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Assessing the impact of shipping emissions on air pollution in the Canadian Arctic and northern regions: current and future modelled scenarios

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Supplementary Materials

Table S1. Regional evaluation statistics for O_3, $PM_{2.5}$, NO_2, and SO_2 (hourly, daily, and seasonal).

Geographical sector	# of sites	MB (ppbv, μg m^{-3})			NMB (%)			RMSE (ppbv, μg m^{-3})			NMSE (%)			r		
		Hly	Dly	Snl	Hly	Dly	Snl	Hly	Dly	Snl	Hly	Dly	Snl	Hly	Dly	Snl
O_3 (ppbv)																
Northern	15	3.0	3.5	3.2	15.5	18.3	16.5	8.4	6.5	4.3	14.5	9.7	4.2	0.57	0.56	0.66
Southeastern	69	5.7	5.7	5.6	24.9	24.6	24.1	12.1	9.8	7.3	19.0	13.2	8.0	0.66	0.67	0.25
Southwestern	54	4.2	4.3	4.1	20.6	21.5	20.9	12.6	9.9	7.5	27.8	19.1	11.5	0.54	0.43	0.30
$PM_{2.5}$ (μg m^{-3})																
Northern	9	-0.7	-0.7	-0.8	-14.4	-14.3	-16.4	6.5	4.6	3.1	201	98.7	53.2	0.08	0.13	-0.27
Southeastern	36	-0.2	-0.1	-0.3	-2.1	-1.8	-3.0	8.9	7.0	3.0	69.7	45.0	12.8	0.58	0.70	0.28
Southwestern	9	-3.3	-3.3	-3.6	-34.3	-34.0	-37.0	19.4	12.2	4.6	257	104	35.7	0.37	0.62	-0.02
NO_2 (ppbv)																
Northern	10	0.3	0.3	0.3	8.3	8.9	8.9	5.6	3.9	2.8	104	53.3	30.3	0.56	0.76	0.86
Southeastern	30	2.6	2.6	2.7	45.7	46.6	47.6	10.3	7.9	5.1	139	90.1	42.3	0.45	0.58	0.72
Southwestern	55	1.4	1.4	1.4	20.2	19.9	20.5	9.0	7.0	6.0	90.4	62.1	50.4	0.55	0.66	0.70
SO_2 (μg m^{-3})																
Northern	18	9.9	9.9	9.9	325.	324.	325.	30.6	21.7	16.1	1360	609	357	0.09	0.30	0.90
Southeastern	17	6.2	6.2	6.5	183	183	197	17.7	12.0	8.8	663	323	194	0.10	0.19	0.39
Southwestern	50	-0.5	-0.5	-0.5	-11.5	-11.8	-11.4	17.1	10.1	5.8	1190	489	181	0.10	0.13	0.15

Table S2a. Comparison of modelled O_3 with observations at Northern sites.

Site	Lat	Lon	Mn-obs (ppbv)	Mn-mod (ppbv)	MB (ppbv)	NMB (%)	URMSE (ppbv)	nURMSE (%)	r
Alert, NU	82.4508	-62.508	24.5	23.6	-0.9	-3.7	3.9	16.6	0.80
Little Fox Lake, YK	61.2067	-149.82	26.5	25.5	-1.0	-3.6	6.7	26.2	0.21
Norman Wells, NT	65.2791	-126.81	17.6	21.6	4.0	23.0	5.8	27.0	0.55
Snare Rapids, NT	63.5086	-116.01	21.8	22.2	0.5	2.1	5.3	23.8	0.61
Yellowknife, NT	62.4521	-114.36	20.1	21.9	0.8	4.1	7.1	34.0	0.43
Fort Chipewyan, AB	58.7088	-111.18	22.6	23.0	0.4	2.0	7.2	31.3	0.48
Fort McKay, AB	57.1894	-111.64	17.8	23.3	5.5	30.8	8.7	37.3	0.69
Syncrude UE1, AB	57.1492	-111.64	16.3	22.1	5.8	35.9	9.1	41.2	0.68
Patricia McInnes, AB	56.7522	-111.48	21.4	24.7	3.3	15.2	8.2	33.2	0.70
Athabasca Valley, AB	56.7328	-111.39	15.8	24.5	8.7	54.9	7.8	31.7	0.68
Goose Bay, NL	53.3111	-60.367	20.7	21.8	1.1	5.11	5.6	25.8	0.58
Barrow, AK	71.3200	-156.60	22.6	23.0	0.6	2.7	5.0	21.7	0.50
Denali, AK	63.7253	-148.97	22.9	25..5	2.6	11.2	7.6	29.8	0.09
Anchorage Borough, AK	61.3219	-149.57	13.0	23.1	10.1	77.1	8.5	36.8	0.10
Anchorage, AK	61.2067	-149.82	11.7	16.1	4.4	37.8	8.0	49.5	0.48

Table S2b. Comparison of modelled $PM_{2.5}$ with observations at Northern sites.

Site	Lat	Lon	Mn-obs ($\mu g\ m^{-3}$)	Mn-mod ($\mu g\ m^{-3}$)	MB ($\mu g\ m^{-3}$)	NMB (%)	URMSE ($\mu g\ m^{-3}$)	nURMSE (%)	r
Inuvik, NT	68.3601	-133.73	5.41	0.98	-4.43	-81.9	5.62	104.0	0.27
Norman Wells, NT	65.2791	-126.81	6.07	1.93	-4.14	-68.2	5.26	86.6	0.14
Yellowknife, NT	62.4521	-114.36	4.64	6.83	2.18	47.0	9.41	203.0	0.16
Fort Liard, NT	60.2358	-123.47	4.06	0.72	-3.35	-82.4	3.16	77.7	0.35
AIRSUSAK6MAT, AK	61.5989	-149.11	3.55	3.95	0.40	11.2	4.24	119.0	-0.04
Anchorage Borough, AK	61.3219	-149.57	3.65	3.43	-0.22	-5.9	3.65	100.0	0.03
AIRUSAKWANC, AK	61.2150	-149.90	4.65	7.89	3.24	69.7	5.35	115.0	0.18
Anchorage, AK	61.2067	-149.82	4.58	7.93	3.35	73.2	5.12	112.0	0.25
Juneau, AK	58.3885	-134.57	6.19	1.91	-4.28	-69.2	6.04	97.7	0.30

Table S2c. Comparison of modelled NO_2 with observations at Northern sites.

Site	Lat	Lon	Mn-obs (ppbv)	Mn-mod (ppbv)	MB (ppbv)	NMB (%)	URMSE (ppbv)	nURMSE (%)	r
Inuvik, NT	68.3601	-133.73	2.84	0.10	-2.73	-96.3	2.11	74.2	0.11
Norman Wells, NT	65.2791	-126.81	1.31	0.92	-0.40	-30.2	1.24	94.6	0.07
Yellowknife, NT	62.4521	-114.36	4.03	3.03	-1.00	-24.9	3.26	80.9	0.17
Fort Liard, NT	60.2358	-123.47	0.65	0.11	-0.54	-82.7	0.77	119.0	-0.02
Fort Chipewyan, AB	58.7088	-111.18	0.83	0.30	-0.53	-64.2	0.70	85.1	0.54
Fort McKay, AB	57.1894	-111.64	3.12	4.80	1.69	54.1	4.74	152.0	0.39
Syncrude UE1, AB	57.1492	-111.64	2.70	6.56	3.86	142.0	6.12	226.0	0.32
Millenium, AB	56.8889	-111.38	10.70	16.70	6.07	58.60	11.3	106.0	0.35
Patricia McInnes, AB	56.7522	-111.48	3.00	2.80	-0.20	-6.8	3.49	116.0	0.26
Athabasca Valley, AB	56.7328	-111.39	6.04	2.76	-3.27	-54.2	4.53	75.1	0.27

Table S2d. Comparison of modelled SO_2 with observations at Northern sites.

Site	Lat	Lon	Mn-obs ($\mu g\ m^{-3}$)	Mn-mod ($\mu g\ m^{-3}$)	MB ($\mu g\ m^{-3}$)	NMB (%)	URMSE ($\mu g\ m^{-3}$)	nURMSE (%)	r
Norman Wells, NT	65.2791	-126.81	1.92	0.03	-1.89	-98.4	2.32	70.3	-0.06
Yellowknife, NT	62.4521	-114.36	2.29	0.61	-1.67	-73.2	2.50	81.3	0.07
Fort Liard, NT	60.2358	-123.47	0.19	0.21	0.02	10.7	0.98	522.0	-0.01
Fort Chipewyan, AB	58.7088	-111.18	0.43	1.19	0.76	174.0	2.43	533.0	0.54
Fort McKay, AB	57.1894	-111.64	3.55	7.81	4.26	120.0	14.20	382.0	0.20
Syncrude UE1, AB	57.1492	-111.64	3.40	17.60	14.20	417.0	21.10	457.0	0.20
Mildred Lake, AB	57.0500	-111.56	4.61	12.40	7.83	170.0	20.20	405.0	0.13
Lower Camp, AB	57.0269	-111.50	3.71	18.50	14.80	398.0	20.30	374.0	0.14
Buffalo Viewpoint, AB	56.9967	-111.59	3.27	18.50	15.20	466.0	22.20	495.0	0.18
MANNIX, AB	56.9678	-111.48	5.36	18.50	13.20	246.0	25.10	399.0	0.11
Millenium, AB	56.8889	-111.38	2.72	18.50	15.78	579.0	21.10	517.0	0.13
Patricia McInnes, AB	56.7522	-111.48	1.95	6.29	4.34	222.0	12.40	595.0	0.16
Athabasca Valley, AB	56.7328	-111.39	1.78	6.29	4.51	254.0	12.20	639.0	0.14
Taylor Town site, BC	56.1508	-120.69	6.20	49.4	43.20	696.0	73.8.00	966.0	0.01
Pine River Hassler, BC	55.6056	-121.97	1.10	3.11	2.01	182.0	9.70	861.0	0.03
Pine River Gas Plant, BC	55.5750	-121.92	10.90	51.30	40.40	372.0	88.60	726.0	-0.15
Smokey Height, AB	55.4050	-118.28	0.47	0.81	0.34	72.1	1.64	340.0	0.18
Evergreen Park, AB	55.1191	-118.73	0.74	0.96	0.22	29.6	3.07	412.0	-0.07

Sites located near Athabasca oil sands and northeastern BC oil and gas facilities are shaded in grey.

Table S3. Land-cover weighted deposition of S and N for eastern Canadian Arctic (60 – 100 W, 60 – 90 N) from the extended full year simulation (2010 base case)

	Land-cover type	**Sulfur** **LC-weighted deposition (kg of S ha^{-1})**			**Nitrogen** **LC-weighted deposition (kg of N ha^{-1})**		
		JAS	**JASO**	**annual**	**JAS**	**JASO**	**annual**
2010	lakes	0.143	0.192	0.652	0.084	0.101	0.274
	tundra	0.116	0.160	0.571	0.068	0.084	0.236
	barren	0.073	0.087	0.288	0.036	0.040	0.137

JAS : July-August-September; JASO : July-August-September-October

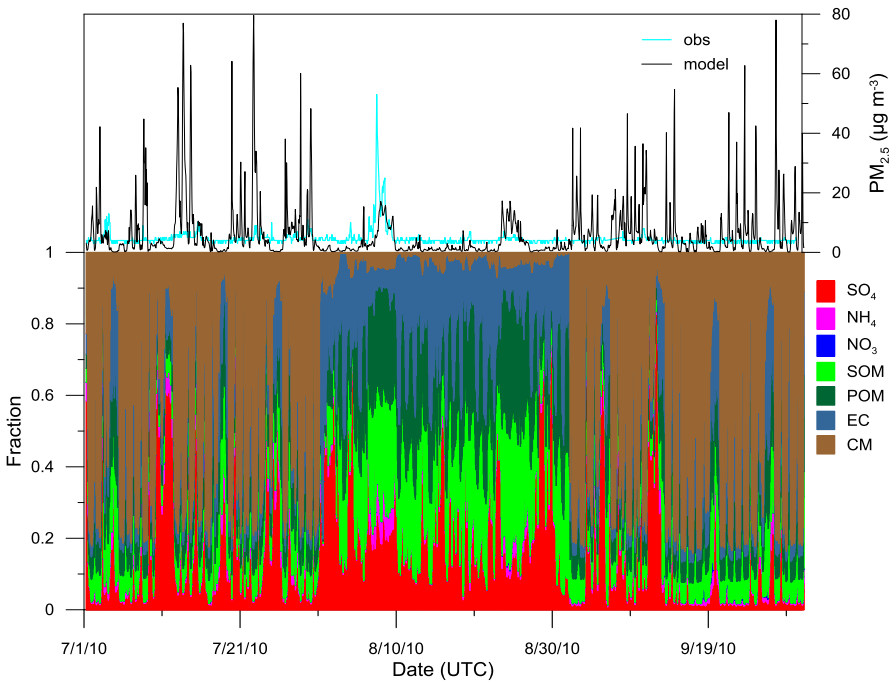

Figure S1 $PM_{2.5}$ at Yellowknife, NT: top panel – ambient $PM_{2.5}$ time series at Yellowknife monitoring site (light blue – observation; black line – model); lower panel shows the modelled fractional $PM_{2.5}$ components at Yellowknife site.

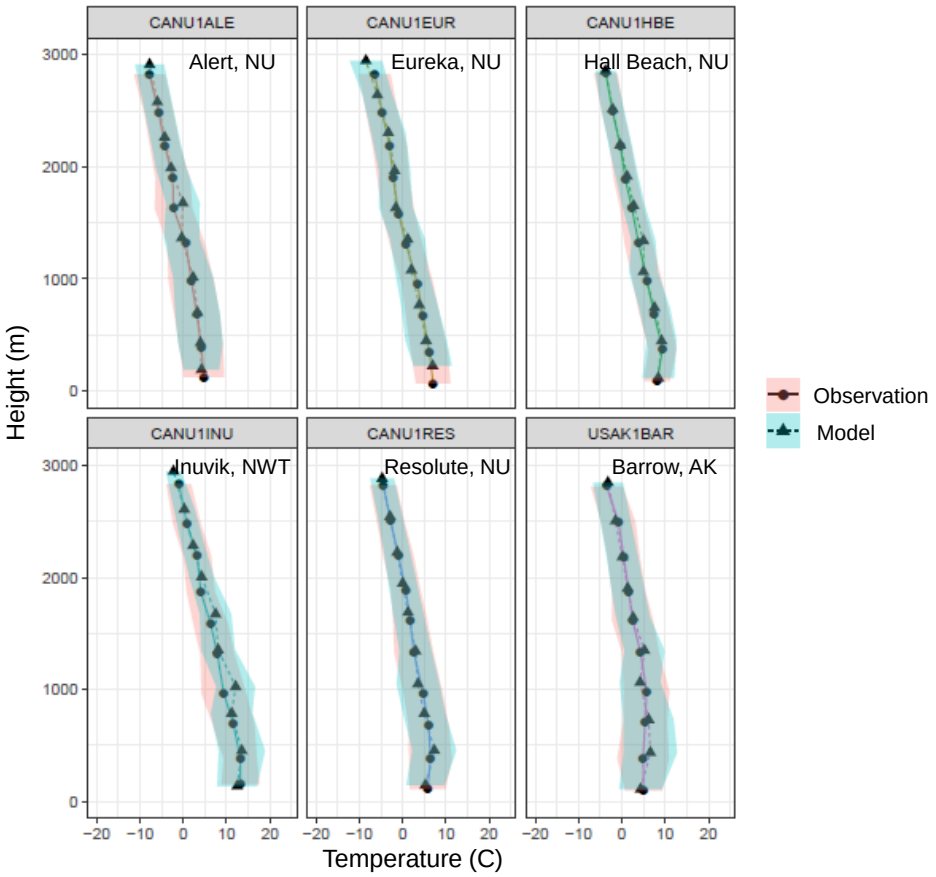

Figure S2a. Comparison of modelled vertical temperature profiles with observations at 6 Arctic upper air sites for July 2010 (monthly means and standard deviations).

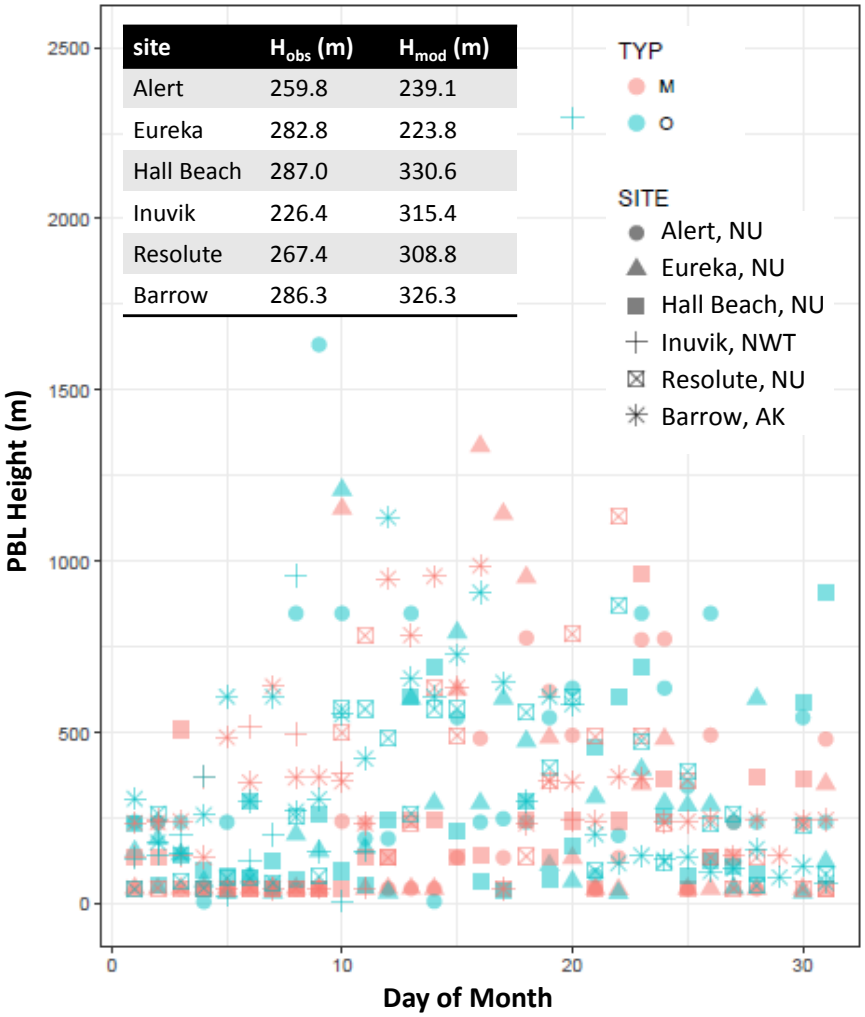

Figure S2b. Diagnosed PBL heights from modelled (pink) and observed (cyan) profiles, based bulk Richardson number, following Mahrt (1981) and Aliabadi et al. (2016), at selected Arctic sites for the month of July 2010. The monthly averaged PBL heights are shown in the table insert.

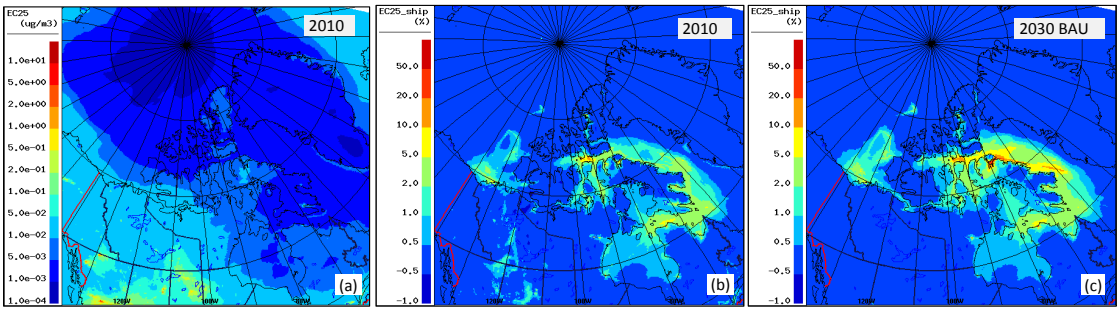

Figure S3. (a) modelled ambient $EC_{2.5}$ averaged over the July-to-September period (base year 2010); (b) Arctic shipping contribution to the July-to-September averaged $EC_{2.5}$ concentration at the current level (2010); (c) contribution from the projected Arctic shipping at 2030 (BAU scenario).

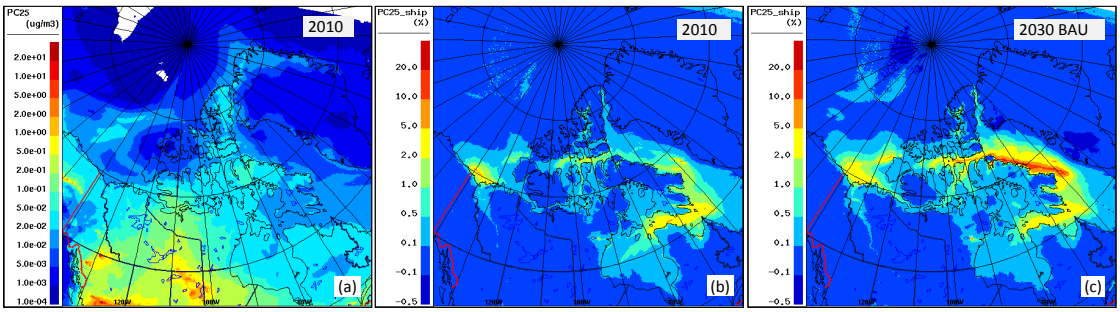

Figure S4. (a) modelled ambient $PC_{2.5}$ averaged over the July-to-September period (base year 2010); (b) Arctic shipping contribution to the July-to-September averaged $PC_{2.5}$ concentration at the current level (2010); (c) contribution from the projected Arctic shipping at 2030 (BAU scenario).

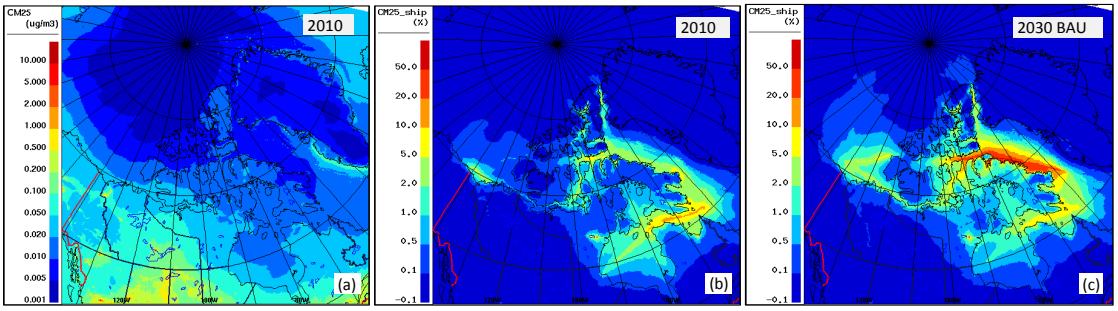

Figure S5. (a) modelled ambient $CM_{2.5}$ averaged over the July-to-September period (base year 2010); (b) Arctic shipping contribution to the July-to-September averaged $CM_{2.5}$ concentration at the current level (2010); (c) contribution from the projected Arctic shipping at 2030 (BAU scenario).

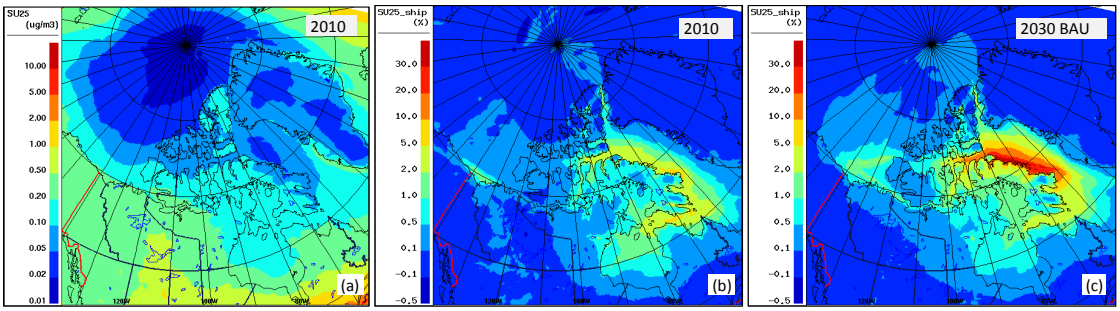

Figure S6. (a) modelled ambient $SU_{2.5}$ averaged over the July-to-September period (base year 2010); (b) Arctic shipping contribution to the July-to-September averaged $SU_{2.5}$ concentration at the current level (2010); (c) contribution from the projected Arctic shipping at 2030 (BAU scenario).

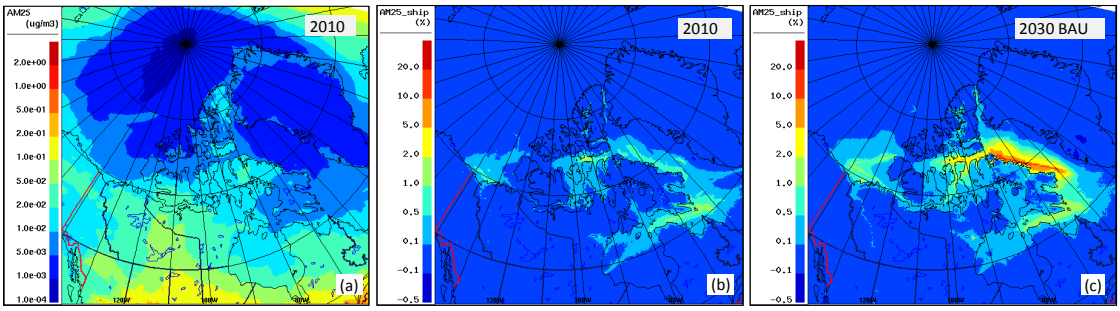

Figure S7. (a) modelled ambient $AM_{2.5}$ averaged over the July-to-September period (base year 2010); (b) Arctic shipping contribution to the July-to-September averaged $AM_{2.5}$ concentration at the current level (2010); (c) contribution from the projected Arctic shipping at 2030 (BAU scenario).

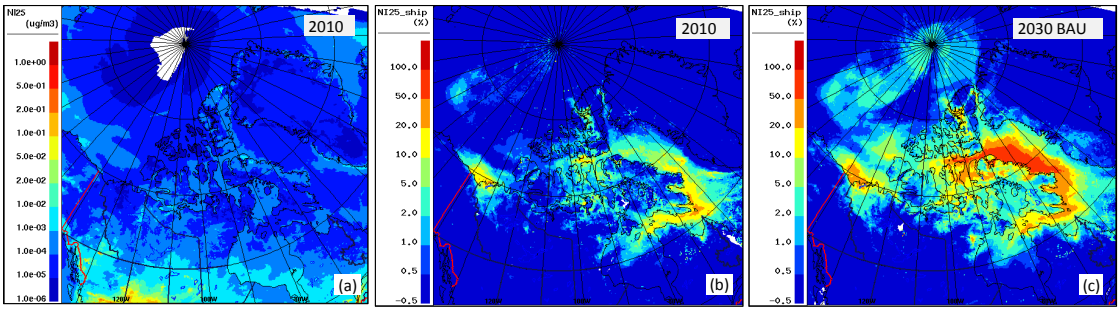

Figure S8. (a) modelled ambient $NI_{2.5}$ averaged over the July-to-September period (base year 2010); (b) Arctic shipping contribution to the July-to-September averaged $NI_{2.5}$ concentration at the current level (2010); (c) contribution from the projected Arctic shipping at 2030 (BAU scenario).

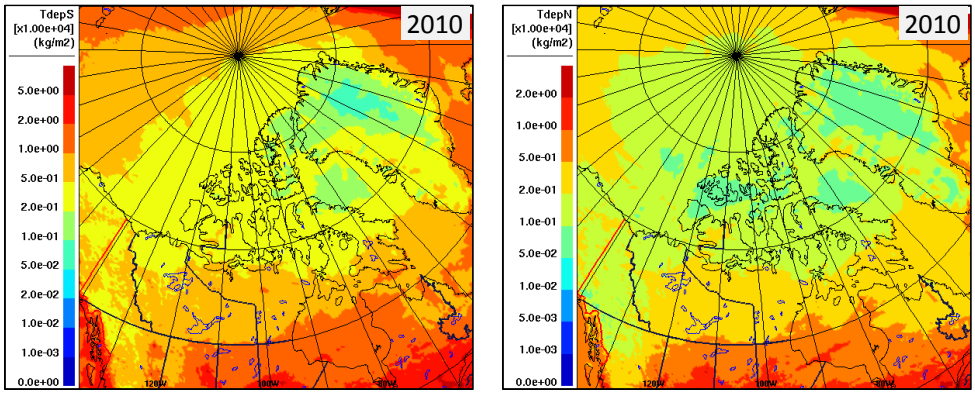

Figure S9. Annual total deposition of S (left panel) and N (right panel) based on the full-year model simulation of the base case (i.e., 2010 with Arctic marine shipping emissions)

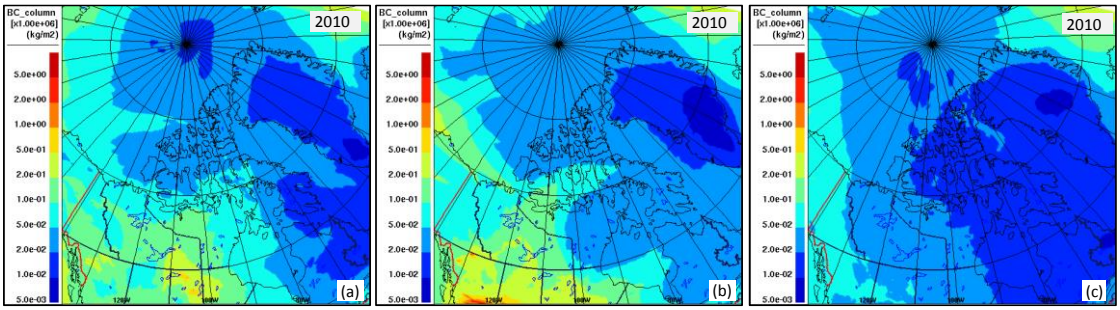

Figure S10. Modelled BC (or EC) column loading averaged for (a) July, (b) August, and (c) September, 2010 (base year).

Reference

Aliabadi, A.A., R.M. Staebler, J. de Grandpré, A. Zadra & P.A. Vaillancourt (2016) Comparison of Estimated Atmospheric Boundary Layer Mixing Height in the Arctic and Southern Great Plains under Statically Stable Conditions: Experimental and Numerical Aspects, Atmosphere-Ocean, 54:1, 60-74, DOI: 10.1080/07055900.2015.1119100

Mahrt, L. (1981). Modelling the depth of the stable boundary-layer. Boundary-Layer Meteorology, 21, 3–19.