A Global View of Swell and Wind Sea Climate in the Ocean by Satellite Altimeter and Scatterometer

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ABSTRACT

Numerous case reports and regional studies on swell and wind sea events have been documented during the past century. The global picture of these common oceanic phenomena, however, is still incomplete in many aspects. This paper presents a feasibility study of using collocated wind speed and significant wave height measurements from simultaneous satellite scatterometer and altimeter sources to observe the spatial and seasonal pattern of dominant swell and wind wave zones in the world's oceans. Two energy-related normalized indices are proposed, on the basis of which global statistics of swell/wind sea probabilities and intensities are obtained. It is found that three well-defined tongue-shaped zones of swell dominance, termed ''swell pools,'' are located in the eastern tropical areas of the Pacific, the Atlantic, and the Indian Oceans, respectively. Regions of intensive wave growth are observed in the northwest Pacific, the northwest Atlantic, the Southern Ocean, and the Mediterranean Sea. Seasonality is distinct for the climate of both swell and wind sea, notably the large-scale northward bending of the swell pools in boreal summer, and the dramatic shift of wave-growing extent from a summer low to an autumn high. The results of this study may serve as a useful reference for a variety of activities, such as ocean wave modeling, satellite algorithm validation, coastal engineering, and ship routing, when information on swell and wind sea conditions is needed.

1. Introduction

Waves are one of the most fundamental and ubiquitous phenomena present at the air–sea interface. Since the spectrum of ocean waves is continuous and infinite, they are likely to cover a wide range of frequency and wavelength. The dominant portion of the wave spectrum in terms of energy is known to be associated with gravity waves whose period ranges from 1 to 30 s [see, e.g., Figs. 1.2–1 of Kinsman (1965)]. Therefore it comes as no surprise that a majority of ocean wave studies are devoted to gravity waves.

Two main classes of gravity waves exist in the ocean, namely, the so-called wind wave (or wind sea when emphasizing its state) and swell. The former refers to young waves under growth or in equilibrium with local wind, while the latter is defined as waves generated elsewhere and propagating over large distances. As a rule of thumb, a period of 10 s may be taken as separating swell from wind wave (Kinsman 1965). Because of the different dynamics involved, studies on swell and wind wave usually have different motivations and concerns. Swell is of increasing concern because of its potentially destructive consequences on coastal structures and sea-going activities (Mettlach et al. 1994). For example, in October 1987 nine elementary school children were drowned by the sudden arrival of a typhoon-generated swell hitting the Mau-Pi-Tou coast of Taiwan (Liang 1990). On the other hand, wind wave with a fetch up to an equilibrium state is of particular importance for the development and verification of wave models. Many previous studies, both theoretical and experimental, have been carried out in this regard (e.g., Pierson and Moskowitz 1964; Hasselmann et al. 1973; Hasselmann et al. 1988; Kahma 1981; Ewing and Laing 1987; Ebuchi et al. 1992).

In view of the different natures and impacts of swell and wind sea, a global knowledge of each individual process in terms of its frequency of occurrence and associated energy is highly desirable. This can be quickly understood by examining the prerequisites of the two categories of studies outlined above. Analysis of swell energy and prediction of its propagation would obviously benefit from a zero-wind condition. On the other hand, a wind-wave-related investigation always seeks an ideal sea state with no swell presence, especially when time and site have to be determined or selected for a field experiment. Despite their different dynamics,

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swell and wind sea often overlap in wave characteristics. Moreover, they are usually a complex mixture at a given location. This sometimes makes it difficult to separate the two phenomena in real observations. In this study, taking the advantage of the newly available simultaneous measurements from National Aeronautics and Space Administration (NASA) satellite sensors, the TOPEX altimeter and the NSCAT and QuikSCAT (hereinafter abbreviated as QSCAT) scatterometers, an energy-based scheme is proposed to estimate the respective degree of swell and wind wave for each collocation site (section 2), on the basis of which global maps of swell and wind sea climate are produced and analyzed (sections 3 and 4). Finally, major swell and wind wave zones in the world's oceans are discussed and summarized (section 5).

2. Data and scheme

a. Wind–wave relation

According to wave forecasting models, sea surface wind speed and significant wave height follow a monotonical relationship under a growing sea up to the fully developed stage. This final stage is usually reached when the phase velocity corresponding to the dominant peak wave slightly exceeds the wind speed. The significant wave heights for fully developed seas were proposed by various authors, for example, Sverdrup and Munk (1947), Neumann (see Kinsman 1965), Pierson and Moskowitz (1964), Ewing and Laing (1987), and Hasselmann et al. (1988). Among these relationships, the Wave Model (WAM)-derived expression is found to have an intermediate overall growth rate for wind speed ranging from 0 to 30 m s^{-1} (see Pierson 1991), and is therefore chosen for our analysis.

Based on the WAM model (Hasselmann et al. 1988), the wind–wave relation for fully developed seas can be expressed as

$$H = 1.614 \times 10^{-2}U^2 \quad (0 \leq U \leq 7.5 \text{ m s}^{-1}) \tag{1a}$$

$$H = 10^{-2}U^2 + 8.134 \times 10^{-4}U^3 \quad (7.5 \text{ m s}^{-1} < U \leq 50 \text{ m s}^{-1}), \tag{1b}$$

where U (in m s^{-1}) is the wind speed at 10-m height, and H (in m) is the significant wave height (Pierson 1991). A graphic illustration of Eq. (1) is shown in Fig. 1 (the thick curve), along with coincident measurements of wind speed from NSCAT/QSCAT and significant wave height from TOPEX (see section 2b). The Pierson and Moskowitz (1964) and the Ewing and Laing (1987) wind–wave relations are also included in Fig. 1 for reference. A direct implication of this graph is that the fully developed relationship may be used as a dividing line for sea state maturity: Measurements lying below the curve are mostly from a growing sea, while those above the curve are probably swell dominated. Of course this inference is not supposed to be valid in an absolute sense due to the complexity of the wind wave–swell coupling. But it is expected to give a meaningful classification of the two regimes from a statistical point of view.

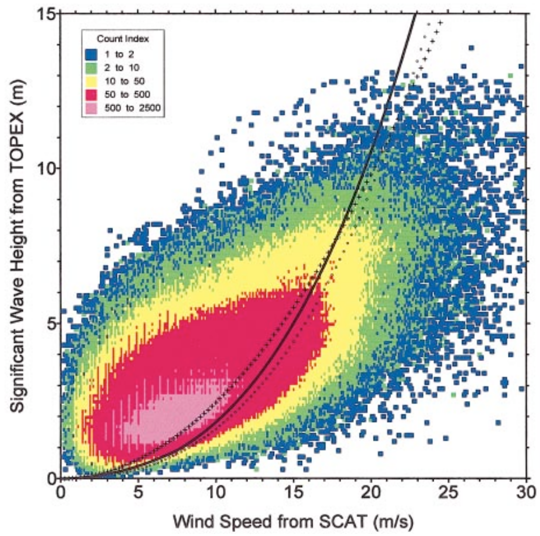

FIG. 1. A scatter diagram of sea surface wind speed and significant wave height based on the collocated TOPEX/NSCAT and TOPEX/QSCAT datasets. The wind speeds are extracted from NSCAT and QSCAT, and the significant wave heights are extracted from TOPEX. The color legend depicts data density. Also overlaid are the theoretical relations between wind speed and significant wave height for fully developed seas according to Hasselmann et al. (1988) (the WAM model), Pierson and Moskowitz (1964), and Ewing and Laing (1987), as depicted by the solid line, the crosses, and the circles, respectively.

5. Summary

Knowledge on the global structure of swell and wind sea probabilities in a climatological sense is believed to be generally poor to date. This study represents the first of its kind toward a better understanding of these important parameters. It has benefited from the availability of simultaneous multisatellite missions, which provide independent measurements of wind speed and significant wave height with unprecedented accuracy. Using the two energy-based indices proposed in this study, the global distribution and seasonal variation of swell and wind sea climate of the ocean is investigated. As a summary, the identified major swell pools (in red) and wind wave zones (in blue) in the world's oceans are indicated in Fig. 7. Given the reasonable results obtained in this study and their general consistency with available field observations and model predictions, the proposed scheme appears to be effective and efficient in characterizing the global swell and wind sea climate. Further exploration based on this feasibility study with longer duration of collocation dataset (which can be readily achievable by incorporating simultaneous TOPEX/ERS measurements as well as other forthcoming concurrent altimeter/scatterometer missions) will undoubtedly lead to a more realistic and more complete description of the swell and wind sea conditions in the ocean, in particular their interannual variabilities on a decadal timescale.