



# Tracking the Dynamics of Individual Ship Plumes Using Ground-Based Imaging DOAS

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## 1. Motivation

- Shipping is a **significant source of pollutants** (NO<sub>x</sub>, SO<sub>2</sub>, PM, CO<sub>2</sub>, CO, BC,..)
  - 70% of ship emissions occur within 400 km from coastlines (Eyring et al. 2010)
    - affect atmospheric chemistry, regional air quality and health, climate
  - Regulated** by the International Maritime Organization (IMO)
    - monitoring necessary
  - Established methods** of measuring ship emissions (e.g. In-situ, MAX-DOAS,...) are often **restricted in spatial coverage** and rely on simplified dispersion models
- **Idea: Imaging** allows for **improving emission estimates** and learning about the **dynamics and evolution** of ship emission plumes

## 2. Imaging DOAS instrument

**IMPACT2 (Imaging MaPper for AtmospheriC observaTions 2):**

- Pushbroom** hyperspectral imager with **41 viewing directions**
- Upgraded version of IMPACT (Peters et al. 2019)
  - Featuring:
    - telescope with wide-angle objective
    - sorted optical fiber bundle
    - new imaging spectrometer (IsoPlane® SCT 320)
    - new CCD camera (PIXIS:2KBUV)
- NO<sub>2</sub> fit window: 425 nm – 490 nm, FWHM: 0.5 nm**

## 3. Measurement setup

- SEICOR measurement campaign **since April 2025**
- Located at the banks of river Elbe in **Wedel**, about **10 km downstream of the port of Hamburg**
- Measurement mode: across the river in a **fixed geometry**, frequency: 2 Hz
- Distance to ships: 200 – 500 m

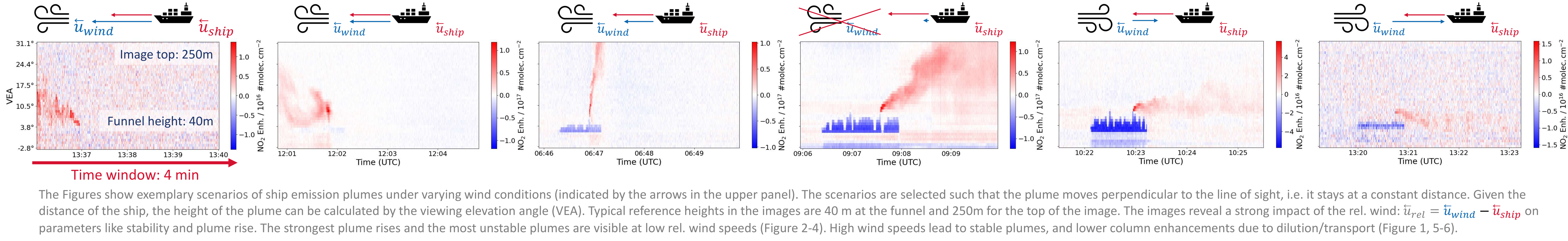
**Co-deployed instruments:**

- AIS receiver (Automatic Identification System)
- Two in situ measurement systems
- Weather station
- Long path DOAS system (LP-DOAS)

## 4. Preprocessing

- Ship passes from AIS signals define possible plume windows
  - Plume NO<sub>2</sub>-enhancements calculated by subtracting NO<sub>2</sub>-background based on clean references before and after the plume window
  - Ship plumes identified using an automated plume identification algorithm
- **More than 600 ship plumes** measured in the first 5 months of the campaign
- **Plumes stick out of the background** variability as a **positive enhancement**
- **Ships are visible as a negative enhancement** (**obstructed light path**)
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## 5. Preliminary results



**Gaussian puff model fit :**

- Models transport and dispersion of the emission plume as a series of Gaussian puffs:

$$C(t, x, y, z) = \sum_{i=0}^t \frac{Q(t_i)\Delta t}{\sigma_x(t_i)\sigma_y(t_i)(2\pi)^{3/2}} \cdot \exp\left(-\frac{(x-x_{adv}(t_i))^2}{2\sigma_x^2(t_i)} - \frac{(y-y_{adv}(t_i))^2}{2\sigma_y^2(t_i)} - \frac{(z-h(t_i))^2 + (z+h(t_i))^2}{2\sigma_z^2(t_i)}\right)$$

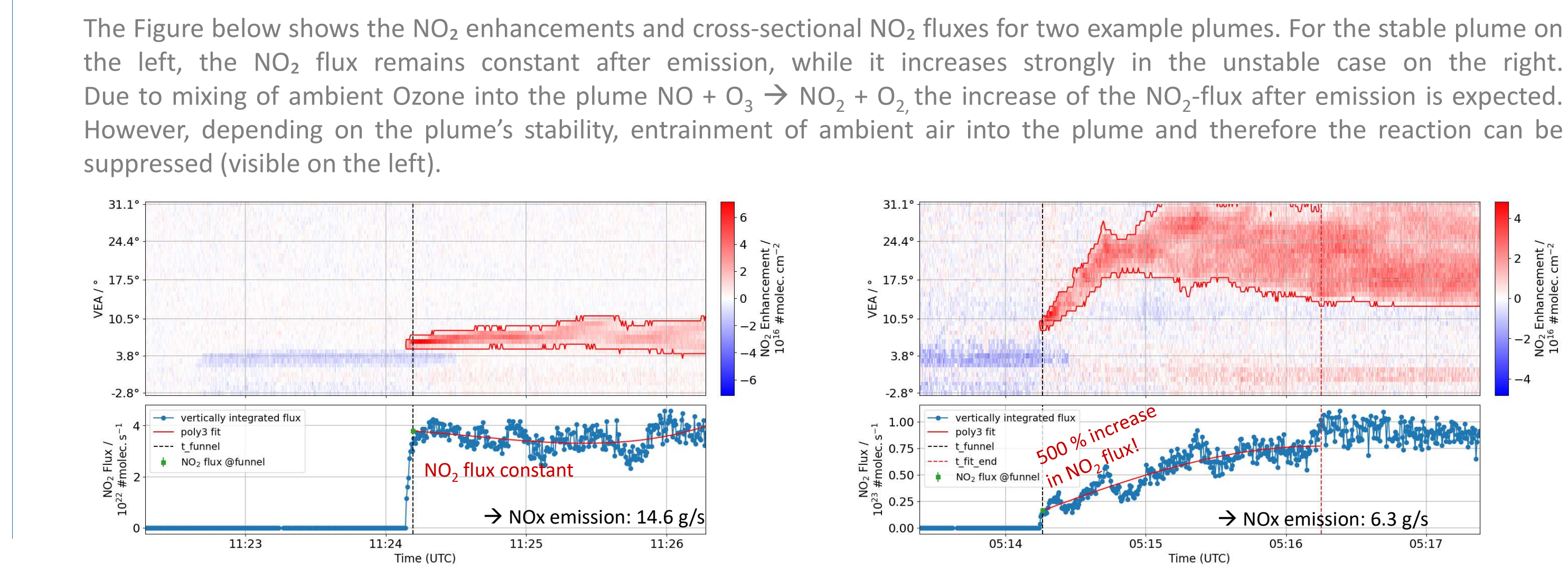
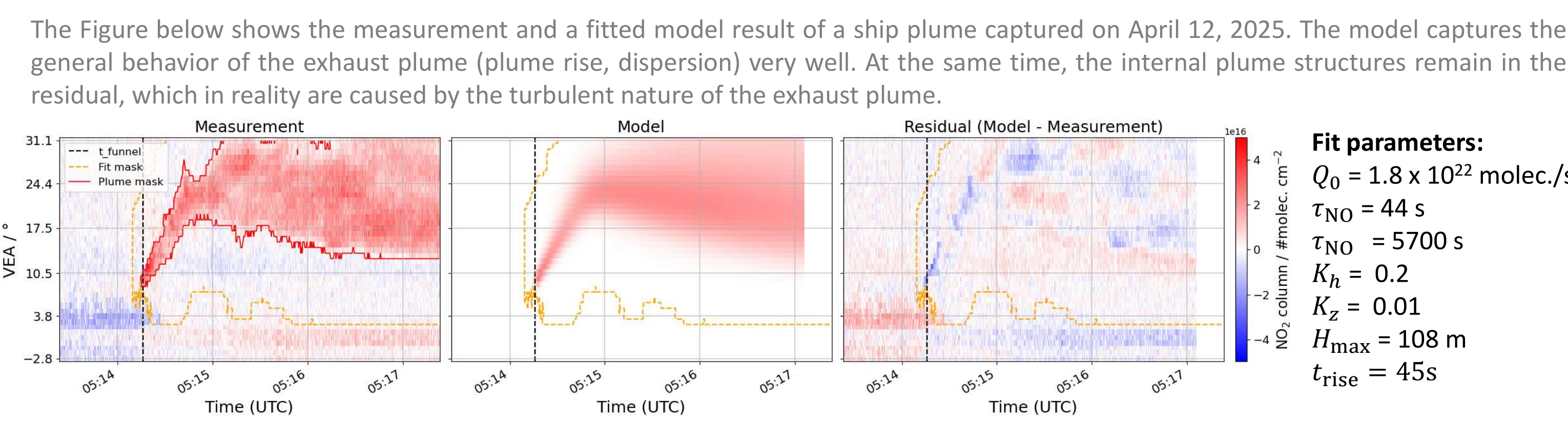
- Accounts for **emission rate  $Q_0$ , advected transport, dispersion  $\sigma(K, t)$ , plume rise** [linear  $h(H_{max}, t_{rise}, t)$  or "briggs"  $h(S, F, t)$  (Chosson et al. 2008)] and **NO → NO<sub>2</sub> conversion  $Q(\tau_{NO}, \tau_{NOx}, t)$**  (Meier et al. 2024)
- Non-linear least squares fit with the parameters:  $Q_0, K_h, K_z, \tau_{NO}, \tau_{NOx}, (H_{max}, t_{rise})$  or  $(S, F)$
- Cannot resolve the internal structure of the exhaust plume but **captures key parameters such as dispersion and plume rise**

**NO<sub>x</sub> emission quantification:**

- Cross-sectional NO<sub>2</sub> flux** through an imaginary vertical curtain (Jacob et al. 2022):  
 $F_i = \sum_j \Delta SC_{i,j} \cdot l_{i,j} \cdot u_{i,j} \cdot \cos(\alpha_{i,j})$
- Polynomial fit to determine NO<sub>2</sub> flux at the funnel
- Conversion NO<sub>2,funnel</sub>/NO<sub>x</sub> = 0.138 (Krause et al. 2021)

➤ Emission estimates in good agreement with literature

*i, j: time index, viewing direction index  
 F<sub>i</sub>: NO<sub>2</sub> flux  
 ΔSC<sub>i,j</sub>: NO<sub>2</sub> slant column enhancement  
 l<sub>i,j</sub>: length element  
 u<sub>i,j</sub>: wind speed  
 α<sub>i,j</sub>: angle between wind and area normal*



## 6. Conclusions & Outlook

- ✓ **Large dataset of shipping NO<sub>2</sub> plumes** with high spatial and temporal resolution (measurements ongoing)
  - ✓ Reliable detection of NO<sub>2</sub>-plumes
  - ✓ Tracking of **plume dynamics and evolution** possible
  - ✓ Quantification of **NO<sub>x</sub> emissions**
- Determine key parameters of plume dynamics using a Gaussian puff model and **relate to meteorological parameters**
- Compare to model results for case studies



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