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Studying the change of average waves of the Caspian Sea using the altimetry data

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For the coastal countries, the Caspian Sea is an essential economic object, including the implementation of transport routes, fishing, the availability of potential mineral resources of the seabed and deeper layers. Also, the ecological state of this region is of great importance. Therefore, the study of the wave climate of the sea is vital for all riparian countries. Satellite altimetry has become an increasingly important technology for monitoring of continental surface waters. In this article, we explore a possibility to obtain reliable information on the wave climate in the Caspian Sea using satellite altimetry. We used measurements of significant wave heights from a Jason-1 mission over ten-year period. The data were cleaned and checked for the possible errors. The analysis of average significant wave heights in the Caspian Sea showed overall a consistent picture. The highest wave heights are observed in the Middle part of the basin. The waves have lesser intensity in the Southern basin and the Northern part. The analysis of seasonal variability showed that the most energetic waves appear in the winter season.
Key words: satellite altimetry, the Caspian Sea, the inland reservoir, wave climate.

Каспий теңізінің орташа толқындарын альтиметриялық мәліметтер бойынша зерттеу

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Каспий теңізі жағалауындағы мемлекеттер үшін көліктік бағыттарды, балық аулау, теңіз түбіндегі және одан да тереңірек қабаттардағы маңызды минералды ресурстарды қоса алғандағы, маңызды экономикалық объект болып табылады. Сонымен қоса, аталған аумақтың экологиялық жағдайы да өте маңызды. Сондықтан теңіздің толқын климатын зерттеу барлық жағалаудағы елдер үшін өте маңызды. Серіктік альтиметрия континенттік су бетін бақылау үшін қолданылатын маңызды технологиялардың біріне айналуда. Бұл

мақалада серіктік альтиметрия көмегімен Каспий теңізіндегі толқын климаты туралы сенімді ақпарат алу мүмкіндіктері қарастырылады. Jason-1 серігінің он жыл көлеміндегі маңызды толқын биіктігінің өлшемдері пайдаланылды. Мәліметтер мүмкін болатын қателіктерден тазартылды. Жалпы алғанда Каспий теңізінің орташа маңызды толқын биіктіктері жүйелі мәліметтер көрсетті. Жоғарғы ретті толқындар бассейннің орталық бөлігінде байқалды. Салыстырмалы түрде төменгі ретті толқындар оңтүстік және солтүстік бөліктерде байқалды. Маусымдық өзгерулерді талдау арқылы, қарқындылығы бойынша ең қуатты толқындар қыс мезгілінде болатынын байқаймыз.
Түйін сөздер: серіктік альтиметрия, Каспий теңізі, ішкі суқоймасы, толқын климаты.

Изучение изменения средних волн в Каспийском море по альтиметрическим данным

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Для прибрежных стран Каспийское море является важным экономическим объектом, включая реализацию транспортных маршрутов, рыболовство, наличие потенциальных минеральных ресурсов морского дна и более глубоких слоев. Кроме того, большое значение имеет экологическое состояние этого региона. Поэтому изучение волнового климата моря жизненно важно для всех прибрежных стран. Спутниковая альтиметрия становится все более важной технологией для мониторинга континентальных поверхностных вод. В этой статье рассматривается возможность получения достоверной информации о волновом климате в Каспийском море с помощью спутниковой альтиметрии. Были использованы измерения значительных высот волн со спутника Jason-1 за десятилетний период. Данные были очищены и проверены на возможные ошибки. Анализ средних значительных высот волн в Каспийском море показал в целом непротиворечивую картину. Наибольшие высоты волн наблюдаются в средней части бассейна. Меньшую интенсивность волны имеют в южном бассейне и северной части. Анализ сезонной изменчивости показал, что наибольшие по мощности волны наблюдаются в зимний сезон.
Ключевые слова: спутниковая альтиметрия, Каспийское море, внутренний водоем, волновой климат.

1 Introduction

The Caspian Sea has a surface area of 371,000 km^2 and is the largest lake in the world, located in the middle latitudes (from 37° N to 47° N). It has a shared border in the west – with Azerbaijan, in the northwest with Russia, in the southeast – with Turkmenistan, in the south – with Iran, and in the north-east – with Kazakhstan. The length of the sea is approximately 600 km along the West-East line and up to 1000 km along the North-South line [1]. The Caspian Sea has a complex bathymetry. The depths reach approximately 800 m in the central part, and $\sim$ 1000 m in the southern basin, whereas the northern part of the basin, is very shallow (depth $<$ 25 m) [2].

The Caspian Sea experienced substantial changes in the water level over the past 50 years which resulted in a variable with time bathymetry. Taking into account the influence of the bottom topography on the wave climate, one can expect that the change in the water level will to some extent affect the wave climate of the Caspian Sea. [1].

Wind waves are the primary factor that forms the shores of inland seas. This is typical of coastal areas where fluctuations in the water level caused by tides are insignificant or absent.

The properties of waves in such water bodies usually have extensive spatio-temporal variability, and the wave climate can vary significantly in different areas of the sea [3]. Although wave properties usually reflect the main wind characteristics, the absence of proper quality wind and wave measurements for the Caspian Sea makes it very difficult to understand and predict the wave action on the coast or to determine wave conditions along the main navigation lines [4].

Figure 1: Caspian Sea, located in the middle latitudes from 37° N to 47° N

2 Literature review

Due to the insufficient number of wave observations around the world, various methods for estimating wave characteristics have been developed. Currently, three sources of wave data are available for the research purposes: direct in-situ measurements, numerical modeling, and satellite altimetry [5]. Direct measurements of waves in the Caspian Sea are performed since the mid-1970s [4], [6], [7], [8]. However, they are not publicly available and provide only qualitative variability of main characteristics of wave fields. Moreover, direct measurements are performed only in a few locations, and it is not possible to investigate spatial characteristics of the wave fields over the entire area of interest. The in-situ datasets in the Caspian Sea have long gaps, and, some frequently used characteristics (e.g., annual mean wave height or average period) can become meaningless for the data with gaps [7], [9]. All these factors lead to insufficient knowledge when only direct in-situ measurements used for the analysis of wave climate in the Caspian Sea.

In recent decades, due to the development of high-speed computers, numerical modeling methods for predicting wave dynamics and their characteristics have been developed. Wellknown models for wave modeling, such as WAM (WAve Model) was applied to deep water conditions [10], [11], and the SWAN spectral wave model (Simulating WAves Nearshore) was used for shallow regions [12], [13], [14]. Simulation of climatic thermohaline circulation in the Caspian Sea was carried out using the method of hydrodynamic diagnosis and adaptation [15]. Numerical methods of mathematical modeling make it possible to show with sufficient accuracy multistep (large, meso- and shallow) water circulation in the Caspian Sea [16]. The numerical models showed higher accuracy in reconstructing the wave fields than the average characteristics available from the direct measurements.

In addition, there are studies on wave properties in the Caspian Sea using artificial neural network (ANN) methods [17], [18], [19] statistical analysis and chaos theory for recruitment wave sensors [20], [21], [22] genetic programming [23]. Fuzzy inference systems (FIS) were also used to predict waves [24].

Despite the fact that wave dynamics of the Caspian Sea has been studied in some works, nevertheless, detailed reconstruction of the wave climate is still a severe problem for this basin. The limitation of numerical simulation methods is that the results strongly depend on the quality of the data entered into the model.

Satellite altimetry provides a good solution to the problem of reconstructing the wave climate on large spatial scales [8]. Satellite remote sensing measurements cover large areas of Earth and provide fairly homogeneous and continuous (along with a certain line) data on the state of the sea with good spatial coverage. Multiple previous studies discussed cross-checking satellite altimetry data with in-situ buoy data. The high quality of the altimetry data has been demonstrated both globally [25], [26], [27] and for small basins [28], [29], [30], [31], [32], [33].

A group of scientists from Estonia developed a technology for analyzing the wave climate for closed water bodies based on satellite altimetry data. The use of this technology has yielded interesting results for the Baltic Sea basin. The altimetry data were carefully validated and showed a good match with the results of in-situ observations. Long-term variations in the properties of waves in a given sea and probable relation to geostrophic airflow over this water body were studied [5], [8].

The use of altimetry data made it possible to reconstruct the extremely interesting spatial patterns of the wave climate and to reveal the unexpected features of climate change [34]. The results obtained are directly applicable for the safety of navigation, the design of offshore and coastal engineering structures, the understanding and prevention of coastal erosion, and for coastal zone management.

The Caspian Sea, similarly to the Baltic Sea, is an inland sea, relatively small, and seasonally covered with ice. Therefore, the same technology can be applied to study the Caspian Sea wave climate. Satellite altimetry data cover approximately 25 years, with a gradual increase over the last years in accuracy and resolution. Based on these data, the wave climate of the Caspian Sea can be reconstructed. The primary goal of the paper is to analyze the changes in the wave climate of the Caspian Sea, applying the technology developed for the Baltic Sea, which is essential for understanding the impact of the climate change on the wave climate and changes in the environmental conditions in the Caspian Sea region.

3 Data and Methods

The satellite altimetry data used in this article are derived from the RADS database (Radar Altimeter Database System, http://rads.tudelft.nl/rads/rads.shtml) [35], [36]. This database provides altimeter data reduced in the same manner for multiple missions. It contains different characteristics of the sea which makes it possible to analyze changes in the wave climate [5], [8]. The RADS database system contains the altimetry data from eleven satellites (Cryosat-2, Envisat, Ers-1, Ers-2, Geosat, GFO-1, Jason-1, Jason-2, Poseidon, Saral, Topex) since 1985 to 2016. The data in the RADS database has worldwide coverage and it is necessary to choose an appropriate subset for the assessment and analysis of the wave climate of the Caspian Sea. Therefore, we specify the Caspian Sea region using shapefiles following the coastline of the sea (obtained from the National Center for Environmental Information, National Oceanic and Administration, https://ngdc.noaa.gov/mgg/shorelines/gshhs.html). The data were selected in the latitude range from 46 to 55 degrees and longitudes from 36 to 48 degrees above the Caspian Sea. Different satellites have different density of observations. For example, the altimeters Cryosat-2, Jason-1, Saral, and Geosat cover the entire surface of the Caspian Sea quite densely during each month. On the contrary, the altimetry data of Jason-2, Poseidon, and Topex have an extent with large gaps (Fig. 2).

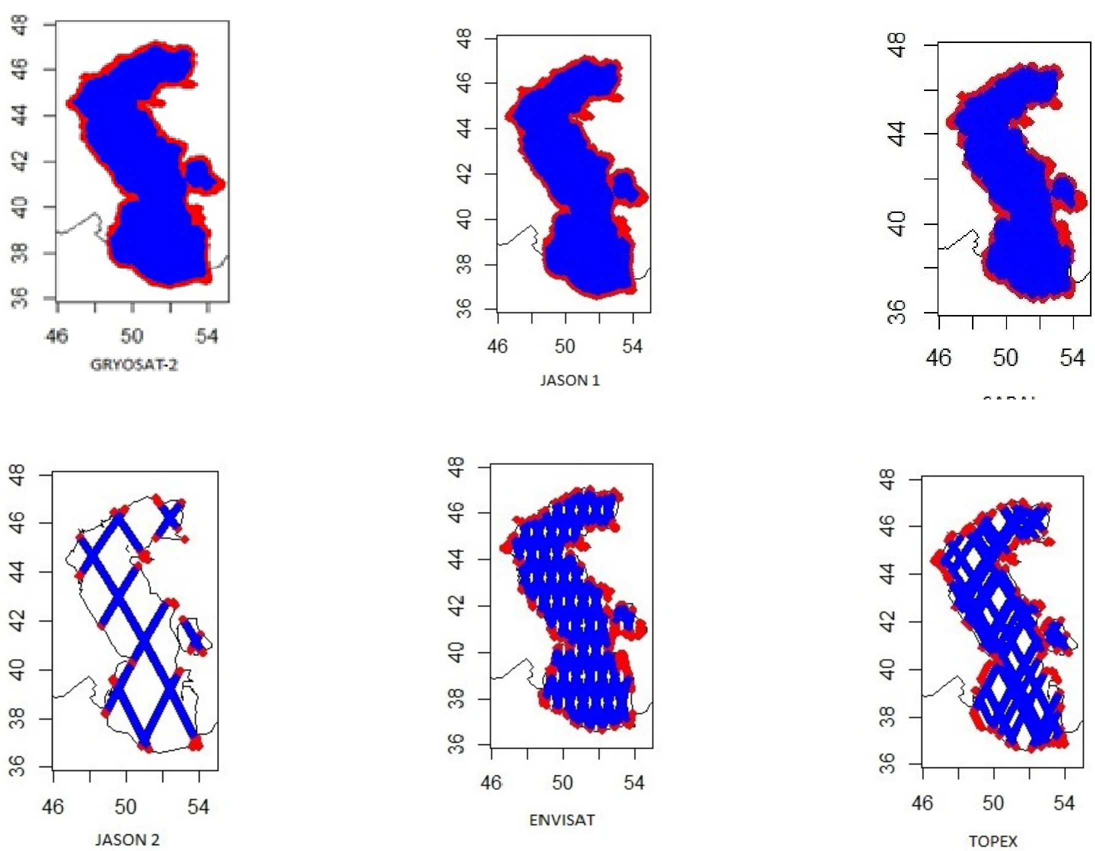


Figure 2: Average significant wave height (m) in the Caspian Sea in 2002-2012 derived from satellite altimetry for each season separately

For the purposes of this paper, the data from the Jason-1 mission were selected. The data have a time extend from 2002 till 2012 and were measured at Ku and C frequency bands. There is a five-month gap between 2012-03-03 and 2012-05-08. The Jason-1 altimeter has very dense coverage over the Caspian Sea. Also, the accuracy of measuring the satellite altitude above the sea surface is 1.7 cm, very high in comparison with other altimetry measurement programs [37], [38].

Since complex coastline, ice coverage, and other phenomena can significantly affect the quality of satellite altimetry; it is necessary to check the data carefully. As mentioned above, the Caspian Sea, like the Baltic Sea, is a closed sea, and the method of satellite altimetry used for the Baltic Sea can be applied to the Caspian Sea. The erroneous measurements were removed following the method developed in [8] for the Baltic Sea. Using the coastline shapefiles of the Caspian Sea, we considered the measurements closer than 0.2 degrees to the coast as unreliable. Also, the data with the backscatter coefficient > 13.5 cdb and errors in the significant wave height normalized standard deviation > 0.5 m were removed. The cutoff level of the backscatter coefficient corresponds to low wind speeds, less than 2.5 m/s. Zero SWH values were deleted as probable erroneous data.

We have also examined a dependence of range difference at two Ku and C frequencies as a possible diagnostics of erroneous data and confirmed that it showed large discrepancy for the data closer than 0.2 degrees from the shore and backscatter coefficients > 13.5. The resulted dataset was additionally checked for possible errors and other shortcomings. The data obtained after processing is assumed to be sufficiently reliable for subsequent analysis.

4 Results

Taking into account the features of the underwater bathymetry, the Caspian Sea is divided into three regions according to physical and geographical characteristics: Northern, Middle and Southern. The Northern part of the sea is shallow, the average depth is 5-6 m (maximum 25 m), in the Middle part of the sea the average depth is 180 m reaching the maximum depth of 790 m in the Derbent Basin area and the Lenkoran Depression area. The South part of the sea has the largest depth of 1025 m.

To study the spatial variability of wave heights from satellite altimetry, a map of mean wave heights throughout the sea was constructed for the period 2002-2012 (Fig. 3). The average SWH of the Caspian Sea in 2002-2012 is in the range of 0.38-1.4 m. We examined the average wave heights in the Caspian Sea from the Jason-1 satellite for the whole period and all seasons separately. Analyzing the results obtained for the entire period, we can say that the most intense waves (1.2-1.3 m) are located in the Derbent basin (Middle part). The waves have lesser intensity in the Southern (deep) basin (0.9-1.1 m). Moreover, the average wave height in the Northern part is low ~ 0.6 m, possibly because of shallow water effects (Fig. 3). Similarly to the wave climate of the Baltic Sea, the Caspian Sea is showing quite high waves, especially in its Middle and Southern parts. In the Northern part of the sea, the wave development is limited by the shallow water. The average wave heights here, as a rule, do not exceed 0.4-0.7 m, only in a few locations in the south-western region of the Northern part of the sea the average SWH reach 1 m. In addition, it was found that the highest energy waves occur in winter, followed by spring and summer. The winter months are identified as the most energetic months in the study area (Fig. 3). The average wave intensity of the

Caspian Sea is low compared to the intensity of open oceanic areas. This is mainly due to the fact that the Caspian Sea is a closed water basin.

Fig. 4 and Fig. 6 show time variability of the annual mean, 75^{th}, 90^{th}, 99^{th} percentiles of significant wave heights with overplotted linear regression, and data quantity for each year. Overall, the wave climate in 2002-2012 can be described as stable in the Caspian Sea region.

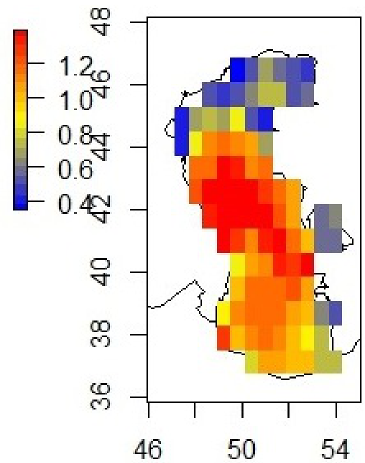
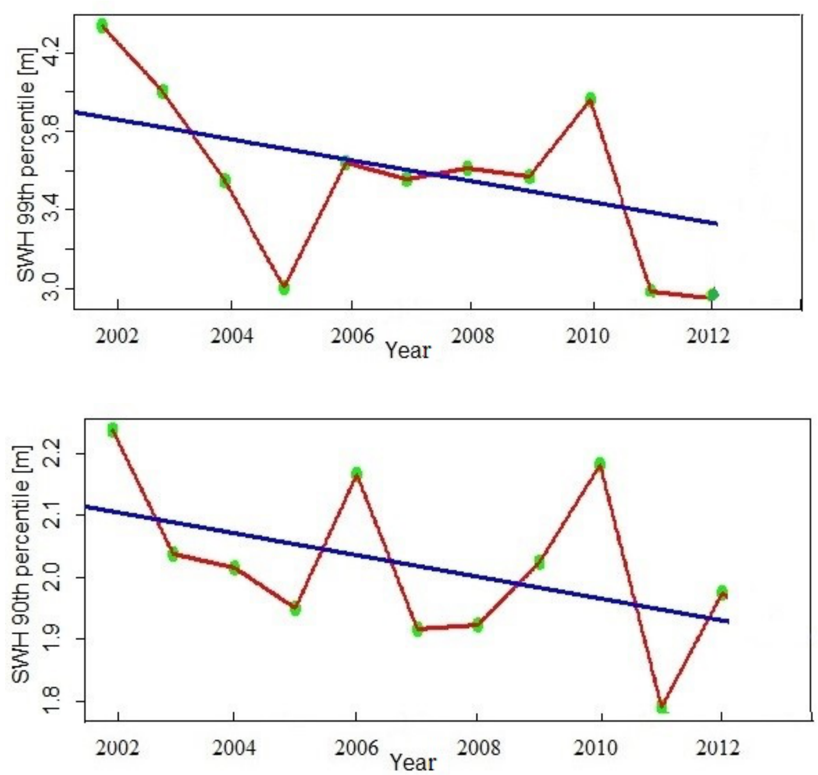


Figure 3: Average significant wave height (m) in the Caspian Sea in 2002-2012 derived from satellite altimetry



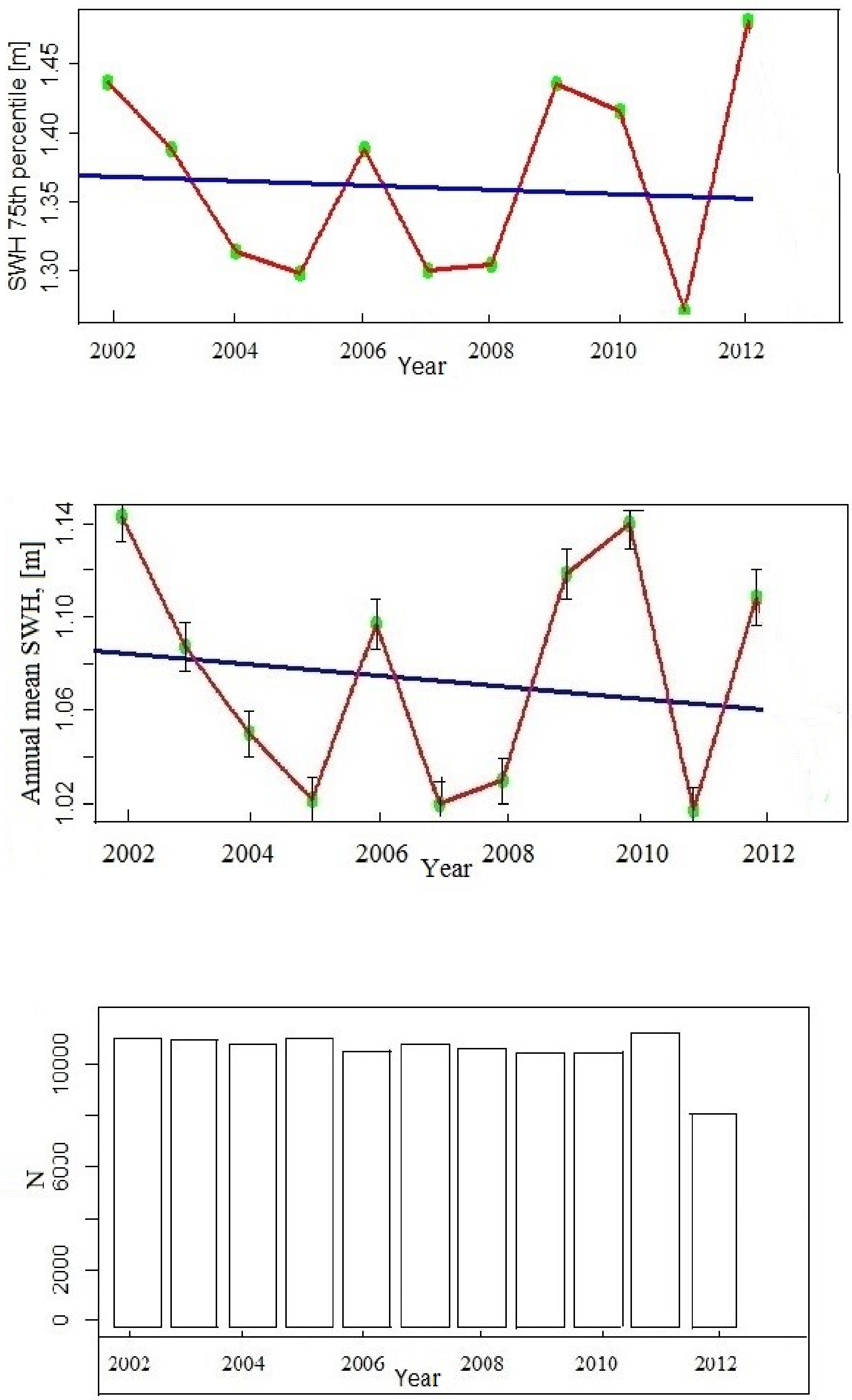


Figure 4: The wave climate for the entire Caspian Sea derived from satellite altimetry Jason-1 data. The panels show (from top to bottom) the 99^{th} percentile, the 90^{th} percentile, the 75^{th} percentile, annual mean SWH, and a number of data points for each year. Blue lines are linear regression lines fitted to the data

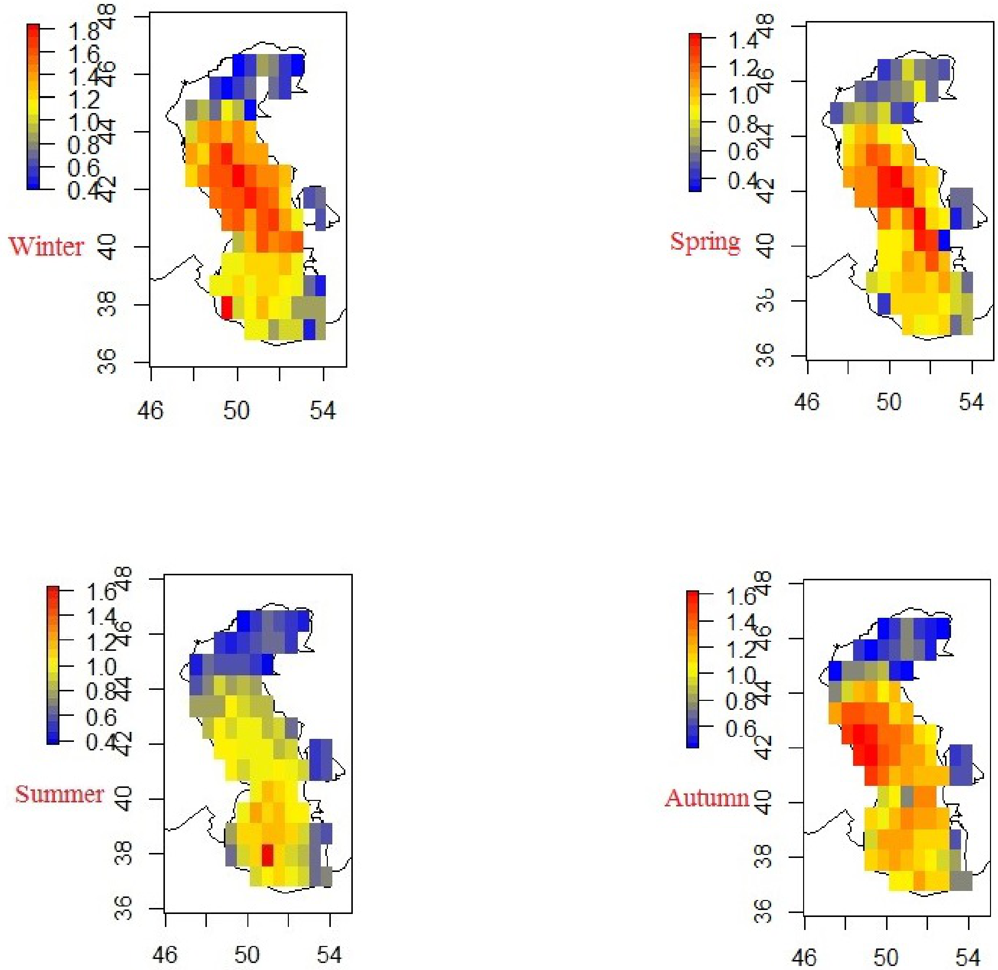
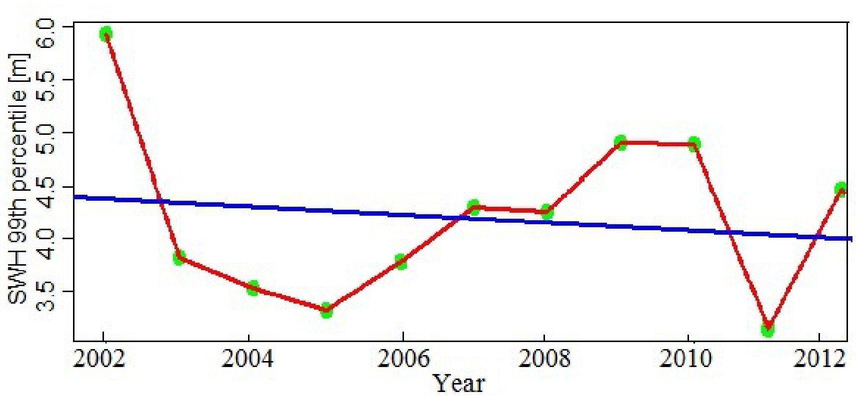
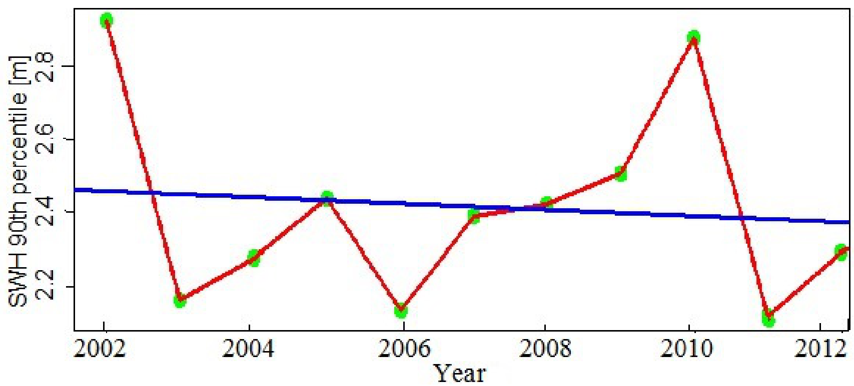
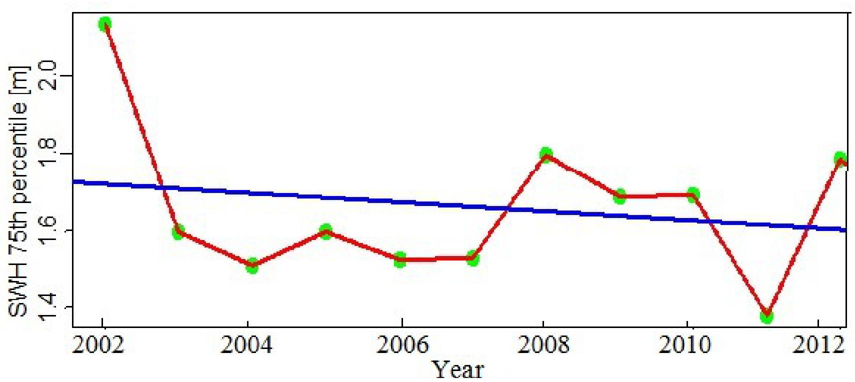


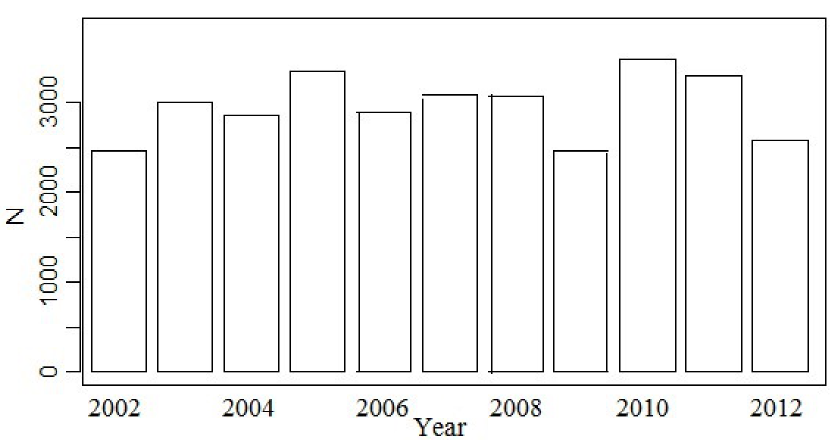
Figure 5: Average significant wave height (m) in the Caspian Sea in 2002-2012 derived from satellite altimetry for each season separately

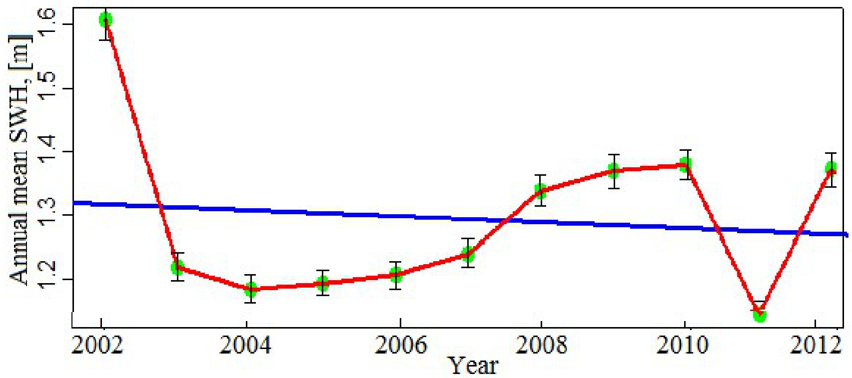
Winter



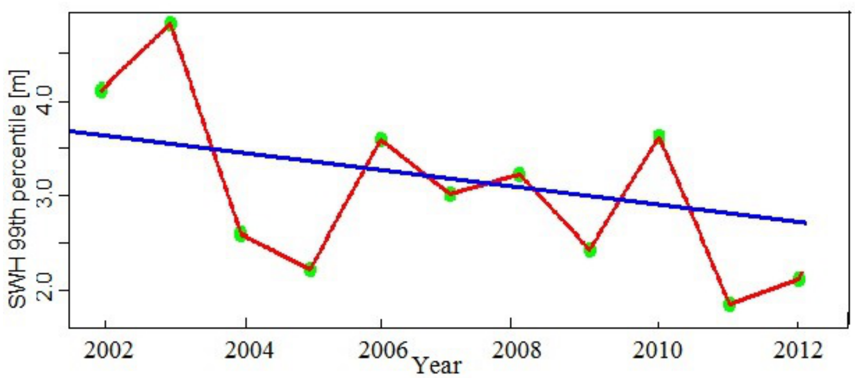

SWH 90th percentile [m]
2.2
2.4
2.6
2.8
2002
2004
2006
2008
2010
2012
Year

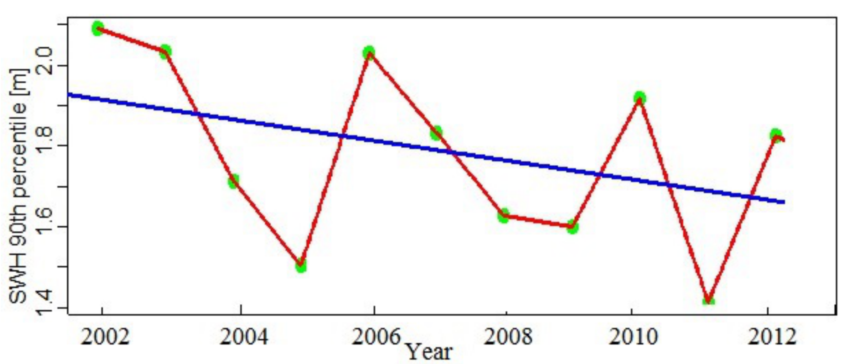

SWH 75th percentile [m]
1.4
1.6
1.8
2.0
2002
2004
2006
2008
2010
2012
Year

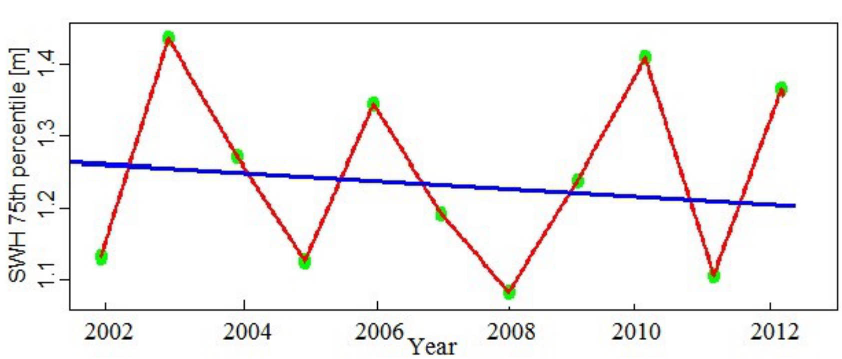

N
0
1000
2000
3000
2002
2004
2006
2008
2010
2012
Year

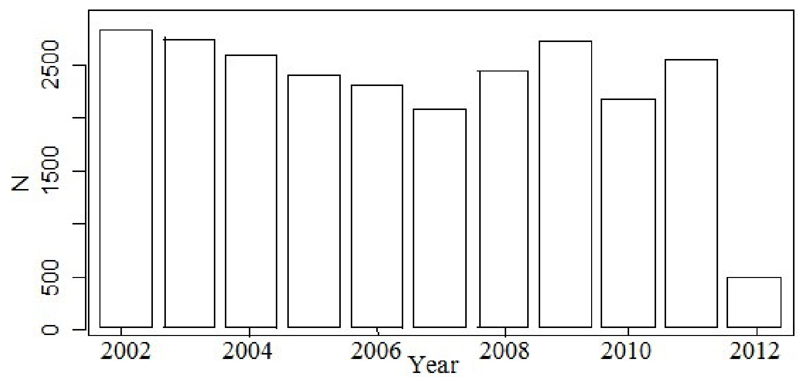

Annual mean SWH, [m]
Year

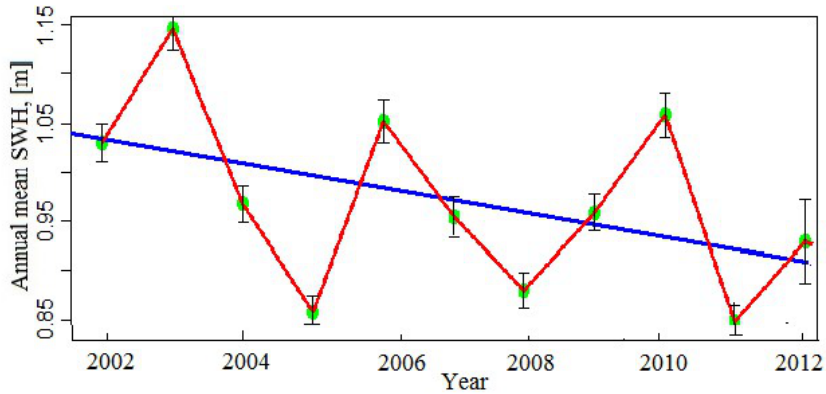
Spring


SWH 99th percentile [m]
Year

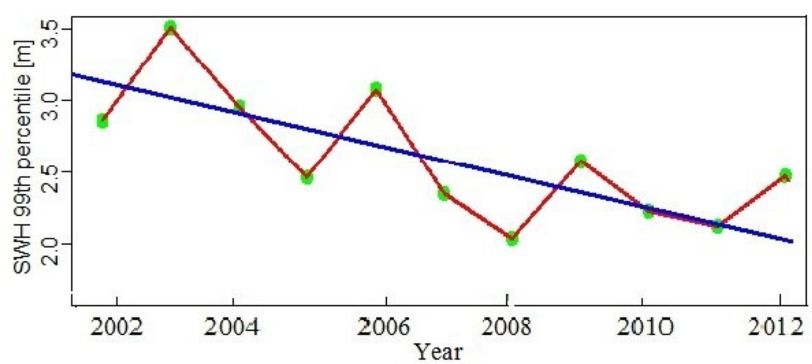

SWH 90th percentile [m]
Year

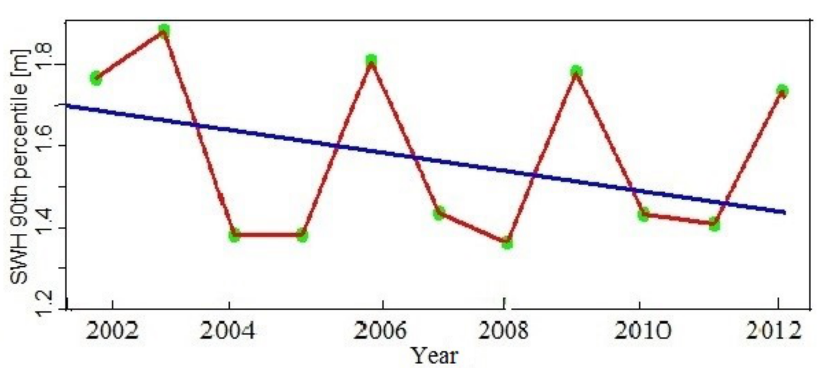

SWH 75th percentile [m]
Year

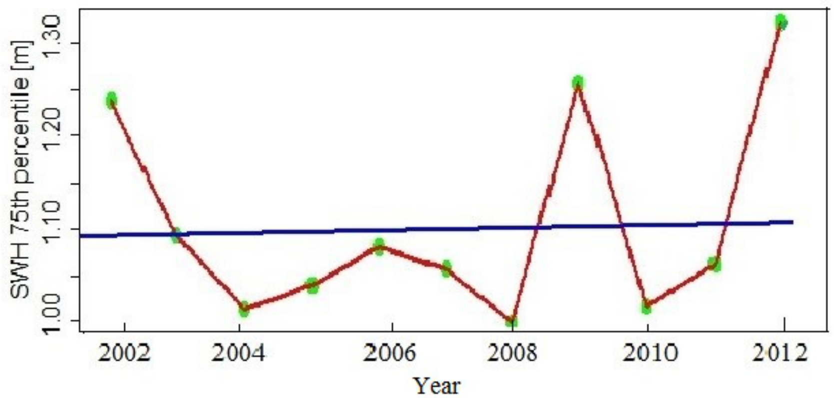

N
0
500
1500
2500
2002
2004
2006
2008
2010
2012
Year

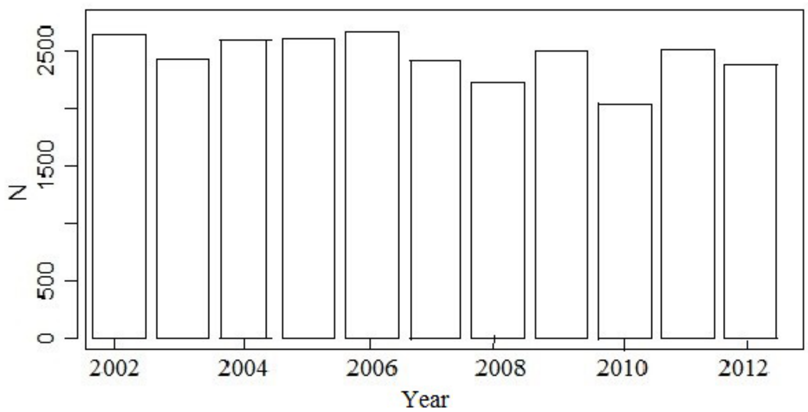

Annual mean SWH, [m]
0.85
0.95
1.05
1.15
2002
2004
2006
2008
2010
2012
Year

Summer


SWH 99th percentile [m]
2.0
2.5
3.0
3.5
2002
2004
2006
2008
2010
2012
Year


SWH 90th percentile [m]
1.2
1.4
1.6
1.8
2002
2004
2006
2008
2010
2012
Year


SWH 75th percentile [m]
1.00
1.10
1.20
1.30
2002
2004
2006
2008
2010
2012
Year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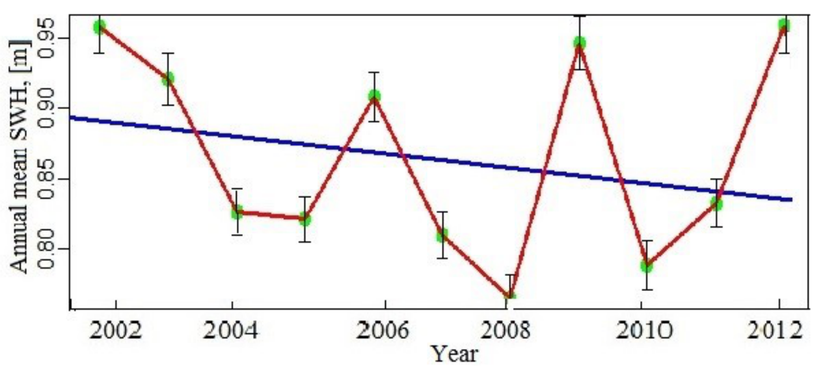
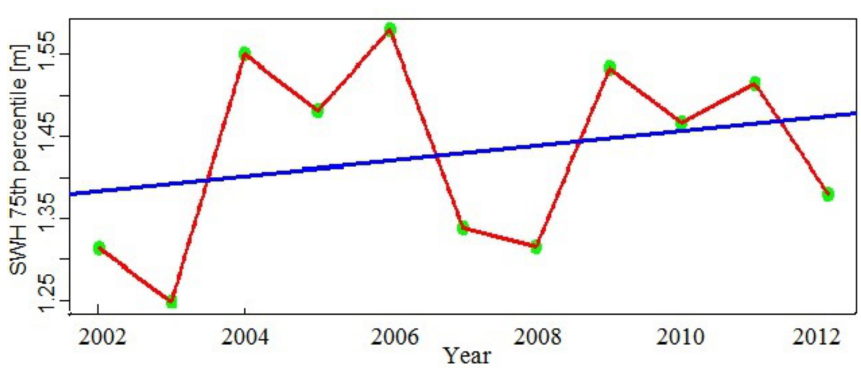
2012
Year


Annual mean SWH, [m]
0.80
0.85
0.90
0.95
2002
2004
2006
2008
2010
2012
Year

Autumn


SWH 75th percentile [m]
1.25
1.35
1.45
1.55
2002
2004
2006
2008
2010
2012
Year

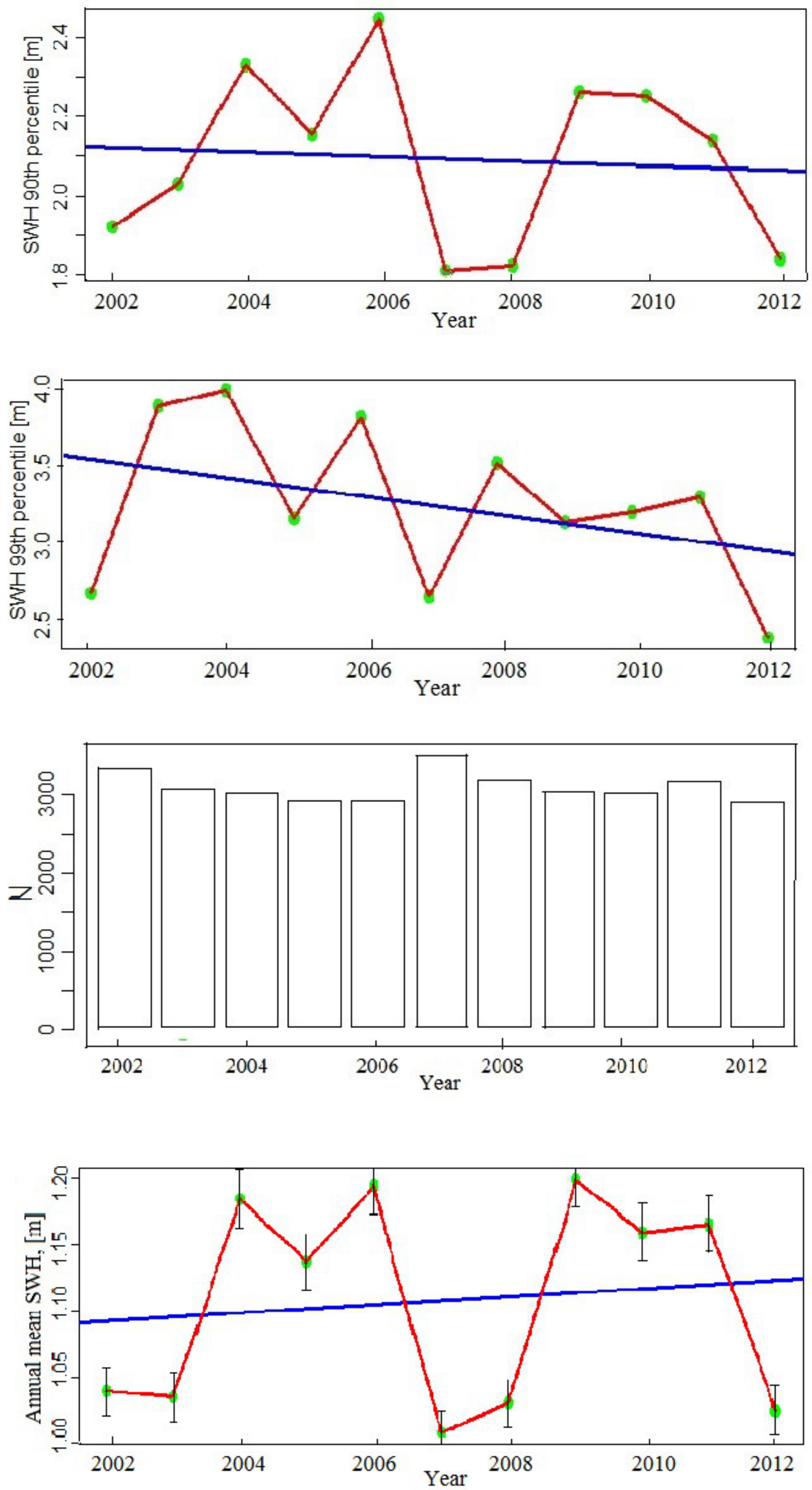


Figure 6: The wave climate for the entire Caspian Sea separated into winter, spring, summer and autumn seasons derived from satellite altimetry Jason-1 data. The panels show (from top to bottom) the 99th percentile, the 90th percentile, the 75th percentile, annual mean SWH, and a number of data points for each year. Blue lines are linear regression lines fitted to the data

5 Conclusion

This study examines the seasonal variability of average significant wave heights of the Caspian Sea. The study is based on data obtained from the Jason-1 mission. The procedures developed for the Baltic Sea conditions were revised for the Caspian Sea. The analysis showed that there is a significant difference between wave heights observed in each region of the Caspian Sea: relatively high waves in the Middle and Southern Caspian, whereas in the Northern part of the sea the results did not show high waves. However, sometimes high waves reach the southwestern part of the northern region. The analysis of seasonal variability showed that the most energetic waves appear in the winter season.

The obtained results are qualitatively consistent with the results previously studied by other methods. For example, with the results of the runs of the three-dimensional hydrodynamic model COHERENS, numerical model HYCOM (HYbrid Coordinate Ocean Model), and MIKE 3 HS FLOW MODEL (for modeling surface flows and related processes) [38], [39], [40], [41]. The average mean wave heights in the south and south-east basins are from 0.3 m to 0.7 meters [42], consistent with the results of this study. Also, the analysis of the seasonal variability of sea climate turnover showed a peak in February [43]. The results based on the analysis of wind speed and sea level from the satellite altimetry data in the Caspian Sea region were described in detail in [44], [45], [46] and showed that the highest average wind speeds are observed in the Middle and Southern parts of the Caspian Sea, in the same areas where the highest significant wave heights are detected in this study. The good correspondence between results of this analysis with the previous studies indicates that the satellite altimetry data provide a real picture of the average wave heights and variability of the wave climate in the Caspian Sea.

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