Matching ship emissions to cloud perturbations

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

- 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 depend on the ship emissions?

Conover, JAS, 1966

Fig. 1. Anomalous cloud lines southeast of the Kuril Islands. Case 11.
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)
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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)
We identified over 17,000 shiptracks by hand in several years of MODIS data, looking at California and Europe.

Gryspeerdt et al., GRL, 2019
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Even though there are no coastal shiptracks in 2015, the cloud deck is still susceptible - San Francisco is making a track!
The disappearance of coastal shiptracks is due to the introduction of emission controls in 2015.
Introduction of controls in ship fuel sulphur content lines up with disappearance of shiptracks.
Emission controls

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

Highlights importance of sulphate despite dominance of organics in ship effluent

Russell et al., BAMS, 2013
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

![Graph showing shiptrack formation conditions](image)

- **Shiptrack formation conditions**
- **a)**
  - Black line: Track-forming
  - Orange line: All ships
  - Blue line: ECA
  - Gray line: Non-ECA

- **Blowing height (m)**
  - 2003 to 2015
  - 0 to 20

- **Low temperature (K)**
  - 2003 to 2015
  - 0 to 50

- **Relative humidity (%)**
  - 2003 to 2015
  - 0 to 100

- **Wind speed (ms)**
  - 2003 to 2015
  - 0 to 20

- **SOx (CTH, m)**
  - 0 to 2500

- **Nd (cm³)**
  - 0 to 200

- **LWP (gm²)**
  - 0 to 200

- **MERRA2 SO4 (gm³)**
  - 0 to 1

- **Track-forming All ships ECA Non-ECA**
Shiptrack formation conditions

- Shiptracks prefer high cloud fractions
- All other plots are for liquid CF>90%
Many properties have little effect on shiptrack formation

- (If liquid CF > 90%)
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Tracks are more common at low cloud-top RH
- Perhaps due to increased in-cloud updraught?
Shiptrack formation conditions

- **a)** $CF_{liq}$ (%)
- **b)** BL height (m)
- **c)** LTS (K)
- **d)** RH850hPa (%)
- **e)** Windspeed ms$^{-1}$
- **f)** CTH (m)
- **g)** $N_d$ (cm$^{-3}$)
- **h)** LWP (gm$^{-2}$)
- **i)** MERRA2 SO$_4$ (gm$^{-3}$)

Categories:
- **Track-forming**
- **All ships**
- **ECA**
- **Non-ECA**
Shiptrack formation conditions

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  - **f)** SOx
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  - **j)** MERRA2 SO$_4$ (gm$^3$)

  - **Track-forming**
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  - **ECA**
  - **Non-ECA**
Ship SO\textsubscript{x} emissions and background N\textsubscript{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
Assuming the ship emissions dominate gives a functional form for the $N_d$ enhancement $\epsilon_N$ of

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

(Where $A_E$ is the ship SOx emissions)
Estimating track strength

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(Where $A_E$ is the ship SOx emissions)

- 35% of the variance in $\epsilon_N$ is explained by $N_{cln}$

Colors are $A_E$, red points are in ECA

Gryspeerdt et al., GRL, 2019
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- 35% of the variance in \( \epsilon_N \) is explained by \( N_{cln} \)
- Only 15% by \( A_E \)
  - \( \epsilon_N \) is not a good measure of \( A_E \)

Colors are \( A_E \), red points are in ECA

Gryspeerdt et al., GRL, 2019
Summary

- Shiptrack occurrence is related to ship $\text{SO}_x$ emissions
  - Big reduction in shiptracks with introduction of fuel sulphur content controls
  - Meteorological controls also important (e.g. RH)

![Map of shiptrack occurrence in different years](image.png)

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of ships</th>
<th>Frequency of tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>N: 2875</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>N: 3616</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>N: 2680</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>N: 3626</td>
<td></td>
</tr>
</tbody>
</table>

Parametrised $\text{SO}_x$ emissions

- Retrieved $\text{SO}_x$ emissions
  - $r = 0.74$
  - $r(N_d < 50) = 0.64$

- Estimated from emissions
  - $r = 0.38$

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The N\textsubscript{d} enhancement in the shiptrack can be estimated with:

- Background N\textsubscript{d}
- Ship SO\textsubscript{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
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