridges are long and narrow, and generally less than 1 m tall. Where distinct, they are separated by obvious swales. Horizontal spacing between sampled ridges is 50–60 m, and the time interval between sampled ridges is about 50–60 years.

The island is made up of sets of 5–18 ridges each (Fig. 3). Ridges in any one set tend to stand higher (or lower) than those in adjacent sets, with a differential of about 1 m. This means that the swales in one set are about as high as the ridge crests in the next set. Some sets are so low that the intervening swales are occupied by marshes or ponds, whereas in higher sets the swales are well drained. As a result, vertical differences in set position are easy to see, either in the field or on aerial photographs. It is important to use set position, rather than ridge position, because the set has more obvious geometrical characteristics than does the individual ridge, and because the set necessarily represents centuries and therefore provides a better time average than does the individual ridge.

6. St. Vincent granulometry

Four sample traverses have been made across the island, two on the same line but at different times. These two traverses cross the best selection of ridges. One of them yielded 59 samples representing a history at least 3000 years long. Samples were collected on seaward faces of successive ridges, at about the middle position up the slope, and at a depth of 30 cm. (The other three traverses show that ridge characteristics are accurately represented by the data.)

The moment measures obtained from these samples have been subjected to mild smoothing (W = 5, 7, and 9) to minimize ridge-to-ridge noise and to emphasize the characteristics of the sets. Seven-point moving averages produce reasonably smooth curves without flattening of any of the features of interest (Fig. 4).

One might reason that the high sets represent high sea level (and the low sets, low sea level), and that the high sets will show low kurtosis values (high values of 1/K). This is, in fact, the relationship. But it is not permissible to associate a given single ridge with a storm (temporary elevation of sea level); Johnson (1938) showed in detail how it is that individual ridges
in a beach-ridge system typically do not represent storms. Individual ridges also must not be taken to indicate "permanent" sea level changes: ridges are commonly spaced a few decades apart, which is too close together for sea level changes of 1-3 m. The ridges in one set tend to have one elevation, and commonly there is an observable change in vertical position at set boundaries.

The kurtosis identifies correctly the vertical position of each set (high or low), and also identifies changes between sets. The mean kurtosis for high sets is 3.09 to 3.24, and the mean kurtosis for low sets is 3.34 to 3.44 (the standard deviation of the kurtosis for any one set is smaller than 0.007). Each change from one set to another was spread over two or three ridges, hence 100 or more years, and was relatively fast, about 1 cm yr\(^{-1}\). Each position (high or low) persisted for four to seven centuries.

It is convenient to identify Type I sea level changes (100 m or more vertically, 10 000 years or more of time) and Type II changes (1 to 5 m, decades or centuries). The events deduced from St. Vincent Island fit into Type II. The major shifts between glacial and interglacial epochs, for example, belong in Type I. Type II changes may have one or more of a number of different causes, and cannot be explained readily by simplistic climatological or geological schemes. (Other types may well exist, but are not needed here.)

7. Other beach-ridge plains

St. Vincent Island has been studied in many different ways, over about 20 years, but it is not unique. More than 20 beach-ridge plains around the Gulf of Mexico have been studied, although some do not go very far back in time (e.g., Tanner and Demirpolat 1988). A long record (exceeding 3000 years) has been obtained from Sanibel Island, where a large number of carbon-14 dates are available (Stapor et al. 1988), and where ridge sets stand at distinctive elevations, thus indicating the same sea level changes as on St. Vincent Island (but the high shell content precludes useful granulometric work).

For the years 1989-1991, a field-and-lab study of beach sands and beach ridges in Denmark and Germany is being made. In the extreme northern part of Denmark, between Fredrikshavn and Skagen, near the town of Jerup, the data bank now contains 182 samples. Two of these, from the western beach (Atlan-
tic Ocean waves), have an average kurtosis of 3.28. Eight samples from the eastern beach near the village of Jerup (low energy) have average kurtosis of 6.31 (standard deviation, 1.329).

The other samples in the area are from slightly older beach deposits that were built by low-energy waves on the east side of the peninsula; the mean kurtosis for the 60 youngest samples (for comparison) is 11 (standard deviation 4.46).

The low-energy beach-ridge plain near Jerup has been profiled and sampled in detail (for a preliminary report, see Tanner 1990b). The record there goes back perhaps as much as 11,000 years; granulometric data for 151 ridges (the most recent 7500 years) are now in hand. Data from the youngest 60 ridges are shown here (Fig. 5) because they cover about the same time span as can be seen on St. Vincent Island. The Little Ice Age is clearly visible near the right end of the profile. This profile shows the same sea level events as do the profiles from St. Vincent Island and Dog Island, Florida, and Mesa del Gavilan, near Boca Chica, Texas, as far back as the record goes in each case.

8. Late Holocene history

The St. Vincent Island data can be taken to be representative of all of the work to date, for the last 3000 years, but the same history can be obtained from the beach ridges near Jerup (Denmark).

In the last 3000 years, sea level has experienced four rises and three drops in the range of 1–3 m (Tanner 1991a). These changes have taken place at rates of about 1 cm yr\(^{-1}\). The high (or low) positions have persisted for a few centuries, up to a maximum—in the stated time interval—of about seven. There is no hint of cyclicity, but the average duration of any one position has been roughly five centuries.

Most interesting, in the present context, is the last millenium on the St. Vincent Island record. Sea level was rising about 1000 years ago. At about 1200 A.D. it began to fall, and somewhere near 1400 A.D. reached a low position: the lowest in 2000 years. This sea level low represents an interval of cold climate: the Little Ice Age (Lamb 1981).

About 1750 A.D., sea level was rising again, and it has continued to rise until at least 1900 A.D.—recovery from the Little Ice Age. Although sea level has not
yet reached as high as it did on at least two previous occasions in the last 8000 years, it nevertheless now stands well above its average position for late Holocene time.

The Little Ice Age shows up clearly in the kurtosis data from St. Vincent Island and Dog Island, Florida; Mesa del Gavilan, near Boca Chica, Texas; and Jerup, Denmark.

The method that has been used in this work does not permit details to be defined in the last century. However, the curve shows a clear warming trend, at a steady rate, since about 1700 or 1750 A.D., up to the last data point. The resolution is approximately 50 years. Because the record provides a sea level history, it is not biased by local or regional effects.

9. Conclusions

1. The nature of the data does not permit dependable statements to be made about the last 50–100 years.
2. The reasonably steady sea level rise since about 1750 A.D. (recovery from the Little Ice Age) apparently was not caused by human activity.
3. It cannot be known from these data whether or not this warming trend is over.
4. If global warming could be demonstrated for the last 50–100 years, this might very well be a continuation of the trend listed in item 2, and therefore cannot be shown from the available data to represent an effect caused by mankind.
5. There is no such thing as “absolute” sea level, in a time sense. The reference, or base line, derived here from kurtosis values, is a mean value, taken across centuries or a few millennia. If the length of the study interval is changed significantly, the mean value changes also (but this will not alter the rises and falls). The changes that are observed led to new sea level positions, which endured for intervals shorter than the base line.
6. Small changes (Type II; 1–3 m) appear to be inherent in the way the air–ocean–ice system operates, at least under present conditions. This type of change can be seen in the Holocene granulometric data, as far back as they go.
7. If we wish to forecast future rises or drops of sea level, it should be done in the light of the small (Type II) changes that are now known from middle and late Holocene time, rather than on the assumed basis of a constant fictitious absolute postglacial sea level that has somehow resisted change for thousands of years up until the advent of industrialized man. This is a fundamental point, because any forecast that attributes all significant near-future change to anthropogenic effects ignores natural effects, and therefore constitutes adoption of the concept of “absolute sea level.”
8. A reasonable prognosis, without considering any anthropogenic input, would be a modest sea level drop (1–3 m), starting sometime in the next few centuries.

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