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Relative sensitivity of Arctic species to physically and chemically dispersed oil determined from three hydrocarbon measures of aquatic toxicity

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ABSTRACT

The risks to Arctic species from oil releases is a global concern, but their sensitivity to chemically dispersed oil has not been assessed using a curated and standardized dataset from spiked declining tests. Species sensitivity to dispersed oil was determined by their position within species sensitivity distributions (SSDs) using three measures of hydrocarbon toxicity: total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbon (PAHs), and naphthalenes. Comparisons of SSDs with Arctic/sub-Arctic versus non-Arctic species, and across SSDs of compositionally similar oils, showed that Arctic and non-Arctic species have comparable sensitivities even with the variability introduced by combining data across studies and oils. Regardless of hydrocarbon measure, hazard concentrations across SSDs were protective of sensitive Arctic species. While the sensitivities of Arctic species to oil exposures resemble those of commonly tested species, PAH-based toxicity data are needed for a greater species diversity including sensitive Arctic species.

1. Introduction

Increasing periods of open water in the Arctic have expanded shipping activities and opportunities for oil and gas exploration and production, resulting in greater potential for oil spills (Corbett et al. 2010; Gautier et al. 2009; Nevalainen et al. 2017; Noble et al. 2013). Exposure of Artic species in the aquatic environment to petroleum hydrocarbons may be compounded by slower hydrocarbon degradation (Brakstad and Bonaunet 2006; Venosa and Holder 2007) and volatilization of toxic fractions at low Arctic temperatures (Perkins et al. 2005), and oil dynamics in and under sea ice (Brandvik and Faksness 2009; Payne et al., 1991; Seelye 1979). Additionally, because of the limited complexity of Arctic food webs (e.g., five trophic levels; Borgå et al. 2004; Bradstreet and Cross 1982; Hobson and Welch 1992; Welch et al. 1992), impacts on key species such as Arctic cod *Boreogadus saida* and lower trophic level invertebrates may result in disruptions of energy transfer to higher trophic level vertebrates. Thus, understanding the sensitivity of Arctic species to oil products and other hazardous materials is of high scientific and ecological importance.

The relative sensitivity of Arctic aquatic species compared to temperate species to both physically and chemically dispersed oil has been a significant area of uncertainty because limited toxicity data generally exist for these species (Camus et al. 2015; Chapman and Riddle 2005; de Hoop et al. 2011; Gardiner et al. 2013). Arctic species have unique biochemical and physiological adaptations that could alter their sensitivity to petroleum hydrocarbons including: 1) lower metabolic rates that contribute to slower contaminant uptake and delayed toxicological effects; 2) larger lipid content, and thus greater bioaccumulation potential; and 3) physiological adaptations including the presence of blood antifreeze peptides (Borgå et al. 2004; Chapman and Riddle 2005; Clarke 1980; Clarke and Johnston 1999). Although region-specific toxicity data are ideal (Aurand and Coelho 2005), there are practical challenges in conducting toxicity tests with Arctic species under controlled laboratory conditions. Challenges include limited seasonal availability of test organisms, and logistical constraints associated with both, culturing tests species and conducting exposures under Arctic conditions. Thus, there are substantial benefits to assessing if previous research on a broader array of species from different regions could be used as surrogates for Arctic species (Barron and Ka'aihue 2003). Consequently, a re-evaluation of aquatic toxicity data with emphasis on Arctic species would provide further information useful in environmental decision making.

Despite the general recognition that polycyclic aromatic hydrocarbons (PAHs) and heterocyclic compounds are the major determinant

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of oil toxicity (e.g., Barron et al. 1999; NRC 2005), most published studies on whole oil products have expressed toxicity as total petroleum hydrocarbon (TPH) concentrations (Bejarano et al. 2014). TPH-based toxicity for a diversity of fish and aquatic invertebrates has been used as a consistent metric for evaluating the relative sensitivity of aquatic species to oil products (e.g., Barron et al. 2013; Bejarano et al. 2014; de Hoop et al. 2011). Toxicity studies of individual hydrocarbon compounds, chemical dispersant-only tests, and the relatively limited studies on physically and chemically dispersed oil products using key pelagic Arctic species have provided insights into their relative sensitivity (de Hoop et al. 2011; Gardiner et al. 2013; Hansen et al. 2014; Hansen et al. 2011; Olsen et al. 2013a; Olsen et al. 2011), and have facilitated comparative assessments based mostly on constant exposures (Camus et al. 2015; de Hoop et al. 2011; Olsen et al. 2011). However, previous comparisons have not included toxicity data of chemically dispersed oil products or have focused solely on spiked declining oil exposures intended to represent typical conditions following surface oil spills. This has implications on the understanding of the relative impacts of chemically dispersed oil and the sensitivity of Arctic species.

The objective of this research was to reassess the acute sensitivity of Arctic and non-Arctic species to oil products using a comprehensive, highly curated and standardized dataset. Data collection focused on tests performed under standardized methods with chemically and physically dispersed oil using three metrics of petroleum hydrocarbon exposure: TPH, total PAHs, and parent naphthalene as a surrogate for water soluble PAHs. To minimize variation due to oil dosing method, only data for spiked declining oil exposures (Fuller et al. 2004; Gardiner et al. 2013) were used in these analyses. This type of research is important to understand if assumptions about the relative sensitivity of aquatic test species hold for species in the Arctic, and to determine if the relative species sensitivity from constant exposures (de Hoop et al. 2011) also apply to declining exposures. Furthermore, the outcomes of these analyses provide information critical to spill response and planning in the Arctic (e.g., derivation of thresholds of concern), including assessments on the relative risks associated with the use of chemical dispersants. Comparisons of relative species sensitivity may also provide further insights on how spill response actions in temperate waters would inform related actions in the Arctic.

2. Methods

Acute toxicity data (median lethal concentrations, LC50) for aquatic species from Arctic and non-Arctic regions were obtained from multiple sources (Anderson et al. 2009; Anderson et al. 1974; Aurand and Coelho 2005; Bragin et al. 1994; Bragin and Clark 1995; Clark et al. 2001; Fuller et al. 2004; Gardiner et al. 2013; Goodbody-Gringley et al. 2013; Hansen et al. 2011; Lin et al. 2009; Liu 2003; Neff et al. 2000; Nordtug et al. 2011; Pace et al. 1995; Perkins et al. 2003, 2005; Rhoton 2000; Rice et al. 1979; Riebel and Percy 1990; Singer et al. 1996; Singer et al. 2001; Singer et al. 1998). Criteria for data inclusion were as follows: test performed with chemically dispersible fresh light and medium oil products (API gravity 31.3–44 and 24.8–30.6, respectively); aqueous exposure media prepared by physical (water accommodated fraction, WAF; and moderate energy WAF or MEWAF) or chemically enhanced oil dispersion (chemically enhanced water accommodated fraction, CEWAF); CEWAF prepared with Corexit 9500 or Corexit 9527; tests performed under spiked declining exposures as these are intended to represent typical exposure conditions that may occur following surface oil spills; LC50 values reported on the basis of measured aqueous exposures of TPH (aromatic and aliphatic hydrocarbons [C9-C44]), parent and alkylated homologue PAHs and/or parent naphthalene; and LC50 values reported without qualifiers. In cases where PAH concentrations were not explicitly reported (i.e., Aurand and Coelho 2005), concentrations were estimated as a proportion of the PAH concentrations in the whole WAF solution. Each record was evaluated and duplicates reported by the same author across several sources removed from the final dataset. In all cases, verification and standardization of currently accepted scientific names was made by querying the world register of marine species (WoRMS Editorial Board 2015), and designation of Arctic species made based on the Arctic register of marine species (Sirenko et al. 2015).

TPH, PAH and parent naphthalene species sensitivity distributions (SSDs) and their associated 5th percentile hazard concentrations (HC5), or concentrations assumed to be protective of 95% of the species on the SSD, were derived using the methodology detailed elsewhere (Bejarano and Farr 2013). Briefly, toxicity values were fitted to a log-normal distribution function and randomly re-sampled 2000 times to derive the SSD mean response and HC5 estimates with associated 95% confidence intervals (95% CI). Only SSDs that passed goodness of fit tests ($\alpha = 0.01$) (the Anderson–Darling for SSDs with > 7 species, and the Kolmogorov–Smirnov test statistics) were included in these analyses (Bejarano and Farr 2013). Comparisons between pairs of SSDs were made via the log-likelihood (chi-square statistic) (Piegorsch and Bailer 1997) by fitting individual (e.g., PAH and TPH SSDs) and pooled (e.g., PAH plus TPH SSD) datasets to a log-normal curve, followed by statistical comparisons of these resulting curves.

3. Results

Toxicity data for 35 aquatic species were included in these analyses, with a total of 8 Arctic species, 2 sub-Arctic species and 25 non-Arctic species, with most data being for crustaceans and fish. Calanoid copepods (*Calanus glacialis* and *C. finmarchicus*) and sculpin (*Myoxocephalus* sp., *M. polyacanthocephalus*) comprised the majority of the data for Arctic species, followed by Arctic cod (*Boreogadus saida*), Kelp shrimp (*Eualus suckleyi*), Dolly varden (*Salvelinus malma*), and a mysid shrimp (*Mysis oculata*). While non-Arctic species included a variety of temperate and tropical species, nearly 60% of all records were for standard test species commonly used in toxicity testing (i.e., mysid shrimp-*Americamysis bahia*, inland silverside- *Menidia beryllina*). There were 26 oil products in the dataset including Arctic North Slope (ANS), Prudhoe Bay (PB), Cook Inlet, Adriatic, Campbell, Harriett, Kuwait, North Sea, Norman-Wells, Norwegian Sea, Venezuelan, and Wonnich crude oil, as well as No. 2 fuel and Bunker C residual oil products, but not all three petroleum hydrocarbon metrics were available for each oil. Since in most cases there were insufficient data to generate SSDs for individual oil products, assessments were based on SSDs that combined oil products with similar physical/chemical properties (e.g., viscosity, hydrocarbon ranges).

3.1. Species sensitivities by region

A first analysis included the comparison of SSDs developed for cold-water species (Arctic/sub-Arctic; combined) and non-Arctic species from WAF (including MEWAF) and CEWAF data. Given data limitations for cold-water species, SSDs were developed by combining data from all oil products. SSDs from WAF data for cold-water species and non-Arctic species, showed a high degree of overlap when data were available for the same petroleum hydrocarbon metric (TPH and parent naphthalene) (Fig. 1). While SSDs for these two groups of species were not statistically significantly different for parent naphthalene (Chi-square statistic; $p > 0.05$), these were different for TPHs ($p < 0.03$) possibly because of a greater species diversity and the presence of a sensitive species (*Montastraea faveolata*; 5th percentile occupied on the SSD) within the dataset for non-Arctic species. Consistently HC5 estimates were comparable between these two groups of species for parent naphthalene, but much larger for cold-water species for TPHs (Table 1).

While there were some CEWAF data for cold-water species for all petroleum hydrocarbon metrics, these datasets were not sufficiently large (≤ 4 species) to generate SSDs. Despite these limitations, the available data showed similarities between cold-water and non-Arctic species even with the variability introduced by combining data across