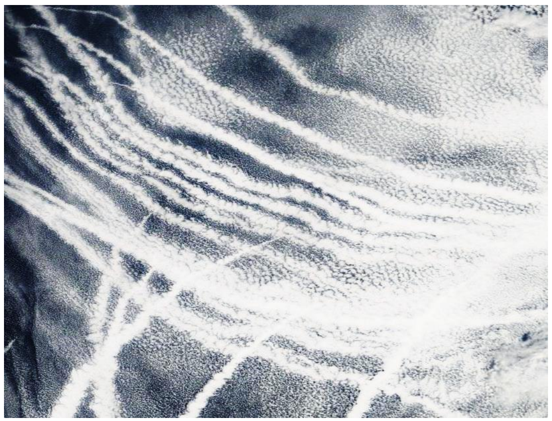
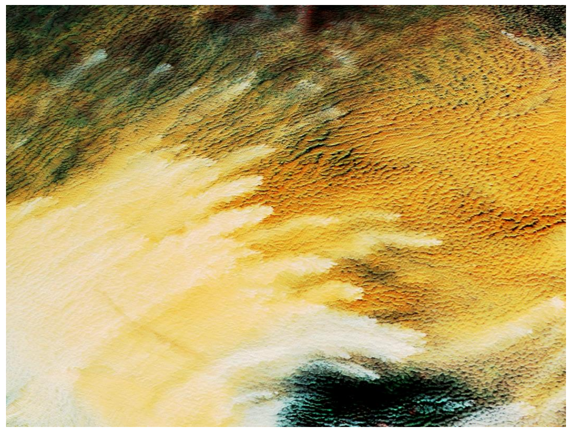
# Real-world laboratories for studying anthropogenic aerosol impacts on clouds and Earth's climate





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# Real-world laboratories beyond ship tracks

**Type 1**

Ship-track-like linear cloud perturbations. Possible aerosol sources inducing such tracks include volcanoes, factories, towns, fires. 10 to few tens of km wide perturbations.

**Type 2**

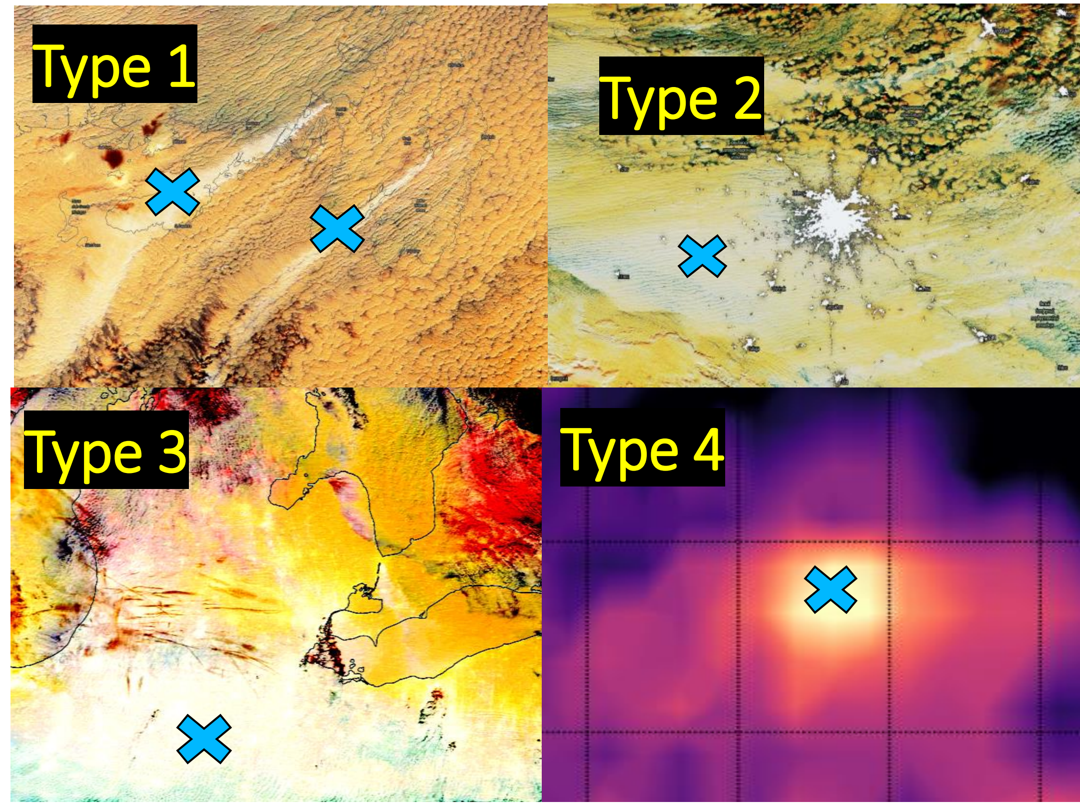
100 to few hundred km wide cloud perturbations. Possible aerosol sources inducing such tracks include large cities, large wildfire outbreaks.

**Type 3**

Thousand(s) km wide cloud perturbations. Possible aerosol sources inducing such tracks are large industrial regions (like SE Asia, Eastern US etc)

**Type 4**

Increases in cloud droplet number at air pollution hot spots are recorded in long-term average of satellite-derived cloud properties.




Blue crosses mark polluted cloud areas.

Clouds polluted by aerosols in these images are brighter compared to nearby unpolluted clouds due to increased cloud droplet number.

# What can polluted cloud tracks tell us?

1) Local CDNC response

$\Delta \ln(CDNC) / \Delta \ln(SO_4)$ Type 4

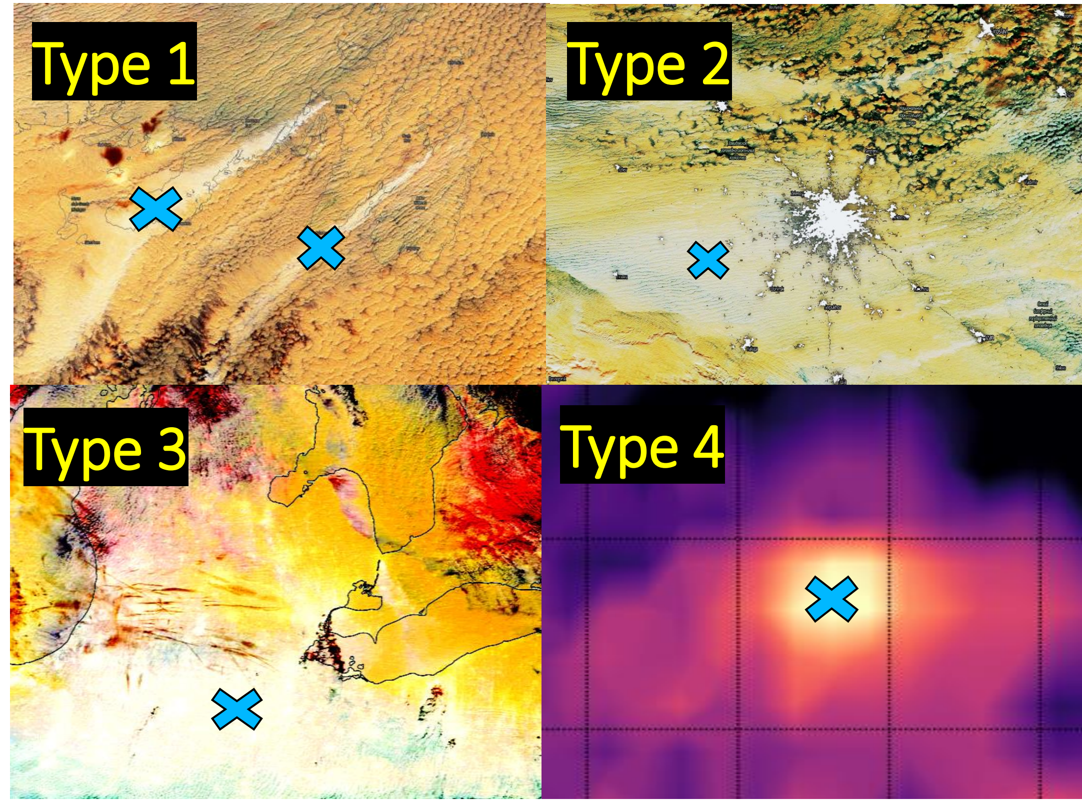
2) Local LWP, CF response

$\Delta \ln(LWP) / \Delta \ln(CDNC)$

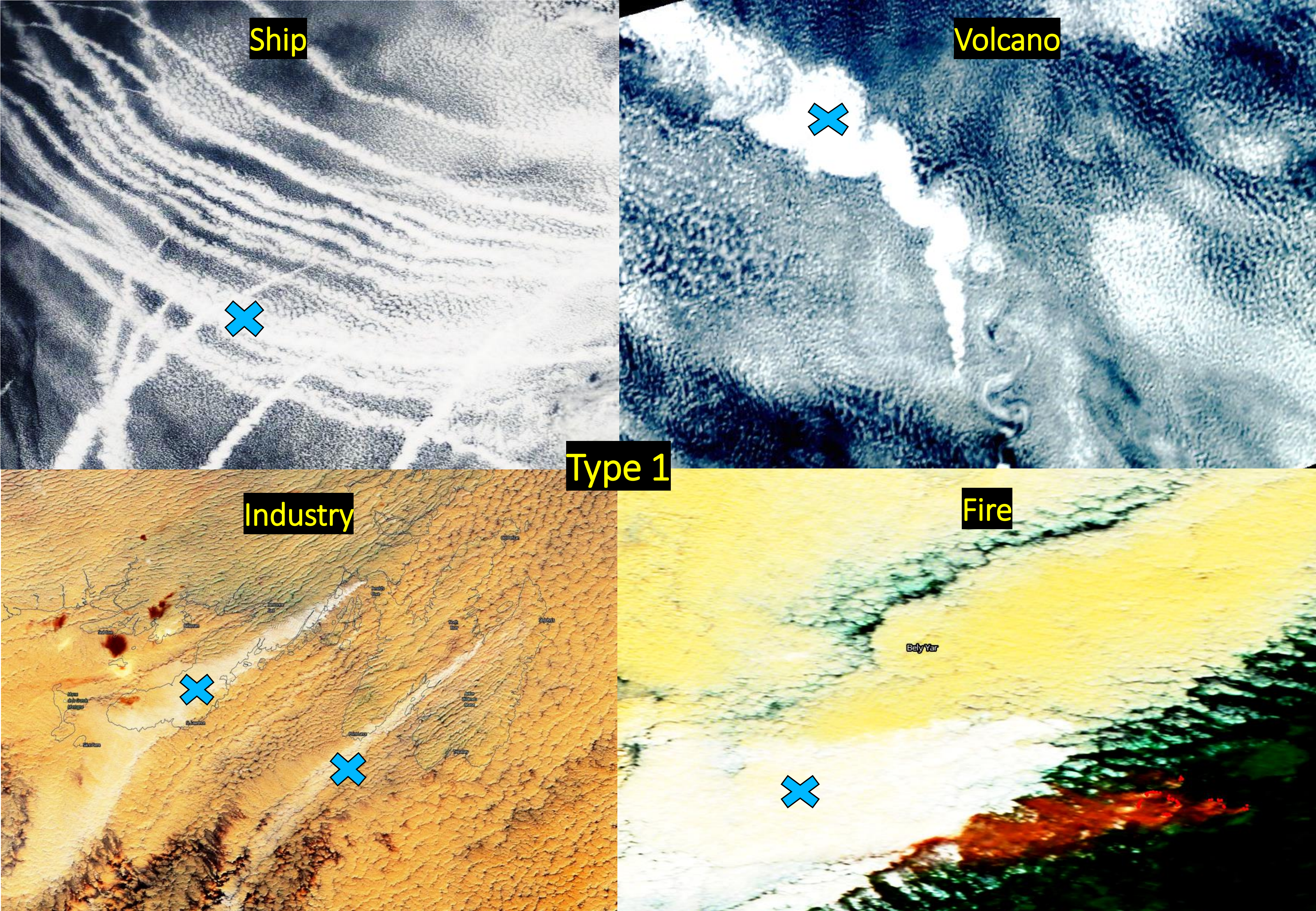
$\Delta \ln(CF) / \Delta \ln(CDNC)$ Type 1,2,3,4

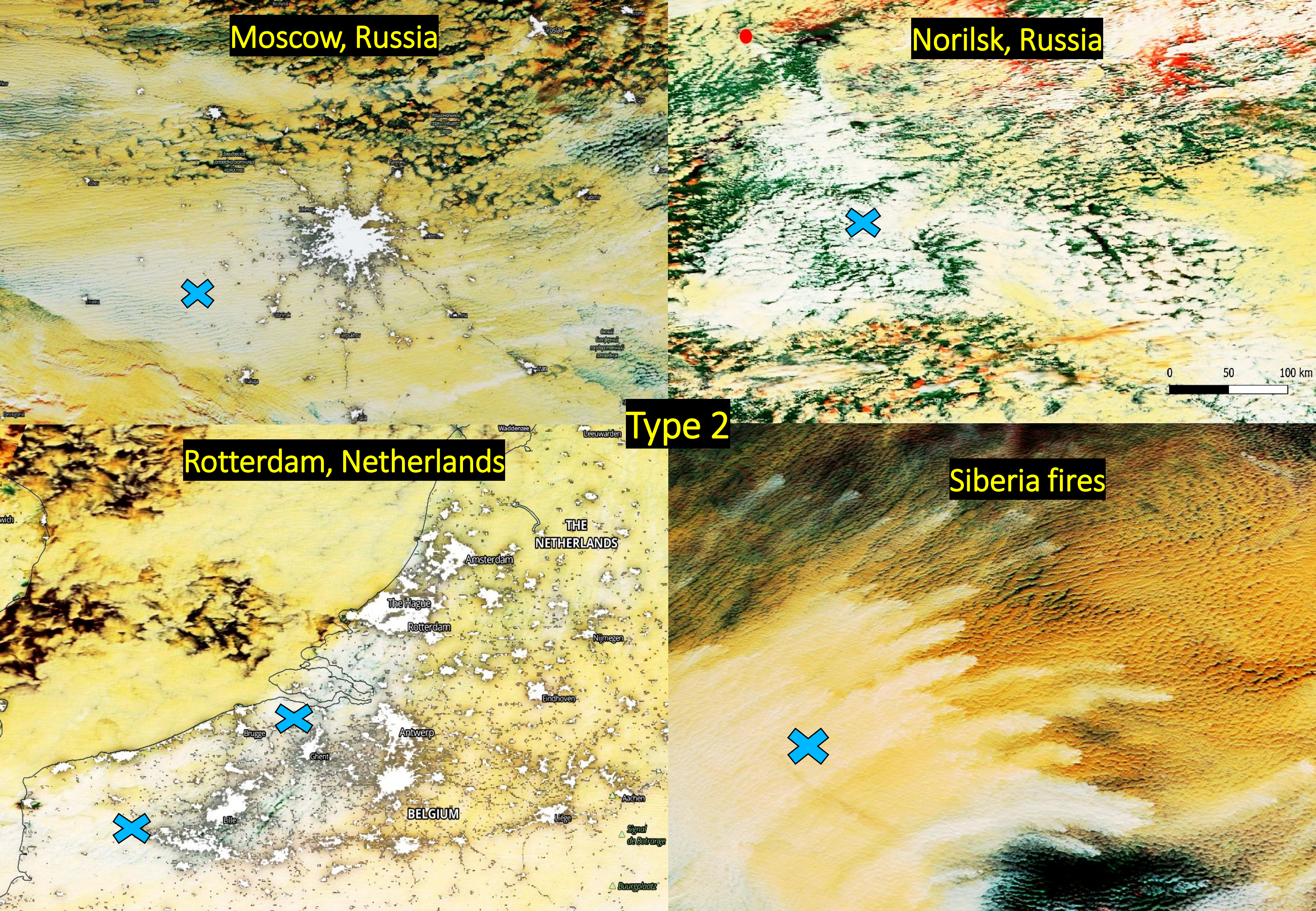
3) Meteorological dependence of aerosol indirect forcing, processes-level understanding

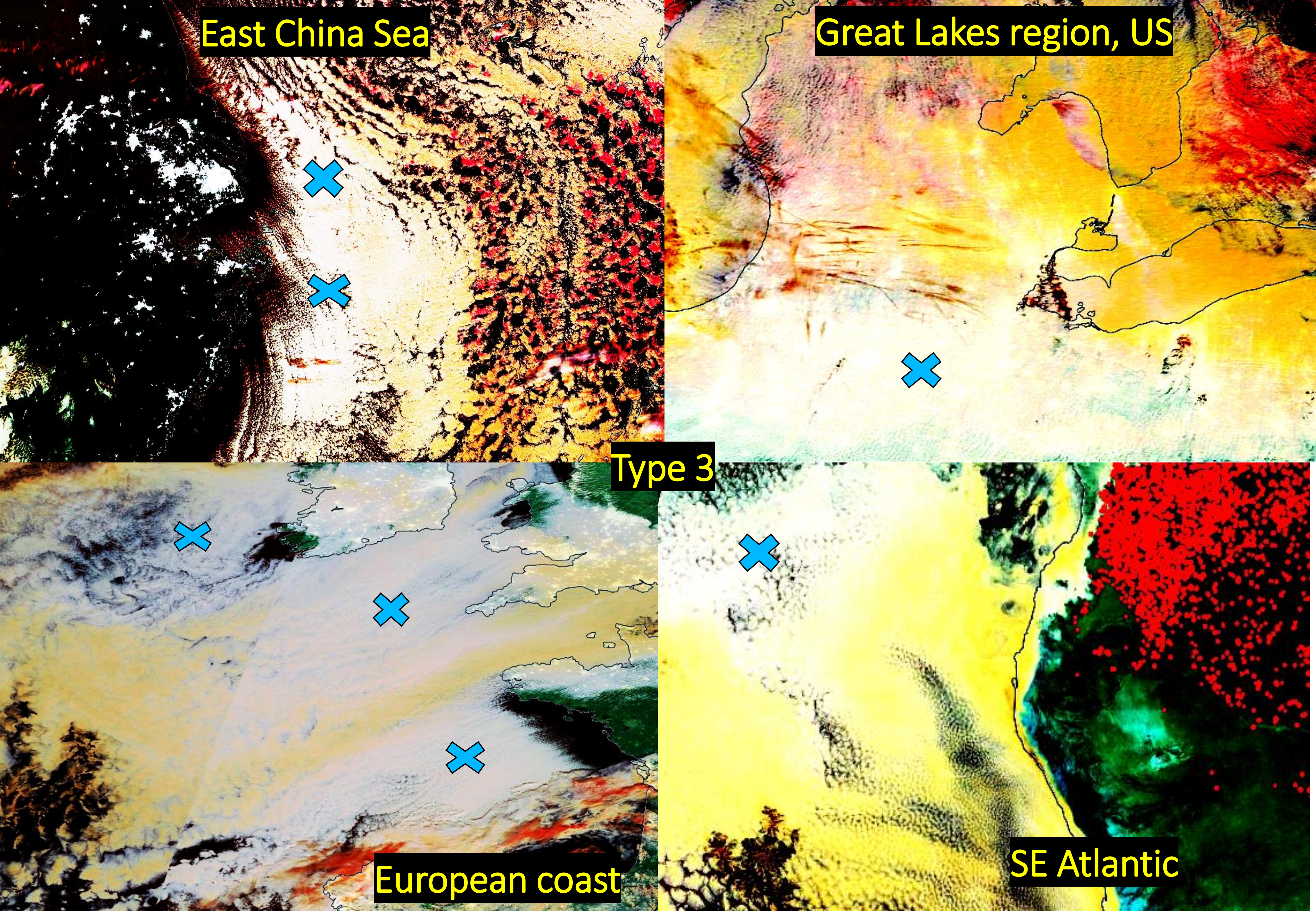
Type 1,2




By sampling local cloud responses via natural experiments for many regions and cloud types (ocean, land, Sc, low-level Cu etc), we can estimate global aerosol indirect radiative forcing more reliably.

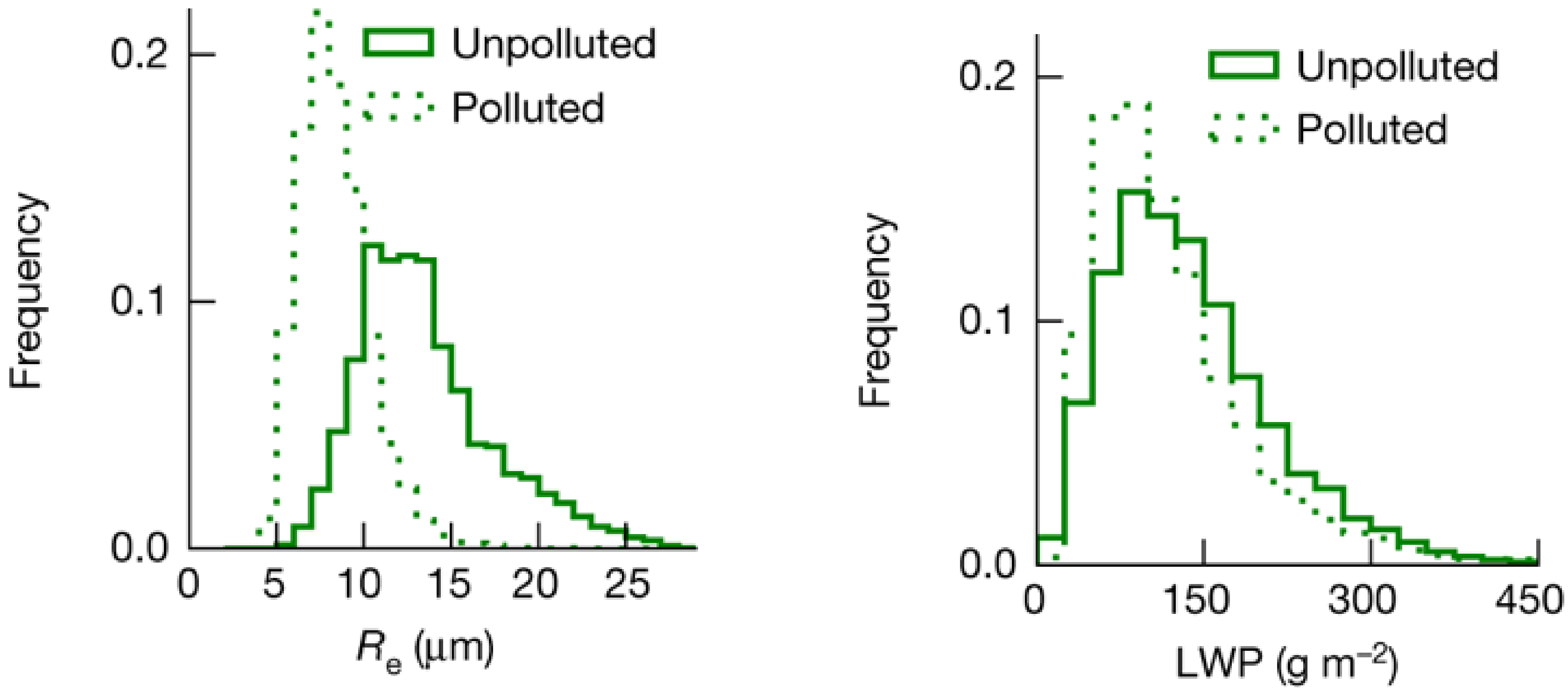

Ship
Volcano
Type 1
Industry
Fire
Bely Yar


Moscow, Russia
Norilsk, Russia
0 50 100 km
Type 2
Rotterdam, Netherlands
Siberia fires
Waddenzee
Leeuwarden
THE NETHERLANDS
Amsterdam
The Hague
Rotterdam
Nijmegen
Eindhoven
Brugge
Antwerp
Ghent
Lille
BELGIUM
Aachen
Liège
Signal de Botrange
Buurgplaatz


East China Sea
Great Lakes region, US
Type 3
European coast
SE Atlantic

The cloud droplet effective radius (Re) is strongly decreased in the polluted clouds.

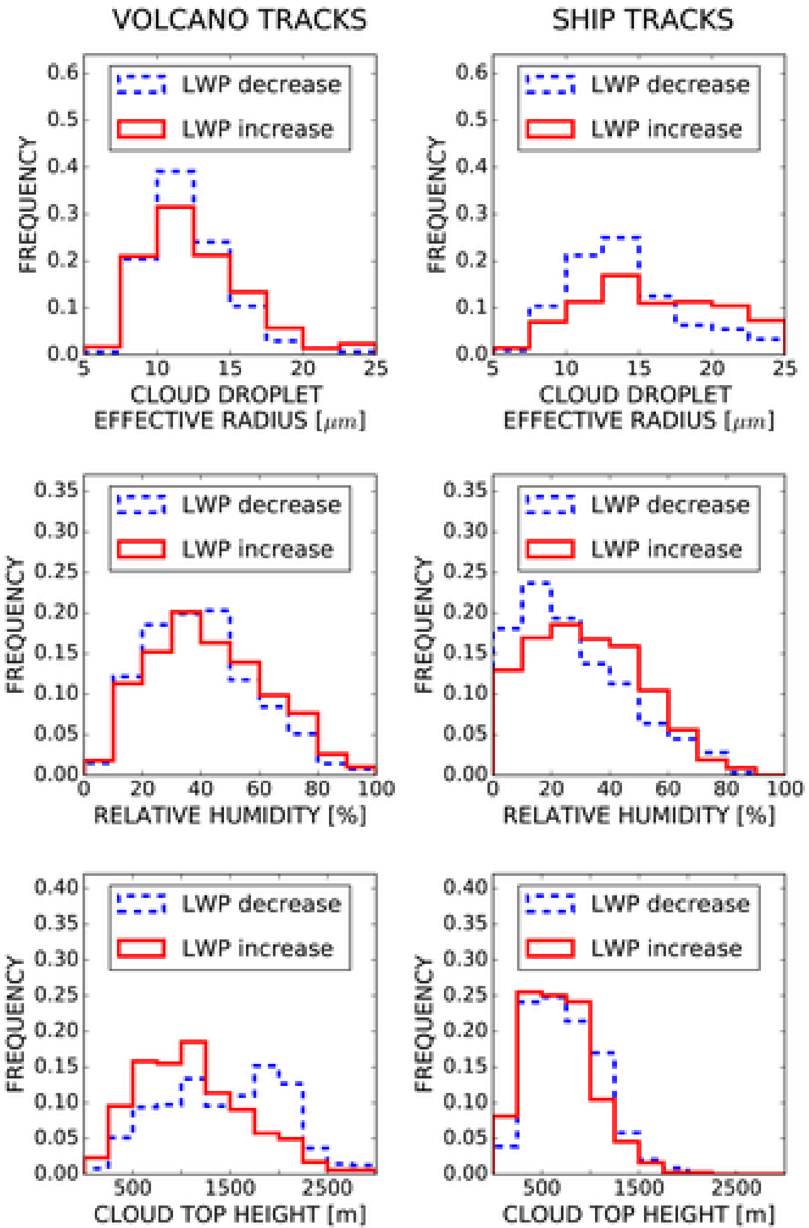
On average, liquid water path (LWP) is only slightly decreased in the polluted clouds.




Comparison between polluted and unpolluted clouds

(Toll et al 2019 *Nature*)

# Meteorological dependence of cloud water response



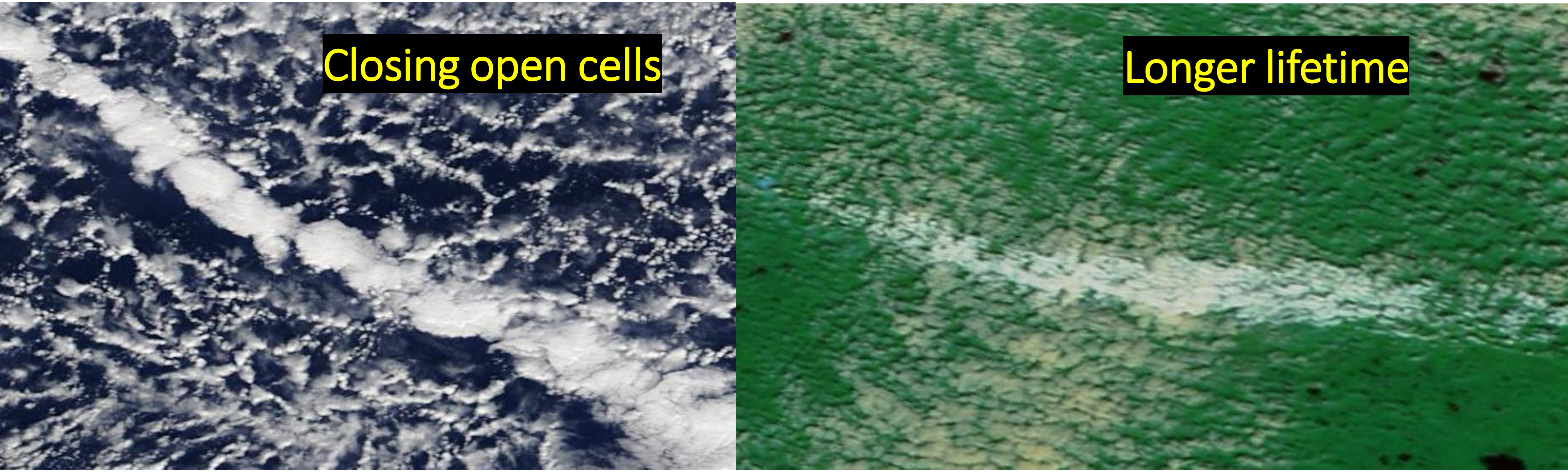

LWP response dependence on cloud droplet size supports suppression of precipitation.

LWP response dependence on relative humidity supports aerosol-enhanced entrainment.

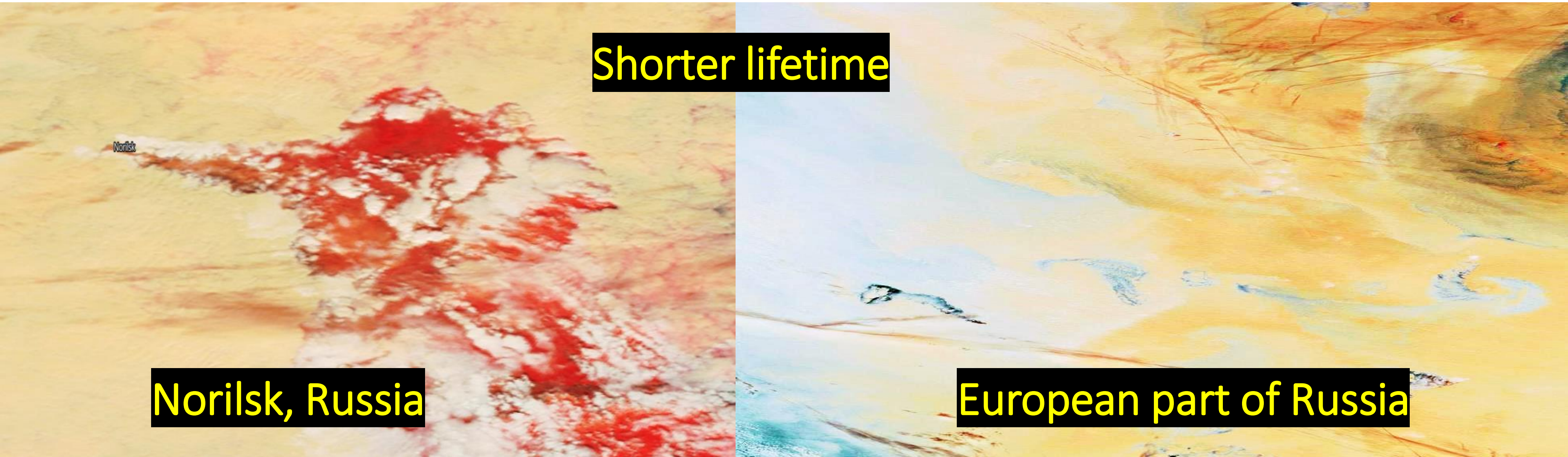
There is a lot of variability in the responses under all conditions: processes controlling LWP increases and decreases need to be better understood.

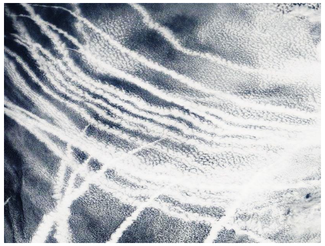
(Toll et al 2017 *GRL*)

# Increased cloud fraction

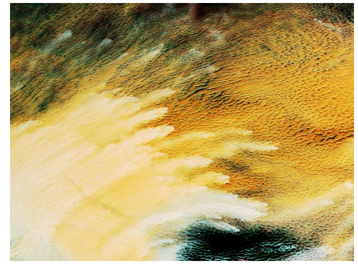



# Decreased cloud fraction





# Conclusions



Contrast between clouds polluted by anthropogenic aerosols and nearby unpolluted clouds at various spatial scales has been visually detected in satellite images.

Both smaller-scale ship-track-like cloud perturbations and larger scale hundreds of kilometres wide cloud perturbations show that cloud water decreases and increases in the polluted clouds act to compensate each ohter.

Polluted cloud tracks show that on average there is relatively weak decrease in cloud water due to anthropogenic aerosols. This decrease in cloud water off-sets part of the Twomey effect.

Cloud droplet number and cloud fraction responses to aerosols can be studied further using observations of polluted clouds at air pollution hot-spots at various spatial and temporal scales.

# References

Toll, V., Christensen, M., Quaas, J., & Bellouin, N. (2019). Weak average liquid-cloud-water response to anthropogenic aerosols. *Nature*, *572*(7767), 51-55.
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Large-scale industrial cloud perturbations confirm bidirectional cloud water responses to anthropogenic aerosols. Trofimov, H., Bellouin, N., & Toll, V. (2020). *JGR Atmospheres* (under review)

Satellite images used in this presentation are MODIS and VIIRS images from NASA GIBS
**https://earthdata.nasa.gov/eosdis/science-system-description/eosdis-components/gibs**