Impact of unregulated ship emissions on air and water quality in southern Alaska

Nicole Mölders[1], Stacy E. Porter[1], Trang T. Tran[2] and Catherine F. Cahill[3]

[1]University of Alaska Fairbanks, Geophysical Institute & College of Natural Science and Mathematics, Department of Atmospheric Sciences, 903 Koyukuk Dr., Fairbanks, Alaska 99775, USA, molders@gi.alaska.edu

[3]University of Alaska Fairbanks, Arctic Region Supercomputing Center, 909 Koyukuk Dr., Fairbanks, Alaska 99775, USA

[3]University of Alaska Fairbanks, Geophysical Institute & Department of Chemistry and Biochemistry, 903 Koyukuk Dr., Fairbanks, Alaska 99775, USA

1. Introduction

High concentrations of primary pollutants are emitted along the ship routes of the Gulf of Alaska. During the tourist season, the charter vessels and cruise ships join the tankers, cargo ships and ferries. Both the ship traffic and tourist cruises are essential for Alaska's economy and welfare. Tourism lives from the uniqueness of the coastal landscape, ecosystems and animals. Thus, its sustainability requires good water and air quality as well as visibility that are affected by influx of pollutants from ship emissions, their transformation and/or deposition.

Alaska's modest air quality standards primarily address aesthetic aspects related to tourism attractions and lack concrete restrictions of ship emissions. Ships within three miles of the coast may not degrade visibility within the exhaust effluent by 20% within an hour. This means ships can release substantial amounts of pollutants into the marine atmospheric boundary layer (ABL). Here some of the primary pollutants may chemically react with species that naturally exist in the atmosphere; some are modified by photo-chemically processes during the long daylight hours of Alaska's summer. Various synoptic situations may yield transport of the resulting secondary pollutants into the coastal landscape. Here, pollutants may react with volatile organic compounds (VOCs) emitted by Alaska's large forests. Consequently, high concentrations of polluted air may occur even in remote areas adjacent to the Gulf of Alaska. Wet and dry deposition processes remove these pollutants from the atmosphere. Due to the different radiative conditions of Alaska as compared to mid-latitudes the impact of ship emissions on air quality and deposition cannot be assessed from lessons learned from studies for mid-latitudes.

To investigate the impact of ship emissions on air quality and atmospheric deposition of highly reactive components in Alaska's coastal regions a ship emission inventory has been developed for Alaska. Here the ship emission inventory of the Alaska Emission Model (AkEM; Mölders 2009) and some results of its application in conjunction with WRF/Chem are presented. Further details on the ship-emission inventory and results of tests and first applications can be found in Porter (2009).

2. Ship emission inventory

Ship emissions are considered by a sea-lane-related emission inventory developed in accord with Corbett and Köhler (2003). The ship-emission inventory uses a bottom-up approach based on ship time tables, port times, routes of tankers, container ships, roll on-roll off cargo ships, ferries, fishing boats and cruise ships, data on the typical fuel usage of these vessels and data on the typical split among the released species (Fig. 1).

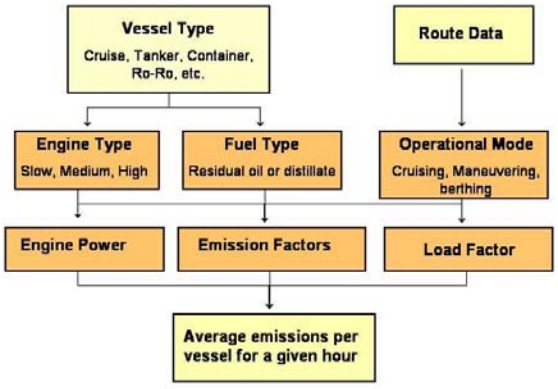

Fig. 1. Schematic view of the ship-emission inventory.

The ship-emission inventory bases on the following assumptions: Gas or steam engines can be neglected because only 1% of the entire world fleet uses these engines and are about to

be replaced. Cruise-ships use medium speed four-stroke diesel engines; tankers and cargo ships use slow speed two-stroke diesel engines. Except for tanker auxiliary engines, ships use residual oil (heavy fuel oil) because its cost-effectiveness. Tanker auxiliary engines use distillate fuel. All main engines and about 71% of the auxiliary engines use residual oil. The average value of engine power for passenger and cruise ships is set to a typical value of 39,563kW independent of vessel-size. Average engine power of tankers, container and cargo ships are assumed as 9,409kW, 30,885kW and 10,696kW, respectively. By using a ratio of 0.27, 0.35, 0.27 and 0.39 of auxiliary to main engine power for passenger vessels, tankers, container and cargo ships average auxiliary power is assumed as 10,682kW, 3,293kW, 8,339kW, 4,172kW, respectively.

Three operation modes – cruising, maneuvering and berthing – are considered with cruising being the dominant mode. One hour of maneuvering is assumed before and after port call. Berthing occurs in ports and only and uses the auxiliary engines except for tankers. A main engine load of 80% and auxiliary engine load of 30% are assumed for cruising ships; a 60% load is assumed for berthing of the auxiliary engines for all ships but tankers. Tankers are assigned 20% and 60% to the main and auxiliary engines; 20% of the main and 50% of the auxiliary engine load is assumed for maneuvering.

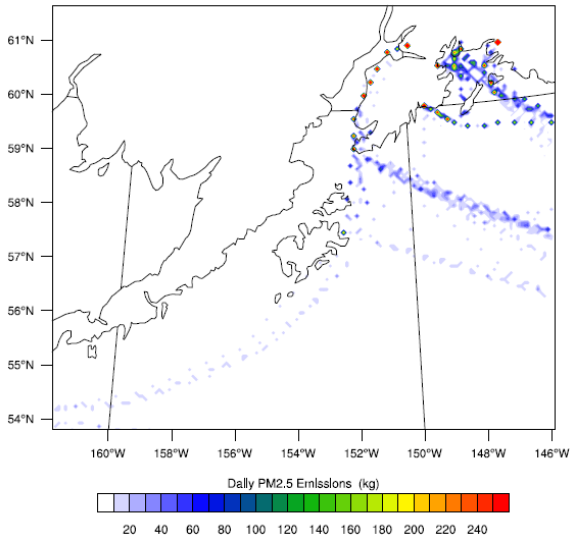

Fig. 2. Daily emissions of $PM_{2.5}$ as obtained from the ship-emission inventory.

The emission factors of CO, VOC and PM depend on the operation mode. Emission factors for NO_x, SO_2, VOCs and particulate matter (PM) are taken from ENTEC UK Limited (2002). The VOCs split among ethane, butane, formaldehyde, pentane, hexane, ethylene, propylene, acetylene, benzene, toluene, xylene, tri-methyl-benzene, and other aromatics follows Eyring et al. (2005). Carbon oxide (CO) and ammonia (NH_3) emission factors stem from Cooper and Gustafsson (2004), and Corbett et al. (2007). The PM emission factor is used for both $PM_{2.5}$ and PM_{10}, and PM is split between PM_{10} and $PM_{2.5}$ in a ratio 1:9. The $PM_{2.5}$ split among sulfate, organic matter, carbon, and unspecified $PM_{2.5}$ follows Petzold et al. (2004). Hourly emission rates are calculated based on the emission factor, average power and load factor of the main and auxiliary engines as a function of latitude and longitude.

Figure 2 exemplarily illustrates the daily ship emissions for an arbitrarily taken June day. Distributions for other species look similar (therefore not shown).

3. Application

3.1 Model setup

WRF/Chem simulates the weather, air quality and atmospheric deposition. We run WRF/Chem with the following physical and chemical packages: The six water-class bulk-microphysics parameterization, a version of the Grell-Dévényi cumulus ensemble approach, the Dudhia short-wave radiation scheme, the RRMT long-wave radiation scheme, the Janjić sublayer scheme, the Mellor-Yamada-Janjić ABL scheme, a modified version of the RUC land-surface model, the RADM chemical mechanism, Madronich photolysis rates, the MADE/SORGAM aerosol chemistry, physics, and wet and dry deposition package, calculated biogenic and soil emissions. The model domain encompasses the atmosphere over south Alaska with 27 vertically stretched layers and 151x128 grid points in the horizontal applying a 7km grid-increment.

3.2 Simulations

The 1.0^ox1.0^o and 6h-resolution NCEP global final analyses provide the meteorological initial and boundary conditions. At the beginning of the tourist season, WRFchem is initialized with idealized vertical profiles of Alaska background concentrations. The chemical distributions obtained after 5d of simulation serve as initial distributions for the first day analyzed in our study (May 20, 2006). All later 5d-simulation use the chemical distribution obtained at the end of the previous 5d-simulation.

We run 5d-simulations from May 15, 2006 to August 20, 2006. As aforementioned, the first

five days serve to spin up the chemical distributions and are discarded from the investigations. We run WRF/Chem once without (REF), and once with inclusion of ship emissions (SEM).

4. First results

On domain average, although ship emissions increase average concentrations and deposition fluxes notably and for some species even significantly (at the 95% or higher confidence level) trends are similar (not shown). For most of the pollutants, the synoptic situations govern the temporal and spatial distribution of the atmospheric composition and deposition. During low-pressure events NO_x concentrations decrease, while PM concentrations increase due to sea spray. SO_2 concentrations decrease throughout the season due to increase in precipitation as time progresses. However, SO_2 concentrations are relatively independent of the synoptic situations otherwise. During calm wind high-pressure regimes, HNO_3 accumulates, while PAN dramatically drops during long-lasting warm high-pressure events. Typically, $PM_{2.5}$ concentrations remain below the current EPA standards despite of ship emissions.

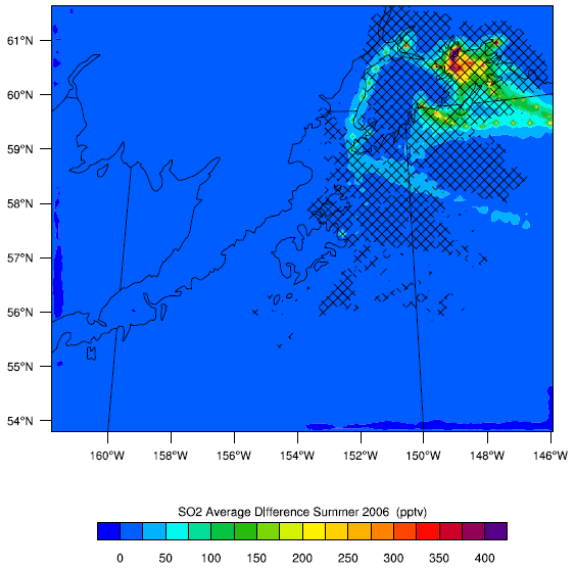

Fig. 3. Average difference SEM-REF in SO_2 concentrations for the tourist season 2006. Distribution for NO_x looks similar, but with slightly smaller areas experiencing significant differences.

Ship emissions increase NO_x and SO_2 concentrations within the vicinity of major sea routes (e.g. Fig. 3). They contribute to more than 90% of the NO_x deposition in Prince William Sound (Fig. 4). Significant impacts of ship emissions on PM_{10} occur only for Anchorage, Valdez, and Whittier that all have large ports. In Prince Williams Sounds, the PM from and/or produced in response to ship emissions reduces visibility up to 30% (Fig. 5).

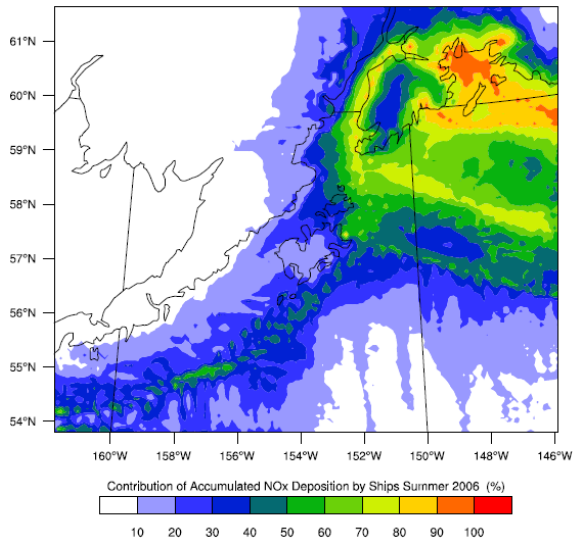

Fig. 4. Average difference SEM-REF in deposition of NO_x for the 2006 tourist season.

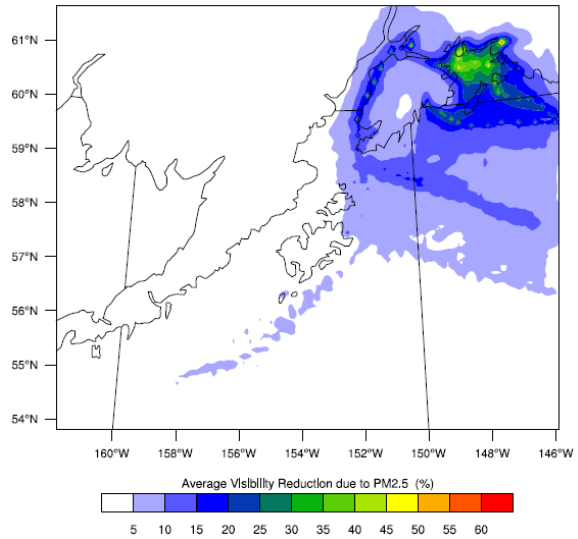

Fig. 5. Reduction of visibility due to ship emissions.

Ozone formation in response to ship emissions remains insignificant despite the long daylight hours. PAN and HNO_3 caused by ship emissions exist in significant amounts even at large distance of the major ship routes (e.g. Fig. 6). The relatively cool Alaska summer temperatures permit PAN to become a huge reservoir for NO_x and to be transported over long distances.

The Gulf of Alaska experience frequently low-pressure systems that lead to onshore winds where the coastline is exposed to the east. Thus, pollutants stemming from ship emissions are transported land-inwards. Due to the topography low-pressure systems often stagnate in Prince William Sound where they eventually dissipate. Here pollutants tend to accumulate because of

the topographic barrier, the typically calm wind from varying directions and the heavy ship traffic. Consequently, more secondary pollutants are produced and lead to enhanced dry and wet deposition as compared to well-ventilated regions.

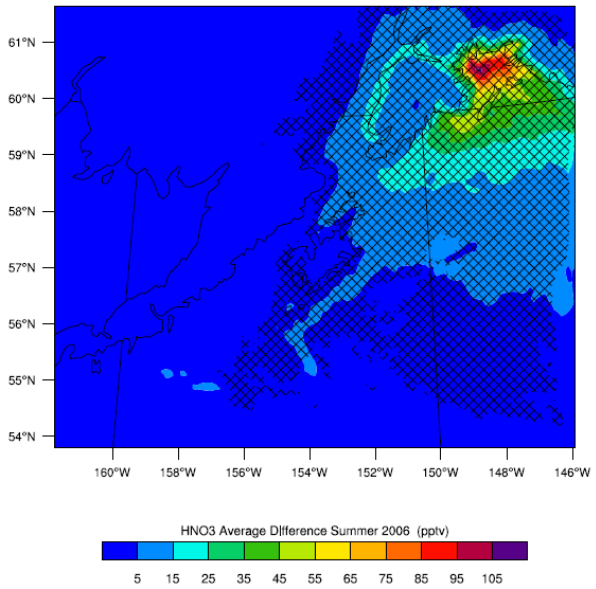

Fig. 6. Like Fig. 3, but for HNO_3 concentrations.

The influx of ship traffic to and from Anchorage mainly impacts Lake Clark National Park and Katmai National Park both located on the western coast of the Cook Inlet. In these parks, deposition of PM remains marginal because no ports exist in the vicinity.

Winds often converge between the Kenai Peninsula and Kodiak Island leading to a channeling of the wind in between these landmarks. This wind system causes strong onshore winds toward Iliamna Lake - a tourist attraction and recreation area between Lake Clark National Park and Katmai National Park. Consequently, primary and secondary pollutants from ship emissions travel further land-inwards.

Ship emissions along the sea-lanes between Seward, Homer and Anchorage strongly affect the Kenai Peninsula and Kenai Fjords National Park. Air quality gradually degrades over the coastal region of the peninsula. This reduction in air quality is even significant for some species.

Acknowledgements

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