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REMOTE SENSING OF WAVE DIRECTIONALITY BY TWO-DIMENSIONAL DIRECTIONAL WAVELETS: PART 2. APPLICATIONS TO THE NUMERICAL AND FIELD DATA

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Summary

This paper presents the results of a study investigating methods of interpretation of wave directionality based on wavelet transform. In part 1 of this paper, the tools to be used in detection of wave directionality, i. e., the Morlet and Cauchy wavelets, were described. This paper presents the application results of the directional wavelet to numerically generated images and video images taken in laboratory wave flume, river, and sea. The results showed that directional wavelet transform can be an efficient tool in detecting wave directionality with extremely low effort and cost when it is compared to traditional practices in use.

Key words: Directionality; Directional wavelets; Morlet wavelet; Cauchy wavelet; Signal.

1. Introduction

The importance of understanding wave directionality has long been recognized in the field of ocean-related science and engineering. It could be a life and death issue to some ship operators. For example, a ship operating in the following sea could lead to dangerous situation by Paulling(1975) [1] and Renilson(1981) [2].The present authors try to propose a scheme which can detect directionality by utilizing directional wavelets by making use of video images of waves. To find out the directionality of ocean waves, the necessary data is just one frame of video images for the proposed scheme. This simplicity in the input data is possible by making use of a directional wavelet. The directional wavelet can be constructed by introducing rotation to one of the continuous wavelets. The introduction of rotation makes it possible to detect edges and directions in the images to be analyzed. The two-dimensional directional wavelet was fully studied by Antoine and Murenzi(1996) [3]. The idea of detection of directionality in signals by using directional wavelet has been studied by wavelet researchers, Antoine et al.(1999) [4], and Antoine and Murenzi(1996) [3,5]. They illustrated the usefulness of angular representation of the continuous wavelet transform (CWT) on the problem of disentangling a train of damped plane waves.

Use was made of directional wavelet to visualize the two dimensional turbulent flow around the obstacle by Wisnoe et al.(1993) [6]. The research on texture orientation was done by directional wavelet by Rao and Schunck et. al.(1991) [7]. Multi-directional wavelet was proposed by simply superposing the directional wavelet by Watson and Ahumada(1989) [8].

Present study adopted the Morlet wavelet and Cauchy wavelet as directional wavelets. The Morlet wavelet was fully examined to see its usefulness in detection of directional features [3]. It was demonstrated that Cauchy wavelet has excellent angular selectivity. The preset paper is organized as follows. The explanation about the CWT will be given in chapter 2. The description about the directional wavelet will be followed by the theoretical explanation on Morlet and Cauchy wavelet. Then, these wavelets will be tested on the numerical images which are intended to show some characteristics of water waves. Finally, conclusion will be drawn. The applications of the Morlet wavelet and Cauchy wavelet to the more complicated numerical data, wave images taken from small wave flume, river wave images, and ocean wave images will be presented in Part 2 of this paper.

The importance of understanding wave directionality has long been recognized in the field of ocean-related science and engineering. There are two major approaches to estimate the wave directionality. The first one is to estimate the directional spectrum of waves based on measured wave data. This procedure includes a directional Fourier series approach by Longuet-Higgins(1963) [1], a maximum likelihood method (MLM) by Jefferey(1981) [2], and a maximum entropy method(MEM) by Lygre(1986) [3]. These methods require a large amount of wave data measured at various locations or at various modes of wave buoys. The MEM and MLM provide better directional resolution when it is compared to the others, but the MEM provides artificial double peaks. There are usually considerable differences in results of these three methods.

The second approach is to analyze the data obtained from remote sensing of waves. Common remote-sensing devices for sensing waves are marine radar Young and Rosental(1985) [4] and the synthetic aperture radar (SAR) (Hasselmann et al. (1985) [5].

The analysis of the measured images of sea waves usually utilizes the Fourier transform of the images over space and time, but this method requires much computation time and high cost for facility.

This study proposes a new algorithm that utilizes only a single picture of wave fields Kwon et al. (2000) [6]. By applying directional wavelet which was examined in part 1 of this paper to the images, the directionality of waves was estimated with a marginal accuracy. The proposed algorithm saves much time and effort when we consider the other methods explained above. However, there are limitations in the proposed algorithm. The proposed scheme can provided the main direction of waves but not the exact energy spreading in terms of direction. Since the proposed scheme utilizes only one frame of the wave fields, 180° ambiguity exists in the direction of the propagation. Other than these limitations, the proposed scheme can be a powerful tool in directing directionality of ocean waves.

This paper is organized in a way described below. Since the description of the Morlet and Cauchy wavelet were given in part 1 of this paper, this paper begins with the calibration of the wavelets and setting of the threshold. The related parameters will be decided to carry out the computation. Then the wavelets will be applied to the numerically generated bi-directional regular waves and irregular waves. The final chapter will deal with the application of the wavelets to video images. The images of waves generated in the wave flume, images taken in the river and ocean will be analyzed by the wavelets. This study shows that the proposed scheme could be a very efficient tool in detecting directionality of waves even in short crested irregular sea.

2. Calibration of the wavelet and setting of threshold in input

Before the application of the wavelets to images, wavelet parameters should be determined to deal with real data rather than simple numerical data as was presented in part 1 of this paper. Let's begin with a video image shown in figure 1. It represents a wave image in the ocean.

When it comes to the Morlet wavelet, the parameters to be determined are very simple. The value of ω_0 was taken as 5.5 which was explained in part 1. The remaining parameters are k_0 and ε.

We need to decide α, β, l and m for the Cauchy wavelet. $|\alpha| = \beta = 5$, $|\alpha| = \beta = 10$, $|\alpha| = \beta = 20$ were tested for $l = m = 4$. The results are presented in figures 2(a), 2(b), and 2(c).

For $|\alpha| = \beta = 10$, $l = m = 1$, $l = m = 2$, and $l = m = 4$, the computations were done. The results are shown in figures 3(a), 3(b), and 3(c).

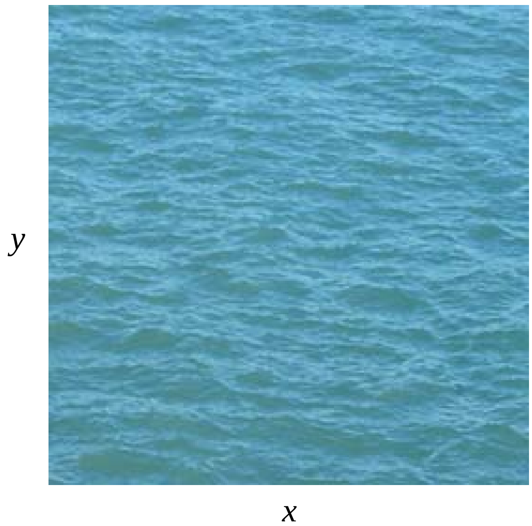
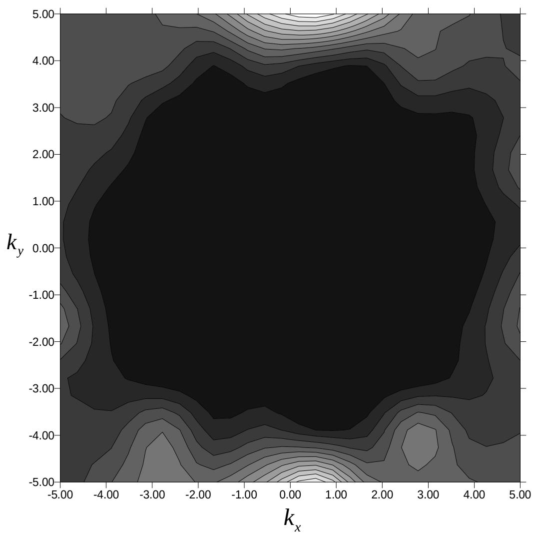
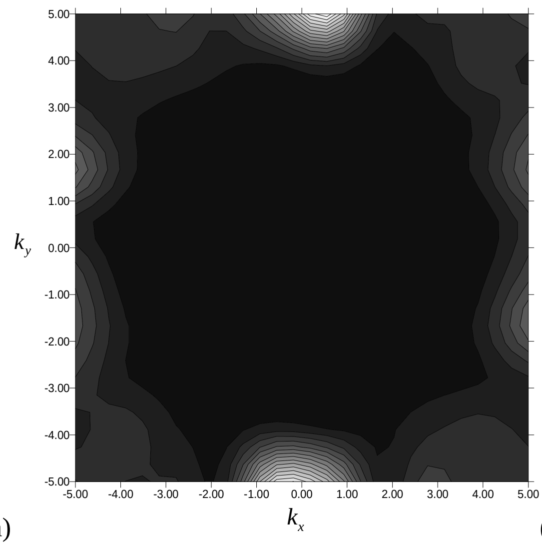


Fig. 1 Ocean Picture



(a)



(b)

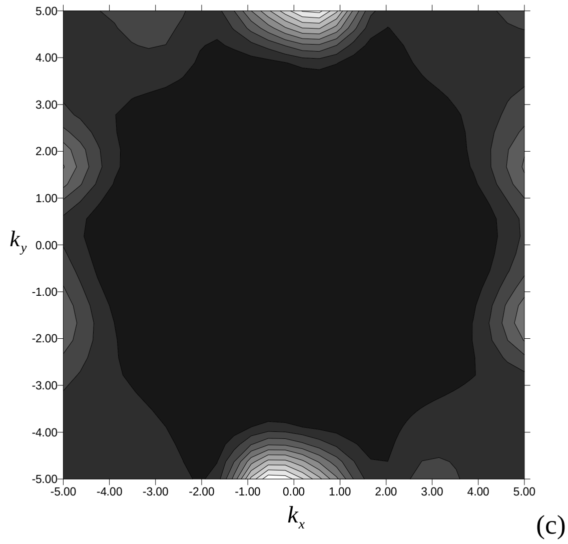


Fig. 2 Cauchy wavelet analysis for (a) $|\alpha| = \beta = 5$, (b) $|\alpha| = \beta = 10$, (c) $|\alpha| = \beta = 20$

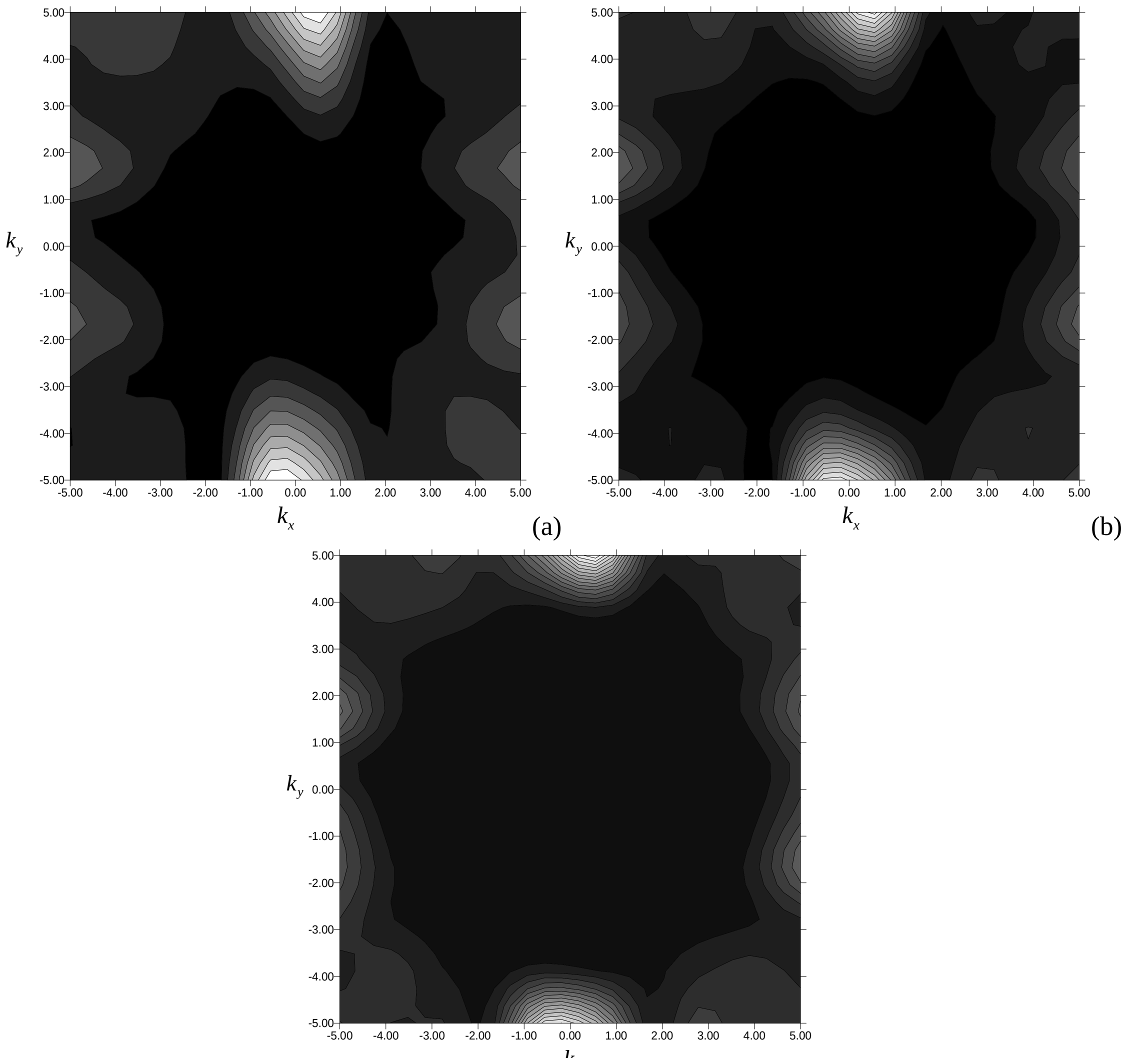


Fig. 3 Cauchy wavelet analysis for (a) $l = m = 1$, (b) $l = m = 2$, (c) $l = m = 4$

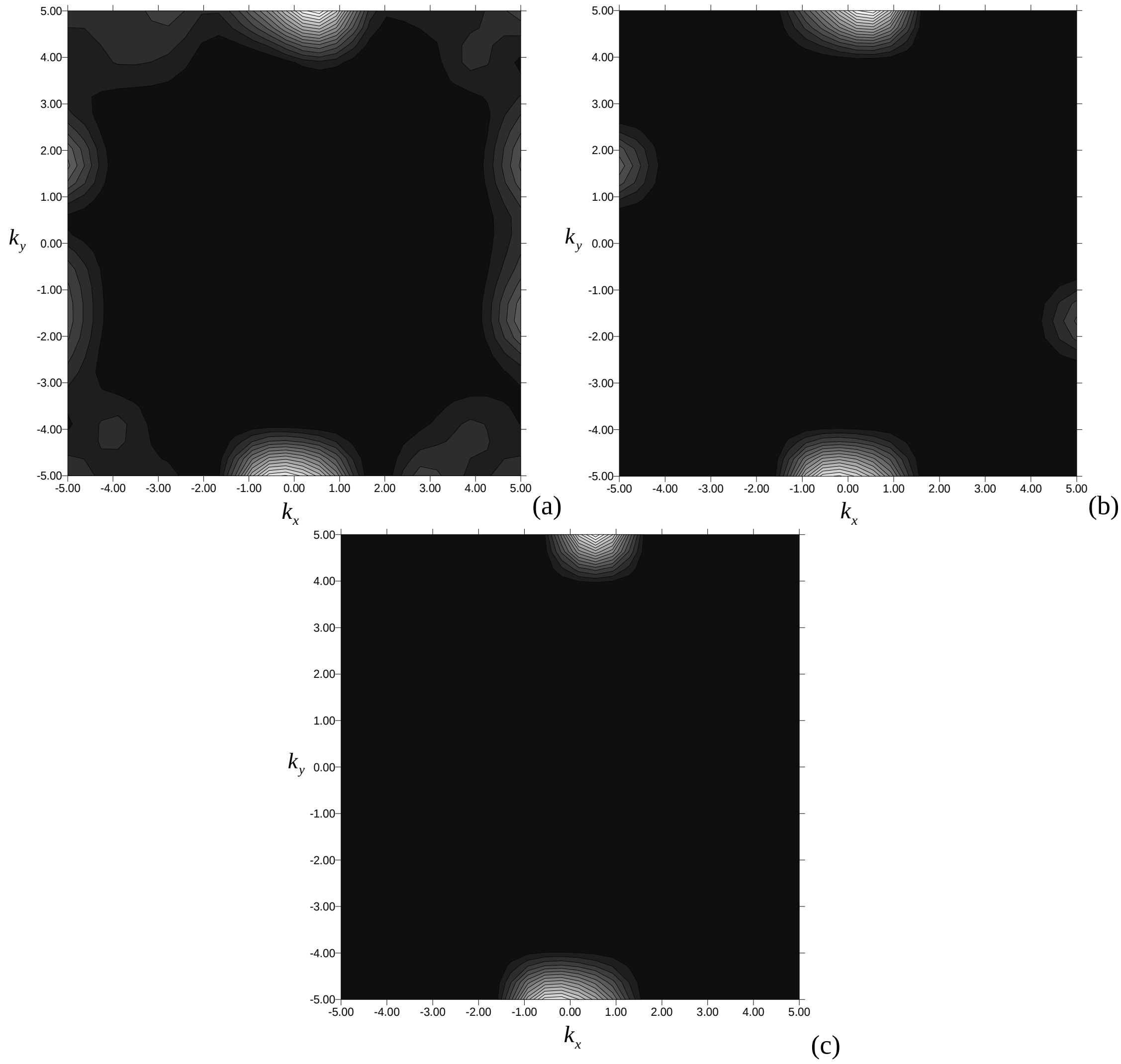


Fig. 4 Cauchy wavelet analysis with threshold level for (a) 10%, (b) 30%, (c) 50%

The results of transformation have noises which are due to the inherent nature of the scheme. We cannot change the size of the base of the effective cone whenever we carry out new computation by changing the necessary parameters. To avoid doing that, we can set a certain threshold to the transformed results. Values of 10%, 30%, and 50% of the maximum value were tested as threshold level as shown in figures 4(a), 4(b), and 4(c). The aim of present study is to find out the main direction of the wave filed. Therefore, using high level of threshold can be tolerated. The results presented hereafter were processed by using 50% threshold level.

3. Directional Wavelets

The first application was done on the two oblique waves propagating in different directions with large amplitude difference. The amplitude ratio of the two waves was 1/4. The purpose of this test was to observe the directional wavelet's ability to detect minor waves which propagate in a different direction. The difference of propagating angle in the propagation direction between the two waves was 17° (0.3 rad). The formula for bichromatic progressive wave elevation can be written

$$\eta(x_m, y_n, t) = \sum_{i=1}^{2} A_i \cos[k_0(x_m \cos\alpha_i + y_n \sin\alpha_i) - \omega(k_0)t + \varphi_i], \quad (1)$$

where $x_m = (m-1)L/(N-1)$, $y_n = (n-1)L/(N-1)$, $L = 676m$, and $n, m = 1, 2, ..., \mathrm{N}$ $(\mathrm{N} = 128)$. A_i is the wave amplitude, α_i is its propagation angle, $k_0 = 0.1\, m^{-1}(\lambda = 63m)$, $H = 30m$ by dispersion relation of finite depth. Amplitude [0.06 0.02] meter and propagation angle $\alpha = [\pi/2 \quad \pi/2 + 0.3]$ are used for this case. The generated data is shown in figure 5(a). Figures 5(b) and 5(c) show the results done by Morlet wavelet transform and Cauchy wavelet transform. The two peaks show the directions of two propagating waves even though the amplitude of small waves is just 1/4 of the large waves.

A numerically simulated irregular wave field was tested. It is generated from a directional frequency spectrum which is obtained by known wave spectrum multiplied by a spreading function. The formula for the directional frequency spectrum is

$$S(\omega, \theta) = D(\omega, \theta) \cdot S(\omega), \quad (2)$$

where $D(\omega, \theta)$ represents the spreading function. It is modeled only function of θ as follows

$$D(\omega, \theta) = \frac{2^{2s-1}}{\pi} \frac{\Gamma^2(s+1)}{\Gamma(2s+1)} \cos^{2s}\left(\frac{\theta}{2}\right), \; s = \begin{cases} s_{\max}(\omega/\omega_p)^5 & : \; \omega \le \omega_p \\ s_{\max}(\omega/\omega_p)^{-2.5} & : \; \omega > \omega_p \end{cases}. \quad (3)$$

Also, the ISSC spectrum is used for the point spectrum, $S(\omega)$

$$S(\omega) = 0.1107 H_s^2 \frac{\bar{\omega}^4}{\omega^5} \exp(-0.4427(\bar{\omega}/\omega)^4), \; \bar{\omega} = 1.296\omega_0, \quad (4)$$

where H_S represents the significant wave height of a particular sea state.

Thus, two-dimensional wave elevation is as follows.

$$\eta(x, y, t) = \sum_{i=1}^{I} \sum_{j=1}^{J} A_{i,j} \cos(k_i x \cos\theta_j + k_i y \sin\theta_j - \omega_i t + \psi_{ij}), \quad (5)$$

where I and J are the respective maximum values of i and j with amplitude spectrum $A_{i,j} = \sqrt{2S(\omega_i, \theta_j)\Delta\omega\Delta\theta}$.

Three-dimensional surface plots and contour plots of the spreading function are presented in figure 6. In this paper, the feasibility of application was tested by taking main propagation direction of $45°$ which can be clearly noticed from figure 6.

The simulated wave field, the results of Morlet wavelet and Cauchy wavelet analysis are shown in figures 7(a), 7(b), and 7(c), respectively. By simply looking at the figure 7(a), one can hardly tell the main direction of the simulated wave field. However, the highest density of contour appeared in the direction of $45°$ in figures 7(b) and 7(c), which corresponds to the main direction of the simulated waves. We can see that the directional wavelets, i.e., Morlet wavelet and Cauchy wavelet, are working nicely in detecting directionality of the simulated wave field.

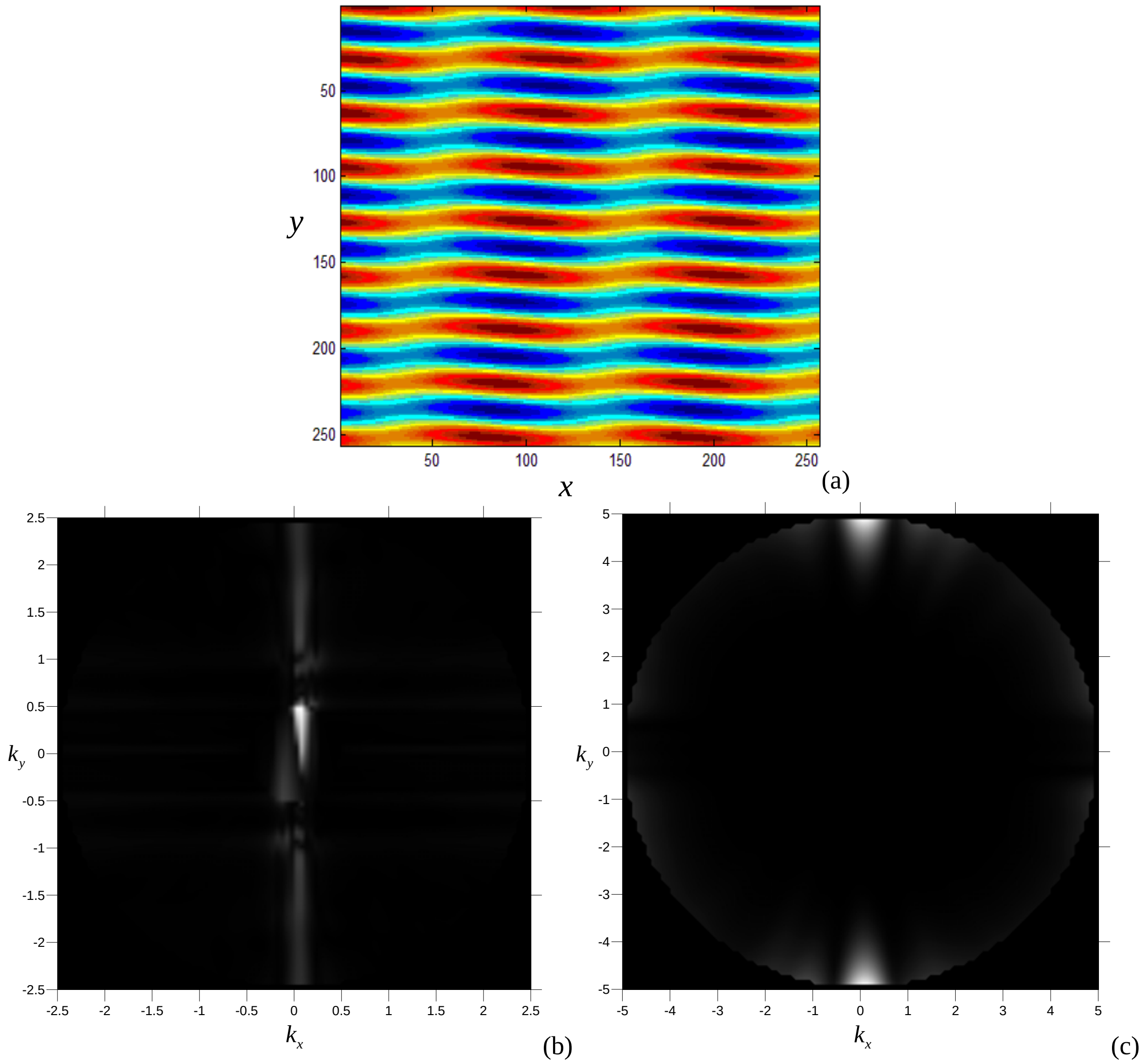


Fig. 5 (a) Numerically simulated wave elevation distribution, $\triangle\theta = 17°$, (b) Morlet wavelet transform, (c) Cauchy wavelet transform

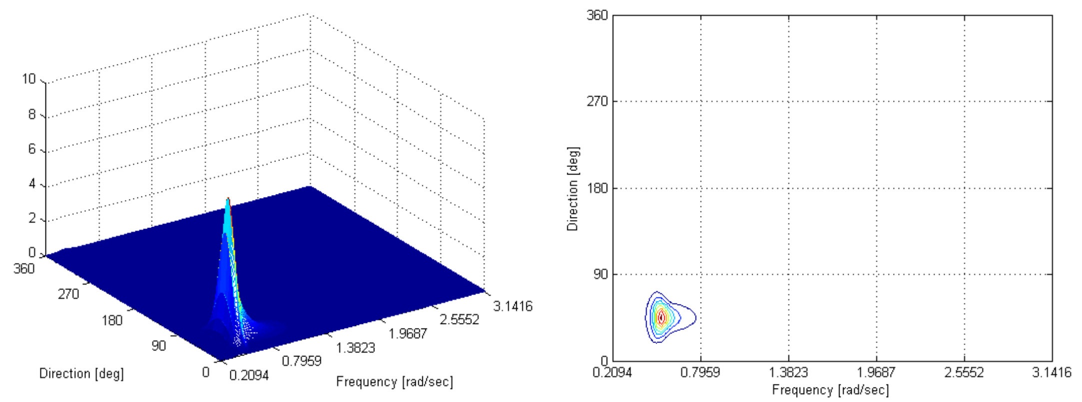


Fig. 6 Directional wave spectrum for simulated data main direction 45°.

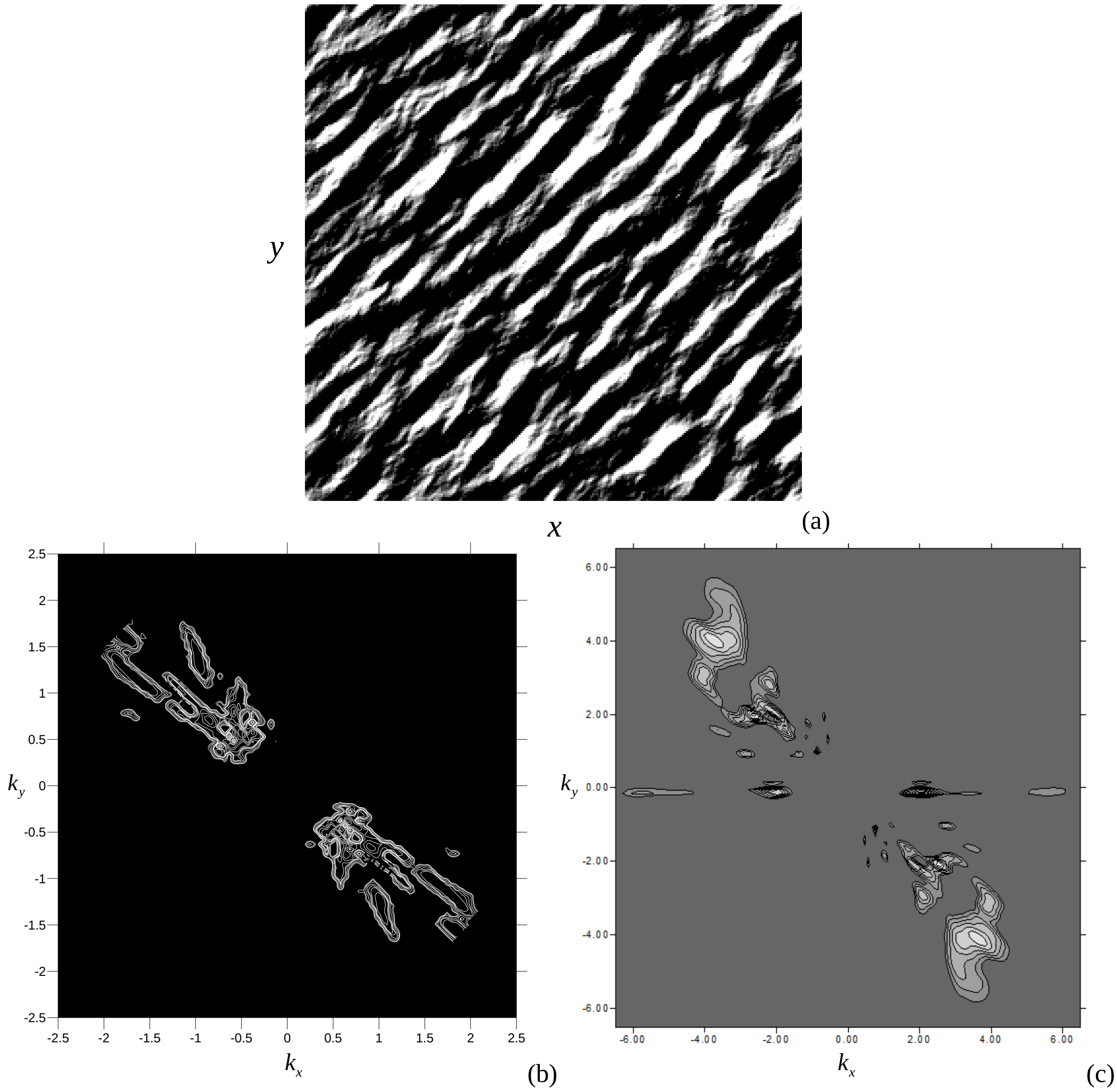


Fig. 7 (a) Simulated wave field, (b) Morlet wavelet transform, (c) Cauchy wavelet transform

4. Video Images

The wavelet transform incorporated with directional wavelet was done on the video images taken from various sources like, a small wave flume, a river, and an ocean. The wave image was taken in a small wave flume. Its image is shown in figure 8(a). The wave flume is 80cm long and 40cm wide. The water depth was 2cm. A small amount of blue ink was added to the water to give clear picture. The average wave height was estimated as 5mm. The wave was generated by moving circular cylinder, whose diameter is 1cm, up and down. The generated waves were not strictly regular waves. The net type wave absorber was installed at four side of the flume to avoid the generation of standing waves. Readers interested in the net type wave absorber are referred to Kwon et. al. (Kwon et. al., 2003). The incoming waves were propagating vertical to the view finder of the video camera. The results are shown in figures 8(b) and 8(c). The next case is oblique waves generated in the same wave flume. Figure 9(a) shows the wave field. The results are shown in figures 9(b) and 9(c). We can see that the propagation directions of the incoming waves are well captured.

The images taken in river were tested. The reason to use images taken in the river is that it is relatively easy to take desired video images in the river than in the ocean. Two cases of propagation were considered. The first image which represents the incoming wave perpendicular to view finder of the video image is shown in figures 10(a). The results are presented in figures 10(b), and 10(c). The images taken to demonstrate the oblique waves are shown in figure 11(a). The analyzed results are shown in figures 11(b) and 11(c). The ocean wave image is shown in figure 12(a) which is approaching perpendicular to the camera view finder. The analyzed results are presented in figure 12(b) and 12(c).

5. Conclusions

The traditional methods to measure the directionality of waves are very costly and needs a lot of efforts. However, the scheme presented in this study requires much less expanse and efforts. The only data to be needed is one frame of video images. Use was made of directional wavelets to do the job. It is shown that the Morlet and Cauchy wavelets show excellent directional selectivity when the rotation is introduced to them. Once all the related parameters of the wavelets and threshold level are selected, no other considerations are necessary at all. It was shown that the directions of simulated data and video images were nicely detected by using proposed scheme. The proposed scheme can be utilized as a very efficient tool in detecting the main direction of ocean wave propagation.

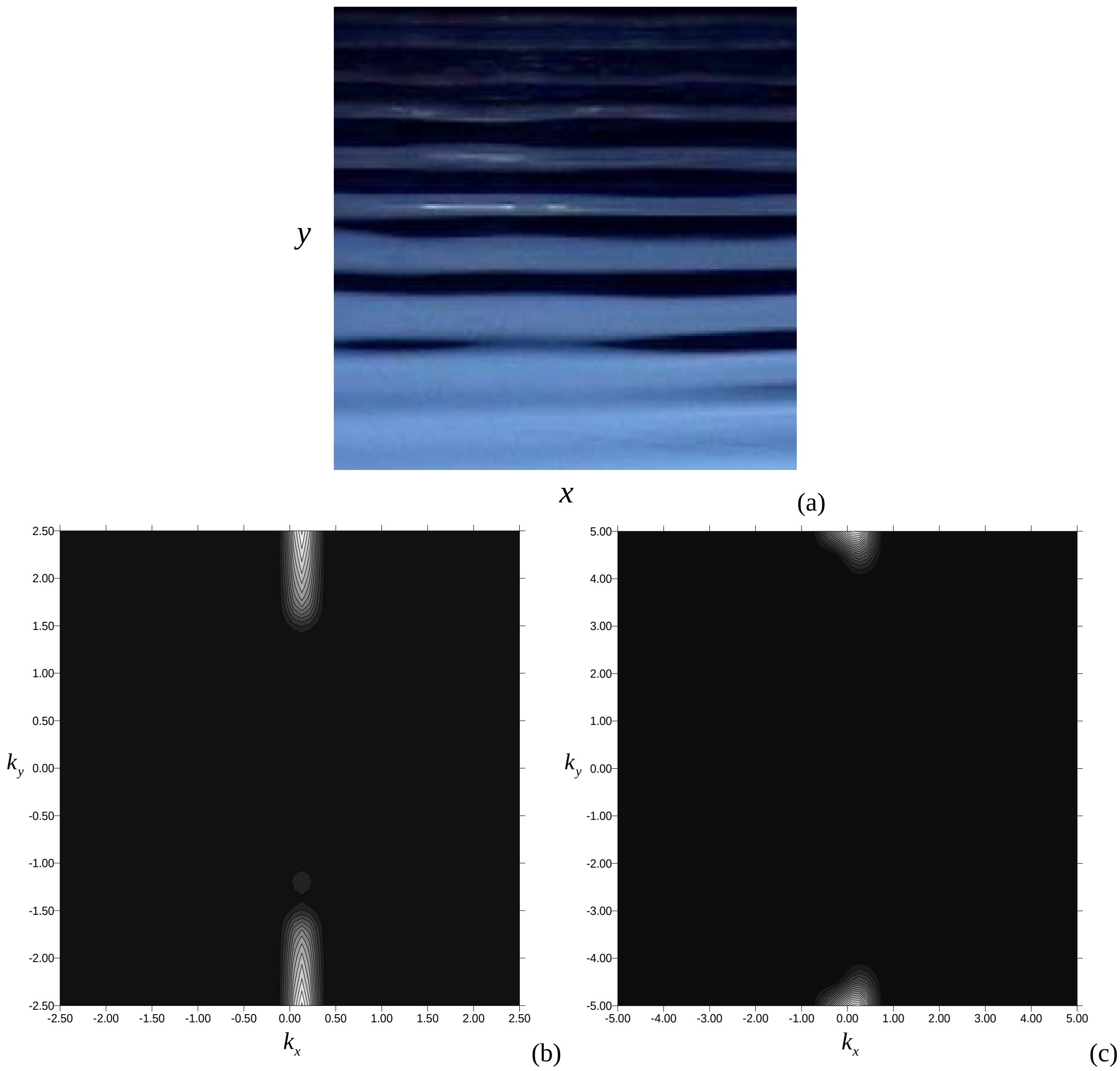


Fig. 8 (a) Small wave flume image 1, (b) Morlet wavelet transform, (c) Cauchy wavelet transform

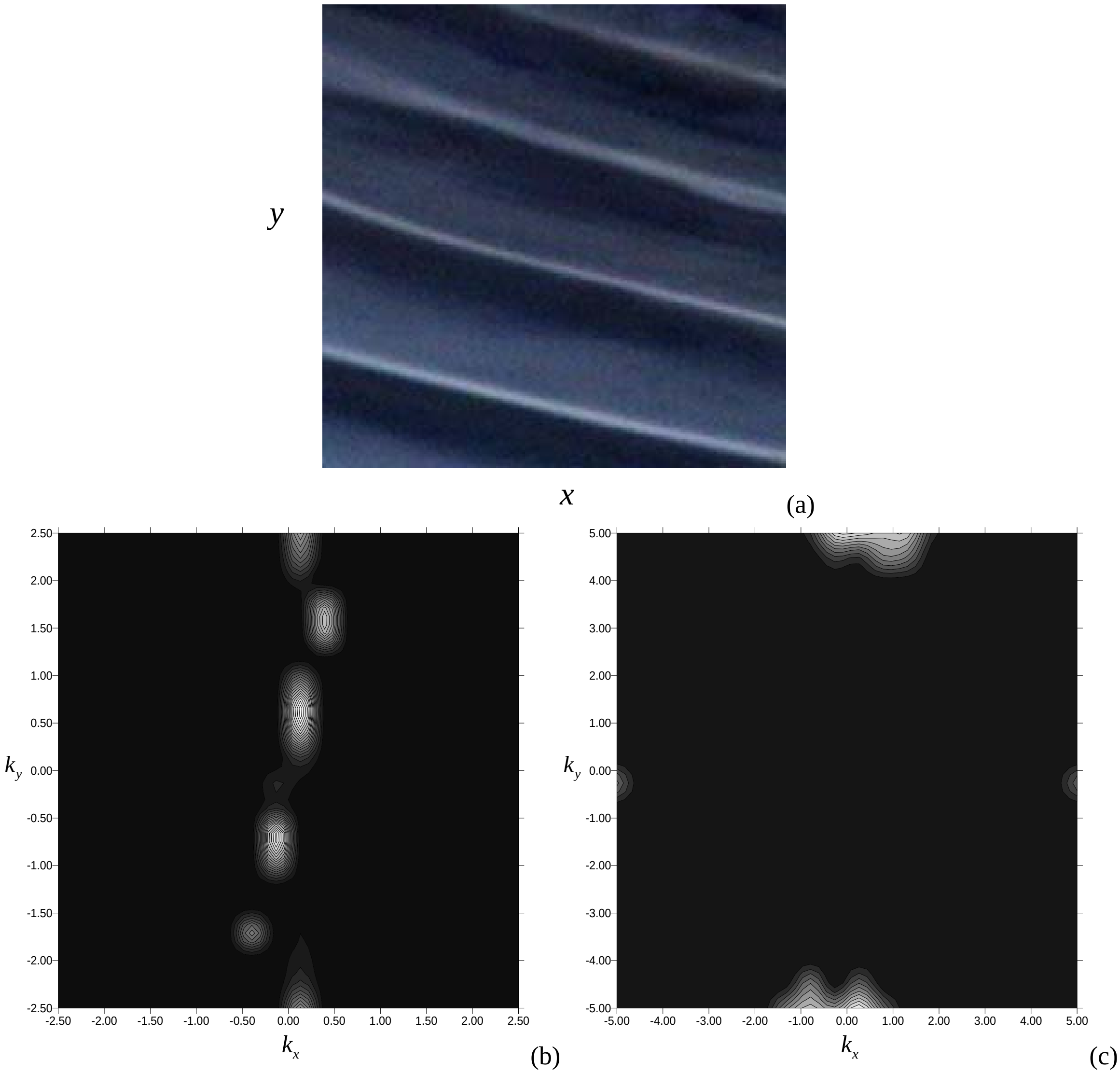
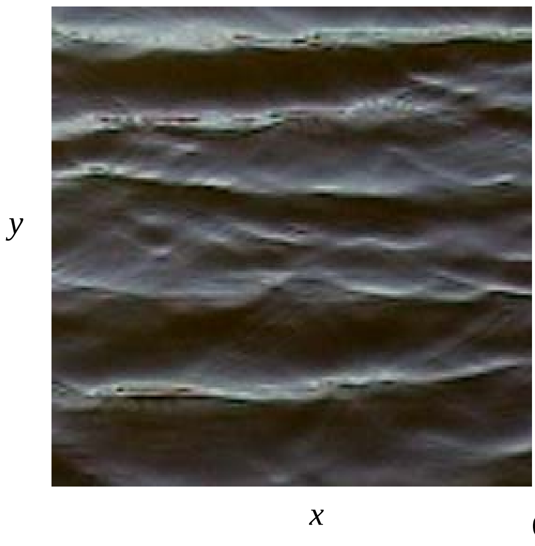


Fig. 9 (a) Small wave flume image 2, (b) Morlet wavelet transform, (c) Cauchy wavelet transform



(b)

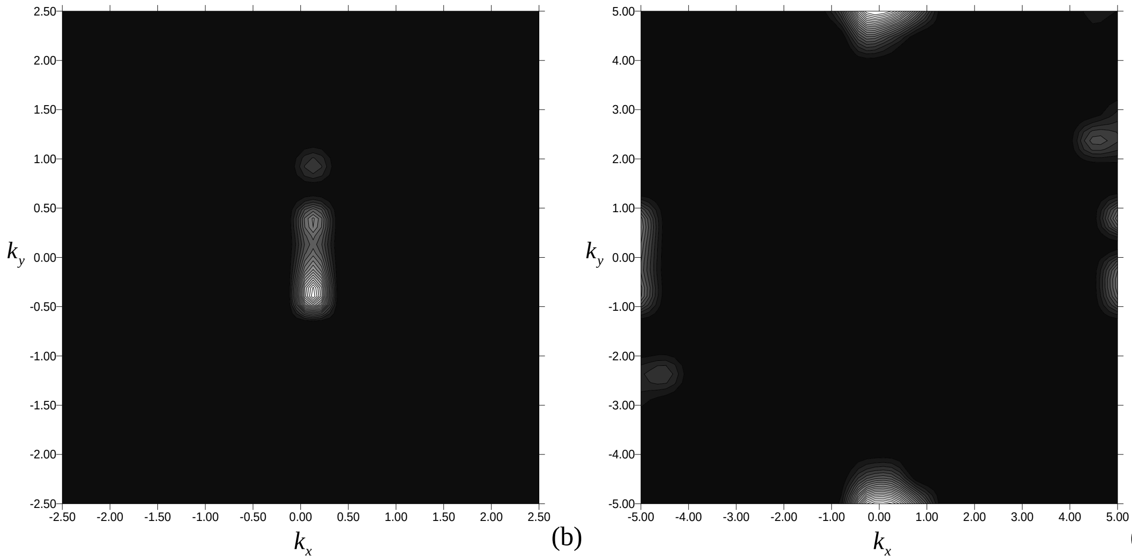


Fig. 10 (a) River image 1, (b) Morlet wavelet transform, (c) Cauchy wavelet transform

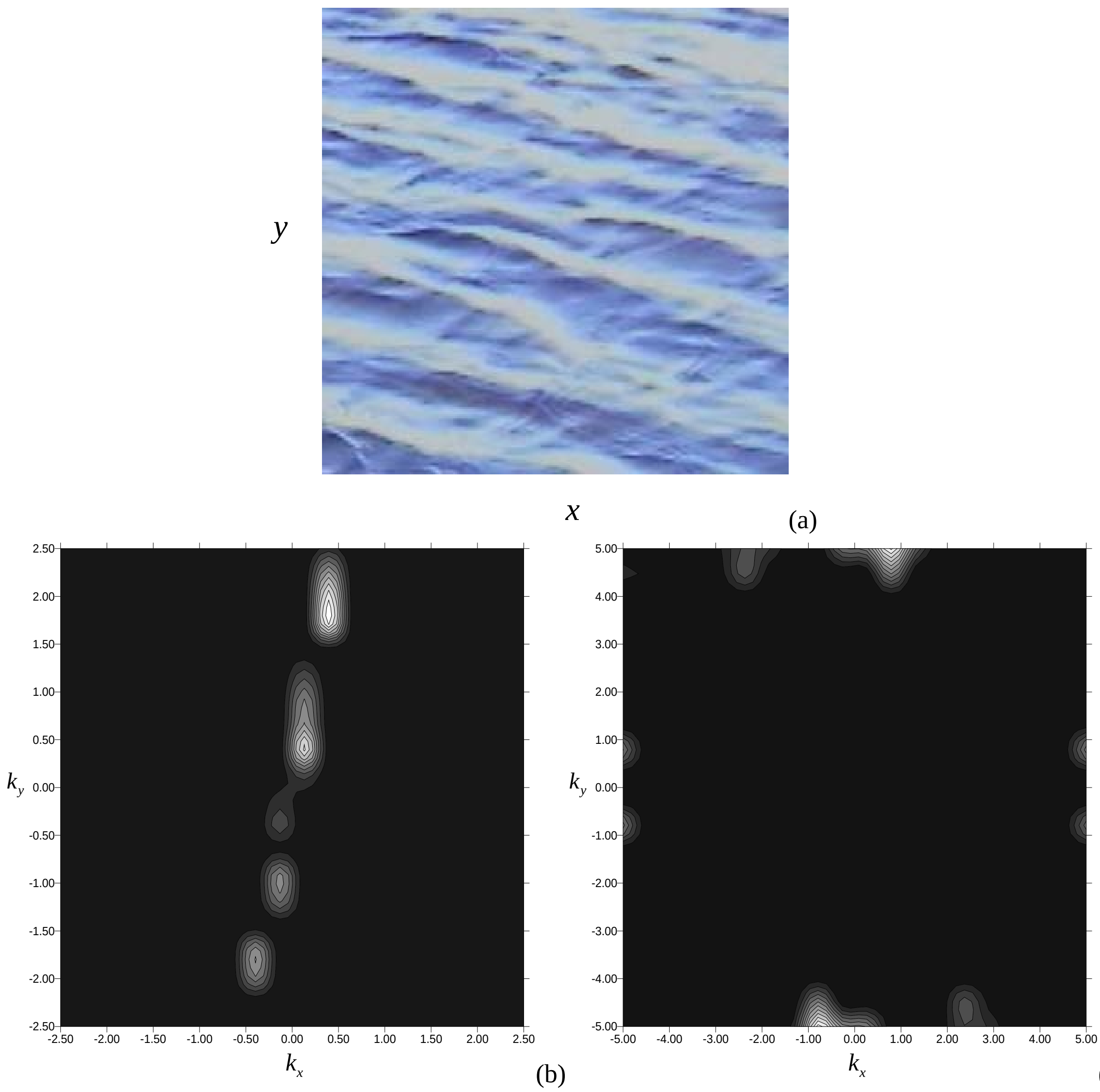


Fig. 11 (a) River image 2, (b) Morlet wavelet transform, (c) Cauchy wavelet transform

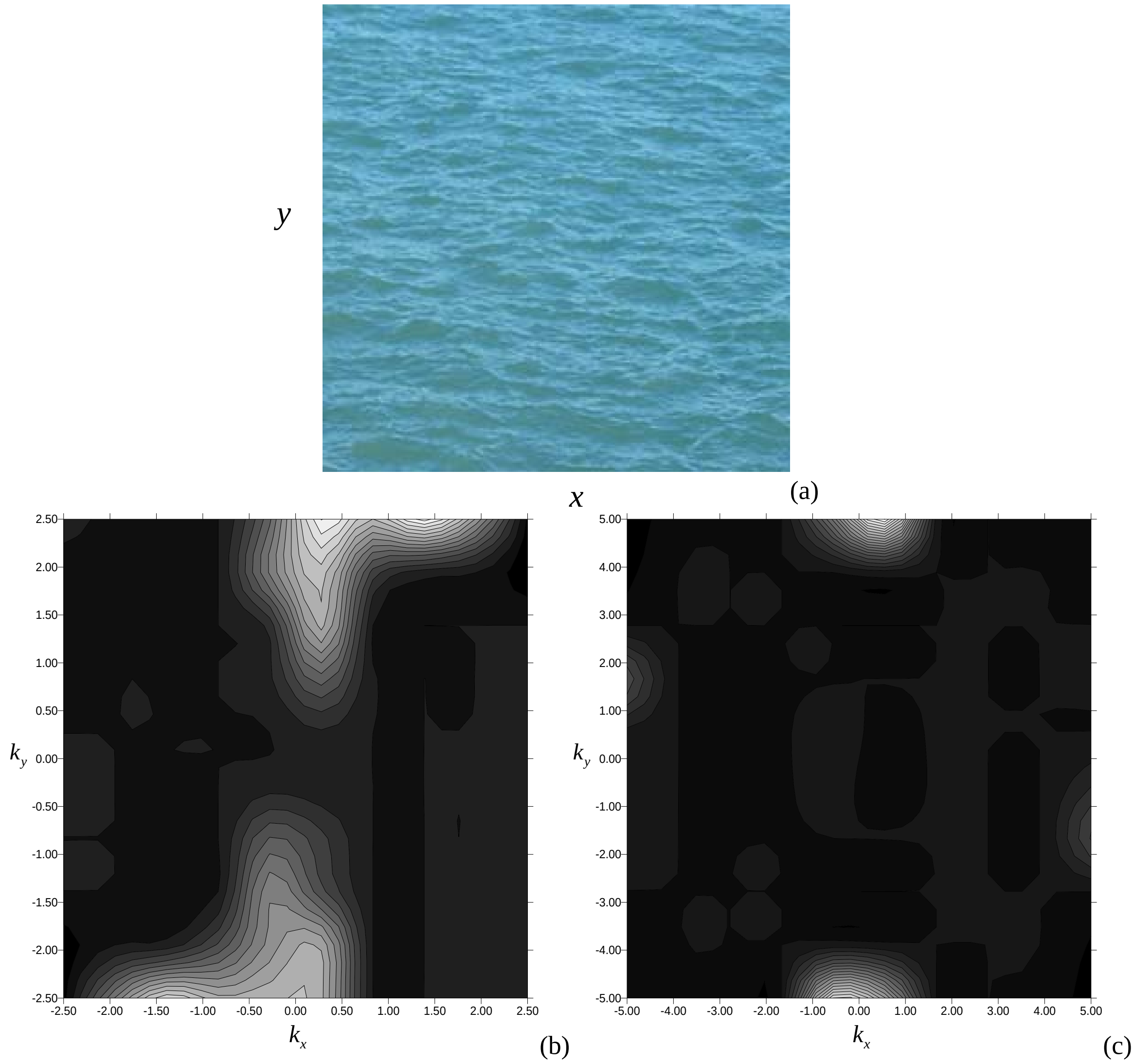


Figure 12. (a) Ocean image, (b) Morlet wavelet transform, (c) Cauchy wavelet transform

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