Storm and fair-weather wave base: A relevant distinction?

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ABSTRACT

Surface waves are an important mechanism for the redistribution of sediment on shallow marine shelves, and are commonly interpreted as comprising two distinct populations: fair-weather waves and storm waves, the latter of which are generally thought to penetrate to greater water depths. Here we used >2.3 × 10^{6} spectral density estimates for the surface ocean collected between 1996 and 2008 from 32 buoys in the Caribbean, the Gulf of Mexico, and the western Atlantic to test the hypothesis that surface waves in the modern ocean comprise two size modes. Although distinct wave size classes occur in some individual measurements and over the time scales of some individual storms, time-averaged frequency distributions of wave size are unimodal. Thus, there is no empirical basis for presupposing a distinct bimodal separation in the size of fair-weather and storm waves, or in the manifestation of such differences in stratigraphic successions. Instead, there is a continuously increasing probability that a wave will reach the bottom with decreasing water depth and a separate probability that describes the hydrodynamic state of the sediment-water interface. Wave size does, however, exhibit significant geographic bimodality. Locations in the relatively protected Gulf of Mexico and Caribbean regions have modal wavelengths that are ~50 m less than waves at locations along the western Atlantic. Time-integrated estimates of the depth of wave penetration provide empirical constraints on the paleo-water depths of ancient sedimentary deposits and highlight differences between sheltered shelf environments, such as those that characterized many ancient epeiric seas, and open-ocean–facing, narrow continental shelves.

INTRODUCTION

The textbook shelf profile (Fig. 1A) is introduced to most students in sedimentology and stratigraphy (e.g., Coe et al., 2003; Reading and Collinson, 1996). However, critical conceptual inaccuracy may be inherent in the practice of placing two important boundaries, fair-weather and storm wave base, at discrete and clearly separated water depths. Wave base in the sedimentary record is identified by the characteristic structures and bedform relationships that are formed by water motion and sediment entrainment. The shoreface to offshore transition zone boundary is defined as the depth at which mean fair-weather wave base intersects the seafloor and is associated with a change from wave ripples and dunes with trough and swaley cross-stratification above to hummocky cross-stratification (HCS) below, the latter of which forms under storm conditions (Dott and Bourgeois, 1982; Duke, 1985; McCave, 1985). The transition to the offshore zone is defined by mean storm wave base and is represented in stratigraphic successions by a change from HCS in muddy and/or silty sediments to mud-dominated intervals that lack HCS below (Sageman, 1996).

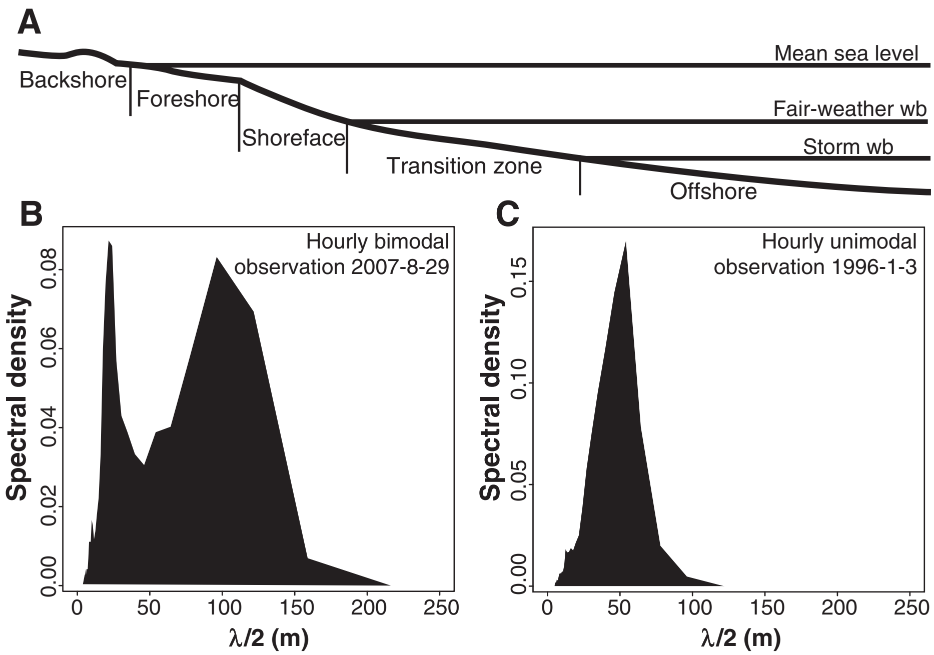

Figure 1. Standard depiction of shelf profile and example hourly measurements of spectral density in surface ocean. A: Standard shelf profile (after Coe et al., 2003) subdivided by tidal range and wave base. B, C: Individual hourly observations from buoy 42040 off coast of Louisiana showing power as function of wave size and wave base (wb) (λ/2).

The sedimentary structures that are used to subdivide shelf deposits reflect hydrodynamics, which in standing bodies of water is typified by the passage of surface gravity waves that cause oscillatory flow at the sediment-water interface. There may also be a component of superimposed unidirectional flow, a hydrodynamic condition known as oscillatory-combined flow (Allen, 1985; Duke et al., 1991). In order for a surface gravity wave to entrain sediment, water depth must be less than or equal to about one-half of its wavelength (Reading and Collinson, 1996). This depth is known as wave base. Oscillatory flow is the most common hydrodynamic state of the surface ocean and is associated with fair-weather (normal) waves. Waves characterized by oscillatory-combined flow are typically associated with storms. Many studies have connected one or both of these hydrodynamic states to the formation of HCS, and there are three postulated mechanisms for its formation: oscillatory flow (Dott and Bourgeois, 1982; Walker et al., 1983), unidirectional-dominated combined flow (Allen, 1985; Swift et al., 1983), and oscillatory-dominant combined flow (Southard et al., 1990; Duke et al., 1991; Dumas and Arnott, 2006).

Beginning in the 1800s (Gulliver, 1899), geoscientists used wave base terminology to describe and interpret sedimentary deposits (Dietz, 1963; Diem, 1985; Aigner, 1985; Sageman, 1996). However, sedimentary structures do not correspond directly to water depth, but reflect instead the interactions between the physical properties of sediment and the hydrodynamic state of the fluid above the sediment-water interface. This is an important distinction because there need not be a simple relationship between the hydrodynamic state of the ocean and the depth of wave penetration, as suggested by the typical conceptualization of fair-weather and storm wave bases (Fig. 1A). This issue is particularly relevant because wave base terminology is widely used to describe and interpret sedimentary successions. As of December 2011, GeoRef (www.georef.org/) returned 635 journal articles with the phrase "wave base" in the title and/or abstract. Many more make use of the concepts of storm and fair-weather wave bases even though the terms are not used in their title or abstract. The goal of this study is to better understand the meaning of these two descriptive and interpretive concepts for sedimentary successions and to test whether there is any significant bimodality in wave size in nature. It is taken into account that, at any given time, many different sizes of waves may exist in the surface ocean, all of which fall into two categories, locally generated wind waves and swell. The latter are wind waves, commonly formed during storms, that have traveled long distances, thereby undergoing sorting and organization by wavelength (Snodgrass et al., 1966).

METHODS

Data were downloaded from the National Data Buoy Center (http://www.ndbc.noaa.gov/) in the fall of 2009. The buoys utilized in this study all have spectral density estimates for the surface ocean, which are central for analysis of wave size. The buoys are dispersed from the Gulf of Mexico through the Caribbean and extend along the western Atlantic (Fig. 2B, inset). Spectral density is a measure of the power of each frequency of wave, which can be converted to wavelength using the deep-water gravity wave equation (Lamb, 1994):

$$\lambda = g/(2\pi f^2), \qquad (1)$$

where g is gravitational acceleration and f is wave frequency measured in Hz. Non-breaking waves change in profile as they encounter the bottom, but their frequency remains constant. Thus, the buoy spectral density estimates used here are useful for estimating wave size even in shallow water locations where waves may encounter the bottom. Buoy data for significant wave height, a historically and nautically prevalent measure of wave size, were also compiled. Each buoy analyzed had as much as 13 yr of data starting in 1996, though several buoys operated for only 1 yr. The combined data set consists of 2.39×10^6 individual spectral density observations. Each observation summarizes the power associated with spectral densities in wave frequencies ranging from 0.02 to 0.485 Hz. Significant wave-height estimates are not emphasized here because only one data point exists for each observation and because significant wave height reflects only the average size of the upper one-third of all waves. Data for each buoy were combined into a single file and analyzed using the R language (R Development Core Team, 2008).

Raw buoy data contain invalid and missing data due to episodic instrument malfunctions and maintenance. However, the missing and spurious data are comparatively few in number; randomly culling many more observations does not have a significant effect on the results. For historical reasons, buoys use two different frequency scales. One scale ranges from 0.02 to 0.4850 Hz in varying increments while the other ranges from 0.03 to 0.4 Hz in even increments of 0.01 Hz. Most of the buoys followed one of these scales for their entire observation interval. However, some buoys switched between scales. In these cases, data for the longest continuous interval were used, though results are insensitive to this convention.

After converting individual hourly measurements to wavelength, the time-averaged power spectrum for each site, which combines all observations into a single composite measurement of the mean state of the ocean, was calculated in two ways. The first normalized each hourly observation by scaling the sum of the power across all wavelengths to unity (row normalization). This method forces each observation to contribute equally to the time-integrated signal. The second method summed all of the hourly data for each frequency class and then normalized the resultant vector to unity (column normalization). This method allows individual measurements with large power at some wavelengths to contribute disproportionately to the time-averaged signal for a buoy. Because row normalization is more representative of the time averaged state of the ocean, it is used here, though results do not depend on this convention.

RESULTS

Individual, hourly observations are diverse in form and include unimodal and bimodal

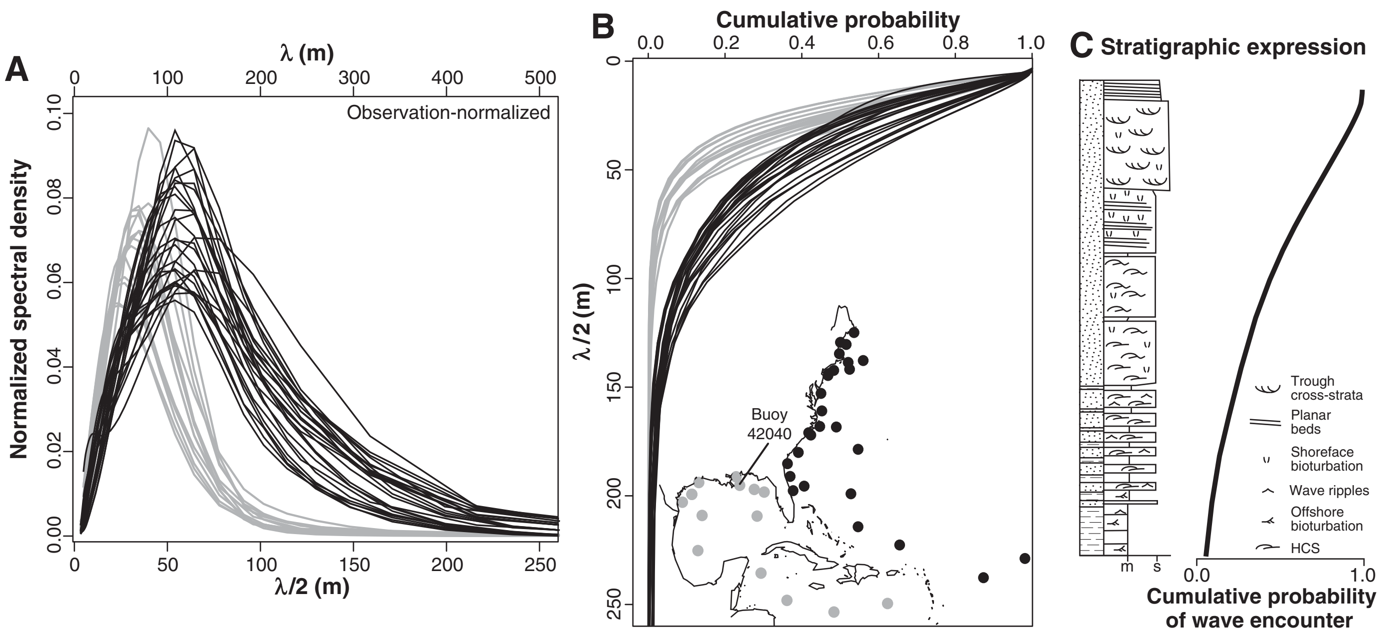

Figure 2. Wave size data from all buoys. A: Spectral density estimates, time averaged over duration of all observations at each buoy (1–13 yr). Axes are same as those in Figures 1B and 1C, except here spectral density is normalized (see the Methods discussion). Gray distributions correspond to gray points in map inset in B, black distributions correspond to black points in B. B: Normalized results expressed as cumulative probability (*x*-axis) versus depth of penetration (*y*-axis). Inset map shows geographic distribution of buoys. Gray and black points correspond to gray and black distributions. C: Example of cumulative probability distribution from B next to generalized regressive shelf sedimentary succession (after Coe et al., 2003). HCS—hummocky and swaley cross-stratification.

distributions of wavelengths (e.g., Figs. 1B and 1C). Observations with bimodal distributions of wavelength (Fig. 1B) support the notion that there are two separate wave size classes, corresponding to two distinct mean depths of wave penetration, as suggested by the depiction of mean storm and fair-weather wave bases intersecting distinct depths on the shelf profile (Fig. 1A). However, there are many more unimodal than bimodal observations, and the two hourly observations from the same buoy shown in Figures 1B and 1C would combine (i.e., time average) to generate a broadly unimodal distribution of wavelengths. More important, modal wavelengths at each buoy do not remain constant at the time scales relevant to this study (hourly observations made over the span of ≤13 yr). Instead, at this scale of temporal resolution there is much variability, both between individual observations and during the course of a year as local and remote storms form and dissipate. For example, in 2005 buoy 42040, located off the Gulf Coast of Louisiana (Fig. 2B), recorded waves generated by Hurricanes Katrina and Rita, both of which passed directly over the buoy, causing many unimodal observations at very long wavelengths (~300 m; see VideoDR1 in the GSA Data Repository[1]). These two storms stand in contrast to 2005 Hurricane Wilma, which did not pass directly over the buoy. Instead, this intense storm generated strongly bimodal wave sizes at buoy 42040, reflecting the contribution of an organized, long-wavelength component of distantly generated storm swell (to ~300 m in wavelength; see Video DR1) with a separate population of superimposed, smaller, and more locally generated wind waves. Seasonality in the frequency and intensity of storms manifests in these spectral density data as shifts in modal wave size during the course of a year, and also contributes to the time-varying signal for individual buoys.

The characteristically unimodal distributions of wavelengths in the surface ocean at each buoy location become even clearer when data are analytically time averaged (Fig. 2A), thereby producing a composite summary that describes the mean state of the surface ocean at each location. Wave-height data (Fig. DR1 in the Data Repository) yield similar unimodal results. Buoys that operated for a single year show essentially the same pattern as those operating for multiple years (Fig. 2) because the signal is established quickly in a time-integrated sense.

Although there is no evidence for distinct size classes of waves at individual buoy locations, there is spatial bimodality between locations in the relatively protected Gulf of Mexico and Caribbean Sea versus those located in the western Atlantic (Figs. 2A and 2B). The protected Gulf and Caribbean buoys have modal wavelengths of ~70 m, whereas modal wavelengths of Atlantic buoys are ~120 m.

DISCUSSION

Buoy results from the modern ocean are inconsistent with the hypothesis that there are two distinct depths of wave penetration corresponding to storm and fair-weather wave bases (and a correspondingly distinct subdivision of the shelf with water depth, as in Fig. 1A), at least in the western Atlantic, Gulf of Mexico, and Caribbean regions. The results presented here, which combine wave size measurements made over the course of 1–13 yr, provide a time-integrated summary of the state of the surface ocean that is relevant to stratigraphic successions, which also preserve time averaged representations of local physical and biological conditions (e.g., Kowalewski et al., 1998; Bentley et al., 2002; Kidwell, 2002).

Time-averaged spectral density data, plotted as the cumulative probability of wave encounter as a function of water depth (Fig. 2B), have geological implications. The probability that any given wave will encounter the sediment-water interface decreases as a continuous, smoothly varying function of water depth. When this probability distribution is juxtaposed against a generalized regressive siliciclastic shelf section (Fig. 2C), it is apparent that there is a continuously increasing probability of wave encounter in shallowing-upward sedimentary successions. Although these probability distributions relate to the depth of wave penetration, they give no indication of the hydrodynamic state of the sediment-water interface, which, in combination with sediment properties and supply, determines the types of sedimentary structures that might be formed. Storms passing directly over a buoy may result in oscillatory-combined flow, thereby establishing the hydrodynamic conditions necessary for generating hummocky cross-stratification. However, distantly generated storm swell, which can consist of equally large waves, will cause oscillatory flow. Thus, the size of a wave does not predict its hydrodynamic state.

The lack of a clear relationship between wave size and hydrodynamics has several implications for the interpretation of stratigraphic successions and depth relationships in the geologic record. For example, HCS formed at shallow water depths has a much lower chance of preservation due to the high probability of later reworking by subsequent fair-weather wave action (and bioturbation). Several instances of HCS in the shoreface and tidal zones have been found in the stratigraphic record (Yang et al., 2006; Budillon et al., 2006; Keen et al., 2006), but the probability of preserving these discrete oscillatory-combined flow events in shallow-water settings is rather low. Conversely, deep shelf environments are less likely to encounter a wave, and they are typically more sediment limited. Thus, the formation and preservation of sedimentary structures in deeper water environments (i.e., the transition zone and offshore) is more closely linked to the across-shelf transport of sediment, which preferentially occurs during the oscillatory-combined flow that is characteristic of storm waves and relaxing storm surges. Although it is possible for sediment exported offshore during storms to be reworked into normal wave ripples and dunes by large fair-weather waves characterized by oscillatory flow, such as distantly generated storm swell, the probability of wave encounter and sediment supply is sufficiently low in offshore settings that it is more common for offshore-exported sediment to remain as discrete, HCS-dominated event beds. It is also possible that the rippleform characteristics of laminations in some offshore mud deposits (Schieber et al., 2007) and the occurrence of some HCS beds with reactivated and normal wave-rippled tops are caused by the impingement on the seafloor of large waves with oscillatory flow. For all of these reasons, the textbook shoreface profile is much better conceived of and expressed as a probability-based profile, with gradational boundaries that are defined by the probability of wave encounter and the formation and preservation of discrete sedimentary structures (Fig. DR3), which reflect sediment supply and hydrodynamics, not absolute water depth.

Cumulative probability distributions of wave encounter (Fig. 2B) also illustrate the difficulty in using sedimentary structures by themselves as indicators of water depth, even in a relative sense and between closely spaced geographic locations. If the probability of wave encounter is in fact related to the formation and preservation of sedimentary structures, then very similar stratigraphic successions could be generated at markedly different absolute water depths, for example, as on the Gulf of Mexico and Atlantic sides of Florida (Fig. 2B) and along the open-ocean and enclosed sides of many Bahamian carbonate banks (Reeder and Rankey, 2009). In the case of Florida, at an estimated 10% probability of wave encounter, the expected depth of wave penetration is ~50 m on the gulf side versus 100 m on the Atlantic side (Fig. 2C). This type of pronounced spatial variability in the probability of wave encounter with depth has implications for paleoenvironmental reconstructions and paleoecological studies that seek to establish or hold constant water depth (e.g., Brett et al., 1993; Miller et al., 2001; Scarponi

[1]GSA Data Repository item 2012149, supplemental materials, methods, figures, and animation, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

and Kowalewski, 2007). Because parameters such as light penetration and temperature are relevant to biological communities, comparisons of the fossil records of semienclosed ancient epicontinental seas versus narrow, open-ocean–facing continental shelves (e.g., Bambach, 1977; Peters, 2007; Miller and Foote, 2009) may be subject to a variety of systematic effects attributable to absolute water depth, even when using sedimentary structures, taphonomy, and sequence stratigraphy to exercise environmental control. Similarly, absolute water depth is unlikely to provide a useful basis for comparing the physical sedimentology and stratigraphy of modern shelf environments from regions that are characterized by different modal wave sizes.

ACKNOWLEDGMENTS

We thank A. Carroll, S. Meyers, and D.C. Kelly for their invaluable input and feedback during the completion of the first draft of this manuscript. B. Wilkinson provided helpful feedback, R.H. Dott provided helpful discussion, and N. Heim drafted the map. M. Kowalewski and an anonymous referee provided helpful reviews that improved the quality of this paper.

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Manuscript received 31 August 2011
Revised manuscript received 21 December 2011
Manuscript accepted 10 January 2012

Printed in USA