Assessment of cruise–ship activity influences on emissions, air quality, and visibility in Glacier Bay National Park

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ABSTRACT

An activity–based emission model was developed to determine cruise–ship emissions. Calculated emissions depend on cruise–voyage data (position, cruise speed, operation mode) and the ships’ characteristics (engine power, size, fuel–type, maximum cruise–speed). Cruise–ship emissions of particulate matter (PM) and its precursors were determined for the 2008 cruise season and for two proposed management actions: a prescribed speed in Glacier Bay, and implementation of an Emission Control Area (ECA) in Alaska at–large. The Weather Research and Forecasting model inline coupled with chemistry served to assess the impact of these management actions on air quality and visibility. On season–average, ships emitted –2.5 μg/m²/s PM in Glacier Bay. Cruising at constant 6.69 m/s anywhere in Glacier Bay decreased PM–emissions by 32% and marginally increased mean visibility. Altered cruise speeds strongly changed the spatial emission and concentration distributions of all species in and up to 30 km downwind of Glacier Bay. Changes differed among species. An ECA reduced PM–emissions from cruise ships by 74% and their impacts on visibility by 0.1, 0.2 and 0.1 deciview for the 10%, 50% and 90%–percentiles of best–visibility–days in Glacier Bay.

Keywords: Activity–based ship–emission model, WRF/Chem, Glacier Bay National Park, air quality, visibility

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1. Introduction

Although the impacts of gaseous and particulate–matter emissions from commercial shipping on air quality are well recognized (Beirle et al., 2004; Eyring et al., 2005), cruise–ship emission impacts have been largely overlooked. Cruise ships constitute a small fraction of the global fleet (Buhaug et al., 2009) and contribute marginally to emissions around heavily utilized shipping lanes. Yet cruise ships increasingly target ports–of–call in remote, undeveloped areas (Snyder, 2007; Eijgelaar et al., 2010) where they may represent the only anthropogenic emission source. In a pristine wilderness, the emissions from a single cruise ship may disproportionately impact air quality and visibility compared to urban ports–of–call, where background concentrations of pollutants are high (Schembari et al., 2012).

In Alaska, cruise–ship tourism is a major industry with nearly 1 million passengers. In 2008, 29 large cruise ships (carrying >250 passengers), made ports–of–call in Alaska many as part of typical 7–day itineraries. Companies advertise Alaska wilderness for these cruises. Viewing wildlife and glacial scenery is a primary motivation for many passengers. Thus, nearly all itineraries to Alaska include multiple “cruise–by” destinations, where passengers remain on board. These destinations include National Parks and wilderness areas such as Tracey Arm Fjord and Glacier Bay National Park (see the Supporting Material, SM, Figure S1), large glacial fjords that offer passengers an opportunity to view tidewater glaciers. Many of these fjords are characterized by steep–walled topography providing favorable conditions for overnight temperature inversions during the summer cruise season. Emitted precursors accumulated under inversions provide good conditions for gas–to–particle conversions (Mölders and Kramm, 2010). The primary and secondary particles from cruise–ship emissions can impact air quality and visibility (Sister and Malm, 2000).

Glacier Bay National Park encompasses nearly 12 141 km² of pristine glacial fjord landscape. No roads connect Glacier Bay with other areas of Alaska. Thus, cruise–ship passengers account for >95% of all visitors. In 2008, 225 cruise ships entered the park, typically spending 9–12 hours per visit all of which include stops in the upper fjords in front of tidewater glaciers. There is concern about potential impacts of cruise–ship visitation on biological resources, air quality, and visitors’ experience due to haze formation.

The National Park Service (NPS) has jurisdictional control over the marine waters of Glacier Bay and regulates the amount and operating conditions of all marine vessels in the park. The NPS allows up to two entries per day and currently restricts speed–through–water to 13 kts (6.69 m/s) in certain areas to meet endangered humpback–whale conservation objectives. While these management measures may prove effective in reducing the probability of severe encounters (Gende et al., 2011) or lethal collisions (Vanderlaan and Taggart, 2007), they may increase emissions as ships spend more time in an area or operate at inefficient loads. The spatial extent of speed restrictions is largely limited to areas where whales aggregate–typically in the lower sections of the park. In the upper fjords, the ships berth for several hours for glacier viewing. Here inversions are more likely to occur.
Reducing cruise speed for conserving one resource may or may not meet conservation objectives for another resource. The objective for our study was to assess the impacts of cruise–ship activities on emissions, air quality, and visibility in Glacier Bay National Park. Recognizing the importance of, and potential impacts from cruise ships, we sought to understand how several possible management actions (reducing speed, dedicating an Emissions Control Area (ECA)) may alter emission impacts while still sustaining the visitor volume. To achieve these goals, we developed a model that creates activity–based cruise–ship emission inventories. We performed simulations with an air–quality model using these inventories as input. Our study focused on the cruise season May 15 to September 15 2008, constituting peak–temperature periods and peak cruise–ship activity in Alaska.

2. Emission Inventories

2.1. Emission model and reference emissions

A model that creates activity–based ship–emission inventories using a bottom–up approach, was developed (see the SM, Figure S2). It uses Automated Information System (AIS) data of ship name, position, and speed as input. We combined the operating mode (berthing, maneuvering, cruising) with ship–specific information (number and type of engines, engine power, maximum speed, fuel–type used, capacity) to determine hourly emission rates for nitrogen–oxides (NOx), sulfur dioxide (SO2), volatile organic compounds (VOC), carbon monoxide (CO), ammonia (NH3), and particulate matter of less than 2.5 μm (PM2.5) and 10 μm (PM10) in aerodynamic diameter.

The operation mode is derived from the ship–location and cruise–speed data. Since the ships operate in mountainous terrain, some blind spots with respect to receiving the AIS–signal exist. Occasionally, a receiver was temporarily unavailable. When a ship reported position X at time A, and position Y at time B with B–A greater than the typical reporting frequency, and/or a distance X–Y > 9.9 km, we assumed the shortest possible waterway L between X and Y. The mean cruise speed was then estimated by the ratio of the traveled distance L to the time B–A needed for this distance. The model assigns the emission rates along the assumed path using the calculated mean cruise speed.

No AIS–reports exist after ships reach ports. Thus, the emission model assumes berthing between the last and next available AIS–report when ships enter ports. Cruise ships also berth for several hours in the parks and wilderness areas for tidewater glacier viewing.

Berthing uses the auxiliary engines to maintain power onboard. Maneuvering is assumed for speeds less than 2 m/s. During a 7–day cruise, cruising predominates. During cruising, emission rates depend on cruise speed (propulsion load) and hoteling demands.

Individual maximum power of the 29 cruise ships that cruised Southeast Alaska in 2008, ranges between 10 400 (8 000) kW and 40 000 (17 700) kW and for the main (auxiliary) engines. We assumed an auxiliary–engine maximum load of 50%, 30% and 60% while berthing, cruising and maneuvering, respectively.

The propulsion law gives the load factor of the i-th ship's main engines as:

\[ LFM_i = \min \left( \frac{v_i}{v_{i,\text{max}}} \right)^3, 1 \]  

(1)

where \( v_i \) and \( v_{i,\text{max}} \) are the cruise speed and maximum cruise speed, respectively. When tidal currents coincide with ship direction, recorded cruise speeds may exceed the maximum cruise speed. Then, the load factor was capped to 1 to ensure that calculated propulsion–engine load factors do not exceed 100%. The maximum cruise speeds of the 29 ships ranged between 10.28 m/s (20 kts) and 12.6 m/s (24.5 kts).

The hourly emission rates \( E_{i,k} \) of the i-th cruise ship for the k-th species were calculated as:

\[ E_{i,k} = EFM_{i,\text{mode}}L\Delta k_iL\Delta M_i(v_i)ME_i + EFA_{i,\text{mode}}L\Delta F\Delta A_iE_i \]  

(2)

where \( L\Delta k_i, L\Delta M_i, ME_i \), and \( AE_i \) are the load factor of the auxiliary engines, the low–load emission effect correction, and the total powers of the main and auxiliary engines, respectively. \( EFM_{i,\text{mode}} \) and \( EFA_{i,\text{mode}} \) are the operation–mode dependent emission factors of the main and auxiliary engines. During berthing, the main engines are assumed to be switched off.

Cruise ships used marine gas oil (sulfur content <1.5%) and intermediate fuel oil (sulfur content <4.5%) for the main engines, except for two that used heavy fuel oil (sulfur content <3.5%). To be conservative, we assumed that ships switched from higher to lower sulfur fuel while in Glacier Bay, if they had the option.

For the auxiliary engines during berthing, including hoteling, the emission model uses the emission factors determined by Schirokauer et al. (2010) for ships that docked in Juneau during summer 2008. The emission factors for auxiliary engines given by U.S. EPA (2002) are assumed for the other ships depending on their characteristics. Following U.S. EPA (2002), emission factors during cruising and maneuvering depend on the used fuel–type.

Compression–cycle combustion engines are less efficient at low than normal loads. The \( L\Delta A_k \), accounts for the fact that mass emissions (in kg/h) decrease as cruise speeds and engine loads decrease, but the emission factors (in g/kWh) increase. At propulsion loads exceeding 20%, \( L\Delta A_k \) equals 1. At low propulsion loads (≤20%), \( L\Delta A_k \) reads (U.S. EPA, 2002):

\[ L\Delta A_{k,i} = \begin{cases} a \cdot \left[ LFM(v_i) \right]^{1.5} + b & k = \text{CO, NOx, PM, VOC} \\ L\Delta A_{k,20\%} & k = \text{others} \end{cases} \]  

(3)

where \( L\Delta A_{k,20\%} \) is the emission rate at 20% load. The numerator gives the emission rate at the load. The coefficients \( a \) are 0.8378, 0.1255, 0.0059, and 0.0667; the intercepts \( b \) are 0.1548, 10.4496, 0.2551, and 0.3859, and exponents \( x \) are 1, 1.5, 1.5 and 1.5 for CO, NOx, PM and VOC, respectively.

VOC and emission rates calculated with Equation (2) represent bulk–emission rates containing several different species. VOCs were split into hexane, ethylene, propylene, acetylene, benzene, toluene, xylene and others, and PM was split into \( PM_{1.3} \) and \( PM_{10} \) at a 9:1 ratio following Eyring et al. (2005). \( PM_{2.5} \) was split into unspecified \( PM_{1.3} \), sulfate, organic matter, and black carbon following Petzold et al. (2004).

Plume–rise calculation considers stack parameters and average meteorological conditions following Peckham et al. (2011). On average, the stacks of the 29 ships are ~52 m above water. Thus, emissions reach up to 100–185 m height.

Emission–rate estimates for maneuvering and in–port activities have higher uncertainty compared to cruising because some operations start with cold main engines. Emissions during operations with cold and warm engines significantly differ, especially for VOC and PM. Engine loads change rapidly during maneuvering which increases variability in emissions. No information existed whether the engines were warmed up prior to...
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start of operation. The emissions determined for the 2008 cruise–ship activity serve as reference emissions (REF).

2.2. Emission control area

In 2010, the International Maritime Organization designated all waters up to 200 miles off the Alaska and North America coasts as areas where large ships, including cruise ships, will have to meet the emission standards of an ECA. By 2016, fuel sulfur content, and NOx emissions have to be reduced to 0.1% 1 000 ppm and by 80%, respectively.

According to U.S. EPA (2002) 97.753% of the fuel sulfur is converted to SO2. Thus, the new SO2–emission factor with an ECA is:

\[ EF_{SO2} = BSFC \times \frac{64}{32} \times 0.97753 \times 0.001 \]  

where BSFC is the specific fuel consumption assumed as 200 g/kW h. As fuel sulfur content decreases, the PM emission factors change. The adjusted PM emission factor reads:

\[ EF_{PM} = EF_{\text{nomin}} \times (S_{\text{actual}} - S_{\text{nomin}}) \times BSFC \times FSC \times MW R \times 0.0001 \]  

Here \( EF_{\text{nomin}} \) is the emission rate at nominal fuel content. \( S_{\text{actual}} \) and \( S_{\text{nomin}} \) are the actual and nominal fuel sulfur content (in \%), respectively. FSC=2.247% and MW R=224/32=7 are the percentage of sulfur in fuel converted into sulfate–PM and the molecular ratio of sulfate–PM to sulfur, respectively. Following the US Environmental Protection Agency (EPA), for low–sulfur fuel, 92% of the PM is assumed PM2.5 as high–sulfur fuels in medium and slow–speed engines produce larger particles than high–speed engines on low–sulfur fuel.

2.3. Speed–zone scenarios

Currently, when ships enter Glacier Bay, they cruise at variable speeds from the mouth to the upper fjords, berth for several hours, head back, and depart, spending 9–12 hours in Glacier Bay. According to Equations (1)–(3), emissions increase with increasing speed and, for some species, with decreasing load when the engines run at low load. Emissions of most species are relatively lower while berthing than maneuvering or cruising. Thus, park management is interested in how cruise–speed regulations affect emissions, air quality and visibility in Glacier Bay. Discussion exists to limit speed to 6.69 m/s (13 kts) everywhere in the park.

We calculated emissions for two speed–based scenarios in Glacier Bay. For both scenarios, the total time spent in Glacier Bay remains like in 2008 to allow ships to meet scheduling requirements at the ports–of–call. The first scenario, called S13, assumed a constant 6.69 m/s speed in Glacier Bay after pickup of the rangers at the park headquarter just outside Bartlett Cove (see the SM, Figure S1). S13 focused on whale protection and ignored the implications to other resources. Average cruise speed during 2008 (REF) was 8.58 m/s (16.7 kts). Thus, S13 reduced berthing time in front of glaciers by 28%.

Another scenario, called S20, served for sensitivity analysis to further–assess the implications of changing speed on emissions. S20 assumed ships cruise at 10.29 m/s (20 kts). The faster transit prolongs berthing at the glacier to meet ports–of–call schedules. In reality, ships cruise at variable speeds and consider the trade–offs of less/more time at the glacier and possibly changing speeds outside the park to meet schedules. The scenarios nevertheless permit an assessment of the implications of changing speed to multiple resources.

For missing AIS–data in Glacier Bay, the total path length \( L_{\text{total}} = L_{\text{Glacier Bay}} + L_{\text{outside}} \) was reconstructed as described above, where \( L_{\text{Glacier Bay}} \) and \( L_{\text{outside}} \) are the legs in and outside of Glacier Bay, respectively. To ensure the “scenario–speed” of the calculated overall speed \( v \) represents the path–weighted average of the speed outside \( v_{\text{outside}} \) and the prescribed speed inside Glacier Bay. When keeping the time in Glacier Bay constant:

\[ v_{\text{outside}} = \left( v - v_{\text{scenario}} \right) \frac{L_{\text{Glacier Bay}}}{L_{\text{total}}} \frac{L_{\text{outside}}}{L_{\text{outside}}} 
\]

3. Experimental Design

3.1. Model setup

To assess the impact of the management options on air quality, and visibility in Glacier Bay, we applied the Weather Research and Forecasting model inline coupled with chemistry (WRF/Chem version 3.3; Peckham et al., 2011) with the modifications by Mölders et al. (2010) and Mölders et al. (2011). Resolvable–scale clouds were considered by the WRF–Single–Moment 5–class cloud–microphysics scheme (Hong and Lim, 2006). A further–developed version of Grell and Devenyi’s (2002) scheme considered subgrid–scale convection. The Goddard two–stream multi–band scheme (Chou and Suarez, 1994) and the Rapid Radiative Transfer Model (Mlawer et al., 1997) were applied for shortwave and long–wave radiation. Convolution, cloud and aerosol–radiation feedbacks followed Barnard et al. (2010). The processes in the surface and atmospheric boundary layer (ABL) followed Janjic (2002). The modified Noah Land Surface Model (Chen and Dudhia, 2001) calculated the exchange of heat and matter at the atmosphere–surface interface, snow, soil–temperature and soil–moisture and frozen ground conditions.

Photolysis rates were calculated with Madronich’s (1987) scheme. The RADM2 chemical mechanism (Stockwell et al., 1990), Modal Aerosol Dynamics Model for Europe (Ackermann et al., 1998) and Secondary Organic Aerosol Model (Schell et al., 2001) including sea–salt emissions, some aqueous phase reactions and dry deposition were used. Dry deposition of gases followed Wesely (1989) with the modifications for Alaska by Mölders et al. (2011).

Biogenic emissions were calculated inline depending on meteorological conditions following Guenther et al. (1995).

3.2. Simulations

The domain of interest is centered at 58.5N, 135.5W (see the SM, Figure S1) with 110x110 grid–points of 7 km–horizontal increment, and a vertically stretched grid of 28 layers to 100 hPa. Mixed forest dominates on land, as most of the region is the Tongass National Forest.

The initial conditions for the meteorological, snow and soil quantities and meteorological boundary conditions stem from the 1x1, 6 h–resolution National Centers for Environmental Prediction global fine analyses. Idealized vertical profiles of Southeast Alaska background concentrations served to initialize the chemical fields and as chemical boundary conditions. A sensitivity study with 10% higher concentrations at the lateral boundaries and 72 h–backward trajectories suggest that using background concentrations as lateral boundary conditions may have negligible impact on the finding for Glacier Bay (see the SM).

We performed four WRF/Chem simulations in retrospective forecast mode for the 2008 cruise season. We initialized meteorology every five days, but used the chemical distributions at the end of a day as chemical initial conditions for the next day. For each of the four simulations, WRF/Chem read in one of the four emission inventories (REF, S13, S20, ECA).
4. Results

4.1. Evaluation

We evaluated WRF/Chem’s meteorological performance by means of twice daily radiosonde data at Yakutat and hourly observations of 2 m–temperature (T2), 2 m–dew point temperature (Td), 10 m–wind speed, and wind direction from 11 buoys, and 31 land–sites (see the SM, Figure S4). No chemical measurements existed at these sites. WRF/Chem’s chemical performance for Alaska has been found acceptable or good in many studies (Grell et al., 2011; Målders et al., 2011; Tran et al. 2011; Målders et al. 2012).

The near–surface observations suggested performance varies among months (see the SM, Figure S4). On average, WRF/Chem overestimates 10 m–wind speed and relative humidity by 1.75 m/s and 2%. It underestimates air–bias (bias =–0.6 K) and dew–point temperature (bias =–0.2 K). Figure S4 (see the SM) indicates good correlation for T, Td and acceptable correlation for wind speed and direction.

WRF/Chem captured the vertical temperature profiles well. The overall bias, root–mean–square error (RMSE) and correlation were 0.1 K, 1.8 K, and 0.84, respectively. In the first 600 m, WRF/Chem underestimated temperatures by −1.4 to −0.3 K. The overall dew–point temperature bias, RMSE and correlation were 0.8 K, 4.6 K and 0.6. Below 1.5 km, WRF/Chem underestimated dew–point temperatures by 0.2–1.2 K. The overall wind–speed bias, RMSE and correlation were −0.3 m/s, 4.13 m/s and 0.69. Correlation increased with height. As typical for complex terrain, WRF/Chem frequently underestimated wind–speed (up to 1.2 m/s) in the lower ABL due to local subgrid–scale channeling effects. The overall wind–direction bias, RMSE and correlation were −12°, 9° and 0.66, respectively.

4.2. Emissions

In Southeast Alaska, cruise ships travel consistent routes, using primary straits and the outer coast or visiting fjords including Glacier Bay. Thus, emissions were highest close to ports and in front of glaciers (Figures 1 and 2) demonstrating that operating for longer periods in an area (berthing, maneuvering) at low loads can more than offset the increased emission rates when cruising through an area. In Glacier Bay, the locations of emission maxima differ among the emission scenarios and emitted species (Figure 2).

Changing the cruise speed in Glacier Bay (S13, S20) changed the time spent in different operational loads and at the glaciers. Consequently, the spatial distribution of emissions within and averaged over Glacier Bay changed as compared to REF. A constant speed avoids the pattern of high and low speeds found in REF. Since the emissions were quite different for cruising [Equation (2)], and the time and duration when and where the emission occurred differed, we discuss changes in two ways: averaging over Glacier Bay permits assessment of the overall impact. However, lower emissions in one mode may hide higher emissions in another mode in the totals depending on the time a ship spent in a given mode. Thus, to assess local changes, we analyzed season–average emissions on a model grid–cell basis in Glacier Bay (Figure 2).

Lifting speed limits means the engines are less frequently at low propulsion loads, at which emission rates increase with decreasing load for all species but SO2 and NH3 for which emission just increase with speed [Equations (2)–(3)]. Therefore, in S13, as low loads occurred less frequently than in REF, SO2 emissions that were lower at than high loads, had no advantage of less time spent at low loads. Consequently, in S13, SO2 emissions increased by 11% on season–average over Glacier Bay compared to REF, while NOx, NH3, VOC, PM2.5, and PM10 emissions decreased by 14%, 13%, 22%, 8% and 32%, respectively (see the SM, Table S1). In Glacier Bay, except for SO2 the season–average emissions in S13 were reduced while where ships travelled slower than in REF. The higher NOx, VOC, PM2.5, and PM10 emissions at low loads in REF exceeded the increased emissions due to higher speed in S13. However, the higher emissions occurred at different places, namely where ships went faster in S13 than in REF. In S13, NOx, VOC, PM2.5, and PM10 emissions remained lower where ships cruised at lower loads than in REF. Consequently, the spatial distribution of emissions in S13 differed notably from those in REF (Figure 2). In S13, the highest local SO2, NOx, PM2.5, and PM10 emission decreases were −5.9 mol/km2/h, 18.1 mol/km2/h, 0.008 µg/m2/s, and 0.001 µg/m2/s, while increases were −10.2 mol/km2/h, 28.5 mol/km2/h, 0.007 µg/m2/s, and 0.001 µg/m2/s, respectively in other places. On season–average, in S13, cruise ships emitted more PM2.5 and NOx close to the glaciers and SO2 emissions decreased in the middle of the bay as compared to REF (Figure 2). In the lower bay, PM2.5, SO2 and NOx emissions marginally changed.

For S20, on season–average over Glacier Bay, SO2 emissions increased by 38% as cruise ships spent less time at low loads. NOx, NH3, VOC, PM2.5, and PM10 emissions increased by 71%, 71%, 54%, 165% and 96%, respectively on season–average over Glacier Bay (see the SM, Table S1) due to increased speed. The spatial emission distributions changed strongly (Figure 2). On season–average, the PM2.5, NOx, and PM10 emissions increased not only everywhere in Glacier Bay where ship traffic occurred. Increases were especially large in front of the glaciers where ships stayed longer than in REF. Locally and temporally SO2, NOx, PM2.5, and PM10 emissions increased up to 10.8 mol/km2/h, 57 mol/km2/h, 0.061 µg/m2/s, and 0.005 µg/m2/s, respectively. Due to the changed cruise pattern SO2, NOx, and PM2.5 emissions decreased temporally in some places up to 4.6 mol/km2/h, 12.4 mol/km2/h, and 0.008 µg/m2/s, respectively, as the total time spent in a grid–cell changed.

In ECA, the cruise–ship emissions decreased dramatically in Southeast Alaska (Figure 1). ECA reduced the season–average of SO2, NOx, PM2.5, and PM10 emissions in Glacier Bay by 87%, 78%, 56% and 74% (Figure 2; see the SM, Table S1). ECA generated the greatest difference in the spatial distribution of emissions compared to REF despite of the same cruise speed for both. In Glacier Bay, SO2, NOx, PM2.5, and PM10 emissions decreased locally and temporally up to 10 mol/km2/h and 25.4 mol/km2/h, 0.008 µg/m2/s and 0.001 µg/m2/s, respectively.

4.3. Air quality

The National Ambient Air Quality Standards for the 24 h–average and annual average of PM2.5 and annual average of PM10 concentrations are 35, 15, and 150 µg/m³, respectively. The simulated concentrations in Glacier Bay are notably below these values, i.e. air quality has to be considered as very good.

Concentrations are sensitive to emissions and meteorology. Particle concentrations were typically higher in fjords and along the major shipping lanes than on the mountains (Figure 3). The simulations showed that pollutants mostly remained between the steep mountains, where emissions occurred, as nighttime inversions frequently trapped them. Thus, high maximum PM2.5 concentrations most frequently occurred at night around 11:00 UTC (~9 h Alaska Standard Time) over the waters of Glacier Bay and Prince of Wales Island, and between 07:00 and 09:00 UTC in Chatham Strait, Juneau, and Skagway (see the SM, Figure S3). High near–surface maximum PM2.5 concentrations over the Pacific Ocean west of Prince of Wales Island between 22:00 and 24:00 UTC related to emission time rather than meteorology. At the top of the ABL (~1.8 km), PM2.5 concentrations were highest around 12:00 UTC in the southern model domain. In the northern part, they were typically highest between 16:00 and 23:00 UTC due to vertical mixing and convective clouds.
In S13 and S20, meteorological processes (mixing, clouds, advection, etc.) led to small concentration differences downwind of Glacier Bay as compared to REF. On season–average over Glacier Bay, in S13, NO\textsubscript{x} concentrations decreased by 27%, and marginally for VOC, PAN and SO\textsubscript{2} (see the SM, Table S2). The mid–section of Glacier Bay had lower NO\textsubscript{x} concentrations, while NO\textsubscript{x} slightly increased in the lower bay and in front of glaciers (Figure 4). The VOC–distribution marginally changed. Particulate–matter concentrations were affected mainly in the mid–section of the bay.

Figure 1. Cruise–season accumulated cruise–ship emissions in REF for (a) PM\textsubscript{2.5}, (c) SO\textsubscript{2}, (e) NO\textsubscript{x}, and ECA for (b) PM\textsubscript{2.5}, (d) SO\textsubscript{2}, (f) NO\textsubscript{x}. 
For S20, averaged over the season and Glacier Bay, SO₂ and NOₓ concentrations increased by 8% and 17%, while PM and PAN–concentrations changed less than ±1%. In Glacier Bay, the average SO₂ concentrations slightly increased in the upper and lower bay (Figure 4) under S20. NOₓ strongly increased along the ship paths. PM concentrations slightly increased in the upper bay.

As compared to REF, the average SO₂ and NOₓ concentrations decreased over the entire domain under ECA (Figures 3 and 4) resulting in high percent improvement of air quality in waterways and their adjacent land. However, since the concentrations were low, the absolute improvement was small. The PM concentrations off the coast along the major cruise–ship lane decreased slightly. In Glacier Bay on season–average, SO₂, NOₓ, PM₂.₅ and PAN concentrations dropped by 42%, 72%, 7%, and 6%, while VOC and PM₁₀ concentrations changed marginally (see the SM, Table S2). These results clearly show that the concentration reductions do not directly reflect the emission reductions (see the SM, Table S1). The decrease in PAN, which is a reservoir for NOₓ, was relatively small as compared to the decrease in NOₓ emissions and concentrations. In Glacier Bay, SO₂ and NOₓ concentrations decreased locally by more than half (Figure 4).

On 12 days, no cruise ship entered Glacier Bay. On these days, SO₂, NOₓ, PAN, PM₂.₅ and PM₁₀ concentrations were on average 23%, 15%, 3%, 15% and 18% lower than on other days. The PM₂.₅ speciation shifted slightly towards more sulfate– and less ammonium–aerosols on days without cruise ships. Other compounds remained nearly unchanged. This increase in sulfate–aerosols resulted from gas–to–particle conversion of precursor SO₂ present from previous ship entries. The small change in PAN highlights its role as NOₓ reservoir. The close to zero difference in VOC concentrations suggests that in Glacier Bay, biogenic emissions from the adjacent land dominate the VOC concentrations.

The percentage difference in PM₁₀ and PAN concentrations on days with and without cruise–ship entries remained quite similar for all emission scenarios. If an ECA was implemented, the average difference in SO₂ concentrations between days with and without ship entries went down from 23% to 6%. However, despite strongly reduced NOₓ emissions in ECA, the average difference in NOₓ concentrations between days with and without cruise–ship entries increased to 39%. The overall lower NOₓ concentrations under an ECA explain the seemingly high impact of cruise–ship emissions. In absolute values, however, cruise ships had a lower impact on air quality in ECA than in REF. Since some ships already used low–sulfur fuel in Glacier Bay, changes in SO₂ are marginal.

4.4. Visibility

Relative humidity enhances the contribution of soluble sulfates and nitrates to reduce extinction (Sister and Malm, 2000). Southeast Alaska’s relative humid climate has a long–term average relative humidity for May to September of ~81%. On average over the 2008 season, simulated near surface relative humidity in Glacier Bay and the domain was ~82%, i.e. our simulations represent a typical season humidity wise.

The calculation of the haze index (HI) and visibility followed Sister and Malm (2000) (see the SM). On the deciview scale, HI close to zero represents a pristine atmosphere under Rayleigh scattering conditions. HI increases as visibility degrades. Visibility less than 1, 1–2, and 2–5 km is associated with fog, mist and haze, respectively.
Our simulations show haze close to the water surface in fjords and offshore on many days (Figure 5). In Glacier Bay, REF simulated near surface fog, mist and haze conditions about 33%, 47% and 19% of the time. On average, near surface visibility was best, but hazy, in front of the glaciers and lowest in the lower bay where cruise ships slowed down and maneuvered to pick up/drop off rangers. In REF, June 30 had the best visibility (average $HI=1.3$ dv) whereas due to meteorology visibility was worst on May 15 (average $HI=9.0$ dv). Nevertheless, on May 15, $HI$ remained less than 12.2 dv everywhere in Glacier Bay. The best visibility

Figure 3. Season–average concentrations of (a) PM$_{2.5}$, (c) SO$_2$, (e) NO$_x$ for REF, and (b) PM$_{2.5}$, (d) SO$_2$, (f) NO$_x$ for ECA.
anywhere in Glacier Bay was on May 26 (HI=1.1 dv). In REF, the HI for the 20\% best, 20\% worst and median (40–60\%) visibility–days were 1.8, 3.0, and 5.2 dv, respectively. These visibility–group ranges are referred to their mid–points as the 10\textsuperscript{th}, 50\textsuperscript{th} and 90\textsuperscript{th} percentiles hereafter (see the SM, Table S3). Note that in Glacier Bay, even the “worst” HI values represented much better visibility than the 2018 target of 25.1 dv set by EPA. Thus, under existing conditions (REF), visibility still is pristine.

\textbf{Figure 4.} Zoom-in on season-average PM\textsubscript{2.5}, SO\textsubscript{2}, and NO\textsubscript{x} concentrations in Glacier Bay: (a–c) REF, (d–f) S13, (g–i) S20, (j–l) ECA. Outside, S13 and S20 concentrations differ marginally.
In S13 and S20, ships berthed a different amount of time at the glaciers, resulting in changed PM and NO\textsubscript{2} concentrations with temporally and locally up to 40 m reduced visibility. For S13, the 10\textsuperscript{th}, 50\textsuperscript{th} and 90\textsuperscript{th} percentiles of HI averaged over Glacier Bay remained as in REF. Nevertheless, in S13, the HI were relatively homogeneously about 0.2 dv lower over large parts of the upper bay on season–average (Figure 5). The highest local reduction in HI was 0.3 dv. In Glacier Bay, the locally best (worst) visibility had a HI of 1.1 (12.1) dv on May 26 (May 15), i.e. visibility marginally improved where it was worst. Close to the water surface, foggy, misty and hazy conditions occurred 32%, 47%, and 20% of the time, which is quite similar to REF.

In S20, averaged over Glacier Bay, the 10\textsuperscript{th}, 50\textsuperscript{th} and 90\textsuperscript{th} percentiles of 1.9, 3.1, and 5.3 dv (see the SM, Table S3), respectively, meant a slight deterioration of visibility in the medium and

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**Figure 5.** Season–average haze indices for (a) REF, (b) season–average haze–indices differences REF–ECA in Southeast Alaska. Zoom–in on season–average haze indices in Glacier Bay for (c) REF, (d) S13, (e) S20, (f) ECA; Changes are marginal outside.
worst–day ranges. The season–average HI were between 0.05 and 0.5 dv higher over Glacier Bay in S20 than in REF except at Bartlett Cove, where they remained similar to REF. The locally best and worst visibility in Glacier Bay had the same HI as in REF. In S20, close to the water surface, the percentage of foggy, misty and hazy days changed to 27%, 47%, and 24%, meaning less (more) time with fog (haze). This sensitivity study further confirmed that under low wind/inversion conditions, visibility decreases where emissions increase.

ECA led to about 0.2 dv lower HI over most of the Southeast Alaska coastal areas and parts of Canada (Figure 5). On average over Glacier Bay, ECA shifted the 10–90th percentiles to 1.7, 2.8, and 5.1 dv, respectively. In Glacier Bay, the locally best (worst) visibility had a HI of 0.8 (12.1) dv on May 24 (May 15). This means that visibility improved on days where it was already best, and on days where it was worst. In ECA, near surface visibility increased up to 5 m in Glacier Bay on season–average, and locally up to 39 m. In ECA, the percentage time in Glacier Bay with fog, mist and haze was 28%, 47% and 24%, i.e. the time with fog (haze) decreased (increased), while the time with misty conditions remained similar to REF.

5. Conclusions

An emission model was developed that permits creating activity–based, cruise–ship emission inventories. It can use actual AIS–derived ship–speed data or use prescribed cruise speeds or combinations thereof. It also permits creating emission inventories for emission control measures.

We applied the emission model to determine activity–based emissions for the 2008 cruise–season in Southeast Alaska. Furthermore, two emission scenarios were created assuming 2008 activity outside of Glacier Bay, but different speeds inside. A third emission scenario assumed the 2008 cruise activity, but under ECA standards.

While an ECA would provide emission changes across all of Southeast Alaska where cruise–ship traffic occurs, the scenarios assuming prescribed speeds in Glacier Bay would provide only local emission changes. The emission inventories reveal that cruise–ship related emissions are highest in ports–of–calls and fjords, where cruise ships maneuver and/or travel with low engine load.

The results from WRF/Chem simulations that alternatively used the four emission inventories, demonstrated that ship related pollutants remained for the most time in the fjords and between the steep mountains adjacent to prominent waterways due to frequent inversions under which the pollutants accumulated. In all simulations, PM1.5 and PM2.5 concentrations remained appreciably below their NAAQS values, meaning that despite cruise–ship entries Glacier Bay has pristine air.

Southeast Alaska’s summers have on average 81% relative humidity. Humidity naturally reduces visibility. Thus, the worst–visibility–days were mainly due to meteorology. Nevertheless, even the worst haze index values derived from the simulations still mean good visibility. In all simulations, visibility was dominated by haze in fjords, and was best on mountains. Fog was frequently simulated over large areas of the Pacific Ocean. Under ECA standards, the reduced emissions from cruise ships contributed to ~0.2 dv lower HI over most of the Southeast Alaska coastal areas and parts of Canada. In Glacier Bay, the local improvements resulting from an ECA would be strongest on worst–visibility–days. Of all scenarios, ECA provided the highest overall improvements in air quality and visibility in Glacier Bay.

As compared to the 2008 activity, the emission changes due to altered cruise speeds marginally affected visibility and haze indices in Glacier Bay. A principle conclusion is that the introduction of a speed of 10.28 m/s assuming that ships will spend more time in front of the glaciers slightly deteriorates visibility on days when visibility is medium or already low in Glacier Bay.

Consequently, longer viewing times at the glaciers increase the likelihood of negative impacts on the viewing experience by cruise passengers and other visitors. On the contrary, a speed of 6.69 m/s in Glacier Bay, implemented for protection of humpback whales, although increasing SO2 emissions, would improve visibility marginally on worst–visibility–days.

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Supporting Material Available

Chemical lateral boundary conditions (S1), Impact of settlements (S2), Determination of haze index and visibility (S3), Model topography and locations (Figure S1), Schematic view of activity–based cruise–ship emission inventory (Figure S2), Evans–plot of maximum PM2.5–concentrations during 2008 cruise season (Figure S3), Taylor–diagram of performance statistics for WRF/Chem for 2008 cruise season based on all available data at 42 sites (Figure S4), Backward–trajectories for May 15, June 15, July 15, August 15, and September 15, 2008 for Glacier Bay (Figure S5), Forward–trajectories for June 1, July 1, August 1, and September 1, 2008 for Juneau and Sitka (Figure S6), Total cruise–ship emissions in Glacier Bay for 2008 (REF), under assumption of 6.69 m/s (S13), and 10.28 m/s (S20) cruise speed in Glacier Bay and ECA–standards in Southeast Alaska (ECA) (Table S1), Average near–surface concentrations in Glacier Bay for 2008 (REF), 6.69 m/s (S13), and 10.28 m/s (S20) cruise speed in Glacier Bay and ECA–standards in Southeast Alaska (ECA) (Table S2), Average haze indices for various percentiles of best–visibility–days on average over, and percentiles for the locally worst and best–visibility–days anywhere in Glacier Bay (Table S3). This information is available free of charge via the Internet at http://www.atmospoles.com.

References


