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Estimation of southern resident killer whale exposure to exhaust emissions from whale-watching vessels and potential adverse health effects and toxicity thresholds

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ABSTRACT

Southern resident killer whales in British Columbia and Washington are exposed to heavy vessel traffic. This study investigates their exposure to exhaust gases from whale-watching vessels by using a simple dispersion model incorporating data on whale and vessel behavior, atmospheric conditions, and output of airborne pollutants from the whale-watching fleet based on emissions data from regulatory agencies.

Our findings suggest that current whale-watching guidelines are usually effective in limiting pollutant exposure to levels at or just below those at which measurable adverse health effects would be expected in killer whales. However, safe pollutant levels are exceeded under worst-case conditions and certain average-case conditions. To reduce killer whale exposure to exhaust we recommend: vessels position on the downwind side of whales, a maximum of 20 whale-watching vessels should be within 800 m at any given time, viewing periods should be limited, and current whale-watch guidelines and laws should be enforced.

1. Introduction

The population of killer whales (*Orcinus orca*) known as the southern residents (SRKW) inhabits waters off southern Vancouver Island, British Columbia (BC) and northern Puget Sound, Washington (WA) during summer months. The declining population has been studied extensively since the 1970s and is currently estimated to contain 89 individuals (Center for Whale Research, 2010). Because of its small size and genetic isolation from other killer whale groups (Barrett-Lennard, 2000), the SRKW population was listed as Endangered under the Canadian *Species at Risk Act* in 2001 (Government of Canada, 2010) and under the United States *Endangered Species Act* in 2005 (NOAA, 2010). Three anthropogenic factors have been identified as possible causes of the population's decline: decreased food availability due to the decline of salmon (their primary food source), exposure to toxic chemicals such as polychlorinated biphenyls (PCBs; Ross, 2006), and vessel disturbance (Bain, 2002).

The SRKWs are followed on average by 20 vessels (Koski et al., 2006) for approximately 12 h per day from May to September (Koski et al., 2006; Lusseau et al., 2009). It is very rare for the SRKWs not to have vessels nearby, and a theodolite study by Bain et al. (2006) found that vessels were within the field of view of the whales 99.5% of daylight hours in 2003 and 98.5% in 2004. Efforts to quantify vessel impacts on killer whales have been primarily limited to studying behavioral responses (Jelinski et al., 2002; Williams et al., 2002) and modeling the effects of vessel noise (Erbe, 2002). The present study investigates an aspect of vessel disturbance not previously considered – the killer whales' exposure to exhaust gases from whale-watching vessels and the risk of adverse health effects.

Numerous studies have investigated increases in human mortality and morbidity from exposure to exhaust emissions from motor vehicles (e.g., Gehring et al., 2006; Maheswaran and Elliott, 2003), non-road diesel engines (e.g., Brüske-Hohlfeld et al., 1999; Wong et al., 1985), and marine vessels (e.g., Corbett et al., 2007; Lu et al., 2006). Thus exhaust emissions from marine engines operating in close proximity to whales have the potential to deteriorate air quality and the health of SRKWs. While direct monitoring of air breathed by watched SRKW would be preferable to air pollution modeling, the measurement challenges are enormous. Body-mounted passive monitors are not an option due to the swimming and surfacing behavior of killer whales. Following whales and their watchers with monitoring equipment would be all but impossible, and enormously disruptive of whales and watchers. Even if measurement were relatively simple, large sample sizes would be required due to variability in a large number of important

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variables. Atmospheric dispersion modeling is a widely accepted approach in many studies of air quality (Arya, 1999; Hanna et al., 1982), and is the approach taken here.

Air pollutants (such as polycyclic aromatic hydrocarbons) bound to exhaust particles induce the cytochrome P450 1A gene subfamily (Takano et al., 2002). Expression of cytochrome P450 1A could be measured in skin biopsies from live killer whales or in the lungs of dead whales by immunohistochemistry (Angell et al., 2004). Polychlorinated biphenyls (PCBs) also induce cytochrome P450 1A (Angell et al., 2004), and since the SRKWs have very high PCB contaminant loads (Ross et al., 2000), cytochrome P450 1A expression per se is not suitable for determining exposure to engine exhaust. Instead, we employed allometric scaling from humans to killer whales to estimate threshold doses for adverse health effects in killer whales.

1.1. Whale-watching in British Columbia

Prior to 1976, there were few commercial whale-watching operations on the west coast of Canada and the United States (Koski et al., 2006), but by the summer of 2005, 39 whale-watching companies operated 74 vessels in BC and WA, and focused primarily on the SRKWs (Koski et al., 2006). These vessels operated mostly in Haro Strait, Juan de Fuca Strait, and Boundary Pass (Fig. 1). In addition to commercial vessels, at least 30% of vessels watching whales in recent years were non-commercial recreational vessels (Koski et al., 2006). Approximately 7% of the vessels near the SRKWs in 2004–2005 were research vessels granted research permits by American or Canadian authorities, which allowed their holders to approach whales closer than other vessels (Koski et al., 2006).

During the summer, the majority of commercial whale-watchers view whales from 0900 to 2100, with the greatest density occurring between 1000 and 1700 (Bain, 2002). The commercial season peaks during May–September, and when whales are present, some whale-watching occurs throughout the winter and early spring (Bain, 2002). Recreational vessels engaged in whale-watching have similar seasonal and daily patterns to commercial whale-watchers (Bain, 2002). During peak summer months, the mean number of whale-watching vessels within 800 m of the whales increased from four in 1990, to 18–26 vessels from 1996 to 2002 (Koski et al., 2006). The maximum number of vessels seen following a single group of SRKWs in each year from 1998 to 2002 ranged from 72 to 120, with the majority being recreational rather than commercial whale-watching vessels (Koski et al., 2006).

Fisheries and Oceans Canada (DFO) and the National Ocean and Atmospheric Administration (NOAA) created voluntary *Be Whale Wise Guidelines* (Fisheries and Oceans Canada, 2008) to reduce vessel disturbance and manage traffic. The guidelines are now law in WA State (Washington State Legislature, 2008). Commercial whale-watching associations have incorporated the guidelines into their professional codes of conduct; however, recreational vessel operators are often unaware of them, and incidents of non-compliance are common and enforcement rare (Koski et al., 2006).

1.2. Atmospheric conditions affecting the dispersion of exhaust gases

Whale watching is a recreational activity that generally occurs under anticyclonic weather conditions, characterized by light winds (and therefore calm sea state), clear skies and subsidence (atmospheric sinking). In these conditions, the lower boundary layer over ocean waters will be neutral or stable. Lower boundary layer temperature measurements in the peak whale-watching season (July and August) in the Strait of Juan de Fuca showed weak, surface based temperature inversions up to 8 m above sea level (Lachmuth, 2008). Based on these observations, we can safely assume that pollutants emitted in vessel wakes are mixed vertically by vessel wake-induced turbulence up to a reasonably well-defined mixing height.

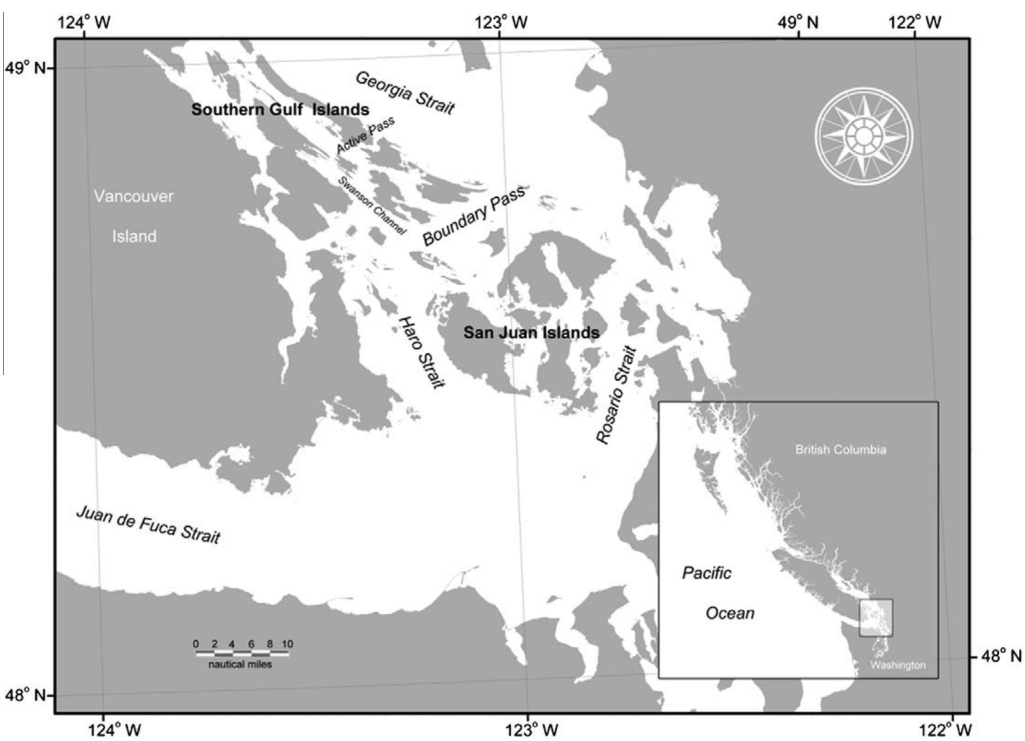

Fig. 1. Map of the summer habitat of the southern resident killer whales in southern British Columbia and northern Washington.

The extent of air pollution buildup over the sea is determined by wind and the strength of the inversion layer, and in order for flushing to occur, a strong synoptic system with high winds is required (Environment Canada, 2004a). Although sea breezes occur most frequently in summer in the Georgia Basin, their effectiveness at dispersing pollutants is low because they are low speed (usually less than 4 m s^{-1}), and because their direction reverses diurnally (Steyn and Faulkner, 1986).

Winds in the prime SRKW whale-watching area are generally light (Lange, 1998) due to merging airflows from the Straits of Georgia and Juan de Fuca, and the ''wake effect'' of Vancouver Island and the Gulf and San Juan Islands (Brook et al., 2004). The wake effect is instrumental in the accumulation and photochemical evolution of air pollutants from terrestrial sources in Vancouver, Victoria, the Lower Fraser Valley, Whatcom County (WA), and from marine vessels in the Georgia Basin (Brook et al., 2004). Since atmospheric conditions during the commercial whale-watching season are predominantly stable with low wind speeds and mixing heights, air pollutants tend to accumulate directly above the water surface in the layer in which killer whales breathe.

Whale-watching vessels are not the only marine sources of air pollutants that potentially affect SRKWs. Their summer habitat experiences high levels of shipping traffic, as Juan de Fuca Strait, Haro Strait, Boundary Pass, and Georgia Strait form western Canada's primary shipping route (Chamber of Shipping, 2007). These waterways also support traffic from cruise ships, harbor vessels (workboats, tugboats, and charter vessels), ferries, fishing vessels, and recreational vessels (Quan et al., 2002). Over the next decade it is predicted that air pollutant emissions from automobiles will decrease in the Lower Fraser Valley, BC; however, emissions from marine sources will increase and surpass automobile emissions by 2010 (Environment Canada, 2004a). Thus exhaust exposure estimates presented here represent only part of the total exposure of southern residents to air pollutants.

1.3. Components of engine exhaust and health effects from exposure

The gaseous and particulate phase of exhaust from marine diesel and gasoline engines contains hundreds of harmful chemical compounds, the most abundant of which are carbon oxides (CO_x), sulfur oxides (SO_x), nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM). HCs in exhaust are composed of unburned fuel (aromatics, alkanes, and alkenes), and partially oxidized phenols and carbonyls (Rijkeboer et al., 2004). The majority of PM from combustion engines is in the submicrometer range (0.02–0.5 μm), and is composed of elemental carbon, adsorbed organic compounds from fuel and oil, sulfates from sulfur in fuel, and trace metals (World Health Organization, 1996). Gasoline and diesel engine exhaust contain several carcinogenic compounds such as 1,3-butadiene, benzene, and formaldehyde (Davis et al., 2007). The International Agency for Research on Cancer (IARC) has classified diesel exhaust as a probable human carcinogen, and gasoline exhaust as a possible human carcinogen (IARC, 1989). Animal studies have shown that there is potential for synergistic, additive, and/or antagonistic interactions between the individual components in fuel exhaust (Ritchie et al., 2001).

Toxicological data for diesel exhaust are considerable, especially when compared to other toxins, and critical health effects have been derived from numerous long-term exposure studies on humans (e.g., Edling and Axelson, 1984; Gamble et al., 1987; Purdham et al., 1987; van Vliet et al., 1997) and animals (e.g., Heinrich et al., 1986, 1995; Mauderly et al., 1996; Nikula et al., 1995). Data on health effects unique to gasoline exhaust is far sparser than that for diesel; however, studies suggest that exposure to gasoline exhaust produces similar noncarcinogenic pulmonary effects as diesel in humans and laboratory animals (Mauderly et al., 1996; Parent et al., 2006; Reed et al., 2008). Acute and chronic exposure to engine exhaust produces different health effects, as they depend on exposure concentrations and duration of exposure, thus chronic exposure produces larger and more persistent cumulative effects than acute short-term exposure (Pope and Dockery, 2006). Observed effects from acute exposure are: asthma aggravation, respiratory infection, transient changes in pulmonary function, pulmonary and systemic inflammation, oxidative stress, arterial vasoconstriction, and mortality (Koenig, 2000; Pope and Dockery, 2006). Effects arising from chronic exposure are: disease prevalence, lung growth or decline, lung inflammation, atherosclerosis, and mortality (Koenig, 2000; Pope and Dockery, 2006).

1.4. Cetacean respiratory anatomy and physiology

While killer whales and humans are both mammals and may be expected to have similar physiological responses to air pollution, there are some important species differences. Killer whales do not have an olfactory system (Marino, 2004) and may not be able to detect – and hence possibly avoid, engine exhaust. Due to the structure of the cetacean blowhole and nasal cavities, the epithelium of the proximal trachea is exposed to higher levels of airborne PM than other mammals (Fanning, 1977). Killer whales are members of the Delphinidae family of cetaceans, a group with higher lung to body size ratios – and hence greater area for PM deposition – than most other marine mammals (Perrin et al., 2002). Cetaceans do not have facial sinuses to remove water-soluble air pollutants before they reach the lungs (Lippmann, 2000).

Most air pollutants do not bioaccumulate in mammals, as they can be cleared or metabolized (Klanjscek et al., 2007). Clearance mechanisms and patterns in the respiratory tract are similar for humans and most other mammals, but the rates of clearance differ among species (Kreyling and Scheuch, 2000). Removal of ultrafine particles across alveolar cells and out of the lungs occurs at a faster rate in larger mammals, but the transport and clearing of particles by cilia is faster in smaller mammals than larger ones (Kreyling and Scheuch, 2000). The retention half-time of insoluble particles for rats, mice, and hamsters is about 50–100 days, and several hundred days for dogs, guinea pigs, and humans (Yu et al., 1991). Humans have a greater lung burden of PM than rats because they inhale greater quantities of PM and have slower clearance rates (Yu et al., 1991). Lung clearance rates have not been measured in killer whales, but based on other mammalian studies, they likely have faster translocation of ultrafine particles across alveolar cells, slower ciliated particle transport, greater PM lung burdens, and longer particle retention half-times than humans.

To avoid nitrogen narcosis and decompression sickness, dolphins experience lung collapse at approximately 40–80 m of depth, at which point air in the lungs is pushed into conducting airways where no gas exchange occurs (Fahlman et al., 2006; Ridgway and Howard, 1979). Like other cetaceans, the lungs of delphinids are highly reinforced with cartilage, sphincters, and smooth muscle to keep the conducting airways open during deep dives while allowing alveoli to collapse (Kooyman, 1989). Large conducting airways allow extremely fast ventilation rates in cetaceans, with most of the tidal volume (the normal volume of air inhaled and exhaled) exchanged within a fraction of a second (Kooyman, 1989). Increasing tidal volume (Kim and Hu, 2006) and breath-holding time (Invernizzi et al., 2006; Möller et al., 2004) causes greater PM deposition in the pulmonary region of the lungs, while increasing inhalation and exhalation flow rates decreases PM deposition (Invernizzi et al., 2006). Even though fast ventilation is expected to reduce PM deposition in killer whales, their large tidal volume exchange and breath holding increases PM deposition, and compared to humans and other terrestrial mammals, killer whales likely have increased PM deposition.

Many marine mammals exhibit adaptations for diving to depth, such as bradycardia and vasoconstriction, which allows maintenance of a constant blood pressure while diving (Butler, 2004). Upon submergence killer whales reduce their resting heart rate by 50% (Spencer et al., 1967). Increased pressure with depth decreases lung volume, causing a higher partial pressure of gasses in the lungs, which increases gas solubility in blood, and ultimately the amount of gas dissolved into tissues (Fahlman et al., 2006; Kooyman, 1973). The rate of blood flow determines when gas saturation of tissue is reached, thus saturation is rapid in myocardial tissue and slow in blubber (Fahlman et al., 2006). Since circulation to the skin and abdominal organs is restricted during deep dives, oxygen is channeled to the organs that require it most (i.e., heart and brain) (Butler, 2004). When the lungs are collapsed at depth no gas uptake occurs, but the shift of blood flow from organs that detoxify blood could allow toxins already in systemic circulation to concentrate in sensitive tissues like the heart and brain.

The SRKWs primarily occupy near-surface waters and spend only 2.4% of their time below 30 m (Baird et al., 2005, 2003). Deep dives last much longer than shallow dives, and adult males make notably more deep dives than adult females (Baird et al., 2005). Greater dive rates and swim speeds occur during the day than at night, and dive depths greater than 150 m occur regularly, with 264 m the maximum recorded depth for a SRKW (Baird et al., 2005). Killer whale lungs would not be collapsed above 30 m in depth, but the atmospheric pressure is three times that at the surface and the whales would experience higher rates of gas transfer into tissues (Fahlman et al., 2006; Kooyman, 1973).

2. Methods

2.1. Modeling air pollution dispersion

For small numbers of identifiable point sources, Gaussian plume or Gaussian puff numerical models are commonly used. These models capture pollution dispersion (the combined effects of downwind advection by wind and the crosswind spread by turbulence) using simple, empirical calculations based on a Gaussian function. Such models are routinely used for regulatory and population exposure purposes (Hanna et al., 1982). A common feature of existing air pollution models is that both sources and receptors of pollution are fixed in space, while wind speed and direction are variable. In our case, we have mobile sources (whale-watching vessels) a mobile receptor (the whale) and varying wind speed and direction. One reasonable simplification is that we may assume vessels and whales move in unison. Building a multiple, mobile source with single, mobile receptor air pollution dispersion model based on a Gaussian dispersion formulation would be a coding task well out of keeping with the first order estimation that is our objective. Instead, we used a programmable multi-agent based model (NetLogo; Wilensky, 1999) to simulate behavior of exhaust gases dispersion from whale-watching vessels, and to estimate concentrations of exhaust gases that SRKWs are exposed to under varying conditions. Multi-agent based models such as NetLogo are increasingly used as a tool for simulating dynamics of complex systems over time (Anwar et al., 2007).

2.2. Model description

The system to be modeled can be described as follows:

- multiple, mobile sources with surface emission of exhaust gas pollutants,
- emission into atmospheric wake area of whale-watching vessels,
- single, mobile receptor,
- vertical limit to dispersion defined by surface based temperature inversion, and
- variable light wind speed and variable wind direction.

The NetLogo program interface consists of a spatial environment comprising a uniformly gridded domain. We used a domain of 500 × 500 cells, each 2 m × 2 m. This size was chosen because the transom width of an average whale-watching vessel is 2 m. Elements referred to as 'agents' move and interact on the grid, which in our case represented the ocean surface. Agents and air pollution did not wrap around to the other side of the grid, and cells on the edge of the domain removed air pollution as if on an infinite plane.

The two types of agents in the model were a group of whale-watching vessels and a single whale. The whale moved forward one cell per time-step in a straight-line trajectory towards the right of the grid (i.e., 90° and the top of the grid is 0°). Williams and Ashe (2007) showed that northern resident killer whales usually follow straight-line trajectories when more than three vessels are within 1000 m of them, and we assumed that SRKWs behave in a similar manner. The modeled whale traveled at a constant swimming speed of 2.85 m s^{-1}, resulting in time-steps of ~0.7 s per cell. Vessels were placed on either side of the whale in uniformly spaced rows to simulate parallel travel (Fig. 2), as commonly practiced, and recommended by the *Be Whale Wise Guidelines* (Fisheries and Oceans Canada, 2008). The first rows of vessels on either side of the whale were set at the buffer distance model variable (the distance vessels maintained from the whale), and distance between vessels was set by the inter-vessel distance model variable. As the number of vessels increased, additional rows of vessels were added on either side of the whale. The vessels moved at the same speed as the whale and remained in the same position relative to each other and the whale for the duration of the simulation.

The "diffuse" function in NetLogo captures isotropic, mass conserving diffusion, and operates by forcing each cell containing pollution to share a fraction of its pollution with its eight neighboring cells each time-step. The fraction of pollution shared is called the

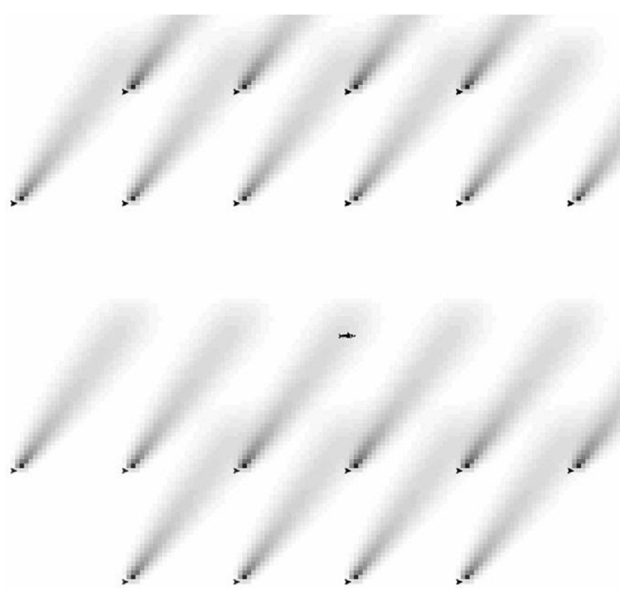

Fig. 2. Enhanced picture of the NetLogo interface. The whale is at the center of the grid and 20 whale-watching vessels (shaped as black triangles) are arranged in two uniformly spaced rows on either side of the whale. The vessels emit pollution plumes a shade of black proportional to the air pollution concentration, which are being moved downwind at a direction of 240°. North (0°) is at the top of the image, and during simulations the whale and vessels moved to the right, or east (90°).

"diffusion constant", and small values (e.g., 0% equals 0% of the pollution shared) produced narrow concentrated pollution plumes and large values (e.g., 1% equals 100% of the pollution shared) produced fanning diluted plumes. Fig. 3a demonstrates the operation of the NetLogo diffusion function. At all values of the diffusion constant, the pollutants diffuse symmetrically away from the plume centerline, and mass is conserved. Fig. 3b shows that the diffusion function results in crosswind spread that grows with distance downwind, and again, mass is conserved. The symmetrical shape of the plume is closely reminiscent of the plume shapes that would be obtained with a Gaussian plume model, and taken together, these two panels give confidence that the way diffusion is captured in the model does not deviate strongly from the way it would be modeled with more sophisticated models.

Advection was captured in the model by programming the pollution to move according to wind speed and direction each time-step. These approaches to advection and diffusion created a mass conserving crosswind plume that grew in width over time. The mixing height assumption resulted in all pollutants in a cell being uniformly mixed up to the mixing height. We have thus recreated an air pollution box model (McDonald et al., 1996) inside NetLogo.

A box model with full mixing models concentration as:

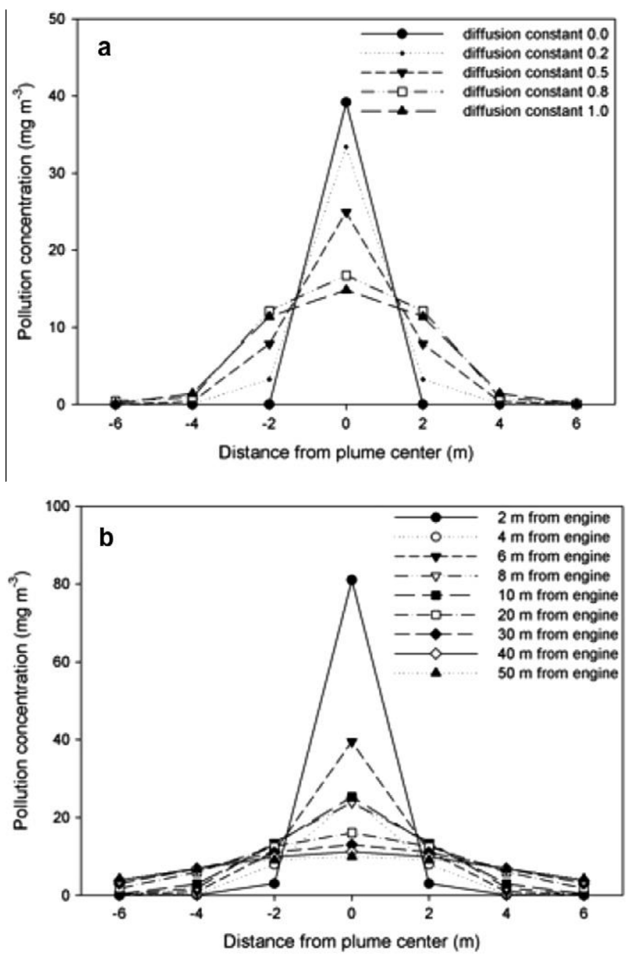

Fig. 3. The pollution concentration astern of a vessel at the plume center (0 m), and at increasing distance from either side of the plume center. (a) Shows the concentration 4 m astern of a vessel as the diffusion constant increases. (b) Shows the pollution concentration as the distance from the vessel increases, with the diffusion constant equal to 0.5. In the simulations used to create the figures, the wind speed was 0.75 m s^{-1}, the wind angle was 90°, and the mixing height was 3 m.

Table 1
The World Health Organization Air Quality Guidelines for Europe (WHO, 2000).

Air pollutant	Standard (mg m^{-3})	Averaging Period
CO	60	30-min
	30	1-h
	10	8-h
NO_2	0.2	1-h
PM	Dose response	n/a

$$C = \frac{e}{c \times z_m \times s},$$

where C is the concentration (in mg m^{-3}), e is the emission rate (in mg s^{-1}), c is the cell area that the pollutant disperses into each time-step, z_m is the pollutant mixing height (in m), and s is the vessel speed (in m s^{-1}). A similar equation is used to calculate pollutant concentration in cells into which pollution is diffused (rather than being directly emitted). Emissions from multiple vessels overlapped at the position of the whale (Fig. 2), and the model used simple addition to determine the concentration. We did not include a pollution deposition function to the water's surface in the model because over-water deposition velocities for the pollutants under consideration are insignificant (Joffre, 1988; Stull, 1988). The cell area experiences instantaneous mixing due to turbulent motion from vessels, thus the cell area is based on vessel size and the cell can be considered as one turbulent eddy.

The whale's air pollutant exposure was calculated as:

$$E = C \times t$$

where E is exposure (in mg h m^{-3}), C is concentration (in mg m^{-3}), and t is time (in h). The length of time used was 1 h for comparison with 1 h CO and NO_2 World Health Organization Air Quality Guidelines (AQG).

2.3. Vessel exhaust emissions

Following Frank et al. (2000), our model makes the simplifying assumption that the vessels in the whale-watching fleet all have the same emissions profile. We obtained data on the number of engines per vessel, engine horsepower (hp), fuel type, and engine type (i.e., inboard or outboard, two or four-stoke) for 23 out of 46 whale-watching companies operating during the 2005 season (Soundwatch Boater Education Program[1], and personal communication with whale-watching companies in 2006). We assumed that other vessels in the fleet operated similar engines. Using data from Soundwatch, we determined that the average whale-watching vessel had either twin 200 hp (total 400 hp) inboard four-stroke diesel engines or twin 200 hp outboard four-stroke gasoline engines. Over 30% of vessels engaged in whale-watching are recreational (Koski et al., 2006), and we assumed that they have the same emissions characteristics as the commercial fleet.

Government agencies in Canada, the United States, and the World Health Organization (WHO) in Europe have set ambient air quality standards and objectives to minimize adverse human health effects and protect the environment (British Columbia Lung Association, 2007). The WHO Air Quality Guidelines (WHO AQG) are expressed as milligrams of pollutant per cubic meter of air (mg m^{-3}), for specific averaging periods (durations of exposure) (Table 1). The WHO considers there to be no short or long-term exposure to PM below which no harmful effects are expected and therefore does not list a standard for it (World Health Organization, 2000). We used the World Health Organization AQGs as

[1] Unpublished data, October 2007. Available from The Soundwatch Boater Education Program, The Whale Museum, PO Box 945, Friday Harbor, WA 98250.

references to determine when the air quality could be considered poor and harmful to human health, and only CO and NO_2 have AQGs based on 1 h averaging periods. The World Health Organization AQGs for other air pollutants have longer averaging periods (8 h, 24 h, and annual), and were not focused on in this study.

Marine engines have either a dry exhaust system that emits exhaust directly into air, or a wet exhaust system that combines exhaust with water or directs it into water to cool, silence, and minimize human exposure (Kado et al., 2000). Hydrophobic volatile exhaust gases bubble out of water into air; however, less volatile gases with greater water solubility remain primarily in the water (Juttner et al., 1995). The proportion of wet and dry exhaust systems in the whale-watching fleet was determined from the Soundwatch Boater Education Program Boat Identification Guide[2]. Approximately 90% of the fleet had wet exhaust systems, and 10% had dry exhaust systems. To obtain wet emissions a 20% reduction was applied to dry CO emissions (Rijkeboer et al., 2004), and a 21% reduction was applied to dry NO_x emissions (Clark et al., 2000). The NO_x emitted by marine engines is usually made up of approximately 6% nitrogen oxide (NO) and 94% NO_2 (Quan et al., 2002; US EPA, 2000), and we applied this to NO_x concentrations.

Ambient air pollutant concentrations scale linearly with emission rates, thus we set the air pollution emission rate for each vessel at a dummy rate of 100 mg s^{-1} (equivalent to 70.2 mg per time-step). The United States Environmental Protection Agency (US EPA) has published emission factors for CO and NO_x in grams per horsepower-hour (g hp^{-1} h^{-1}) for zero-hour, steady-state, non-road gasoline and diesel marine engines of varying horsepower (US EPA, 2004a,b). Emission factors for the average whale-watching vessel engine were obtained by averaging the US EPA emission factors for marine twin diesel engines with a power rating of 175–300 hp, and for four-stroke outboard twin gasoline engines with a power rating greater than 175 hp (US EPA, 2004a,b). We multiplied each pollutant's emission factor (in g hp^{-1} h^{-1}) by the rated horsepower of the engine (200 hp) to obtain the emission rate (in g h^{-1}) for each pollutant. The emission rate was converted to milligrams emitted per second (mg s^{-1}) and divided by the dummy air pollutant emission rate of 100 mg s^{-1} to obtain multiplication factors for each air pollutant. The multiplication factors for the average whale-watching vessel (average of emissions from pre-controlled twin 200-hp, 4-stroke diesel and gasoline, with 90% wet and 10% dry exhaust engines) are 118 for CO, and 0.42 for NO_2. We multiplied the factors by the dummy air pollutant concentrations predicted by the dispersion model to obtain specific air pollutant concentrations.

In Canada, new marine engines beginning with the model-year 2001 must comply with US EPA emission standards (Environment Canada, 2004b); however, it takes about 12 years for a 90% fleet turnover (Northeast States for Coordinated Air Use Management, 1999). Therefore we considered only pre-controlled engines in the model. The US EPA also applies adjustment factors for changes in engine load and speed because steady-state and transient emissions can be quite different; for example, acceleration dramatically increases PM emissions (US EPA, 2002, 2004a,b). However, the US EPA does not apply adjustment factors to recreational marine engines due to lack of data (US EPA, 2004a,b). Thus we assumed steady-state operation in the model, based on the observation that speed and load of engines are more consistent in marine applications than in land vehicles.

The constant killer whale swimming speed of 2.85 m s^{-1} is representative of long distance travel found to range from 2.9 m s^{-1} (Ford, 1989) to 3.1 m s^{-1} (Kriete, 1995). However, traveling/foraging is the dominant activity state in resident killer whales and the average NRKW swimming speed during this activity in Johnstone Strait is 1.6 m s^{-1} (Williams and Noren, 2009), which is similar for SRKWs (Williams et al., 2009). The vessels match the killer whale speed, and higher vessel speeds will result in higher dilution of the exhaust, if the vessel emission rate (mg s^{-1}) is independent of vessel speed because this pollution will be emitted into a larger volume of air and hence be more diluted. However, the emission rate will generally increase with vessel speed since higher speed means higher power output which means more fuel consumed and hence more pollution emitted. The two effects will cancel each other out to some extent, until the vessel speed becomes "high" when emission rate increase will take over. Since whale-watching vessels are moving at low speed (relative to their capability and horsepower) the two effects will virtually cancel and thus the air pollutant concentration is largely independent of killer whale swimming speed. Therefore, slowing the killer whale swimming speed to reflect foraging activity will have no effect on the air pollutant concentration the killer whale experiences.

2.4. Model parameters

The model contains two types of variables: model structural variables (the diffusion constant, domain and cell size, and time-step) and model representations of real world qualities (wind speed, wind direction, the mixing height of pollutants in the atmosphere, the buffer distance, the inter-vessel distance, and the number of vessels). In order to understand the influence of model variables, we performed a "one-factor-at-a-time" sensitivity analysis in which each variable was set at a base value, except for the variable being analyzed, which experienced a realistic range of values with at least six increments within that range. Saltelli et al. (2008) demonstrate that this is an acceptable procedure as long as the modeled phenomena are not severely non-linear. Simulations were run until pollutant concentrations the whale experienced reached a constant value (for consistency the concentration at the 100th time-step was used).

Obviously the modeling system is invariant to mirror reflections of wind direction relative to whale motion (e.g., 30° was equivalent to 150°, relative to the whale); thus, only angles from one side of the compass rose were used (i.e., 90°, 120°, 150°, 180°, 210°, 240°, 270°). The base wind direction used was 180°. During the whale-watching season anticyclonic weather dominates (generally quasi-stationary), thus we can safely assume constant wind speed and direction in geographic coordinates over periods of an hour or less. Wind direction changes associated with frontal passages can thus be ignored and we kept wind speed and direction constant within a given model run.

The minimum wind speed was 0.71 m s^{-1}, the stall speed of most anemometers, and the wind speed increased by 1.42 m s^{-1} increments (i.e., 0.71, 2.14, 3.56, 4.99, 6.41, 7.84, 9.26, 10.69, 12.11, and 13.54). At greater wind speeds large waves are created on the ocean surface and it is likely that whale-watching vessels would be unable to find and follow killer whales. The base wind speed was 5.7 m s^{-1}. The lowest pollutant diffusion constant was 0, and increased by 0.2 increments to a maximum of 1.0 (i.e., 0, 0.2, 0.4, 0.6, 0.8, and 1.0). The base pollution diffusion constant was 0.5.

The model structure assumed a uniformly mixed lower atmospheric layer up to mixing height z_m, above which the concentration was zero. The mixing height in the dispersion model was independent of cell size, and instead was 1–10 times the average vessel transom length (2–20 m) due to aerodynamic drag of the moving vessel. The lowest mixing height was 0.5 m and increased by 1 m increments to a maximum of 9.5 m (i.e., 0.5, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5, 7.5, 8.5, and 9.5). Vessel drag produces a turbulent

[2] Unpublished data, December 2008. Available from The Soundwatch Boater Education Program, The Whale Museum, PO Box 945, Friday Harbor, WA 98250.

wake in which pollutants mix, and is influenced by the shape and speed of the vessel (Health Effects Institute, 1988). Because of reduced vertical mixing over cool water, the maximum mixing height considered was only 9.5 m since mixing heights greater than 5 m are unlikely. The base mixing height was 3 m.

The smallest buffer distance was set at 2 m (since whales often swim directly under vessels) and increased by 20 m increments up to 122 m (i.e., 2, 22, 42, 62, 82, 102, and122), as the *Be Whale Wise Guidelines* (Fisheries and Oceans Canada, 2008) advise (require in WA waters) vessel operators to maintain at least 100 m from whales. We included an additional buffer distance at 6 m to further explore the effect of vessels in close proximity. The base buffer distance was 60 m. The smallest number of vessels was 1 and increased by increments of 15 vessels up to 121 vessels (i.e., 1, 16, 31, 46, 61, 76, 91, 106, and 121). The base number of vessels was set at 20. The closest inter-vessel distance was 4 m and increased by 20 m increments (i.e., 4, 24, 44, 64, 84, and 104) to the maximum of 104 m, as vessel operators attempt to maintain a 100 m distance between vessels, and due to vessel size and safety issues we assumed that vessels would not approach each other closer than 4 m. The base inter-vessel distance was 50 m.

We ran further simulations with variables set at average-case whale-watching values to investigate specific phenomena and situations relevant to our study. We used the full range of wind speeds and mixing heights previously described, and set the buffer distance and inter-vessel distance at 100 m, the diffusion constant to 0.5, and the number of vessels to 20. This caused the furthest vessels to be 316 m from the whale, which is much closer than average real-world whale-watching conditions of 20 vessels within 800 m (Koski et al., 2006). Thus average-case simulations may have produced higher exposures than would occur in the real world.

Additional simulations were conducted with reasonable "worst-case" variables values, which were within bounds of known whale, vessel, and atmospheric behavior. The buffer distance and inter-vessel distance were set to 50 m, the number of vessels to 40, the mixing height to 2 m, the diffusion constant to 0.5, and the wind speed varied from 2.6 to 6.7 m s^{-1}. We ran simulations at the two wind directions that produced the highest air pollutant concentrations in the average-case simulations, 210° and 240°.

We also ran simulations to explore how random changes in wind direction would affect the whale's pollutant exposure. In these simulations the wind direction changed randomly every time-step around a normally distributed mean wind direction (SD = 22.5°). This standard deviation of wind direction fluctuation is expected in stable to slightly stable atmospheres for time periods of 1 h or less (Hanna et al., 1982). The random wind angle fluctuations produced smoother peaks and valleys in air pollutant concentrations (i.e., lower maximum concentrations and higher minimum concentrations) when compared to simulations with a constant wind direction. Despite this, the air pollutant concentrations from both types of simulation were within an order of magnitude, thus we limited our results and discussion to simulations that had a constant wind speed.

2.5. Allometric Scaling to estimate pollutant doses and health effects

Allometric scaling is a commonly used extrapolation method that allows quantitative comparison of function between or within species, since physiological functions (such as respiratory mechanics) are often related to body mass (Mb) (West et al., 1999). Metabolic rate (oxygen consumption) in vertebrates tends to scale to $Mb^{0.75}$ (Kleiber, 1961; Sample and Arenal, 1999), as do respiratory variables related to gas exchange (i.e., respiratory minute volume), but size-related variables of the respiratory system (i.e., tidal volume) tend to scale to Mb^1 (Milsom, 1989; West et al., 1999). The United States Environmental Protection Agency (US EPA, 1992) recommends scaling to $Mb^{0.75}$ for the extrapolation of laboratory animal carcinogenicity data to humans, and for wildlife risk assessment Sample et al. (1996) also recommend scaling to $Mb^{0.75}$ when using mammalian toxicity data. Since respiratory rates also scale to $Mb^{0.75}$, species-specific carcinogenicity and toxicity scale directly with respiratory rate (Schneider et al., 2004). We used a scaling exponent of 0.75 since it accounts for uncertainty in interspecies extrapolation with allometric rules (Schneider et al., 2004).

If the lowest observed adverse effects level (LOAEL) is available for a mammalian laboratory animal ($LOAEL_L$), an allometric scaling exponent (b), and the body mass of the laboratory animal (Mb_L) and wildlife species (Mb_W) are known, one can calculate the equivalent LOAEL for a mammalian wildlife species ($LOAEL_W$) by the equation (Sample et al., 1996):

$$\mathrm{LOAEL}_W = \mathrm{LOAEL}_L \left(\frac{Mb_L}{Mb_W}\right)^{1-b}$$

The World Health Organization (2000) Air Quality Guidelines (AQG) for 1 h exposure to CO (30 mg m^{-3}) and NO_2 (0.2 mg m^{-3}) were used as the laboratory species LOAEL, rendering humans the laboratory species. AQG concentrations are associated with minimally adverse effects in humans, thus are equivalent to the LOAEL (World Health Organization, 2000).

When determining a pollutant dose all sources of exposure need to be considered (i.e., ingestion, skin penetration, inhalation), as does the individual's activity level because ventilation rate is used to determine dose (Koenig, 2000). However, we assumed that inhalation was the only route of exposure to vessel exhaust pollutants for SRKWs. Koenig (2000) provides an equation for a basic estimate of an inhaled pollutant dose that is completely absorbed internally:

$$D = C \times t \times \dot{V}$$

where D is the dose (in mg), C is the concentration (in mg l^{-1}), t is the duration (in min), and $\dot{V}$ is the ventilation rate (in l min^{-1}). Calculated LOAELs for male and female killer whales were used in the basic dose equation (Koenig, 2000), to calculate toxicity doses for killer whales. The toxicity dose is a threshold above which adverse health effects would be expected. For comparison a toxicity dose for humans was also calculated by using the World Health Organization AQG for 1 h exposure to CO and NO_2 as the concentrations in the equation. The mean CO and NO_2 concentrations predicted by average-case and worst-case whale-watching simulations were also used in the basic dose equation (after the concentrations were converted from mg m^{-3} to mg l^{-1}), and these estimated exposure doses were compared to the calculated toxicity dose.

Doses were divided by the mass of a male or female killer whale to obtain the dose per kg of body mass for both sexes. We also used the effective ventilation rate (ventilation in the alveolar region (tidal volume minus dead space volume) multiplied by breathing frequency), as it provides a more accurate internal dose estimate than simply calculating dose using minute volume, which includes dead space volume. A free-swimming breathing frequency for killer whales was used to calculate effective ventilation, because in the dispersion model the killer whale was traveling at 2.85 m s^{-1}, which is similar to speeds measured during long distance travel (Ford, 1989; Kriete, 1995). For comparison we included pollutant doses per kg body mass for a 70 kg human during mild exercise (requiring less than 60% maximum oxygen uptake) (American College of Sports Medicine, 2006).

3. Results

3.1. Dispersion model sensitivity analysis

Only qualitative results are provided for the sensitivity analysis, as the base values are not indicative of typical whale-watching scenarios. Wind direction variation produced the greatest extremes in air pollution concentration that the killer whale was exposed to, followed by the buffer distance, the mixing height, the inter-vessel distance, the number of vessels, and finally the wind speed.

Wind directions of 210° and 240° in relation to the whale (traveling at 90°) consistently produced the highest air pollutant exposures, because at these directions exhaust plumes from vessels moved downwind straight over the whale (see Fig. 2). When wind came from directly ahead (90°) or directly behind (270°), the whale was only exposed to very limited pollution from diffusion because vessel exhaust plumes went right past the whale rather than over it.

At all wind speeds the wind directions of 90°, 120°, and 270° had air pollution concentrations that were essentially zero. For other wind angles, the highest air pollution concentrations occurred at mid-range wind speeds (2–8 m s^{-1}). Increasing wind speed caused air pollution plumes to bend as pollution was swept downwind at a faster rate, which changed the direction of plume spreading and caused the air pollutant concentration to peak when vessel plumes moved directly over the whale.

The diffusion constant was strongly dependent on whether vessel exhaust plumes passed directly over the whale or if they passed by the whale. A large diffusion constant caused the whale to experience a high air pollutant concentration if the whale was not in a direct exhaust plume (i.e., at wind directions of 90°, 120°, 150°, 270°), because pollution spreading eventually reached the whale. In contrast, when the whale was in a direct exhaust plume a low diffusion constant (e.g., 0.2) exposed the whale to a highly concentrated plume, and as the diffusion constant increased the plume was diluted.

The air pollutant concentration declined rapidly as the mixing height increased, but leveled off without reaching zero. The air pollution concentration tended to be inversely proportional to the buffer distance. Increases and decreases in pollution concentration over time occurred because the whale was either in a direct exhaust plume or not due to changing vessel positions as buffer distance increased. The air pollution concentration generally increased with the number of vessels, and generally decreased with increasing inter-vessel distance. Air pollutant concentrations were very low when the inter-vessel distance was less than 10 m because wind moved the pollution away before it had time to spread to the whale. Conversely, as the inter-vessel distance increased, some vessels were positioned well in front of the whale, thus more pollution ended up in the whale's path. The air pollution concentration fluctuated over time because changing the inter-vessel distance caused exhaust plumes to move over the whale.

The sensitivity analysis illustrated that the dispersion model captured important dynamics of air pollutant dispersion and behaved in a way that is intuitively correct.

3.2. Dispersion model average- and worst-case simulations

Under average-case whale-watching conditions, wind speeds in the range of 2–9 m s^{-1} produced CO concentrations that exceeded the World Health Organization AQG only when wind came from directions of 210° and 240° (Fig. 4). Thus mid-range wind speeds were most problematic. The World Health Organization AQG for NO_2 was never exceeded with average-case whale-watching conditions (Fig. 4). Mixing heights less than approximately 1 m, 2.1 m, 6 m, and 0.5 m produced CO concentrations that exceeded the World Health Organization AQG at wind directions of 150°, 180°,

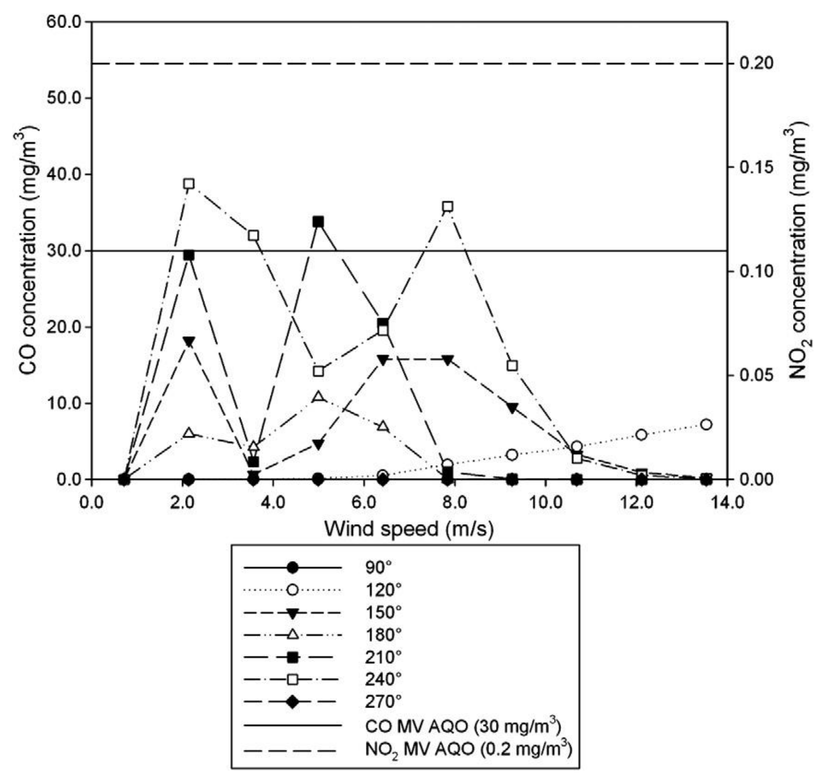

Fig. 4. The effect of wind speed and direction on the CO and NO_2 concentrations under average-case whale-watching conditions. The air pollutant concentrations have been scaled to the engine emission factors for the "average" whale-watching vessel (described in the text). The reference lines indicate the World Health Organization Air Quality Guidelines (WHO AQG) for 1 h of exposure to CO and NO_2 (World Health Organization, 2000).

210°, and 240°, respectively (Fig. 5). While mixing heights less than approximately 1 m, 1.5 m, 3 m resulted in concentrations that exceeded the World Health Organization AQG for NO_2 at wind directions of 150°, 180°, and 210°, respectively (Fig. 5). Thus low mixing heights produced the highest pollutant exposures for the whale. The mean CO concentration of all average-case simulations was 10.92 mg m^{-3} (SEM = 3.31) and ranged from 0 to 338.6 mg m^{-3}. The mean NO_2 concentration of all average-case simulations was 0.04 mg m^{-3} (SEM = 0.01) and ranged from 0 to 1.21 mg m^{-3}. These mean values are well under the 1 h World Health Organization AQG for both CO and NO_2.

In the worst-case simulations the World Health Organization AQG for CO and NO_2 were exceeded at all wind speeds and both wind directions considered (Fig. 6). The mean CO concentration was 69.5 mg m^{-3} (SEM = 14.07), and ranged from 0 to 159.2 mg m^{-3}. The mean NO_2 concentration was 0.25 mg m^{-3} (SEM = 0.05), and ranged from 0.14 to 0.57 mg m^{-3}. Both of these mean concentrations (especially that for CO) are above the 1 h World Health Organization AQGs.

3.3. Killer whale air pollution doses

The calculated LOAELs for male and female killer whales (Table 2) are much lower than the World Health Organization AQGs for CO and NO_2, as killer whales only require approximately 39% of the pollutant concentrations specified in the World Health Organization AQG to reach their LOAEL. Even though killer whales have a much lower breathing frequency, much greater effective ventilation rate, and extremely large tidal volume compared to humans, the calculated 1 h toxicity doses of CO and NO_2 per kg body mass that male and female killer whales receive were only approximately 12% of the human dose (Table 2). Based on the calculated average and worst-case doses of CO and NO_2 per kg body mass, killer whales are estimated to receive only approximately 34% and 26% of the human dose, for male and female killer whales, respectively, (Table 2).

The calculated toxicity doses of CO and NO_2 were very similar to the received doses predicted using the average-case simulation concentrations. For male and female killer whales, the calculated average-case doses of CO and NO_2 for 1 h of exposure were both lower than the toxicity doses for CO and NO_2. In comparison, the calculated worst-case doses of CO and NO_2 for male and female killer whales were much higher than the toxicity doses. The worst-case CO dose was 638% and 571% higher than the calculated CO 1 h toxicity dose, for male and female killer whales, respectively. The worst-case NO_2 dose was 333% and 294% higher than the calculated NO_2 toxicity dose, for male and female killer whales, respectively.

4. Discussion

Under average-case whale-watching conditions with 20 vessels maintaining the recommended 100 m distance from the whale and each other, the World Health Organization AQGs for CO and NO_2 were occasionally exceeded. In comparison, they were always exceeded during worst-case simulations. Generally the World Health Organization AQGs were exceeded in average-case simulations when: the wind was not coming directly in front or behind the whale, but rather when it came at directions of 150°, 180°, 210° or 240° (relative to the whale traveling at 90°); the mixing height was less than 6 m; and the wind speed was between 2 and 9 m s^{-1}. The minimum recommended approach distance to whales of 100 m (Fisheries and Oceans Canada, 2008), which we ran average-case simulations at, is violated frequently (Koski et al., 2006).

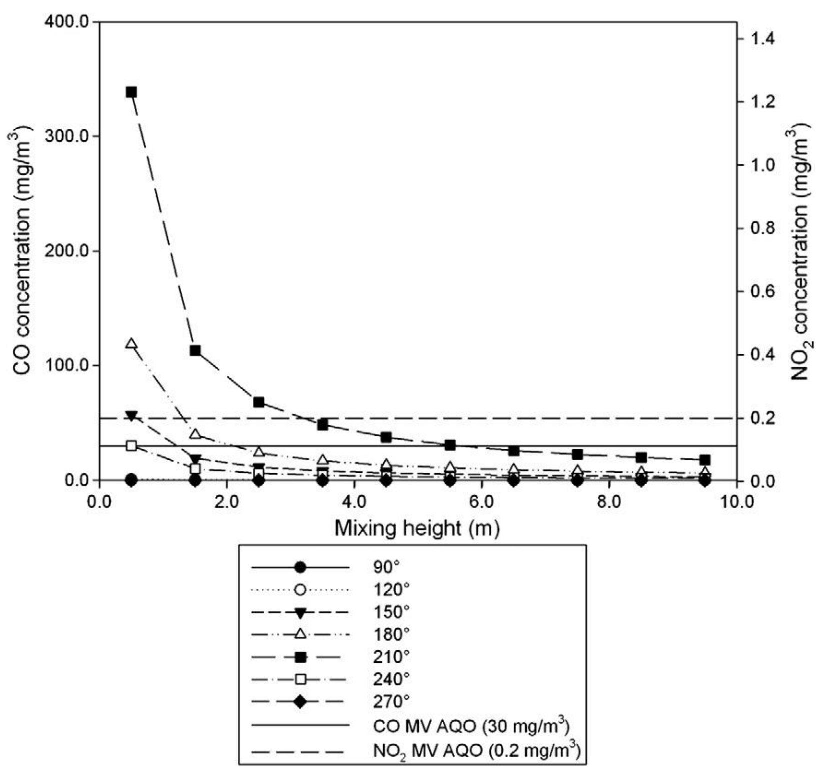

Fig. 5. The effect of the mixing height and wind direction on the CO and NO_2 concentrations under average-case whale-watching conditions. The air pollutant concentrations have been scaled to the engine emission factors for the "average" whale-watching vessel (described in the text). The reference lines indicate the World Health Organization Air Quality Guidelines (WHO AQG) for 1 h of exposure to CO and NO_2 (World Health Organization, 2000).

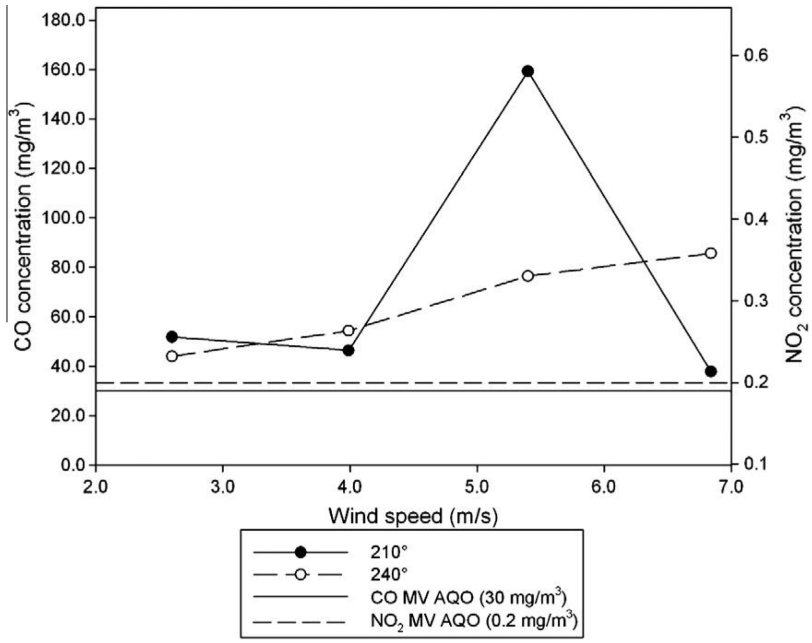

Fig. 6. The effect of the wind speed and direction on the CO and NO_2 concentrations under worst-case whale-watching conditions. The air pollutant concentrations have been scaled to the engine emission factors for the "average" whale-watching vessel (described in the text). The reference lines indicate the World Health Organization Air Quality Guidelines (WHO AQG) for 1 h of exposure to CO and NO_2 (World Health Organization, 2000).

Table 2
Calculated NO_2 and CO dose to lungs of male and female killer whales and humans via inhalation, and the variables used in the calculations.

Parameter	Male killer whale	Female killer whale	Human
Body mass (kg)	3766.5[a]	2427.5[a]	70[b]
Lung dead space volume ($l\,b^{-1}$)	7.5[c]	4.9[c]	
Respiration rate ($b\,min^{-1}$)	1.63[d]	1.74[d]	
Tidal volume ($l\,b^{-1}$)	210[a]	100[a]	
Minute volume ($l\,min^{-1}$)	342.3[e]	174.0[e]	
Effective ventilation ($l\,min^{-1}$)	330.08[f]	165.47[f]	18.0[b]
CO LOAEL ($mg\,m^{-3}$)	11.13[g]	12.38[g]	30[h]
NO_2 LOAEL ($mg\,m^{-3}$)	0.074[g]	0.082[g]	0.2[h]
CO toxicity dose ($mg\,kg^{-1}$)	0.058[i]	0.049[i]	0.46[i]
NO_2 toxicity dose ($mg\,kg^{-1}$)	0.00039[i]	0.00034[i]	0.0031[i]
CO average-case dose ($mg\,kg^{-1}$)	0.057[i]	0.045[i]	0.17[i]
NO_2 average-case dose ($mg\,kg^{-1}$)	0.00021[i]	0.00016[i]	0.00062[i]
CO worst-case dose ($mg\,kg^{-1}$)	0.37[i]	0.28[i]	1.07[i]
NO_2 worst-case dose ($mg\,kg^{-1}$)	0.0013[i]	0.0010[i]	0.0039[i]

[a] Kriete, 1995.
[b] American College of Sports Medicine, 2006.
[c] $V_D = 2.76\ Mb^{0.96}$(Stahl, 1967).
[d] Kriete, 2002.
[e] Respiration rate ($b\,min^{-1}$) × tidal volume ($l\,b^{-1}$).
[f] (Tidal volume ($l\,b^{-1}$) − dead space volume ($l\,b^{-1}$)) × respiration rate ($b\,min^{-1}$).
[g] $LOAEL_W = LOAEL_L\left(\frac{Mb_L}{Mb_W}\right)^{1-b}$ (Sample et al., 1996).
[h] World Health Organization, 2000.
[i] (Concentration ($mg\,l^{-1}$) × time (min) × effective ventilation ($l\,min^{-1}$))/Mb (Koenig, 2000).

The mean CO concentrations predicted by average-case and worst-case simulations were 10.9 $mg\,m^{-3}$ and 69.5 $mg\,m^{-3}$, respectively. This is approximately 5 and 31 times greater, respectively, than the 2.0–2.5 $mg\,m^{-3}$ range of CO concentrations measured 30 m from a busy Los Angeles highway (Zhu et al., 2002). The mean NO_2 concentrations predicted by average-case and worst-case simulations were 0.04 $mg\,m^{-3}$ and 0.25 $mg\,m^{-3}$, respectively. This is just above the range and 7 times greater, respectively, than the NO_2 concentrations measured at a distance of 115 m from busy motorways (0.032–0.037 $mg\,m^{-3}$) (Roorda-Knape et al., 1998).

Shallow mixing heights produced high air pollutant concentrations, and stable atmospheric conditions with shallow mixing heights predominate during the whale-watching season. In addition, mean wind speeds measured in SRKW habitat (BCARB, 2008) are within the range of wind speeds that produced the highest air pollutant concentrations in average-case simulations. Since atmospheric conditions during the whale-watching season are highly conducive to air pollutant accumulation, the potential to exceed the World Health Organization AQGs is high.

Empirical roadside studies indicate that dispersion of vehicle exhaust can be rapid. Emissions decline rapidly to approximately

50% of the original at distances 100 m from the road, and reach background levels 200–300 m downwind (Hitchins et al., 2000). At 100 m from roads, air pollution concentrations are usually below air quality standards, yet under certain conditions (e.g., low wind speeds, limited vertical mixing) concentrations can remain high (Health Effects Institute, 1988). Our modeled vessel concentrations at 100 m from the source decreased to a greater extent (on average to 31% of original) than empirical roadway studies, which suggests that our dispersion model is conservative.

Alternative fuels and new technology have the potential to lower air pollutant emissions from marine engines; however, there can be unintended consequences. For example, increasing fuel injection pressure can increase NO_x emissions (Watson and Janota, 1982), and creates higher rates of fuel atomization and evaporation, which can produce PM in the exhaust in the nanometer size range (Abdul-Khalek et al., 1998; Pagan, 1999). Thus relying on engine and fuel improvements to reduce killer whale exposure to air pollutants may not be effective.

We predict that Killer whales are more sensitive to air pollutants than humans, and experience toxic effects from as little as 39% of the toxicity dose for exhaust gas exposure in humans. For a 1 h exposure to average-case whale-watching conditions, we calculated the SRKWs receive doses of CO that are at the threshold of adverse health effects, while doses of NO_2 are below the threshold. Calculated worst-case doses of CO and NO_2 are well above those predicted to cause adverse health effects in SRKWs.

The SRKWs are exposed to whale-watching vessels on average of 12 h per day during peak season (Koski et al., 2006; Lusseau et al., 2009), however, this study only considered a 1 h exposure. Dose–response relationships are generally strongly non-linear (often exponential), such that the less time exposed, the higher the dose required to reach threshold. Thus exposures lasting longer than 1 h require more stringent air quality standards because the potential occurrence of harmful health effects increases. For example, the World Health Organization (2000) AQG for an 8 h exposure to CO (10 mg m^{-3}) is much lower than the 1 h AQG (30 mg m^{-3}), and it is also lower than the predicted killer whale's 1 h exposure (10.92 mg m^{-3}, under average-case whale-watching conditions). Thus the potential exposure to exhaust and resulting health effects is greater than what was captured by using a 1 h exposure and 1 h AQGs.

As discussed above in relation to humans and other terrestrial mammals, killer whales may be more sensitive to air pollution due to their respiratory anatomy and physiology alone. Furthermore, killer whales experience pressure differences in the lungs while diving that likely also influences pollutant uptake. Since the calculated toxicity doses for CO and NO_2 do not account for the effects of diving, they may be misleading, and much lower concentrations may actually pose an adverse health threat to killer whales.

Life history also plays a role in pollutant sensitivity as human infants, children, and the elderly are especially sensitive to air pollution (Koenig, 2000), and current urban levels of air pollution result in chronic, adverse effects on lung development in children (Gauderman et al., 2004). Almost half of the SRKW population (43%) is comprised of calves, juveniles, and post-reproductive females (Center for Whale Research, 2010). In addition, pregnant females and their developing embryo may be at increased risk from exposure to pollutants because the female is stressed during gestation and the embryo is undergoing rapid growth and differentiation (Sample et al., 1996). This underscores the importance of regulating emissions since air quality standards are designed to protect most but not all members of sensitive subpopulations (Beck and Cohen, 1997).

The SRKWs are among the most contaminated populations of marine mammals in the world (Ross et al., 2000), mostly by persistent organic pollutants (e.g., PCBs). The toxicity of extremely high levels of persistent organic pollutants could be additive or synergistic with the toxic effects of diesel and gasoline exhaust (Kagawa, 2002). Furthermore, other threats imposed by whale watching on SRKWs could aggravate diesel exhaust toxicity (Williams et al., 2006). Marine mammals contaminated by persistent organic pollutants, such as the SRKWs, have highly induced cytochrome P450 enzymes that convert pollutants to metabolites. Thus high enzyme activity may protect them from toxic effects of exhaust pollutants, and other suspected protective mechanisms (e.g., antioxidants, enhanced binding via hemoglobin and myoglobin) may also provide a level of protection against exposure.

We used modeling techniques based on highly predictable dispersion properties of gases to estimate killer whale exposure to vessel exhaust pollution under average and worst-case weather and vessel scenarios. This study helped identify data gaps and the challenges resulting from a general lack of models that characterize marine vessel emissions. The dispersion model had many simplifying assumptions and sources of uncertainty:

1. Published information on the types of engines used by recreational whale-watchers and the emissions produced does not exist, which prevented their inclusion in the dispersion model.
2. The engine configurations for half the whale-watching fleet were unknown and were assumed to be identical to known vessels.
3. The emission rates for vessels were not adjusted for age or other factors.
4. The percent retention of wet exhaust constituents in the water column was obtained from a limited number of studies.
5. The dispersion model only considered a very specific situation where whales and vessels were continuously moving at a constant speed, yet whale-watching vessel operators commonly shut down their engines when viewing whales. However, transient operating conditions (during arrival, repositioning, and exiting) often have increased emissions compared to steady-state operation (US EPA, 2002, 2004a,b).
6. The SRKWs are also exposed to air pollution from numerous sources not included in the model, which could greatly increase ambient pollutant concentrations.

There are also many simplifying assumptions and sources of uncertainty in the allometric model. Animal-to-human extrapolation is based on the similarity in response of laboratory animals and humans to toxins (Goddard and Krewski, 1992). However, parameters such as uptake, deposition, biotransformation, mode of toxic action, toxicological response, and clearance can differ among species in qualitative and quantitative ways (Blaauboer, 1996), and often toxins will produce tumors in animals but not humans (Knight et al., 2006). Additional uncertainties arise with extrapolations from high-dose animal studies to low-dose human exposures and differences in health effects that occur in short-term versus long-term studies (Kalberlah et al., 2002). Safety and uncertainty factors applied to air pollution LOAELs may provide a level of protection for more sensitive individuals. The uncertainty factor for inter-individual variability is 10, as is that for animal-to-human extrapolation (Renwick and Lazarus, 1998), thus the total uncertainty factor from the allometric model is 100. However, differences in the sensitivity of individual killer whales have not been quantified, and these differences may be larger than what the uncertainty factors account for. We assumed that the health effects from exposure to air pollutants that occur in small mammals and humans also occur in killer whales. We assumed that inhalation was the only route of exposure to exhaust pollutants, which may not be the case (especially with wet exhaust engines). Some of the model parameters could not be measured, and were calculated using formulae with their own simplifying assumptions (e.g., using the equation by Stahl (1967) to estimate respiratory dead space volume). Some of the respiratory rates, volumes, and body masses for male and female killer whales used to calculate dose were obtained from allometric scaling of data from captive killer whales, and are likely inappropriate for all animals in the SRKW population.

This study is the first investigation of whale-watching vessel exhaust emissions, and has demonstrated that in certain situations the SRKWs may be inhaling concentrations of air pollutants that have the potential to cause serious adverse health effects. The exposure to exhaust gases is one threat to the SRKW population that can be easily managed. The dispersion model determined that the most important factor is that vessel operators position their vessels downwind of whales. However, in reality it may be difficult for vessels to do so; therefore, capping the number of vessels that can whale-watch at one time to the average of 20 vessels within 800 m of whales may be a more feasible solution. The dispersion model also found that 20 vessels usually produce exposures below the World Health Organization AQG, thus based on engine emissions few large vessels would produce lower concentrations of air pollutants than many small vessels (US EPA, 2004a,b). Other strategies include limiting the amount of time that vessels remain with whales, diligent enforcement of the 100 m minimum vessel approach distance to whales as specified by the *Be Whale Wise Guidelines* (Fisheries and Oceans Canada, 2008) and Washington House Bill 2514 (Washington State Legislature, 2008), and a requirement that vessel operators maintain 100 m distance from each other.

We also recommend further modeling studies utilizing more sophisticated physiological models, and empirical studies (e.g., biopsy sampling, and collection of exhalation gases) to determine if the SRKWs are experiencing adverse health effects from this exposure. Until further studies provide more reliable estimates of killer whale exposure and health effects, the precautionary principle should be adhered to. Decision makers (in Canada, the Ministry of Fisheries and Oceans) need to decide if the SRKWs' involuntary exposure to current levels of exhaust emissions are an acceptable or tolerable risk to the population, based on the probability of harmful health effects, means of controlling emissions, and expected costs and benefits of doing so (McColl et al., 2000). It must also be recognized that air pollution from vessels is not only a health threat to this endangered population, but also a threat to the health of vessel operators, naturalists, and on-board tourists.

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