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Sunscreen use during recreational activities on a French Atlantic beach: Release of UV filters at sea and influence of the air temperature

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Abstract

Organic UV filters are emerging contaminants contained in personal care products such as sunscreens. These compounds already showed their toxicity in several marine species. However, few studies focused on the anthropogenic drivers leading to UV filters contamination. In this work, a survey conducted on a site of the French Atlantic coast (i) described beach-goers behaviors (sunscreen use and beach frequentation) (ii) provided an estimation of UV filters released at sea and (iii) highlighted the effect of air temperature on these behaviors and on the release of UV filters.

In parallel with these estimations of the UV filters released at sea, *in situ* chemical measurements were performed. By comparing results of both approaches, this interdisciplinary work gave an insight of how the observations of beachgoers behaviors modulations and attendance levels fluctuations could be used to prevent events of UV filters contaminations and ultimately manage the ecotoxicological risk.

1. Introduction

Shoreline anthropogenic activities are responsible for the release of many contaminants in marine water. These contaminations could subsequently affect coastal ecosystems which are of high ecological and economic values (Costanza et al., 1997). While the sources and the fate of historical contaminants (e.g. hydrocarbons, pesticides, heavy metals...) have already been studied and are now well documented (e.g. GESAMP, 2020), on the other hand, regarding emerging contaminants, there is still a need to understand how these compounds are transferred and behave in the coastal environment.

Among these emerging contaminants, sunscreens are considered as a growing threat for aquatic ecosystems (Ramos et al., 2015) due to both their release in the environment and their potential toxicity.

Regarding the toxicity, it is worth noting that sunscreens contained organic UV Filters (OUVFs) that already showed their toxicity upon several species of the marine biota (Carve et al., 2021). The impact of these compounds upon corals communities (Danovaro and Corinaldesi, 2003; Danovaro et al., 2008; Downs et al., 2016) have been highly publicized and is now known by the public at large. In the last decade, toxicological studies regarding the impact of OUVFs have extended to other orders than *scleractinia* (i.e. corals) (reviewed in Caloni et al., 2021, Prakash and Anbumani, 2021) and authors showed effects upon several biological processes such as the developmental (Kaiser et al., 2012; Blutghen et al., 2014), the neurological (Zhou et al., 2019; Tao et al., 2020) and the reproductive ones (Weisbrod et al., 2007; Campos et al., 2019). Carve et al. (2021) stated that most of these biological alterations seems to be associated with endocrine disruption and the production of reactive oxygen species.

Regarding the release at sea of sunscreen products, two main paths of contamination can be highlighted: an indirect release in the aquatic environment through wastewater treatment plants, and a direct release through bathing activities. This last path of contamination is responsible of 4,000-6,000 tons per year, only in tropical countries, according to Danovaro et al (2008).

While a substantial corpus of literature investigating the ecotoxicological effects of sunscreens components already exists, a more limited number of social science researches were interested in understanding the causes of the water contamination by characterizing sunscreen use and/or bathing activities that lead to the release of this pollutant into aquatic environment. In this framework, Langford and Thomas (2008) conducted one of the first interdisciplinary study showing the importance of recreational activities in the OUVFs water contamination processes. More precisely these authors highlight the significance of bathing as a source of contamination by comparing this input with the indirect input of wastewater treatment plants. Another study conducted by Bachelot et al. (2012) characterized the seasonal evolution of OUVFs concentrations in wild *Mytilus edulis* collected in bathing areas. Unsurprisingly, these authors showed an increase, in the soft tissues of wild mussels, of two commonly used OUVFs (octocrylene and 2-ethylhexyl-4-methoxycinnamate), during the summer touristic season. Moreover, these authors also showed the influence of the geographical configuration of the sampling sites since mussels presents in beaches closed to the wide ocean showed relatively high concentrations of OUVFs, which could be due to the absence of contaminant dilution in these closed areas. Recently, Labille et al. (2020) conducted an interdisciplinary study coupling a social survey, characterizing the sunscreen use habits and the bathing practices, with a chemical study, allowing the measurement of both mineral and organic UV filters contamination in three beaches of the Mediterranean sea. This work allowed a quantitative description of some of the beachgoers behaviors and also exposed the spatial repartition of the UV filters concentrations in the water column and in different bathing zones. Moreover, their chemical and behavioral results taken together enable to suggest that several physico-chemical mechanisms (e.g. photodegradation) are responsible for the disappearance of organic UV filters after their release at sea.

Regarding these studies (Langford and Thomas, 2008; Bachelot et al., 2012; Labille et al., 2020), it seems that interdisciplinary approaches linking human geography with chemistry allow a better understanding of the sources and the fate of OUVFs as emerging contaminants of coastal ecosystems. Moreover, chemical measurements and social surveys are both complementary approaches in the aim of estimating the environmental risk due to OUVFs released at sea. *In fine*, these studies could give information for decision makers in order to set-up environmental protection policies and consequently prevent and/or reduce the coastal OUVFs contamination.

Thus, based on the limited number of studies investigating the link between beachgoers behavior and OUVFs contamination and also based on the importance of this type of research for decision makers, we proposed an interdisciplinary approach at the interface between sociology and chemistry.

More precisely, a social science approach, based on surveys conducted on an Atlantic site, aims at describing quantitatively sunscreen use habits and beach attendance levels and at estimating the release of sunscreens products (SPs) at sea. In addition, this study gives information to understand how a meteorological factor (air temperature) could modify these behaviors and the number of beach visitors to consequently modulate the quantity of SPs entering the coastal waters.

In parallel, a chemical approach enables to measure the OUVFs concentrations in the water column - octocrylene (OC) and avobenzone (AVO) - thereby bringing further information to estimate the release processes.

In fine, in the framework of this interdisciplinary work, results of the social science and the chemical studies were cross-referenced and discussed in order to evaluate the potential of these approaches to assess and predict the environmental risk linked with OUVFs contamination.

2. Material and Methods

2.1. Description of the study sites

This study was conducted on the Atlantic beach of Arcachon, a popular seaside resort (11 557 inhabitants), which starts at the west of the Thiers jetty (44.664; -1.117) and ends before the Arcachon harbor (44,662: 1,153) for the eastern most part. During the summer season, the beach experiences a high level of attendance due to the recreational activities of inhabitants and holidaymakers (Bachelot et al., 2012). However, it should be noted that, in addition to inhabitants and holidaymakers, Arcachon beach also experiences the visit of day-trippers from the city of Bordeaux (814 000 inhabitants) located within 70 km. Waste waters from the 10 municipalities are not released in the Arcachon bay but via the *Wharf de la Salie* situated at 18 km in the open ocean.

Minimum, maximum, mean and range of air temperature recorded during the summer season were obtained from Meteofrance (from the weather station being in Cap-Ferret i.e. 7.2 km from the studied beach) for each year between 2010 and 2019. Averages of these ten years data show that air temperature minimum was 20.4 (± 0.4 °C) °C, maximum was 37.0 (± 0.3 °C), mean was 26.3 (± 0.3 °C) and range was 16.4 (± 0.4 °C) (\pm standard error of the mean).

2.2. Estimates of beach visitation

The method to estimate the numbers of visitors on the beach was divided in two steps.

Firstly, an analysis of the past trends was conducted on this beach. To do so, aerial photographs from Google Earth Pro (version 7.3.6.9345) were used in order to assess the variation in the attendance distribution in different areas of the beach in July and August during the ten last years. On the basis of this knowledge, it was possible to choose a representative area and, from the number of beachgoers at a given time in this given area, to estimate by extrapolation the number of visitors on the entire beach at a given time (see Le béguec et al, 2023 for more details about the method). The representative area is a strip of beach of 20 meters large and it was selected according to its attendance (areas should welcome more than 4 persons per 100 square meters at any time of the day), the stability of its frequentation over years (less than 25% of interannual variation during the 10 last years) and the ease of the counting on this area (possibility of visual counting).

Secondly, counting was conducted in this area when the forecast wind was inferior to 10 knots and exclusively on sunny day, in order to ensure similar conditions between the different days of sampling. Counting was performed at 1PM, 4PM and 6 PM. It was conducted on July 20,

2020, when the air temperature of the day at 4PM was 26°C (forecasted by meteoFrance), on August 6, 2020, when the air temperature of the day at 4PM was 35°C and on October 8, 2020, when the air temperature was 20°C at 4PM. It was operated thanks to photographs. Persons in the beach as well as persons swimming in the sea in the representative areas were considered. Finally, from the counting and thanks to previous analysis of the past trends (described above), the number of visitors on the entire beach at 1, 4 and 6 PM was estimated on July 20, August 6 and October 8, 2020.

In parallel, an estimation of the daily temporal evolution of the summer crowd is given thanks to a model developed by Guyonnard et al. (2016, 2020). This model enables to estimate, from the number of visitors on the entire beach at a given time, the total number of beachgoers who visited the entire beach, during the entire day.

2.3. Social survey questionnaire

A questionnaire was carried out on the beach from 12 AM to 6 PM, from July 15 until August 15, 2020. 797 persons were surveyed during this period. Beachgoers were firstly asked questions about their personal profile (gender, age, homeplace) and the reason of their venue on the beach. Then, sunscreen use behaviors were analyzed in order to know (i) the different parts of the body covered in order to estimate a body surface covered (BSC), (ii) the number of applications during a beach session (N_{app}) and (iii) the type of sunscreens used (brand, sun protecting factor, oil/spray). In parallel, visitors were questioned about their bathing habits in order to evaluate (i) the proportion of the population both bathing and using SPs (P), (ii) the frequency of bathing (N_{bath}) and (iii) the degree of immersion *i.e.* the percentage of the body immersed during the bath (BI).

Finally, each day, the meteorological conditions (time of the tide, cloud cover, air and water temperature) were established in order to determine if the respondent behavior could be influenced by such factors.

2.4. Estimated amount of UV filters released at sea per person for average and above-average air temperature conditions

In order to estimate the effect of air temperature on the sunscreen use behaviors, 29 °C was chosen as a threshold value separating average and above-average air temperature conditions. Average mean temperature was 26.3°C over the past 10 years and 13.3% of the days during the summer touristic period showed temperatures at 4PM higher than 29 °C. Among the 797 surveys conducted in this study (and described above), 400 surveys were conducted when the air temperature was lower than 29 °C (mean temperature for the days of survey was 25.0 °C) while 397 surveys were conducted when the air temperature was higher than 29 °C (mean temperature for the days of survey was 32.2 °C)

Based on these surveys and on an equation inspired by the approach of Poiger et al. (2004), the quantity of SP released at sea per person ($Q_{SPs\ released}$ in g/pers) as well as the quantity of the UV filters OC and AVO ($Q_{UV\ filters}$ in g/pers) were calculated for both types of meteorological conditions (average and above-average air temperatures) and for different categories of the population (men, women and children *i.e.* persons under 12 years old) as well as for these three categories pooled together (indicated as ‘all categories’ in **Table 1**).

The equations were the following ones:

$$(1) Q_{SPs\ released} = BSC \times BI \times Q_a \times N \times P \times WO$$

with $Q_{SPs\ released}$ (in g/pers): estimation of the quantity of sunscreen products released at sea per person; BSC (in m²): average Body Surface Covered by sunscreen products (determined thanks to the survey); BI (in %): average percentage of the body immersed during bath (determined thanks to the survey); Q_a (in g.m⁻²): quantity of sunscreen product used per application (on the basis of Ficheux et al., 2016, this value was fixed at 4.90 g.m⁻²); N: average number of

applications or baths per person (between number of applications or number of baths, the highest value was chosen); P: proportion of the population both bathing and using sunscreen (determined thanks to the survey); WO: proportion of the sunscreen washed-off from the skin into the sea (estimated at 50 %, according to Poiger et al., 2004)

$$(2) Q_{UV \text{ filters}} = Q_{SPs \text{ released}} \times \%_{UV \text{ filter}}$$

with $Q_{UV \text{ filter}}$ (in g/pers): estimation of the quantity of the UV filters (OC and AVO) released at sea per person; $Q_{SPs \text{ released}}$ (in g/pers): estimation of the quantity of sunscreen products released at sea per person; $\%_{UV \text{ filter}}$ (in %): average percentage of the UV filters entering the sunscreen composition (estimated at 7 % for OC according to Matta et al., 2019; at 3 % for AVO according to Slijkerman and Keur, 2018 and Matta et al., 2019)

2.5 Estimated quantities of sunscreen products released by the whole population and estimated concentrations of UV filters

Estimated quantities released by the whole population were calculated for average and above-average meteorological conditions multiplying the number of visitors at 1,4,6 PM and also the number of visitors during the entire day by the appropriate (i.e. depending on meteorological conditions) $Q_{SPs \text{ released}}$ and $Q_{UV \text{ filters}}$.

Estimated concentrations were obtained dividing the estimated quantities of UV filters ($Q_{UV \text{ filters}}$) by an estimated volume of dilution of a 20 m wide near-shore strip. This strip was used since almost all the bathers (89%, according to countings made from aerial photographs) do not go longer than 20 m from the shore on the Arcachon beach. More practically, the estimated volume was obtained using a deeper pro + sounder (Navicom, France). With this sounder, water height was determined at high tide and adjusted to hydrographic zero along 6 transects perpendicular to the beach: 2 transects of 70 meters and 4 transects of 40 meters. These results enabled to draw 7 isobaths along the shore of the beach. On this basis and using Qgis software (3.22), a digital bathymetric field model was generated. This model enables to estimate the volume of water in the first 20 metres wide near-shore strip for the several water heights (which depend on the tide) recorded at 1,4 and 6 PM on July, 20, on August, 6 and on October, 8.

2.6. Beach water samplings

Samplings were conducted on the same day when the beach attendance levels were performed: on July, 20 and on the August, 6 and once after the summer on October, 8. On these days, water salinity was respectively 32.8, 33.6 and 32.2 ‰. Field sampling of water was conducted at 1PM, 4PM and 6PM. Water was sampled in three different points (at the geographical coordinates 44.6643, -1,1643) along a 20-meters transect parallel to the shore and situated at 15 meters from it. Water samples were taken at 50 cm under the sea surface by opening an immersed 250-ml glass tainted bottle. Samples were then stored for 24h at 8 °C (during transportation), extracted with MTBE when received at the laboratory (see conditions below in section 2.7). These extracts were then stored at -20 °C until analysis. These conditions of storage had been previously checked by inter-day and intra-day analysis of standards prepared in natural seawater samples and extracted with MTBE, with concentration variations below 4.3%, if stored less than three months.

2.7. Chemical analysis on water samples

UV filter concentrations were determined by liquid chromatography coupled to a quadrupole/time-of-flight mass spectrometry (HPLC-QToF/MS, Acquity, Waters) coupled with electrospray ion (ESI) source (Synapt G2 HDMS, Waters, MA, USA), after acidification at pH3 and liquid-liquid extraction (LLE) with methyl-tertio-butylether (MTBE). 50 mL of water sampled -acidified at pH3- were extracted with 5 mL MTBE. The organic phase was then

evaporated thanks to a nitrogen stream (50 °C), and the extracts were then resuspended in 5 mL methanol, allowing an overall concentration factor of 10. Chromatographic separations of the analytes were performed at 40 °C with an Acquity UPLC BEH C18 column (Waters, 2.1×100 mm inner diameter × length-, 1.7 μM -particle size-) thanks to a gradient elution at 0.4 ml min⁻¹. Both solvents used as mobile phase (A: H₂O; B: CH₃OH) contained 5mM of ammonium formate from Fisher Chemical (Optima LC/MS). Gradient starts at 20% of B and increases to reach 90%. Data were recorded in the full scan mode in ESI(+) mode in the mass range m/z 50–600, and compounds detected as their protonated molecules ([M + H]⁺). An external standard approach using the reference standard benzophenone-d10 was used to establish the calibration curves, and by using spiking reconstituted seawater with UV filters as calibration standards. Quantitation was performed using the fragment having the highest abundance. The percent recovery was assessed by using nine determinations over three concentration levels and determined as ranging between 89 and 117%. The relative standard deviation (RSD) ranged between 8 and 16% and the calibration curves (between LOQ and 5 μg L⁻¹) were linear (R² > 0.99) within the studied concentration range. Limits of quantification (LOQ) were 0.1 and 0.2 μg L⁻¹, for AVO and OC, respectively, and determined according to the ICH method (2005).

2.8. Statistical analysis

Pearson correlation coefficients r were calculated for the following linear relationships (i) *in situ* measured concentrations of UV filters (AVO and OC) as function of their estimated concentrations; (ii) *in situ* measured concentrations as function of their estimated quantities (Total Q_{UV Filter}) release on the entire beach and (iii) *in situ* measured concentrations as function of the number of visitors. In parallel, p -values were obtained using Pearson correlation statistical tests using the software Past4.

3. Results and discussion

3.1. Sunscreen use behavior in a French Atlantic beach

The survey was conducted on cells of beachgoers (i.e. groups of people forming an interactive cluster on the beach spot). 797 cells of beachgoers were questioned, corresponding to a representative beach population of 2,076 people with 32% of men, 55% of women and 13% of children (under 12 years old). This suggests that young children represent a minority of the beachgoers while women are overrepresented at the beach.

Regarding the sunscreen use habits (see **Table 1**) for average air temperature conditions (i.e. inferior to 29 °C), the results show that a high proportion of children both bath and use sunscreen (96.6%). Other categories, i.e. men and women, expose lowest proportions (63.9 and 66.7 % respectively). Our results expose proportions in the same range than Labille et al. (2020) since these authors showed that 68 % of the persons surveyed on 3 Mediterranean beaches are using sunscreen and that, among them, approximatively 90% of them are bathing frequently or every time they are going to the beach.

Regarding the body surface covered (BSC) by sunscreen products, a heterogeneity of results appears between categories (varying from 1.37 m² for men until 0.77 m² for children), which is mainly due to the fact that the average body surface of men is more important than the body surface of women and children.

The sunscreen use behaviors survey also reveals that the number of SPs applications per person is relatively uniform between the categories with 2.10 applications for children, 2.17 for men and 2.56 for women. This result exposes a slightly lower number of applications, when compared with the study of Labille et al. (2020) on the French Mediterranean coast (Marseille), since these authors estimated 2.6 applications per person (for all categories).

In contrast with the number of applications, the number of baths show an important between-categories heterogeneity with 3.71 baths per child while men only bath twice during their beach session. During these baths, 62,5 % of men's bodies and 56,6% of women's bodies were immersed with children bathing 67.9 % of their body.

Table 1: Sunscreen use behaviors for several categories of the population (men, women, children, all categories), beach attendance levels and release of contaminants (sunscreens products and organic UV filters), for average and above-average air temperatures. “All categories” results were calculated from those obtained in men, women and children categories. Total Q_{SPs released}: Quantity of sunscreen products released by the whole population of the beach; Total Q_{UV filters released} (AVO; OC): Quantity of UV filters (avobenzone; octocrylene) released by the whole population. n.e.: not evaluated. ¹individuals under age 12; ²individuals over 12 years old.

	Average air temperature conditions (<29°C)				Above-average air temperature conditions (>29°C)				% of increase (for all categories)	
	Men ¹	Women ¹	Children ²	All categories	Men ¹	Women ¹	Children ²	All categories		
Sunscreen use behaviors	<i>P</i> (in %) Proportion of the population both bathing and using SPs	63.9	66.7	96.6	n.e.	68.7	72.0	100.0	n.e.	n.e.
	<i>BSC</i> (in m ²) Body surface covered by SPs	1.37	1.24	0.77	1.19	1.46	1.31	0.87	1.28	+ 7.00%
	N _{app} Number of SPs application per person	2.17	2.56	2.10	2.36	2.49	2.71	2.39	2.59	+ 9.75%
	N _{bath} Number of bath per person	2.00	2.26	3.71	2.45	2.75	2.56	3.25	2.74	+ 11.80%
	<i>BI</i> (in %) Percentage of the body immersed during bath	62.5	56.6	67.9	n.e.	81.8	68.4	75.1	n.e.	n.e.
	Q _{SPs released} (in g/pers) Quantity of SPs released per person	2.68	2.60	2.61	2.63	5.00	4.04	3.84	4.32	+ 64.3%
Q _{UV filter} (AVO ; OC) (in g/pers) Quantity of UV filters released per person	0.080 ; 0.188	0.078 ; 0.182	0.078 ; 0.183	0.079 ; 0.184	0.150 ; 0.350	0.121 ; 0.283	0.115 ; 0.269	0.130 ; 0.303		
Attendance levels	Total number of visitors during the entire day (estimated from modelisation)			3090				2670		-13.5%
	Number of visitors on the beach at 1 PM			569				483		-15.1%
	Proportion = number of visitors at 1 PM / total number of visitors			18.4%				18.1%		
	Number of visitors on the beach at 4 PM			1393				1165		- 16.4%
	Proportion = number of visitors at 4 PM / total number of visitors			45.1%				43.6%		
	Number of visitors on the beach at 6 PM			540				995		+ 84.2%
Total release of contaminants	Proportion = number of visitors at 6 PM / total number of visitors			17.5%				37.3%		
	Total Q _{SPs released} at 1 PM (in kg)			1.494				2.088		+ 39.7%
	Total Q _{UV filter} (AVO ; OC) at 1 PM (in g)			44.8 ; 104.6				62.6 ; 146.2		
	Total Q _{SPs released} at 4 PM			3.658				5.035		+ 37.6%
	Total Q _{UV filter} (AVO ; OC) at 4 PM (in g)			109.7 ; 256.1				151.1 ; 352.5		
	Total Q _{SPs released} at 6 PM			1.418				4.300		+ 203.2%
Total Q _{UV filter} (AVO ; OC) at 6 PM (in g)			42.5 ; 99.3				129.0 ; 301.0			
Total Q _{SPs released} during the day (in kg)			8.126				11.534		+ 41.9%	
Total Q _{UV filter} (AVO ; OC) during the day (in g)			243.8 ; 568.9				346.0 ; 807.4			

In summary, our results exploring the sunscreen use behaviors expose a between-categories homogeneity of some variables such as the body surface covered by SPs, the number of applications and the percentage of the body immersed. On the other hand, heterogeneity was observed for several other parameters: proportion of persons both bathing and swimming, BSCs and number of baths per person. Be that as it may, these between-categories differences cancel out when calculating the quantity of SPs released at sea per person (presented in the section *Sunscreen use behaviors* of the **Table 1**). Indeed, results reveal that, whatever the category, 2.60 to 2.68 g of sunscreen products are released at sea per person during their beach sessions, which correspond to 0.08 g of AVO and 0.18 g of OC per person.

3.2. Effects of air temperature increase on the sunscreen use behaviors

In order to investigate the effect of air temperature on the sunscreen use habits, the survey previously described has also been conducted when air temperature was superior to 29 °C. Our results (see **Table 1**) first highlight that, due to temperature, the proportion of the population bathing and using SPs increase by 7.5, 7.8 and 3.5% for men, women and child, respectively. In the same way the body surface covered increases by 7% when considering all categories. This 7% increase is due to behavioral changes in all population categories *i.e.* men, women and child. In the same way, number of SPs application per person increases, by 9.8%, with the temperature. Regarding the number of baths per person our results expose a 11.8% increase when taking into account all categories. However, it appears that while an increase of the number of baths is observed for men and less extensively for women, children baths are surprisingly reduced. This decrease in the number of baths could be due to the fact that children could take longer bath when the air temperature is higher. Thus, considering the duration of bath could be of interest for further studies, particularly since a longer period of bathing could induce a more important release of the sunscreen products.

Regarding the percentage of the body immersed during bath, results highlight that the increase due to temperature is more intense for men: an increase of 30.9, 20.8, 10.6 % was observed for men, women and child, respectively.

In fine, these behavioral changes lead to a 64.3 % increase of the quantity of SPs released at sea per person. Indeed, for average air temperature conditions (<29 °C) 2.6 g of SPs were released at sea per person while, when the temperature increases above 29 °C, 4.3 g of SPs are released at sea (results for all categories). Regarding more specifically, it appears that men participate more than the other categories (women and child) to this increase: when the air temperature is above 29 °C, our results exposed a release of 5.0 g of SPs per person for men, 4.0 g for women and 3.8 g for children. The number of baths is the parameter that shows the more important influence on this increase of SPs released in the men category.

Thus, this study showed that an increase of air temperature above the average modulates sunscreen use and consequently could enhance the release of compounds at sea. However, these results, expressed as g of SPs per person, do not take into account the number of visitors presents in the beach. In order to integrate this important parameter, our study also investigates the population dynamic of beachgoers. Ultimately, the quantity of SPs released at sea per person (determined thanks to the behavioral survey) and the beach attendance levels would enable to estimate the SPs released by the entire population of the beach, for average and above-average meteorological conditions.

3.3. Beach attendance and effects of air temperature increase

Beach attendance levels were obtained thanks to counting performed at 1, 4 and 6 PM on a representative area. To these countings were applied two demographic models in order to estimate (i) the population on the entire beach at the time of counting and ultimately (ii) the

total number of beachgoers visiting the entire beach from 1 to 6 PM. Off-season (countings performed on October, 8), no beachgoer was present on the representative area, suggesting a negligible number of visitors on the entire beach. During the summer season, our results exposed a slightly higher number of visitors for the average than for the above-average air temperature days (3090 versus 2670 visitors, respectively). However, it should be noticed that this trend is only determined by a single day for each meteorological condition. Regarding the literature, authors described heatwaves as “not too negative” and “the least important climate change impact” for beach tourism, when compared to rain or low temperature (Moreno, 2010; Ruddy and Scott, 2014). Thus, several days of counting and subsequent statistical analysis could be of interest in order to confirm or disprove this trend. Regarding more precisely the diurnal evolution of the number of visitors, our results show that, for average temperature conditions, the higher proportion (number of visitors at a given time / total number of visitors during the entire day) was observed in the middle of the afternoon, at 4 PM : 45.1%. This finding is in accordance with previous studies describing highest attendance levels at this time of the day on Atlantic beaches (Guais, 2012; Guyonnard, 2020). Concerning the effect of temperature on such a pattern, it seems that, during a warmer day (maximum daily temperature reported by meteorofrance was 35°C) people stay later on the beach. Indeed, at 6 PM the proportion of beachgoers represent 17.5% (of the total population which visit the beach on this day) for average temperature condition while they represent 37.3% for the above-average one. Although scarce information is present in the literature to confirm such an effect of temperature on the pattern of attendance, data collected in another beach of the French Atlantic coast (plage des Minimes, La Rochelle, data not shown) are in accordance with the results presented in this study. Indeed, in La Rochelle, when the daily optimum was 36°C, similar proportions of the number of visitors were observed between 4 and 6PM (43.9% and 45.9%) suggesting that people also stay later on the beach. However, further studies are needed in order to confirm these trends.

Such results are of interest in the aim to predict the levels of attendance in the beach according to the meteorological conditions. Moreover, these results describing the attendance levels, in parallel with results describing the sunscreen use and the consequent quantity of SPs released at sea per person, will allow an estimation of the total release on the entire beach.

3.4. Release of sunscreen products and modulation by the meteorological conditions

The quantity of sunscreen products released on the entire beach and more specifically the quantities of AVO and OC were calculated by multiplying the number of visitors by the quantity of compounds released per person. Results were obtained for 1 PM, 4 PM, 6 PM and were also estimated taking into account the total number of beachgoers on the entire beach during the all day. These results showed that 8.126 kg of SPs as well as 243.8 and 568.9 g of avobenzone and octocrylene (respectively) were released (per 3090 persons) during an entire day with an average air temperature (i.e. on the 20 of July). More precisely, the temporal release of compounds showed that the more intense one occurred at 4 PM (3.658 kg of SPs), which is due to the increase of the population at this time of the day. When comparing with the study of Labille et al. (2020), it could be noticed that these authors found higher levels of SPs released at sea (52 kg for 3000 visitors for the entire day) which is mainly due to the fact that we estimated 2.6 g of SPs released per person while they used 15 g in their calculations. The potential causes of this discrepancy are the wash-off factor (WO) used in our study (and not used in the study of Labille et al. 2020) as well as the consideration of the body surface covered. Regarding the effect of warmer conditions on the release of UV filters, our results showed that quantities of compounds (SPs or UV filters) increase by 41.9 % when above-average temperatures were recorded. This increase of release is driven by sunscreen use behaviors but

is also limited by a reduction of the number of visitors due to warmer condition (from 3090 to 2670 of visitors during the entire day, as previously described).

More precisely, taking into account the results obtained at several hours of the day, our study first described that, at 1 and 4 PM, a moderate increase of the SPs release occurred due to warmer conditions i.e. 39.7 % and 36.7 % increases between average and above average conditions. However, at the end of the day (6 PM), a 203.2 % increase of the release was observed. This is due to both (i) an increase of the population at this time of the day when the air temperature is above-average, and (ii) changes of sunscreen use behaviors inducing a more intense release of SPs (and consequently UV filters) at sea.

Comparison of these results with other ones in the literature could be of interest. However, literature on this specific topic (i.e. effects of air temperature on the release at sea of SPs products) is still scarce although results obtained recently by Thallinger et al. (2023) on Mediterranean beach also suggest that heatwaves induced higher concentrations of UV filters (such as avobenzone and octocrylene) in the water column.

Thus, our results showed that an increase of air temperature above average air temperature conditions would be concomitant with an increase of SPs release at sea. This finding highlights the fact that two stressors of marine ecosystems (i.e. heatwaves and SPs) could superimpose and induce cumulative impact. Moreover, regarding the fact that heatwaves will be longer, more intense and more frequent in the future (Hobday et al., 2016), it could be predicted that the release of SPs at sea will also increase over the next decades.

In parallel of these results obtained thanks to surveys conducted on Arcachon beach, a chemical approach also permitted to measure the UV filters (OC and AVO) concentrations in the water column. The chemical and the sociological approaches conducted in parallel enabled to investigate different aspects of the SPs release and therefore could improve the understanding of the several processes leading to the water contamination.

3.5. Chemical assessment of UV filters in the water column and comparison of the sociological and chemical approaches.

Curves of figures 1 (A) and (B) exposed the concentrations of AVO and OC chemically assessed in samples collected *in situ* at 1, 4 and 6 PM on July 20 and on August, 6. Results for October, 8 are not presented since no chemical compounds were detected. In parallel, histograms expressed the estimated concentrations at the same time-slots *i.e.* the estimated quantities of UV filters released by the whole population at 1, 4 and 6PM (see **Table 1**) divided by the estimated volumes of dilution in a 20 m wide near-shore strip. Regarding *in situ* concentrations, results exposed values varying between 0.1 and 1.2 $\mu\text{g/L}$ (for AVO and OC), this range of concentration being in accordance with several studies conducted in beaches of Atlantic and Mediterranean coastlines (e.g. Sanchez Rodriguez et al., 2015; Bratkovics et al., 2015). On the other hand, estimated concentrations show values between 1 and 20 $\mu\text{g/L}$. This difference by approximately one order of magnitude between the two approaches could be explained by several factors.

First of all, the estimation of concentrations by the survey does not take into account the contaminant dissemination to the open ocean while waves and current are presents in these areas and can potentially induce this phenomenon. Secondly, photodegradation could also decrease the *in situ* chemically assessed concentrations of UV filters (Manasfi et al., 2017; Jentzsch et al., 2019) thereby amplifying the difference with the estimated ones. Thirdly, in our study, samples were taken in the water column (50 cm below the surface). However, due to the lipophilic nature of the UV filters, their partitioning is in favor of the surface rather than the water column (Tovar-Sanchez et al., 2013; Labille et al., 2020). This could explain the low values chemically measured, *in situ*, in the water column. Finally, in order to estimate the UV filters release, calculations considered that 50% of the products are washed-off from the skin

into the aquatic environment. This value is based on a single study from Poiger et al., (2004) and few studies, to our knowledge, precisely quantified this wash-off factor. Thus, the difference in the order of magnitude between *in situ* measured concentrations and estimated ones could also be due to an overestimation of this factor.

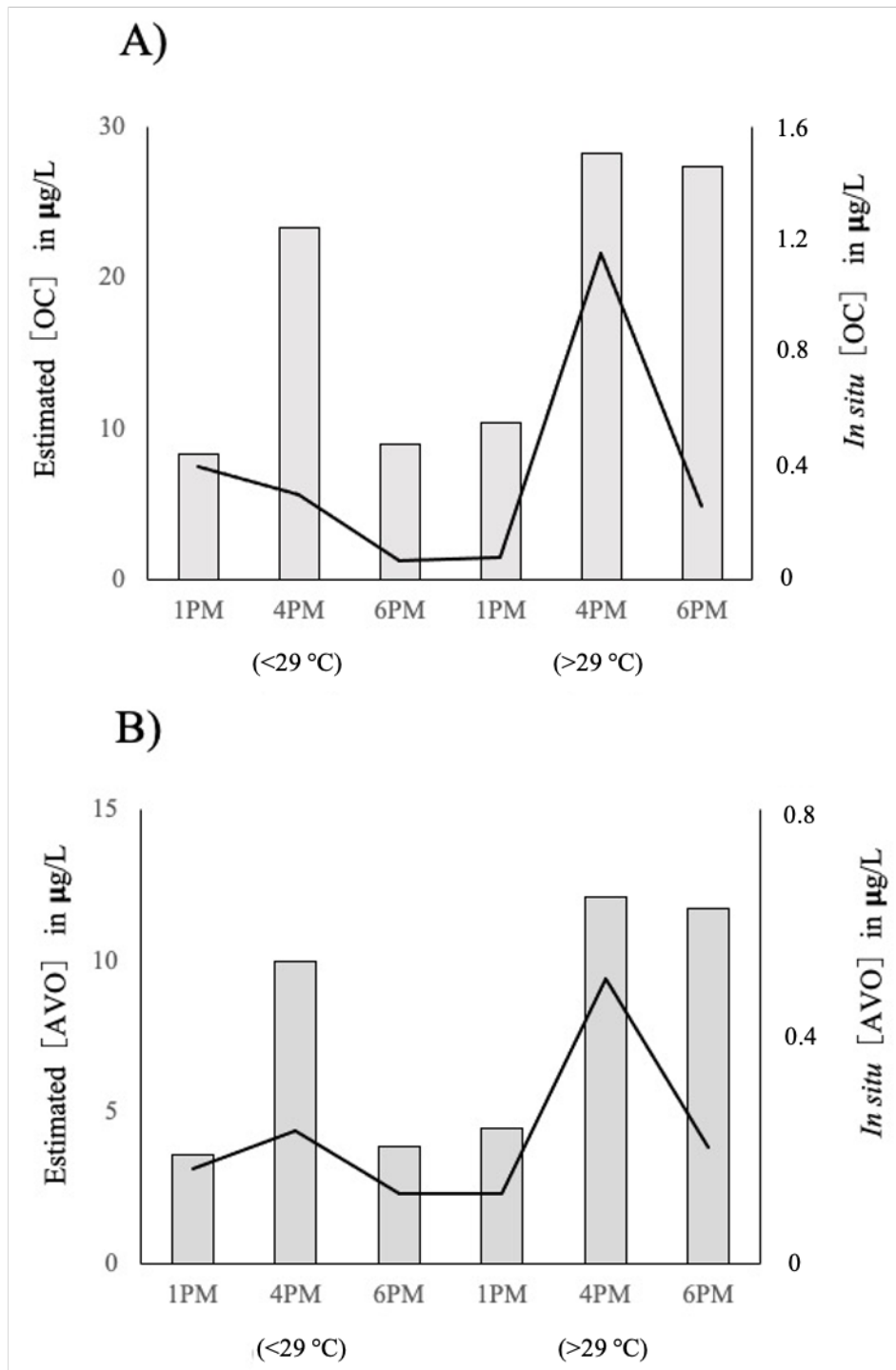


Figure 1: Concentrations of octocrylene (A) and avobenzone (B) estimated thanks to beach surveys (grey histograms) and chemically measured *in situ* (black curves), at several hours of the day (1, 4 and 6PM), for average and above average air temperature conditions (<29 °C and >29 °C), in the water of Arcachon beach during the summer touristic season.

Regarding the effect of meteorological conditions on UV filters concentrations, *in situ* measured concentrations are in accordance with estimated concentrations since both types of evaluation showed higher values when the air temperature increases above 29°C.

Regarding temporal variations, similar patterns could be observed between both types of evaluation (chemical or sociological ones). Indeed, for both estimated and *in situ* measured concentrations (i) highest UV filters concentrations are often observed at 4 PM and (ii) lowest concentrations are often observed at 1 or 6 PM.

Regarding *in situ* measured concentrations of AVO and OC, it should also be stated that they follow the same variations. These similar patterns, between the two assessed UV filters, validate the robustness of the results obtained thanks to the chemical analysis.

Be that as it may, some discrepancies between the estimated and the *in situ* measured concentrations of UV filters can be highlighted. First of all, while our results showed that concentrations of AVO and OC, estimated from the sunscreen release (grey histograms), exposed a maximum at 4 PM, this maximum value was not observed for the *in situ* measured concentrations of octocrylene when air temperature was under 29°C (black curve). These divergent results could be due to processes of degradation and/or dissemination which depend on meteorological and/or hydrodynamic conditions on the beach site on that specific day at this specific hour. Thus, the UV filters released at sea could have been rapidly degraded/disseminated and were consequently not chemically detected in the water column.

Another discrepancy lies in the fact that, for above-average air temperature conditions (>29°C), estimated UV filters concentrations exposed an increase at 4PM and a plateau until 6PM (grey histograms). On the other hand, the plateau is not observed for *in situ* measured concentrations (black curves). This could be due to an over-estimation of the UV filters released at sea. Indeed, it might be conceivable that a smaller proportion of beachgoers take baths at 6PM, when compared with 4PM. However, in the calculation of the estimated concentrations, the beachgoers behaviors, such as the number of baths, are supposed to be stable during the all day. This postulate may have contributed to over-estimate the release and consequently the estimated concentrations of UV filters at 6PM. On this basis, although it involves technical challenges, it could be of interest to understand the temporal variations of the behaviors during a beach day.

Although some discrepancies can be observed between estimated and *in situ* measured concentrations, the similarity of the general patterns lead to think that estimated concentrations could potentially be correlated with UV filters concentrations chemically measured in sea water.

Thus, in this study, the quality of the correlation between *in situ* measured concentrations of UV filters (AVO and OC) and their estimated concentrations was evaluated by calculating the Pearson correlation coefficients r (strength of the linear relationship) and the associated p -values.

For comparison purpose, quality of the correlation was also established for the following relationships: (i) between *in situ* measured concentrations and the quantities of UV filters (Total $Q_{UV\ Filter}$) release on the entire beach ; (ii) between *in situ* measured concentrations and the number of visitors.

Results are presented in **Table 2**. In general, and unsurprisingly, they expose the fact that high values of Pearson correlation coefficients r are associated with low p -values. This suggests that the stronger the linear relationship is, the more statistically probable is its existence.

Table 2: Table of correlation (Pearson correlation coefficients r and associated p -values) linking *in situ* measured concentrations of avobenzone (AVO) and octocrylene (OC) with (i) their estimated quantities (Estimated Total $Q_{UV\ filter}$); (ii) their estimated concentrations (Estimated [UV filter]) and (iii) the estimated number of visitors

	<i>In situ</i> OC	<i>In situ</i> AVO
Number of visitors	$r = 0.502$ $p\text{-value} = 0.310$	$r = 0.642$ $p\text{-value} = 0.169$
Estimated Total $Q_{UV\text{filter}}$	$r = 0.679$ $p\text{-value} = 0.138$	$r = 0.807$ $p\text{-value} = 0.052$
Estimated UV filter	$r = 0.616$ $p\text{-value} = 0.193$	$r = 0.730$ $p\text{-value} = 0.100$

Regarding more precisely, correlations linking estimated quantities, estimated concentrations or number of visitors with *in situ* measured concentrations were of better quality (highest r and lowest $p\text{-value}$) for avobenzone than for octocrylene. This suggests that the relation between the estimations given by the social sciences approach and the measurements of concentrations given by the chemical approach are more qualitative with AVO than with OC.

This could be due to the fact that OC shows a higher K_{ow} (octanol-water coefficient) than AVO (7.35 versus 2.41 according to Manasfi et al., 2017). Consequently, OC used by beachgoers is more likely to be adsorbed by the skin and/or being located in the surface layer of the sea water, instead of being situated in the water column, *i.e.* where the concentrations were *in situ* measured. Such phenomenon could be responsible of the less qualitative relationship between estimated and *in situ* measured concentrations of OC.

Moreover, our results show that correlations linking the estimated concentrations (or the estimated quantities) with *in situ* measured concentrations are of better quality than correlations linking the number of visitors with *in situ* measured concentrations. Since estimated concentrations and estimated quantities consider the beachgoers behaviors in addition to the number of visitors, these results suggest that the integration of these behaviors enables a better correlation. Thus, these results participate for the validation of the equation that was developed to integrate sunscreen use habits (*cf.* 2.4.).

Surprisingly, the quality of the correlations between estimated quantities of UV filters and *in situ* measured concentrations (of AVO or OC) was higher than the correlations between estimated concentrations and *in situ* measured concentrations. Since the estimated concentration is the estimated quantity divided by the volume of water, it could be stated that the volume of dilution decreases the quality of the correlation. Consequently, an improvement of the method used to estimate the dilution volume (*cf.* 2.5.) should be conducted for further studies.

In summary, these results first expose the difference in the order of magnitude between the estimated concentrations and the *in situ* measured concentrations (see Fig 1A and 1B), this discrepancy being probably due to the intervention of physical phenomenon such as photodegradation or dissemination of the contaminant to the open ocean. On another hand, results also expose the quality of the correlations linking the estimated release of contaminants at sea (estimated quantities or concentrations) and the number of visitors with *in situ* measured concentrations. The correlation between estimated quantity of AVO release at sea and *in situ* measured concentrations of AVO showed the strongest relationship ($r=0.807$) with the lowest $p\text{-value}$ (0.052). On the basis of such a correlation, it would be of interest to predict the variation of *in situ* UV filters concentrations by observing the variations of the estimated quantity of UV

filters release at sea. More practically, it would be possible to prevent events of high contamination by UV filters - and consequently to prevent environmental risk - by considering beachgoers behaviors modulations and by measuring attendance levels fluctuations.

3.6. Concluding remarks

Our interdisciplinary study first describes the behavior of sunscreen use considering 3 categories of the population (men, women and children). Although this part of the work was mainly descriptive it also enables to estimate the quantities of SPs and UV filters released at sea per person. These results, associated with the evaluation of the beach attendance levels, allowed to estimate the quantity of sunscreens and UV filters released at sea by the entire population visiting the beach.

Another line of this study was to evaluate the effect of air temperature on SPs released at sea and also on both beach attendance levels and sunscreen use behaviors. An increase of air temperature from average (i.e. $<29^{\circ}\text{C}$) to above-average conditions (i.e. $>29^{\circ}\text{C}$) led to a rise of the total quantities of SPs release at sea during an entire day. Interestingly, this rise seemed to be rather due to a change of sunscreen use behavior than to a modulation of attendance. Indeed, regarding results obtained on an entire day, it appeared that warmer conditions did not induce a rise of the number of beachgoers while on the other hand such meteorological conditions intensified the sunscreen use behaviors leading to release of SPs at sea.

Thus, our results highlight other environmental concerns than the ecotoxicological one. Indeed, the fact that SP release increase under warmer conditions suggests that UV filters and marine heatwaves could superimpose and consequently induce cumulative effects on the biota.

Finally, chemical measurements were conducted in order to be cross-referenced with the estimates from the social science study. The comparison of both approaches first show that chemical measurements of UV filters concentrations are lower by one order of magnitude when compared with sociological estimations, which could be due to physical phenomenon (e.g. photodegradation and/or dissemination of UV filters) as well as due to the fact that chemical assays were conducted on the water column while UV filters could be more concentrated in the surface layer. On the other hand, when focusing on the variation of UV filters concentrations, both methods expose similar fluctuations. In this line, the quality of the correlations between the estimations of UV filters released (social sciences approach) and the measurements of concentrations (chemical approach) was evaluated. Results suggest that, it could be of interest to observe beachgoers behaviors modulations and attendance levels fluctuations in order to prevent increase of *in situ* UV filters concentration. On this basis, outcomes of this study could be informative for decision makers who aim at conducting environmental policies preventing events of contamination in the marine environment.

While this study aims at linking day-to-day air temperature with beach attendance levels and beachgoers behaviors in order to finally estimate the modulation of coastal UV filters contamination, further investigations should be conducted in this research field in order to prevent the environmental risk. Indeed, many other factors than air temperature, could modulate the release of UV filters at sea. For instance, geographical location of the beach site could be of importance. Indeed, our study was conducted on an Atlantic site in France. However, sunscreen use behaviors could be different in other sites or other countries. For instance, preliminary surveys conducted on a Mediterranean beach of the French coast (data not shown) revealed lower proportions of the population using SPs and bathing, higher number of baths per person and higher percentage of the body immersed, when compared with the Atlantic site of Arcachon. Moreover, other meteorological factors than air temperature could influence the sunscreen release. For instance, depending on the water temperature, the number, the duration and the modalities of baths could be different. This is even more true since bath temperature under 20°C is considered unpleasant by beachgoers (Hu et al., 2020). Finally other sources of

contamination could be considered. In this study, waste waters were not considered given the geographical situation of their discharge in the open ocean (*cf.* 2.1.). However, other secondaries contributions could be considered such as inputs from rivers deltas or estuaries. Thus, further studies are needed to extend our knowledge and therefore identify the processes leading to UV filters release. To do so, interdisciplinary studies bringing together chemistry and social sciences provide an interesting framework since these approaches enable to prevent, warn on and manage the ecotoxicological risks by highlighting practices leading to a release of UV filters in the coastal ecosystems and by measuring the *in situ* concentrations in these bathing zones.

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