APPENDICES AVAILABLE ON THE HEI WEBSITE

Special Report 22

Impacts of Shipping on Air Pollutant Emissions, Air Quality, and Health in the Yangtze River Delta and Shanghai, China

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Appendix A. Methods

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Appendix F. Future (2030) Ship Activity, Emissions, Air Quality, and Health Results

These Appendices were reviewed solely for spelling, grammar, and cross-references to the main text. They have not been formatted or fully edited by HEI.

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Appendix A. Methods

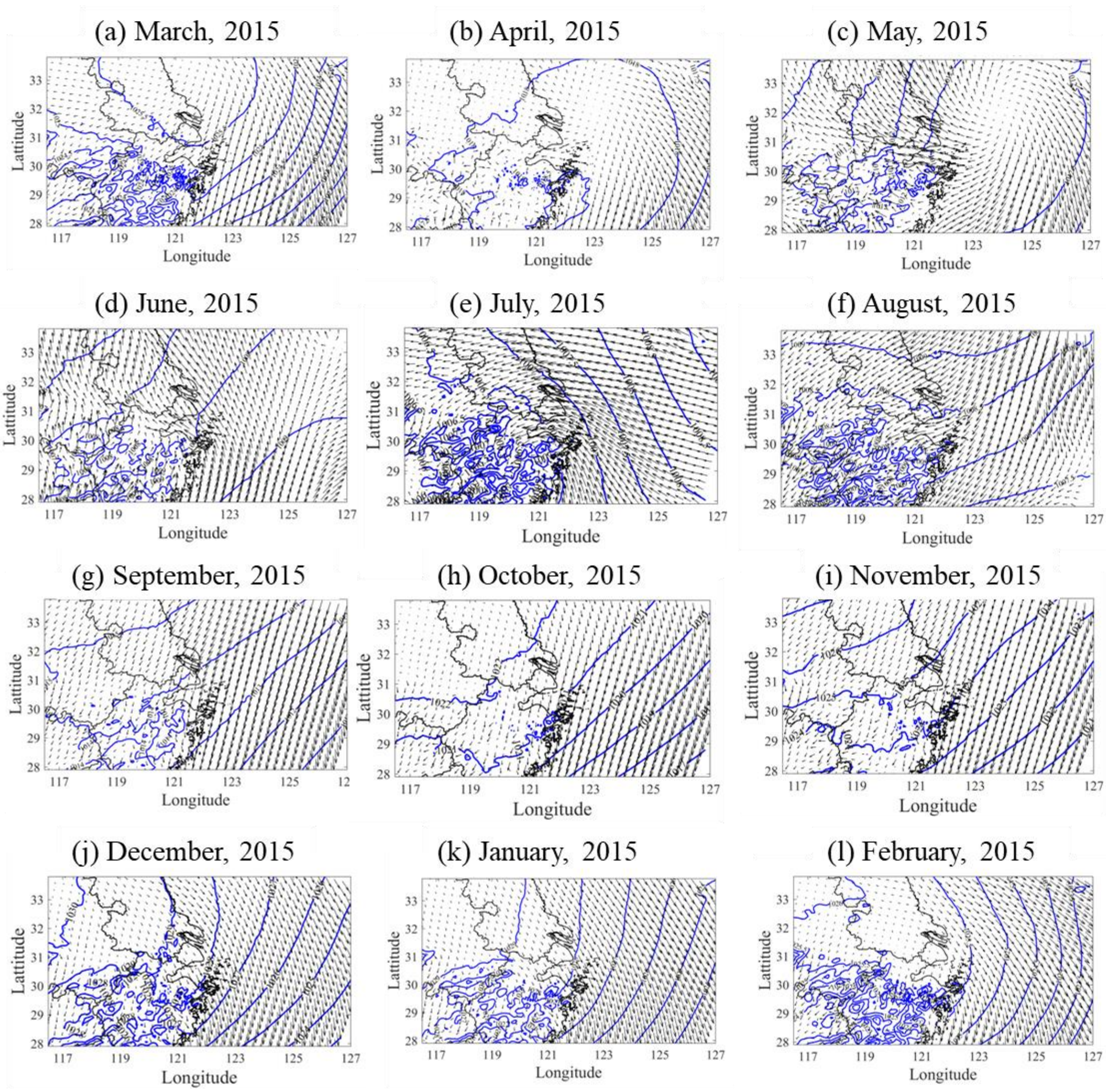

Figure A.1. Monthly average wind field at sea-level pressure in spring: (March, April, and May, a-c), summer (June, July, and August, d-f), autumn (September, October, and November, g-i), and winter (December, January, and February, j-l) in 2015.

Table A.1. Main engine and auxiliary emissions factors used for ships with AIS tracking in the present study (g/kWh)

Machine Type	Fuel type	Engine Type	SO_2	NO_x	CO	NMVOCs	PM_{10}	$PM_{2.5}$
ME	RO	SSD	10.30	18.1	0.5	0.3	1.378	1.22
ME	RO	MSD	11.31	14.0	1.1	0.2	1.22	1.22
ME	RO	HSD	11.31	12.7	1.1	0.2	0.650	0.50
AE	MD	MSD	2.12	13.9	1.1	0.2	0.328	0.30

Abbreviations: ME = main engine; AE = auxiliary engine; RO = residual oil; MD = marine distillate; SSD = slow speed diesel; MSD = medium speed diesel; HSD = high speed diesel.

Table A.2. Low load adjustment multipliers (LLAM) for main engine emission factors relative to SO_2 and a load of 0.2 or higher (which had multipliers of 1)

Load	NO_x	CO	NMVOCs	PM_{10}, $PM_{2.5}$, OC, EC
0.01	11.47	19.32	59.28	19.17
0.02	4.63	9.68	21.18	7.29
0.03	2.92	6.46	11.68	4.33
0.04	2.21	4.86	7.71	3.09
0.05	1.83	3.89	5.61	2.44
0.06	1.60	3.25	4.35	2.04
0.07	1.45	2.79	3.52	1.79
0.08	1.35	2.45	2.95	1.61
0.09	1.27	2.18	2.52	1.48
0.10	1.22	1.96	2.20	1.38
0.11	1.17	1.79	1.96	1.30
0.12	1.14	1.64	1.76	1.24
0.13	1.11	1.52	1.60	1.19
0.14	1.08	1.41	1.47	1.15
0.15	1.06	1.32	1.36	1.11
0.16	1.05	1.24	1.26	1.08
0.17	1.03	1.17	1.18	1.06
0.18	1.02	1.11	1.11	1.04
0.19	1.01	1.05	1.05	1.02

Table A.3. Emission factors for the main engine (g/kWh)

Engine type	PM_{10}	$PM_{2.5}$	NO_x	SO_x	CO	NMVOC
Middle speed	1.5	1.2	13.0	11.5	1.1	0.5

Source: Agrawal et al. 2011

Table A.4. Fuel correction factor for sulfur content of fuel (unitless)

Fuel type	S%	PM	NO_x	SO_x	CO	NMVOC
General diesel fuels	0.005%	0.17	0.94	0.002	1	1

Source: Agrawal et al. 2011

Table A.5. Baseline and future CMAQ simulations with details of their inputs

Run #	Run name	Initial Conditions	Boundary conditions	Land-Based Emissions	Shipping and port-related emissions
	Domain 1 (D1), 81-km				
1	D1 baseline	defined by default values	defined by default values	National-scale land-based emissions inventory (Tsinghua and IIASA)	National-scale shipping inventory based on AIS
	Domain 2 (D2), 27-km				
2	D2 baseline	defined by default values	D1 baseline	National-scale land-based emissions inventory (Tsinghua and IIASA)	National-scale shipping inventory based on AIS
	Domain 3 (D3), 9-km				
3	D3 baseline	defined by default values	D2 baseline	Local land-based emissions inventory (SAES)	YRD shipping emissions inventory based on AIS +; Shanghai river ship emission based on visa data (without AIS +); Container trucks and port machineries
4	Remove all coastal ships, ocean-going ships and inland ships	defined by default values	D2 baseline	Local land-based emissions inventory (SAES)	Container trucks and port machineries
5	Remove 12-200 NM	defined by default	D2 baseline	Local land-based	Ship emissions less than 12 NM

	shipping sources	values		emissions inventory (SAES)	from shore
6	Remove 24-200 NM shipping sources	defined by default values	D2 baseline	Local land-based emissions inventory (SAES)	Ship emissions less than 24 NM from shore
7	Remove 48-200 NM shipping sources	defined by default values	D2 baseline	Local land-based emissions inventory (SAES)	Ship emissions less than 48 NM from shore
8	Remove 96-200 NM shipping sources	defined by default values	D2 baseline	Local land-based emissions inventory (SAES)	Ship emissions less than 96 NM from shore
	Domain 5 (D5), 1 km				
9	D4 baseline	defined by default values	D3 baseline	Local land-based emissions inventory (SAES)	OGVs, coastal vessels, and local shipping inventory for inland water developed by SEMC and Fudan University; Container trucks and in-port machinery
10	Remove cargo trucks and in-port operating machines	defined by default values	D3 baseline	Local land-based emissions inventory (SAES)	OGVs, coastal vessels, and local shipping inventory for inland water developed by SEMC and Fudan University
11	Remove inland-water-	defined by default	D3 baseline	Local land-based	OGVs, coastal vessels; In-port

	going ships (including international ships operating on the rivers)	values		emissions inventory (SAES)	operating machines (SAES); Container trucks (STDR)
12	Remove coastal ships and ocean-going vessels	defined by default values	D3 baseline	Local land-based emissions inventory (SAES)	Inland-water ships; In-port operating machines (SAES); Container trucks (STDR)

Table A.6. Summary of the main features of health impact functions (HIFs) included in this analysis

Health Endpoints	Pollutants/ Exposure Duration	References	Coefficients (β)	Location
Mortality, stroke	$PM_{2.5}$, long-term	Cohen et al. (2017)	Pooled: 0.00118 (0.000477, 0.00154)	Global
Mortality, COPD			Pooled: 0.00073 (0.00042, 0.00106)	
Mortality, IHD			Pooled: 0.00147 (0.00117, 0.00171)	
Mortality, lung cancer			Pooled: 0.000934 (0.000470, 0.00125)	
Mortality, all cause	$PM_{2.5}$, long-term exposures	Burnett et al. (2018)	Pooled: 0.000144 (0.000117, 0.000171)	Global
Mortality, stroke			Pooled: 0.000286 (0.000140, 0.000429)	
Mortality, COPD			Pooled: 0.000251 (0.000118, 0.000383)	
Mortality, IHD			Pooled: 0.000336 (0.000301, 0.000365)	
Mortality, lung cancer			Pooled: 0.000294 (0.000173, 0.000414)	
Mortality, all cause	$PM_{2.5}$, short-term exposures	Chen et al. (2017)	0.000219 (0.000184, 0.000250)	China
Mortality, cardiovascular			0.000269 (0.000223, 0.000315)	
Mortality, respiratory			0.000289 (0.000228, 0.000356)	
Hospital admission, all cause	$PM_{2.5}$, short-term exposures	Tian et al. (2019)	0.000189 (0.000129, 0.000246)	China

Abbreviations: COPD = chronic obstructive pulmonary disease, IHD = ischemic heart disease.

Table A.7. Summary of the baseline mortality and morbidity rates for health outcomes studied in the YRD and Shanghai in 2015

Health endpoints	Age group	Baseline rates (10^{-3}/year)	
		YRD	Shanghai
Mortality, all cause[a]	0-99	7.61	6.01
	25-44	0.81	0.58
	45-54	4.44	3.64
	65-99	39.35	38.84
Mortality, cardiovascular[a]	0-99	1.23	0.77
Mortality, respiratory[a]	0-99	0.65	0.54
Mortality, stroke	25-44	0.05	0.04
	45-54	0.50	0.38
	65-99	7.23	5.42
Mortality, IHD	25-44	0.05	0.03
	45-54	0.31	0.22
	65-99	5.54	6.68
Mortality, COPD	25-44	0.01	0.01
	45-54	0.13	0.10
	65-99	4.75	4.80
Mortality, lung cancer	25-44	0.03	0.02
	45-54	0.52	0.49
	65-99	2.63	2.67
Hospital admissions, all cause	0-99	17.87	22.11

[a]To obtain a mortality rate for all-causes of death for each age group, we (1) divided death counts by mortality rates to obtain the population numbers of each age group; (2) summed the total population of all age groups; (3) summed the total number of deaths from all causes for all age groups; and (4) calculated the all-cause mortality rate for all ages.

Abbreviations: COPD, chronic obstructive pulmonary disease, IHD, ischemic heart disease.

Source: China CDC, personal communication, June 2018.

References

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Appendix B. Emissions Results

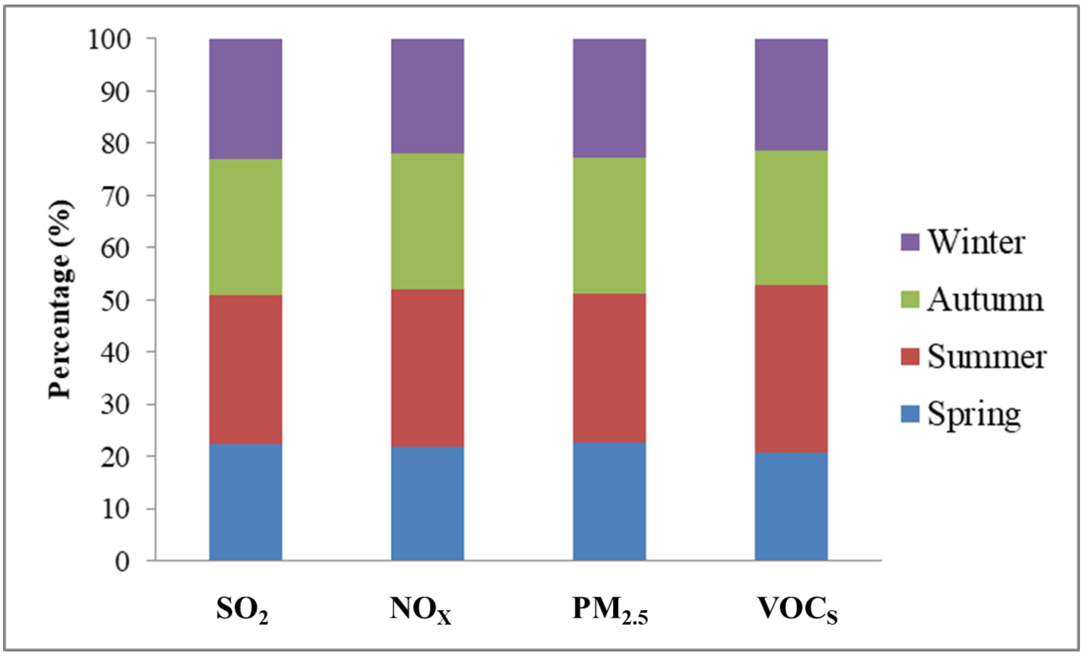

Figure B.1. Emission share (%) of 4 pollutants (SO_2, NO_x, $PM_{2.5}$, and VOCs) for shipping in the YRD region in 2015 in spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February).

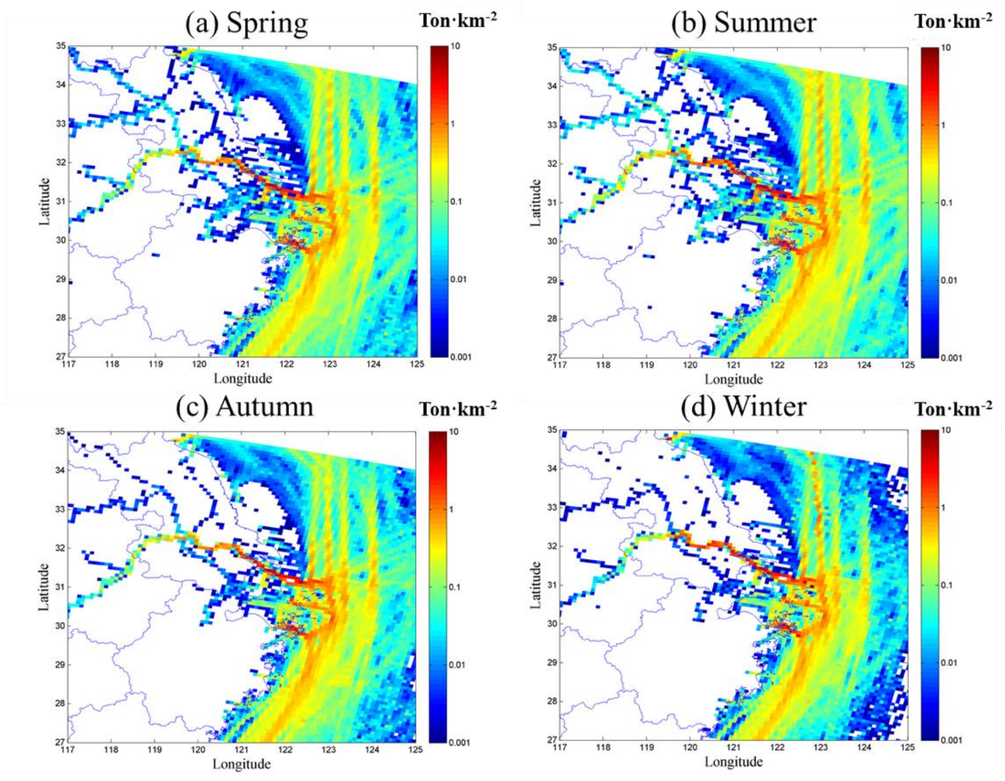

Figure B.2. Spatial distribution of SO_2 emissions (metric tons/km^2) from shipping in the YRD region in (a) spring; (b) summer; (c) autumn; and (d) winter.

Table B.1. Comparison of YRD ship emissions in the current study with other studies

Sources	Year	Geographic scope (Study area)	Spatial resolution	SO_2 (metric tons)	NOx (metric tons)	$PM_{2.5}$ (metric tons)	PM_{10} (metric tons)
Current study	2015	Expand to 200 NM (27°N - 35°N，116.5°E - 126°E)	9 km × 9km	2.2×10^5	4.7×10^5	2.7×10^4	2.93×10^4
Chen et al. (2017)	2014	At least 400 km from the coast; results for the YRD region only (full model domain was 14°N - 41°N, 102°E – 126°E)	0.005°×0.005°	3.6×10^5	6.1×10^5	4.9×10^4	/
Liu et al. (2018)	2013	Results presented here for YRD only (modeling domain was all of China)	1 km × 1 km	$(3.19\pm0.17)\times10^5$	/	/	$(3.97\pm0.29)\times10^4$
Fu et al. (2017)	2013	Latitude and longitude not provided	1 km × 1 km	2.7×10^5	3.6×10^5	/	3.3×10^4

/ = not available.

Table B.2. Comparison of emissions from ships in Shanghai in the current study with other studies

Reference	Year	Shipping activity data source	SO_2 (metric tons)	NO_x (metric tons)	$PM_{2.5}$ (metric tons)	PM_{10} (metric tons)
This study	2015	AIS	4.9×10^4	1.2×10^5	5.8×10^3	6.4×10^3
Fu et al. (2017)	2013	AIS	5×10^4	7×10^4	/	6.5×10^3
Fu et al. (2012)	2010	Shipping visas	3.5×10^4	5.7×10^4	3.7×10^3	4.6×10^3

/ = not available.

References

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Appendix C. Air Quality Results

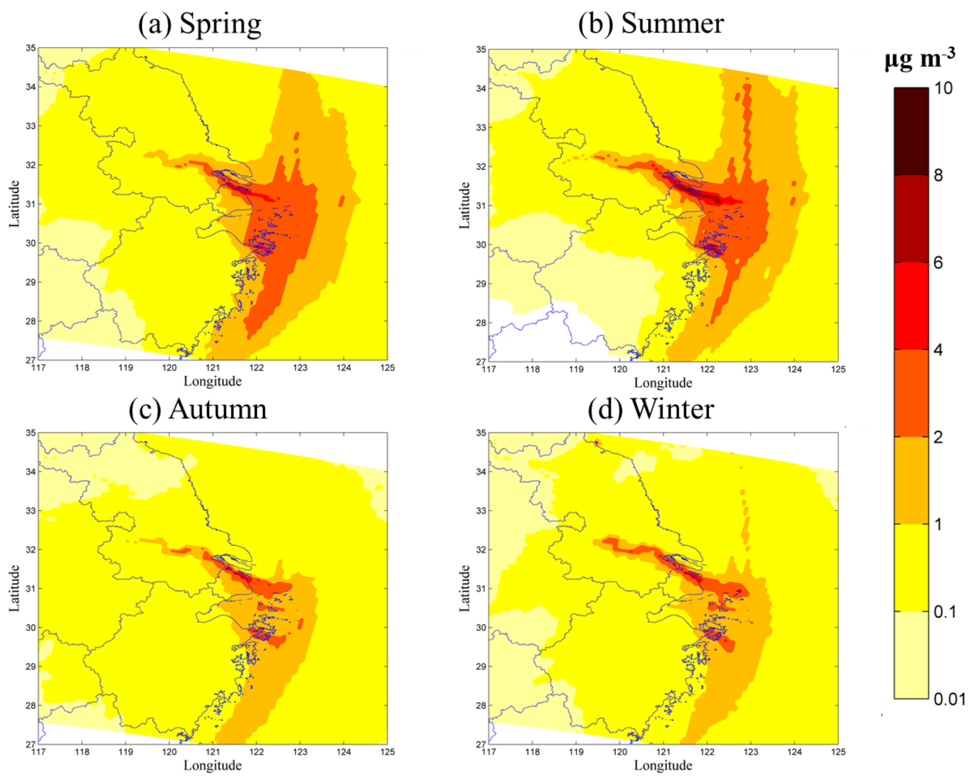


Figure C.1. Contribution of shipping sources to ambient SO_2 concentrations (µg/m^3) in the YRD region: spring (a), summer (b), autumn (c), and winter (d).

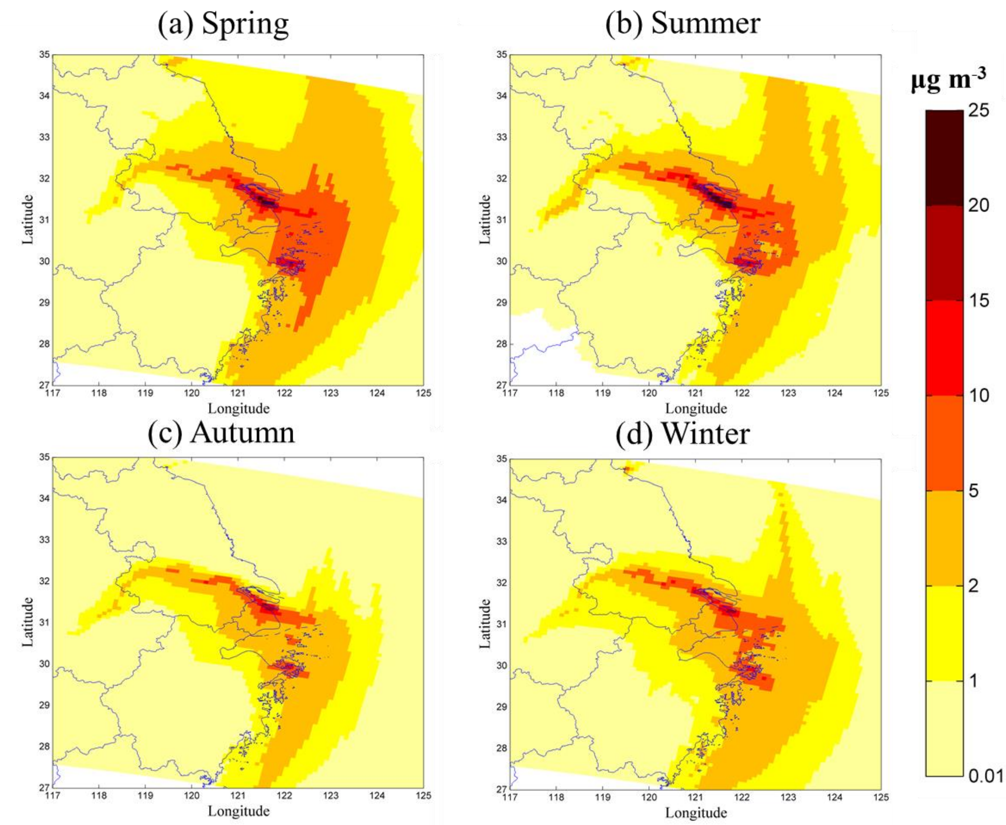


Figure C.2. Contribution of shipping sources on ambient NO_x concentrations ($\mu g/m^3$) in YRD region: spring (a), summer (b), autumn (c), and winter (d).

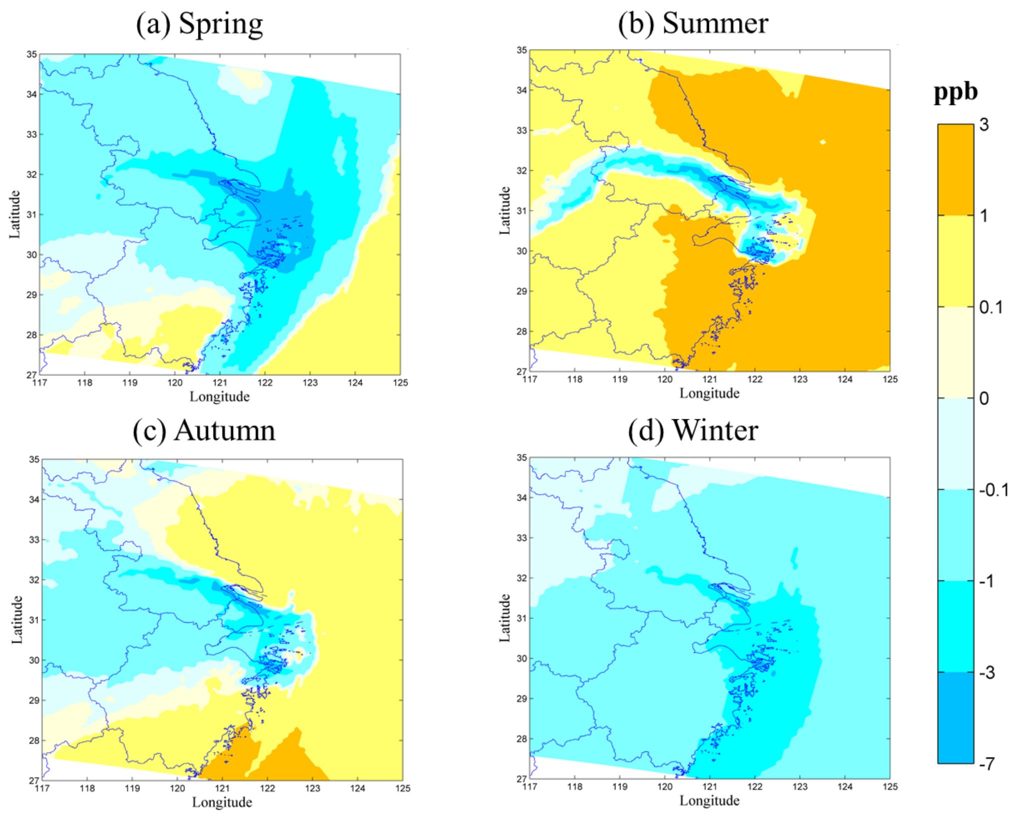


Figure C.3. Contribution of shipping sources to ambient O_3 concentrations (ppb) in YRD region: spring (a), summer (b), autumn (c), and winter (d).

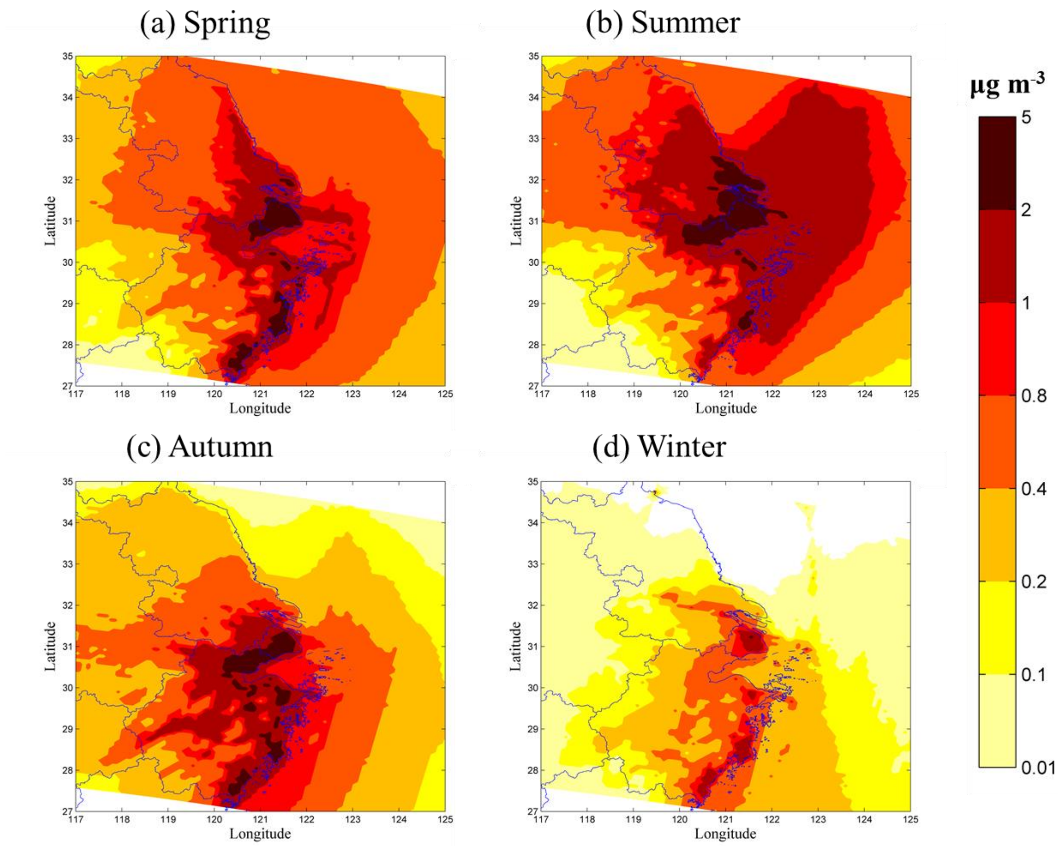


Figure C.4. Contribution of shipping sources to ambient $PM_{2.5}$ concentrations ($\mu g/m^3$) in the YRD region: spring (a), summer (b), autumn (c), and winter (d).

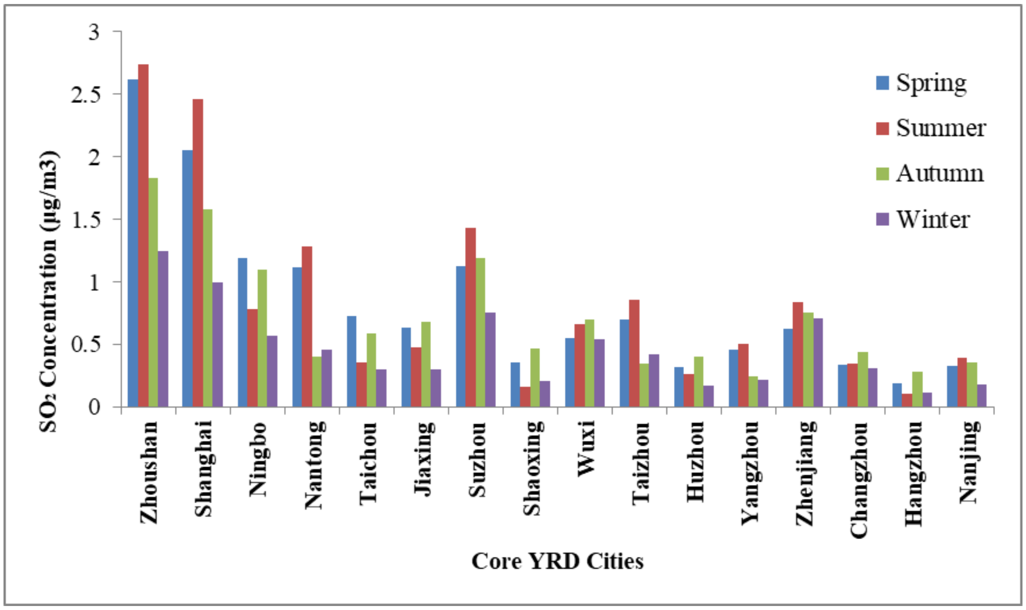


Figure C.5. Seasonal average contributions of ship-related SO_2 concentrations (μg/m^3) in 16 core YRD cities.

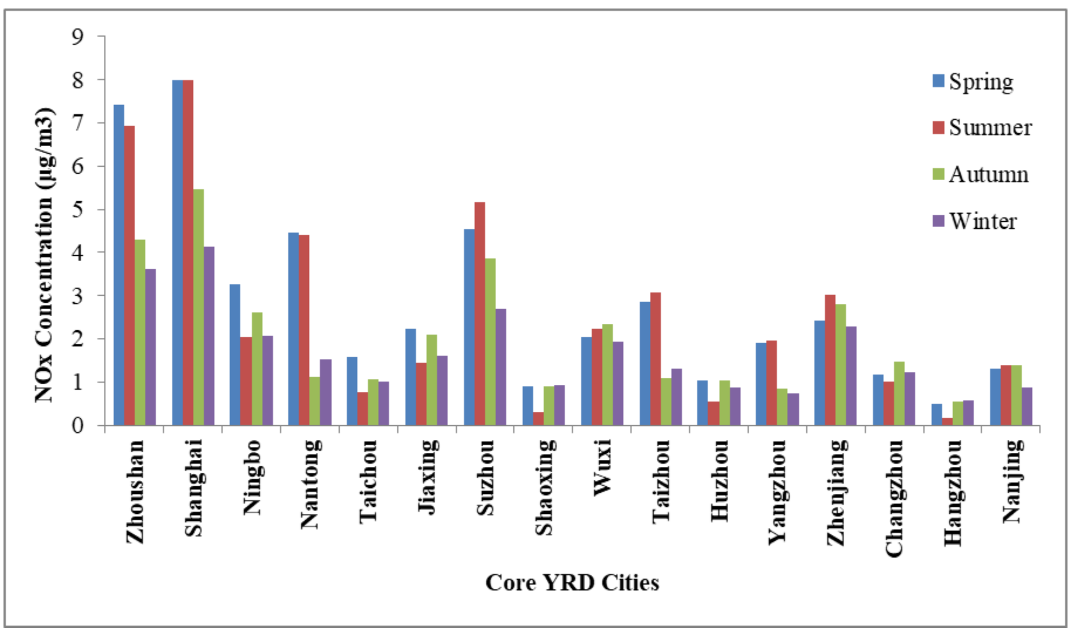


Figure C.6. Seasonal average contributions of ship-related NO_x concentrations (μg/m^3) in 16 core YRD cities.

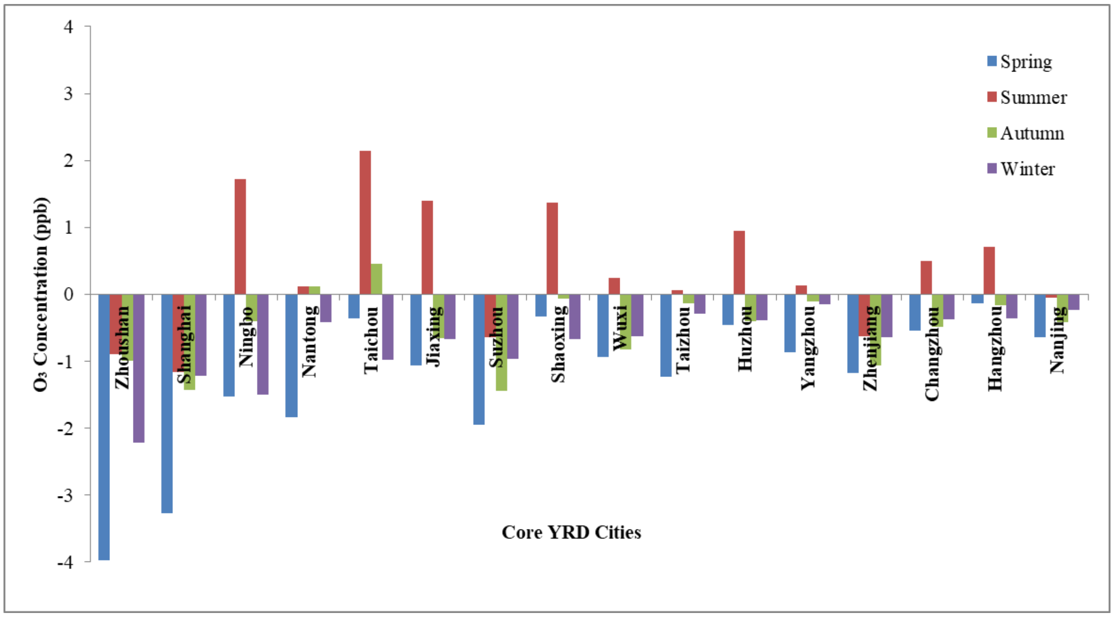


Figure C.7. Seasonal average contributions of ship-related O_3 concentrations (ppb) in 16 core YRD cities.

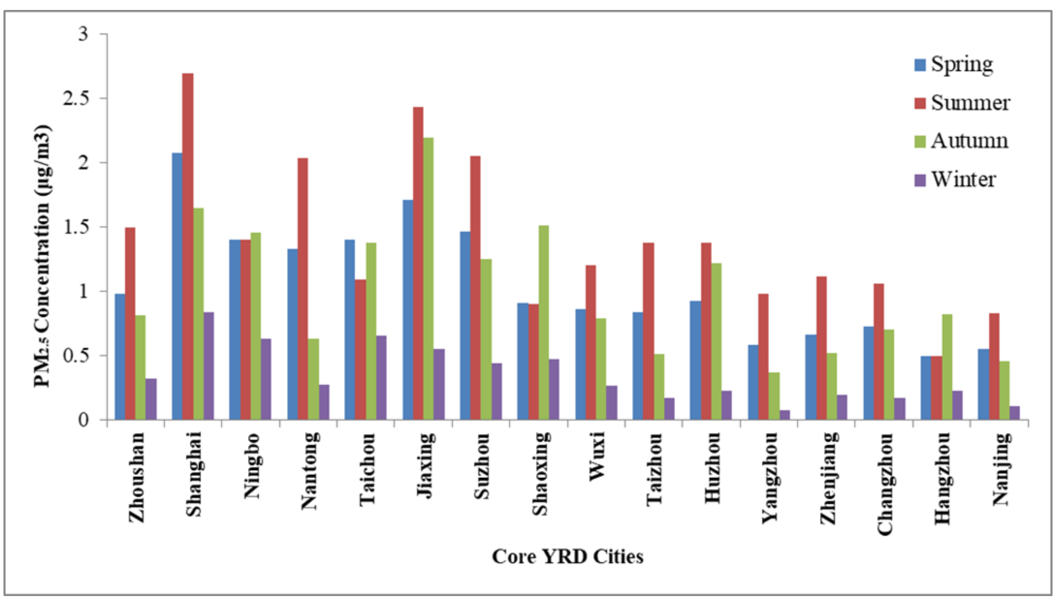


Figure C.8. Seasonal average contributions of ship-related $PM_{2.5}$ concentrations ($\mu g/m^3$) in 16 core YRD cities.

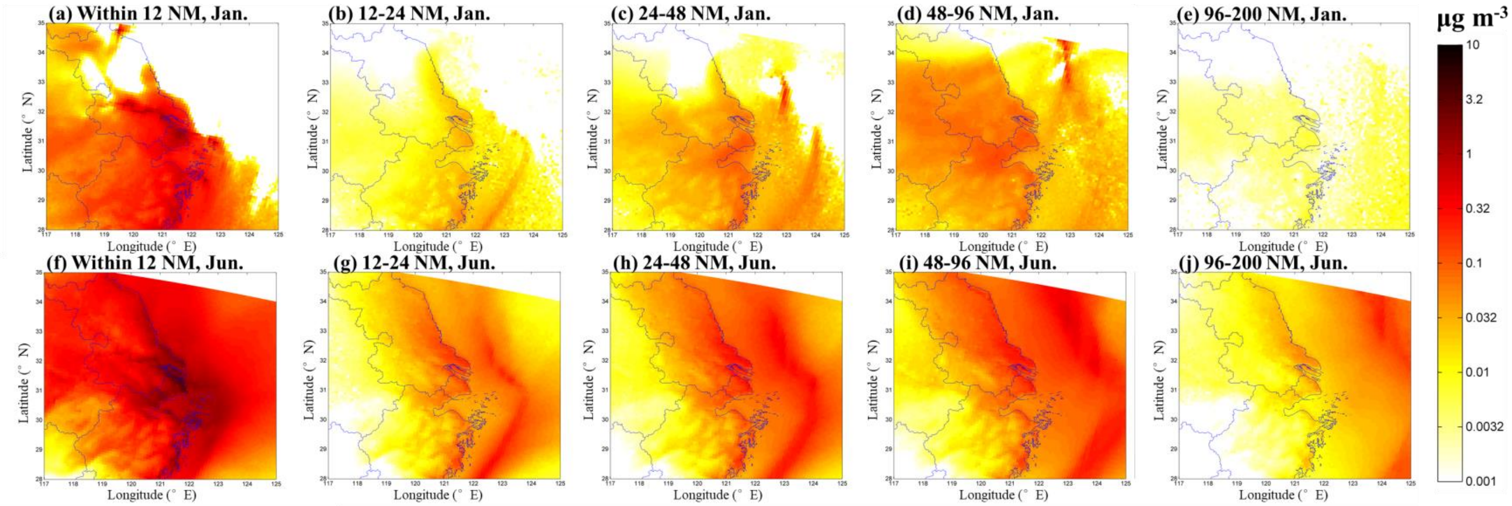


Figure C.9. Contributions to PM2.5 concentrations (μg/m³) from shipping emissions at distances within (a, f) 12 NM of shore (including inland waters); (b, g) 12 to 24 NM from shore; (c, h) 24 to 48 NM from shore; (d, i) 48 to 96 NM from shore; and (e, j) 96 to 200 NM from shore in January 2015 (a-e) and in June 2015 (f-j).

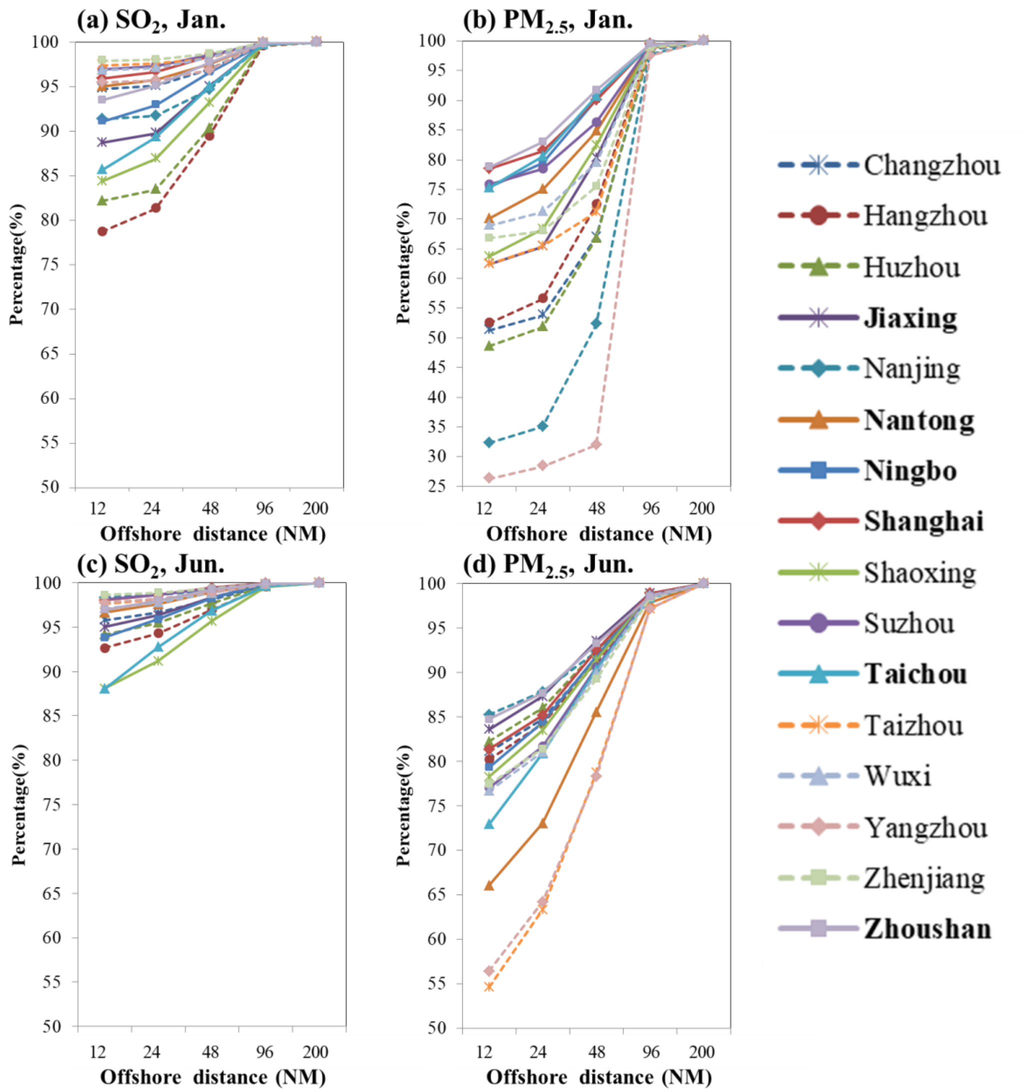


Figure C.10. Cumulative contributions of shipping emissions to SO_2 concentrations (a, c) and $PM_{2.5}$ concentrations (b, d) in January 2015 (a, b) and in June 2015 (c, d) in the YRD at distances within 12 NM of shore (including inland waters), 24 NM from shore, 48 NM from shore, 96 NM from shore, and 200 NM from shore. Names of coastal cities are bold in the legend.

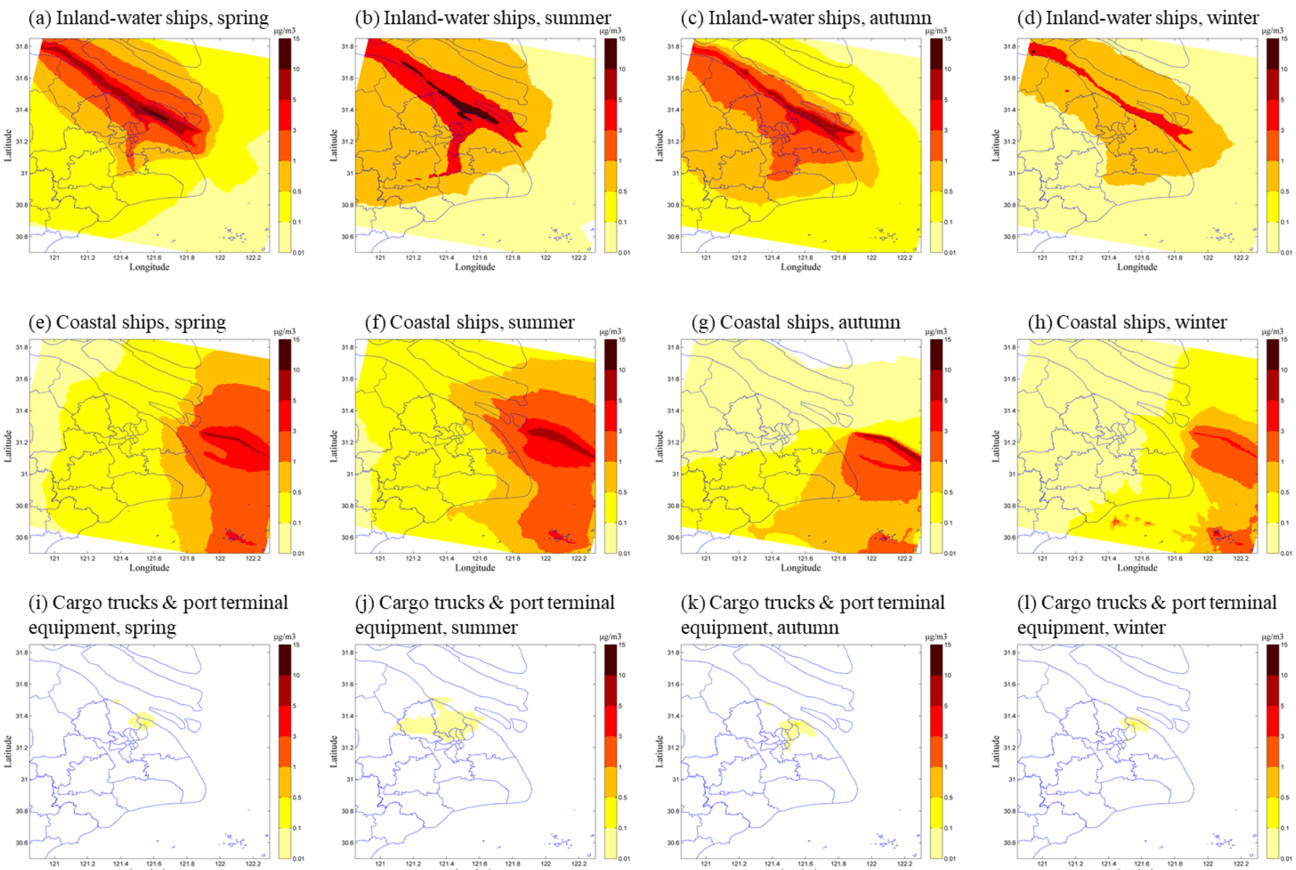


Figure C.11. Contributions to SO_2 concentrations (μg/m^3) from inland-water ships (a-d), coastal ships (e-h), and container-cargo trucks and port terminal equipment (i-l) in spring (a, e, i), summer (b, f, j), autumn (c, g, k), and winter (d, h, l).

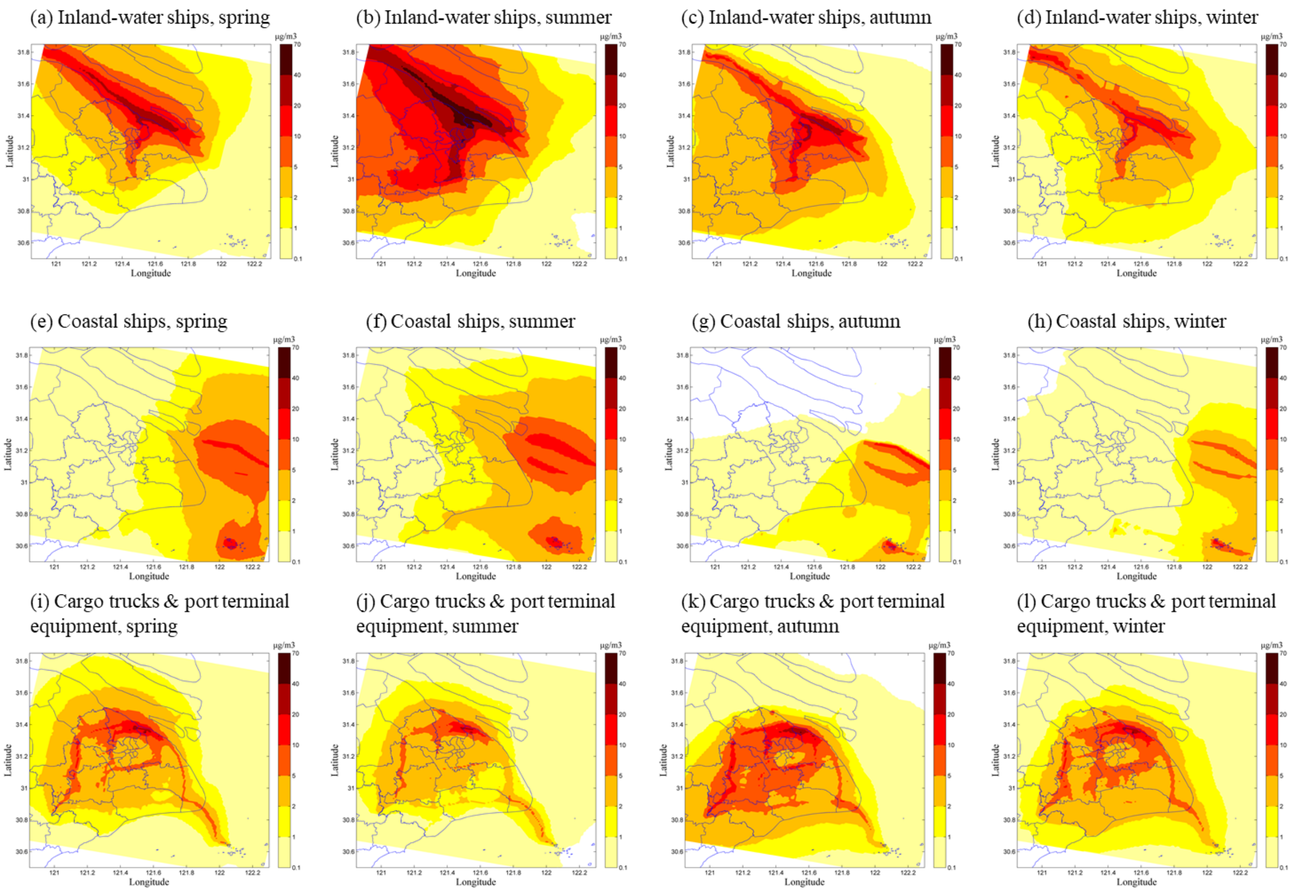


Figure C.12. Contributions to NO_x concentrations (µg/m^3) from inland-water ships (a-d), coastal ships (e-h), and container-cargo trucks and port terminal equipment (i-l) in spring (a, e, i), summer (b, f, j), autumn (c, g, k), and winter (d, h, l).

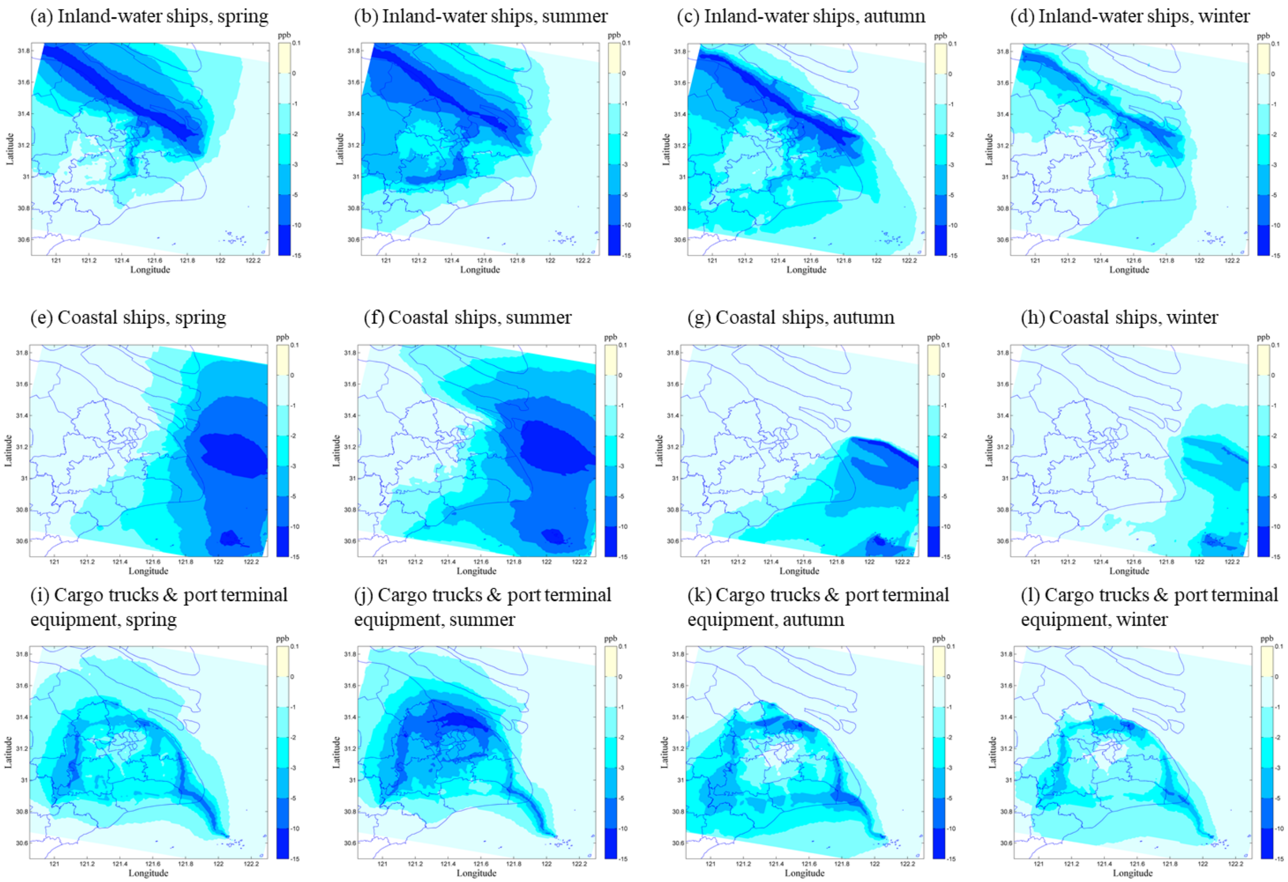


Figure C.13. Contributions to O_3 concentrations (ppb) from inland-water ships (a-d), coastal ships (e-h), and container-cargo trucks and port terminal equipment (i-l) in spring (a, e, i), summer (b, f, j), autumn (c, g, k), and winter (d, h, l).

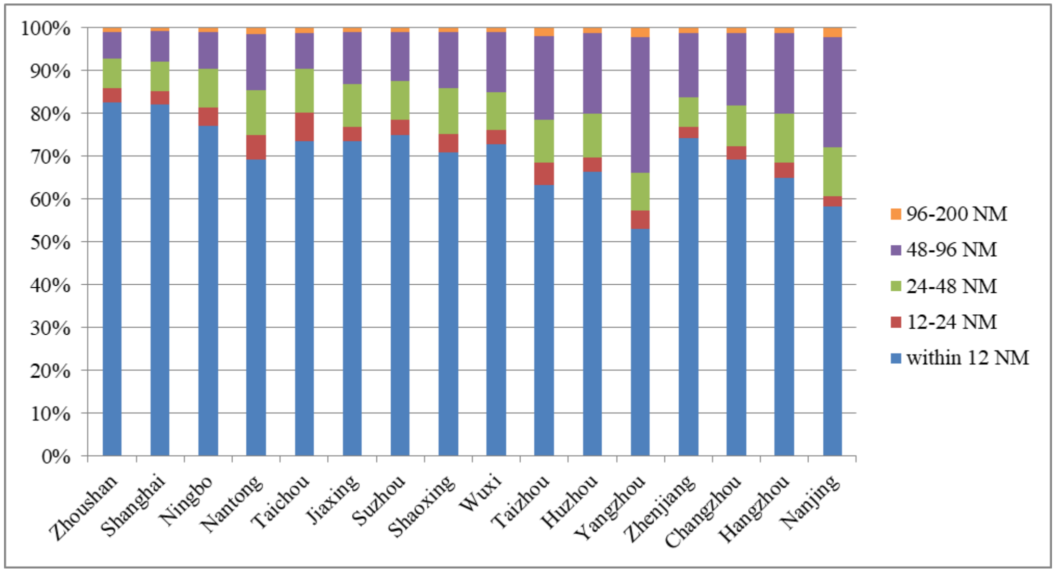


Figure C.14. Average share (%) of population-weighted $PM_{2.5}$ in 16 YRD cities caused by different offshore coastal areas in all ships.

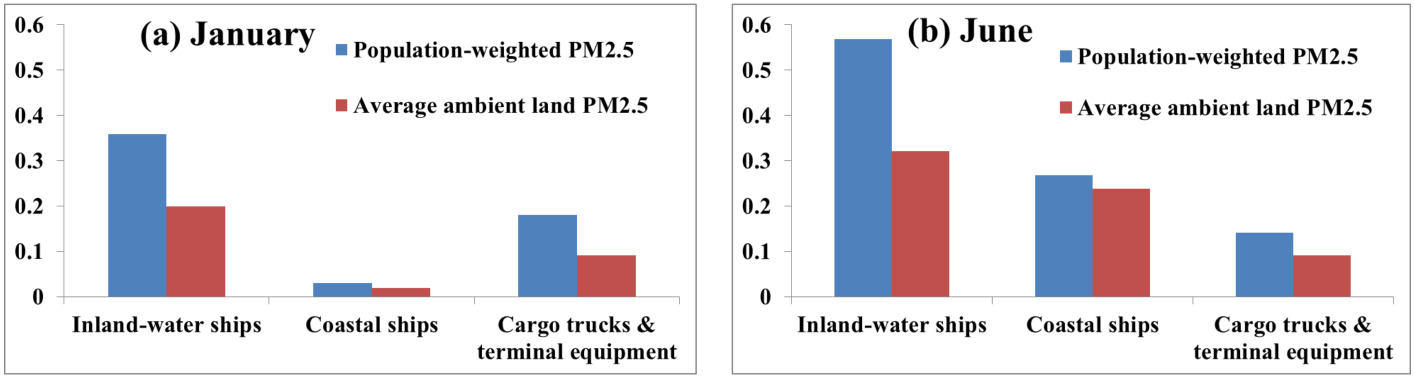


Figure C.15. Population-weighted $PM_{2.5}$ ($\mu g/m^3$) and average $PM_{2.5}$ ($\mu g/m^3$) caused by different ship-related sources in Shanghai, in January (a) and in June (b).

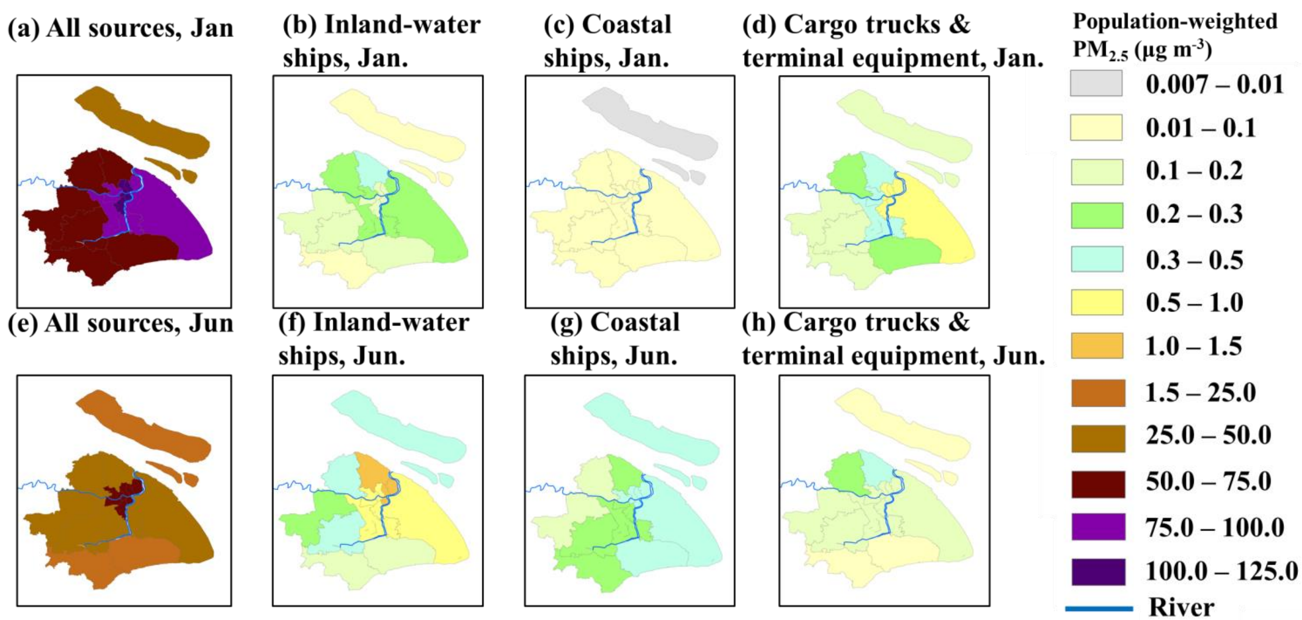


Figure C.16. Population-weighted $PM_{2.5}$ caused by all pollution sources (a, e), inland-water ships (b, f), coastal ships (c, g), and container-cargo trucks and port terminal equipment (d, h) in 16 districts in Shanghai, in January 2015 (a-d) and June 2015 (e-h).

Table C.1. Comparison of the ship-related $PM_{2.5}$ concentrations in the current study with the estimates in other studies

Reference	Period	Method	Spatial Resolution	Contribution of ship emissions to $PM_{2.5}$[a]
YRD				
Current study	2015	WRF/CMAQ model	9 km × 9 km	0.4–1.3 μg/m^3, 0.5–2.5%
Lv et al. (2018)	2015	WRF/CMAQ model	36 km × 36 km	1.0–2.7 μg/m^3, 2.0–7.8%
Chen et al. (2019)	2014	WRF/CMAQ model	9 km × 9 km	/, 1.2–6.2%
Shanghai				
This study	2015	WRF/CMAQ model	1 km × 1 km	1.0–2.5 μg/m^3
Lv et al. (2018)	2015	WRF/CMAQ model	36 km × 36 km	2.8–5.2 μg/m^3
Liu et al. (2017)	Apr 2009 to Jan 2013	ATOFMS measurements	/	1–10%

[a] Absolute contribution (μg/m^3) or relative (%) of all pollution sources.
Abbreviations: / = not available; ATOFMS = aerosol time-of-flight mass spectrometer.

Table C.2. Average and peak contributions of ship emissions to ambient SO_2 and $PM_{2.5}$ concentrations in different offshore coastal areas of the YRD region in January and June 2015

Offshore distance	Average contribution ($\mu g/m^3$)				Maximum contribution ($\mu g/m^3$)			
	SO_2		$PM_{2.5}$		SO_2		$PM_{2.5}$	
	January	June	January	June	January	June	January	June
Inland and within 12 NM of shore	0.52	0.70	0.24	0.56	6.00	8.79	1.62	4.02
12-24 NM	0.005	0.007	0.01	0.04	0.03	0.05	0.05	0.20
24-48 NM	0.01	0.009	0.04	0.07	0.06	0.05	0.11	0.34
48-96 NM	0.02	0.008	0.07	0.07	0.05	0.03	0.14	0.30
96-200 NM	0.00	0.001	0.003	0.01	0.004	0.003	0.02	0.05

References

Chen D, Tian X, Lang J, Zhou Y, Li Y, Guo X, et al. 2019. The impact of ship emissions on PM2.5 and the deposition of nitrogen and sulfur in Yangtze River Delta, China. Science Total Environ 649:1609-1619; 10.1016/j.scitotenv.2018.08.313.

Liu Z, Lu X, Feng J, Fan Q, Zhang Y, Yang X. 2017. Influence of Ship Emissions on Urban Air Quality: A Comprehensive Study Using Highly Time-Resolved Online Measurements and Numerical Simulation in Shanghai. Environ Sci Technol 51:202-211; 10.1021/acs.est.6b03834.

Lv Z, Liu H, Ying Q, Fu M, Meng Z, Wang Y, et al. 2018. Impacts of shipping emissions on PM2.5 pollution in China. Atmos Chem Phys 18:15811-15824; 10.5194/acp-18-15811-2018.

Appendix D. Health Analysis Results

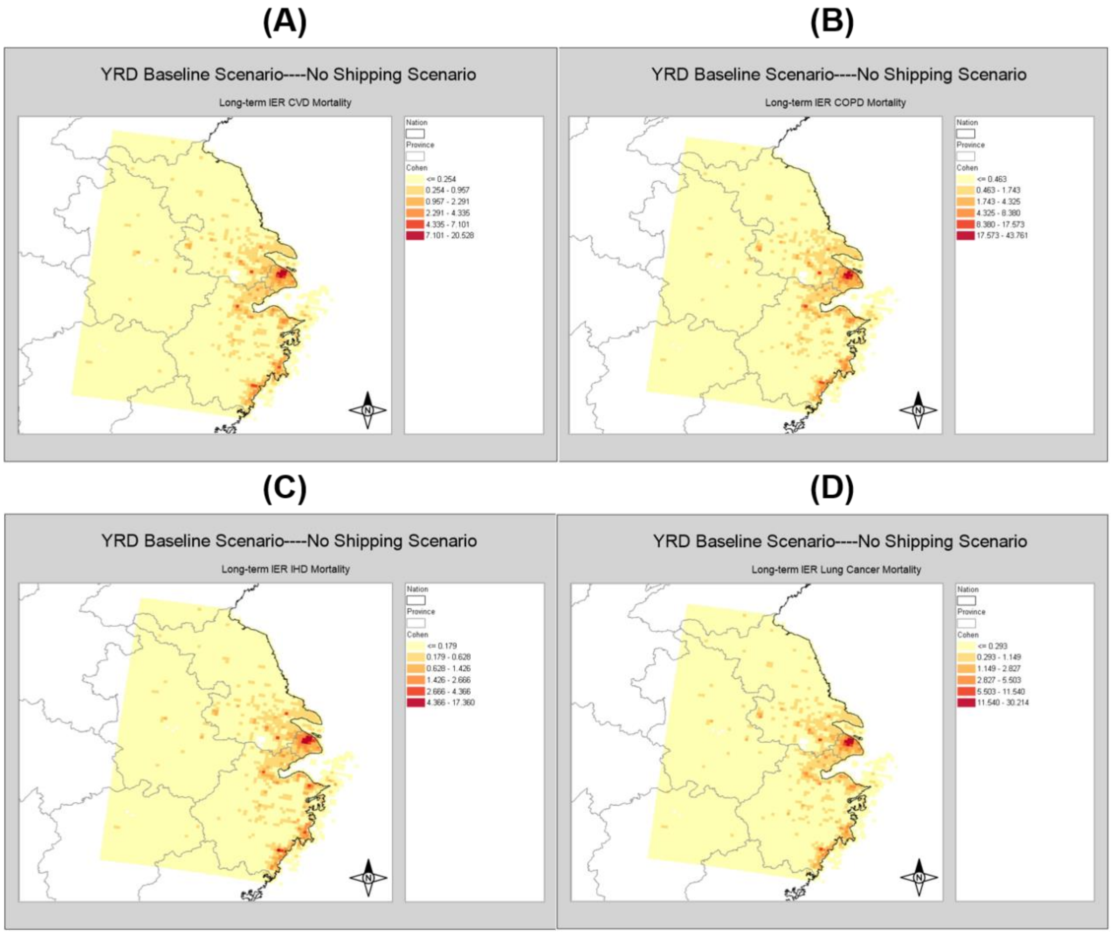


Figure D.1. Health impacts of long-term exposure to $PM_{2.5}$ from port emissions using the integrated exposure response (IER) function on mortality in the YRD region: (A) stroke mortality; **(B)** chronic obstructive pulmonary disease mortality; **(C)** ischemic heart disease mortality; and **(D)** lung cancer mortality.

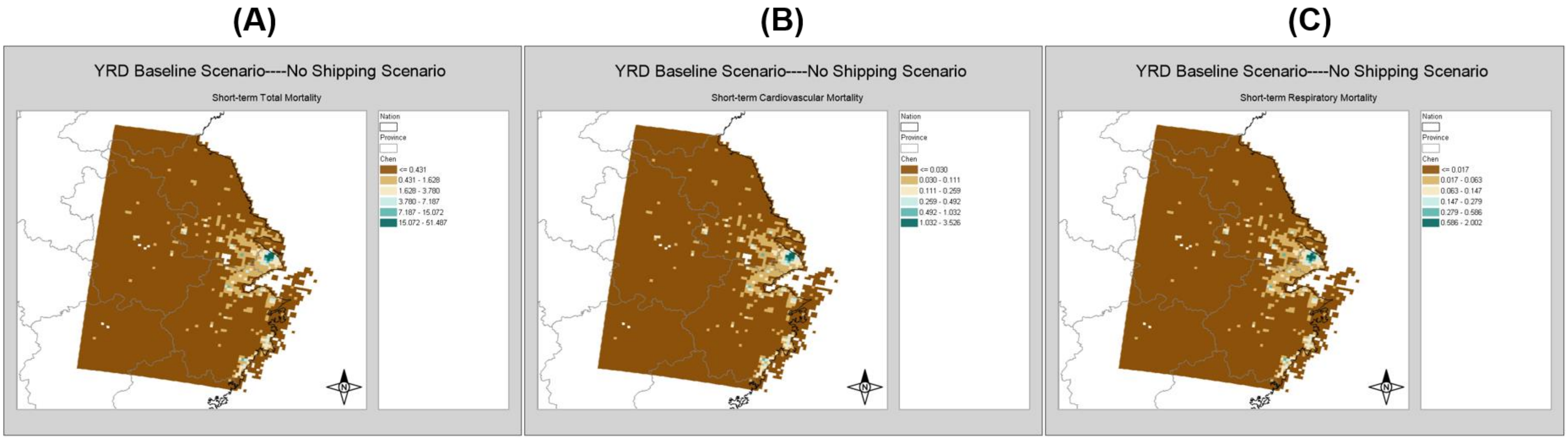


Figure D.2. Impacts of short-term $PM_{2.5}$ exposure from ship emissions on mortality in the YRD region in the baseline year: (A) all-cause mortality; **(B)** cardiovascular mortality; and **(C)** respiratory mortality.

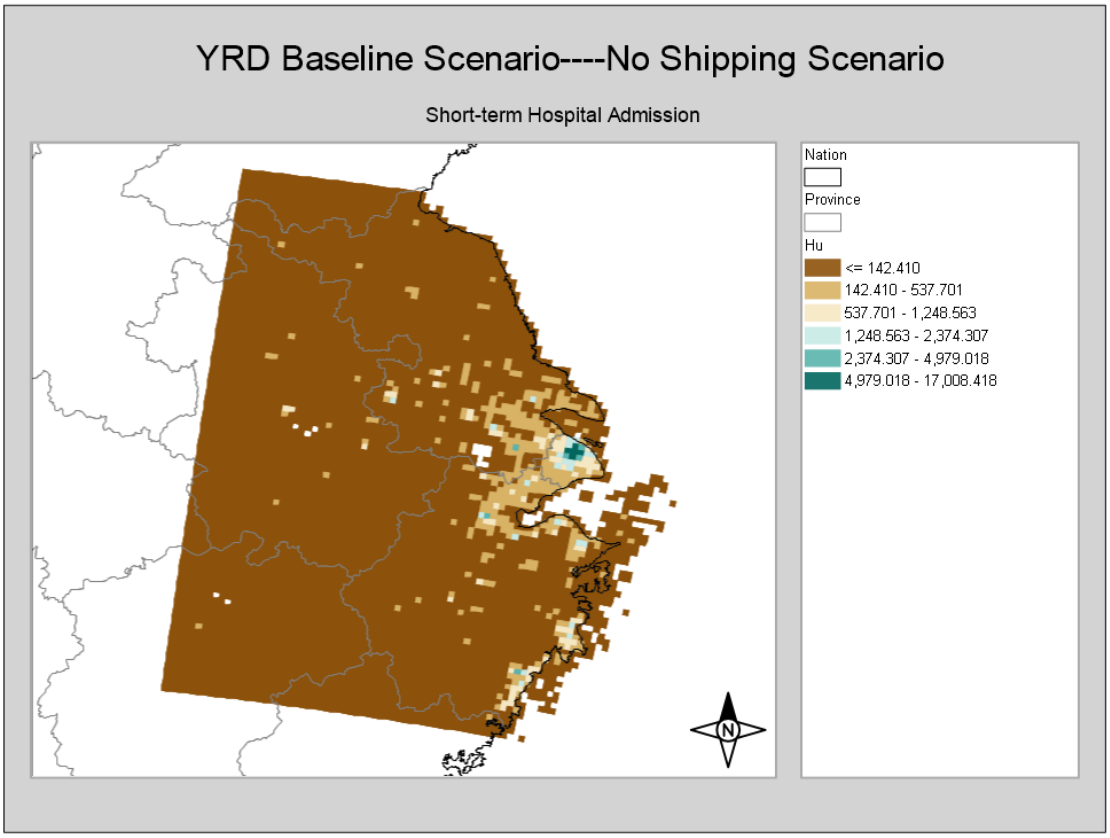


Figure D.3. Hospital admissions associated with short-term $PM_{2.5}$ exposure from port emissions using in YRD region.

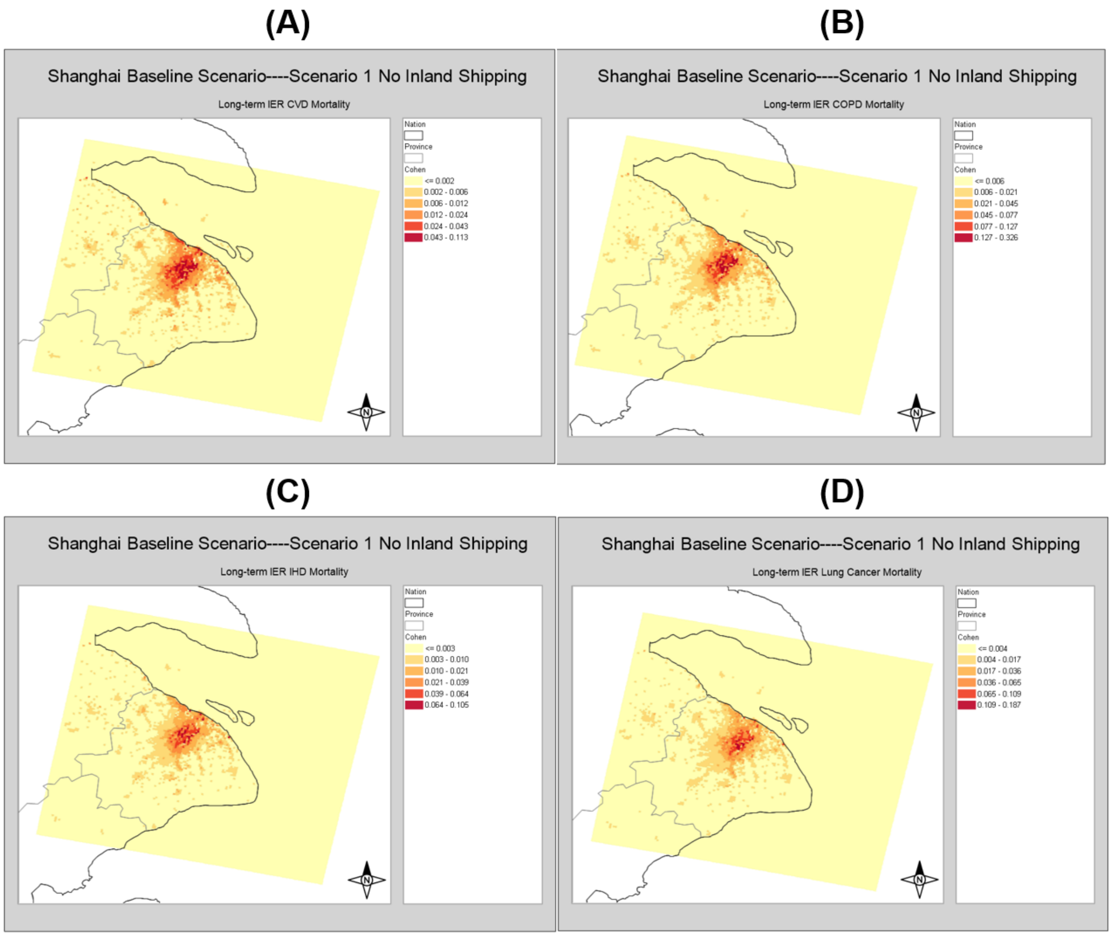


Figure D.4. Health impacts of long-term $PM_{2.5}$ exposure from inland shipping using the integrated exposure response (IER) function on mortality in Shanghai: (A) stroke mortality; **(B)** chronic obstructive pulmonary disease mortality; **(C)** ischemic heart disease mortality; and **(D)** lung cancer mortality.

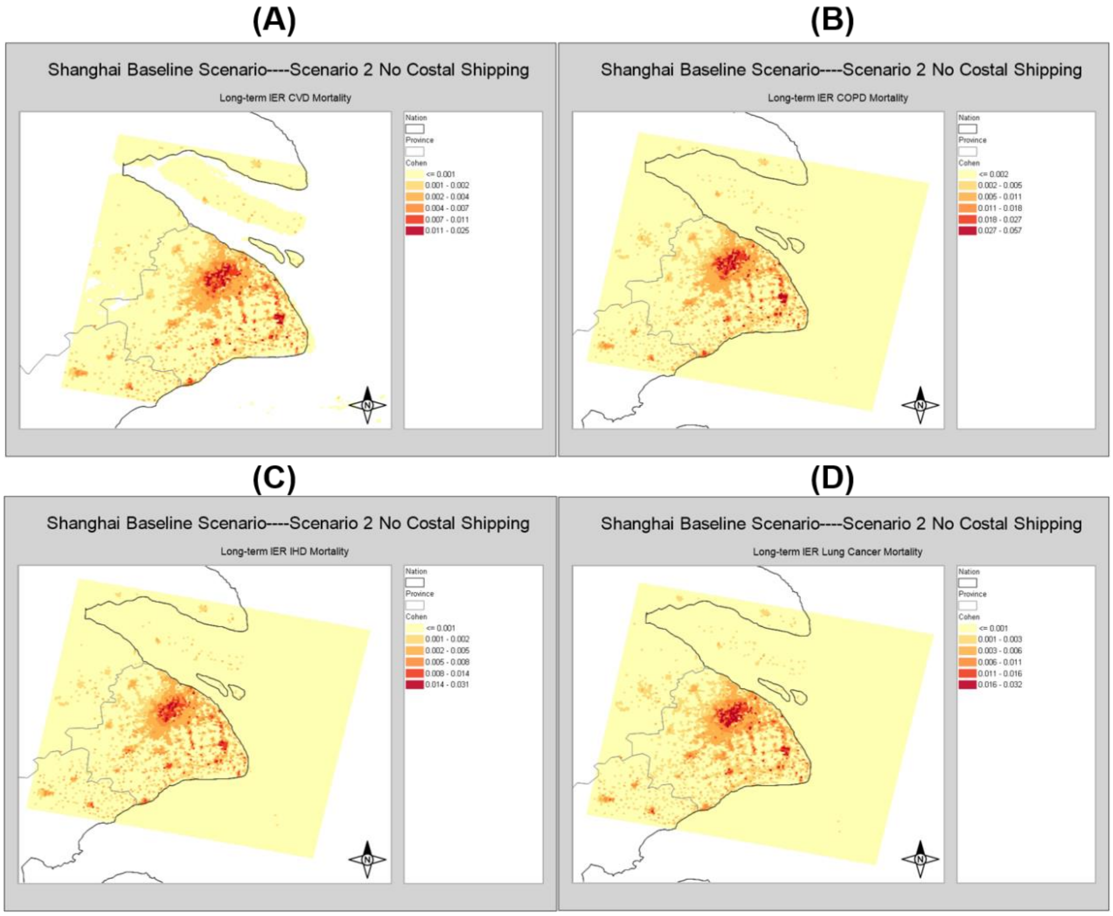


Figure D.5. Impacts of long-term $PM_{2.5}$ exposure from coastal shipping using the integrated exposure response (IER) function on mortality in Shanghai: (A) stroke mortality; **(B)** chronic obstructive pulmonary disease mortality; **(C)** ischemic heart disease mortality; and **(D)** lung cancer mortality.

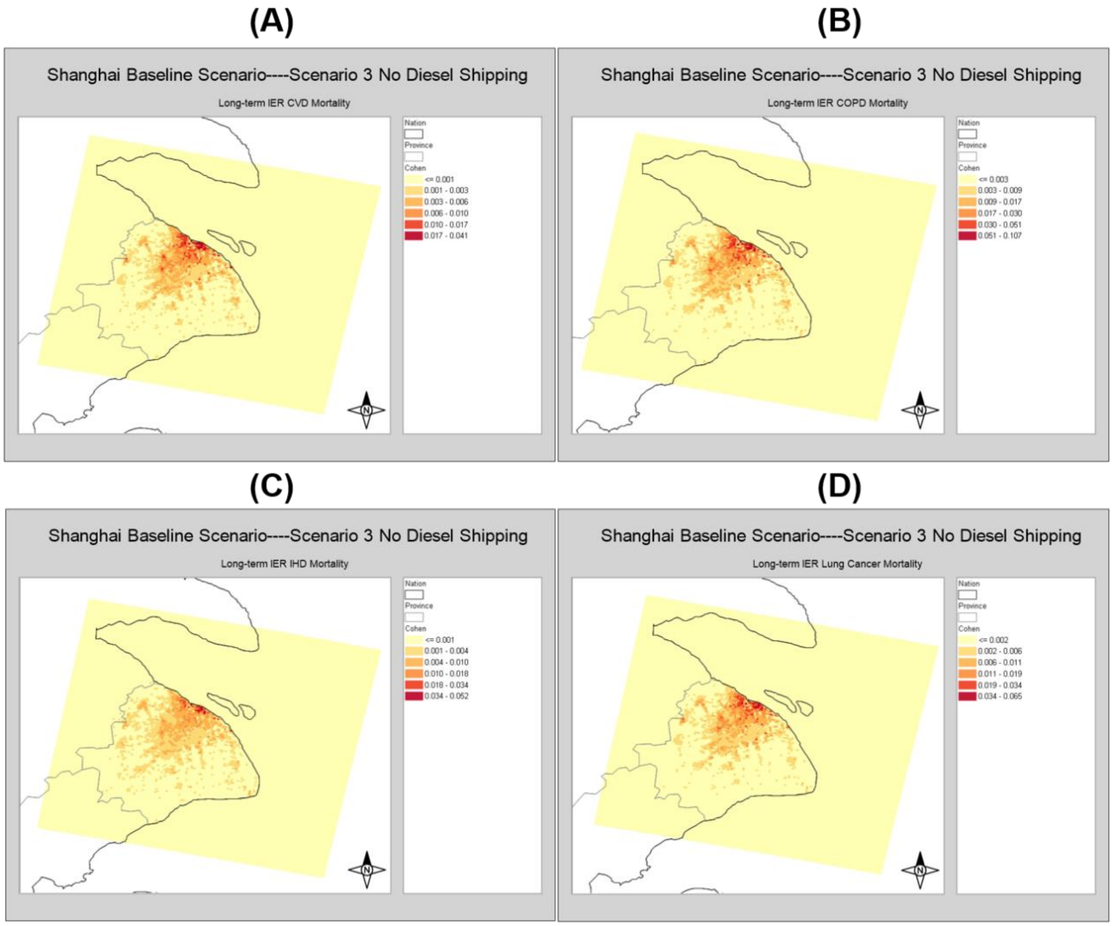


Figure D.6. Impacts of long-term $PM_{2.5}$ exposure from cargo trucks and port machinery using the integrated exposure response (IER) function on mortality in Shanghai region: (A) stroke; **(B)** chronic obstructive pulmonary disease; **(C)** ischemic heart disease; and **(D)** lung cancer.

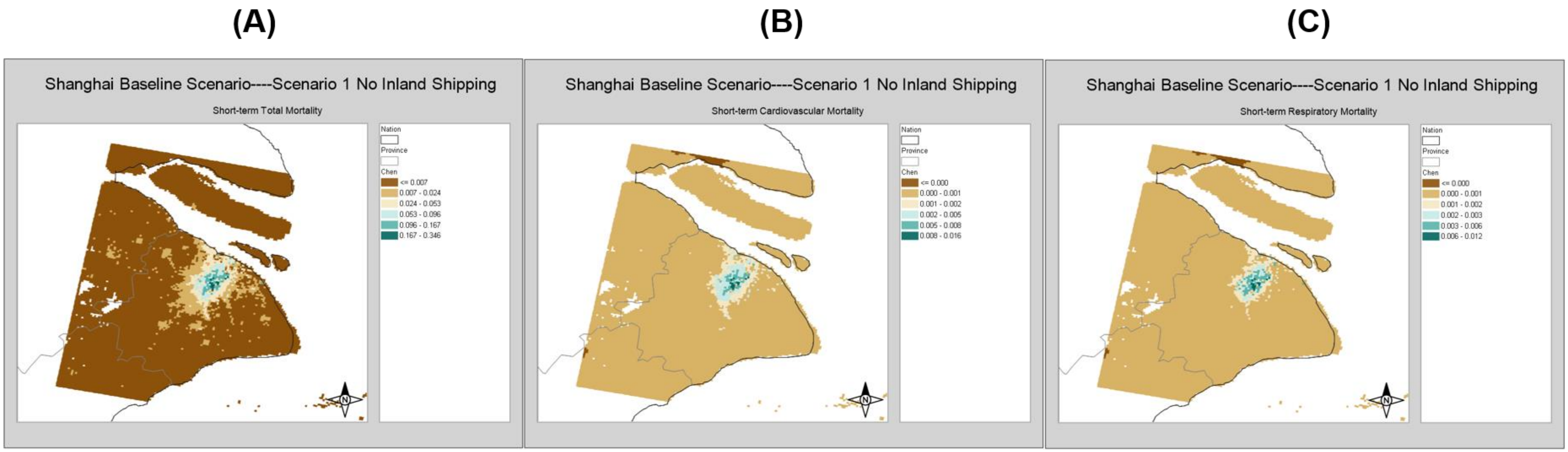


Figure D.7. Impacts of short-term $PM_{2.5}$ exposure from inland shipping on mortality in Shanghai: (A) all-cause mortality; **(B)** cardiovascular mortality; and **(C)** respiratory mortality.

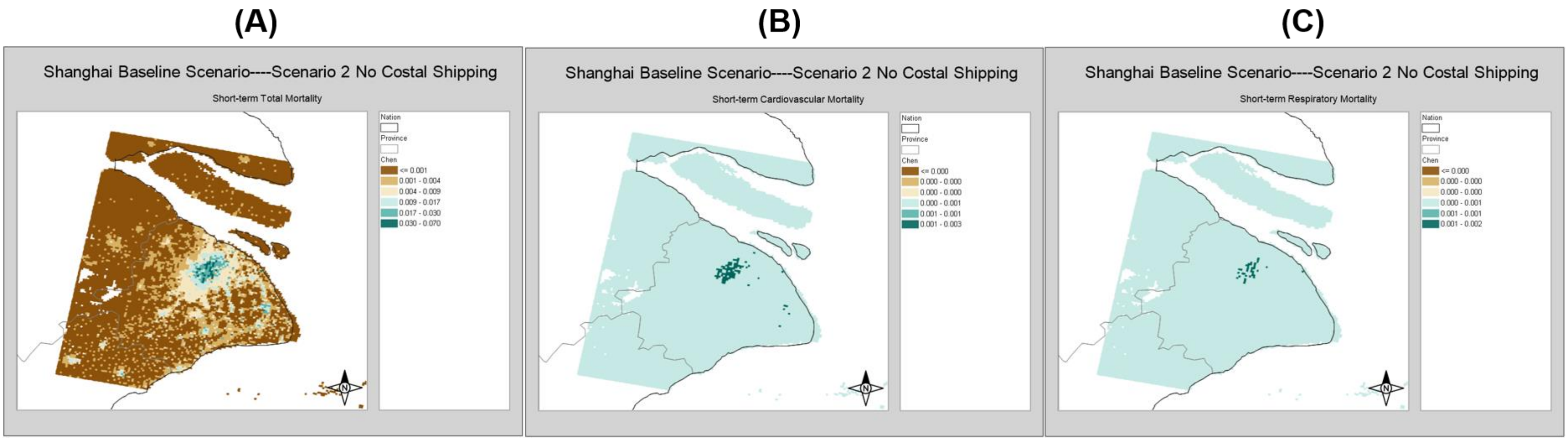


Figure D.8. Impacts of short-term $PM_{2.5}$ exposure from coastal shipping on mortality in Shanghai region: (A) all-cause mortality; **(B)** cardiovascular mortality; and **(C)** respiratory mortality.

(A) (B) (C)

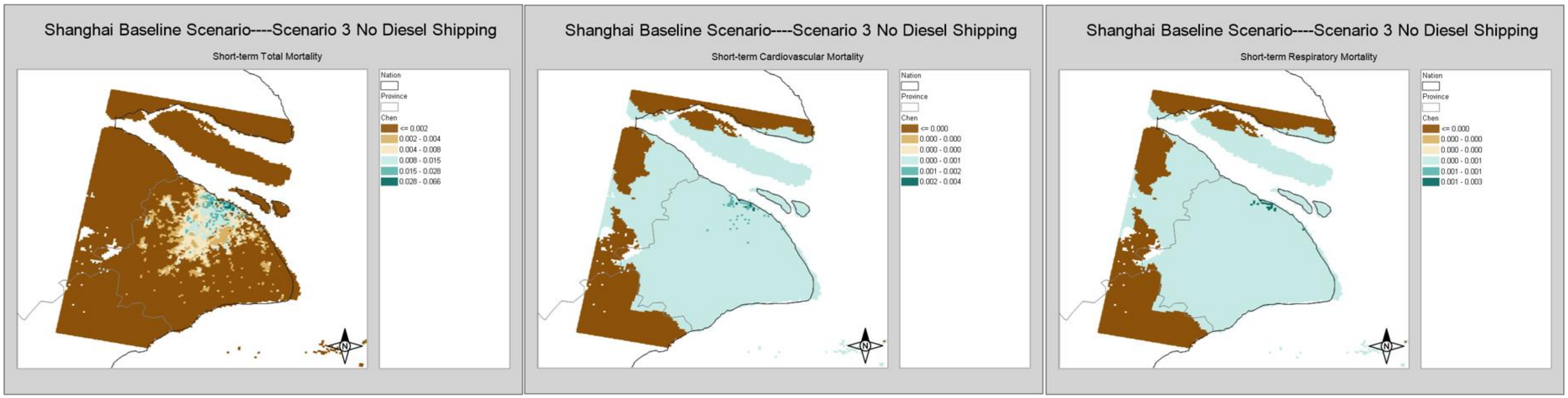


Figure D.9. Impacts of short-term $PM_{2.5}$ exposure from diesel cargo trucks and port machinery on mortality in Shanghai: (A) all-cause mortality; **(B)** cardiovascular mortality; and **(C)** respiratory mortality.

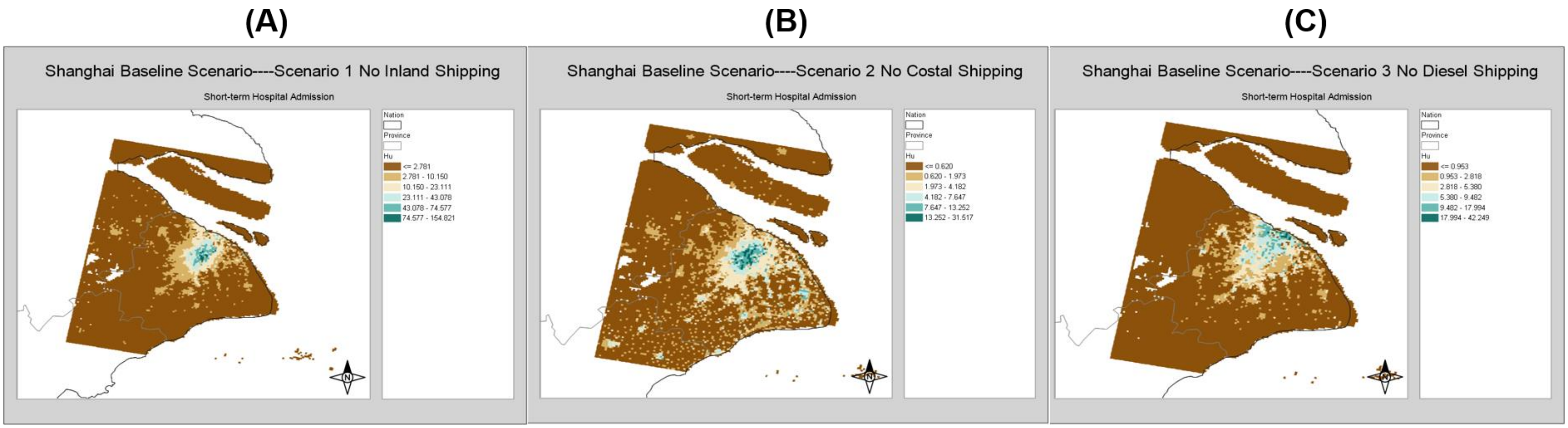


Figure D.10. Hospital admissions associated with short-term $PM_{2.5}$ exposure from port emissions in Shanghai: (A) inland shipping; **(B)** coastal shipping; and **(C)** diesel cargo trucks and port machinery.

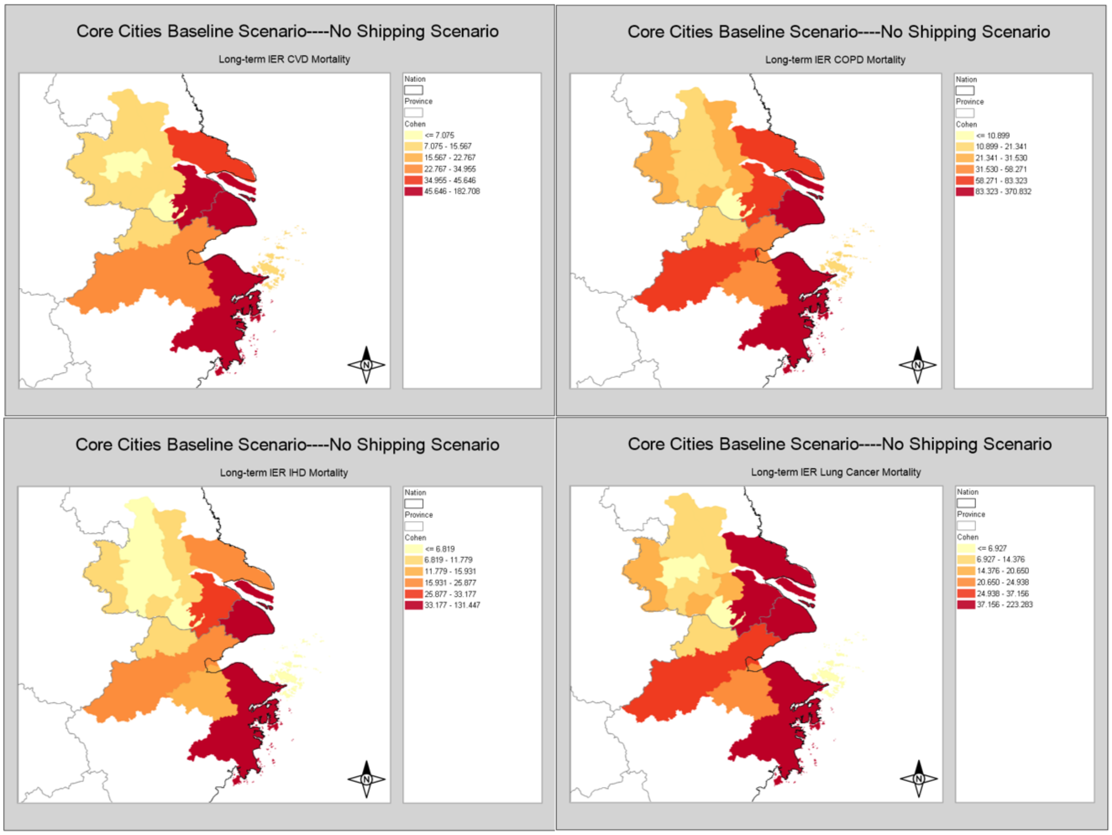


Figure D.11. Cause-specific mortality impacts of long-term $PM_{2.5}$ exposures from ship emissions using the integrated exposure response (IER) functions in 16 core cities of the YRD region: (A) stroke mortality; **(B)** chronic obstructive pulmonary disease mortality; **(C)** ischemic heart disease mortality; **(D)** lung cancer mortality.

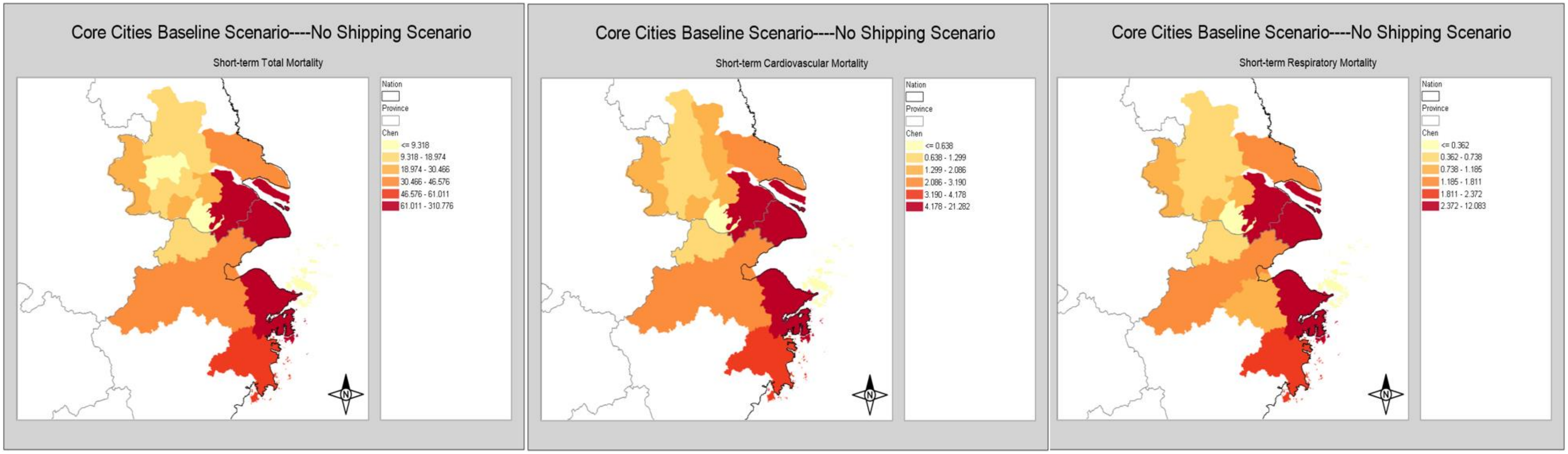


Figure D.12. Impacts of short-term $PM_{2.5}$ from ship emissions on mortality in 16 core cities of the YRD region in the baseline year: (A) all-cause mortality; **(B)** cardiovascular mortality; and **(C)** respiratory mortality.

Table D.1. Comparison of mean impacts of long-term $PM_{2.5}$ exposure on mortality in Shanghai and YRD region using emission inventories from domains 3 and 4[a]

Endpoints	Shanghai domain 4 1*1 km	Shanghai extracted from domain 3 9*9 km	YRD domain 3 9*9 km
Sum of cause-specific mortality[b]	236	1118	3591
Stroke	36	227	749
COPD	99	453	1452
IHD	40	164	549
Lung Cancer	60	273	841

[a] Shanghai (1*1km), sum of health impacts from 3 three scenarios using emission inventory of domain 4; Shanghai of YRD (9*9km), health impacts in Shanghai of the YRD region using emission inventory of domain 3; YRD (9*9km), health impacts in the YRD region using emission inventory of domain 3. The definitions of Shanghai city and the Shanghai modeling domain are not identical, so the results here are not expected to be the same as those reported in the 16 core city analyses.

[b] The sum of cause-specific mortality is the sum of mortality from stroke, COPD, IHD, and lung cancer associated with long-term exposure to $PM_{2.5}$. In the absence of a reliable concentration–response function for all natural-cause mortality associated with $PM_{2.5}$, this estimate is provided for comparison with mortality from short-term exposure to $PM_{2.5}$.

Table D.2. Summary of mean number of deaths associated with long-term and short-term exposure to $PM_{2.5}$ from shipping-related emissions in 16 core cities of the YRD region in 2015

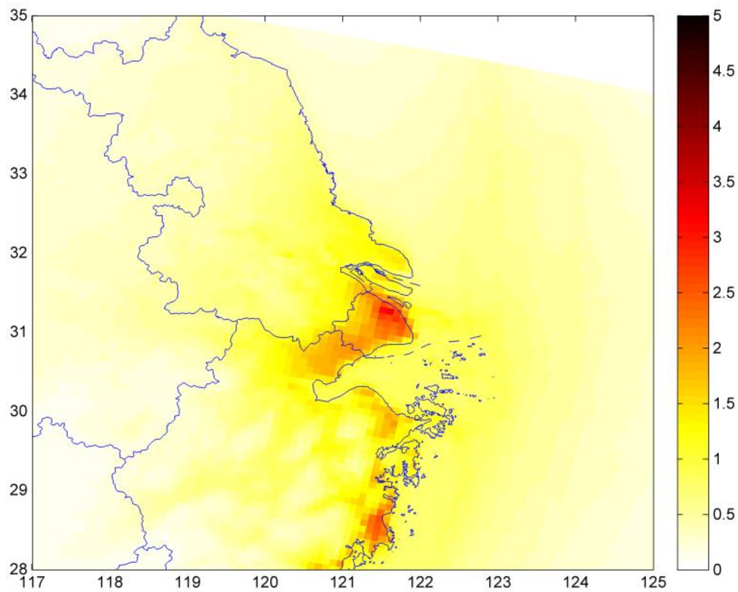
City [a]	Long-term Exposure				Short-term Exposure		
	Stroke	COPD	IHD	Lung Cancer	Total non-accidental	Cardio-vascular	Respiratory
Changzhou	9.3	18.9	6.8	11.2	16.1	1.1	0.6
Hangzhou	29.5	58.3	20.9	33.3	46.6	3.2	1.8
Huzhou	11.2	21.3	8.7	13.8	18.4	1.3	0.7
Jiaxing	29.2	54.5	22.1	34.0	44.4	3.0	1.7
Nanjing	13.7	27.9	10.2	18.1	23.9	1.6	0.9
Nantong	35.0	68.2	25.9	37.2	43.1	3.0	1.7
Ningbo	52.6	98.3	38.0	54.1	61.0	4.2	2.4
Shanghai	182.7	370.8	131.4	223.3	310.8	21.3	12.1
Shaoxing	22.8	44.0	15.9	24.9	30.5	2.1	1.2
Suzhou	45.6	83.3	33.2	51.9	67.7	4.6	2.6
Taichou	55.3	97.6	42.5	55.6	59.2	4.1	2.3
Taizhou	12.3	24.2	9.1	14.4	19.0	1.3	0.7
Wuxi	15.6	31.5	11.8	20.6	26.9	1.8	1.0
Yangzhou	9.0	17.9	6.3	10.4	14.5	1.0	0.6
Zhenjiang	5.2	10.9	4.0	6.9	9.3	0.6	0.4
Zhoushan	7.1	14.6	5.1	5.8	5.4	0.4	0.2
16 core cities (sum)	536.0	1042.3	391.8	615.5	796.7	54.6	31.0

[a] Names of coastal cities in bold.

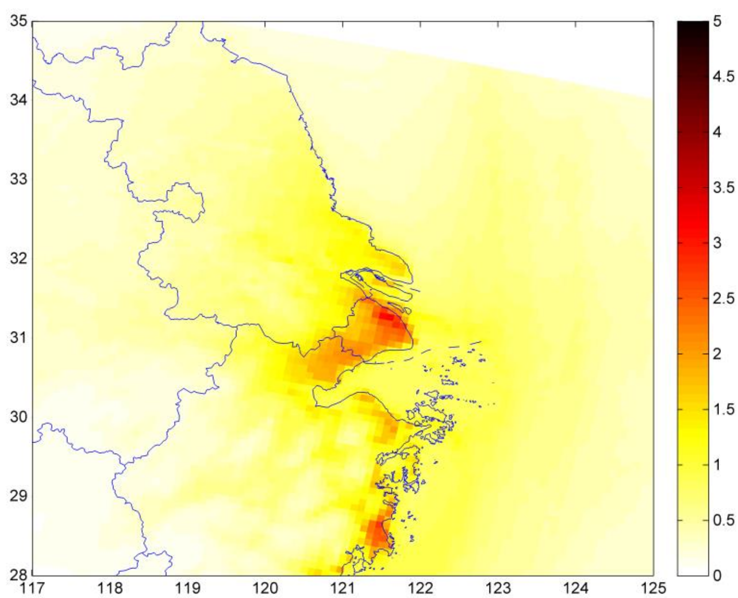
Appendix E. Evaluation

APPENDIX E, SECTION 1. EVALUATION OF REPRESENTATIVE MONTHS

Based on 12 months:



Based on 4 representative months (January, April, June, and October):



Difference (%):

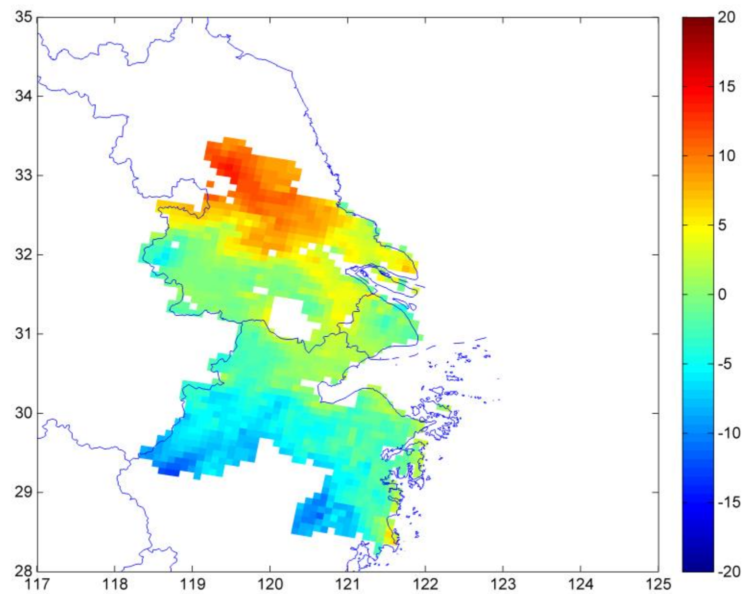


Figure E.1. Annual average $PM_{2.5}$ in the YRD based on (A) the full year and (B) 4 representative months, with (C) the percentage difference between the annual average $PM_{2.5}$ concentrations estimated by these two averages.

APPENDIX E, SECTION 2. CMAQ MODEL EVALUATION

Methods

We conducted both visual and statistical evaluation of the CMAQ model simulations for 2015. Model evaluation statistics were calculated as defined by Eder and Yu (2007):

$$\text{NMB} = \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n} O_i} \times 100\% \quad (1)$$

$$\text{NME} = \frac{\sum_{i=1}^{n}|S_i - O_i|}{\sum_{i=1}^{n} O_i} \times 100\% \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \quad (3)$$

$$r = \frac{\sum_{i=1}^{n}(S_i - \bar{S})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2 \sum_{i=1}^{n}(O_i - \bar{O})^2}} \quad (4)$$

where

S_i = the daily-average simulated data at a certain monitoring station, day i

O_i = the daily-average observation data at a certain monitoring station, day i

$\bar{S}$ = the average simulated data at a certain monitoring station of all days

$\bar{O}$ = the average observation data at a certain monitoring station of all days

n = the total numbers of days of the monitoring stations for which the simulated results are compared with the observed ones

Results

Our evaluation of the simulated daily and monthly average concentrations by comparison with monitoring results in the YRD region showed that the model was able to capture the spatial variation of shipping-related $PM_{2.5}$ and SO_2 concentrations, especially in Shanghai, along the Yangtze River, and along the coastal area of Zhejiang Province. Simulated results for January and June 2015 were mostly consistent with measurements made during the same month (Appendix E, Figure E.2).

In most of the 16 core cities, measured SO_2 and $PM_{2.5}$ concentrations were underestimated to varying degrees (normalized mean bias [NMB] ranged from -36% to -18% for SO_2 and −34% to 8% for $PM_{2.5}$, respectively) (Appendix E, Table E.1). Deviations between the simulation results and the monitoring data could be explained by uncertainties in the emission inventories and in the meteorological and air quality models.

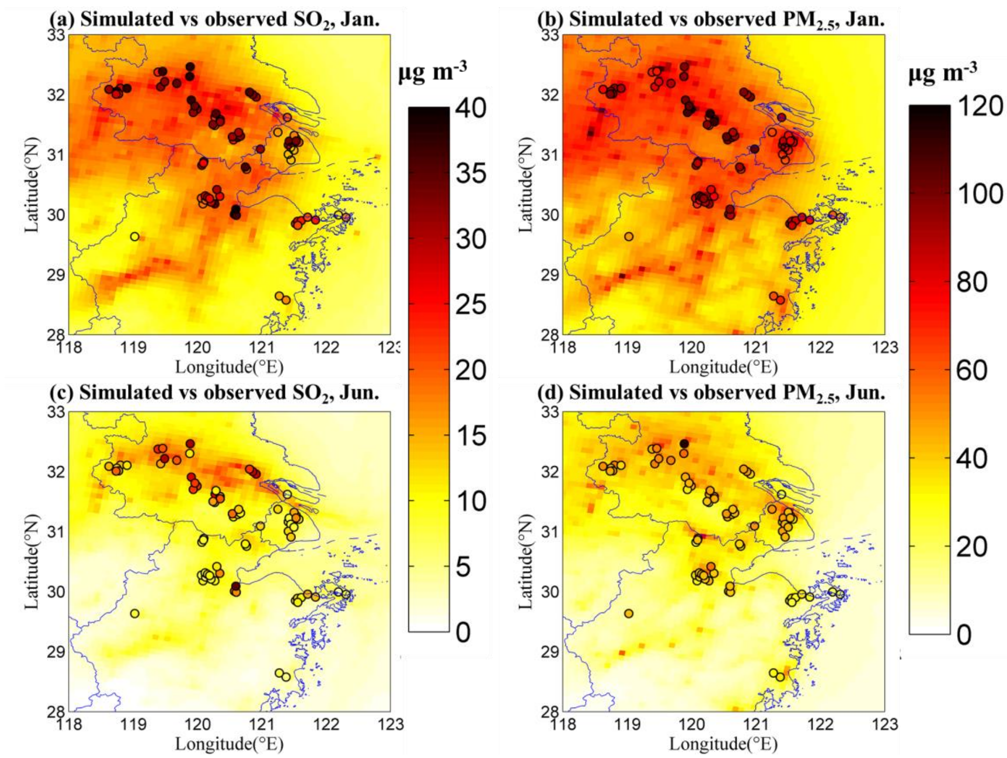


Figure E.2. The simulated (grid) and observed (circles) SO_2 concentration distribution in the YRD region in January 2015 (a) and June 2015 (c); the simulated (grid) and observed (circles) $PM_{2.5}$ concentration distribution in the YRD region in January 2015 (b) and June 2015 (d).

Table E.1. Statistical metrics of the model evaluation for January and June case[a]

City	SO$_2$						PM$_{2.5}$					
	Obs.	Sim.	NMB (%)	NME(%)	RMSE (μg m^{-3})	*r*	Obs.	Sim.	NMB (%)	NME (%)	RMSE (μg m^{-3})	*r*
Changzhou	31.24	20.14	-35.55	40.85	15.79	0.80	74.21	68.27	-8.01	32.51	31.99	0.76
Hangzhou	16.84	13.75	-18.35	28.74	6.77	0.83	59.35	56.96	-4.03	28.21	22.05	0.75
Huzhou	19.25	14.73	-23.52	38.81	11.45	0.80	65.13	70.50	8.25	45.60	39.17	0.47
Jiaxing	25.37	16.84	-33.67	50.58	17.31	0.75	61.31	57.01	-7.02	33.98	29.96	0.65
Nanjing	22.39	16.38	-20.60	26.50	10.13	0.76	68.20	55.71	-14.06	27.80	32.30	0.60
Nantong	32.73	22.05	-32.66	49.69	23.21	0.70	68.69	51.15	-25.54	39.27	37.23	0.69
Ningbo	16.20	10.47	-35.42	42.01	7.64	0.83	55.47	48.06	-13.37	34.51	28.49	0.75
Shanghai	19.16	12.32	-35.72	40.23	10.72	0.83	63.64	67.77	6.50	36.18	28.71	0.75
Shaoxing	22.47	14.63	-34.91	40.03	10.36	0.80	61.90	56.86	-8.15	34.06	27.21	0.70
Suzhou	21.37	15.16	-29.09	37.26	10.39	0.85	67.11	56.45	-15.89	33.41	28.76	0.76
Taichou	10.72	7.55	-29.64	34.07	5.25	0.80	47.55	43.69	-8.11	35.35	24.09	0.52
Taizhou	29.64	20.84	-29.70	61.53	22.63	0.67	74.56	62.82	-15.75	31.75	33.49	0.63
Wuxi	24.64	18.89	-23.35	30.85	10.58	0.87	73.45	59.36	-19.20	31.80	30.92	0.77
Yangzhou	25.78	18.75	-27.31	44.22	15.17	0.62	62.30	60.12	-3.50	46.10	37.08	0.57
Zhenjiang	29.65	21.50	-27.51	39.49	16.23	0.61	67.78	62.61	-7.63	33.88	30.31	0.59
Zhoushan	9.99	8.04	-19.60	40.42	6.73	0.64	30.13	19.81	-34.28	49.15	16.82	0.78

[a] Observed data (Obs.) and simulated data (Sim.) for each city are the average of monthly values of January and June case. NMB, NME, RMSE, and *r* were calculated based on the daily-average observed and simulated data.

APPENDIX E, SECTION 3. SENSITIVITY ANALYSIS OF HEALTH IMPACT FUNCTIONS

Table E.2. Impacts of long-term $PM_{2.5}$ exposure from ship emissions on cause-specific mortality in the YRD region in 2015.

Endpoints	GBD IER	GEMM (15 cohorts)	GEMM (14 cohorts)
Sum[a]	3592.5 (2414.6, 6856.7)	20271.1 (15252.8, 25259.6)	18873.2 (13474, 24239.5)
Stroke	749.3 (439.6, 1592.5)	4260.4 (1898.3, 6597.2)	2912.1 (338.2, 5456.2)
COPD	1452.6 (968.6, 2806.3)	2219.9 (1047.7, 3381.4)	1731.4 (641.1, 2811.9)
IHD	549.6 (392, 1408.2)	3841.8 (3390.4, 4290.6)	2320.4 (1500.1, 3134.8)
Lung Cancer	841 (614.4, 1049.7)	1595.4 (942.9, 2242.2)	1459.3 (604.4, 2305.2)

[a]For the IER, this value is the sum of mortality from stroke, COPD, IHD, and lung cancer associated with long-term exposure to $PM_{2.5}$. In the absence of a reliable concentration–response function for all natural-cause mortality associated with $PM_{2.5}$, this estimate is provided for comparison with mortality from short-term exposure to $PM_{2.5}$ and with the GEMM estimates. The GEMM provides a function for all-natural cause mortality that includes both the specific causes listed as well as others.

Abbreviations: stroke = cerebrovascular disease; COPD = chronic obstructive pulmonary disease, IHD = ischemic heart disease.
Notes: GBD IER: estimates generated from IER 2015; GEMM (15 cohorts): estimates generated from GEMM functions of 15 cohorts, including Chinese male cohorts; GEMM (14 cohorts): estimates generated from GEMM functions of 14 cohorts, without Chinese male cohorts.

Table E.3. Impacts of annual average $PM_{2.5}$ exposure from shipping-related sources on cause-specific mortality in Shanghai in 2015.

Scenario	Endpoints	GBD IER	GEMM (15 cohorts)	GEMM (14 cohorts)
Inland shipping in Shanghai	Sum[a]	135.5 (95.4, 260.8)	746.8 (561.6, 931.1)	621.2 (443.2, 798.4)
	Stroke	20.8 (12.5, 46.4)	118.8 (52.8, 184.3)	69.5 (8.1, 130.6)
	COPD	56.8 (39, 115.4)	85.9 (40.5, 131.1)	57.7 (21.3, 93.9)
	IHD	23.1 (17.2, 57.2)	184.6 (162.8, 206.3)	94.6 (61.1, 127.9)
	Lung Cancer	34.8 (26.7, 41.8)	62.0 (36.6, 87.3)	48.9 (20.2, 77.5)
Coastal/international shipping in Shanghai	Sum[a]	55.1 (38.3, 106.1)	302.0 (227.1, 376.6)	264.6 (188.7, 340.1)
	Stroke	8.6 (5.1, 18.9)	49.8 (22.1, 77.4)	31.1 (3.6, 58.4)
	COPD	23.2 (15.8, 46.3)	35.3 (16.6, 53.9)	25.1 (9.3, 40.9)
	IHD	9.6 (7.1, 24.3)	74.4 (65.6, 83.1)	40.4 (26.1, 54.7)
	Lung Cancer	13.7 (10.4, 16.7)	25.5 (15.0, 35.9)	21.5 (8.9, 34.0)
Diesel cargo trucks and port machinery in Shanghai	Sum[a]	45.6 (31.9, 88)	255.6 (192.2, 318.7)	219.2 (156.4, 281.8)
	Stroke	6.9 (4.2, 15.4)	41.7 (18.5, 64.7)	24.7 (2.9, 46.4)
	COPD	19.1 (13, 38.6)	29.6 (13.9, 45.2)	20.2 (7.4, 32.8)
	IHD	7.8 (5.8, 19.6)	62.9 (55.5, 70.3)	32.8 (21.2, 44.3)
	Lung Cancer	11.8 (8.9, 14.4)	21.4 (12.6, 30.2)	17.3 (7.2, 27.4)

[a] For the GBD IER, this the sum of mortality from stroke, COPD, IHD, and lung cancer associated with long-term exposure to $PM_{2.5}$. In the absence of a reliable concentration–response function for all natural-cause mortality associated with $PM_{2.5}$, this estimate is provided for comparison with total all-cause mortality estimated using the GEMM. The GEMM provides a function for all-natural cause mortality that includes both the specific causes listed as well as others.

Abbreviations: stroke = cerebrovascular disease; COPD = chronic obstructive pulmonary disease, IHD = ischemic heart disease.
Notes: GBD IER: estimates generated from IER 2015; GEMM (15 cohorts): estimates generated from GEMM functions of 15 cohorts, including Chinese male cohorts; GEMM (14 cohorts): estimates generated from GEMM functions of 14 cohorts, without Chinese male cohorts.

Appendix F. Future (2030) Ship Activity, Emissions, Air Quality, and Health Results

Table F.1. Estimated YRD regional total ship traffic activity and actual GDP by year

Year	Estimated ship traffic activity in YRD, kWh	Actual GDP in the YRD region, billion yuan[a]
2013	5.1×10^{10}	10198.9
2014	4.8×10^{10}	11863.6
2015	1.1×10^{11}	13857.0
2016	1.2×10^{11}	14719.4
2017	1.4×10^{11}	16517.1
2030	1.9×10^{11}	19815.51 (projected to 2030)

[a] Source: National Bureau of Statistics of China (*http://data.stats.gov.cn/*). See Figure 5.8 for visualization of these data.

Table F.2. Estimated YRD regional total ship emissions for 2015 and for three scenarios in 2030

	2015	2030 current policy scenario (Future S1)	2030 stricter policy scenario (Future S2)	2030 aspirational policy scenario (Future S3)
SO_2	219645.5	59011.5	48530.8	20143.6
NO_x	472743.5	409546.3	296471.5	151423.9
$PM_{2.5}$	27863.2	7571.2	6158.8	2697.4

See Figure 5.9 for visualization of these data.

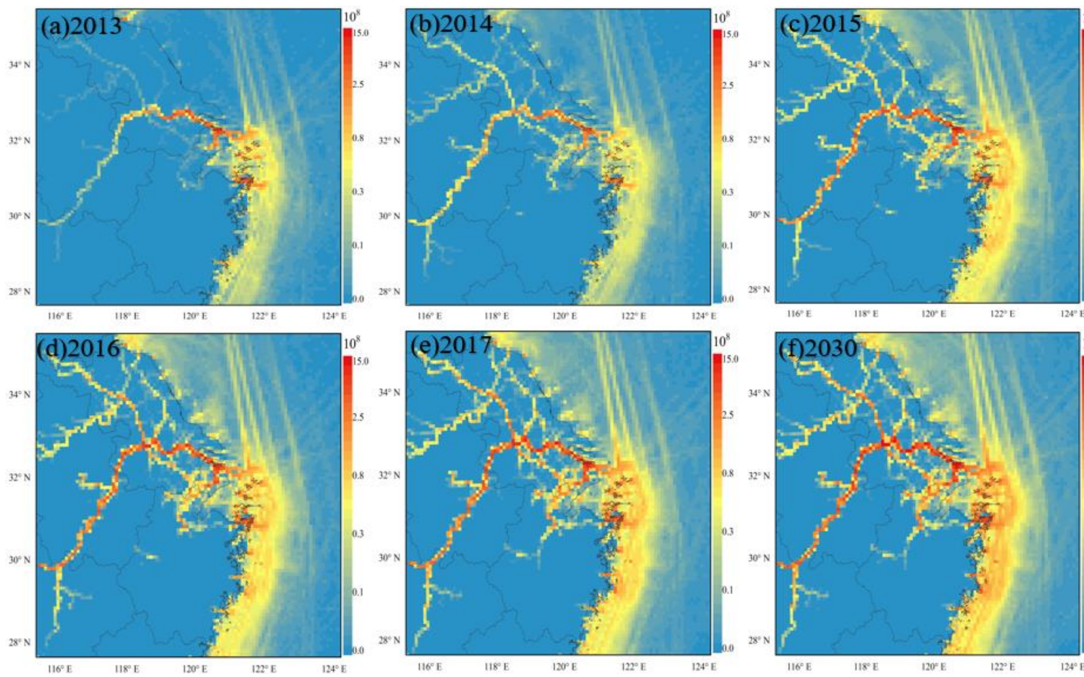


Figure F.1. Spatial distribution of ship traffic activities (kwh/grid) in the YRD region in (a) 2013, (b) 2014, (c) 2015, (d) 2016, (e) 2017, and (f) projected to 2030.

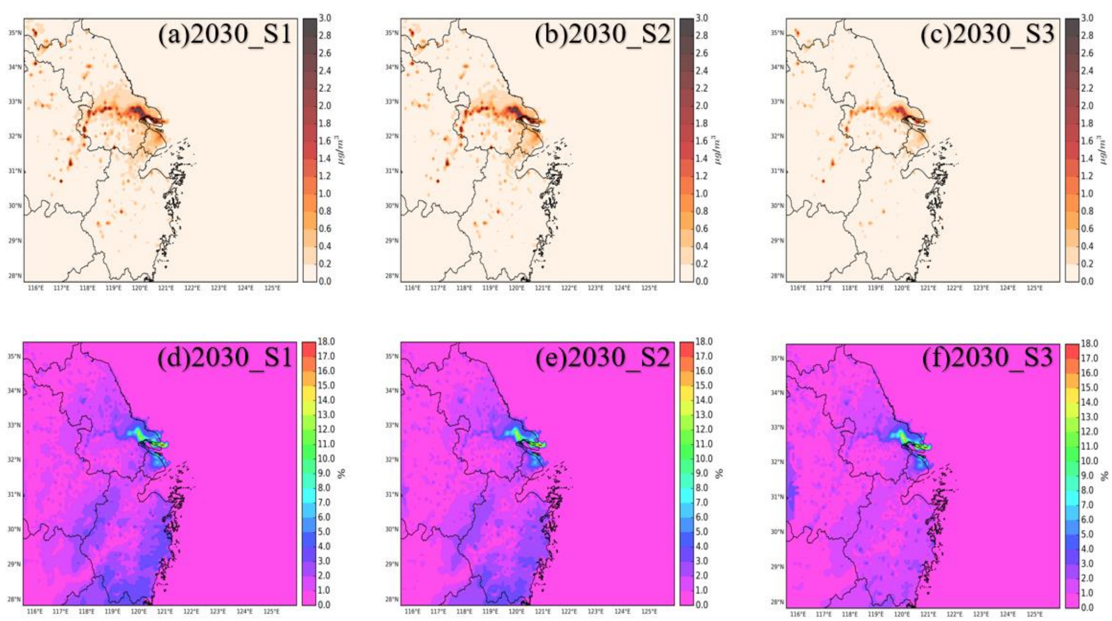


Figure F.2. Contributions of absolute contributions (top) and relative contributions (bottom) of ship emissions to the annual mean SO_2 concentrations in the YRD region in 2030 under the current policy (S1, left), stricter policy (S2, middle), and aspirational policy (S3, right) scenarios.

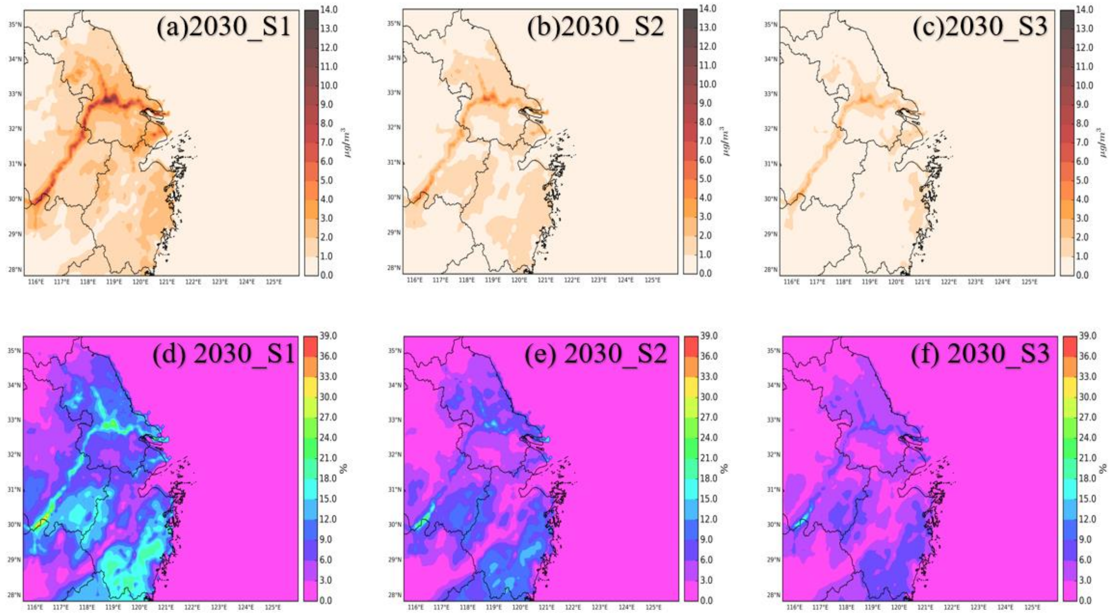


Figure F.3. Contributions of absolute contributions (top) and relative contributions (bottom) of ship emissions to the annual mean NO_x concentrations in the YRD region in 2030 under the current policy (S1, left), stricter policy (S2, middle), and aspirational policy (S3, right) scenarios.

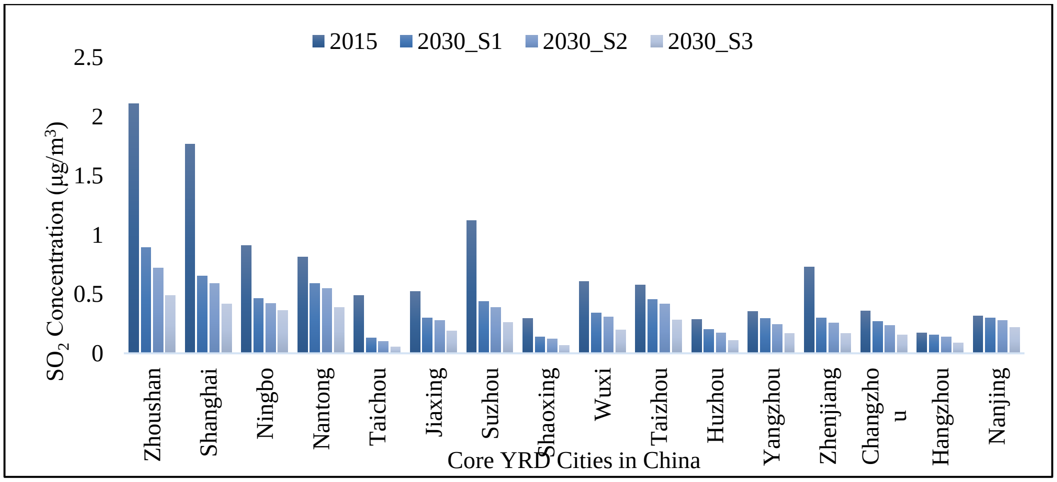


Figure F.4. Annual average contributions of ship-related SO_2 concentrations in 16 core YRD cities in 2015 and under the current policy (S1), stricter policy (S2), and aspirational policy (S3) scenarios for 2030.

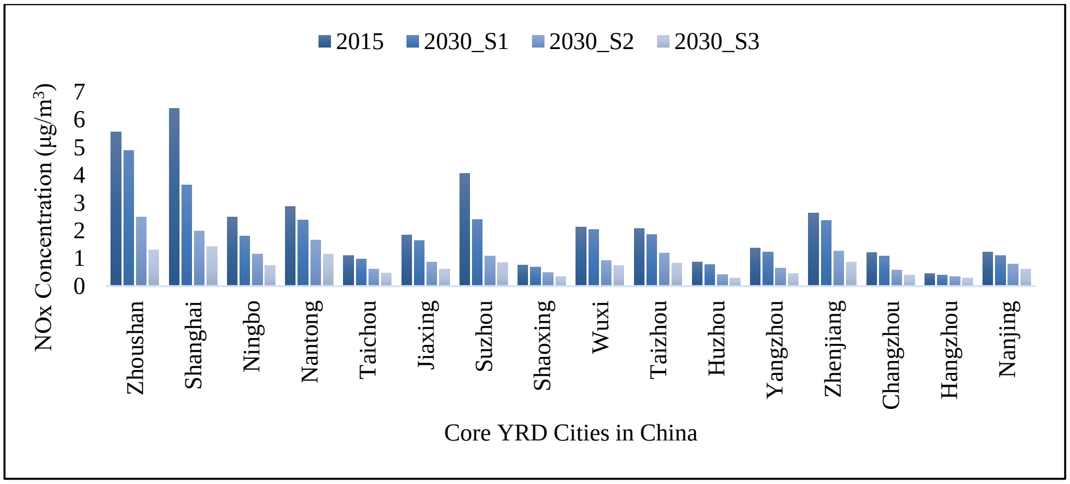


Figure F.5. Annual average contributions of ship-related NO_x concentrations in 16 core YRD cities in 2015 and under the current policy (S1), stricter policy (S2), and aspirational policy (S3) scenarios for 2030.

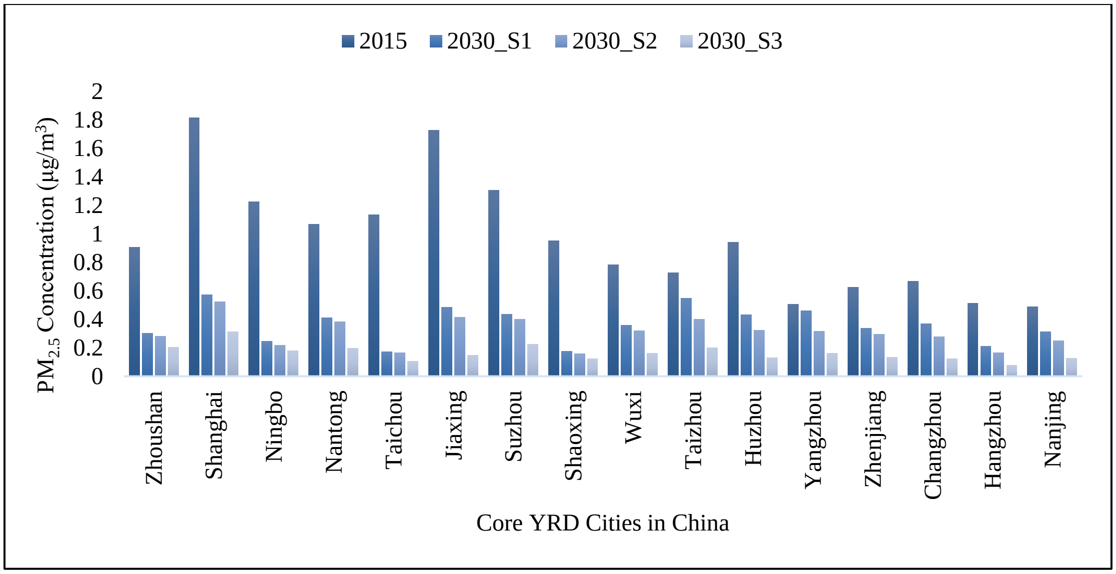


Figure F.6. Annual average contributions of ship-related $PM_{2.5}$ concentrations in 16 core YRD cities in 2015 and under the current policy (S1), stricter policy (S2), and aspirational policy (S3) scenarios for 2030.

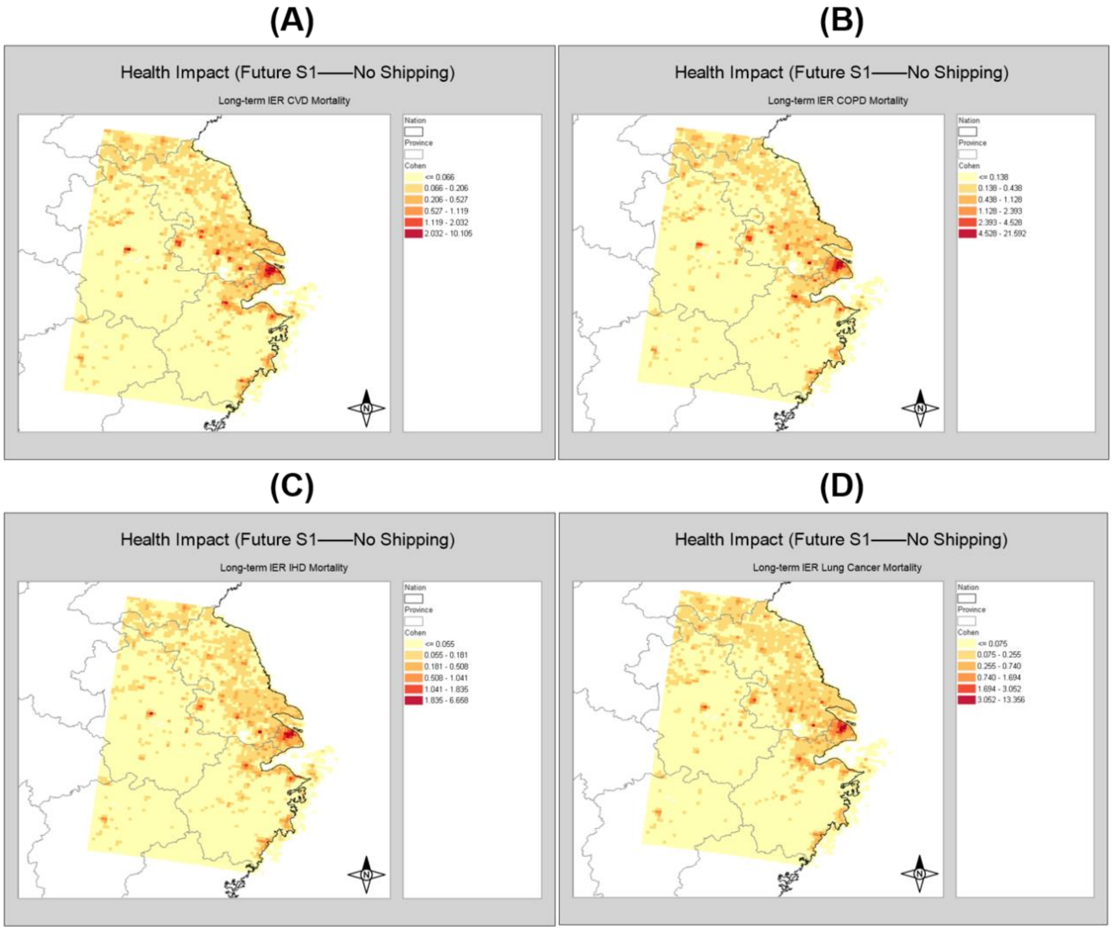


Figure F.7. Mortality contributed by long-term exposure to $PM_{2.5}$ from ship emissions in the YRD region in 2030 under the current policy scenario (S1) using integrated exposure response (IER) functions: (A) stroke mortality; **(B)** chronic obstructive pulmonary disease mortality; **(C)** ischemic heart disease mortality; and **(D)** lung cancer mortality.

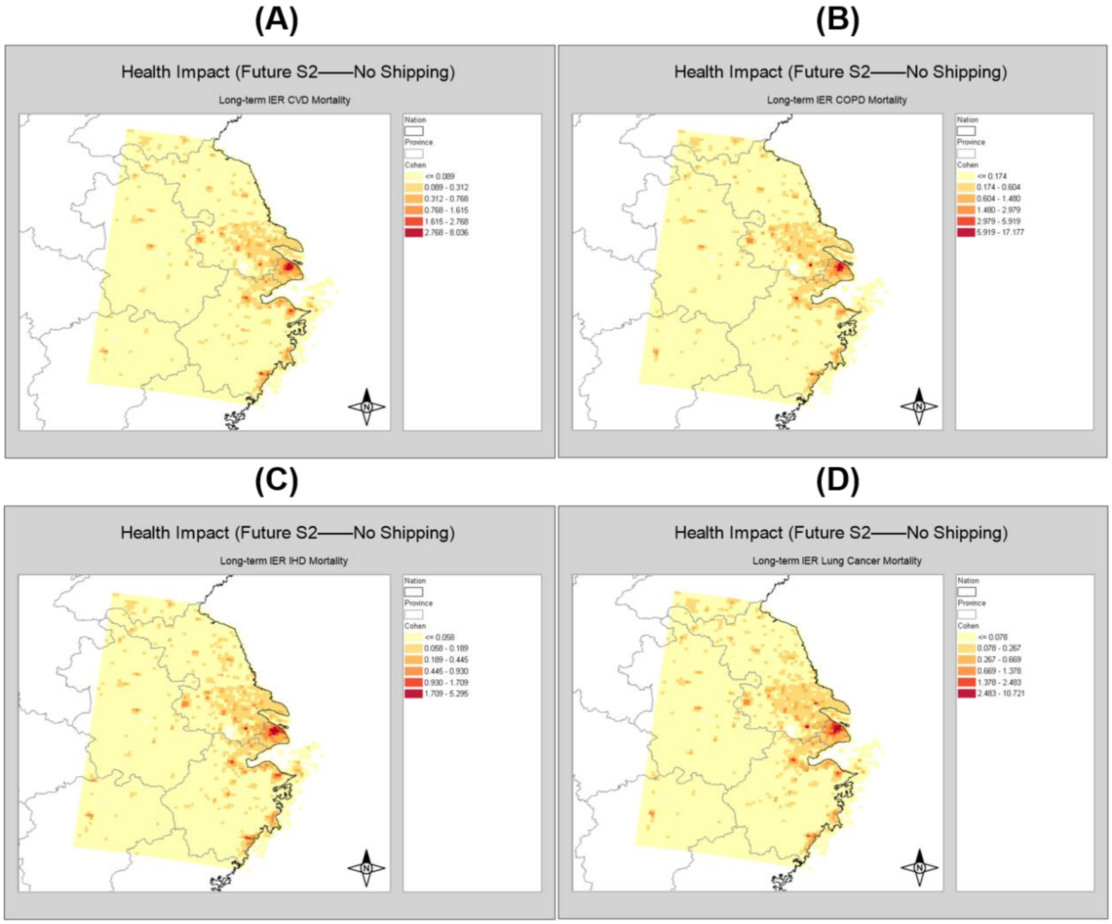


Figure F.8. Mortality contributed by long-term exposure to $PM_{2.5}$ from ships in 2030 in the YRD region under the stricter policy scenario (S2) using integrated exposure response (IER) functions: (A) stroke mortality; **(B)** chronic obstructive pulmonary disease mortality; **(C)** ischemic heart disease mortality; and **(D)** lung cancer mortality.

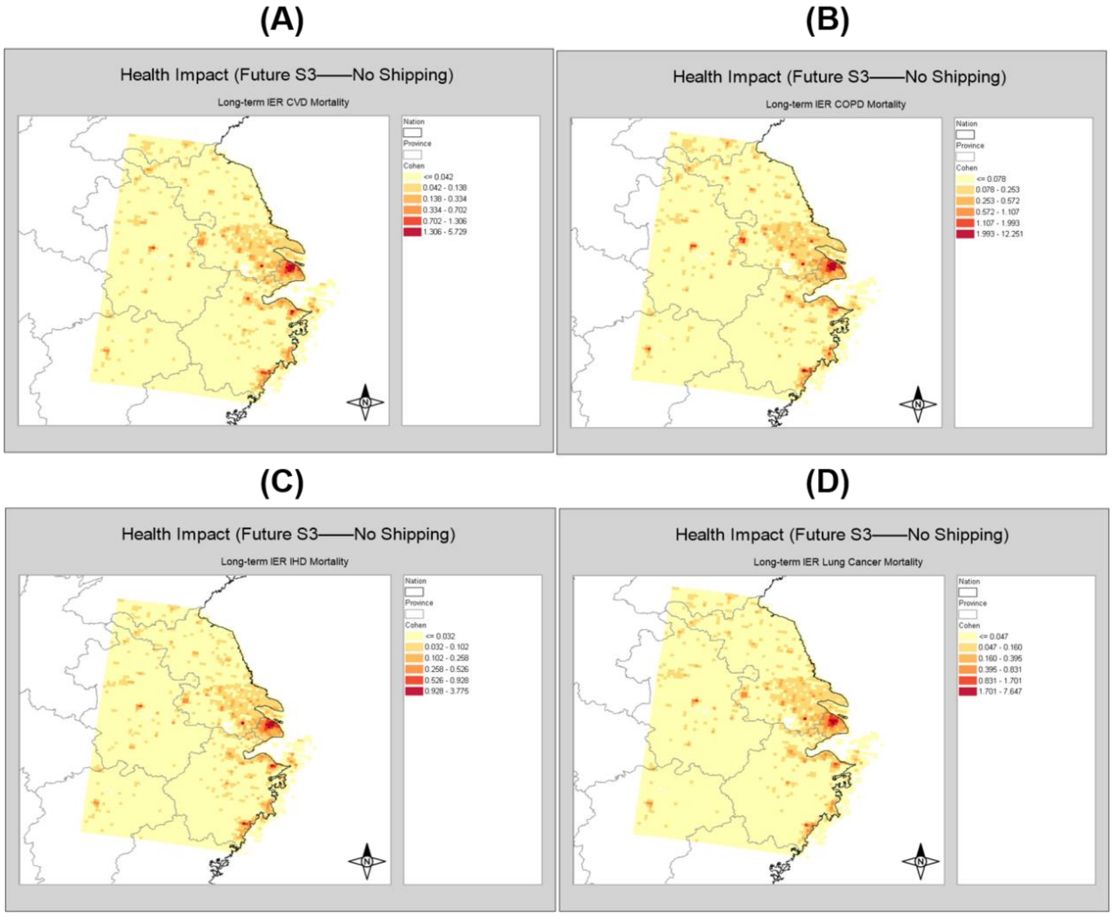


Figure F.9. Mortality contributed by long-term exposure to $PM_{2.5}$ from ships in 2030 in the YRD region under the Aspirational Scenario 2 (S3) in the YRD using integrated exposure response (IER) function: (A) stroke mortality; **(B)** chronic obstructive pulmonary disease mortality; **(C)** ischemic heart disease mortality; and **(D)** lung cancer mortality.

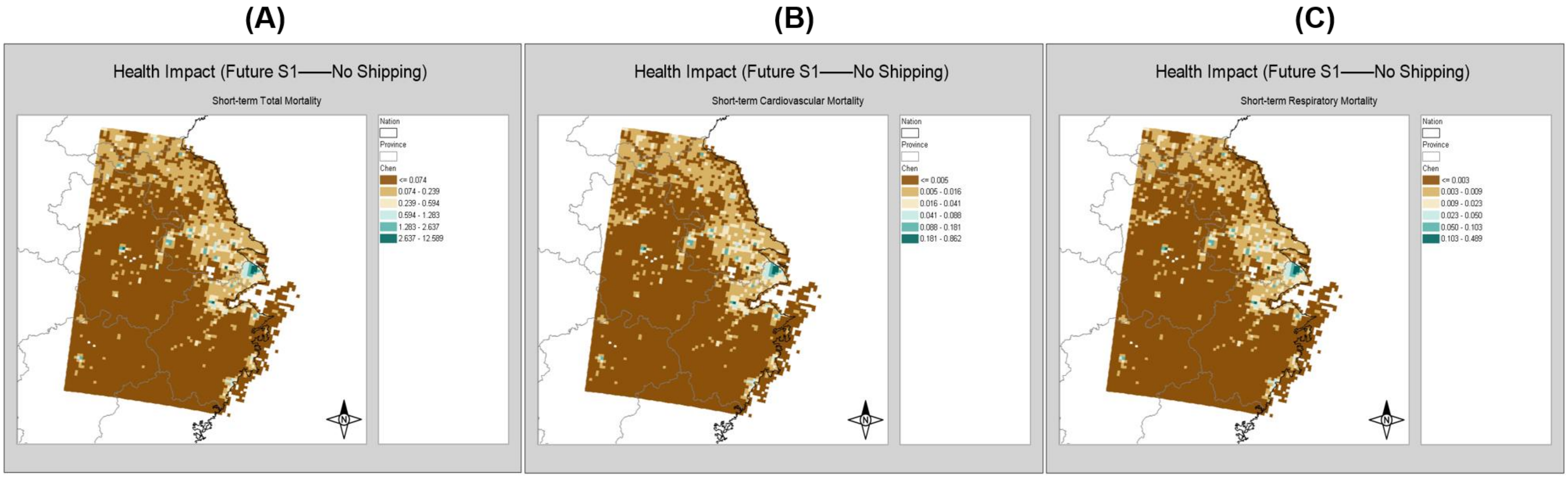


Figure F.10. Mortality contributed by short-term exposure to $PM_{2.5}$ from ships in 2030 in the YRD under the current policy scenario (S1): (A) all-cause mortality; **(B)** cardiovascular mortality; and **(C)** respiratory mortality.

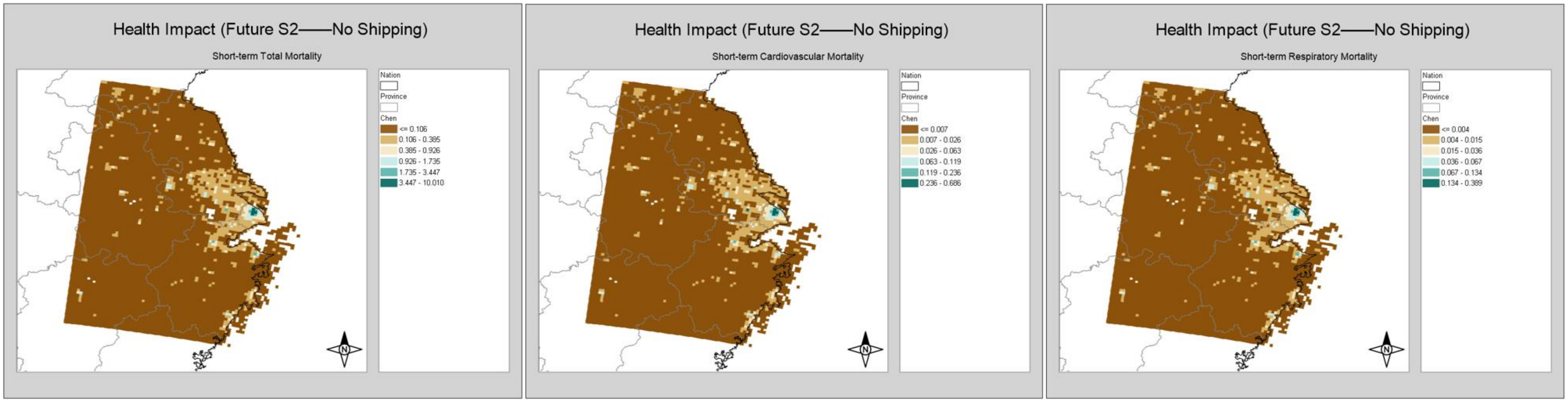


Figure F.11. Mortality contributed by short-term exposure to $PM_{2.5}$ from ships in 2030 from ship emissions in the YRD under the stricter policy scenario (S2): (A) all-cause mortality; **(B)** cardiovascular mortality; and **(C)** respiratory mortality.

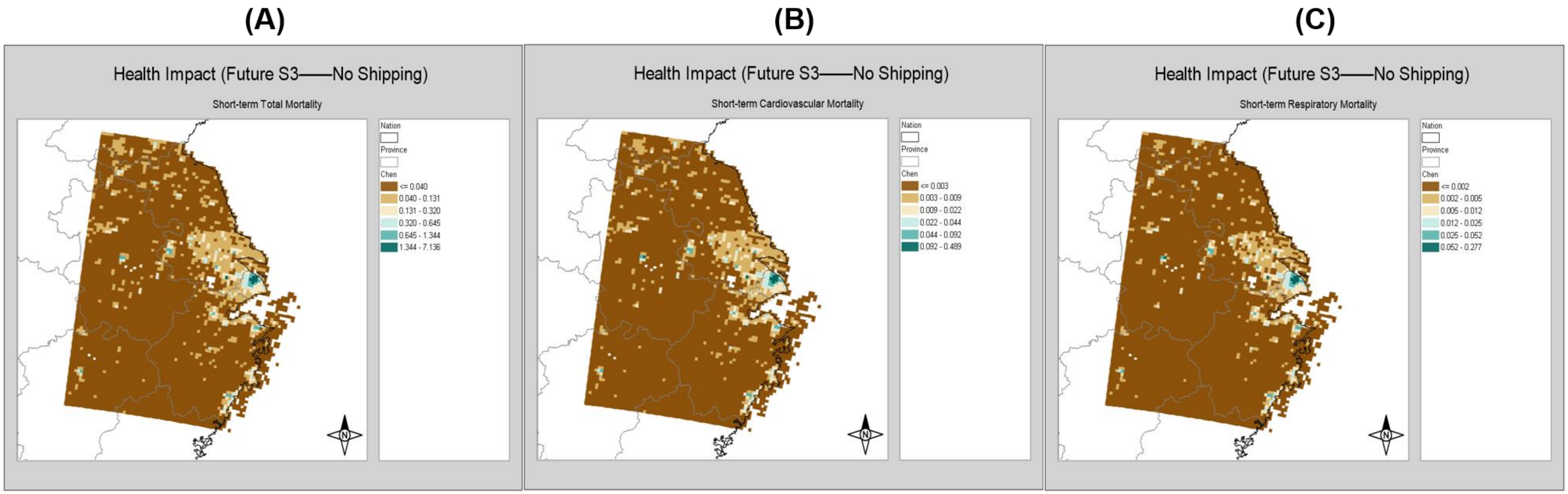


Figure F.12. Mortality contributed by short-term exposure to $PM_{2.5}$ from ships in 2030 in the YRD for the aspirational policy scenario (S3): (A) all-cause mortality; **(B)** cardiovascular mortality; and **(C)** respiratory mortality.