Observations of Steep Wave Statistics in Open Ocean Waters

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ABSTRACT

A new wavelet analysis methodology is proposed to estimate the statistics of steep waves. The method is applied to open ocean wave height data from the Southern Ocean Waves Experiment (1992) and from a field experiment conducted at Duck, North Carolina (1997). Results show that high wave slope crests appear over a wide range of wavenumbers, with a large amount being much shorter than the dominant wave. At low wave slope thresholds, all wave fields have roughly the same amount of wave crests regardless of wind forcing. The steep wave statistic decays exponentially with the square of the wave slope threshold, with a decay rate that is larger for the low wind cases than the high wind cases. Comparison of the steep wave statistic with independent measurements of the breaking wave statistic suggests a breaking wave slope threshold of about 0.12. The steep wave statistic does not scale with the cube of the wind speed, suggesting that other factors besides the wind speed also affect its level. Comparison of the steep wave statistic to the saturation spectrum reveals a reasonable correlation at moderate wave slope thresholds.

1. Introduction

Breaking waves are a ubiquitous phenomenon of the world's oceans. They disrupt the aqueous boundary layer causing surface renewal, thereby enhancing the diffusion of gases and heat across the air–sea interface. Breaking waves are also responsible for the dissipation of wave energy and thus directly affect the evolution of the wind wave spectrum. With advances in technology, new direct observations of the two-dimensional spatial surface wave topography have been made. These data allow for the opportunity to go beyond linear analysis and study the nonlinearity of the surface wave field, in particular, the statistics of steep and breaking waves.

Recent field studies of breaking waves have been varied. Ding and Farmer (1994) obtained breaking-surface wave data from a hydrophone array correlating breaking wave events with acoustical noise produced by bubbles in the water column. They observed a distribution of the speed of breaking wave propagation and found that the results were 45%–75% smaller than the phase speed of the dominant wind waves. This implied that most breaking events occur with waves shorter than the dominant waves. Gemmrich and Farmer (1999) performed conductivity measurements at high sea state in the open ocean. They again found breaking wave events over a wide range of wave scales with breaking occurring predominantly at wave scales between 5% and 80% of the dominant wave scale. In addition, they found that the fraction of breaking wave events relative to the total number of dominant waves did not scale with wind speed or wave age. A scaling based on wind energy input to waves was proposed and found to collapse the diverse datasets obtained by the authors.

Banner et al. (2000) analyzed three different datasets with different wind conditions in an effort to understand the major environmental parameters that control the breaking of waves. They surmised that the probability of dominant wave breaking is strongly correlated with significant wave steepness. Banner et al. (2002) further extended the above analysis of the breaking probability to high wavenumbers with the inclusion of scales smaller than the peak wavenumber. They found

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that a spectral measure of wave steepness in the form of the spectral saturation was strongly correlated with the probability of breaking.

Phillips et al. (2001) obtained radar measurements of breaking waves off the coast of Hawaii. They found that at a set wind speed the number of events detected per unit area per unit time was of the same order as that found by Ding and Farmer (1994). However, the distribution of scales of breaking wave events was narrower with the fastest breaking wave events possessing a speed of about 60% of the dominant wave speed. In addition, they calculated $\Lambda(\mathbf{c})d\mathbf{c}$, the average length of breaking wave crests per unit surface area of ocean surface traveling at velocities in the range $(\mathbf{c}, \mathbf{c} + d\mathbf{c})$. They found that the amount of breaking waves increased as the scale decreased, indicating the importance of small-scale breaking to energy dissipation.

Melville and Matusov (2002) obtained images of ocean whitecaps from an aircraft. They tracked the evolution of whitecaps using image velocimetry and thus were able to calculate the breaking wave statistic, $\Lambda(\mathbf{c})$. Their observations indicated an exponential dependence of $\Lambda(\mathbf{c})$ on $\mathbf{c}$ with a local approximation consistent with $\Lambda(\mathbf{c}) \propto \mathbf{c}^{-6}$ for large values of $\mathbf{c}$ and $\Lambda(\mathbf{c}) \propto \mathbf{c}^{-1}$ for small values of $\mathbf{c}$.

While most of the previous observational studies used whitecaps or bubbles to detect breaking wave events, new mathematical methods of data analysis have been exploited in trying to detect breaking wave phenomena from the wave height record. In particular, Liu (1994) used the wavelet transform to analyze ocean wave data taken with a wave wire mounted on a buoy. He proposed to designate as a breaking wave any wave that possessed a value for $a\omega^2$ that exceeds a limiting fraction of the gravitational acceleration, where a is the wave amplitude and ω is the angular frequency obtained from averaging over a selected high-frequency region of the wavelet transform.

Although Liu's (1994) approach is limited to a narrowband wave system and cannot be applied to open ocean surface wave data, the wavelet transform approach, in principle, should be suitable for detecting wave breaking. This is because previous theoretical studies (Dold and Peregrine 1986; Banner and Tian 1998) suggest that breaking wave events are associated with wave groups with strong nonlinearity rather than with a single steep wave, and wave groups can be detected by the wavelet transform.

Dold and Peregrine (1986) examined the evolution of wave groups numerically using a fully nonlinear two-dimensional, free-surface computational model. They found that whether the initial wave group evolved to breaking was dependent not only on the initial carrier wave slope but also on the number of waves N in the modulation interval. For a given N, breaking always occurred above a particular wave slope threshold value. Banner and Tian (1998) performed a numerical study of the onset of wave breaking for unforced nonlinear modulated wave groups through the use of a wave slope threshold variable. Using the same code as Dold and Peregrine (1986), they examined the evolution of wave groups in terms of the relative wave growth rates of the local mean energy and momentum densities. They found evidence of a universal threshold for the local relative growth rates of the mean momentum and energy densities that differentiates between the breaking and nonbreaking wave groups.

In this study, we propose a new approach to estimate the statistics of steep wave events (wave groups of large amplitude) by applying the wavelet transform to broadband open ocean wave fields. We make use of the spatial wave topographic data obtained during the Southern Ocean Waves Experiment (SOWEX) and the experiment conducted off Duck, North Carolina, in September 1997 (hereafter termed the DNC experiment). The results are then used to examine how the statistic of nonlinear wave groups may correlate with the true breaking wave statistic. In this study, we present a one-dimensional data analysis based on the assumption that all steep wave events propagate in the mean wind direction. In a companion paper (Scott et al. 2005), we examine the directionality of the steep wave statistics.

6. Conclusions

The wavelet analysis methodology presented here is able to detect steep wave events and give estimates of the amount of high wave slope events that cover a given area of ocean. Analysis of the results shows that high wave slope crests appear over the entire range of wavenumbers resolved, with a large amount being much shorter in wavelength than the dominant wave. At low wave slope thresholds, the total crest length is approximately independent of wind forcing for all wave fields considered. The steep wave statistic $\Lambda_{cT}(k)$ then decays exponentially with the square of the slope threshold T. The exponent p of the exponential decay is smaller for higher winds, yielding a larger number of very steep wave events.

If the steep wave statistic is hypothesized to evolve into the breaking wave statistic at a specific wave slope threshold, comparison of $\Lambda_{cT}(k)$ with previous independent measurements of the breaking wave statistic gives a wave slope threshold of about 0.12. This threshold is consistent with the results of the numerical studies of Dold and Peregrine (1986). Comparison of the steep wave statistic at this extrapolated wave slope threshold with independent breaking wave measurements suggests that the steep wave statistic does not scale with the cube of the wind speed with other factors besides the wind speed affecting its level. Finally, $\Lambda_{cT}(k)$ at moderately large wave slope threshold correlates with the saturation spectrum $B(k)$ reasonably well.