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Investigation of Infragravity Waves Dependency on Wind Waves for Breaking and Nonbreaking Conditions in the Sandy Beaches of Southern Caspian Sea (Nowshahr Port)

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ABSTRACT

In this study, the evolution and dependency of infragravity waves (IGWs) on wind waves for breaking and nonbreaking conditions is separately investigated. The efficiency of two constant cutoff frequencies (0.125 and 0.14 Hz) is compared for wave data measured in the sandy beaches of Nowshahr at the Southern Caspian Sea. It is found that the frequency of 0.125 Hz results higher correlation coefficients between IGWs energy content and two wind wave groups. Two pair different correlation patterns between IGWs in one side and wind waves higher and lower than 0.125 Hz in another side were recognized for breaking and nonbreaking conditions. It can be concluded that the IGWs excitation is controlled by the frequency distribution of wind wave energy.

According to 0.125 Hz as more successful option, the correlation of IGWs with swell waves is generally more significant than sea waves. In the nonbreaking wave condition, the IGWs are well correlated with sea waves, whereas no considerable correlation between IGWs and sea waves is found in the breaking condition. It is resulted that IGWs energy is approximately linearly proportional of both swell and sea waves in nonbreaking condition. In the high and moderate conditions of incident wave energy, the density of IGWs energy grows shoreward, while energy attenuation can be detected for IGWs in very low energy waves.

1. Introduction

Low frequency or infragravity waves (IGWs) are more significant in the coastal zones. Several studies focused on this type of long waves (1-3). The importance of IGW is well understood in the nearshore shallow waters. The sediment transport pattern and incident wave field can be influenced by IGW, strongly. Also, shoreline erosion, sand bar formation and specific morphology can be pointed out as the consequent phenomena of these long waves.

The correlation of low frequency wave energy to higher harmonics and generation of this type of waves by shorter waves (swell and/or sea waves) was demonstrated by several studies (4-6).

In this paper, the correlation of IGW energy content with wind wave groups is observationally investigated in the sandy beaches of Nowshahr port. The Field data were included water level fluctuations measured near the shore. In section 2, the previous studies due to low frequency waves dependency on wind waves are reviewed. In the next section the field data campaign and analytical specifications are presented. The results are discussed in section 4 and the study is finally summarized in the last section.

2. Background and Previous Studies

Infragravity waves are impressive on many shallow water processes. The various consequent effects of IGWs were investigated by means of field measurements, laboratory observations and numerical modelling (7-12).

This type of low frequency waves was firstly observed by Munk (13) and named surf beat. Tucker (14) as an example pointed out that the infragravity waves energy level was correlated with short wave energy content. Ruessink (15) concluded that IGWs are locally generated by incident short waves.

As waves propagate shoreward, two main processes arise. The first is shoaling occurred before wave breaking for low and moderate wave energy condition. The consequent nonlinearity enhancement during shoaling increases the bound IGWs energy as a result of difference nonlinear wave by wave interactions. The second process is wave breaking during high energy condition. In this process, the swell and sea waves energy dissipates dramatically and random group wave breaking releases the bound IGWs as free long waves (16-18). Therefore, it is expected that the dominance of bound IGWs during a moderate energy level, replaces to free one during energetic waves and sever breaking in the surf zone. Both of these two types of IGWs were recorded and reported by field measurements and experimental studies (3, 6, 15, 19, 20). The released IGWs harmonics are reflected by the shore line and propagate seaward direction. The leaky and edge waves are two types of subsequent phenomena of this process. Several studies were planned to illustrate the correlation of two IGW groups energy to higher frequency bands energy for different wave conditions (4-6, 15). Therefore, the separation and classification of waves seems important and impressive from this aspect.

Okihiro, Guza (21) recommended the 0.04 Hz frequency as the threshold between IGWs and swell to ensure that IGWs content were not contaminated by long-period swell. Elgar, Herbers (4) selected the 0.004-0.04 Hz frequency band for IGWs range, 0.14 Hz and 0.30 Hz as the constant swell-sea separation frequency and upper wind wave limit, respectively. Herbers, Elgar (5, 22) considered the range of 0.005-0.05 Hz as the IGWs frequency band. These criteria were sometimes similar or dissimilar in other studies. Brander, Kench (23) and Ogawa (24) supposed that IGWs frequency band ranges up to 0.05 Hz, as well as, swell energy distributes in band of 0.05-0.125 Hz and sea waves range is in the frequency band of 0.125-0.33 Hz.

The wave energy of each group is proportional to the integration of energy density variance spectrum on each frequency band $\left(E_{f_1-f_2} \propto \int_{f_1}^{f_2} S(f)df\right)$. Elgar, Herbers (4) found that the IGWs energy is more correlated with swell waves than sea waves. They reported the linear proportionality of total IGWs energy to swell waves. In that study, the wind waves were separated to swell and sea groups, but the wave condition (breaking or nonbreaking) was not emphasized. Ruessink (6) pointed out that the total IGWs energy is linearly correlated to wind waves (swell or sea 0.04 – 0.33 Hz), while this correlation for bound IGWs is quadratic. Ruessink (6) did not classify wind waves to swell and sea separately and the wave condition was not underscored in Ruessink (15), may be due to studied intermediate water depth stations. Herbers, Elgar (5) evaluated the dependency of IGWs on swell and abandoned sea waves. Based on previous studies, it seems that the dependency and correlation of IGWs with swell and sea waves for breaking and nonbreaking wave conditions can be separately studied in details.

3. Field Measurements and Data Analysis

Field data acquisition was including the water level fluctuations measurements on a shore perpendicular transect located on the western sandy beaches of Nowshahr Port in the southern Caspian Sea (Figure 1). In the studied area, tidal level variation is negligible and less than 10 cm.

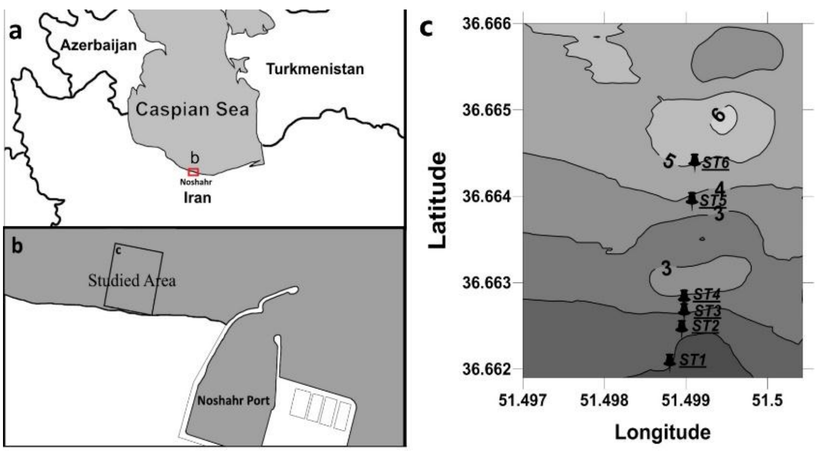

Figure 1. Location of Nowshahr in the Southern Caspian Sea, b) Nowshahr Port and the study area, c) Bathymetry of the studied area (31)

Wave data were recorded by using six synchronized pressure sensors deployed within the near shore zone as depicted in Figure 2. Bathymetry of the studied area was surveyed using a single beam echo-sounder in the beginning and end of the field campaign, which showed inconsiderable changes during the measurement period. The beach profile and the location of data gathering stations are depicted in Figure 2. Bottom profile exhibits a single bar system which has a seaward slope of ~0.025.

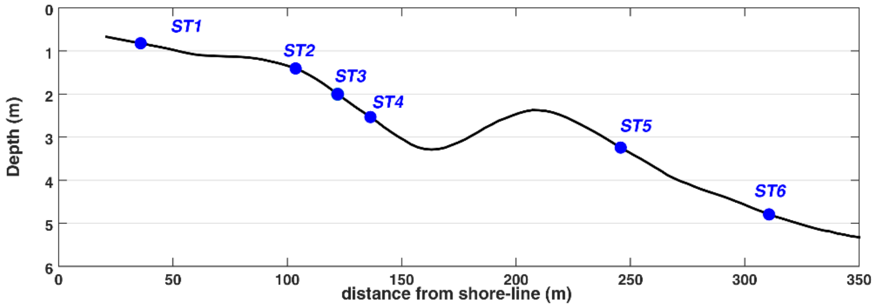

Fig. 2. Beach profile and the position of measurements in the transect

The instrumentation details are shown in Table 1. Wave data were continuously recorded in ST1, ST2, and ST6 while in ST3, ST4 and ST5 because of low data logger capacity, data retrieval was necessary after a period of two-day measurement. Therefore, the acquisition was interrupted and including of three couples of days at ST3, ST4 and a single couple of days at ST5. The sampling rate was set to 4Hz at ST1, ST2 and 2Hz at ST6, while this rate at other stations was 1Hz.

Table 1. Details of instrumentation including sampling rate, depth and distance from shore for each station

Stations	Instrument	Sampling rate	Depth (m)	Distance from shore (m)	Duration
ST1	RBRvirtuoso	4 Hz	0.8	35	3/4/2014– 3/16/2014 (continuously)
ST2	RBRvirtuoso	4 Hz	1.4	103	3/4/2014– 3/16/2014 (continuously)
ST3	DST-centi Star-Oddi	1 Hz	2.0	120	3/5/2014–3/7/2014, 3/9/2014–3/11/2014, 3/12/2014–3/14/2014
ST4	DST-centi Star-Oddi	1 Hz	2.5	135	3/5/2014–3/7/2014, 3/9/2014–3/11/2014, 3/12/2014–3/14/2014
ST5	DST-centi Star-Oddi	1 Hz	3.2	245	3/5/2014–3/7/2014
ST6	ADCP	2 Hz	4.8	310	3/3/2014– 3/16/2014(continuously)

Two non-locally generated storms (approximately 600 km far from the study area, according to MetOcean data, http://www.bocmetocean.com/forecast_maps.php) passed over the study area during the measurement period. It should be noted that no wave breaking was observed for offshore waves till ST6 in the total period of the measurements. More details of instrumentation, measurements, field specifications and observations can be found in Mahmoudof, Badiei (25).

The depth attenuation correction was applied for all pressure sensors. For two shallower stations (ST1 and ST2), 4096 data of water level corresponding to each 17.07-minute burst were detrended and divided into 512-point segments with 50% overlap to produce the wave spectrum with approximately 32 degrees of freedom (d.o.f.). Then, spectral analysis was performed for each 128 second duration segment data and spectra were averaged for all segments of each burst. The resulted spectrum frequency resolution was $\Delta f = 0.0078 Hz$. The similar process method was implemented for ST3, ST4, ST5 and ST6, except that each burst data was divided into 128-point segment for first three stations and 256-point for ST6 because of the slower sampling rate.

Based on resulted spectra, other spectral characteristics were achieved. For the present study objectives, it is supposed that IGWs range from 0.004 up to 0.05 Hz (similar to (5) and (22)) and upper limit of wind waves is 0.35 Hz. But the swell and sea separation threshold is investigated according to two constant frequencies of 0.125 and 0.14 Hz. The energy of each wave group is calculated as

$$E_{IGWs} \approx \int_{0.005Hz}^{0.05Hz} S(f)df \quad (1)$$

$$E_{swell} \approx \int_{0.05Hz}^{f_s} S(f)df \quad (2)$$

$$E_{sea} \approx \int_{f_s}^{0.35Hz} S(f)df \quad (3)$$

where f_s is the separation frequency of sea and swell waves.

4. Results and discussion

Time series of significant wave height at ST1, ST2 and ST6 are illustrated in Figure 3. It is clear that two storms with maximum significant wave heights of approximately 1.4m and duration of 16 and 29 hours were occurred in the study area. The peak periods of both were about 9.5s. It can be found that the dissipation and wave breaking were dominant shoreward direction from 03/08/2014 5:00 to 03/09/2014 12:00 and 03/13/2014 4:00 to 03/14/2014 12:00. In the following, the correlation between IGWs energy and wind waves was evaluated similar to earlier studies (4-6, 15). This evaluation is separately performed for swell and sea wave groups in the breaking and nonbreaking conditions.

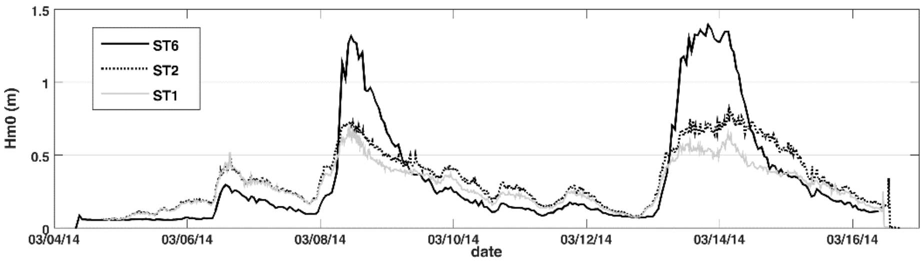

Figure 3. Time series of significant wave height at ST1 (solid-bright), ST2 (dotted) and ST6 (solid-dark)

In the present study, the fitted proportionality between IGWs and two wind wave groups energy are evaluated by means of relation $E_{IGWs} \propto E^{m}_{sea/swell}$, where $E_{sea/swell}$ is the energy density of sea or swell waves. The exponent *m* (slope) clarifies the dependency type (linear or quadratic) of IGWs energy on higher harmonics. Also, the correlation of IGWs energy with swell and sea is investigated by means of two aforementioned constant separation frequencies. For both of cutoffs, ~3200 bursts were analyzed and evaluated in the study area, totally. The resulted correlation coefficients and exponent *m* are presented in tables 2 and 3 for both cutoffs. It is obvious that the *m* value is vague and not meaningful for categories with low correlation coefficients. These exponent coefficients are shadowed in the resulted tables.

Table 2. The IGWs dependency on swell and sea separation based on constant frequency of 0.125 Hz

		Swell		Sea	
		Breaking	*Nonbreaking*	*Breaking*	*Nonbreaking*
Correlation Coefficients	ST6	-	0.94	-	0.84
	ST5	-	0.89	-	0.85
	ST4	0.79	0.88	0.58	0.83
	ST3	0.78	0.86	0.52	0.84
	ST2	0.80	0.93	0.30	0.94
	ST1	0.78	0.94	0.02	0.95
Slope (*m*)	ST6	-	0.69	-	0.92
	ST5	-	1.19	-	0.80
	ST4	0.62	1.26	1.57	0.90
	ST3	0.63	1.27	1.57	0.97
	ST2	0.88	1.13	2.33	1.64
	ST1	1.35	1.17	0.70	1.70

Table 3. The IGWs dependency on swell and sea separation based on constant frequency of 0.14 Hz

		Swell		Sea	
		Breaking	*Nonbreaking*	*Breaking*	*Nonbreaking*
Correlation Coefficients	ST6	-	0.92	-	0.79
	ST5	-	0.89	-	0.85
	ST4	0.78	0.85	0.51	0.83
	ST3	0.77	0.82	0.44	0.84
	ST2	0.78	0.91	0.17	0.93
	ST1	0.88	0.94	0.39	0.89
Slope (*m*)	ST6	-	0.64	-	0.96
	ST5	-	1.10	-	0.80
	ST4	0.64	1.02	1.57	0.90
	ST3	0.64	1.05	1.55	0.97
	ST2	1.12	1.18	1.69	1.65
	ST1	1.10	1.20	3.07	2.07

Both separation frequencies exhibit two different types of correlation and dependency trends of IGWs energy on the swell and sea waves, especially for breaking waves. It means that including swell and sea waves energy into a single group of wind wave (such as Ruessink (6)) is not well-advised. Some of the results can be ambiguous as a result of neglecting this hint. Therefore, it is necessary to evaluate the correlation and dependency of IGWs formation on the sea and swell waves, separately.

Based on the correlation coefficients resulted by constant frequency of 0.125 and 0.14 Hz (Tables 2 and 3, respectively), it can be derived that the correlation of IGWs energy with both of swell and sea groups is more significant in the nonbreaking than breaking condition. Normally, it is expected that free IGWs are more dominant in the breaking condition. Therefore, it can be concluded that the dependency of bound IGWs on wind waves is more significant than free ones'. This outcome is consistent with the results presented in Table 1 in Ruessink (6). Also, it is perceptible that the IGWs are slightly more correlated with swell than sea in nonbreaking condition. It is consistent with lower correlation coefficients for sea waves in Elgar, Herbers (4) and Ruessink (15).

In Tables 2 and 3, it is demonstrated that the IGWs energy is well correlated with sea wave energy for nonbreaking waves. Unlikely, no remarkable correlation can be reported between IGWs and sea waves for breaking condition. This result was indirectly reported by Ruessink (6).No line was fitted for IGWs energy versus Ess (the total energy of swell and sea waves) in that paper for breaking waves.

Considering two constant method results for exponent *m*, it can be resulted that the IGWs energy is approximately linearly proportional of swell energy for nonbreaking condition. In this condition, the exponent values varied 1.02~1.27, except ST6. This finding is reliable for sea waves in nonbreaking condition for ST3 to ST6, too (the m varies between 0.80 and 0.97). The increment of exponent *m* at very shallow water (ST1 and ST2) for nonbreaking wave condition can be interpreted as the nonlinearity enhancement and bound IGWs growth as a result of depth reduction and wave shoaling. This finding is consistent with the bound wave theory (16). As well as, the increment of exponent of *m* for swell waves is clear in the breaking condition. But this finding can be explained as a result of released IGWs growth due to random wave breaking. The best method to clarify the proportional bound and free IGWs is Bispectral analysis (16, 17), which is not in the present study scope.

However, the constant frequency 0.125 Hz is slightly more accurate than 0.140 for the studied area. The dependency of IGWs energy on swell and sea waves at all stations for breaking and nonbreaking conditions is depicted in Figures 4 to 7, resulted from 0.125 Hz cut-off. Taking account into the 0.125 Hz as the more appropriate separation frequency, the evolution of IGWs is studied across the shore. The percentage of each wave group (IGW, swell and sea) was estimated for three stations (ST1, ST2 and ST6) where the data acquisition was continuous. It is depicted in Figure 8 that the percentage of IGWs energy is negligible during all of the field measurements period at ST6. Coincident with the storm peaks the contribution of swell and sea energy was approximately 50% at this station. From ST6 to shoreline the relative dissipation of swell waves was more serious than sea waves during storms, then the swell percentage energy was diminished at ST2.

In Figures 8 and 9, it can be observed that the IGWs energy grew across the shore as the high and moderate energetic waves passed through the surf-zone. The relative IGWs energy amplification is concurrent with relative sea descent in ST1 during the storms. However, both of swell and sea wave groups were absolutely dissipated across the shore for breaking wave condition (Figure 9b and 9c).

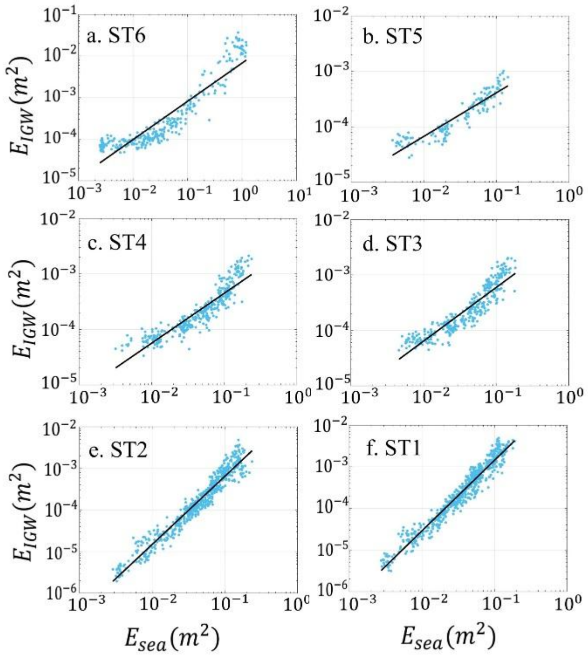

Figure 4. Correlation of IGWs with sea waves for nonbreaking condition

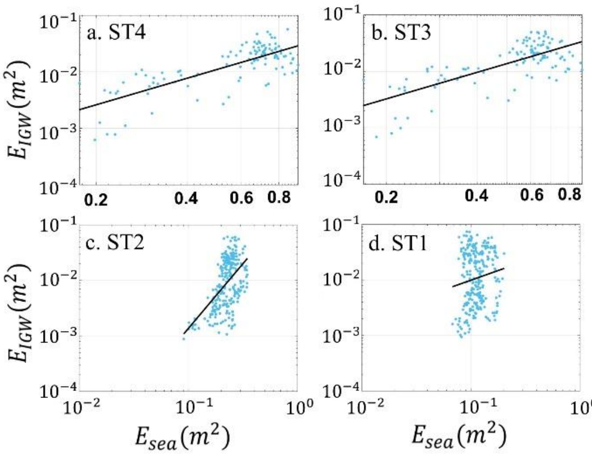

Figure 5. Correlation of IGWs with sea waves for breaking condition

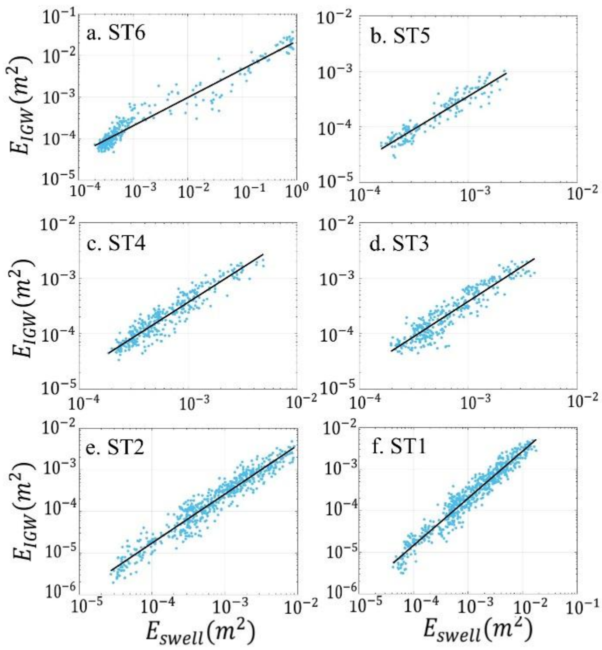

Figure 6. Correlation of IGWs with swell waves for nonbreaking condition

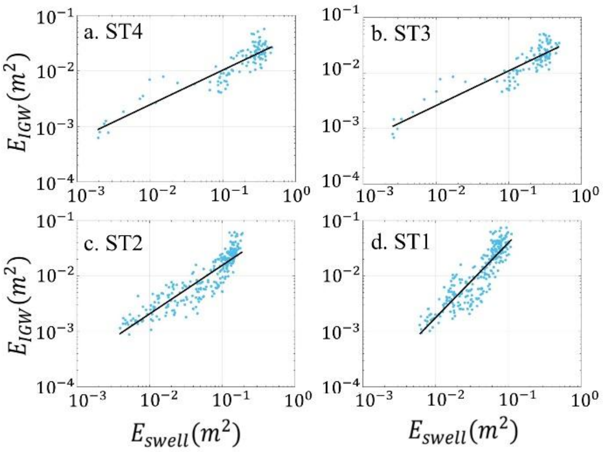

Figure 7. Correlation of IGWs with swell waves for breaking condition

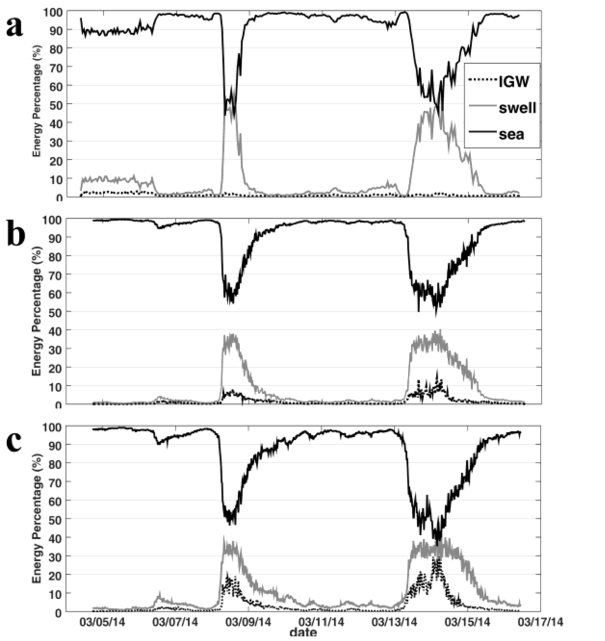

Figure 8. The percentage of each waves group energy at: a) ST6; b) ST2 and c) ST1.

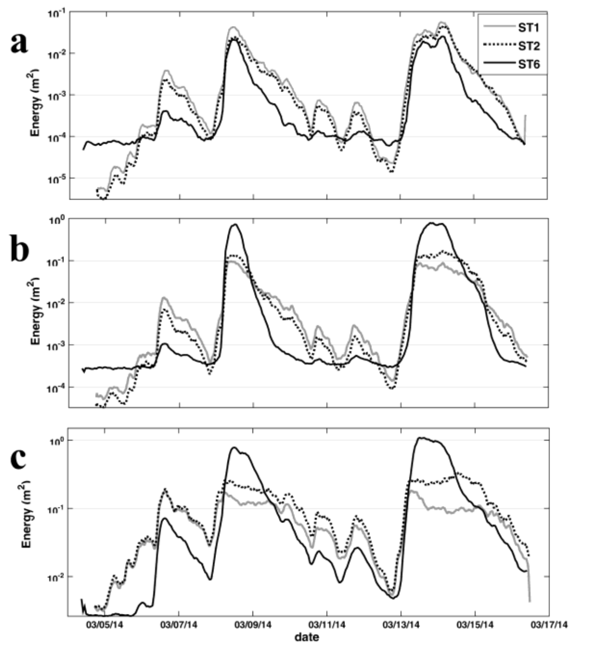

Figure 9. The evolution of each wave group from ST6 till ST1: a) IGWs; b) swell waves; c) sea waves.

In Figure 9a the IGWs attenuation can be observed for very low energy condition of incident waves. Several possible mechanisms have been reported for IGWs decay near the shore. The first guilty phenomena for this event is bottom friction, especially on rough gravel or coral reef bottoms (26). But on the fine sandy beaches, it seems that the bottom friction is the secondary responsible mechanism (27, 28). Several studies reported that nonlinear energy transfer back to the primary wind waves energy can be regarded as the key factor for IGWs attenuation on steep beaches (29, 30). On the gently sloping beaches with IGWs dominancy climate, the nonlinear triad interactions between very long IGWs can result in steepening shorter IGWs and thus the breaking of these type of IGWs losses considerable energy content (27, 29, 30). However, considering the above explanations and in-situ observational evidences, it seems that the IGWs decay for very low wave energy content illustrated in Figure 9a is a result of bottom friction.

5. Conclusion

In this study, the evolution and dependency of Infragravity waves (IGWs) on swell and sea waves on a sandy beach at the west of Nowshahr Port in the southern coasts of Caspian Sea was separately investigated. The wave gauges were deployed at 6 stations on a shore perpendicular transect. The recorded storms were originally generated more than 600 km far away from the studied area in the central part of Caspian Sea. The significant wave height of observed storms was more than 1.3m and peak periods were approximately 9.5s.

The swell and sea wave groups were separated according to two constant cutoff frequencies of 0.125 and 0.14 Hz.

The spectral analysis was accomplished for about 3200 bursts with 17.07-minute duration. The energy of each wave group was evaluated by integrating the energy variance density ranged between 0.004-0.05 Hz as IGWs, 0.05-fs and fs-0.35 as swell and sea waves, respectively. The correlations and dependencies of IGWs energy on swell and sea energy resulted from each cutoff frequencies were separately evaluated in the breaking and nonbreaking conditions. Both of cutoffs present high correlation coefficients. This outcome implies that the IGWs energy excitation is controlled by frequency distribution of wind wave energy. By means of both separation cutoffs, different correlation patterns between IGWs and two wind wave groups has been resulted. It can be concluded that the including swell and sea waves in one wind wave group to predict the dependent IGWs energy is not advised and two wind wave groups must be separated.

The frequency of 0.125 Hz resulted slightly higher correlation coefficients and showed more reliable predictability of IGWs based on swell and sea energy distribution in the studied area. For nonbreaking waves, the correlation of IGWs with swell and sea is very robust. In the breaking condition, the dependency of IGWs on sea waves is negligible while the IGWs are considerably dependent on swell waves. However, the dependency of IGWs on swell waves is generally more significant than sea waves. The IGWs energy showed a linear proportionality with both swell and sea waves for nonbreaking waves.

The general investigations revealed that the IGWs energy density increased in the shoreward direction in the moderate and high energy wave condition due to nonlinearity enhancement (result of shoaling) and wave breaking, respectively. In during of very low energy level, the IGWs dissipation was observed as a possible bottom friction consequence.

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