Impact of Using ammonia as shipping fuel

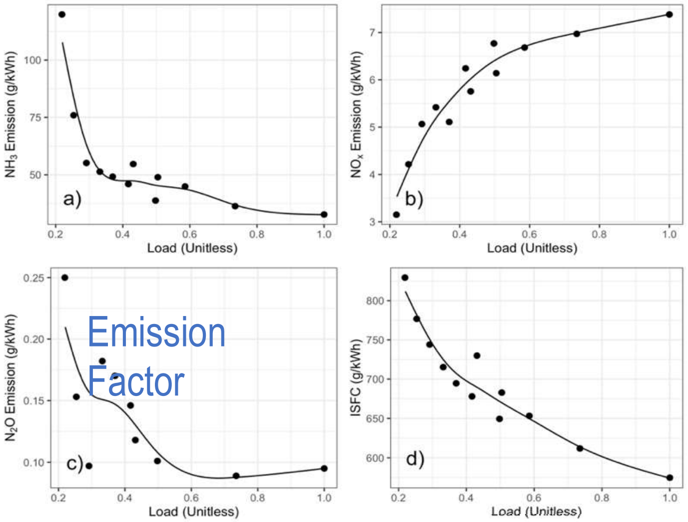
- Bottom–up approach combining ammonia engine experiment results and ship track data to estimate global tailpipe NO_x, NH_3 and N_2O emissions from ammonia-powered ships
- 2 possible engine technologies (NH_3–H_2 vs pure NH_3 combustion)
- 3 emission regulation scenarios (with corresponding assumptions in emission control technologies)

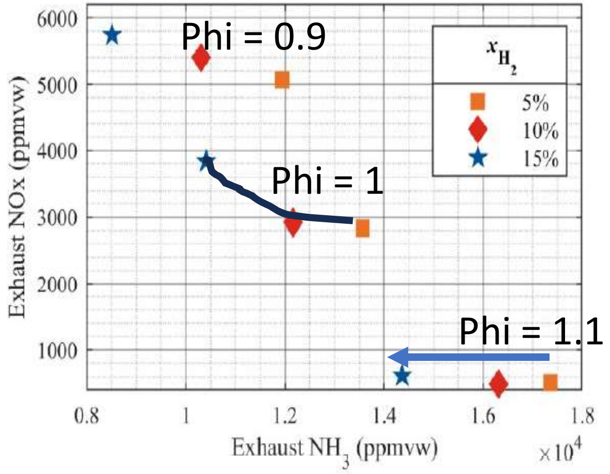
Study initiated and done by Anthony Y. H. Wong*, *Noelle E. Selin, Sebastian D. Eastham,* Christine Mounaïm-Rousselle, Yiqi Zhang, *Florian Allroggen* Climate and Air quality Impact of using ammonias as an Alternative Shipping Fuel, **accepted in Environmental research letters,**

**MIT, Cambridge,USA*

Impact of Using ammonia as shipping fuel

- **Methodolody :** To estimate the global NOx, NH3 and N2O emissions (Emission Factor) from converting **the entire fleet into NH3–powered ships**
  - as a function of engine technologies
    - Pure NH3 : very high NH3 emissions
    - NH3-H2 : more Nox emissions
  - H_2 increases combustion and thermodynamic efficiency
  - But extra energy to crack more H_2 into NH_3,
    - Lowers the overall efficiency as engine load decreases
  - N_2O EF and load curve = same between pure NH_3 and NH_3-H_2
  - Engine emissions also influenced by engine size and speed
    - lack of experimental data : 24% of EF penalty added to under 100m to account for the lower thermodynamic efficiency fror which is consistent with Imhoff et al. (2021)





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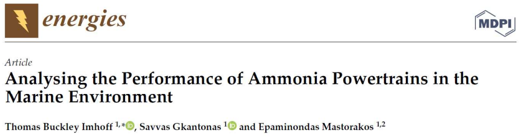

energies

MDPI

Article

Analysing the Performance of Ammonia Powertrains in the Marine Environment

Thomas Buckley Imhoff [1,*], Savvas Gkantonas [1] and Epaminondas Mastorakos [1,2]

Scenario

- 6 scenario

AIS-based shipping emission model (Zhang et al 2019) to estimate the global spatially-resolved pollutant and GHG emissions for every ship track in 2015 following the technology and policy assumptions of each scenario.

The emission model calculates ship emissions as a function of

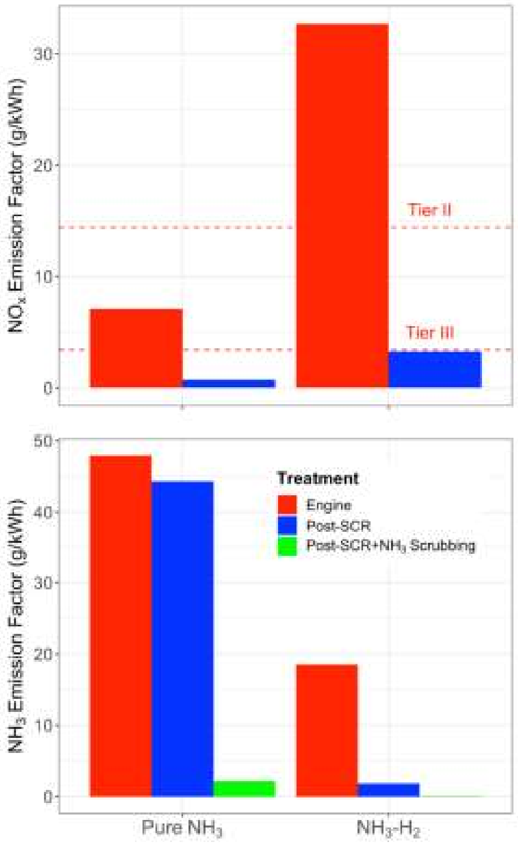
- engine power demand,
- ship specifications,
- emission factors (EF)
- activity time.

Scenario	Emission control inside current ECA	Emission control outside current ECA	Equivalent policy scenario
Baseline	Zhang et al. (2021) inventory for 2015 shipping with 0.5% sulphur cap		
Post-2020 NO_x baseline	Baseline with Tier III NO_x (post-2020) standard imposed globally		

TIER	boat build date	Limit Nox emission (g/kWh) n = engine speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	janv-00	17,0	$45 \cdot n^{(-0.2)}$ 11.3	9,8
II	janv-11	14,4	$44 \cdot n^{(-0.23)}$ 9	7,7
III	janv-16	3,4	$9 \cdot n(-0.2)$ 2.26	2,0

Scenario

- 6 scenario



Pure NH3 engine :

- Comply with Tier II NO$_x$ emission guideline even without emission control technology
- [NH$_3$] >> [NO$_x$], SCR cannot control NH$_3$
  - Need scrubbing to clean up the excess NH$_3$
  - Possible techs: acid scrubbing/ammonia oxidation catalyst ?

NH3+H2 :

- Higher NO$_x$ emissions, than Tier II
  - if SCR is 90% effective comply with Tier II (and more or less Tier III)
- [NH$_3$] ≈ [NO$_x$], assumption : SCR can control NH$_3$
  - Small quantity of NH3 : scrubbing small ?

Scenario

- 6 scenario

EMISSION CONTROL AERA

Scenario	Emission control inside current ECA	Emission control outside current ECA	Equivalent policy scenario
Baseline	Zhang et al. (2021) inventory for 2015 shipping with 0.5% sulphur cap		
Post-2020 NO_x baseline	Baseline with Tier III NO_x (post-2020) standard imposed globally		
$[NH_3–H_2]_{2020}$	SCR	SCR	2020 NO_x limit
$[NH_3–H_2]_{NH3\_ECA\_LIM}$	SCR+NH_3 scrubbing	SCR	Additional NH_3 limit in ECA
$[NH_3–H_2]_{GLOB\_LIM}$	SCR+NH_3 scrubbing	SCR+NH_3 scrubbing	Global NO_x and NH_3 limits
$[Pure\ NH_3]_{2020}$	SCR	None	2020 NO_x limit
$[Pure\ NH_3]_{NH3\_ECA\_LIM}$	SCR+NH_3 scrubbing	None	Additional NH_3 limit in ECA
$[Pure\ NH_3]_{GLOB\_LIM}$	SCR+NH_3 scrubbing	SCR+NH_3 scrubbing	Global NO_x and NH_3 limits

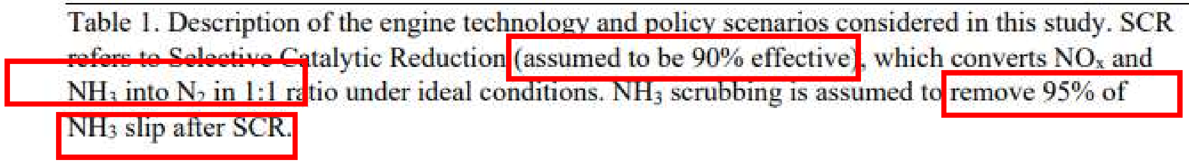
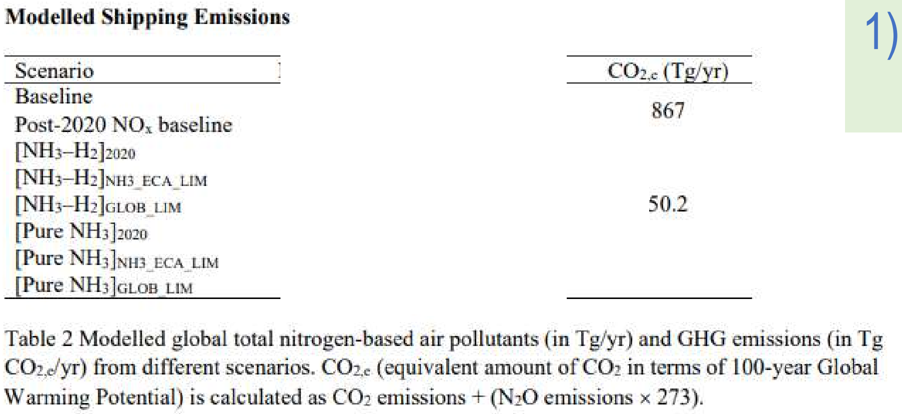


Table 1. Description of the engine technology and policy scenarios considered in this study. SCR refers to Selective Catalytic Reduction (assumed to be 90% effective), which converts NO_x and NH_3 into N_2 in 1:1 ratio under ideal conditions. NH_3 scrubbing is assumed to remove 95% of NH_3 slip after SCR.

Current (2020) NO_x limits : Tier III within emission control area (ECA, North American coast), Tier II elsewhere
Proposed Ammonia–focused policy scenarios:
“NH_3_ECA_LIM”:
NH_3 scrubbing required in Tier III NO_x regions
“GLOB_LIM”:
Both NH_3 scrubbing and Tier III NO_x regulations extend globally

CO2, GLOBAL WARMING IMPACT



Modelled Shipping Emissions

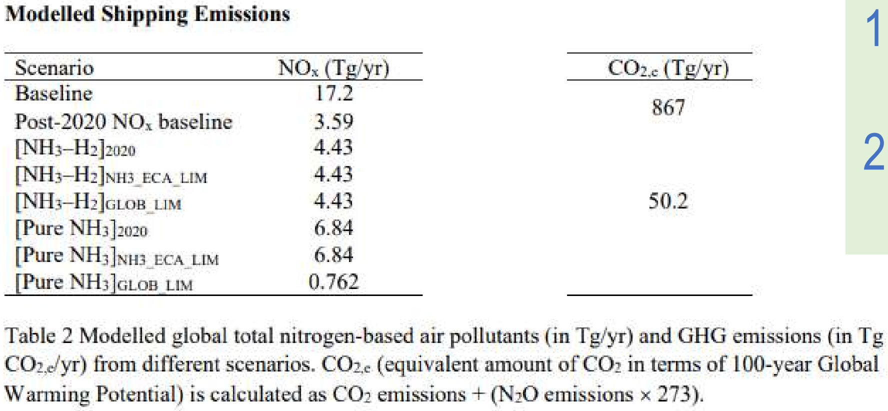
Scenario	$CO_{2,e}$ (Tg/yr)
Baseline	867
Post-2020 NO_x baseline	
$[NH_3–H_2]_{2020}$	50.2
$[NH_3–H_2]_{NH3\_ECA\_LIM}$	
$[NH_3–H_2]_{GLOB\_LIM}$	
$[Pure\ NH_3]_{2020}$	
$[Pure\ NH_3]_{NH3\_ECA\_LIM}$	
$[Pure\ NH_3]_{GLOB\_LIM}$	

Table 2 Modelled global total nitrogen-based air pollutants (in Tg/yr) and GHG emissions (in Tg $CO_{2,e}$/yr) from different scenarios. $CO_{2,e}$ (equivalent amount of CO_2 in terms of 100-year Global Warming Potential) is calculated as CO_2 emissions + (N_2O emissions × 273).

Tg/yr = the burden (Tg) divided by the mean global sink (Tg/yr) for a gas in steady state

1) Tailpipe CO2 from the ammonia-powered fleet = 5.8% of that from the current fossil-fuel powered fleet !

Map of NOx Emission

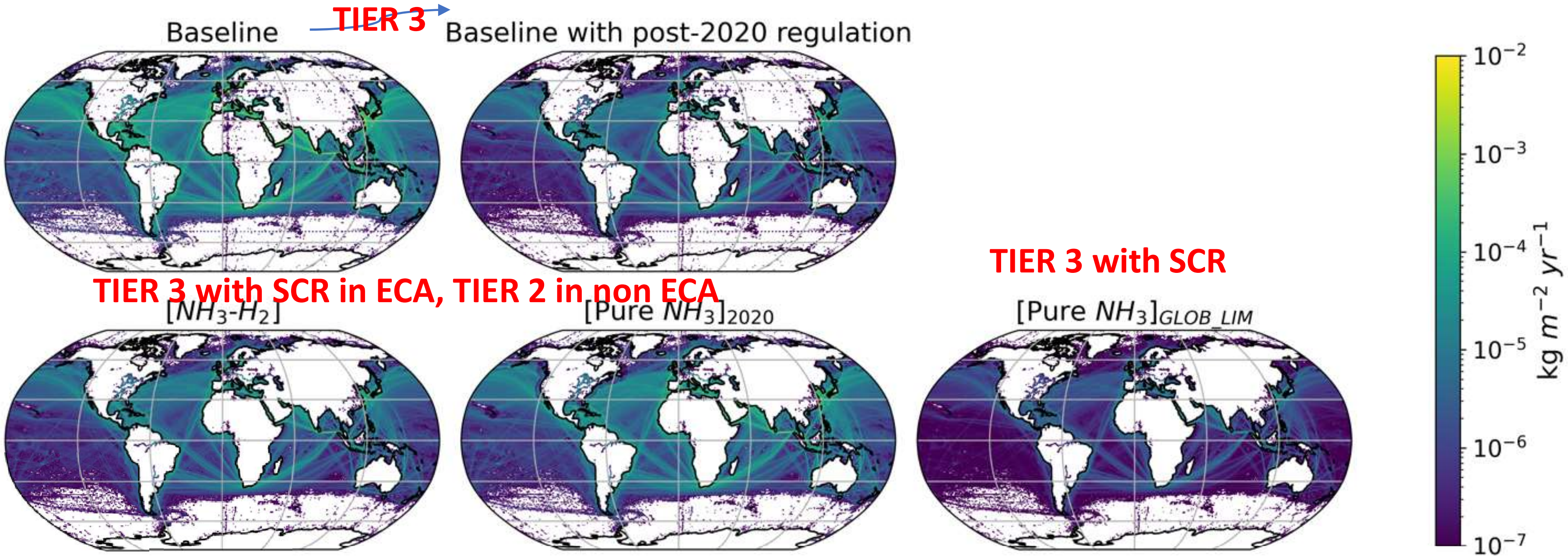


Modelled Shipping Emissions

Scenario	NO_x (Tg/yr)	$CO_{2,e}$ (Tg/yr)
Baseline	17.2	867
Post-2020 NO_x baseline	3.59	
$[NH_3–H_2]_{2020}$	4.43	50.2
$[NH_3–H_2]_{NH3\_ECA\_LIM}$	4.43	
$[NH_3–H_2]_{GLOB\_LIM}$	4.43	
$[Pure\ NH_3]_{2020}$	6.84	
$[Pure\ NH_3]_{NH3\_ECA\_LIM}$	6.84	
$[Pure\ NH_3]_{GLOB\_LIM}$	0.762	

Table 2 Modelled global total nitrogen-based air pollutants (in Tg/yr) and GHG emissions (in Tg $CO_{2,e}$/yr) from different scenarios. $CO_{2,e}$ (equivalent amount of CO_2 in terms of 100-year Global Warming Potential) is calculated as CO_2 emissions + (N_2O emissions × 273).

1) Tailpipe CO2 from the ammonia-powered fleet = 5.8% of that from the current fossil-fuel powered fleet !
2) lower NO_x level (currently 18 Tg/yr) from (newer) NH_3 ships improves O_3 air quality



Baseline

TIER 3

Baseline with post-2020 regulation

TIER 3 with SCR in ECA, TIER 2 in non ECA

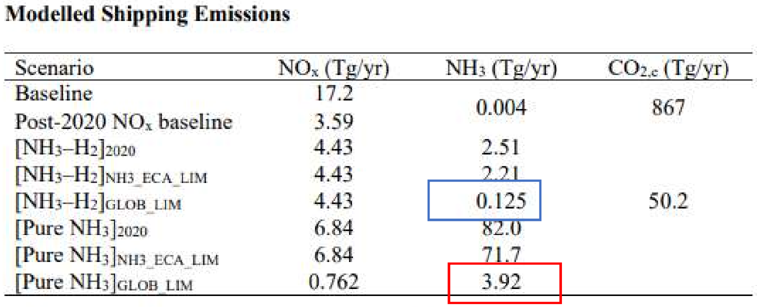
$[NH_3$-$H_2]$

$[Pure\ NH_3]_{2020}$

TIER 3 with SCR

$[Pure\ NH_3]_{GLOB\_LIM}$

MAP OF NH3

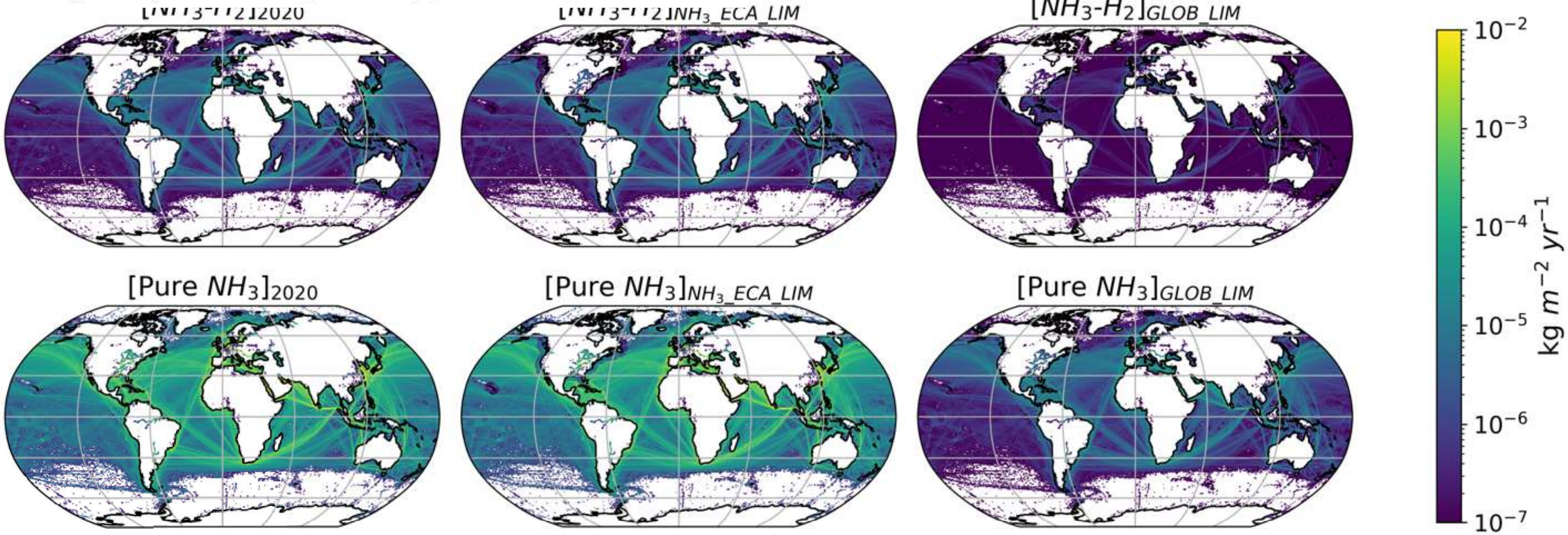


Modelled Shipping Emissions

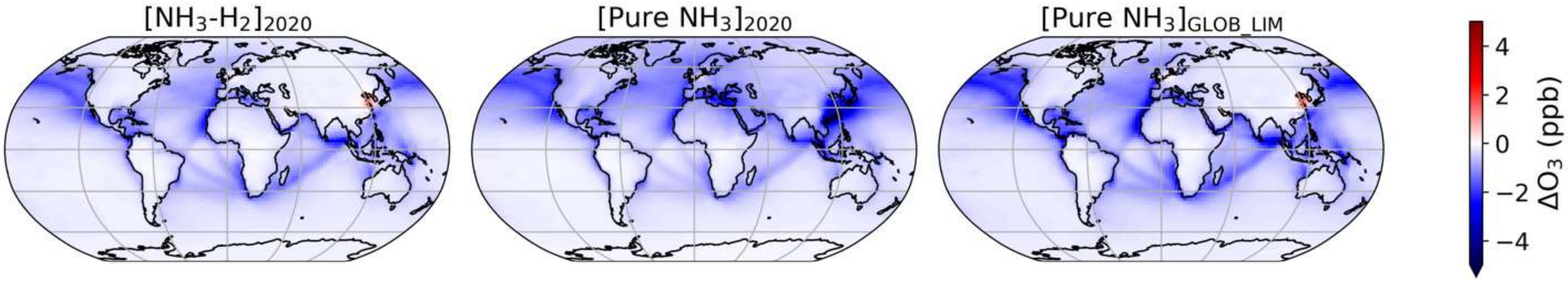
Scenario	NO_x (Tg/yr)	NH_3 (Tg/yr)	$CO_{2,e}$ (Tg/yr)
Baseline	17.2	0.004	867
Post-2020 NO_x baseline	3.59		
$[NH_3–H_2]_{2020}$	4.43	2.51	
$[NH_3–H_2]_{NH3\_ECA\_LIM}$	4.43	2.21	
$[NH_3–H_2]_{GLOB\_LIM}$	4.43	0.125	50.2
$[Pure\ NH_3]_{2020}$	6.84	82.0	
$[Pure\ NH_3]_{NH3\_ECA\_LIM}$	6.84	71.7	
$[Pure\ NH_3]_{GLOB\_LIM}$	0.762	3.92	

Table 2 Modelled global total nitrogen-based air pollutants (in Tg/yr) and GHG emissions (in Tg $CO_{2,e}$/yr) from different scenarios. $CO_{2,e}$ (equivalent amount of CO_2 in terms of 100-year Global Warming Potential) is calculated as CO_2 emissions + (N_2O emissions × 273).

1) Tailpipe CO2 from the ammonia-powered fleet = 5.8% of that from the current fossil-fuel powered fleet !
2) lower NO_x level (currently 18 Tg/yr) from (newer) NH_3 ships improves O_3 air quality
3) NH_3 emission kept very low globally, NH_3 ships can be very clean !



OZONE IMPACT



Changes in annual mean MDA8 O_3 concentration (ΔO_3, ppb) for different ammonia-powered ship scenarios

- NH3 does not damage the ozone layer. Ammonia is rated zero on Ozone Depletion Potential (ODP)
- O3 is simulated from a coupled154 O3-NOx-VOCs-CO-halogen-aerosols chemical mechanism
  - Lower NOX = lower depleting effect !
- sensitivity of O_3 response to assumptions in ship plume chemistry (mainly NO_x lifetime)
  - ➢ the lower NO_x emissions from ammonia-powered ships reduce over highly NO_x–saturated coasts near northern China, northern Europe, and Persian Gulf,
- local increases in surface O_3 are simulated especially under the scenarios with greater NOx reductions ([NH3-H2]2020 and [Pure NH3]GLOB_LIM)
- N_2O could have an effect on ozone layer :
  - ➢ Ozone-depletion potential (ODP) of N_2O = 0.017
    = a unit mass of N_2O destroys 0.017 times the amount of stratospheric ozone destroyed by releasing a unit mass of chlorofluorocarbon 11 (CFC-11) = too small effect !

PM2.5

1. NH_3 = precursor of ammonium salts(ammonium sulfate, ammonium nitrate and ammonium chloride)

$$NH_3(g) + HNO_3(g) \rightleftharpoons NH_4NO_3(s)$$

$$H_2SO_4\,(g) + 2NH_3(g) \longrightarrow (NH_4)_2SO_4(s)$$

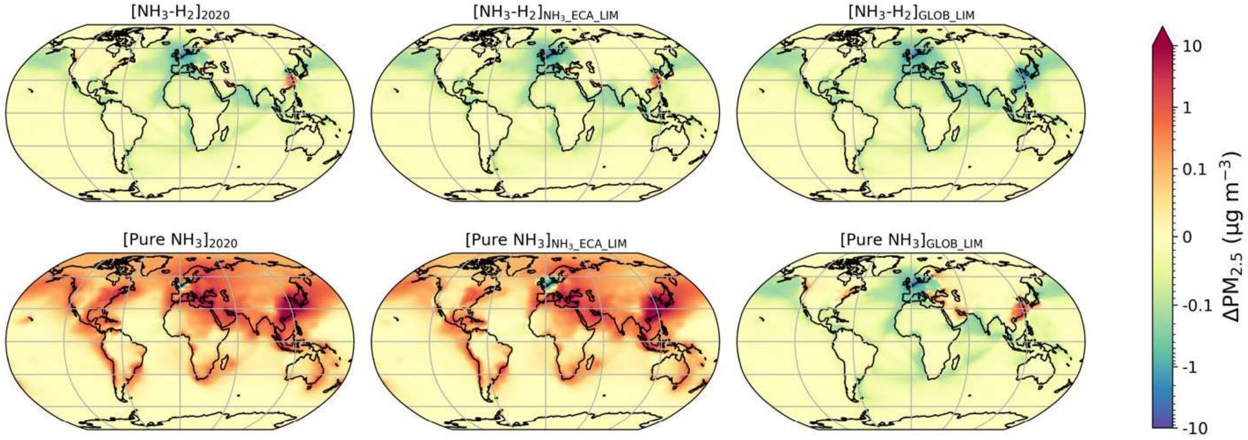
can represent 50 % of the mass of particulate matter ($PM_{2.5}$) (Behera et al., 2013) during peaks of spring air pollution in Europe !

- ➢ $PM_{2.5}$ with anions and acids in sea spray : extra sensitivity of $PM_{2.5}$ to NH_3 emissions !

2. Pure NH_3 engines : high NH_3 emission > NH_3-H_2 engines
   - ➢ higher $PM_{2.5}$ levels under the same policy scenarios !

➢ If NO_x and SO_x emissions well controlled with NH_3 .

PM2.5 reduced in global scenario



Conclusion

- Globally, switching to NH_3–H_2 engines avoids 33,100 (18900 to 47300, 95% confidence interval) mortalities annually,
    - while the unburnt NH_3 emissions (82.0 Tg NH_3 yr^{-1}) from pure NH_3 engines could lead to 595,100 additional mortalities annually under current legislation. ☹
- Requiring NH_3 scrubbing within current Emission Control Areas leads to smaller improvements in public health outcomes (38,000 avoided mortalities for NH_3–H_2 and 554,200 additional mortalities for pure NH_3 annually, respectively),
- While extending both Tier III NO_x standard + NH_3 scrubbing requirements globally leads to larger improvement in public health outcomes associated with a switch to ammonia-powered ships (79,100 and 21,100 avoided mortalities for NH_3–H_2 and pure NH_3 annually, respectively). ☺
- While switching to ammonia fuel would reduce tailpipe greenhouse gas emissions from shipping, stringent ammonia emission control is required to mitigate the potential adverse effects on air quality.
- Strong assumptions : no marine engine experiments, no data on scr efficiency,
- In reality : not all ships will be shifted to ammonia engine ☹