Analysis of Rain Effects on Wave Height Estimation from X-Band Nautical Radar Images

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***Abstract*—In this paper, the analysis of rain effects on wave height estimation from X-band nautical radar sea surface images is presented. A modified shadowing-analysis-based algorithm is applied to the radar data acquired in a sea trial in the North Atlantic Ocean under both rainy and rain-free conditions. The result shows that rain enhances the image pixel intensity and reduces shadowed areas, leading to the underestimation of wave heights. An increase of about 0.31 m in the bias with respect to *in-situ* measurements is found in the wave height retrieved from rain contaminated data compared to the results obtained from data without rain.**

I. Introduction

Algorithms for ocean wave information retrieval using X-band nautical radars have been largely developed during the last several decades [1]–[3]. However, since the radar image is not a direct representation of the ocean surface, calibrations using additional reference sensors are usually required for wave height estimation [4]–[6]. Recently, a shadowing-analysis-based algorithm was proposed to estimate wave height without the necessity of calibrations [7]. Some modifications were made to the algorithm in [8] and [9] in order to achieve more robust results.

Rainfall is one of the most common atmospheric phenomena which has a significant impact on the radar signal backscattered from the ocean [10]. In general, rain-contaminated radar images have been identified and discarded from wind and wave information extraction [9], [11]. However, as the rain contamination on radar images cannot be avoided, the effects of rain on wave height measurement need to be investigated.

The analysis of rain effects on wave height estimation from X-band nautical radar images using a modified shadowing-based algorithm described in [9] is conducted. The paper proceeds as follows: Section II contains an overview of the radar data used in this work. In Section III, the effects of rain on X-band nautical radar sea surface images are depicted and briefly discussed. In Section IV, the effects of rain on wave height estimation are analyzed. A conclusion and future directions for this work appear in Section V.

II. Data Overview

Data used in this work were provided by Defence Research and Development Canada (DRDC). The data collected from 23:43 on Nov. 26 to 12:06 on Nov. 29 (2008) in a sea trial approximately 300 km south-southeast of Halifax, Nova Scotia, Canada were employed. To measure the wave field for validating the radar results, three free-floating Triaxys directional wave buoys were deployed about 4 to 15 km apart. The distances between the ship and the buoys were generally less than 10 km, but occasionally up to 15 km throughout the trial.

A standard HH-polarized Decca marine radar that operated at 9.41 GHz with a sampling frequency of 20 MHz was utilized in the sea trial [9]. The radar antenna having a rotation speed of 28 rpm was installed at a height of 21.9 m above sea level. The radar range extended from 240 m to 2160 m with a range resolution of 7.5 m, and there was azimuth of coverage of 360°. The beam width was 2°. The radar was connected to a Wave Monitoring System II (WaMoS II) [12]. The system digitized and stored the radar backscatter signals in gray levels using an 8-bit unsigned integer format (i.e., ranging from 0 to 255). The lowest radar return was scaled as 0 (black in the radar image) and the maximum radar return was scaled as 255 (white in the radar image).

III. The Effects of Rain on X-Band Nautical Radar Sea Surface Images

Examples of rain-free and rain-contaminated raw radar images appear in Fig. 1. Fig. 1(a) is a rain-free radar image collected at 00:35 on Nov. 27, while Fig. 1(b) is a rain-contaminated radar image collected at 02:52 on Nov. 27. It can be clearly seen that the radar backscatter intensity in Fig. 1(b) is significantly enhanced by rain. Moreover, the radar image is uniformly bright and the wave signature is obscured.

Lund *et al.* [13] observed the strong impact of rain on the number of zero-intensity pixels in X-band nautical radar images, and used the zero-pixel percentage (ZPP), which is defined as the ratio of the number of zero-intensity pixels to the total number of pixels in an image, as a parameter for rain recognition. Since the data used here is the same as that in [11], pixels with gray scale intensity lower than 5 are also regarded as zero-intensity pixels, and images with ZPP less than 10% are considered as rain-contaminated. For Fig. 1(a), which is rain free, the ZPP is 19.32%, while for Fig. 1(b), which is rain contaminated, the ZPP is 1.32%.

IV. The Effects of Rain on Wave Height Estimation

In this paper, based on the shadowing-analysis-based wave algorithm proposed by Gangeskar [7], modifications including edge pixel intensity histogram smoothing and subareas selection are implemented. The modified algorithm is introduced in detail in [9].

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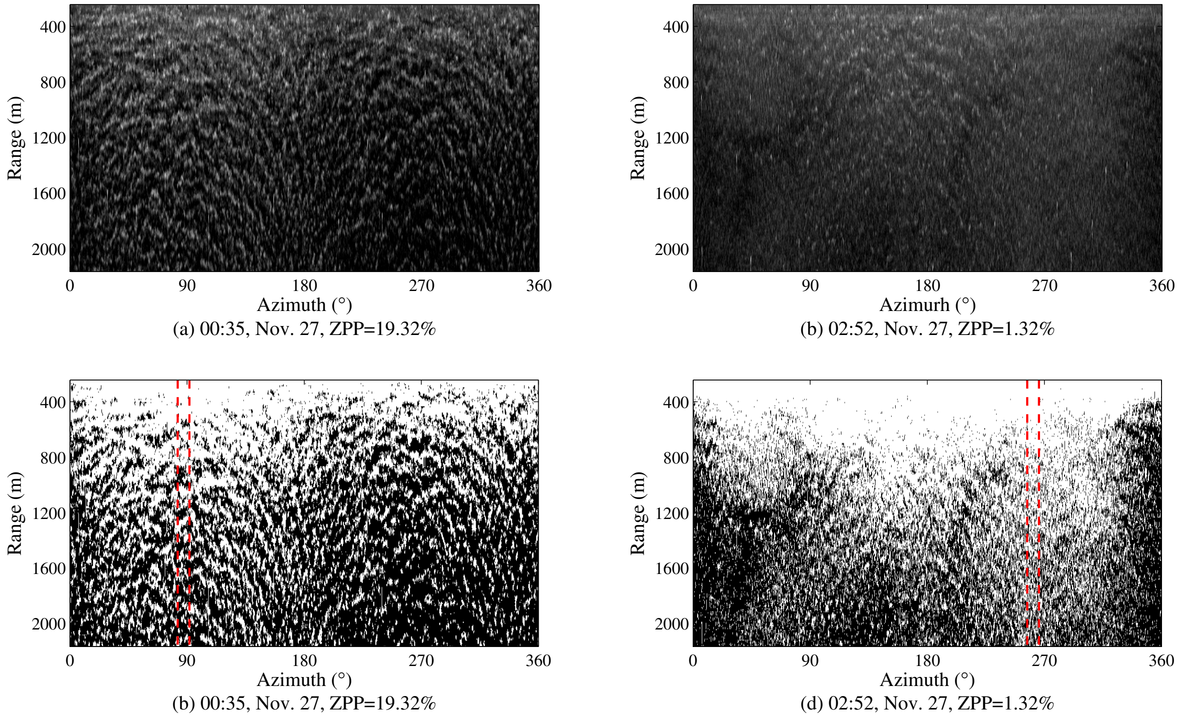

(a) 00:35, Nov. 27, ZPP=19.32%

(b) 02:52, Nov. 27, ZPP=1.32%

(b) 00:35, Nov. 27, ZPP=19.32%

(d) 02:52, Nov. 27, ZPP=1.32%

Fig. 1. The comparison of rain-free and rain-contaminated radar images: (a) raw radar image in the absence of rain; (b) raw radar image in the presence of rain; (c) shadow image in the absence of rain; (d) shadow image in the presence of rain.

Fig. 1(c) and Fig. 1(d) are the corresponding shadow images of Fig. 1(a) and Fig. 1(b), respectively. It can be seen that in the presence of rain, most parts of the shadow image appear as white (i.e., they may be mistakenly considered as sea surfaces that are illuminated by the radar). Thus, the detected shadowed areas are significantly reduced. The subarea extracted for wave height estimation in the modified algorithm is around the upwind direction in each shadow image (see the area enclosed by the dashed lines in Fig. 1).

The time sequences of the radar-derived and buoy-measured significant wave heights are displayed in Fig. 2(a). The data corresponding to low-backscatter images that appear almost completely black due to low wind speed or unknown system errors are not shown. Fig. 2(b) illustrates the corresponding time sequences of the ZPP and rain rate. When the ZPP is lower than 10% (the red dash line in Fig. 2(b)), the data are considered to be contaminated by rain. The rain rate was calculated based on the precipitation data recorded by a Non-Acoustic Data Acquisition System (NADAS) installed on the ship. The precipitation was measured by two rain gauges, and the averaged value was used. Rain rate reveals the actual strength of rainfall during the sea trial. It can be seen in Fig. 2(b) that the rain rate and the recognized rain cases (with ZPP less than 10%) agree well for most of the period. From Fig. 2, it can be observed that wave heights were underestimated for most of the rain cases. From 02:10 to 05:40 and 08:10 to 11:30 on Nov. 27, it can be observed that wave heights were significantly underestimated. The underestimation is due to the reduction in shadowed areas resulting from the enhancement in the radar image pixel intensity caused by rain. This agrees with the fact that sea states with lower wave heights generate smaller shadowed area.

The scatter plots of Fig. 3 show a comparison of the radar-retrieved significant wave heights in the absence and presence of rain with the buoy data. Compared with the results retrieved from rain-free data, the bias in the case of rain is augmented by about 0.31 m.

V. Conclusions and Outlook

In this paper, the effects of rain on the estimation of wave height from X-band nautical radar images are analyzed. A modified shadowing-analysis-based wave height algorithm is employed in this work. It has been found that as rain enhances the image intensity, shadowed areas are reduced, resulting in the underestimation of wave height. For the wave height retrieved from rain-contaminated data, the bias between the radar-deduced and *in-situ* measurements is augmented by about 0.31 m, compared to the results obtained from rain-free data. However, as rain cannot be avoided, a method is needed to overcome the negative effects of rain. This will be investigated in the next phase of the work.

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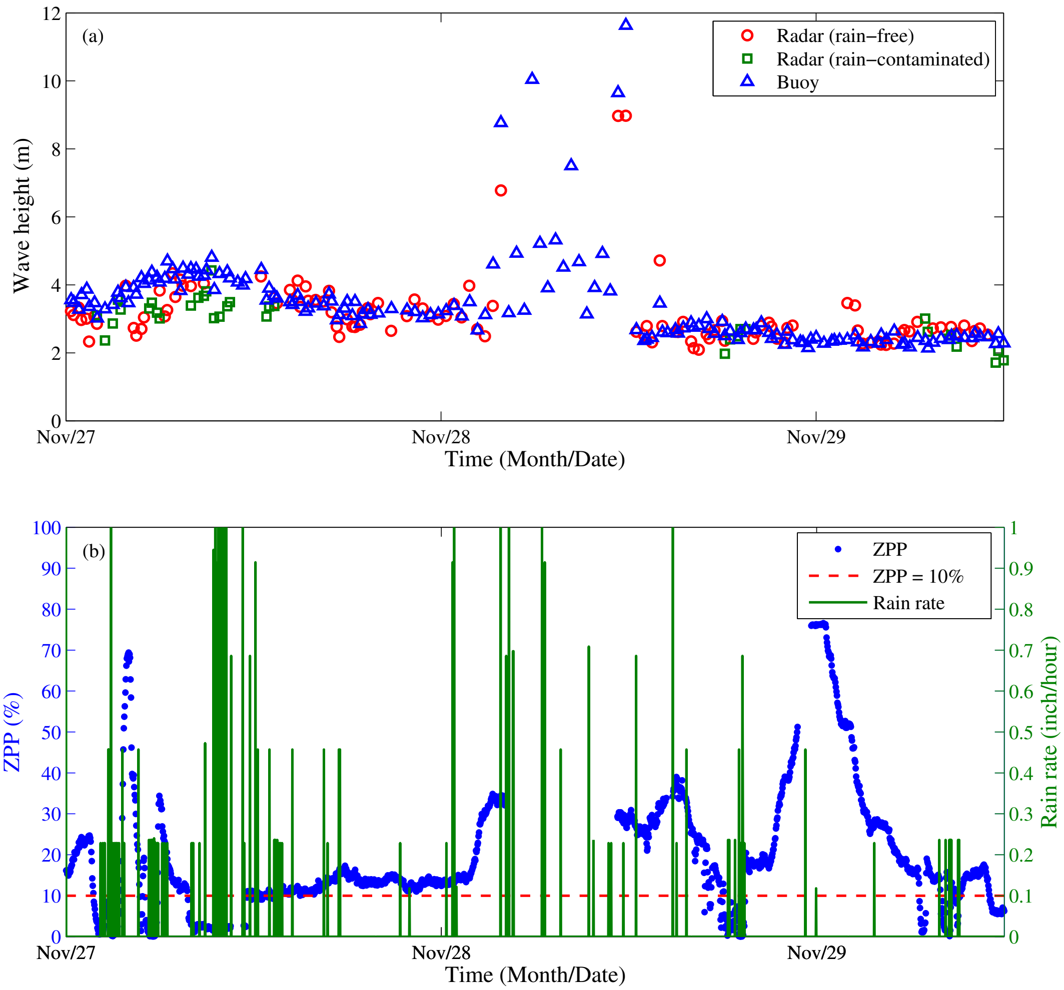

Fig. 2. Time sequences of (a) radar-derived and buoy-measured significant wave heights; (b) ZPP and rain rate.

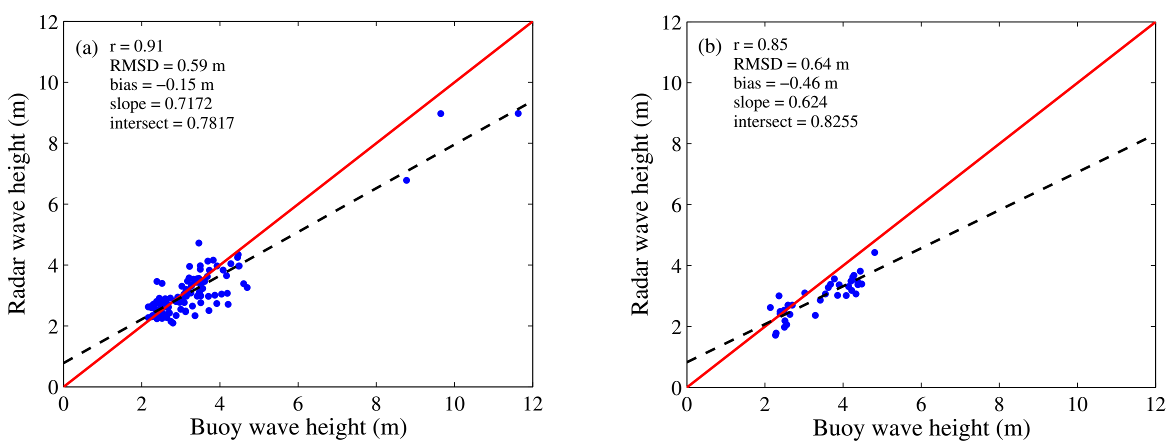

Fig. 3. Scatter plots of significant wave heights: (a) in the absence of rain; (b) in the presence of rain.

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