

1 **Biogeosciences**

2 **Research Paper**

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4 **Baseline for ostracod-based northwestern Pacific and Indo-Pacific shallow-**  
5 **marine paleoenvironmental reconstructions: ecological modeling of species**  
6 **distributions**

7

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28 Abstract:

29 Fossil ostracods have been widely used for Quaternary paleoenvironmental  
 30 reconstructions especially in marginal, marine environments (e.g. for water depth,  
 31 temperature, salinity, oxygen levels, pollution). But our knowledge of indicator  
 32 species, autoecology, the base of paleoenvironmental reconstructions, remains limited  
 33 and commonly lacks robust statistical support and comprehensive comparison with  
 34 environmental data. We analysed marginal, marine ostracod taxa at 52 sites in Hong  
 35 Kong for which comprehensive environmental data are available. We applied linear  
 36 regression models to reveal relationships between species distribution and  
 37 environmental factors for 18 common taxa (mainly species, a few genera) in our  
 38 Hong Kong dataset, and identified indicator species of environmental parameters. For  
 39 example, *Sinocytheridea impressa*, widely distributed euryhaline species throughout  
 40 the East and South China Seas and the Indo-Pacific, indicates eutrophication and  
 41 bottom-water hypoxia, *Neomonoceratina delicata*, widely known species from  
 42 nearshore and estuarine environments in the East and South China Seas, and the Indo-  
 43 Pacific, indicates heavy-metal pollution and increased turbidity, The 18 taxa used for  
 44 this study are widely distributed geographically and divided into Widespread  
 45 (throughout the northwestern Pacific and Indo-Pacific regions), Temperate [South  
 46 China Sea to Russia (Sea of Japan coast) and Japan], Subtropical (Indo-Pacific to the  
 47 East China Sea), Tropical (Indo-Pacific and South China Sea), and Globally  
 48 Distributed Groups. With statistical support from ecological modeling and  
 49 comprehensive environmental data, these results provide a robust baseline for

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69 ostracod-based Quaternary-Anthropocene paleoenvironmental reconstructions in the  
70 tropical–extratropical northwestern Pacific and Indo-Pacific widely.

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72 Key words: Autoecology, Distribution modeling, Indicator species, Ostracoda,  
73 Paleoenvironmental reconstruction, Proxy.

74

### 75 Key points

76 1. We provide a robust baseline for ostracod-based (microscopic Arthropods)  
77 paleoenvironmental reconstructions from Quaternary and Anthropocene marginal  
78 marine sediments.

79 2. The studied species have wide distributions over the tropics and extratropics of the  
80 northwestern Pacific and Indo-Pacific.

81 3. Ecological modeling established reliable indicator ostracod species for  
82 paleoenvironmental reconstructions.

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### 86 1. Introduction

87 Because of their small size, high abundance and excellent fossil record, fossil  
88 ostracods (microcrustaceans) have been widely used to reconstruct Quaternary  
89 environmental conditions including water-depth, salinity, temperature, oxygen, and  
90 pollution, especially in marginal marine sediments (Boomer & Eisenhauer, 2002;  
91 Cronin, 2015; Frenzel & Boomer, 2005; Horne et al., 2012; Ruiz et al., 2005). In the  
92 northwestern Pacific and Indo-Pacific there are numerous deltas (Woodroffe et al.,  
93 2006) hosting accumulated Holocene marine sediments. Many studies have

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97 reconstructed the depositional environments of these sediments (Alberti et al., 2013;  
98 Dong et al., 2012; Irizuki et al., 2015b; Tanaka et al., 2011; Yasuhara & Seto, 2006;  
99 Yasuhara et al., 2005; Zhou et al., 2015; [Wang et al., 2018](#)). Due to high  
100 sedimentation rates (> 1 cm per year), fossil ostracods allow the high-resolution  
101 reconstruction of human-induced environmental changes (pollution, eutrophication,  
102 bottom oxygen depletion) over the past century (Irizuki et al., 2011; [Irizuki et al.,  
103 2015a](#); [Irizuki et al., 2018](#); Yasuhara et al., 2003; [Yasuhara et al., 2007](#)).

104  
105 Many have evaluated the autoecology of ostracod indicator species as the  
106 basis for paleoenvironmental reconstructions (Hazel, 1988; Irizuki et al., 2003; Ozawa  
107 et al., 2004; Stepanova et al., 2003; Wang et al., 1988; Yasuhara & Seto, 2006; Zhao,  
108 1984; Zhao & Wang, 1988a, 1988b). Yet these studies tend to focus on only one or a  
109 few targeted environmental factor(s) and lack rigorous statistical evaluation,  
110 particularly statistical modeling, a common approach in contemporary ecology. This  
111 is probably due to the fact that comprehensive environmental datasets are often  
112 unavailable and an ecological modeling approach (especially regression modeling and  
113 model selection) has not been common in this field of micropaleontology.

114  
115 Hong Kong constitutes an ideal location for a marine ecological modeling  
116 approach in the northwestern Pacific and Indo-Pacific regions because of extensive  
117 and intensive marine environmental monitoring program and subtropical location  
118 where tropical and temperate species coexist. This program provides robust datasets  
119 for ecological modeling and the subtropical location allows the investigation of  
120 species with different latitudinal and geographical distributions. We employed  
121 regression modeling of Hong Kong shallow-marine ostracod species to show

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143 statistical relationships between species abundance, distribution and environmental  
144 factors. This study allows the autoecology and statistical evaluation of common  
145 tropical and extratropical species, providing a baseline for ostracod-based shallow-  
146 marine paleoenvironmental reconstructions of the northwestern Pacific and Indo-  
147 Pacific regions.

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## 149 2. Study area

150 Hong Kong is situated at the southeastern corner of the Pearl River (Zhujiang) Delta,  
151 and has an area of 2500 km<sup>2</sup> (Fig. 1), at 22° 12.021' to 22° 33.817' N latitude, 113°  
152 53.388' to 114° 26.920' E longitude. It is an ideal location to study natural and/or  
153 anthropogenic impacts on benthic communities due to its complex hydrology and  
154 long history of human influence. Western Hong Kong is affected by input from the  
155 Pearl River, particularly during the summer heavy rainfall (Morton & Wu, 1975),  
156 when surface water salinity is strongly influenced by rainfall. Eastern Hong Kong  
157 waters are mainly marine and derived from the South China Sea. As one of the most  
158 urbanized coastal areas in the world, human activities, including rapid industrialization,  
159 sewage discharge, trawling, dredging and land reclamation have led to a deteriorated  
160 marine benthic ecosystem (Blackmore, 1998; Hodgkiss & Yim, 1995; Hong et al.,  
161 2017; Hu et al., 2008; Morton, 1996; Morton & Blackmore, 2001; Owen & Sandhu,  
162 2000; Shin, 1977; Tanner et al., 2000).

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## 164 3. Materials and Methods

### 165 3.1. Samples and laboratory procedure

166 In January and July of 2011 we used a Van Veen Grab to collect 100 ml of sediment  
167 from the uppermost centimeter of the sea floor from 52 sites in Hong Kong marine

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173 waters (Fig. 1; Supplement A), 41 of which are in open waters and 11 in typhoon  
174 shelter sites. Typhoon shelters are semi-enclosed areas of water designed to protect  
175 moored vessels in extreme weather (Environmental Protection Department, 2011). All  
176 sites are included in the Hong Kong EPD marine water and sediment quality  
177 monitoring program, which has been conducted monthly since 1986 (for water) and  
178 biannually (for sediment), providing comprehensive environmental data for all  
179 stations (see below).

180 Sediments were wet-sieved over a 63  $\mu\text{m}$  mesh sieve and air dried or oven-  
181 dried at 40 °C. The residue was dry-sieved over a 150  $\mu\text{m}$  mesh sieve, and ostracod  
182 specimens larger than 150  $\mu\text{m}$  were picked; smaller individuals [are mostly early instar](#)  
183 [juveniles that are often not preserved \(because their shells are usually thin and](#)  
184 [delicate\) or difficult to identify \(see Yasuhara et al., 2009 and Yasuhara et al., 2017](#)  
185 [for more details\)](#). In samples containing fewer than 200 specimens, we picked all  
186 individuals. If there were more than 200 specimens, we picked ostracods from a split.  
187 We identified each counted specimen to species level when possible. We considered  
188 both an entire carapace or a single valve as one individual for counting.

189

### 190 3.2 Environmental Variables

191 We selected parameters from the EPD monitoring program (Table 1) for our  
192 regression modeling (see below), including surface productivity (Chlorophyll-a, Chl;  
193 Fig. 2), water depth (D; Fig. 2), bottom water dissolved oxygen (DO; Fig. 2), bottom  
194 water salinity (Sal; Fig. 2), turbidity (Tur; Fig. 2), summer bottom water temperature  
195 (ST – June to September average; Fig. 2), winter bottom water temperature (WT –  
196 November to February average; Fig. 2), mud content (MD; Fig. 2), and heavy metal  
197 concentration (Cu, Zn, and Pb; Fig. 3). These parameters are known to control

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202 ostracod faunal properties (Cronin, 2015; Cronin & Vann, 2003; Hazel, 1988; Ikeya  
203 & Shiozaki, 1993; Irizuki et al., 2005; [Irizuki et al., 2015a](#); [Irizuki et al., 2018](#); Ruiz et  
204 al., 2005; Yasuhara et al., 2007; Yasuhara et al., 2012b). We used averages over the  
205 entire monitoring period (1986–2011), because the ostracods in this study were  
206 mostly dead shells, thus the samples should be considered time averaged. Bottom  
207 water DO is the average of the summer season (June–September), due to the likely  
208 importance of summer bottom water oxygen depletion.

209

#### 210 **4. Regression modeling**

211 Multiple linear regression modeling was used to determine the relationship between  
212 common ostracod species (relative abundance of each species) and environmental  
213 parameters (Supplement B). All environmental parameters were log-transformed and  
214 zero centered. Salinity outliers (salinity <25: DS2 and DS3) and samples with low  
215 abundance (<50 specimens: ES5, MS7, VS21, VS5 & VS6) were removed from the  
216 models.

217 The best-fitting models were selected based on Akaike's Information Criterion  
218 (AICc) for small sample size, in which the lower score indicates the better model  
219 support considering both goodness-of-fit and model complexity (Anderson &  
220 Burnham, 2002). Akaike weights were used to summarize proportional support for all  
221 candidate models (Anderson et al., 2000) (Table 2). We considered parameter  
222 estimates averaged over models, proportional to the support that each model received  
223 (Anderson et al., 2000) (Table 3). This approach accounts for the uncertainty in model  
224 selection and thus leads to appropriately broader confidence intervals than obtained  
225 by relying only on the single, best-supported model. The relative importance of  
226 various predictor variables was measured by the sum of Akaike weights of models

227 that included the variables in question (Brunham & Anderson, 2002).

228 We explored linear dependencies by computing variance inflation factors (VIF)  
229 (Legendre & Legendre, 1998) and pairwise correlations between predictor variables  
230 to assess whether multicollinearity was likely to influence regression results  
231 (Yasuhara et al., 2012b). The degree of freedom is more than one for the geographic  
232 region variable (see below), thus we computed generalized variance inflation factors  
233 (GVIF). For continuous variables, GVIF (Table 4) is the same as VIF, but for  
234 categorical variables, GVIF has degrees of freedom (Df) equal to the number of  
235 coefficients associated with it (Hendrickx et al., 2004). Thus, we used  $GVIF^{1/2df}$  to  
236 make GVIF values comparable among those with different Df.  $VIF > 20$  is usually  
237 indicative of high collinearity (Legendre & Legendre, 1998). Thus we calculated an  
238 equivalent threshold of 4.47 (equal to  $\sqrt{20}$ ) for  $GVIF^{1/2df}$  to assess conlinearity. Also,  
239 adjusted  $R^2 > 0.8$  indicates a strong correlation of variables (Hoffman, 2015). In all  
240 datasets, summer temperature (ST) and ~~z~~copper (Cu) were highly correlated  
241 ( $R^2=0.8217$ ), and the GVIFs of ST and Cu are  $>20$ , indicating that these correlations  
242 may influence regression results. Thus, we re-ran the linear regression modeling  
243 without ST and Cu. The new GVIFs of all variables were under 4.47 (Table 4).

244 We considered the degree of spatial autocorrelation in model residuals by the  
245 calculation of Moran's *I* index for the five best models. The neighborhood size was  
246 set as 2, 5, 10, 20 and 50 km. We found significant spatial autocorrelation in model  
247 residuals for many cases, thus we forced the geographic region variable (R) (Water  
248 Control Zones defined by EPD) to be included in all models. After this treatment,  
249 spatial autocorrelation was detected only in a few models for *Propontocypris* spp.,  
250 *Stigmatocythere roesmani*, and *Hemikrithe orientalis*.

251 The multiple linear regression model analyses were implemented in R

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253 programming language (R Core Team, 2016). We used 'M<sub>U</sub>MI<sub>N</sub>' (Bartoń, 2013) for  
254 model averaging and 'SPDEP' (Bivand & Piras, 2015) to measure spatial  
255 autocorrelation.

256

## 257 5. Results and discussions

258 The comprehensive ostracod dataset for the 52 sites and the environmental variables  
259 enabled us to elucidate distribution patterns of common ostracod taxa and their related  
260 environmental factor(s). We identified 151 species belonging to 76 genera  
261 (Supplement A). Among them, 18 common taxa (mainly species, a few genera) of

262 *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Nipponocythere bicarinata*,

263 *Spinileberis quadriaculeata*, *Phlyctocythere japonica*, *Loxoconcha epeterseni*,

264 *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Keijella kloempritis*,

265 *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Hemicytheridea reticulata*

266 *Loxoconcha malayensis*, *Alocopocythere goujoni*, *Hemikrithe orientalis*,

267 *Propontocypris* spp., *Neonesidea* spp. and *Xestoleberis* spp. (Supplement B) were

268 used for regression modelling, and their relative abundances (to the total ostracod  
269 abundance in a sample) show a significant relation with environmental parameters.

270 The best three regression models are presented in Table 2 and the model-averaged  
271 parameter estimates in Table 3. A small percentage of specimens of phytal genera

272 (e.g., *Xestoleberis* spp., *Neonesidea* spp.) were contained in each sample, which are

273 basically allochthonous specimens in bottom sediments transported from surrounding

274 phytal environments. The value of allochthonous species to environmental

275 interpretation is limited, however, most ostracod specimens in each sample are

276 composed of benthic, muddy sediment dwellers which are considered autochthonous.

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312 Ostracods were divided into four groups based on their geographic  
313 distributions, including (a) Widespread Group; (b) Temperate Group; (c) Subtropical  
314 Group; (d) Tropical Group; and (e) Globally distributed Group (Fig. 4).

317 a. **Widespread Group**

318 Only one species *Pistocythereis bradyi* constitutes Widespread Group.  
319 *Pistocythereis bradyi* is widely distributed throughout the marginal marine  
320 environments of Japan, the East and South China Seas, and the Indo-Pacific (Fig. 4).  
321 Relative abundance of *P. bradyi* was highly correlated with salinity (positive), water  
322 depth (negative) and Pb (negative) (Tables 2 and 3). This indicates that the species  
323 prefers relatively shallow environments with high salinity (Figs. 2 and 5). In the Pearl  
324 River Delta and shallow South China Sea (Fig. 4), *P. bradyi* is dominant along the  
325 inner continental shelf at water depths <100 m (mostly common between 10–50 m),  
326 and at salinities from 30–40 (Li, 1985; Zhao & Wang, 1990; Zhao et al., 1986).  
327 *Pistocythereis bradyi* is a typical middle muddy bay species in Japan (Irizuki et al.,  
328 2006; Yasuhara & Irizuki, 2001; Yasuhara & Seto, 2006), and known from open bays  
329 such as Gamagyang Bay in Korea (Abe, 1988) and Malacca Strait (Whatley & Zhao,  
330 1988b). In these studies, *P. bradyi* prefers relatively high salinity and deeper water in  
331 the inner continental shelf. Our data agree as to the preference for high salinity, but  
332 inconsistent with the literature regarding shallower water depths (Tables 2 and 3).  
333 Salinity may be more important than depth, but the restricted depth range of our sites  
334 (<35 m) may also be a reason for this inconsistency. Our results indicate that *P.*  
335 *bradyi* is sensitive to metal pollution (Tables 2 and 3).

337 b. **Temperate Group**

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520 Five species including *Bicornucythere bisanensis* s.l., *Nipponocythere*  
521 *bicarinata*, *Spinileberis quadriaculeata*, *Phlyctocythere japonica* and *Loxoconcha*  
522 *epeterseni* are distributed from Japan-Russian Coast to South China Sea.

523 *Bicornucythere bisanensis* s.l. is very common in most samples, the relative  
524 abundance of which was significantly correlated with water depth (negative) (Tables  
525 2 and 3) and this species prefers shallower environments (Figs. 2 and 5). In Chinese  
526 and Japanese coastal areas, *B. bisanensis* s.l. is abundant in brackish water (salinity:  
527 20–30) at depths less than 10 m (Ikeya & Shiozaki, 1993; Irizuki et al., 2006; Zhao et  
528 al., 1986). Our results confirm this preference for shallow depths. In Japan,  
529 *Bicornucythere bisanensis* is tolerant of anthropogenic impacts, especially  
530 eutrophication and the resulting bottom water hypoxia (Irizuki et al., 2003; Irizuki et  
531 al., 2011; Irizuki et al., 2015a; Irizuki et al., 2018; Yasuhara et al., 2003; Yasuhara et  
532 al., 2007; Yasuhara et al., 2012a). We did not see a significant relation between  
533 relative abundance and metal concentration, productivity, or dissolved oxygen.  
534 Possibly, the more dominant presence of *S. impressa* and *N. delicata*, that are neither  
535 dominant or distributed throughout most of Japan, could explain this difference.  
536 These species may have a higher tolerance than *B. bisanensis* s.l.. Another  
537 explanation may be that different morphotypes have different ecological preferences  
538 (Abe, 1988), and only Form A is known to be tolerant to eutrophication and bottom-  
539 water oxygen depletion (Irizuki et al., 2011; Irizuki et al., 2015a; Irizuki et al., 2018;  
540 Yasuhara & Yamazaki, 2005; Yasuhara et al., 2007). Form A is less abundant in  
541 Hong Kong, and due to the difficulty of juvenile identification, we did not divide *B.*  
542 *bisanensis* into morphotypes. *Bicornucythere bisanensis* s.l. is widely distributed  
543 throughout marginal marine environments around Japan, Russia (Sea of Japan coast),  
544 and the East and South China Seas (Fig. 4).

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552 Relative abundance of *N. bicarinata* correlated with productivity (negative)  
553 (Tables 2 and 3). This is a typical middle bay species in Japan (Irizuki et al., 2006),  
554 abundant on muddy substrates at water depths >10 m (Yasuhara & Seto, 2006;  
555 Yasuhara et al., 2005). We found *N. bicarinata* to be sensitive to eutrophication,  
556 preferring lower productivity (Figs 2 and 5). This species is know from marginal  
557 marine environments around Japan and the East and South China Seas (Fig. 4).

558 Relative abundance of *S. quadriaculeata* correlated to productivity (positive),  
559 and turbidity (negative) (Tables 2 and 3). This is a typical inner muddy bay species in  
560 Japan (Irizuki et al., 2006), which prefers silty substrates in brackish waters, at  
561 salinities from 20–30, and water depths of 2–7 m (Ikeya and Shiozaki, 1993). This  
562 study shows a preference for waters with higher productivity but relatively low  
563 turbidity (Tables 2 and 3), so that the species is abundant in Tolo Harbour (higher  
564 productivity, lower turbidity) but not in Deep Bay (higher turbidity) (Figs. 2 and 5).  
565 *Spinileberis quadriaculeata* is not tolerant to seasonal anoxia or oxygen depletion (0–  
566 1 mg/L) in Uranouchi Bay, Japan (Irizuki et al., 2008), but we do not find a  
567 significant correlation with dissolved oxygen content, probably due to the relatively  
568 high bottom-water oxygen content (2.96–6.84 mg/L) in Hong Kong (Fig. 2;  
569 Supplement B). *Spinileberis quadriaculeata* is widely distributed in marginal, marine  
570 environments around Japan, Russia (Sea of Japan coast), and the East and South  
571 China Seas (Fig. 4).

572 Relative abundance of *P. japonica* correlated with water depth (positive)  
573 (Tables 2 and 3). This species is known from relatively deeper waters (>40 m) in the  
574 East China Sea (Ishizaki, 1981; Wang et al., 1988). At our sites, it has its greatest  
575 abundance at the deeper southern sites (Fig. 5). *Phlyctocythere japonica* is distributed  
576 around Japan (Yasuhara et al., 2002) and the East and South China Seas (Fig. 4).

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587 Similarly to *P. japonica*, relative abundance of *L. epeterseni* correlated with water  
 588 depth (positive), and turbidity (negative) (Tables 2 and 3). It occurs in the southern  
 589 and eastern, deeper and less turbid regions of Hong Kong waters, but the trend is not  
 590 very clear (Figs 2 and 5). This species is also known from the deeper parts of Osaka  
 591 Bay (Yasuhara & Irizuki, 2001) and marginal marine environments around Japan  
 592 (Ishizaki, 1968), the East China Sea (Hou et al., 1982), and the South China Sea (Cao,  
 593 1998) (Fig. 4). This species is reported as *Loxoconcha modesta* in Hou & Gou (2007),  
 594 and also has been misidentified as *Loxoconcha viva* and *Loxoconcha sinensis* (Hou &  
 595 Gou, 2007). Ishizaki (1968) described *Loxoconcha laeta* and *Loxoconcha modesta*,  
 596 but these are the females and males of the same species (Ikeya et al., 2003). Ishizaki  
 597 (1981) gave the new species names *Loxoconcha epeterseni* and *Loxoconcha*  
 598 *tosamodesta* for *Loxoconcha laeta* and *Loxoconcha modesta*, respectively, because  
 599 these names were junior homonyms. Since *Loxoconcha laeta* (= *epeterseni*) appears  
 600 earlier than *Loxoconcha modesta* (= *tosamodesta*) in the original description (Ishizaki,  
 601 1968), we use the name *Loxoconcha epeterseni* for this species (e.g., see Ikeya et al.,  
 602 2003).

603

604 **c. Subtropical Group**

605

606 Six species including *Sinocytheridea impressa*, *Neomonoceratina delicata*,  
 607 *Keijella kloempritisensis*, *Neosinocythere elongata*, *Stigmatocythere roesmani* and  
 608 *Hemicytheridea reticulata* are reported from the East China Sea to Indo-Pacific area.

609 *Sinocytheridea impressa* [= *Sinocytheridea latiovata*; see Whatley and Zhao  
 610 (1988a)] is the most dominant species in this study, the relative abundance of which  
 611 significantly correlated with salinity (negative), dissolved oxygen (negative), mud  
 612 content (positive) and productivity (positive) (Tables 2 and 3). This species is

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631 noticeably dominant in areas characterized by a muddy bottom including northern  
 632 Mirs Bay, Port Shelter and coastal Southern Waters (Fig. 5). It is also abundant in  
 633 Tolo Harbour, an area known for its summer hypoxia and eutrophication (Hu et al.,  
 634 2001; Sin & Chau, 1992). These results are consistent with previous studies indicating  
 635 that *S. impressa* is dominant in low salinity, nutrient-rich and turbid estuaries (Irizuki  
 636 et al., 2005; Tanaka et al., 2011), but we did not see a significant relation with  
 637 turbidity (Tables 2 and 3). *Sinocytheridea impressa* is known as a euryhaline species  
 638 widely distributed throughout the East and South China Seas [abundant in water  
 639 depths of <20 m; Whatley and Zhao (1988a)], and the Indo-Pacific (Fig. 4).

640 *Neomonoceratina delicata* (= *Neomonoceratina crispata*; see Hou & Gou,  
 641 2007) is very common in most of the samples, and the relative abundance  
 642 significantly correlates with Zn (positive), salinity (positive) and turbidity (positive)  
 643 (Tables 2 and 3). *Neomonoceratina delicata* is a nearshore species, abundant at depths  
 644 less than 30 m, at relatively high salinities (>30; Zhao and Wang, 1988). It prefers the  
 645 higher salinity waters in Hong Kong (Figs. 2 and 5; Tables 2 and 3), and in view of its  
 646 positive correlation with Zn and turbidity, is likely tolerant to human-induced  
 647 environmental stress such as pollution and eutrophication. This species is widely  
 648 known from nearshore and estuarine environments in the East and South China Seas,  
 649 and the Indo-Pacific (Fig. 4).

650 The relative abundance of *K. kloempritis* correlated only with water depth  
 651 (positive) (Fig. 6; Tables 2 and 3). Widely known from the tropical Indo-Pacific  
 652 region, *K. kloempritis* is abundant along the inner continental shelf of the South  
 653 and East China Seas (Fig. 4), at water depths ranging from 20–50 m and salinity close  
 654 to normal marine (Zhao & Wang, 1990). Our modelling results are consistent with  
 655 this, showing a preference for the relatively deeper waters in our study (Tables 2 and

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676 3). Thus, this species is probably useful for reconstructing past sea-level changes in  
677 the broad tropical and subtropical Indo-Pacific and northwestern Pacific regions as a  
678 deeper water indicator.

679 Relative abundance of *N. elongata* correlated only with turbidity (positive)  
680 (Tables 2 and 3). This species occurs along the entire coast of China (Fig. 4) in  
681 marginal marine, especially estuarine environments shallower than 20 m (Dong et al.,  
682 2012; Hou & Gou, 2007; Liu et al., 2013; Liu et al., 2017; Zhao & Whatley, 1993)  
683 (Fig. 4). Known from the Indo-Pacific region, our modeling results and previous  
684 studies indicate consistently that *N. elongata* prefers shallow, turbid waters like Deep  
685 Bay and the Pearl River Estuary (Figs 2 and 6).

686 The relative abundance of both *S. roesmani* and *H. reticulata* correlated with  
687 Pb (negative) (Tables 2 and 3), thus they are sensitive to metal pollution (but note the  
688 significant autocorrelation with the modeling result of *S. roesmani*) and absent in  
689 areas with high metal concentrations, e.g., Tolo and Victoria Harbours (Fig. 3, 6).  
690 Relative abundance of *H. reticulata* also correlated with water depth (negative)  
691 (Tables 2 and 3). This species is abundant in Tolo Harbour and the inner part of Mirs  
692 Bay (Fig. 6), at shallow depths, and is also consistently found in very shallow waters  
693 from the Indo-Pacific (Zhao & Whatley, 1989). Their metal-pollution sensitivity is  
694 contradictory because they occur in Tolo and Victoria Harbours, both polluted regions  
695 of Hong Kong, and further research is needed to better understand these results (Figs  
696 2 and 6). They occur in the East and South China Seas and the Indo-Pacific region  
697 (Fig. 4).

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699 d. Tropical Group

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719 Three species including *Loxoconcha malayensis*, *Alocopocythere goujoni* and  
720 *Hemikrithes orientalis* are distributed from the South China Sea to the Indo-Pacific.  
721 Relative abundance of *L. malayensis* correlated with dissolved oxygen  
722 (negative) and mud content (negative) (Tables 2 and 3). It is a typical tropical species  
723 known from the Indo-Pacific and the South China Sea (Fig. 4). We did not find a  
724 correlation with temperature, likely due to the small range of variation of bottom  
725 water temperatures in Hong Kong (winter temperature: 19.10–21.49°C). This species  
726 prefers coarse sediments and is resistant to low oxygen content (Table 2 and 3), as  
727 seen by its abundance in Victoria Harbour (Figs. 2 and 6).  
728 Relative abundance of both *A. goujoni* and *H. orientalis* correlated with  
729 natural factors only. *Alocopocythere goujoni* correlated with salinity (positive)  
730 (Tables 2 and 3) and occurs not only in Mirs Bay where the salinity is higher, but also  
731 in Deep Bay and North Western Waters where the salinity is lower than in other areas  
732 (Figs 2 and 6). The Deep Bay and North Western Waters are shallow and have  
733 relatively low oxygen content. The modeling result of this species shows a marginally  
734 insignificant but negative relationship to oxygen content and water depth with  
735 moderately high relative importance (Table 3). We explain this inconsistency by  
736 considering their preference for higher salinity and shallow water depths, and also  
737 their resistance to low oxygen conditions, but further research is needed to know their  
738 autoecology with better confidence. Relative abundance of *H. orientalis* correlated  
739 with water depth (positive) (Tables 2 and 3; but note the significant autocorrelation  
740 with the modeling result of this genus), and it is more abundant in deeper waters  
741 including southern Mirs Bay (Fig. 6). It is known from depths of 20–50 m in the  
742 South China Sea (Zhao & Wang, 1988a), and reported from tropical Indo-Pacific  
743 marginal marine environments (Fig. 4). Our regression modeling consistently shows a

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757 positive relationship between relative abundance and winter temperatures, with  
758 moderately high relative importance, although the correlation is marginally  
759 insignificant (Table 2 and 3).

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761 e. **Globally Distributed Group**

762 *Propontocypris* is known as a cosmopolitan genus. The relative abundance of  
763 *Propontocypris* spp. significantly correlated with productivity (negative) (Tables 2  
764 and 3). This negative correlation with productivity (but note a significant  
765 autocorrelation with the modeling result of this genus) indicates that the genus prefers  
766 less eutrophic waters (Fig. 6). *Propontocypris* is a good swimmer (Maddocks, 1969),  
767 and thus may have an advantage in obtaining food in relatively food-limited  
768 environments.

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769 Phytal genera including *Neonesidea* spp. and *Xestoleberis* spp. have global  
770 distribution and are correlated with various environmental factors. The relative  
771 abundance of *Neonesidea* spp. correlated with dissolved oxygen (positive), as  
772 expected for a phytal species (Smith & Kamiya, 2002; Yamada, 2007) (Table 2 and 3;  
773 Fig. 7). Similarly, phytal (Irizuki et al., 2008; Sato & Kamiya, 2007; Yasuhara et al.,  
774 2002) *Xestoleberis* spp. correlated with dissolved oxygen (positive), turbidity  
775 (negative) and mud content (negative) (Table 2 and 3; Fig. 7). This taxon's habitat  
776 preference including clear water, coarse sediment, and high oxygen content are  
777 reflected in our modeling. As mentioned above, the value of allochthonous phytal  
778 species to environmental interpretation is limited, but they broadly reflect adjacent  
779 phytal environments.

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781 **Summary**

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787 Benthic ostracods from Hong Kong marginal marine waters studied here include  
788 widespread (i.e., *one species* distributed throughout the northwestern Pacific–Indo-  
789 Pacific region), temperate (i.e., *five species* distributed from the South China Sea to  
790 Japan and Russia), subtropical (i.e., *six species* distributed from the Indo-Pacific to  
791 the East China Sea), and tropical (i.e., *three species* distributed in the Indo-Pacific and  
792 South China Sea) species and three globally distributed genera (Fig. 4). We provide a  
793 robust baseline of autoecology for these common ostracod taxa based on rigorous  
794 statistical modeling using comprehensive environmental data. We established reliable  
795 indicator *taxa* for water depth, mud content, salinity, turbidity, dissolved oxygen,  
796 heavy metal pollution (Pb and Zn) and eutrophication (chlorophyll-a) (Table 5). Thus  
797 our results are applicable for future ostracod-based paleoenvironmental studies in a  
798 wide range of localities from the tropics to the extratropics, and from the Indian  
799 Ocean to the northwestern Pacific. We established pollution and eutrophication  
800 indicator species in tropical environments for the first time. Anthropocene  
801 paleoenvironmental and paleoecological studies in the tropics are urgently needed  
802 because (1) the tropics are seriously under-studied (Wilkinson et al., 2014; Yasuhara  
803 et al., 2012a), (2) tropical environments and ecosystems are vulnerable and sensitive  
804 to human influences (Jackson et al., 2001; Pandolfi et al., 2003), and (3) Indo-Pacific  
805 tropical environments have been seriously degraded by the human activity of rapidly  
806 developing countries (Bellwood et al., 2004; Jackson, 2008; Knowlton & Jackson,  
807 2008). Our results provide useful and reliable tools for tropical Anthropocene  
808 research in the broad Indo-Pacific region.

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## 810 Acknowledgement

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1359 | paleoenvironments, *Mar. Geol., Quatern. Geol.*, 35(4), 114–123, 2015 (in  
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1363 | **Captions**

1364 |

1365 | Fig. 1 Locality map showing the 52 sampling sites across Hong Kong, including 41  
1366 | open water sites (blue dots) and 11 typhoon shelter sites (red open dots). From west to  
1367 | east, DS: Deep Bay; NS: North Western waters; SS: Southern waters; VS: Victoria  
1368 | Harbour; ES: Eastern Buffer; JS: Junk Bay; TS: Tolo Harbour; PS: Port Shelter; MS:  
1369 | Mirs Bay.

1370 |

1371 | Fig. 2 Spatial distribution of environmental parameters in Hong Kong. Mean surface  
1372 | water chlorophyll-a concentration; water depth; summer (June to September) bottom-  
1373 | water dissolved oxygen content; mean bottom-water salinity; mean turbidity; mean  
1374 | summer (June to September) bottom-water temperature; mean winter (November to  
1375 | February) bottom-water temperature; and mean mud content. All are averaged values  
1376 | of the data obtained during 1986–2013 (Table 1).

1377 |

1378 | Fig. 3 Spatial distribution of environmental parameters in Hong Kong. Mean copper  
1379 | (Cu) concentration, mean lead (Pb) concentration, and mean zinc (Zn) concentration  
1380 | in surface sediments. All are averaged values of the data obtained during 1986–2013  
1381 | (Table 1).

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1388 Fig. 4 Geographical distributions of the 18 taxa in the northwestern Pacific and Indo-  
1389 Pacific regions, including *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l.,  
1390 *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Phlyctocythere japonica*,  
1391 *Loxoconcha epeterseni*, *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Keijella*  
1392 *kloempritensis*, *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Hemicytheridea*  
1393 *reticulata* *Loxoconcha malayensis*, *Alocopocythere goujoni*, *Hemikrithe orientalis*,  
1394 *Propontocypris* spp., *Neonesidea* spp. and *Xestoleberis* spp.. The following references  
1395 were used mainly to determine the geographical distributions of the species: Al  
1396 Jumaily and Al-Sheikhly (1999); Dewi (1997); Dong et al. (2012); Fauzielly et al.  
1397 (2013); Gu et al. (2017); Hong et al. (2017); Hou and Gou (2007); Hussain et al.  
1398 (2004); Hussain et al. (2010); Hussain and Mohan (2000, 2001); Irizuki et al. (2006);  
1399 Irizuki et al. (2009); Iwatani et al. (2014); Jie et al. (2013); Li (1985); Mostafawi  
1400 (1992); Nishath et al. (2017); Noraswana et al. (2014); Pugliese et al. (2006);  
1401 Schornikov et al. (2014); Tanaka et al. (2009); Tanaka et al. (2011); Wang et al.  
1402 (1988); Wang and Zhang (1987); Wang and Zhao (1985); Zhao (1984); Zhao and  
1403 Wang (1988a, 1988b, 1990); Zhao and Whatley (1993); Zhou et al. (2015). Note that  
1404 *Sinocytheridea impressa* is know to be distributed in Japan, but their Japanese  
1405 distribution is very limited in certain areas of the southern part of Japan (Iwasaki,  
1406 1992; Tanaka et al. 2019). Thus, we did not indicate their Japanese-Russian coast  
1407 distribution in this figure.

1408  
1409 Fig. 5 Spatial distribution of the relative abundance for *Pistocythereis bradyi*,  
1410 *Bicornucythere bisanensis* s.l., *Nipponocythere bicarinata*, *Spinileberis*  
1411 *quadriaculeata*, *Phlyctocythere japonica*, *Loxoconcha epeterseni*, *Sinocytheridea*

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1414 *impressa*, and *Neomonoceratina delicata* in Hong Kong. See Figure 1 for sampling  
1415 stations.

1416  
1417 Fig. 6. Spatial distribution of the relative abundance for *Keijella kloempritis*,  
1418 *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Hemicytheridea reticulata*  
1419 *Loxoconcha malayensis*, *Alocopocythere goujoni*, *Hemikritha orientalis*, and  
1420 *Propontocypris* spp. in Hong Kong. See Figure 1 for sampling stations.

1421  
1422 Fig. 7. Spatial distribution of the relative abundance for *Neonesidea* spp. and  
1423 *Xestoleberis* spp. in Hong Kong. See Figure 1 for sampling stations.

1424  
1425  
1426 Table 1. Summary of marine water/sediment parameters. Note: 1. Summer: June,  
1427 July, August and September. 2. Winter: November, December, January and February.

1428  
1429 Table 2. Best three regression models of the relative abundance of common species,  
1430 including *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Nipponocythere*  
1431 *bicarinata*, *Spinileberis quadriaculeata*, *Phlyctocythere japonica*, *Loxoconcha*  
1432 *epeterseni*, *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Keijella*  
1433 *kloempritis*, *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Hemicytheridea*  
1434 *reticulata* *Loxoconcha malayensis*, *Alocopocythere goujoni*, *Hemikritha orientalis*,  
1435 *Propontocypris* spp., *Neonesidea* spp. and *Xestoleberis* spp. The table shows the  
1436 coefficient of each term, adjusted R<sup>2</sup>, the Akaike information criterion corrected for  
1437 small sample size (AICc), and the Akaike weight (AW). Bold denotes significance at

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1509 P < 0.05. Overall P is < 0.05 in all models. R: region. Other abbreviations are found in  
1510 Table 1.

1511  
1512 Table 3. Model-averaged parameter estimates and CIs of the relative abundance for  
1513 common species, including *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l.,  
1514 *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Phlyctocythere japonica*,  
1515 *Loxoconcha epeterseni*, *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Keijella*  
1516 *kloempritisensis*, *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Hemicytheridea*  
1517 *reticulata* *Loxoconcha malayensis*, *Alocopocythere goujoni*, *Hemikrithie orientalis*,  
1518 *Propontocypris* spp., *Neonesidea* spp. and *Xestoleberis* spp.. CIs, confidence  
1519 intervals; RI, relative importance (the sum of the Akaike weights of models that  
1520 include the variable in question; see Materials and Methods); R, region. Other  
1521 abbreviations are found in Table 1. Bold denotes CIs that exclude zero. For R,  
1522 coefficient, lower CI, and upper CI values shown are averages of those for geographic  
1523 regions.

1524  
1525 Table 4. GVIF value for Environmental Variables. Df, degree of freedom; R, region.  
1526 Other abbreviations are found in Table 1.

1527  
1528 Table 5. Summary of autoecology for common ostracod taxa. Chl: Chlorophyll-a; D:  
1529 Water Depth; DO: Dissolved Oxygen; MD: Mud Content; Sal: Salinity; Tur:  
1530 Turbidity; WT: Winter Temperature; Pb: Lead; Zn: Zinc; R: Region. + and - marks  
1531 indicate significant positive and negative correlations, respectively.

1532  
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1534 Supplement A. Ostracod faunal list.

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Supplement B. Dataset used for the regression modeling.