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Persistent Organic Pollutants in Polar Ecosystems: Current Situation and Future Challenges Under Climate Change

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ABSTRACT
The polar regions had long been regarded as healthy ecosystems free of any hazardous traces left by human activity. Unfortunately, since the intensification of industrial activities leading to huge releases into environment, anthropogenic pollutants through global atmospheric and ocean currents were found with more or less high concentrations in all polar ecosystem compartments. Among these pollutants, one of the most dangerous categories is persistent organic pollutants (POPs). Since polar ecosystems are fragile and have a limited capacity for resilience, their contamination can generate unforeseeable consequences that can affect global cycles. Our work aims to compile data collected through a review of studies carried out within the framework of POPs evolution in polar regions, and then to compare them in order to identify future improvements to be made within the framework of POPs monitoring in the Arctic and Antarctic. According to our observations, POPs concentrations in all ecosystem compartments in Arctic are much higher than in Antarctica. Moreover, global warming influencing the abiotic factors of diffusion and mobility of POPs has led to a massive revolatization of POPs in the Arctic as well as an increase in their concentrations in large mammals. We also noted a lack of availability of consistent and continuous long-term data in Antarctic, which is why an ambiguity persists in the understanding of the POPs contamination routes, their evolution as well as the application of projection models.

Keywords: persistent organic pollutants; arctic; Antarctic; bioaccumulation; environmental monitoring

INTRODUCTION
Although geographically and ecologically distinct, Arctic and Antarctic are two regions that show a great deal of similarity in their climatic composition as well as their ecosystem morphology. Some of these similarities include the presence of glaciers, icebergs, and snowstorms although both are among the regions of the Earth with the lowest precipitations and temperatures [1]. These extreme climatic conditions, their geographical isolation, their minimal prevalence of industrial and agricultural operations have favored the absence of human activities (mines, industries, etc.), as a result, these two areas have long been regarded as having safe environments free of any hazardous traces left by human activity [2]. However, during the 1960s, scientists carried out several studies which unfortunately put an end to this scientific assumption by detecting the presence of several anthropogenic pollutants in polar regions. Among the detected pollutants, persistent organic pollutants (POPs) were present for the first time in the polar atmosphere as well as in biological tissues[3, 4].

From then on, studies followed one another in order to first be able to understand the origin of these contaminants as well as the routes by the routes by which they reach the polar regions, and secondly, to assess the level of POPs contamination and to be able to project their short- and long-term impacts.

The studies thus carried out have revealed that there is a systematic transfer of persistent compounds from warmer regions to colder regions. In the Arctic, contamination is carried out massively in winter and these contaminants originate particularly from Europe and the eastern Soviet Union. Ottar in his research explained that the Arctic would actually be the final sink for POPs [5]. More or less high concentrations of POPs were thus detected in the two poles and because of their excessive use in other regions of the world, strict measures were taken to curve their production and emission, since once released in the environment they have the ability to migrate and contaminate polar regions [5, 6].

After the application of these restrictions, a considerable reduction of POPs concentration was recorded, on the other hand, the bioaccumulative character was greatly expressed because an accumulation of certain compounds such as PCBs (Polychlorinated biphenyls) was observed at the level of marine organisms such as seals and penguins [7].

Over the years, science evolution has made it possible to classify POPs among the most relatively toxic anthropogenic contaminants, bioaccumulative, persistent and with a global diffusion through atmospheric and oceananic exchange. Due to their volatile or semi-volatile and persistent nature, POPs are mainly propagated through atmospheric diffusion. They undergo multiple cycles of volatilization and deposition, until they reach the polar regions where the climate is extremely cold [8-11]. The low temperatures favor POPs retention in polar regions by "cold trapping" thus exacerbating their persistence even more [12-15].

In recognition of the danger represented by these characteristics mentioned above and their toxicological threat, in 2001, the United Nations Environment Program (UNEP) coordinated the Stockholm Convention which targets to reduce or eliminate the use, discharge and emission of 12 specific POPs globally, as well as to guide for their management, disposal and storage, in order to improve and preserve ecosystem health as well as reduce the human risks [16, 17]. This list is constantly updated, and in 2017, 16 new POPs were added [18]. As part of the Stockholm Convention Global Monitoring Plan, regular monitoring of POPs in biological (human and animal tissues) and environmental (air, soil and water) compartment is undertaken with the ultimate goal of monitoring their temporal trends and thus assess the effectiveness of achieving the objectives of the Stockholm Convention [19, 20]. That said, this surveillance is greatly accentuated in polar regions because, on one hand, they are the most vulnerable regions and the most affected by POPs toxicity, and on the other hand, these regions represent important sentinels in the functioning of global environmental cycles and their processes. Subtle changes in these regions are likely to affect the entire global environmental cycle, is the reason why long-term pollution monitoring in polar ecosystems is nowadays seen as a valuable and versatile scientific tool to assess anthropogenic influences on environment, as well as to monitor the efficiency of international regulation measures [19, 21, 22].

According to ISI Web of Knowledge (in 2020), since the first studies carried out on the presence of POPs in polar regions, less than 500 articles have been published on Antarctic and more than 2000 on Arctic. Among these articles, there are respectively less than 10 reviews for Antarctic and more than 50 for Arctic. Through a large bibliography, we deduct that studies conducted on the evolution, impact and monitoring of POPs in polar areas are mostly focused on Arctic [23]. Through their work, Scientists have established very clear information on the current and future impacts of POPs on Arctic ecosystems by addressing in deep detail several aspects of this contamination such as the space-time monitoring of the atmospheric trend of POPs for decades.

This research studies have also allowed to analyze the influence of climate change on POPs life cycle, their bioaccumulation through food chain and the danger they represent for global biodiversity in general and particularly polar bear [22-27]. On the other hand, in Antarctic, the understanding of POPs contamination and their ecosystem impact remains in ambiguity. The majority of researches are focused on POPs bioconcentration [28] and while very few addressed temporal monitoring of the atmospheric trend and impact of climate change on POPs evolution [29, 30].

Based on the pre-existing data, this modest work aims in general terms to compare data and influence of climate change on POPs accumulation in polar ecosystems. To achieve this, we will first trace and study the evolution of POPs in all compartments of polar ecosystems (air, water, biota and soil) while emphasizing climate change influence on POPs increasing. Then in a second place, we will approach a relevant synthesis of POPs fate and their impact in these two regions. This study won't only rend possible the compilation of works available on the two poles, but it will also provide a good picture of the current state of POPs as well as potential directions for their successful management in polar zones.

TOPICS COVERED IN POLAR RESEARCH ON POPs

Our bibliographic survey revealed that after the first detections of POPs in polar regions, studies were not carried out en masse throughout the 1990s and it was only after the entry into force of the Stockholm Convention (2004) that there has been a massive increase in the number of publications, this could be explained by the fact that monitoring in all ecosystem compartments is carried out to be able to assess the effectiveness of international measures and initiatives, so as to ensure the monitoring and continuous detection of POPs.

From 1972 to 2020, the number of researches in the Arctic greatly exceeded those carried out in Antarctica. According to ISI Web of Knowledge, Figure 1-column graph illustrates all the annual studies conducted on POPs in the polar region. And Figure 1-circular graph breaks down these studies as a percentage under the basis of various ecosystem matrices (air, biota, soil and sediments, and water). Regarding Biota, it is the matrix with the largest number of publications. It mainly deals with the accumulation and danger of POPs on polar biocenosis, the expression of their bioaccumulative characteristics through trophic chain and the health risk they represent for humans. As for atmospheric matrix, the studies were based on transport mechanisms, spatio-temporal distribution and concentrations monitoring. Regarding the aquatic matrix, it mainly deals with monitoring the concentrations of POPs contained in lakes, ocean currents, polar caps, snow, and ice caps. In addition, some researchers have been interested in explaining and monitoring the phenomenon of water-air exchange of POPs (revolatization), in particular with climate change as a factor aggravating this phenomenon. Compared to the research carried out on the three compartments mentioned above, studies of POPs relating to the soil and the sediment matrix are mainly focused for the two regions on the contamination of soils by POPs as part of the oil pollution in association with microbial diversity.

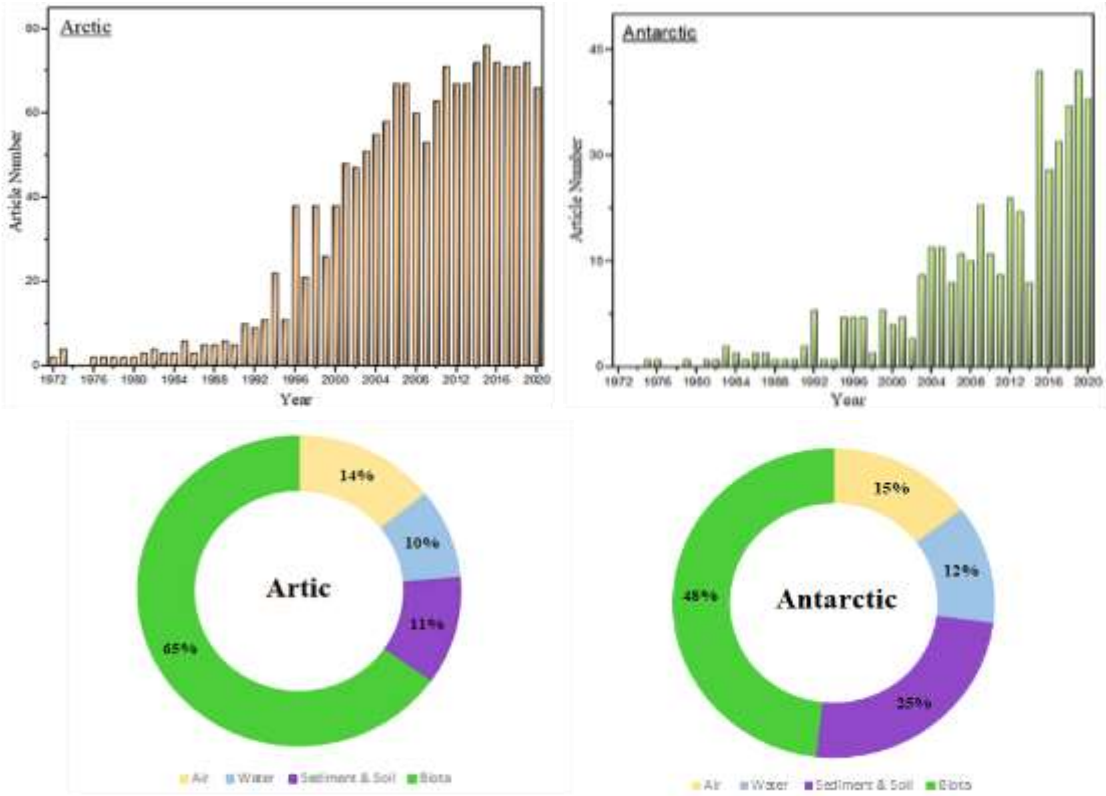

FIGURE 1: Article statistics in different years for various ecosystem compartments in the Arctic and Antarctic (Source: Web of Science).

The continuous updating of these studies is of great importance insofar as it represents a tool for evaluating the measures taken in the context of environmental and human protection during the Stockholm Convention. Likewise, these studies are necessary in Antarctica because the Madrid protocol (1991) declares it as a natural reserve. Environmental monitoring is therefore necessary in order to ensure good management and conservation of the biocenosis and biotopes.

MAIN CONTAMINATION ROUTES OF POLAR REGIONS

• Transport mechanism

POPs migration processes are governed on one hand by environmental factors such as the geographic location of the emission sources, climatic conditions, and on another hand by the POPs physicochemical properties[14, 31, 32]. They are generally transported from low latitude areas to high latitude areas through atmospheric and/or aquatic current[33-35]. The intensity of POPs distribution in the environment vary with the compound physical parameters (volatility, solubility, and adsorption capacity) combined with the different transport routes [36-38].

For atmospheric transport, volatile or semi-volatile POPs (in form of gas or aerosols) go through a geochemical process termed "Grasshopper Effect" or "Global Distillation". This process is mainly characterized by several cycles of evaporation and condensation which are a function of temperatures. High temperatures promote the evaporation of compounds whereas low temperatures their deposition from the atmosphere on soil and water [37, 39, 40]. They thus travel long distances and once arrived in polar regions, they accumulate there, since these ecosystems [41] are endowed with numerous environmental and climatic characteristics allowing POPs to remain intact longer and even to become more persistent [33].

As for aquatic transport, it is very often linked to atmospheric transport by air-water exchanges, it remains however essential to aquatic ecosystems contamination. This transport is favored by the season, the force of the current of oceanic and marine waters as well as the HLC

value of the POPs [42]. This mode of transport is much more intense in Arctic, river inputs are considered to be an important source of POPs. Moreover, ocean currents have been held responsible for transporting over 80% of β-HCH present in the Arctic Ocean [43]. Particles transported to the coast by great Arctic rivers during the melting period are contaminated with pollutants from industrial areas in the northern Urals and western Siberia. After several physical processes, the particles end up trapped in the ice which can then carry enormous loads of contaminated sediment [14].

From 1945 to 2000, approximately 27,700 t of α-HCH (< 1% of the world's emissions from agricultural land to the atmosphere) reached the Arctic circle. The main transport routes for these POPs are estimated to be 50% atmospheric and 34% ocean currents (34%) [44]. Also, it has been estimated that Arctic receives annually by atmospheric transport 5914 kg (89 kg) of PCB28 (PCB180) and 1217 kg (26 kg) respectively from Europe and North Atlantic. And by the same way, Artic exports to North America and Asia respectively 2413 kg (8.7 kg) of PCB-28 (PCB-180) and 21.4 kg PCB-180 Huang et al. [45]. In summer 2016, marine import of Endosulfan from Western Pacific to the Arctic Oceans was estimated at 0.36 t per month [42].

• Revolatilization of POPs: Effect of climate change

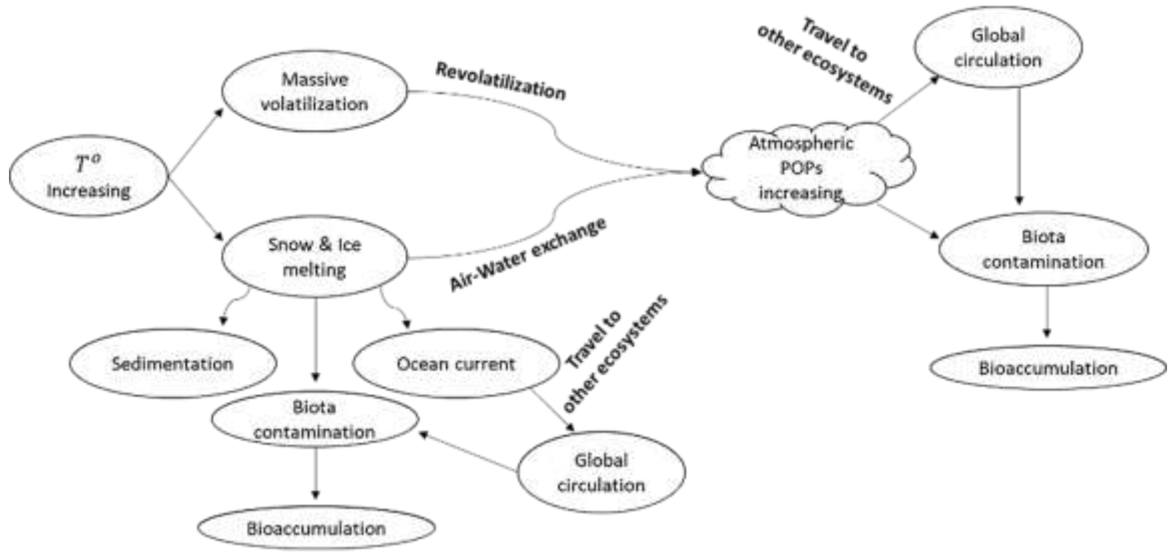

FIGURE 2: Impact of temperature rise in polar regions on the global fate of POPs.

After the application of the measures taken at the time of the Stockholm convention, Atmospheric concentrations of POPs have significantly decreased in polar regions [46]. However, the effectiveness of these measures was reduced in the mid-2000s as an increase in atmospheric concentrations of certain restricted POPs was observed in Arctic. This increase in concentration could be explained by the rise in temperatures which has led to the melting of the permafrost, ice and snow which for decades had housed large quantities of POPs [24, 47, 48]. As some researchers explained, the formation of sea ice in polar regions acts as a real storage reservoir for POPs [49-51]. Thus, with climate change, melting ice would release a large amount of these contaminants into the environment.

As illustrated above at (Figure 2), the temperature increase destabilizes the state of POPs in the polar ecosystemic compartment. The intensity of air-water particulate and gaseous exchanges is driven by the physicochemical properties of pollutants, seasonal variations and biological activities of the environment. Thus, in the Arctic, this exchange process alternates between net volatilization of POPs in summer and net condensation in winter when temperatures are very low [52-54].

However, due to climate change, water-air exchanges in polar regions increase considerably in pace with temperatures increase. Several researches have been carried out on the evolutionary study and modeling of the impact of climate change on traveling, condensation and cycling of POPs.

However, since in Antarctica the atmospheric trend of POPs has been monitored in the short term, there are not yet any studies associating climate models with atmospheric concentrations of POPs, nor even specific studies on their revolatilization [10, 23, 29]: the future warmer climate would lead to an intense transport of emerging contaminants as well as their accumulation in the Arctic [55]. Also, the volatility of a typical POP could increase up to 15% with an increase of 1°C [56]. Such an increase in temperature would increase the annual volatilization fluxes of dichlorodiphenyldichloroethylene (DDE) and hexachlorobenzene (HCB) by 8.5% and 7.8% respectively. And if the temperature rise is 2 and 3°C, the volatilization flux could be respectively 9.4% to 10.4% for DDE, and 8.6% to 9.3% for HCB [57]. By the end of the 2090s, the mass of PCBs could vary between 38% lower to 17% higher than their mass during the 90s. Similarly, the quantity of HCHs could rise to 38% more [55].

AIR

• Atmospheric monitoring stations

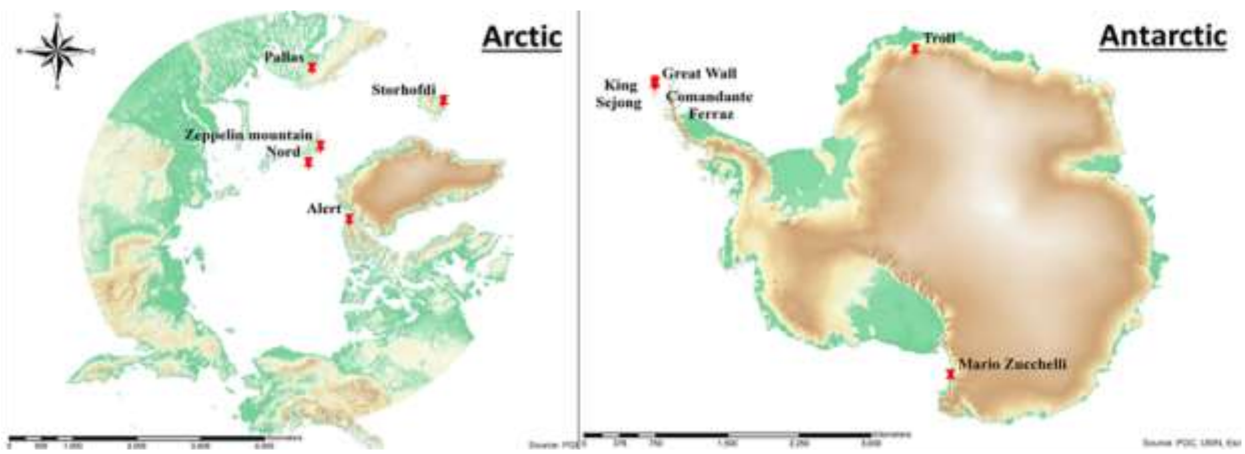

FIGURE 3: Polar air monitoring long term stations map

The fastest route of transporting contaminants to sensitive environments, particularly polar regions, is long-range atmospheric transport (LRT). Thus, atmospheric monitoring research and long-term measurements of persistent organic pollutants (POPs) are carried out as part of the protection of these ecosystems and fight against the spread of contaminants.

In Arctic, this atmospheric monitoring of POPs began in the 1990s. There are currently five long-term observation stations (FIGURE 3) and these continuously record atmospheric monitoring data for polychlorinated biphenyls (PCBs), isomers of

- dichlorodiphenyltrichloroethane (DDT)
- dichlorodiphenyldichloroethane (DDD)
- dichlorodiphenyldichloroethylene (DDE)
- hexachlorocyclohexanes (α- and γ-HCH)

Three of these stations (Alert, Zeppelin, and Storhofdi) also reported atmospheric concentrations of hexachlorobenzene (HCB) and chlordanes (trans isomers and isomers of chlordane and nonachlor). Alert station also includes other organochlorines such as mirex, endrin, and many others. But the latter turned out to be at concentrations below detection limits, so their atmospheric concentrations were not used to assess long-term trends. Thus, this great availability of data facilitates the application of /multiple prediction models, studies combined with several parameters such as transport and climatic models, as well as essential information on spatial and temporal distributions[21].

Antarctic also has five monitoring stations shown in Figure 3b. However, the longest survival time of atmospheric POPs in this region is seven consecutive years recorded at the Chinese Great Wall Station. During this expedition, nineteen PCBs, twelve polybrominated diphenyl ethers (PBDEs) and twenty-five OCPs were targeted by deploying Passive Air Sampling [58].

Note also that this same station recorded atmospheric monitoring over three years including PCBs and PBDEs [29, 30], the Troll station monitored over three years also Thirty-two PCBs, HCB, α- and γ-HCH, DDTs, DDD and DDE [10]. These monitoring are preceded by that of organochlorine pesticides (OCPs) and PCBs at the King Sejong Antarctic station [59]. In addition, there are stations at the two poles that perform monthly [21, 60] or annual [61-65]. These are carried out by a number of polar science-related research teams and organizations.

• Atmospheric concentrations comparison

Using active air samplers (AAS) and passive air samplers (PAS), researchers quantify atmospheric POPs concentrations [66-68]. Since early of the 1990s, the monitoring of legacy POPs began in Arctic [21], which leads to greater availability of long-term atmospheric monitoring data in Artic. Apart from this continuous monitoring program, other shorter-term concentrations are also recorded at some stations.

By going through several studies of atmospheric POPs monitoring in the two poles at different stations, we had made a compilation of the concentrations of seven specific legacy and emergent POPs (PCBs, HCHs, HCB, PBDEs, DDTs, endosulfans and chlordanes) from 1990 to 2018 (presented in Tables S1 and S2 in the Supporting Information). In order to compare the concentrations recorded at stations in the Arctic and Antarctic, Table 1 presents a summary of the ranges over this time interval. According to this table, we can see that the concentration margins of all the seven POPs considered are higher in the Arctic. This could be explained by the presence of anthropogenic activities in this region representing potential sources of POPs emissions (for example, the exploration and production of oil and gas in the Russian Arctic [14]).

TABLE 1: Comparison of atmospheric concentrations range of POPs in Arctic and Antarctic (pg/m^3)

	HCB	PCBs	PBDEs	Endosulfan	DDTs	HCHs	Chlordane
Arctic	0.18 - 760	0.17 - 330	0.09 - 47	0.01 - 130	0.2 - 217.8	0.06 - 288	0.12 - 39.1
Antarctic	0.6 - 252	1.5 - 985	0.7 - 16.1	0.2 - 88.5	0.03 - 103	0.13 - 74.3	0.02 - 3.26

Then, we used a radar graph to compare the means of these concentrations in the two regions. Through this graph, we note that the most abundant POPs in the two polar regions are HCBs and PCBs due to their wide emission in high latitude regions, as well as their physicochemical characteristics allowing them to be discovered more quickly in colder regions. HCHs are also at very high concentrations in the Arctic atmosphere.

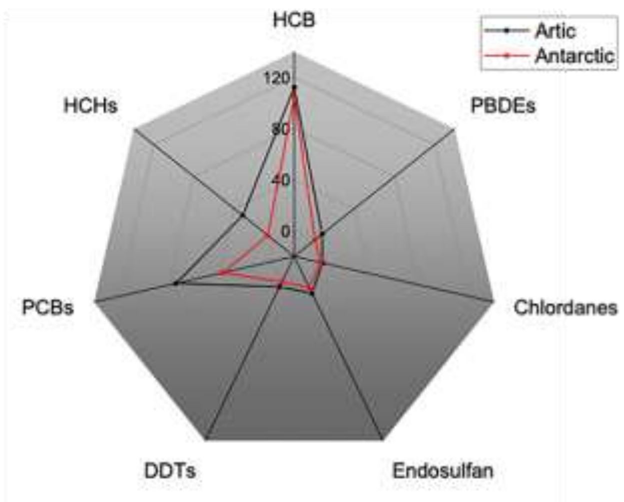

FIGURE 4: Comparison of the concentration average of atmospheric POPs in Arctic and Antarctic. Data and references used in this figure can be found in the SI.

According to more recent literature, there is a continual decrease in atmospheric POPs concentrations at the two poles [58]. In West Antarctica for example, from 2011 to 2017 the average concentration of eight PCBs (11, 28, 52, 101, 118, 138, 153 and 180) went from 15.8 to 2.7 pg/m^3, that of PBDEs from 1.2 to 0.5, HCHs from 9.6 to 1.11, DDTs from 4.7 to 0.7, endosulfane went from 6.73 to 0.5 and HCB varied from 222 to 149 pg/m^3.

WATER

Playing a vital role in the transport and storage of POPs in polar regions, water is a more or less complex ecosystem component insofar as its state changes with temperature. Through oceanic and marine currents, it transports pollutants to polar regions where they are trapped during the formation of glaciers in winter [14]. When seasons change and temperatures increase, the pollutants are released into water, then they contaminate biota before revolatilizing in the atmosphere [23, 53, 69]. Thus, the monitoring of this matrix is largely carried out first because it constitutes a "sink" for the pollutants and secondly because in recent years the process of seasonal migration of pollutants with the transition of the states of water (solid, liquid and gas) was accentuated due to the global warming [22, 24, 70, 71]. Like the other ecosystem components, the water matrix is no exception to the fact that researches are more concentrated in the Arctic. The concentrations of HCHS and PCBs in the Arctic Ocean have been the most abundant with a wide range of concentrations respectively 0.1 to 3156 pg/L [72, 73] and from 0.13 to 400000 pg/L [74-76]. The concentrations of Endosulfane, PBDEs and DDTs recorded were below 1 pg/L [72].

Regarding Antarctic, POPs concentrations are relatively low compared to the Arctic, with organochlorines compounds concentrations varying between 1.73 and 6.31 pg / L. It has also been reported that Emerging Pops concentrations such as PFASs (Per- and polyfluoroalkyl substances) are more or less high in both polar regions [53, 77].

BIOTA

One of the utmost dangers of POPs is related to their toxic character which is expressed mainly in fauna and humans [78]. According to the WHO, chronic exposure to POPs causes dysfunctions of the endrocrine, immune and reproductive system, neurocomportal and developmental disturbances, and cancer [79]. Being lipophilic compounds, once in the polar region, POPs accumulate in the lipid tissues of living organisms and then biomagnify through the food chain [80-82]. The polar biota, therefore, represents an appropriate biological indicator for global POPs emissions [83-89]. Several articles discuss the adverse effects on wildlife and humans, the mechanisms of bioconcentration and bioaccumulation as well as the temporal trends of POPs in polar biota [27, 90-95].

In this section, we will discuss the biomagnification mechanism of POPs in the polar food chain while considering the temporal trends performed as well as the climate change as a factor that can impact onthe intensification of the POPs propagation.

- ***Bioaccumulation***

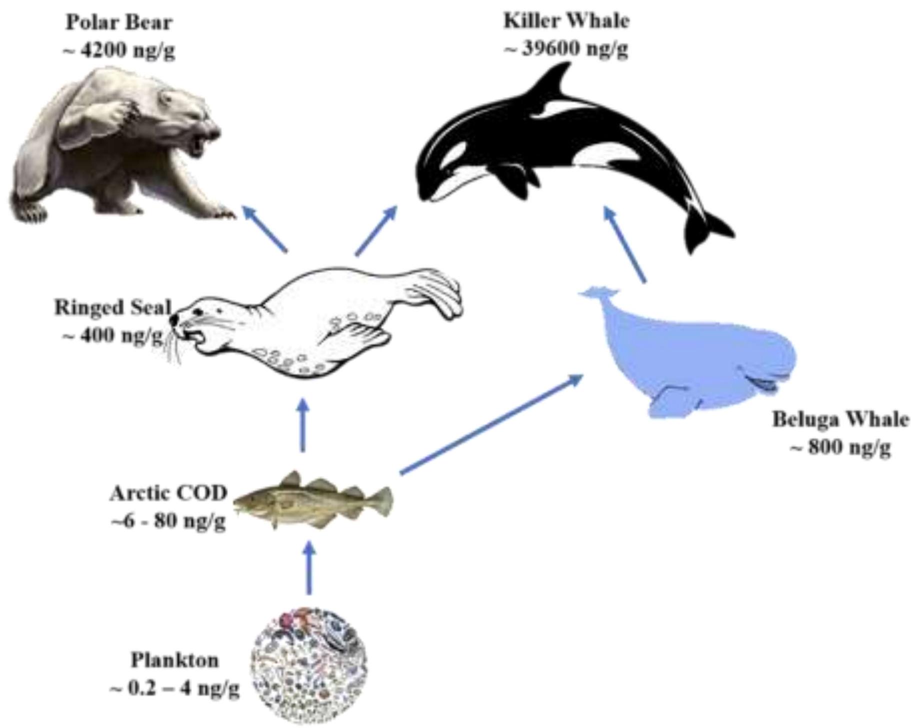

FIGURE 5: Schematic view of Σchlordanes (ΣCHL: cis-nonachlor, transnonachlor, cis- chlordane, trans chlordane, oxychlordane, and heptachlor epoxide) bioamplification in the arctic marine food web (lipid concentrations). Data are collected from: Polar Bear [80, 126, 127], Killer Whale [80, 103], Beluga Whale [80, 128], Ringed Seal [107, 128, 129], Arctic COD [80, 128], Plankton [128].

Food is a major route of exposure of living organisms to pollutants for wildlife and humans. The planktons ingest the particulate POPs contained in the water and sediments, then by trophic transfers, the POPs bioaccumulate through the polar food chains where the increase in the cumulative concentration of the POPs can reach the order of 7 to 10 [24]. Thus, the character Fat-soluble POPs make the main aquatic predators very vulnerable to their toxicities [96].

FIGURE 5, is an exemplification of chlordane biomagnification through the arctic marine food chain. On the one hand, from Plankton to arctic cod to ringed seal then polar bear, and on the other hand from Plankton to Killer Whale via arctic cod, ringed seal/Begula whale we note that the Chlordanes absorption is at a rate faster than that at which they are eliminated, thus leading to higher concentrations at the marine predator apices.

These higher concentrations represent a major risk not only for the well-being of biota and it conservation, but also for indigenous peoples for whom the higher trophic levels contribute to the traditional diet.

In the Antarctic, POPs concentrations in biota are relatively lower than Arctic [97, 98]. However, HCBs have been detected with very higher concentrations in Antarctic marine pelagic [98], also the temporal monitoring of PBDEs in Antarctic biota between 2000 and 2014 showed that the concentrations increased, unlike Arctic where there is a significant decrease [91]. It should also be noted that in Arctic, unlike many legacy pollutants, the concentrations of polychlorinated biphenyls (PCBs) and Chlordanes have remained relatively higher over the past decade in fauna[99-101]. Moreover, Higher concentrations of PCBs have been proven responsible for weakening the immune system of polar bears in Arctic [102, 103].

• ***Concerns over increasing concentrations of POPs in biota with climate change***

The thermodynamic equilibrium of POPs distribution between the various environmental compartments is disturbed by the effects of climate change (CC). This would lead to a more intense water-air exchange resulting in a large escape of POPs out of the water, and as the CC would cause an increase in vapor pressure, POPs transport would be more active in the vapor phase. Likewise, the decline of the Arctic sea ice at a rate twice the global average is considered to be one of the most worrying indicators of CC [104]. Arctic sea ice representing key habitat for many species, and its extent and thickness declining, along with rising temperatures, less snow and altered nutrient availability, have all led to Arctic ecosystems disturbance. However, it should be noted that since CC would favor metabolism, thus probably weighing the balance of risk of increased release of POPs [105, 106]. To come back to the impact of global warming on the risk of increasing POPs in the biological compartment, several studies have looked towards a high probability of high bioconcentration of POPs in high trophic level species (Humans, Polar bear, marine large mammals, etc.) [24, 107].

It is also important to mention that nowadays, the best evidence justifying the correlations between the consequences of climate change with the increase of POPs concentration in biota comes from Polar Bear as it is about an alpha predator dependent primarily on a sea ice ecosystem, which has recently known remarkable changes [87, 108, 109].

In the AMAP 2018 report [88], a linkage between the increase of PCBs concentration in the body of certain mammals with climate change in Arctic was made. The following conclusions were drawn as a result of this:

- PCBs increased in Polar Bears and Ringed seals by Climate change
- No effect on PCBs by climate warming detected in Arctic foxes and some Ringed seals
- PCBs decreased by climate warming in Eider and Murre
- PCBs co-vary with climate oscillation indices in Glaucous gull and some Ringed seals.

In Antarctica, POPs concentrations reported in the biological compartment do not currently represent a risk in terms of adverse health effects because the reported values were used to estimate the exposure risks and have been shown to be an order of magnitude lower than those considered to cause physiological effects in aquatic mammals [110, 111].

SOIL AND SEDIMENTS

Deprived of POPs potential emissions sources, Polar regions soil and sediments constitute on one hand a real storage place of POPs and on the other hand in perfect natural archives on a long time scales of information on POPs levels evolution and even past ecosystem events [112, 113].

Although polar soil represents a "sink" of POPs, it should be noted that air-soil exchanges of POPs vary according to several factors such as variations in temperature and organic matter in the soil. In the Arctic and Antarctic, the spatial distribution of POPs in soil has been mainly examined at a small scale [114-118]. In Arctic soil, the concentrations of PCBs and HCB were found to be the highest with concentrations varying respectively from 300 to 950 pg/g and from 616 to 1477 pg/g [116]. At the Eastern coast of Antarctica, concentrations of several POPs have been recorded: HCHs (86 - 469 pg/g), DDTs (110 - 1220 pg/g), HCB (20-25280 pg/g) and PCBs (200 - 410 pg/g) [115]. Likewise, according to a study carried out in Antarctic, it has been indicated that the increase in temperature and the organic matter content of the soil lead to greater remobilization of PCBs [114].

Sediments are environmental components known to be recorders of atmospheric deposition. Besides, their vertical analysis is able to trace the history of global emissions of certain pollutants such as POPs [119-122]. Also, through the temporal and characteristic analysis of the POPs identified in the sediments, it is possible to determine the primary emission sources [123]. In the context of global warming, a second peak of DDT and HCH has been observed in the sediments of glacial lakes after the restriction of these compounds [124]. More recently, a study on the identification and quantification of Polychlorinated dibenzo-p-dioxins, dibenzofurans (PCDD/Fs) and their precursors - pentachlorophenol (PCP) and triclosan (TCS) contained in sediments in the Arctic and Antarctic, has revealed that 60% of these compounds were identified in the bottom sediments collected. Furthermore, 50% of the samples exceeded environmental limits, even reaching concentration levels comparable to those observed in mid-latitude regions [125]. These remarks thus could constitute an extreme risk for the conservation, prevention and sustainability of polar ecosystems.

CONCLUSION

From various parts of the world, many Persistent Organic Pollutants have long been detected in the polar atmosphere. A great wave of research has focused on their migration mechanisms as well as their temporal trends. However, it should be noted that these studies were mainly concentrated in the Arctic, thus offering a great availability of data allowing on the one hand to apply several models by considering several factors such as climatic parameters and seasonal variations, and on the other hand to provide clear scenarios on the behavior and fate of POPs in order to facilitate to international decision-makers the establishing of strategies for environmental protection and biodiversity conservation. This lack of data availability in Antarctic thus creates a great complexity in the development of explanatory models of transport mechanisms as well as evolutionary scenarios of POPs. In addition, the effects of climate change bringing a lot of changes in the structure and functioning of polar ecosystems such as melting ice, would lead to a Revolatilization of POPs. This phenomenon has been observed in Arctic and several research studies have been devoted to it, as for Antarctic the subject remains ambiguous due to a lack of continuous and coherent data. Thus, long-term atmospheric monitoring of POPs concentrations and emission inventories would be of significant help to the scientific community.

Having a lipophilic character, many studies have identified POPs in living organisms and their biomagnification through trophic chains (aquatic in majority). In Antarctica, the concentrations recorded turned out to have no negative impact on biodiversity and human health, which is not the case in the Arctic, where high concentrations have been detected in large mammals and would even be responsible for immune disorders in polar bear. However, more work is needed on animals at the highest trophic levels due to their involvement in the traditional diet of people in the Arctic and the changes noted in their diets in response to the onset of climate change.

Finally, despite the enormous efforts that are being made on a global scale for in-depth research on the monitoring and management of POPs, ambiguity remains as regarding the fate of POPs in the polar region. Therefore, continuous updates on all ecosystem compartments would be strongly recommended.

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CONFLICTS OF INTEREST: The authors declare no conflict of interest.

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