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On the growth of ocean waves

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Abstract

The availability of 10 h of continuous, uninterrupted field measurements of wind waves recorded in the western Pacific and containing a complete wave growth episode, has provided a distinct opportunity for us to make a novel, unprecedented examination of detailed wave growth processes. We found that the significance of the size of data used in the measurement, which can only be addressed with continuous and uninterrupted measurements, reflected the ineptness of the conventional approach toward further detailed understanding of realistic wave growth processes, as the conventional 20 min data size essentially stamped out any dynamics with time scale below 20 min. While our conventional understanding and modeling were generally operative and useful, they left no real vestige on time localized mechanisms such as wave grouping or wave breaking processes all with time scales much less than 20 min.

Keywords: Ocean waves; Ocean wave growth processes; Time-frequency analysis

1. Introduction

The question "how do ocean wind waves grow" may strike someone as rather superfluous since twice in the last century, the problem of wave generation and growth was considered as theoretically solved. The first was in the mid-1920s after the publications of Jeffreys (1925) which advanced the concept of sheltering mechanism between wind pressure and the ambient atmosphere over waves. Then just over three decades later in 1957, the virtually simultaneous publication of Phillips (1957) and Miles (1957) separately and jointly formed the basic components of modern wind wave modeling that is still being used today. While Jeffreys' theory suffered a lack of observational supports, the substantiation for Phillips and Miles conjectures from experiments and field measurements had been mostly circumstantial at best. In a recent historical review, Mitsuyasu (2002) rightfully surmised that "we are still not in a position to completely understand the mechanism". So it does not matter how one might comprehend the classical, theoretical aspects of wind generation and growth, it is unlikely that anyone can unreservedly answer the question of how do wind waves grow. It is not our intent in this paper to belabor the theoretical aspects of wind waves. Rather we wish to present some unconventional, empirical evidences of wave growth processes based on continuous wave measurements that may help stimulate and steer new insights toward future theoretical considerations, since results from actual field measurement are still relatively rare.

2. The data

The data used in this study were recorded in the western Pacific Ocean, northeast of Taiwan outside the Bisa fishing harbor to the east of the city of Keelung. Wave measurements were made with an ultrasonic wave gage (Tsai et al., 2004) equipped with a 200 kHz upward looking acoustic transducer mounted on a gimbal mechanism, along with a pressure transducer and an electromagnetic current meter. The wave gage was deployed at (121.783 °E, 25.150 °N) in 26 m water depth and set to record three 20 min segments of data hourly at 2 Hz resolution. The

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continuous measurements, stretched across various extended time periods from the autumn of 1999 through the summer of 2003, had covered numerous cases of complete episodes of wave evolution process from calm sea, through growth to decay. Fig. 1 presents an example of one of the unexplored wave growth cases that displayed continuous time-series data for a 10 h sweep that ran through the morning hours of October 3, 1999. This is the data set we use in this paper. As there was no directly measured wind data at the wave measurement site, a set of corresponding hourly averaged wind speed and wind direction, recorded from the nearby Keelung harbor is plotted in Fig. 2 with the time concurrent part shown in red. It appears that the wave growth correlates with the rising in wind speed consentaneously.

3. The conventional approach

The first step of the conventional approach in basic analysis of recorded wind wave data is customarily the calculation of a frequency spectrum for a 20 min segment of the time-series data. From the calculated spectrum, usual wave characteristics, such as significant wave height and various wave periods can be readily extracted. These extracted wave parameters are generally used to test and calibrate wave models. One of the most important and widely used parameter is the significant wave height. There are, however, two approaches in extracting this basic parameter that were taken for granted and used interchangeably. One approach is based on the original use of significant wave height, $h_{1/3}$, defined as the average of the highest one-third of the crest to trough waves in that segment of time series by sifting through each individual trough to crest waves in the data. The other, perhaps more prevalently used, approach of getting the significant wave height, h_s is simply obtained by four times the standard deviation, as it is also the square root of the variance of the data segment, corresponding to the integration of the calculated wave frequency spectrum. While for an assumption of Rayleigh distribution for the wave heights, the two approaches, h_s and $h_{1/3}$, are, theoretically, expected to yield the same outcome. In actuality, however, they can vary by as much as 5–10 percent. In this paper, we choose to make a pertinent distinction. We feel it is timely and apropos to clarify the indistinct practice by literally calling the height obtained from variance, h_s, the *standard deviation wave height*, which is more factual than the commonly mixed labeling of significant wave height.

In analyzing the episode shown in Fig. 1, we focused our interest on two parameters in particular: the standard deviation wave height and the maximum zero-upcrossing wave height. The results based on consecutive 20 min segments of time-series data recorded in the morning of October 3, 1999 illustrated a reasonably smooth, composed display of conventionally accustomed wave height growth picture as shown in Fig. 3. Perhaps the only difference

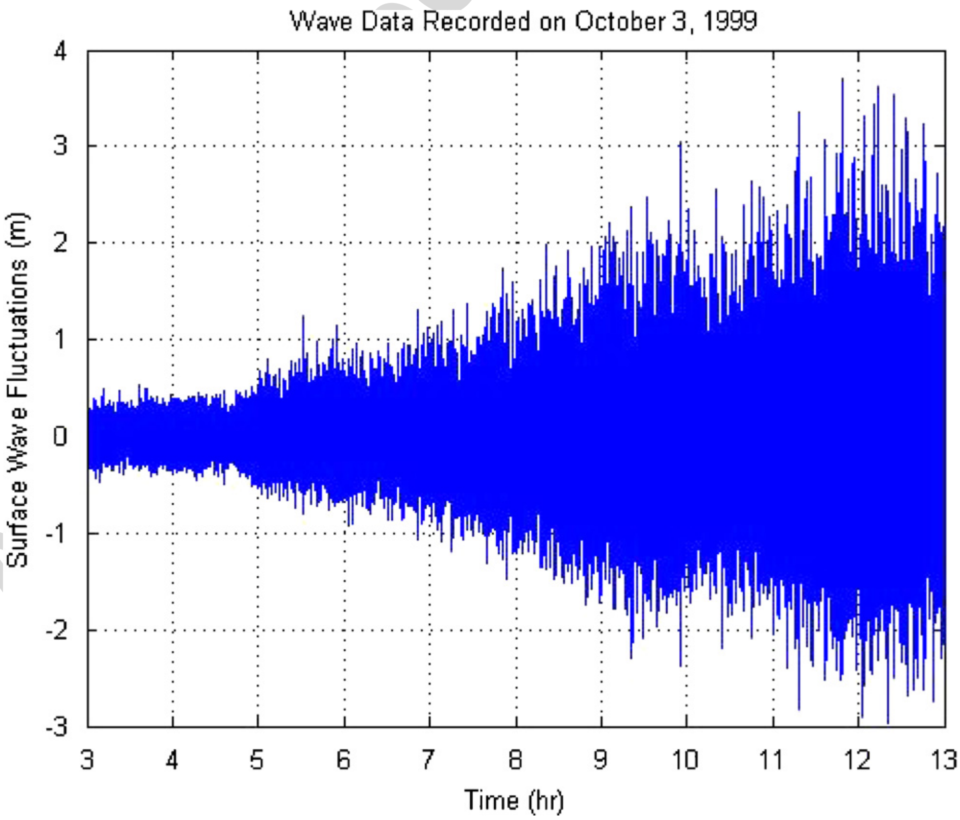

Fig. 1. An episode of continuous wave growth time-series data on October 3, 1999.

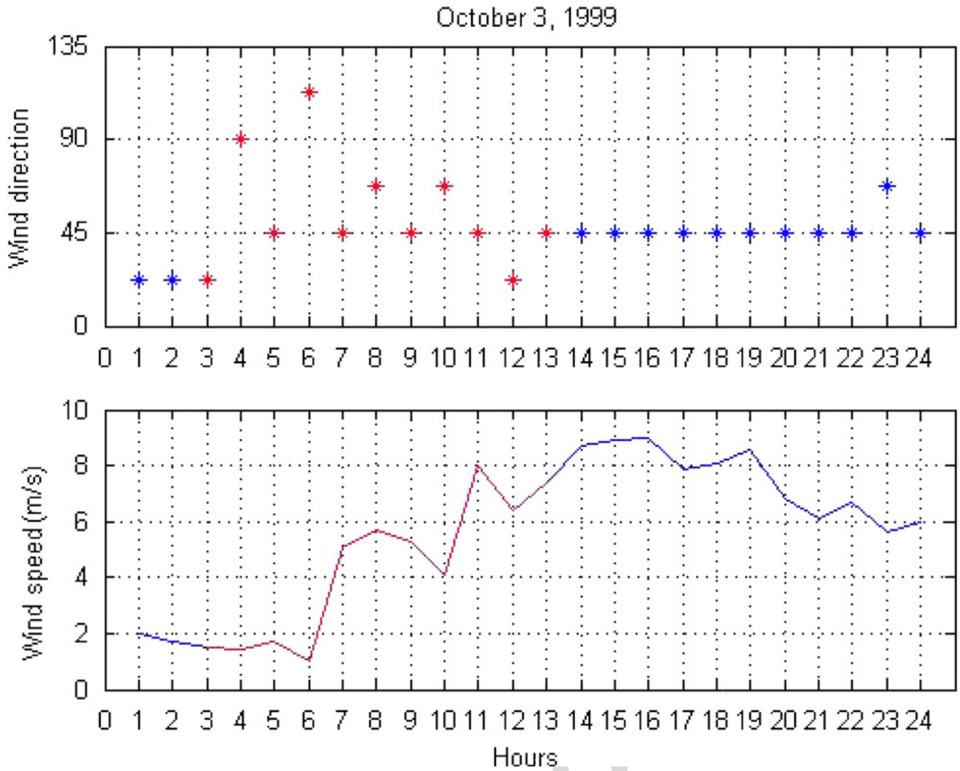

Fig. 2. Corresponding wind data from the nearby Keelung Harbor.

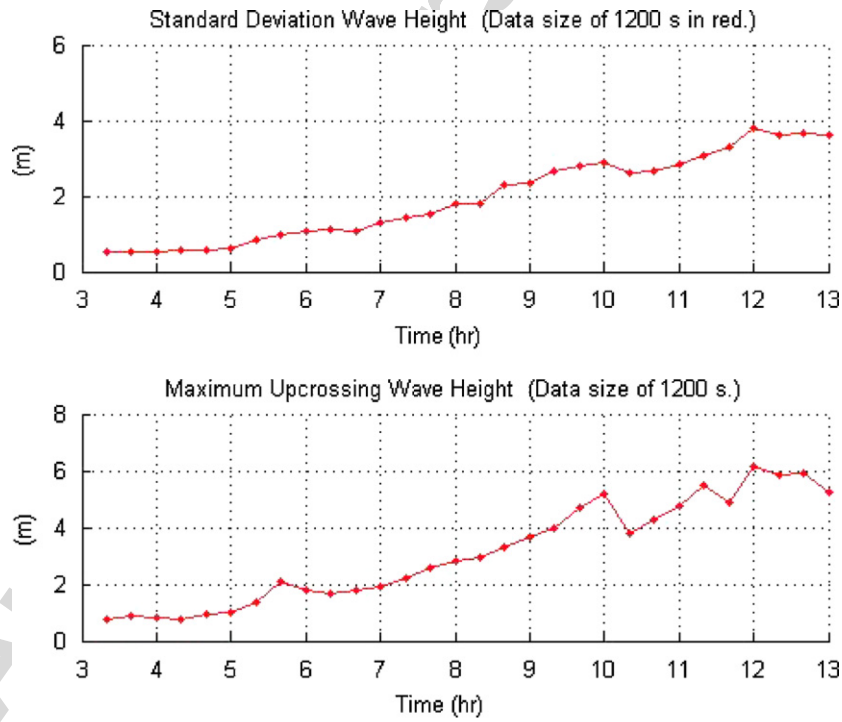

Fig. 3. Calculated episodic standard deviation wave heights and maximum zero-upcrossing wave heights based on consecutive 20 min data segments.

between common conventional practice and what we are showing here is that we have three data points of each hour instead of just one. It is certainly tempting to conclude that the smoothed display really signifies a substantiation of the conventional understanding of wave growth. Because for a given growing wind field, one would intuitively expect conventional wind wave models will indeed predict this kind of wave height growth pattern. Fig. 3 further attests to the likelihood that data can be interpolated. But do these uplifting prospects truly reflect the realistic dynamics of the actual wave surface?

4. Does the size of data matter?

To answer the question posed at the end of last section concerning representation of the true dynamics at the wave surface, we would like to first raise a relevant, corollary question: "Does the size of time-series data segment matter?"

It seems that ever since wave studies settled on a rather subjective data size, 20 min, which had so conspicuously become the default standard for wave measurement that data size has never been envisioned as an issue thereafter. Understandably, expediency is a part of the reason to use a data size of 20 min. Shorter size may render the data statistically unstable, whereas a longer size could undermine the stationary assumption for the wave process. At the time, around the 1960s when the 20 min recording size was established, the recording capacity was also a major concern. The explosive technology advancement over the past decades since then, however, has mostly eliminated the storage limit provision in the recording system. It is interesting to note that the data used in this study, while recognizing the need for continuous and uninterrupted recordings, but still retained the old-line 20 min recording procedure, only to accomplish the continuousness by making consecutive, non-interrupted 20 min measurements. The availability of continuous measurements facilitated an opportunity for us to examine the general effects of using different sizes of data segments, especially smaller data sizes. Figs. 4–7 present results of using data segments of 10, 5, 2.5, and 1.25 min, respectively, shown in blue with the conventional 20 min data results, plotted in red for comparison. The figures expressly reveal that a smaller data segment conduce the results to fluctuate from the general form of smooth growth set by the 20 min segments. It started with little wiggles for 10 and 5 min segments and turned into staggering and oscillatory clusters as the size of data segments became smaller. While the 20 min standard deviation wave height goes through the fluctuating clusters of the others, the 20 min maximum upcrossing wave height seems to be the upper boundary of the others. What one can readily infer from these figures is that while the 20 min data segments provide a fair representation as far as how the data are defined, in reality the dynamic growth of the wind wave process is by no means as idyllic as the smooth growth in Fig. 3, one might otherwise presume.

5. Growth in time–frequency domain

Wavelet transform spectrum analysis (Liu, 2000) is a relatively newer approach for the time-series wave data analysis. Although there were various efforts that made use of the wavelet applications, scarcely any have tried to educe direct physical effects from the wavelet transform exercise. The conventional approach has been and continues to be manifestly governed by the Fourier spectrum analysis. Fourier spectrum analysis requires the data to be stationary and carried out over a fixed time window. While

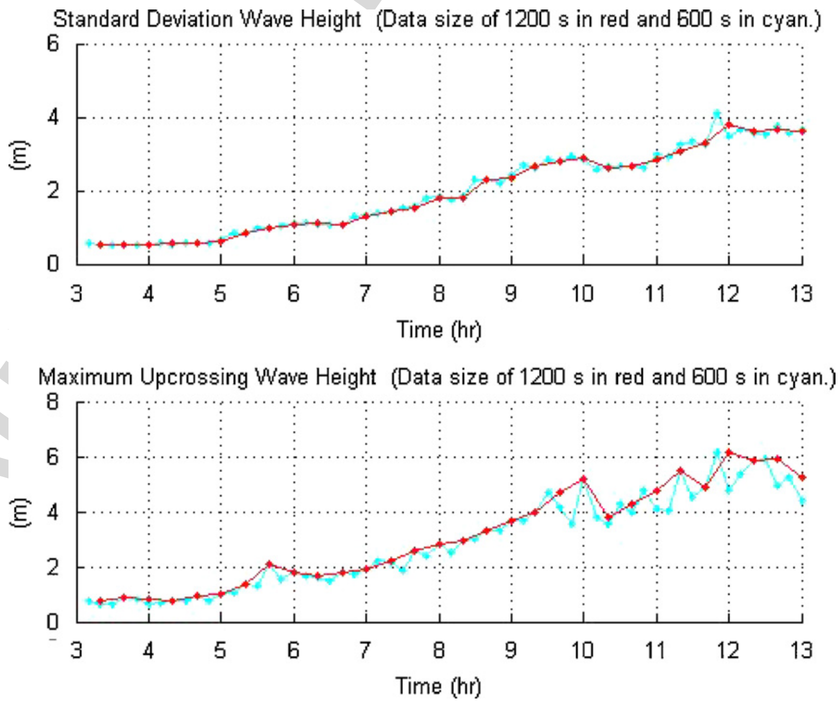

Fig. 4. Calculated episodic standard deviation wave heights and maximum zero-upcrossing wave heights based on consecutive 10 min data segments as compared to 20 min data segments.

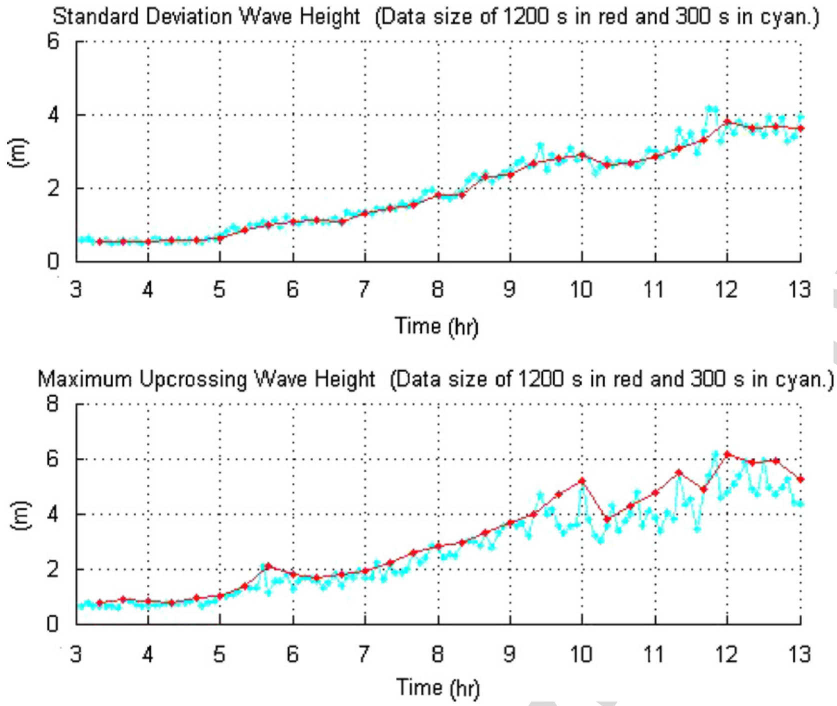

Fig. 5. Same as Fig. 3 for consecutive 5 min data segments.

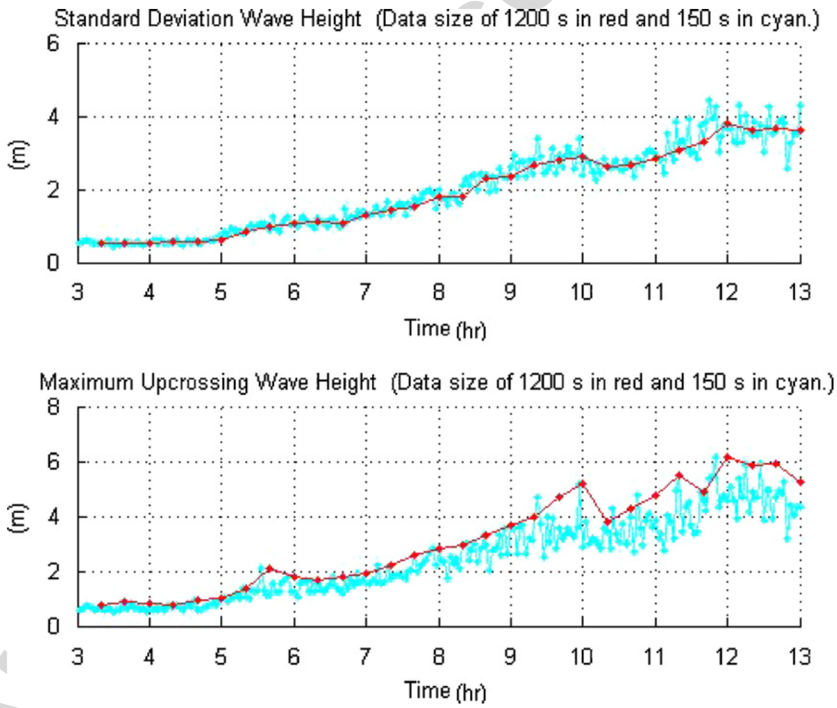

Fig. 6. Same as Fig. 3 for consecutive 2.5 min data segments.

we have shown earlier that varying the size or length of this time window greatly affects the basic outgrowth of the representation of the processes, the expediency of a convenient data size for this window, e.g. 20 min has nevertheless become a standard practice. Wavelet transform spectrum analysis, on the other hand, will not be impeded by the predicament of data size in general. An application of the wavelet transform spectrum analysis to the time-series data given in Fig. 1 leads to Figs. 8 and 9, which are two different perspectives of the same result of the energy bearings in the time–frequency domain. Ostensibly the image of growth, one would obtain from envisaging the two-dimensional contour plot of Fig. 8 or the three-dimensional spatial plot of Fig. 9 would be

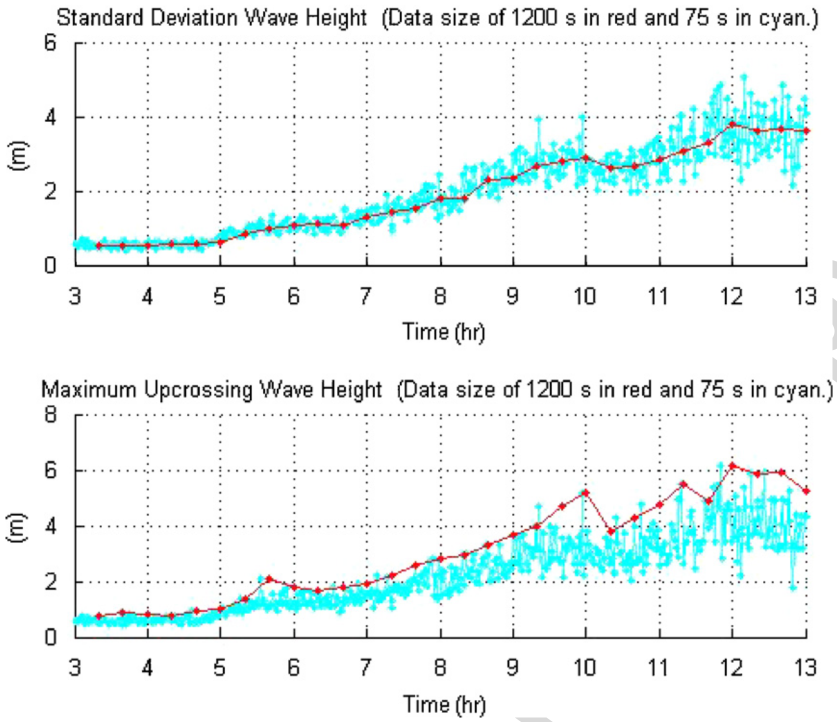

Fig. 7. Same as Fig. 3 for consecutive 1.25 min data segments.

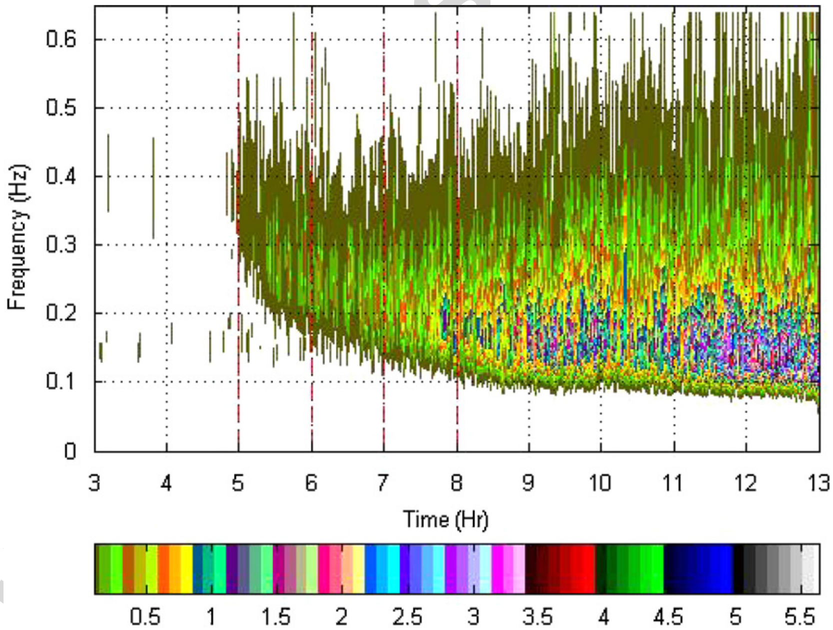

Fig. 8. Contour plot of time–frequency wavelet spectrum for the October 3, 1999 time series wave data of Fig. 1. The unit for energy density is approximately m^2/Hz.

substantially different from viewing the wave height's growth based on 20 min data in Fig. 3. These new depictions of wave growth process is conceivably representative of the ultimate outcome one would expect from viewing the time-series data but the exercise of using smaller and smaller data size, presented in Figs. 4–7, along with the conventional Fourier transform approach, certainly cannot be presumed to be able to emulate a similar outcome. At any rate, the depictions shown in the time–frequency domain as given in Fig. 8, and maybe more distinctly in Fig. 9, have given us a glimpse of what in essence a realistic process of wave growth might entail, which is clearly far beyond any of the available conventional wave models can accommodate.

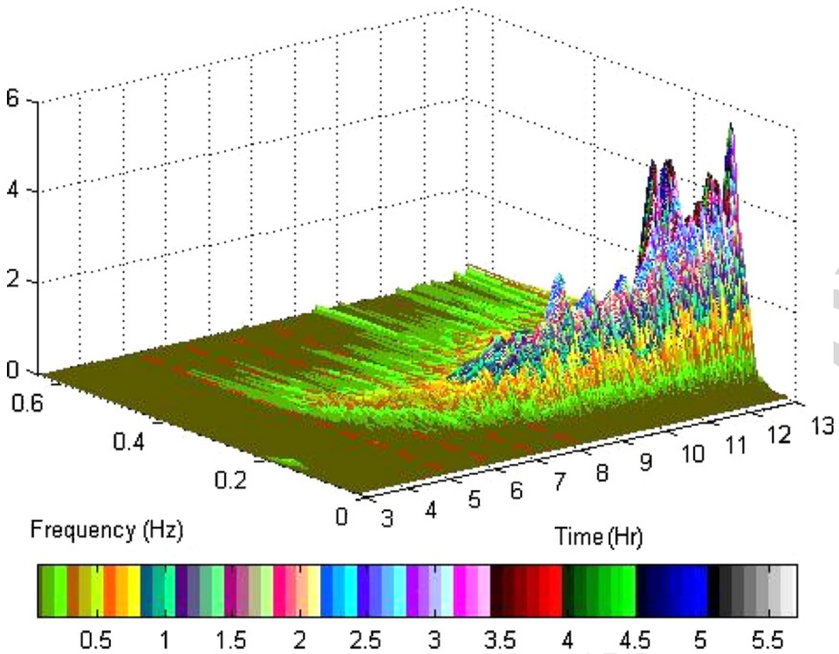

Fig. 9. Three-dimensional plot of time–frequency wavelet spectrum for the October 3, 1999 wave data of Fig. 1. The unit for energy density is approximately m^2/Hz.

6. What is known, what is not?

The general features one can discern from the depictions of Figs. 8 and 9 are by no means entirely new. One can readily notice the pronounced shifting of peak frequency towards lower frequencies, which has long been recognized as one of the wave growth characteristics. What is not previously known, however, is that the process of shifting toward lower frequency is not persistent; it is more of an incipient occurrence at the early stage of the growth. As the waves continue to grow, the shifts become less conspicuous and proceeded to coalesce into a unified predominant peak frequency during the vigorous wave growth stage. A further observation, incidentally, is that this description, for which the processing of shifting of peak frequency towards lower frequencies, pertains only to the general trend of the process. The local, detailed process that configured the trend cannot be easily disentangled. For the individual values of local peak-energy frequency, plotted with respect to time in Fig. 10, shows that the trend that shifts toward lower frequency is only noticeable visibly between the hours 5 and 9 during the morning of the October 3, 1999 episode. But it is really an overwrought fluctuation process that continued throughout the episode that manifested the trend we surmise. Indeed, when we similarly plotted the corresponding local peak spectrum energy logarithmically with respect to the linear time scale, as shown in Fig. 11, we also recognized the well-known exponential growth trend shown during the same incipient stage of wave growth. Again it only approximates the trend that typifies the dynamics of a rather frenziedly fluctuating process. This seemingly exorbitant fluctuating process that embodied the detailed wave activities shown in Figs. 10 and 11 may be an enigma that was not explored before, but it is certainly not inconceivable. Our conceptual basis was seated deeply in the premise of conventional Fourier frequency spectrum analysis, which essentially blotted out or suppressed any localized individual activities of wave processes within 20 min, the standard time length of the segment of the data. Consequently, the dynamics represented by the conventional conceptualization and modeling is necessarily delimited by the 20 min size as the minimum time element of the wind wave processes. Thus the model can, at most, show a trend of the growth process but not the abstrusely fluctuating effects that actually fomented the trend as shown in the figures.

7. Concluding remarks

In this brief note, we presented some novel empirical results that do not seem to have been alluded to before. The results may be presumptuous and unconventional, as it is for the first time that an extensive panoramic kind of view on a complete episode of wave growth process were made from 10 h of continuous and uninterrupted wind wave measurements. At first sight, continuous and uninterrupted wind wave measurements may appear to those who are holding conventional perspectives as something redundant. But it certainly presents a very different outlook of wave growth process from those that have been accustomed. The fact that our longstanding perception of exponential growth for individual frequency components and down shifting of front face peak frequency are all pertaining to only the trend of an

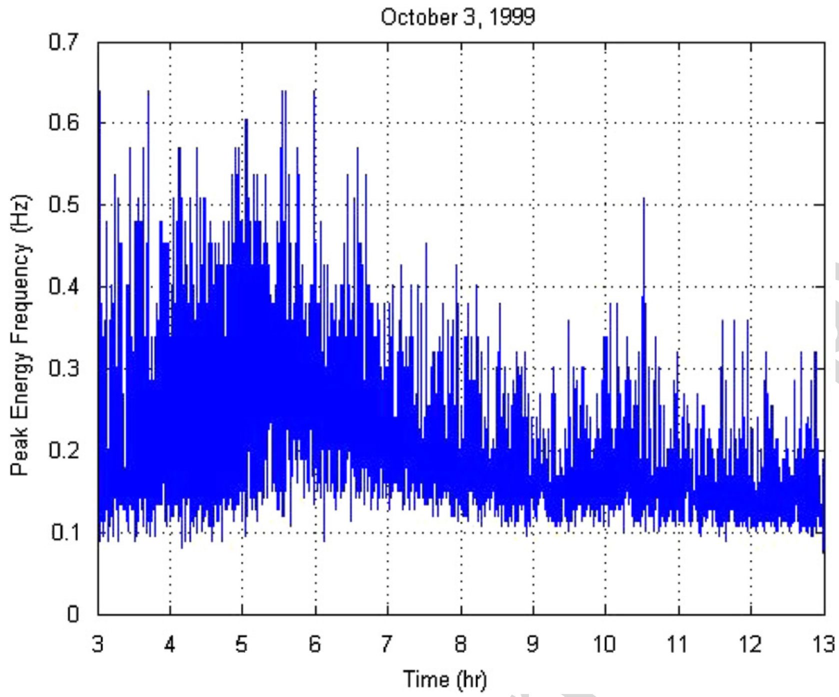

Fig. 10. Values of local peak energy frequency with respect to time.

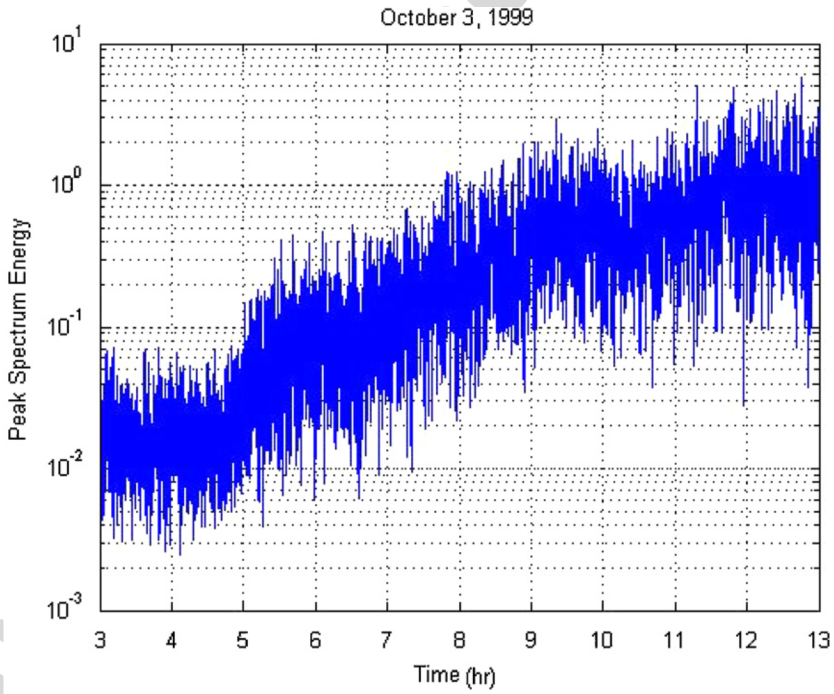

Fig. 11. Values of local peak spectrum energy with respect to time.

inordinately fluctuating process can be disheartening. The reality of the wave growth process is clearly not what the conventional approach and modeling has perceived it to be. As the conventional conceptualization was basically formulated in the middle of last century before all the advancements in modern technology in the recent decades, maybe it is timely now for a reexamination of our half-century old conceptual ideas on wind waves. At any rate, we are convinced that making continuous and uninterrupted wind wave measurements; along with detailed data analysis in the time–frequency domain would be vital, venturous pursuits for future wind wave studies.

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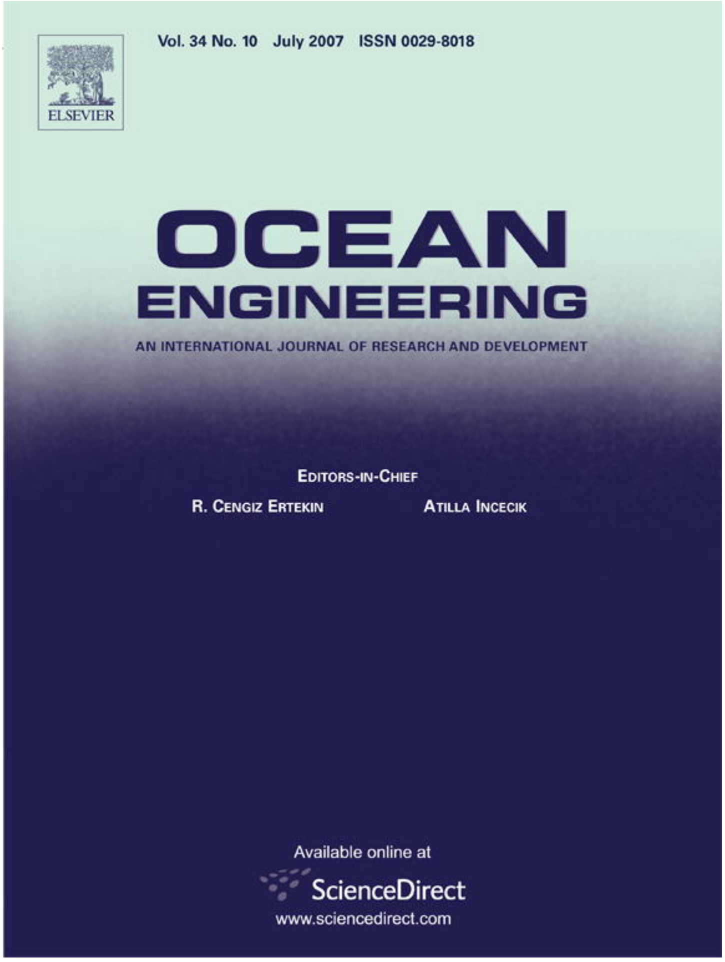
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