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Improved monitoring of shipping NO_2 with TROPOMI: decreasing NO_x emissions in European seas during the COVID-19 pandemic

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S1 NECA and SECA guidelines

Inside the so-called Nitrogen Emission Control Areas (NECAs), the amount of maximum allowed NO_x emitted per engine kWh output is regulated by IMO guidelines. The limit of allowed NO_x emissions per ship is based on the building year of a ship (Table 1). Globally, all new ships have to comply with IMO's Tier II NO_x standard. Since 1 January 2021 , the stricter Tier III standard applies to new ships operating within the European NECA, which is expected to reduce per ship emissions by 75% relative to Tier II. The new Tier III guidelines have been in place for American NECAs since 1 January 2016.
The Sulphur Emission Control Area (SECA) has been in place in Europe since May 2005. The amount of sulphur allowed in the ship's fuel is capped by MARPOL Annex VI at 4.5% globally, but with progressively tighter limits after that date. Within SECA zones, the amount of fuel sulphur content has been tightened from 1.5% in 2005 to 0.1% after 2015. On January 1st 2020, the amount of sulphur allowed outside SECAs has been sharply reduced (Table 2). Furthermore, the number of SECA areas is being expanded. For example, late 2021 it was decide to assign a Mediterranean SECA starting 1 January 2025.

S 1: NECA guidelines according to MARPOL Annex VI. These guidelines apply to newly built ships operating within an emission control area (ECA).

	Ships built after	Total weighted cycle emission limit $NO+NO_2$ (g/kWh) for engine speed n (revolutions per minute)		
		n = 130	n=1000	n = 2000
Tier I	1 January 2000	17.0	11.3	9.8
Tier II	1 January 2011	14.4	9.0	7.7
Tier III	1 January 2021	3.4	2.3	2.0

S 2: SECA guidelines according to MARPOL Annex VI. These guidelines apply to all ships.

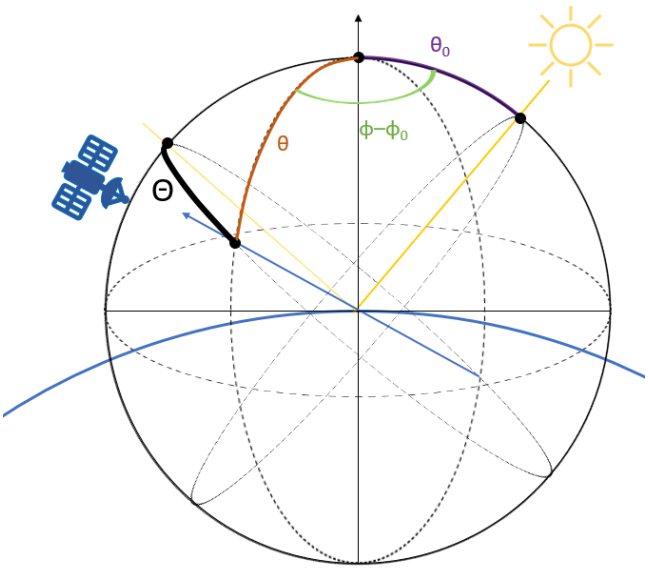
Date of enforcement	Maximum fuel sulphur content allowed outside SECA (in %)	Maximum fuel sulphur content allowed inside SECA (in %)
May 2005	4.50	1.50
July 2010	4.50	1.00
January 2012	3.50	1.00
January 2015	3.50	0.10
January 2020	0.50	0.10

S2 Scattering Angle

The scattering angle Θ can be calculated as

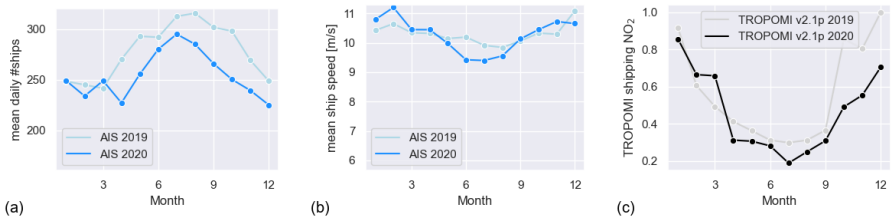
$$\Theta = \arccos\left[\cos\theta\cos\theta_0 - \sin\theta\sin\theta_0\cos\left(\phi_0 - \phi\right)\right] \tag{1}$$

where θ and θ_0 are the solar and viewing zenith angles and ϕ and ϕ_0 the solar and viewing azimuth angles, respectively.

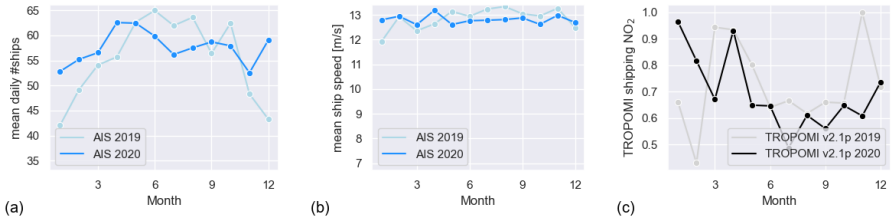


S 1: Sketch of satellite and solar geometry. The thick and thin yellow lines indicate the incoming and directly reflected solar light, respectively. The blue arrow indicates the light scattered in the direction of the satellite. The large blue arc is the Earth's surface. In green we show the difference of the viewing (satellite) and solar azimuth angle, orange and purple show the viewing and solar zenith angles, respectively. The thick black arc is the scattering angle, i.e the angle between the reflected sunlight and the viewing direction.

S3 COVID



S 2: Left: Monthly mean of daily number of ships passing the Strait of Gibraltar in 2019 (light blue) and 2020 (darker blue) as defined in Section 2.4 for the main text. Center: Same but with average ship speed. Right: Monthly shipping NO_2 for 2019 (grey) and 2020 (black) from TROPOMI in arbitrary units for the area shown as purple rectangles in Fig. 1 (c) of the main text.



S 3: Left: Monthly mean of daily number of ships passing the Mediterranean shipping lane in 2019 (light blue) and 2020 (darker blue) as defined in Section 2.4 for the main text. Center: Same but with average ship speed. Right: Monthly shipping NO_2 for 2019 (grey) and 2020 (black) from TROPOMI in arbitrary units for the area shown as purple rectangles in Fig. 1 (c) of the main text.

S4 Top-down emission uncertainties

For Figures 10 and F1 (e-f) we considered the following sources of uncertainty: $\sigma_{area} = 5\%$, $\sigma_{meteo} = 20\%$ and $\sigma_{\beta} = 0.15$.
To determine σ_{area} we performed a sensitivity analysis, making the cross sections used to calculate the TROPOMI shipping NO_2 20% smaller. As the difference in the relative changes between this and the default calculation was 5%, we use $\sigma_{area} = 5\%$ as the uncertainty of TROPOMI shipping NO_2.
σ_{meteo} is the Root Mean Square of the differences between Vertical Column Densities with the same emission strength but different meteorology on a monthly average between 2019 and 2020. This is estimated to be 16% for Gibraltar and 11% for the Eastern Mediterranean. For this we used monthly mean NO_2 columns in the CAMS European Air Quality Forecasts ensemble mean ([METEO FRANCE et al., 2020]) for 2019 and 2020 for the areas of study. This forecast represents a business-as-usual scenario where the meteorological conditions are taken into account, but emissions are not corrected for possible reductions due to COVID-19.
As we take β values for 2006 for changes between 2019 and 2020, we estimate a temporal variability in β from the 2005-2006 difference found in [Vinken et al., 2014] and combine this with the standard deviation of all β values from [Verstraeten et al., 2015] in the are of study as monthly $\sigma_{\beta} = 0.15$.
Other sources of uncertainty are considered to be of minor importance. For example, while single TROPOMI columns have large (random and systematic) uncertainties these cancel out largely when taking the relative differences between 2 years. The large spatial and temporal sampling smoothens the random error while the systematic errors cancel out largely in the relative changes studied here.

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