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Environmental drivers of meiofaunal natural variability, Egypt, Southeastern Mediterranean

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Abstract Sandy beaches are challenging ecosystems, in which biota experience extreme physical conditions. We sampled meiofauna in conjunction with environmental factors that are well-known to affect faunal associations to describe the ecological state of sandy beaches that experience natural and human-made disturbances. We applied a random stratified sampling design with monthly collections (1800 cores) at three beaches on the Alexandria, Egypt, coast during two sampling periods over 1 year from November to April and May to September. We used multivariate analyses to compare beaches for water quality, particle size, and meiofaunal assemblages. The environmental analysis explained 60% of the total variation of physical factors among beaches and grouped beaches that moderately sorted fine-grained sand and high water salinity vs. the beach with well-sorted, coarse-grain, and low salinity. Meiofaunal analyses revealed unexpected results. The abundance and temporal variation were low, and the explained proportion of natural variation by the putative environmental factors was small. The natural variation was an indicator of long-term beach ruin and oligotrophic conditions. Our results suggest that a large fraction of natural variation in beach meiofauna is stochastic or that other, non-measured, the natural forces (e.g., storm events) or human-made forces (e.g., tourism activities) are essential contributors to variation. Our best models indicate that meiofauna is more resilient to natural disturbances than to human-made stressors, and the higher the beach exposure to the synergetic effects of natural forces and anthropogenic stressors, the lower the ecological state is.

Keywords Marine bacteria · Tourism activities · Winter storms · Stochastic variations · Management decision-makers

Introduction

Sandy beaches are physically controlled ecosystems that are challenging for different biota to withstand and flourish. They may appear to be devoid of life

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Highlights for review Meiofaunal Natural variability is a good indicator of beach ruin.
Stochastic distribution, winter storms, and touristic activities are the fundamental causes of the large fraction of the unexplained variation in meiofaunal communities.
The beach that experiences the synergetic effect of natural forces and human-made activities has a worse ecological state.
Human-made disturbances; mechanical engineering, pollution, tourism activities, and the natural forces; winter storms, high energy, and rip currents are essential contributors for management decision-makers.

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due to the absence of attached plants, the small-sized animals, and the high mobility of animals on exposed beaches. This physical habitat is determined by water, sand, and wind, which in turn govern the biotic distribution and community structure (Brown & McLachlan, 2010). Storms and associated erosion cause the most faunal challenges. This ecosystem contains a complex array of microscopic and macroscopic biota that interact in a trophic network of sandy beach ecosystems (McLachlan & Defeo, 2017). Anthropogenic influences including coastal engineering, pollution, and tourism development extensively affect sandy shores, and these activities vary from beach to beach, inhibit or alter the natural sand transport and budget, and cause severe erosion. However, this ecosystem varies in space and time, even without human influence. The understanding of the physical, ecological, and socio-economic factors impinge on any sandy beach, which is very important for beach assessment and management (McLachlan et al., 2013). Natural variability is an essential ecological assessment (Landres et al., 1999), and it is the key to understand the mechanisms of population regulations (Ranta et al., 1998). Schlacher et al. (2014) addressed some cases of habitat change and loss at sandy beaches based on the natural variability of fauna and flora. Others recorded that the higher the oscillation rates of natural variability, the higher the indication of ecosystem stresses is (Armenteros, 2006; Brown & McLachlan, 2010).

Benthos are sensitive indicators of natural or anthropogenic disturbances (Reiss & Kroncke, 2005), and their distributions depend on physicochemical factors and biological interactions (Montagna, 1984; Moreno et al., 2006). Meiofauna is metazoans with a patchy distribution that ranges in size between 63 and 1000 μm (Giere, 2009) and dominated by two main taxa: nematode and harpacticoida with exceptions (Coull, 1999). Meiofauna organisms are known to be sensitive indicators of environmental perturbation due to high abundance, lack of larval dispersion, small size, ubiquitous distribution, high turnover, and intimate association with sediments (Alves et al., 2013; Semprucci et al., 2015). Marine sediment bacteria act as food for macrofauna, meiofauna, and microfauna (Ha et al., 2014; Moens et al., 2013). Bacteria are vital for the breakdown of organic matter in the sediment (Danovaro, 1996), and Coliform bacteria are sewage pollution indicators in the marine environment (Abdelhamid et al., 2013).

The Alexandria coast extends for about 42 km (Fig. 1; Table 1) and experiences natural and anthropogenic stressors (EEAA, 2015), beach erosion, rip currents, sea-level rise, and coastal engineering (El-Raey et al., 2015). The Egyptian Environmental Affairs Agency has declared

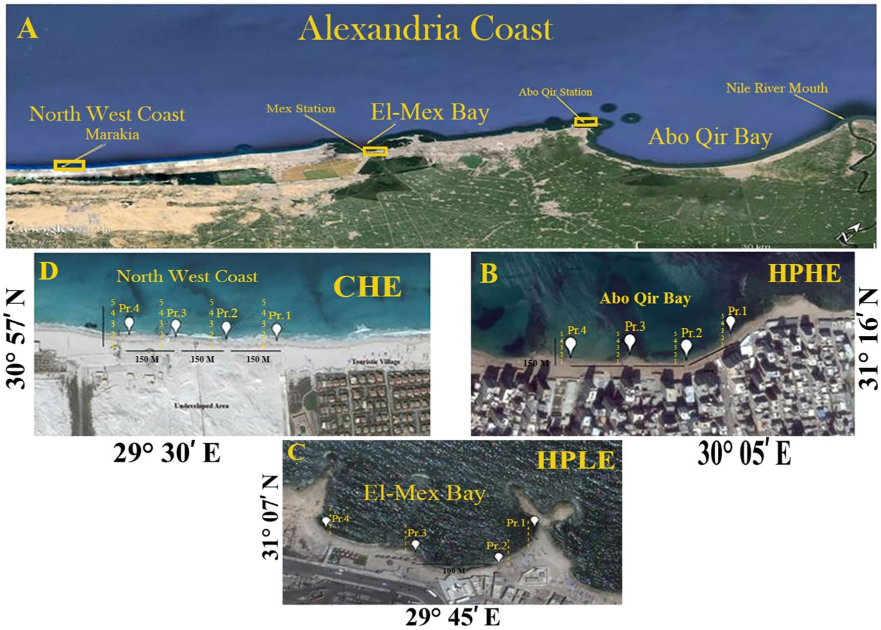

Fig. 1 Egyptian Mediterranean Coast of Alexandria (**a**). Abbreviations: HPHE (**b**) High Polluted High Energy beach, Abo-Qir Bay; HPLE (**c**) High Polluted Low Energy beach, El-Mex Bay; CHE (**d**) = Clean High Energy beach, North West Coast beach

Table 1 Geographical coordinators and environmental-bacterial data reported in mean ± standard deviation, (SD) among beaches and during sampling periods

Period	Predictors	HPHE	HPLE	CHE	Overall mean
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
	Latitude	31° 16′–31° 28′ N	31° 07′–31°15′ N	30° 57′–30° 60′ N	31° 00′–31°. 30′ N
	Longitude	30° 04′–30° 20′ E	29° 45′–29°54′ E	29° 30′–29° 28′ E	29 ° 30′ –30 ° 30′ E
Mild Cold period November 2012 –April 2013	Temperature (T◦c)	20.00 ± 2.00	21.00 ± 2.00	20.50 ± 1.50	20.58 ± 1.89
	Salinity (PSU)	37.54 ± 0.52	28.63 ± 0.81	38.12 ± 0.42	34.75 ± 4.5
	Water alkalinity (pH)	7.91 ± 0.05	8.13 ± 0.11	8.22 ± 0.02	8.00 ± 0.15
	Mean Grain size (φ)	1.05 ± 0.35	0.34 ± 0.39	1.47 ± 0.20	0.93 ± 0.60
	Sediment sorting coefficients (sorting)	0.67 ± 0.23	0.42 ± 0.16	0.51 ± 0.06	0.54 ± 0.22
	Total organic matter (%TOM)	2.12 ± 0.96	1.74 ± 1.02	1.25 ± 0.75	1.66 ± 1.30
	Total Bacteria (TB, CFU/ml)	50,143 ± 4997	67,870 ± 6531.0	35,293 ± 5250	51,177 ± 14,487
Mild warm period May 2013 to September 2013	Temperature (T◦c)	27.5 ± 1.00	30.00 ± 1.5	29.50 ± 1.5	29.23 ± 2.0
	Salinity (PSU)	38.81 ± 0.29	31.34 ± 3.14	38.75 ± 1.34	36.69 ± 3.7
	Water alkalinity (pH)	8.32 ± 0.13	8.67 ± 0.30	8.6 ± 0.17	8.6 ± 0.26
	Mean Grain size (φ)	1.09 ± 0.02	0.51 ± 0.24	1.40 ± 0.14	1.02 ± 0.45
	Sediment sorting coefficients (sorting)	0.66 ± 0.05	0.45 ± 0.23	0.54 ± 0.07	0.56 ± 0.22
	Total organic matter (TOM %)	1.72 ± 0.20	1.96 ± 1.17	1.65 ± 0.78	1.87 ± 1.32
	Coliform Bacteria (CB)	2.93 ± 7.74	17.42 ± 23.51	2.37 ± 6.78	7.65 ± 16.46

HPHE high polluted high energy beach, *HPLE* high polluted low energy beach, *CHE* clean high energy beach

two polluted hotspots sandy beaches: Abo-Qir Bay and El-Mex Bay at the east and the west of Alexandria coast, respectively, due to high anthropogenic influences (EEAA, 2015). Several studies have documented the deterioration of the ecological status of these two beaches (El Nemr et al., 2013; Shreadah et al., 2019). Few studies have investigated the meiofaunal abundance along the Egyptian Mediterranean coast (Mitwally, 1999; Mitwally et al., 2004), and few studies have attempted to correlate meiofauna and bacterial abundance (Jammo, 2004).

The current study aimed first to assess the responses of natural variability of meiofauna assemblages to relevant physicochemical, sedimentological factors, and microbes at three sandy beaches that experience different stressors, and second to test which factor is the best predictor of or contributor to meiofaunal variability. Finally, the study aims for the first time to use the meiofaunal variability as an environmental tool discriminating and assessing the ecological status of subtropical sandy beaches at the Alexandria Southeastern Mediterranean coast, Egypt.

Materials and methods

Study design

We collected meiofaunal sediment samples for 10 months during two sampling periods over the years 2012–2013: the mild-cold period (MC) November to April, except for March, and the mild-warm period (MW) May to September. The study design is a random stratified sampling design (Schlacher et al., 2008). We sampled four random perpendicular profiles at each beach. Each profile extended between the drift and the wrack lines and consisted of five random stations, where triplicate sediment samples were collected. Beaches designated as highly polluted high energy (HPHE), highly polluted low energy (HPLE), and clean high energy (CHE). The design has two fixed factors: period and beach. The interval distances among profiles were 150 m at HPHE and CHE and 100 m at HPLE, whereas the distances between stations were 5, 2, and 8 m apart, respectively, for HPHE, HPLE, and CHE.

The study area (Fig. 1)

Abo-Qir Bay (HPHE)

It is a shallow, semi-closed basin border by Rosetta mouth of the Nile at the northeastern and Abo-Qir headland at the southwestern (Table 1). The bay occupies an area of ~ 500 km^2 with an average depth of 10–12 m. It received several land-based sources of nutrients, a high load of freshwater nutrients from the Rosetta mouth of the Nile, and Lake Edku discharge. El-Tabia pumping station is the essential source of industrial and domestic wastes. The bay also experiences hydrocarbon oil and thermal pollution due to fishing boats and Electrical Power stations. The physicochemical characteristics of the bay have received attention (Ismail et al., 2017; Khairy et al., 2012) and designated as a highly energetic dissipative sandy beach with dramatic erosion and sea-level rise (Frihy et al., 1996; Nafaa & Frihy, 1993).

El-Mex Bay (HPLE)

It has an elliptical shape that extends for about 15 km at the Western coast of Alexandria (Table 1) and a mean depth of 10 m. Lake Maruti's discharge through the El-Mex Pump station and El-Umum drain canal are the essential sources of different industrial, agricultural, domestic, and hydrocarbon pollutants. The bay has a rocky shoreline with a narrow sandy beach, a microtidal estuary character, and the eddy current affect many parts (Hamdy, 2015; Shreadah et al., 2014).

North West Coast beach (CHE)

The Northwest coast beach lies at 100 km to the west of Alexandria near the touristic "Marakia" village (45 m; Table 1). This area is oligotrophic, highly energetic (Zaki et al., 2009), far away from urban development, and characterized by water clarity, extensive beachfront, and a very gentle shore slope (Frihy, 2009). The Northwest coast beaches of Alexandria classified between reflective and moderately dissipative beaches, with hazards rip currents (Frihy et al., 1996). Egyptian government built several engineering projects to create safe places for swimming (Iskander et al., 2007) that have disturbed the hydrodynamic system by creating a new pattern of sedimentation (Frihy & Deabes, 2012).

Field and laboratory work

Field work

A handheld corer of 4.8-cm^2 surface area and 11-cm length was used for sediment sample collection and a 4% formalin solution, with rose Bengal dye for sediment preservation. For microbial and sedimentological analysis, we collected two additional samples at each station that were stored in sterilized bags in the refrigerator for a maximum of 24 h for further investigation. Water temperature was measured by the mercury thermometer. The water salinity was collected using a salinity bottle, and pH was measured using HANNA HI 98,107 pH meter.

Physico-chemical and sedimentological factors

We applied the Strickland and Parsons (1972) method for salinity determination and El Wakeel and Riley (1957) and Olausson (1975) procedures for analysis and calculation of organic carbon and total organic matter, respectively. We used the Folk and Ward (1957) method for mean grain size and sediment sorting coefficient measurements.

Microbial and meiofaunal analysis

Total bacterial abundance was determined, according to Ben-David and Davidson (2014). Serial dilutions were made by aseptically removing 1 g of wet sediment into 99 ml filtered sterilized seawater, mixed vigorously, and sonicated for 2 min. Then, 1 ml from each sample was inoculated onto marine agar medium (DifcoTM, 2216), incubated at 37 °C for 24 h, and colonies were counted and expressed as colony-forming units (CFU/ml) during the mild-cold period. Coliform bacteria (CB) were inoculated on Endo Agar–less dehydrated medium (HiMedia, M1106). All colonies were counted, purified, and biochemically characterized using API 20E and API 20NE kits (BioMérieux, Marcy I´Etoile, France) according to the manufacturer's instructions and incubated at 37 °C for 24 h during the mild-warm period. Interpretation of results was performed using the computer-aided database API-WEB™V.5.0 software (Hamdan et al., 2016).The Huys et al. (1996)

technique for staining, extraction, sorting, and identification of meiofauna to higher taxonomic groupings was applied using a stereomicroscope, and abundance was expressed as individuals 10 cm^{-2}.

Data analysis

Physico-chemical, sedimentological, and microbial data were transformed to square-root and normalized to avoid strong skewness in the distribution over samples and to overcome different measurement scales (Anderson et al., 2008). Draftsman plots were performed to test for multicollinearity among variables. The Euclidean distance-measure index was applied to build an environmental-microbial resemblance. Principal component analysis (PCA) was conducted to assess the environmental and microbial data variation between the sampling periods and among beaches. The data matrix consisted of 300 observations for each sampling period.

Taxa that had zero cells more than 25% were omitted from the meiofaunal matrix, to avoid rare-species problems, and conduct different multivariate analyses (Cunningham & Lindenmayer, 2005; Ortega Cisneros et al., 2011). Data were square-root transformed, and the simple matching measure index applied to build a meiofaunal resemblance. The PERMANOVA (Anderson, 2005) was done to test for variation in mean meiofaunal data between periods, among beaches, within profiles, stations, and their interaction and nesting effects. The pair-wise comparison analysis was performed within fixed and random factors. The PERMANOVA ran with type III of sum squares (partial); the number of permutation was 999, a reduced model of residuals permutation, and Monte-Carlo probability. To seek temporal and spatial visual discrimination based on the meiofaunal resemblance, the non-multidimensional scaling (nMDS) analysis was applied using the fixed factors as variables, and the matrix consists of 900 observations for each sampling period.

Distance-based linear models (DISTLM) analysis was applied to estimate the proportion of variation in the meiofauna community explained by the measured environmental factors (Anderson, 2003). Replicated meiofaunal data were pooled at each station to fit the factors' matrix. We conducted the analysis based on Euclidean distance resemblance of seven factors; physicochemical, sedimentological, bacterial predictors, and a simple-matching measure resemblance of eight meiofaunal variables. Marginal and sequential tests in a linear regression model with a step-wise procedure applied between and among the fixed effects: period and beach. The Akaike (AICc) information criterion and coefficient of determination (R^2) were chosen for the best model of each sequential test (Anderson et al., 2008). The permutation number for each analysis is 999. Unlike the R^2 or the adjusted R^2, the AICc values will not continue to increase to get better as the number of variables increases in the model, and the best model has the smallest AICc value (Anderson et al., 2008).

Distance-based redundancy analysis (dbRDA) was performed to visualize the percentage of variability in the original meiofaunal resemblance that fitted the constrained linear combination model of response criterion and predictor variables (Legendre & Anderson, 1999). The relative contribution of each environmental variable (strength and direction) in driving the variation along dbRDA axes was visualized by the vector overlays on the ordination diagram with one vector for each variable. The analysis ran between and among fixed factors: period and beach. All the multivariate analyses applied using the PRIMER 7^+ software package.

Pearson correlation analysis was applied to seek for non-linear relationships between any of/and all permanent meiofaunal taxa vs. the proposed microbial food data (TB and CB). All statistical results were described based on actual p values and sample size to avoid the arbitrary rejection rate of significant vs. non-significant (Smith, 2019).

Results

Environmental factors

The mean ± SD values of the physicochemical (T°c, PSU, pH), sedimentological factors (φ, sorting, %TOM), and microbial data (TB and CB) were tabulated in Table 1. Physicochemical and sedimentological variables had smaller mean during the mild-cold than that during the mild-warm period except for %TOM at HPHE. Draftsman analysis revealed correlation values less than the cutoff 0.95 among the physicochemical, sedimentological, and microbial variables. Therefore, the environmental matrix included all the measured variables. During the mild-cold period (Fig. 2a), the 1st and 2nd PCs accounted for ~ 60%

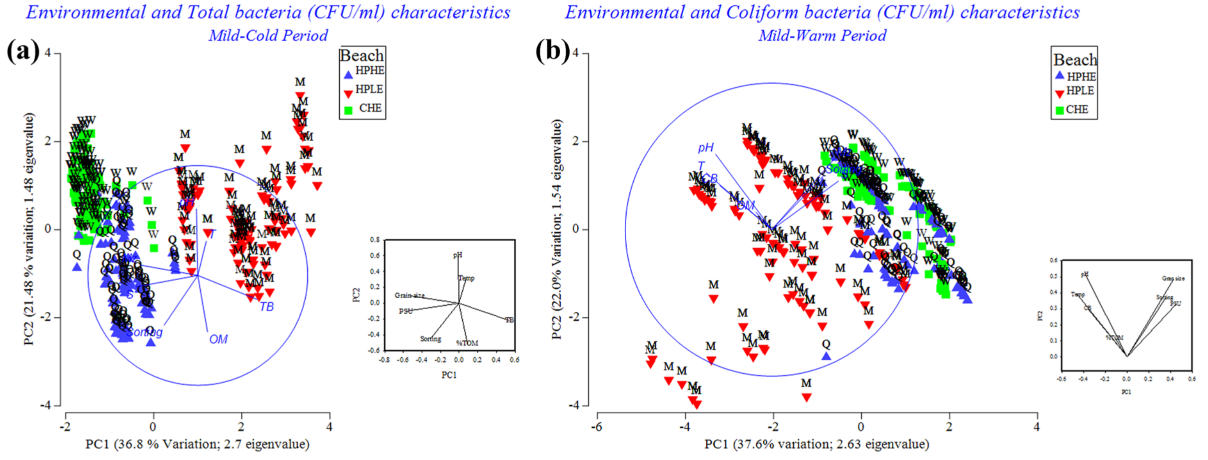

Fig. 2 Principal component analysis based on the Euclidean distance index of seven environmental factors during the mild-cold period (**a**) and the mild-warm period (**b**). Abbreviations: T°c temperature, PSU salinity, pH water alkalinity, *φ* mean grain size, sorting sediment sorting coefficients, %TOM total organic matter, TB total bacteria, CB coliform bacteria, and beach abbreviations listed in Fig. 1

of the total variation of the physical factors among beaches. The PC1 separated data at HPLE (right-hand side) from HPHE and CHE (left-hand side). The PC2 barely separated within HPHE, CHE, and HPLE data. During the mild-warm period (Fig. 2b), the 1st and 2nd PCs accounted for ~ 60% of variations. The PCs separated HPLE data from HPHE and CHE. The HPHE and CHE data collapsed together. All variables loaded positively on PC2.

Meiofauna assemblages

Meiofaunal community structure consisted of 12 taxonomic groups. Eight taxa are permanent meiofauna; Nematode (40%), Polychaete (31.5%), Harpacticoida (18%), Turbellaria (4%), Ostracods (1.8%), Archannelida (1.5%), Foraminifera (1.2%), and Halicardia (1%). Nauplius larvae and three temporary taxa: Gastropod, Isopoda, and Bivalve, totaled 0.8%. The overall mean total meiofaunal abundance was 38 ± 67 individuals 10 cm^{-2} (MC; Fig. 3a), and 46 ± 108 individuals 10 cm^{-2} (MW; Fig. 3b). At HPLE, total abundance was ~ 3.5 and 5 times higher than the abundance at HPHE and CHE beaches, respectively. Meiofaunal abundance attained its maximum during MC (February) and ranged from 1260 ± 1001 individuals 10 cm^{-2} (HPLE) to 285 ± 177 individuals 10 cm^{-2} (CHE; Fig. 3a). The lowest abundance was found during MW (July) and ranged from 189 ± 705 individuals 10 cm^{-2} (HPLE) to 69 ± 53 individuals 10 cm^{-2} (CHE; Fig. 3b). The abundance at HPLE had a wider standard deviation range than that at HPHE and CHE. The meiofaunal abundance at HPHE and CHE beaches tracked each other with limited oscillations, and it was 1.5 times higher at HPHE beach.

Archannelida was omitted from the meiofaunal analysis due to high number of zero cells. PERMANOVA results revealed that there was no significant variation among meiofaunal communities between the mild-cold and mild-warm periods (Table 2; *Pseudo-F*$_{1,\,1200}$ = 1.34, P_{perm} = 0.211, U-Perm = 999, P_{MC} = 0.306). Among beaches, variation in meiofaunal communities was significant (*Pseudo-F*$_{2,\,1200}$ = 13.36, P_{perm} = 0.001, U-perm = 999, P_{MC} = 0.001). The variability in the meiofaunal assemblages was significant within month nested in period (*Pseudo-F*$_{8,\,1200}$ = 5.93, P_{perm} = 0.001, U-perm = 999, P_{MC} = 0.001) and stations nested in profile and beach (*Pseudo-F*$_{48,\,1200}$ = 3.83, P_{perm} = 0.001, U-perm = 999, P_{MC} = 0.001). The interaction effect between the nested factors (month (period) * profile (beach)) revealed higher significant variability in meiofaunal assemblages than the interaction effect between the nested factors (month (period) * (station (profile (beach)), (*Pseudo-F*$_{72,\,1200}$ = 2.60 and *F* $_{384,\,1200}$ = 2.04, respectively, at P_{perm} = 0.001, U-perm = 999, P_{MC} = 0.001). The smallest variability was detected for the interaction between month nested in period and beach (*Pseudo-F*$_{16,\,1200}$ = 1.08, P_{perm} = 0.008, U-perm = 998, P_{MC} = 0.015).

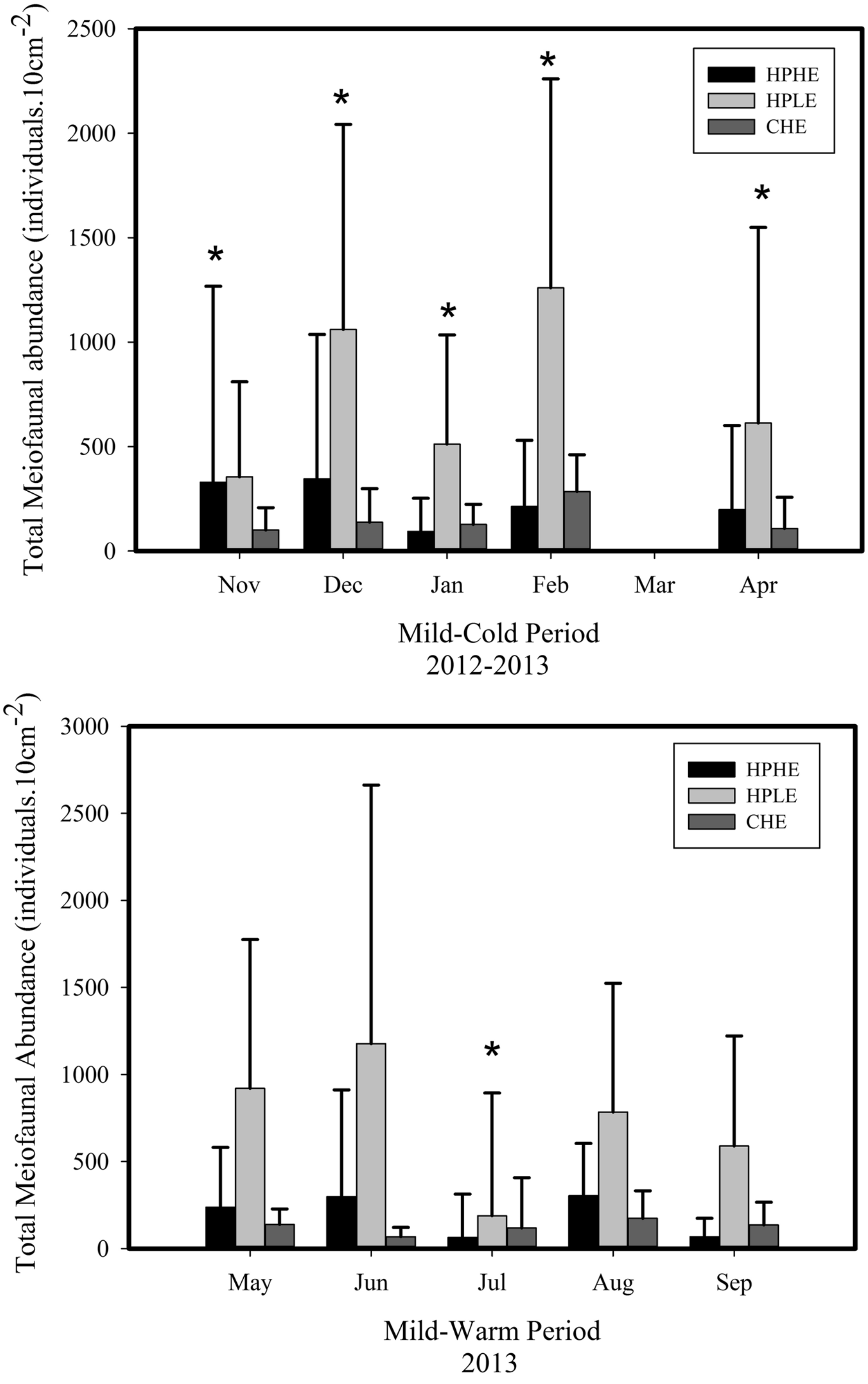

Fig. 3 Temporal and spatial meiofaunal distribution (individuals 10 cm^{-2}). A list of Abbreviations is in Fig. 1. The asterisk sign indicates the significant variation at the actual *p*-value (Appendix 1)

Results of pair-wise tests based on meiofaunal communities, revealed small significant variations between MC and MW periods (Table 3; *t*-test = 1.73, P_{perm} = 0.008, U-perm = 996, P_{MC} = 0.075). Among beaches, the highest significant variation was detected between HPHE and HPLE, then between HPLE and CHE and after then between HPHE and CHE (*t*-test = 3.74, 3.67, and 3.46 at P_{perm} = 0.001, U-perm = 999, 998, and 997, P_{MC} = 0.001, 0.001, and 0.003 respectively). The within-month variability was

Table 2 PERMANOVA results based on the simple matching resemblance of 8 criterion data; Nematodes, Polychaete, Foraminifera Harpacticoida, Turbellaria, Halicardia, Ostracods, and total meiofauna among and within fixed and random factors at actual probability

Source	df	SS	MS	*Pseudo*-F	P_{perm}	U-perms	P_{MC}
Pe	1	9719.9	9719.9	1.34	0.211	999	0.306
be	2	79,145	39,572	13.36	0.001	999	0.001
mo(Pe)	8	59,804	7475.5	5.93	0.001	999	0.001
pr(be)	9	6706.6	745.18	0.40	1.000	996	0.992
Pe*be	2	8530.7	4265.4	1.82	0.043	997	0.150
st(pr(be))	48	89,053	1855.3	3.83	0.001	996	0.001
Pe*pr(be)	9	6528	725.33	0.69	0.943	997	0.905
mo(Pe)*be	16	36,985	2311.6	1.83	0.008	998	0.015
Pe*st(pr(be))	48	23,905	498.01	1.03	0.418	999	0.424
mo(Pe)*pr(be)	72	90,737	1260.2	2.60	0.001	995	0.001
Mo(Pe)*st(pr(be))	384	1.86E+05	484.86	2.04	0.001	992	0.001
Residuals	1200	2.85E+05	237.11				
Total	1799	8.82E+05					

df degree of freedom, *SS* sum squares, *MS* mean square, *Pseudo*-F *Pseudo*-F statistic, *P*-perm probability, *U*-per unique-permutations, *P* (MC) Monte Carlo probability, *Pe* period, *be* beach, *mo* month, *pr* profile, *st* station

higher during the mild-cold than that during the mild-warm period (Fig. 3; Appendix 1). The pair-wise analysis within different levels of the fixed factors and their interactions revealed scattered results shown at Appendices 1–4 at actual probability values. The *n*MDS analysis did not visualize clear groupings between periods and among beaches. Therefore, the results were not shown here.

The DISTLM model during the mild-cold period, marginal test, revealed that six environmental factors, each alone, had a significant contribution to meiofaunal communities at $p = 0.001$: φ, sorting, pH, T°C, PSU, and TB (Table 4). However, each factor explained a low proportion of meiofaunal community variation, and salinity explained the highest contribution (9.5%). The sequential analysis showed the best model based on the lowest AICc (5499.4) value contained six factors and explained 15% of the cumulative variation in meiofaunal communities. During the mild-warm period, each variable out of four environmental factors contributed significantly to meiofaunal assemblages, but with a low proportion of variation: %TOM, φ, sorting, and PSU at *p*-value (0.001), and grain size explained the highest proportion (3.5%). The best model consisted of the combination of six physicochemical and sedimentological factors and explained 9% of the cumulative variation at the lowest AICc value (4389.2). However, DISTLM models capture a little of explained variation that fitted the linear regression with R^2 equals to 0.151 and 0.089 at significant $p = 0.020$ and 0.010 during the mild-cold and warm periods, respectively.

Table 3 Results of pair-wise a posteriori comparisons using PERMANOVA analysis based on the simple matching resemblance of 8 criterion data, listed at Table (2) within the fixed factors at actual probability

Fixed factor	Groups	*T*-test	P_{perm}	U-perm	P_{MC}
Period	MC, MW	1.73	0.008	996	0.075
Beach	HPHE, HPLE	3.74	0.001	999	0.001
	HPHE,CHE	3.46	0.001	997	0.003
	HPLE,CHE	3.67	0.001	998	0.001

MC mild cold, *MW* Mild warm, *U*-per unique-permutation, *P*-perm probability, *P (MC)* Monte Carlo probability. A list of abbreviations in Table 1

Results of dbRDAs analysis revealed that the 1st and 2nd dbRDA plots were responsible for 75.3% and 19.8% of the fitted variation and 11.3% and 3% of the total variation, respectively, during MC (Fig. 4a). The 1st dbRDA correlated negatively with the PSU (−0.75) and sorting (−0.50) data. The 2nd dbRDA correlated positively and negatively with TB (0.63) and pH (−0.67), respectively. The dbRDA plots visualized two groupings: the HPLE grouping loaded on the right-hand side, whereas the HPHE and CHE grouping loaded on the left-hand side. During the mild-warm period, the 1st and 2nd dbRDAs were responsible for 69.9% and 27.4% of the fitted variation, respectively (Fig. 4b), and 6.1% and 2.5% of total variations, respectively. The 1st dbRDA had a positive correlation with sorting (0.60), φ (0.45), and PSU (0.42) data, whereas the 2nd dbRDA correlated positively with φ (0.5), T°C (0.44), and %TOM (0.43) data. The dbRDA plots visualized two groupings of

Table 4 DISTLM results based on the simple matching resemblance of 8 criterion data, listed at Table 2 and Euclidean distance resemblance of 7 predictors' data between the mild cold and mild-warm periods

Marginal tests

Predictor	Mild cold				Mild warm			
	SS$_{trace}$	*P*-F	*P*	*Prop*	SS$_{trace}$	*P-F*	*P*	Prop
TOM%	889.01	01.70	0.207	0.002	4515.9	09.55	0.001	0.013
φ	21,384	42.77	0.001	0.045	12,528.0	27.12	0.001	0.036
Sorting	25,174	50.78	0.001	0.054	9695.4	20.81	0.001	0.028
pH	16,975	33.62	0.001	0.036	0692.6	01.45	0.265	0.002
T◦C	5847	11.30	0.001	0.012	0754.3	01.58	0.200	0.002
PSU	44,516	93.87	0.001	0.095	9405.7	20.17	0.001	0.027
TB/CB	23,055	46.28	0.001	0.049	748.34	1.56	0.241	0.002
Res.df	898				718			

Sequential tests

Predictor	Mild cold						
	SS$_{trace}$	*P*-F	*P*	Prop	Cum	AICc	Res. df
+PSU	44,516	93.87	0.001	0.095	0.095	5547.5	898
+pH	13,649	29.70	0.001	0.029	0.124	5520.2	897
+Sorting	6198.3	13.68	0.001	0.013	0.137	5508.6	896
+T◦C	3072.2	6.82	0.002	0.007	0.143	5503.8	895
+TOM%	1996.7	4.45	0.016	0.004	0.148	5501.4	894
+TB	1773.8	3.96	0.020	0.004	0.151	5499.4	893
Best solution	AICc	R^2	RSS	Selection		Variation%	
	5499.4	0.151	0.9917E+05	6 (1, 3–7)		15.0%	
Mild warm							
	SS$_{trace}$	*P-F*	*P*	Prop	Cum	AICc	Res. df
+*φ*	12,528	27.12	0.001	0.036	0.036	4419.5	718
+Sorting	5614.9	12.35	0.001	0.016	0.053	4409.3	717
+TOM%	4157.0	9.25	0.001	0.012	0.065	4402.1	716
+pH	3172.4	7.12	0.002	0.0092	0.074	4396.9	715
+PSU	3049.1	6.90	0.002	0.0089	0.083	4392.1	714
+T◦C	2152.9	4.90	0.010	0.0063	0.089	4389.2	713

Table 4 (continued)

Mild warm							
	SS_{trace}	*P-F*	*P*	Prop	Cum	AICc	Res. df
Best solution	AICc	R^2	RSS	Selection		Variation%	
	4389.2	0.089	0.14E+05	6 (1–6)		~ 9.0%	

SS_{trace} Sum square (Trace), *P-F Pseudo* F ratio, *P* probability values, *Prop* % proportion of each variable in affecting the meiofaunal community, *Cum* cumulative proportion, *AICc* Akaike information criterion, R^2 coefficient of determination, *Res. Df* Residual degree of freedom, *RSS* $SS_{Residual}$. A list of abbreviations in Table 1

data. The first grouping consists of HPHE, CHE, and some HPLE data loaded on the right-hand side, whereas the second grouping consists of the rest of HPLE data on the left-hand side.

The DISTLM analysis among beaches, marginal tests, revealed that one or two factors explained a small amount of the variation in meiofaunal assemblages at each beach during the mild-cold period; sorting at HPHE, TB at HPLE, sorting, and pH at CHE (Table 5) at p = 0.04, 0.03, 0.03, 0.02 respectively. The sequential analysis based on the lowest AICc selection revealed that the best model consisted of sorting, T◦C, and TB at HPHE; TB and sorting at HPLE; and pH, sorting, and φ at CHE that explained 6.0% (R^2 = 0.059), 6.5% (R^2 = 0.065), and 10% (R^2 = 0.098) of the total variation in meiofaunal assemblages, respectively. During the mild-warm period, marginal test (Table 6), %TOM, was the only factor that explained significant contribution to the community, but with a small proportion of variation at HPLE (p = 0.03) and CHE (p = 0.01). At HPLE, the best model based on the lowest AICc value consisted of the combination of %TOM and φ that explained a small proportion of variations, 6.5% (R^2 = 0.065) in the meiofaunal assemblages, whereas the best model at CHE consisted of five combined factors and explained 16% (R^2 = 0.16) of the total variation in the meiofaunal community. The sequential analysis at HPHE revealed that the combination of the measured environmental factors did not contribute significantly to meiofaunal assemblages (Table 6).

Pearson's correlation (Table 7) revealed that during the MC, total bacterial counts correlated significantly with total meiofaunal abundance and the abundance of different meiofaunal taxa, and the R values for all significant correlations ranged between ~ 0.2 and ~ 0.4, except for Ostracods and Archannelida. During the mild-warm period, Harpacticoida and Turbellaria abundance had a weak significant positive and negative correlations with the coliform count at p = 0.001 and 0.016, respectively.

Discussion

In an attempt to assess the ecological states of three sandy beaches that experience natural disturbances and anthropogenic stressors at the Alexandria coast, Egypt (Nafaa & Frihy, 1993), we studied the natural

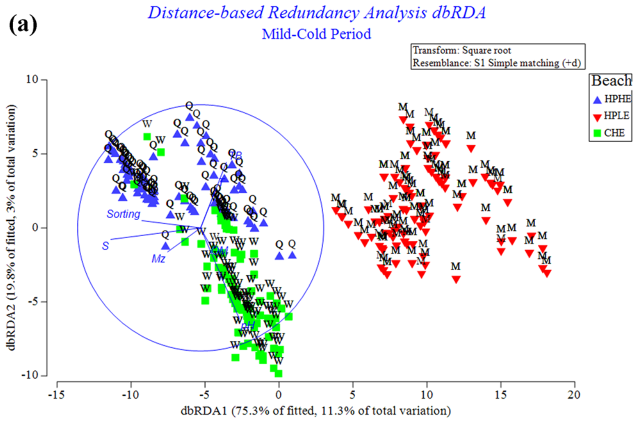

Fig. 4 The dbRDA plots, a constrained model based on the resemblance of simple matching index of 8 criterion data; Nematodes, Polychaete, Foraminifera Harpacticoida, Turbellaria, Halicardia, Ostracods, total meiofauna, and Euclidean distance resemblance of 7 predictors' data between (**a**) the mild cold and (**b**) the mild-warm periods. A list of abbreviations is in Figs. 1 and 2

variability of the meiofaunal organisms as an ecological assessment tool (Balsamo et al., 2012; Costa et al., 2016). Our study addressed the most well-known environmental factors affecting meiofaunal distribution (Giere, 2009), and contributor to the variability. The study revealed unexpected results, low abundances, lack of temporal variation, and a low contribution of environmental and microbial factors to meiofaunal variability. However, there was evidence that the measured factors controlled meiofaunal natural variability, the highest contribution of salinity, and sand particles to meiofaunal variability during the cold and warm periods, respectively. Despite the low proportion of environmental contribution, our results indicated that natural variability at each beach is a case study, stand-alone indicating beach-stress level. A thorough discussion will go through points that explain our findings.

Understanding of natural variability is essential to provide reference points as a basis not only for evaluating ecosystem management (Swanson et al., 1994) but also for distinguishing between disturbed and undisturbed ecosystems (Power, 1999). Investigating meiofaunal natural variability herein revealed some points that could indicate the ecosystem disturbances. The number of recorded higher meiofaunal taxa (12) agreed with other subtropical studies (Kotwicki et al., 2005), but sensitive taxa in many coastal areas, according to Zeppilli et al. (2015), were absent herein (Gastrotrichs, Tardigrade), or had a low contribution; Ostracods. However, a total number of permanent taxa (8) assigned our sandy beaches within the lower limit of sufficient environmental quality score according to Danovaro's classification (Gambi & Dappiano, 2004; Pusceddu et al., 2007). The overall mean meiofaunal abundance was smaller than the minimal values worldwide with few exceptions (Baldrighi et al., 2019; Gheskiere et al., 2002; Moreno et al., 2006). It was, also, smaller than earlier studies (Mitwally, 1999; Mitwally et al., 2004), whereas the abundance decreased from the overall mean 1581 ± 606 individuals 10 cm^{-2} during 1996 to overall mean values 38 ± 67 and 46 ± 108 individuals 10 cm^{-2} during 2012–2013, suggesting long-term beach ruin probably due to the coastal engineering that started at the end of the last century. Some studies documented a significant decrease in macrofauna and meiofaunal abundances, and their community structures due to coastal engineering (Hamdy & Ibrahim, 2019) or in the post dredging sites (Szymelfenig et al., 2006). To conclude, that the low meiofaunal abundance was an indicator of human-made activities. Moreover, the low meiofauna herein could also indicate the low productivity along beaches. Coull and Fleeger (1977) commented that low meiofaunal density is an indicator of low area productivity. The oligotrophic conditions dominate the eastern Mediterranean (Danovaro et al., 1999), southeastern Mediterranean (Dowidar, 1984), and the northwest coast of Alexandria (Zaki et al., 2009), suggesting that meiofaunal natural variability could be a good indicator of the low productivity.

Table 5 DISTLM results based on the simple matching resemblance of 8 criterion data, listed at Table (2) and Euclidean resemblance of 7 predictors among the beach factor and during the mild-cold period (MC). A list of abbreviations in Table 1 and 4

Predictor	Marginal tests-MC											
	HPHE				HPLE				CHE			
	SS_{trace}	*P-F*	*P*	Prop	SS_{trace}	*P-F*	*P*	Prop	SS_{trace}	*P-F*	*P*	Prop
%TOM	963.0	1.68	0.22	0.008	−5.8	−0.02	0.87	−0.000	271.9	0.92	0.44	0.009
φ	1403.5	2.46	0.07	0.012	306.2	0.81	0.48	0.008	579.8	1.98	0.16	0.020
Sorting	1873.3	3.30	0.04	0.016	1061.7	2.85	0.06	0.028	1069	3.70	0.03	0.036
pH	754.1	1.31	0.31	0.007	325.6	0.86	0.48	0.009	1145	3.98	0.02	0.039
T°C	1099.3	1.92	0.17	0.010	291.2	0.77	0.50	0.008	505.4	1.71	0.22	0.017
PSU	1542.1	2.70	0.07	0.013	679.3	1.80	0.18	0.018	558.2	1.9	0.17	0.019
TB	267.0	0.46	0.66	0.002	1375.0	3.72	0.03	0.037	−61.87	−0.2	0.94	−0.00
Res. df	198				198				198			

Sequential tests-MC

HPHE							
Predictor	SS (trace)	*P-F*	*P*	Prop	Cum	AICc	Res. df
+Sorting	1873.3	3.30	0.04	0.016	0.016	1270.6	98
+T°C	2155.1	3.86	0.01	0.019	0.035	1268.8	97
+TB	2746.3	5.00	0.01	0.024	0.059	1265.9	96
Best solution	AICc	R^2	RSS	Selection		Variation%	
	1265.9	0.059	0.077 E+05	3 (3,5,7)		~ 6.0%	
HPLE							
+TB	1375.0	3.72	0.03	0.037	0.037	593.24	98
+Sorting	1050.9	2.90	0.05	0.028	0.065	592.42	97
Best solution	AICc	R^2	RSS	Selection		Variation%	
	592.42	0.065	35,133	2 (3,7)		6.5%	
CHE							
Predictor	SS (trace)	*P-F*	*P*	Prop	Cum	AICc	Res. df
+pH	1144.9	3.98	0.02	0.039	0.039	568.33	98
+%Sorting	1128.6	4.04	0.03	0.038	0.077	566.37	97
+*φ*	0594.0	2.15	0.14	0.020	0.098	566.32	96

Table 5 (continued)

CHE							
Predictor	SS (trace)	*P-F*	*P*	Prop	Cum	AICc	Res. df
Best solution	AICc	R^2	RSS	Selection	Variation%		
	566.32	0.098	6,549,426,481	3(2–4)	~10.0%		

Lack of temporal variations and a low contribution of environmental factors to meiofaunal variability, in the current study, suggested that meiofaunal assemblages could have a stochastic distribution. The fundamental causes of a stochastic pattern are the rate of organisms birth, death, immigration, and emigration that occur at random (Gansfort et al., 2020). Despite the well-known patchy distribution of spatial meiofaunal abundance (Giere, 2009; Higgins & Thiel, 1988), some studies commented that meiofaunal distribution tends to have a stochastic pattern over time and space (Mitwally & Abada, 2008; Traunspurger & Majdi, 2017). In the current study, three tolerant taxa having different dispersal abilities Nematodes, Polychaete, and Harpacticoida were dominating our sandy beaches, and they could be the reason behind the increase in the role of local stochastic distribution. Dorgham et al. (2014) documented the dispersion patterns of macrofaunal polychaete along the Alexandrian coast that could impact the temporal meiofaunal distribution. At the same time, high energy could disturb meiofaunal abundance causing the passive migration into the water column or deeper inside the sediment, reducing the numbers, masking the responses to the environmental factors, and increasing the chances of stochastic distribution. Erosion causes a reduction in meiofaunal abundance and richness (Giere, 2009; Semprucci et al., 2011), and meiofauna at the exposed beaches can reach deep in sediment to avoid the effects of currents and wave action (Rodríguez, 2003).

Despite the lack of temporal variations, the within-month variability during the mild-cold period was high (Table 2; Appendix 1), suggesting that the temporal pattern was due to, perhaps, density-independent events; winter storms. Seasonal changes in natural forces drastically affect the temporal fluctuations of meiofaunal density (Riera et al., 2011; Sevastou et al., 2011; Sun et al., 2014), and winter storms effect could last for 2 weeks for meiofaunal recovery (Grémare et al., 2003). Groupings of meiofaunal data (Figs. 2a and 4a) resembled the physical data groupings, suggesting the importance of water quality factors as meiofaunal drivers. Salinity and pH explained about 12.5% of the total meiofaunal variation during the mild-cold period (Table 4), suggesting that they act as a proxy for other natural events, e.g., winter storms. Rain decreases water salinity over the Mediterranean Sea (Milner et al., 2012), salinity gradients affect nematode abundances (Adao et al., 2009), and the pH explained most

Table 6 DISTLM results based on the simple matching resemblance of 8 criterion data, listed Table 2, and Euclidean resemblance of 7 predictors' data among the beach factor and during the mild-warm period (MW). A list of abbreviations in Table 1 and 4

Predictor	Marginal tests-MW											
	HPHE				HPLE				CHE			
	SS_{trace}	P-F	P	Prop	SS_{trace}	P-F	P	Prop	SS_{trace}	P-F	P	Prop
%TOM	197.3	0.34	0.73	0.003	1376.8	3.36	0.03	0.033	1632	4.30	0.01	0.042
φ	835.5	1.47	0.25	0.015	1066.6	2.58	0.08	0.026	145.8	0.37	0.72	0.004
Sorting	63.4	0.11	0.82	0.001	0941.0	2.27	0.11	0.023	581.8	1.49	0.242	0.015
pH	489.38	0.86	0.46	0.009	0706.1	1.69	0.20	0.017	875.4	2.26	0.13	0.023
T◦C	−176.5	−0.3	0.97	−0.00	0525.2	1.26	0.34	0.013	1110	2.88	0.06	0.029
PSU	86.3	0.15	0.82	0.001	0070.2	0.17	0.80	0.002	−86.70	−0.2	0.91	−0.00
CB	123.6	0.21	0.79	0.002	0373.8	0.89	0.46	0.009	327.8	0.83	0.50	0.009
Res. df	98				98				98			

Sequential tests-MW

HPHE							
Predictor	SS (trace)	P-F	P	Prop	Cum	AICc	Res. df
+ φ	835.45	1.47	0.27	0.015	0.0145	636.44	98
− φ	835.45	1.47	0.28	0.015	0	635.84	99
Best solution	AICc	R^2	RSS	Selection		Variation%	
	635.84	0.000	56,567	*0*		0.0%	
HPLE							
+ %TOM	1376.8	3.36	0.04	0.033	0.033	603.66	98
+ φ	1305.9	3.26	0.04	0.031	0.065	602.48	97
Best solution	AICc	R^2	RSS	Selection		Variation%	
	602.48	0.065	38,852	2 (1, 2)		6.5%	
CHE							
Predictor	SS (trace)	P-F	P	Prop	Cum	AICc	Res. df
+ %TOM	1632.7	4.30	0.013	0.042	0.042	596.12	98
+ T◦C	1349.5	3.65	0.037	0.035	0.077	594.55	97
+ Sorting	1077.8	2.97	0.057	0.028	0.104	593.67	96
+ pH	1010	2.84	0.061	0.026	0.130	592.95	95
+ PSU	1176.4	3.39	0.045	0.030	0.161	591.67	94

Table 6 (continued)

CHE							
Predictor	SS (trace)	P-F	P	Prop	Cum	AICc	Res. df
Best solution	AICc	R^2	RSS	Selection	Variation		
	591.67	0.16	32,625	5 (1, 3–6)		16.0%	

Table 7 Pearson's correlation analysis between square root transformed data of meiofaunal taxa, total meiofauna, and square root transformed the bacterial data (total bacteria and Coliform bacteria) during mild-cold and mild-warm periods

Criterion	Predictor			
	Total bacteria		Coliform bacteria	
	N = 900		*N* = 900	
	R	*P*	R	*P*
Nematode	0.389	0.000	0.059	0.077
Polychaete	0.220	0.000	0.036	0.276
Foraminifera	0.194	0.000	0.002	0.961
Harpacticoida	0.256	0.000	0.109	0.001
Turbellaria	−0.063	0.057	−0.080	0.016
Halicardia	0.304	0.000	−0.034	0.313
Ostracods	0.064	0.054	−0.034	0.305
Archannelida	0.052	0.116	−0.034	0.310
Total meiofauna	0.342	0.000	0.049	0.139

N number of observations, *R* Pearson coefficient, *P* actual probability values, *df* degree of freedom

of the benthic biomass variability (First & Hollibaugh, 2010). A low water salinity value with a high standard deviation (Table 1) indicated that natural disturbances, winter storms, and heavy rain could be a key factor affecting the meiofaunal community. Moreover, the frequent intrusion of freshwater from the River Nile at the HPHE and HPLE could impact the faunal assemblages.

During the mild-warm period, despite the overall low contribution of environmental factors, sand particles alone explained a significant proportion, 3.5% (Table 4) to the total meiofaunal variation suggesting the importance of grain size in affecting meiofaunal distribution but other non-quantified factors, e.g., touristic activities, could homogenize sediment, minimize the within-month variability (Appendix 1), and mask the particle contribution. Many studies documented that despite the socio-economic profits of tourism, the rapid development of these activities resulted in beach disturbance, that characterized by low organic matter, low meiofaunal abundances, and species diversity (Defeo et al., 2009; Gheskiere et al., 2005; Nordstrom, 2004; Sun et al., 2014). Besides, touristic activities have proved as the essential source of fecal pollution (Korajkic et al., 2018; Torres-Bejarano et al., 2016). Studies along the Alexandrian coast classified beaches from very clean to highly polluted (El-Shenawy & El-Shenawy, 2009) based on coliform bacteria. However, the detected numbers were less than the Egyptian guide standards (500 CFU/100 ml) for recreational waters (George, 2009). Most of the unexplained variation in the meiofaunal community herein could be due to the effect of some non-quantified factors, e.g., winter storms and human-made stress, or because of the stochastic distribution. Alves et al. (2013) concluded that anthropogenic effluents caused a lack of meiofaunal temporal variations. Ostracods community analysis showed a large proportion of unexplained variation due to its highly stochastic variation (Gansfort et al., 2020). The proportion of variation in the meiofaunal community was higher during the mild-cold period (15%) than that during the mild-warm period (9%), suggesting that meiofaunal assemblages are more resilient to sources of natural disturbances than to anthropogenic stressors.

Among beaches, the contribution of environmental factors to the total variation of meiofaunal communities stated different ecological states, despite the overall low proportion of the explained variation, suggesting that each beach should be considered a unique case study for management decision-makers. Sediment sorting and total bacteria had a significant contribution to meiofaunal communities at the two highly polluted beaches (Table 5), indicating the importance of the sorting coefficient as an indicator of the wave action effect on sediment composition, which in turn drive meiofaunal community. The sediment sorting coefficient is a fundamental factor reflecting the hydrodynamic severity on grain particles, reshaping, influences sediment characteristics, and affect meiofaunal communities (Maria et al., 2013; Santos et al., 2019; Urban-Malinga et al., 2004). The significant contribution of total bacteria to the total meiofaunal (Table 5) is an indication of the biodegradation levels, and meiofauna could stimulate bacteria for biodegradation rather than for the feeding process. The contribution of total bacteria to the total meiofaunal variation was higher at a low energy beach (3.7%) than that at the high energy (2.4%), indicating that wave action affects meiofaunal-bacterial relationships. Meiofauna should have a high abundance to affect the microbial structure (Montagna, 1984), graze on 3% of total bacterial production (Pascal et al., 2008), and both communities responded to the environmental variability in the same way (Papageorgiou et al., 2007). High energy causes a large scale of pollution dispersion (Defeo et al., 2009), and low energy induces a high retention rate of pollutants and reduces the biodegradation rate (Lee & Levy, 1991; Lo et al., 2018). To conclude, the synergetic effects of energy strength, pollution, and stochastic distribution at the highly polluted beaches could be the main reasons behind the low prediction of meiofaunal drivers during the cold period (6% and 6.5%).

The lack of significant contribution or the weak contribution of environmental factors to total meiofaunal variations (Table 6) could be a proxy for the beach ruin due probably to the touristic activities that synergistically added more stressor effect at the polluted beaches (Table 6). Itoh et al. (2011) considered a lack of significant contribution of environmental factors to meiofaunal variation as a proxy for important non- quantified forces in their study, and beaches experience high recreational levels are designated moderately and highly disturbed areas (Pereira et al., 2017). The higher the proportion of the environmental contribution to the total meiofaunal variation at the mild-cold period than that at the mild-warm periods at the highly polluted beaches suggested that the meiofaunal community was more resilient to natural forces act on sediment structure high energy during the winter than to human-made disturbance during summer tourism activities.

The clean high energy beach, CHE, stated a different ecological state, where it occupied the lowest meiofaunal abundances (Fig. 3) and the highest proportion of environmental contribution to the total meiofaunal variation (Tables 5 and 6). In contrast to the polluted beaches, this proportion was higher during the mild-warm period than during the mild-cold period (16% vs. 10%), indicating that the lower the human-made activities, the higher the response of meiofaunal assemblages to their environmental factors during the warm period. This beach could be under the antagonistic effects of different natural and human-made forces. The CHE is non-urbanization and had a low rate of touristic activities that could explain the higher the environmental contribution to the meiofaunal communities, whereas wave energy, rip currents (Nafaa & Frihy, 1993), and the dominance of oligotrophic conditions (Zaki et al., 2009) affect meiofaunal assemblages, concluding that touristic activities and coastal engineering harm meiofaunal communities more than the natural disturbances.

Our best model results indicate that the low contribution of environmental factors to the meiofaunal community was a beach assessment tool. The beach, Abo-Qir Bay, under the synergetic effect of natural disturbances and many land-based sources of nutrients, industrial, and domestic wastes at HPHE, revealed the worse prediction. The beach EL-Mex Bay that experiences mainly anthropogenic discharges: industrial, agricultural, sewage, and hydrocarbon pollution at HPLE, had a low estimation, and the beach North West Coast that experiences natural disturbances and limited anthropogenic stressors, such as coastal engineering at CHE, revealed the most tolerable prediction. However, many studies commented that it is difficult to differentiate between the effect of the natural disturbance from the anthropogenic stressors (Schratzberger et al., 2009; Semprucci et al., 2011), and many indirect factors complicate the relationships between the faunal assemblages and their driving forces (Tolhurst et al., 2010). Our low meiofaunal abundances and their environmental contribution suggested that the more the beach exposure to different sources of anthropogenic stressors, the higher the beach ruins are. The beach state became worse when the natural disturbances integrated synergistically with human-made activities. We suggest for management decision-makers to consider each beach a unique case study and manipulate alone, putting into consideration human-made activities the mechanical engineering, pollution, tourism activities, besides the natural forces winter storms, high energy, and rip currents.

The weak and a lack of correlation between bacterial communities and different meiofaunal taxa (Table 7) suggested the idea of the alternative food meiofauna grazed bacteria when algal abundance and biomass are very low (Pascal et al., 2009). Studies documented strong meiofaunal-algal correlations (Evrard et al., 2012; Mitwally et al., 2004). The dynamical character of our sandy beaches and the high levels of sediment toxicity at the polluted beaches are other causal factors that could mask the meiofaunal-bacterial interaction as many studies (Maria et al., 2016; Montagna et al., , 1987, 1989; Urban-Malinga et al., 2004) suggested. Our study does not prove the importance of bacteria as a meiofaunal food source. However, the low counts of coliform bacteria (Table 1) evidenced that Alexandrian sandy beaches are free of pathogenic diseases, and we recommended further studies for a better understanding of the meiofaunal-bacterial relationship.

Conclusions

The current work is the first study that has investigated the environmental drivers of meiofaunal natural variability at the southeastern Mediterranean coast, Alexandria, Egypt, in an attempt to assess the ecological status of three challenging sandy beach ecosystems. Low meiofaunal abundance indicates that natural variability is a good indicator of long-term beach ruin and oligotrophic conditions. Lack of temporal variation indicates that the meiofauna could have a stochastic distribution. The significant contribution of water salinity and sand particles to the total meiofaunal variations, despite their low proportion, indicate their role as proxies for winter storms and touristic activities. The synergetic effect of stochastic variation, natural disturbances, and human-made disturbances controlled the meiofaunal natural variability and masked the contribution of the well-known environmental factors to the total meiofaunal variation. The ecological assessment of sandy beaches ranged from very bad, bad, and to some extent, tolerable according to the contribution of the well-known environmental factors to the meiofaunal natural variability.

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