The Role of Nonlinear Momentum Fluxes on the Evolution of Directional Wind-Wave Spectra

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ABSTRACT

It has long been known that nonlinear wave-wave interactions produce stationary solutions related to constant energy flux through the equilibrium range when a deep-water spectrum follows an $f^{-5}$ form, as has been verified in numerical studies in which spectra follow a constant angular spreading distribution. This paper shows that, although energy fluxes through such spectra remain essentially constant, momentum fluxes do not. On the other hand, if the angular distribution of a spectrum is allowed to behave in a manner consistent with observations, both the energy flux and the momentum flux tend to remain constant through a major portion of the spectrum. Thus, it appears that directional distributions of energy within wind-wave spectra adjust to a form consistent with nondivergent nonlinear fluxes, suggesting that these fluxes likely play a very prominent role in the evolution of directional spectra during wave generation.

1. Introduction

Over the last 40 yr, two classical spectral forms for ocean wave spectra have evolved within the scientific literature. Essentially, both forms are expressed in terms of power laws of frequency: that is, $\hat{\alpha}_n f^{-n}$, where $n$ is an integer constant and $\hat{\alpha}_n$ is a parameter with appropriate dimensions. The earliest of these, the $f^{-5}$ spectral form, was initially based on dimensional scaling that used only frequency and gravity (Phillips 1958) but subsequently evolved into forms that included wind speed (Kitagorodskii 1962; Pierson and Moskowitz 1964; Hasselmann et al. 1973). The second form, involving an $f^{-4}$ spectral dependence, originated in the work of Zakharov and Filonenko (1966) and Toba (1972, 1973). Theoretical arguments have suggested that the $f^{-5}$ form is created when wave breaking is the dominant source (sink) term affecting the spectral energies (Phillips 1958; Kitagorodskii 1962; Pierson and Moskowitz 1964; Hasselmann et al. 1973), whereas the $f^{-4}$ form has been theoretically linked to nonlinear energy fluxes from low- to high-frequency regions of the spectrum (Zakharov and Filonenko 1966; Kitagorodskii 1983). Because different portions of a spectrum can have different source term balances affecting them, it is possible that spectral shapes will change their form within different frequency ranges. In fact, Forristall (1981) and Long and Resio (2007) have presented observational evidence suggesting that spectra shift from an $f^{-4}$ form in the equilibrium range to an $f^{-5}$ form at high frequencies.

Two schools of thought relative to the role of nonlinear fluxes during wave generation have also emerged during the latter part of the last century. The primary difference in these approaches centers on the relative magnitude of the nonlinear transfer source term compared to other source terms in the energy-balance equation, written here as

$$\frac{\partial E(f, \theta)}{\partial t} = -e_v \cdot \nabla E(f, \theta) + \sum_k S_k(f, \theta),$$

where $E(f, \theta)$ is the spectral energy density at frequency $f$ and propagation angle $\theta$, $e_v$ is the vector group velocity, $\nabla$ is the spatial gradient operator, and $S_k(f, \theta)$ is the...
Statistical properties of hurricane surge along a coast

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[1] The validity and accuracy of approaches used to determine hurricane surge hazard risk received much attention following the hurricane seasons in mid- to late-2000, which caused record surge-related damage along the Gulf of Mexico coastline. Following Hurricane Katrina in 2005, research showed that most extreme-value statistics approaches underestimated the risk associated with this surge event. In this paper, two of the most popular methods for determining hurricane surge extreme-value statistics are reviewed: the historical surge population approach and the joint probability method. Here, it is demonstrated that both limited historical record length and random along-coast variability in hurricane landfall location can introduce significant errors into surge estimates. For example, the historical surge population approach gives errors of 9% to 17% for return periods between 50 and 1000 years when a surge record of 100 years is considered. In contrast, it is shown that the joint probability method yields significantly more reliable surge estimates, with errors of 2% to 3% for return periods between 50 and 1000 years when a storm record of 100 years is considered. Finally, we show that both methods remain robust when decadal-scale climate variability in the storm rate of occurrence is considered, so long as the hurricane history is long enough to capture the full decadal cycle. When used in conjunction with continuous surge response information, it can be concluded that the joint probability method is a practical and reliable approach for determining extreme-value hurricane surge statistics.


1. Introduction

[2] An accurate and reliable estimation of coastal surge hazards is important for many reasons, including coastal planning, engineering design, evacuation planning, and communication of flood hazard to the public. The estimation of hurricane surge hazards has typically followed two very different approaches. In one approach, modeled surge values from historical storms are combined with information on historical storm frequencies to estimate local surge hazards; and in the other, modeled surge values from a set of parameterized storms are combined with information on the multivariate probabilities of the storm parameters to obtain similar estimates. To some extent, many scientists and engineers around the world have assumed that either approach, properly executed, will yield comparable estimates of actual hazard levels; hence, either of these would be acceptable for application to real-world problems. Given the critical need for accurate hazard estimates in coastal areas around the world, it is important to evaluate such an assumption in a very careful manner.

[3] In this paper, we review both commonly used methods, the historical surge population (HSP) approach and the joint probability method (JPM) in terms of the storm surge generated by a single storm and in terms of all surges generated by the general hurricane population. We show that, because of the relatively small spatial extent of high surges from individual storms combined with the small number of historical storms that produce large surges in a local sample, HSP approach introduces large errors in extreme-value estimates. In contrast, the JPM, which considers many more storms, albeit parameterized, yields statistically reliable surge estimates for comparable record lengths. Last, we investigate the potential role of climate variability, both secular and nonsecular decadal-scale variations, on hazard levels.

2. Background

2.1. The HSP and JPM Approaches

[4] In the HSP approach, surge values for the set of historical storms are obtained for some region of interest via a high-resolution surge model [e.g., Bumya et al., 2010; Dietrich et al., 2010] or from long-term water level gauge measurements. In the set of maximum values from each storm at a given location, the values are first ranked from lowest to highest. This infor-