Imperial College London

THE ROYAL SOCIETY

Matching ship emissions to cloud perturbations

Edward Gryspeerdt[1], Tristan Smith[2], Eoin O'Keeffe[3], Matthew Christensen[4] and Fraser Goldsworth[1,4]

[1]Space and Atmospheric Physics Group, Imperial College London [2]UCL Energy Institute
[3]University Maritime Advisory Service, [4]University of Oxford

4th May 2020 Contact: e.gryspeerdt@imperial.ac.uk

Image: Sentinel-1 SAR image of ships in the English Channel.

Shiptracks

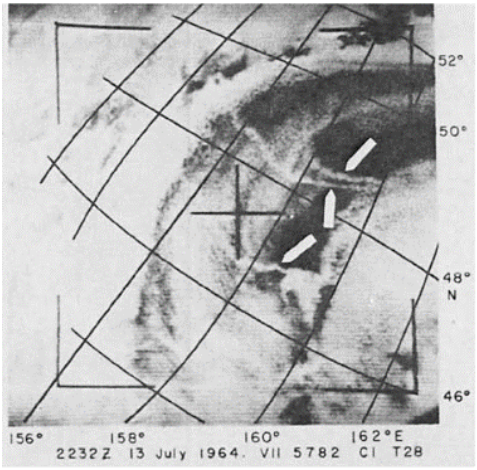
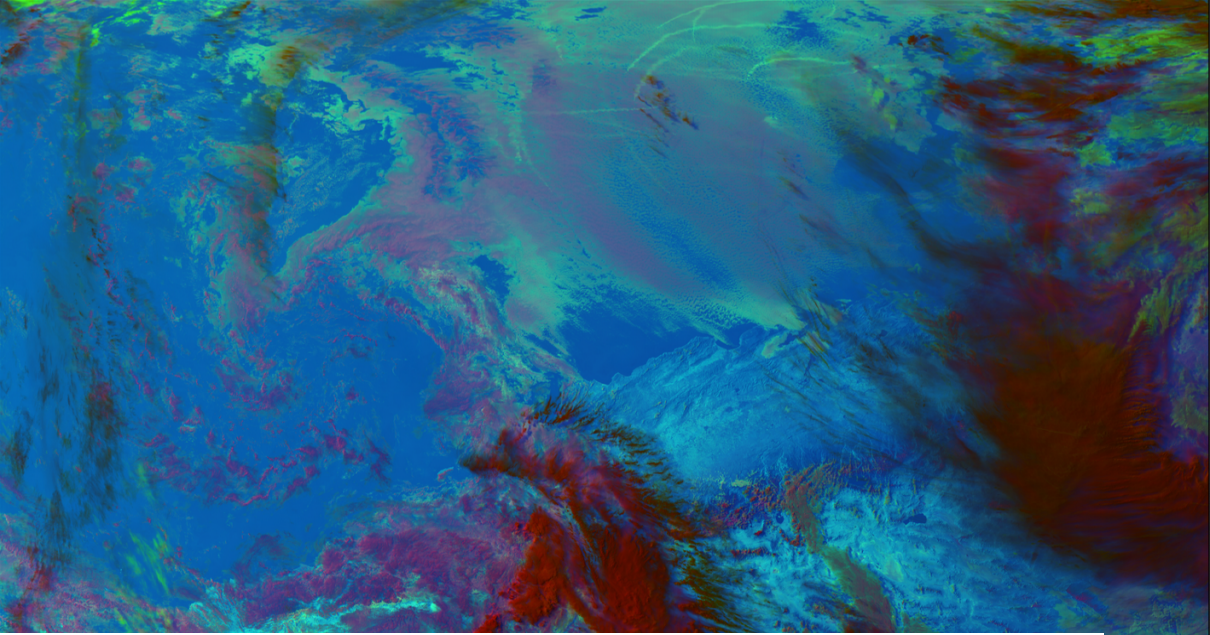


FIG. 1. Anomalous cloud lines southeast of the Kuril Islands. Case 11.

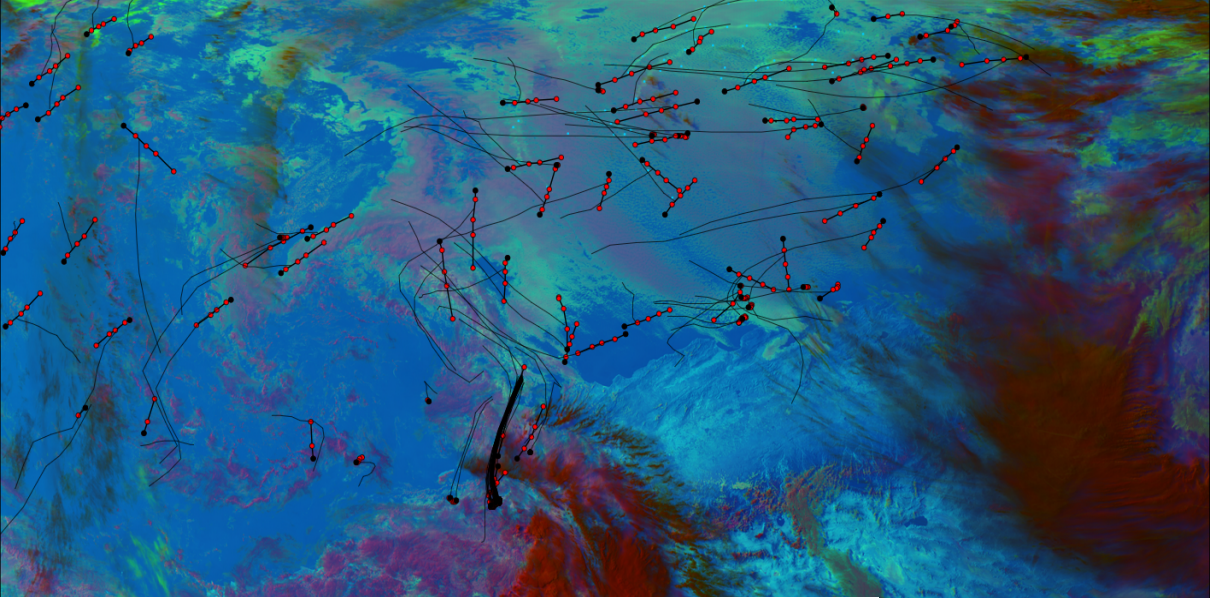
- Linear cloud perturbations following ships
- Considered good evidence of an aerosol impact on clouds
- Still a number of factors that are unclear
  - Which clouds are susceptible to ship emissions?
  - How do shiptrack properties depends on the ship emissions?

Conover, JAS, 1966

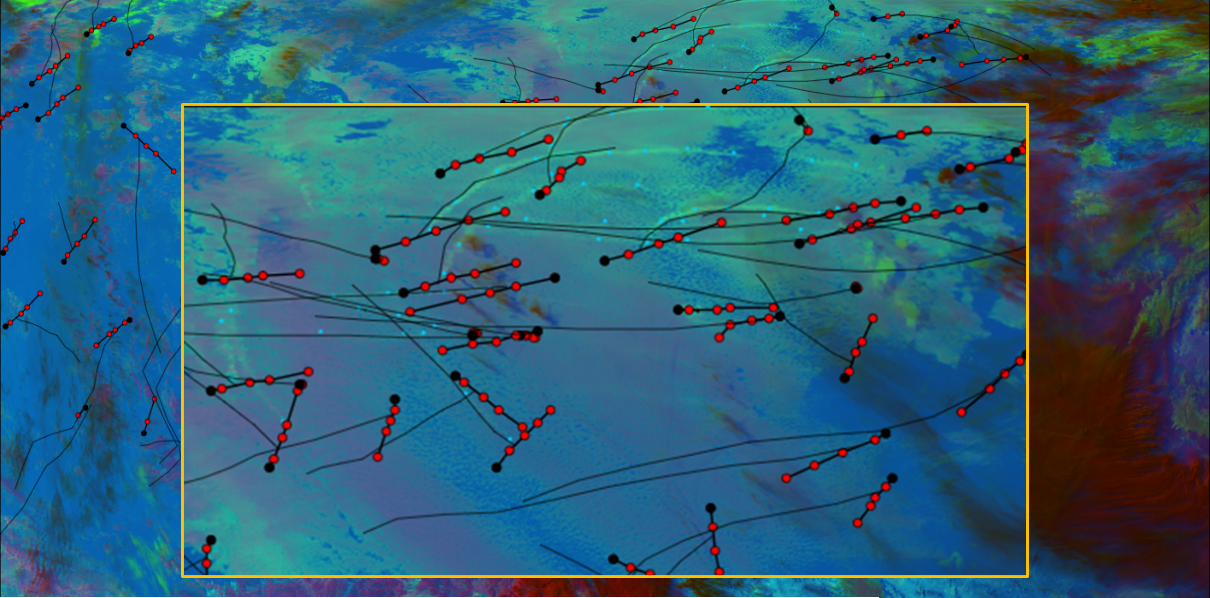
California, North to the right



Day microphysics image of same region. Note shiptracks as green lines near the top

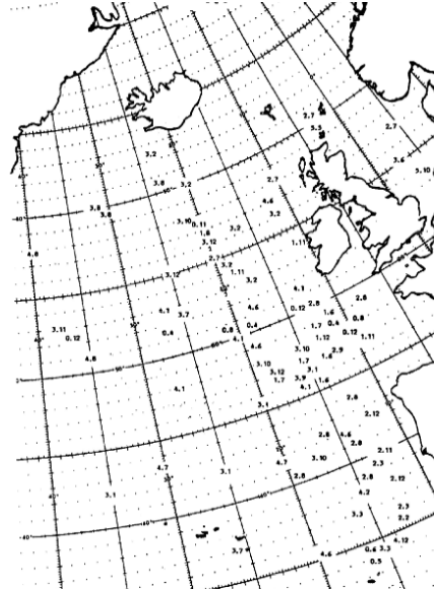


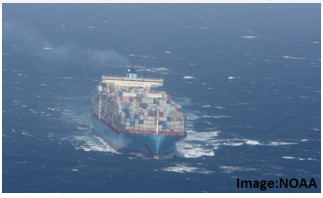
Ship locations in black, red dot are previous ship locations
Thin line is estimated ship emissions locations (using ERA5 winds)



Ship locations in black, red dot are previous ship locations
Thin line is estimated ship emissions locations (using ERA5 winds)

Where do they occur?

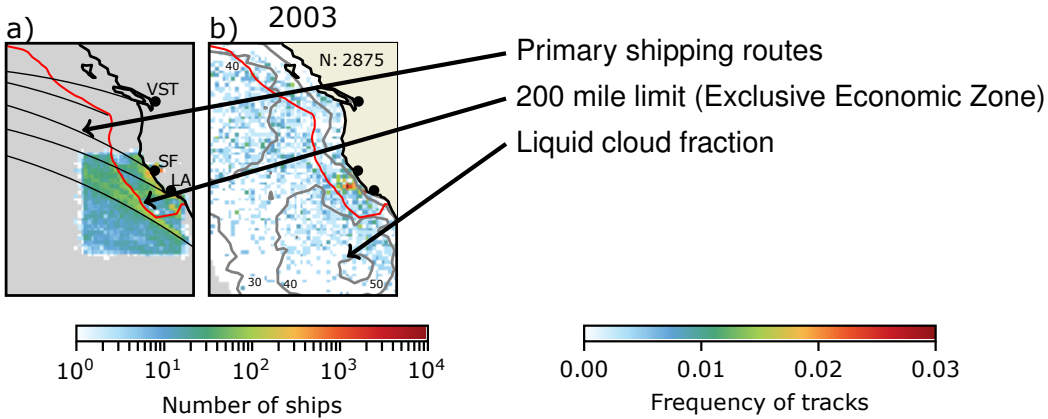




One of the earliest climatologies of shiptracks comes from Scorer, Atm. Env. (1987)

In a region around the UK, he found only 47, or 6.6 cases a year (Plot to the left)

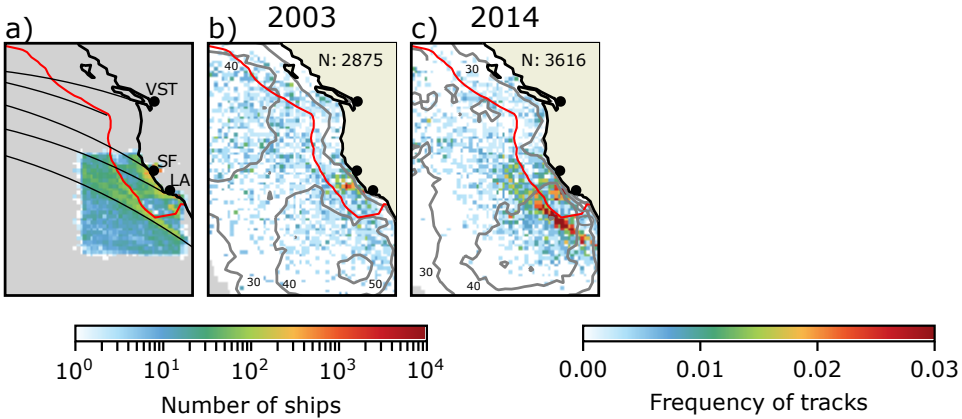
Shiptrack occurrence



We identified over 17,000 shiptracks by hand in several years of MODIS data, looking at California and Europe.

Gryspeerdt et al., GRL, 2019

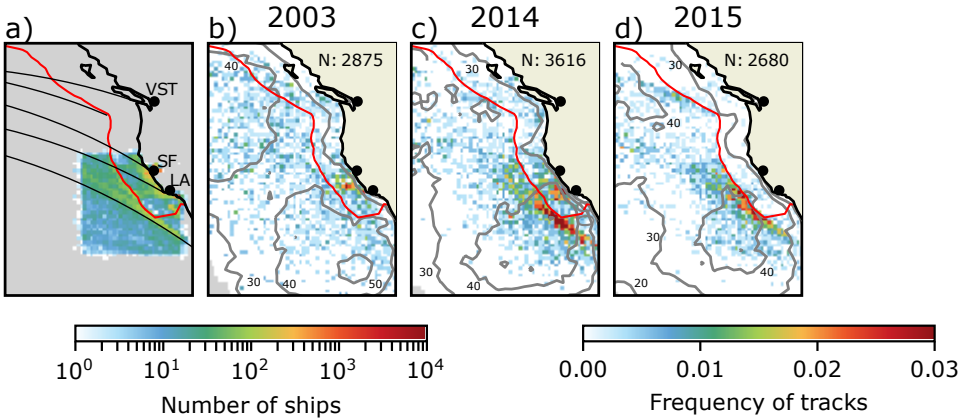
Shiptrack occurrence



We identified over 17,000 shiptracks by hand in several years of MODIS data, looking at California and Europe.

Gryspeerdt et al., GRL, 2019

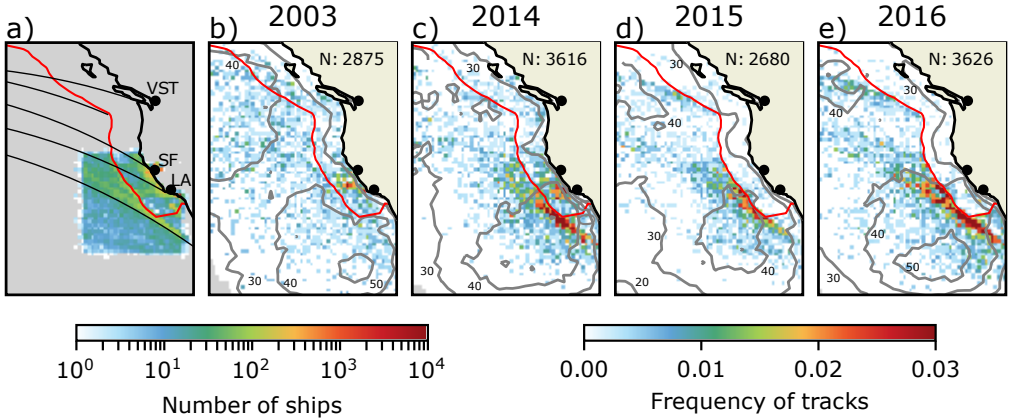
Shiptrack occurrence



We identified over 17,000 shiptracks by hand in several years of MODIS data, looking at California and Europe. Note the big change in 2015

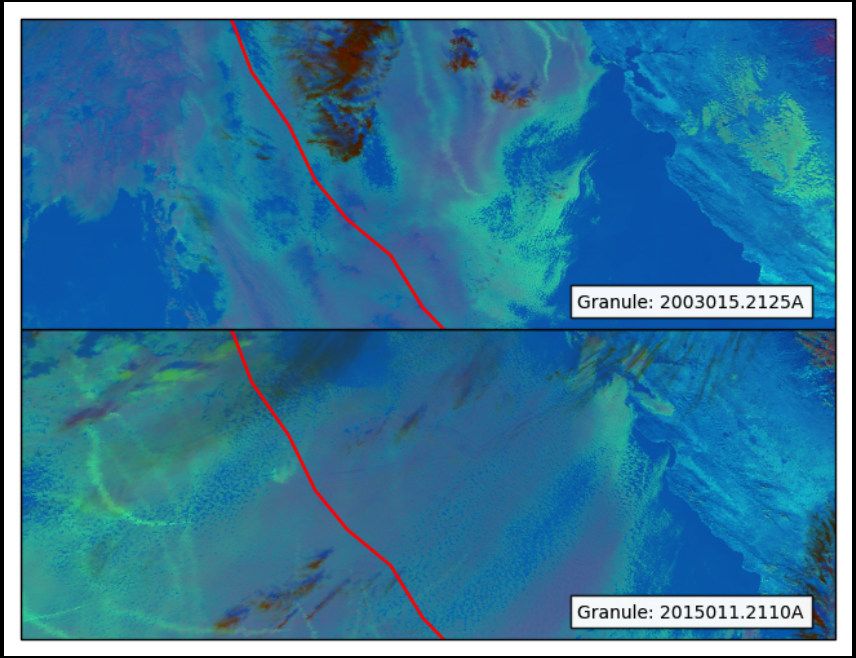
Gryspeerdt et al., GRL, 2019

Shiptrack occurrence



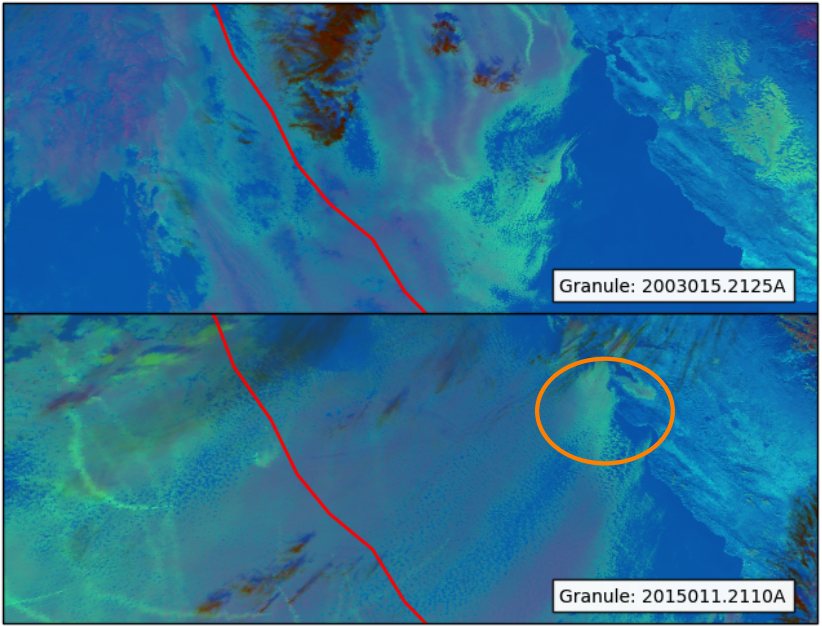
We identified over 17,000 shiptracks by hand in several years of MODIS data, looking at California and Europe. Note the big change in 2015

Gryspeerdt et al., GRL, 2019



This change is even visible comparing images from 2003 and 2015.

Gryspeerdt et al., GRL, 2019

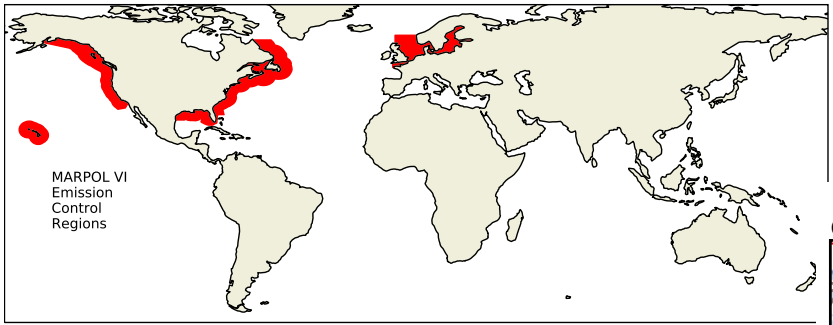


Gryspeerdt et al., GRL, 2019

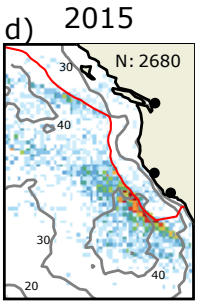
This change is even visible comparing images from 2003 and 2015.

Even though there are no coastal shiptracks in 2015, the cloud deck is still susceptible - San Francisco is making a track!

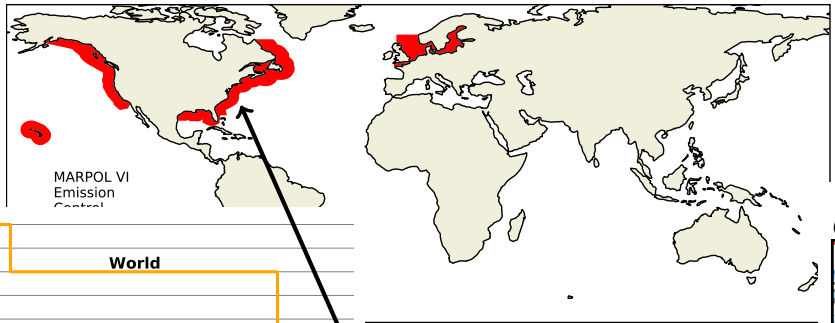
Emission controls

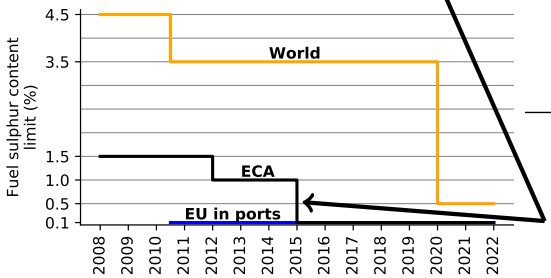


The disappearance of coastal shiptracks is due to the introduction of emission controls in 2015

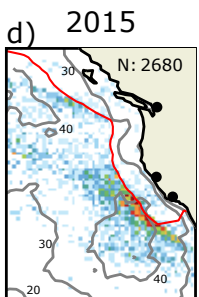


Emission controls

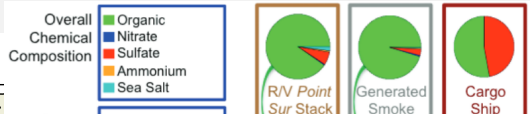




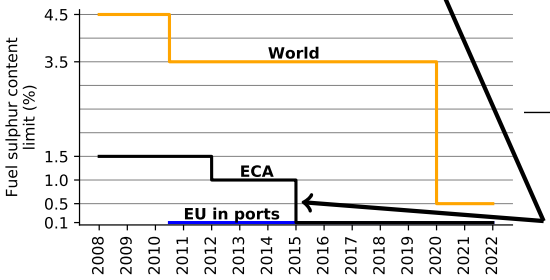
Introduction of controls in ship fuel sulphur content lines up with disappearance of shiptracks



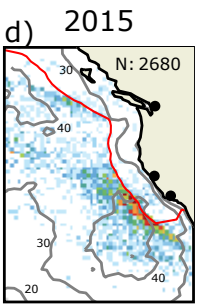
Emission controls



Highlights importance of sulphate despite dominance of organics in ship effluent

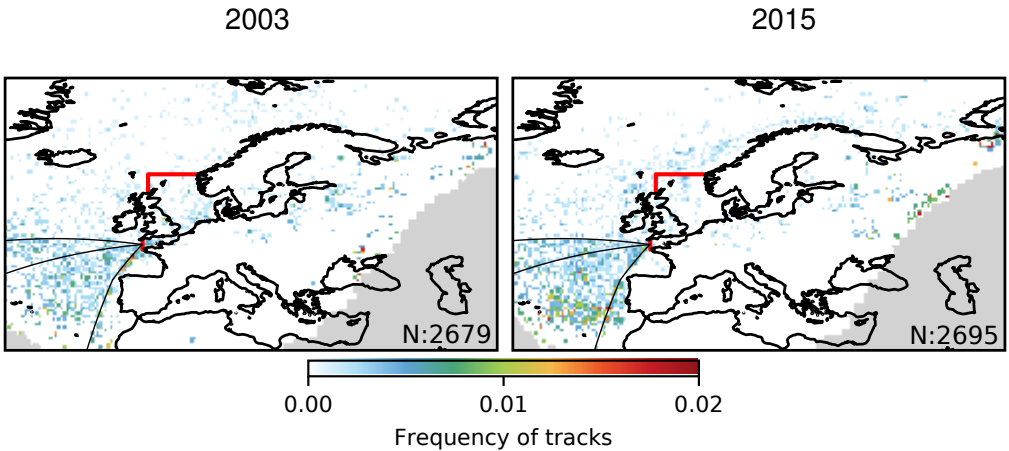


Introduction of controls in ship fuel sulphur content lines up with disappearance of shiptracks



Russell et al., BAMS, 2013

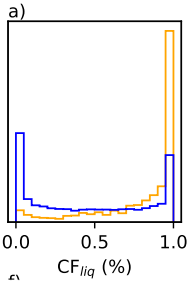
European tracks



Similar changes are visible around Europe, although they are less clear as the European emission control region has a higher background level of aerosol.

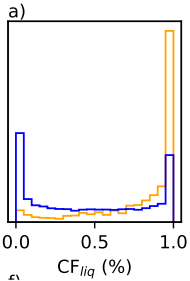
Gryspeerdt et al., GRL, 2019

Shiptrack formation conditions



Track-forming All ships ECA Non-ECA

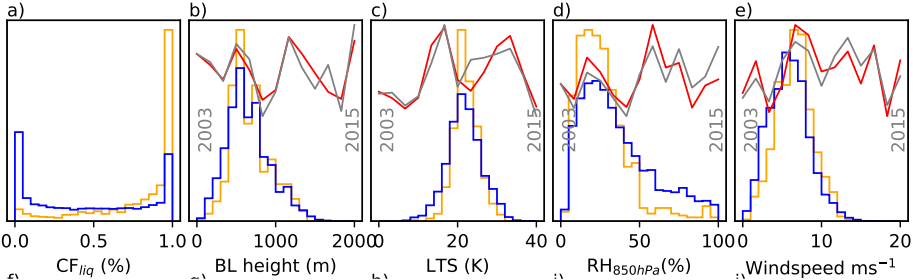
Shiptrack formation conditions



- Shiptracks prefer high cloud fractions
- All other plots are for liquid CF>90%

Track-forming All ships ECA Non-ECA

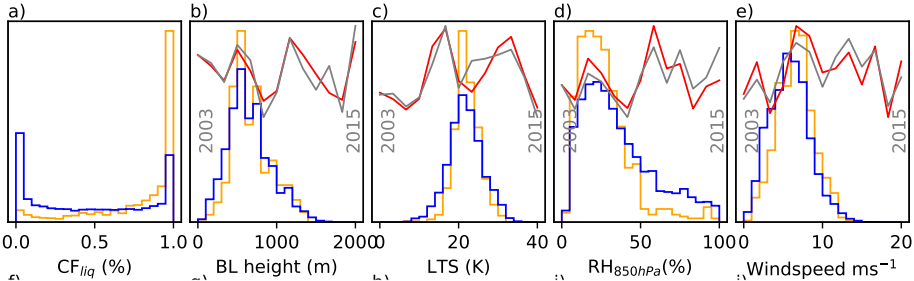
Shiptrack formation conditions



- Many properties have little effect on shiptrack formation
  - (If liquid CF $>$ 90%)

Track-forming All ships ECA Non-ECA

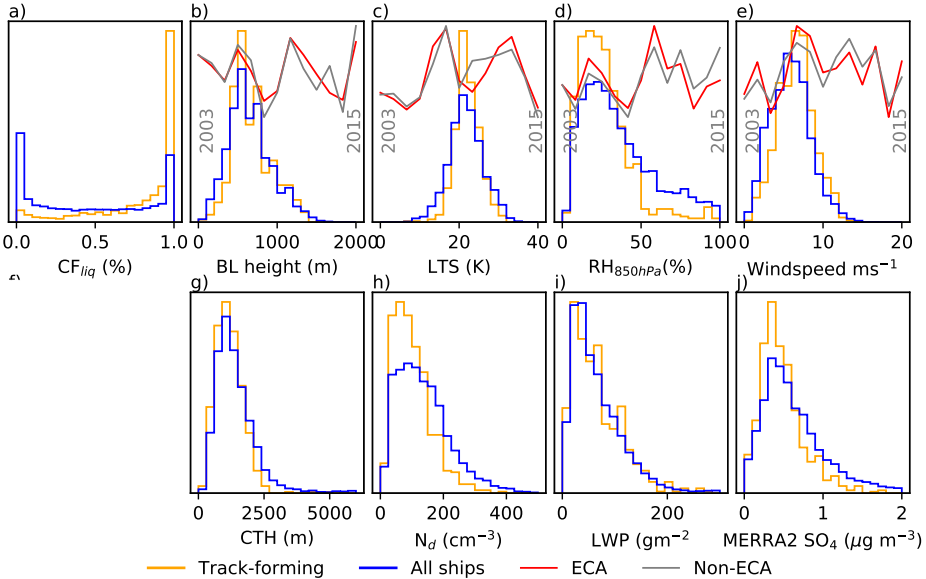
Shiptrack formation conditions



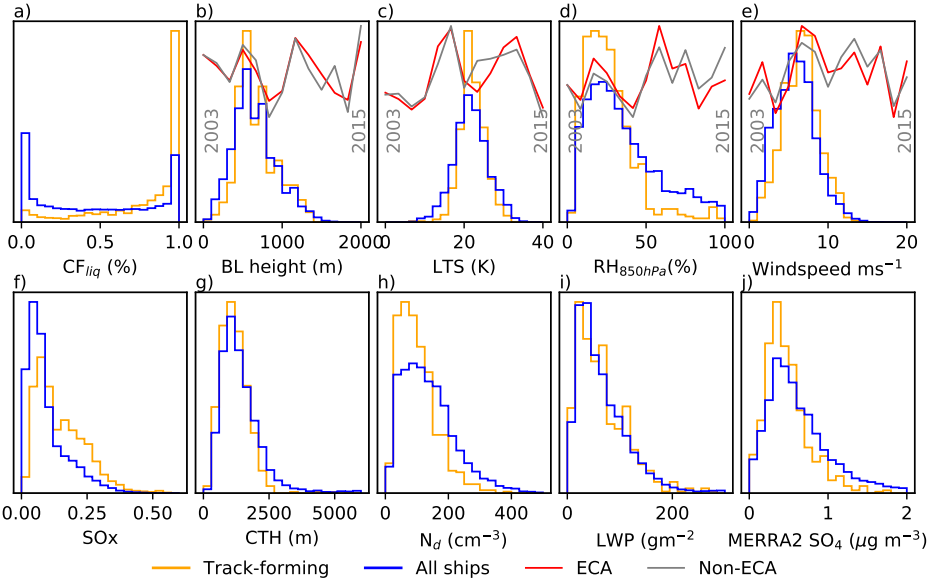
- Many properties have little effect on shiptrack formation
  - (If liquid CF $>$ 90%)
- Tracks are more common at low cloud-top RH
  - Perhaps due to increased in-cloud updraught?

Track-forming All ships ECA Non-ECA

Shiptrack formation conditions



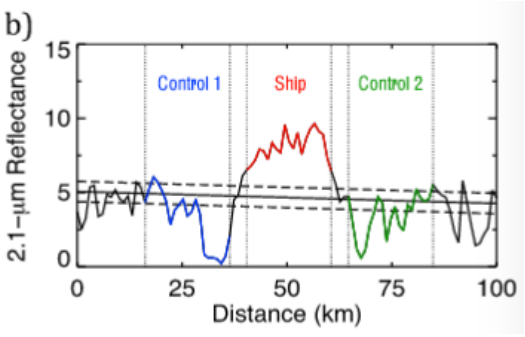
Shiptrack formation conditions



Shiptrack properties

- Ship SO_x emissions and background N_d are important for shiptrack formation
- Shiptrack occurrence is a binary measure, so hides a number of factors
- What about shiptrack properties?

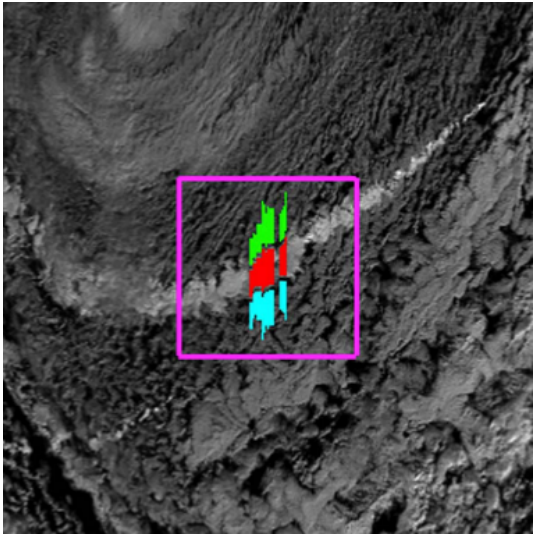
Identifying track properties



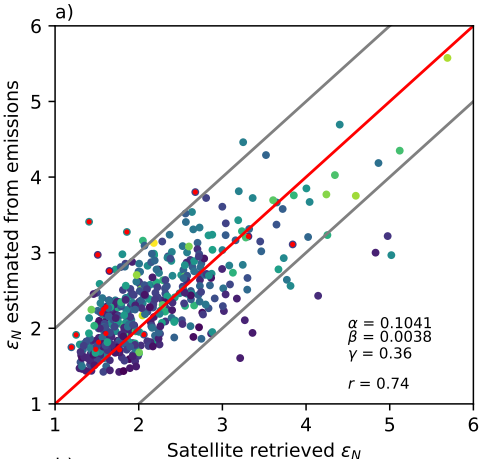
Follow algorithm from Christensen et al, 2011

- Polluted pixels are those significantly larger than background (N_{pol})
- Keep pixels 20km either side of track as control (N_{cln})

Christensen et al, JGR, 2011



Estimating track strength



Colors are A_E, red points are in ECA

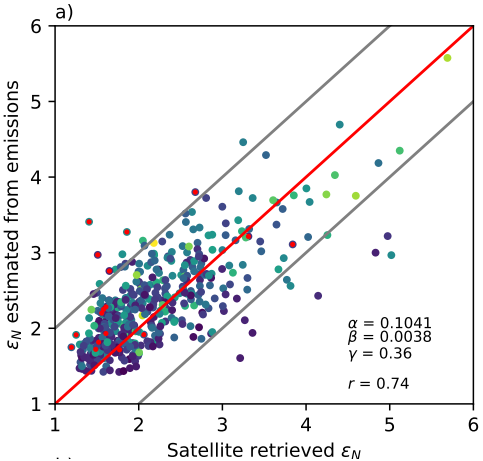
Gryspeerdt et al., GRL, 2019

- Assuming the ship emissions dominate gives a functional form for the N_d enhancement ϵ_N of

$$\epsilon_N = \frac{N_{pol}}{N_{cln}} = \frac{A_E^{\gamma}}{\alpha + \beta N_{cln}} + 1 \qquad (1)$$

(Where A_E is the ship SO_x emissions)

Estimating track strength



Colors are A_E, red points are in ECA

Gryspeerdt et al., GRL, 2019

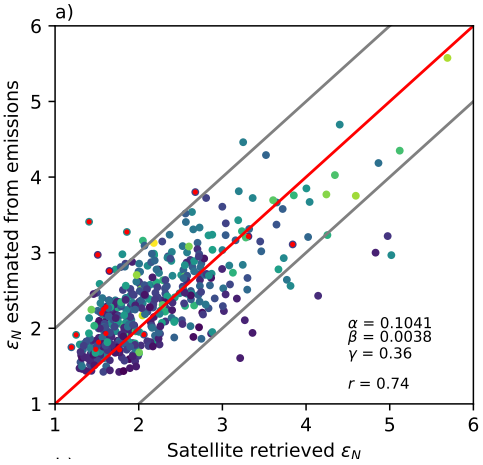
- Assuming the ship emissions dominate gives a functional form for the N_d enhancement ϵ_N of

$$\epsilon_N = \frac{N_{pol}}{N_{cln}} = \frac{A_E^{\gamma}}{\alpha + \beta N_{cln}} + 1 \qquad (1)$$

(Where A_E is the ship SO_x emissions)

- 35% of the variance in ϵ_N is explained by N_{cln}

Estimating track strength



Colors are A_E, red points are in ECA

Gryspeerdt et al., GRL, 2019

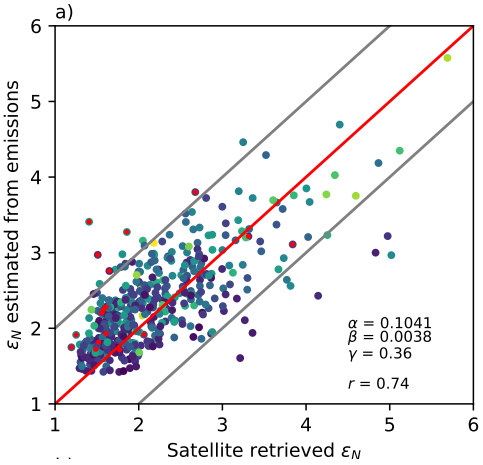
- Assuming the ship emissions dominate gives a functional form for the N_d enhancement ϵ_N of

$$\epsilon_N = \frac{N_{pol}}{N_{cln}} = \frac{A_E^{\gamma}}{\alpha + \beta N_{cln}} + 1 \qquad (1)$$

(Where A_E is the ship SO_x emissions)

- 35% of the variance in ϵ_N is explained by N_{cln}
- Only 15% by A_E

Estimating track strength



Colors are A_E, red points are in ECA

Gryspeerdt et al., GRL, 2019

- Assuming the ship emissions dominate gives a functional form for the N_d enhancement ϵ_N of

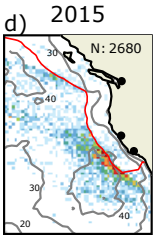
$$\epsilon_N = \frac{N_{pol}}{N_{cln}} = \frac{A_E^{\gamma}}{\alpha + \beta N_{cln}} + 1 \qquad (1)$$

(Where A_E is the ship SO_x emissions)

- 35% of the variance in ϵ_N is explained by N_{cln}
- Only 15% by A_E
  - ϵ_N is not a good measure of A_E

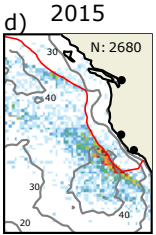
Summary

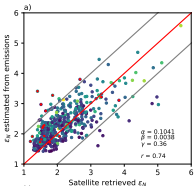
- Shiptrack occurrence is related to ship SO_x emissions
  - Big reduction in shiptracks with introduction of fuel sulphur content controls
  - Meteorological controls also important (e.g. RH)



Summary

- Shiptrack occurrence is related to ship SO_x emissions
  - Big reduction in shiptracks with introduction of fuel sulphur content controls
  - Meteorological controls also important (e.g. RH)
- The N_d enhancement in the shiptrack can be estimated with:
  - Background N_d
  - Ship SO_x emissions (secondary factor)





Summary

- Shiptrack occurrence is related to ship SO_x emissions
  - Big reduction in shiptracks with introduction of fuel sulphur content controls
  - Meteorological controls also important (e.g. RH)
- The N_d enhancement in the shiptrack can be estimated with:
  - Background N_d
  - Ship SO_x emissions (secondary factor)
- More details are in Gryspeerdt et al, GRL, 2019
  - "The impact of ship emissions recorded by cloud properties"
  - Also includes an estimate of non-visible shiptrack occurrence
  - And a potential method for retrieving ship sulphate emissions from space
  - `http://dx.doi.org/10.1029/2019GL084700`