First airborne in situ SO_2 observations of two coal-fired power plants in Serbia and Bosnia-Herzegovina: Potential for top-down emission estimate and satellite validation

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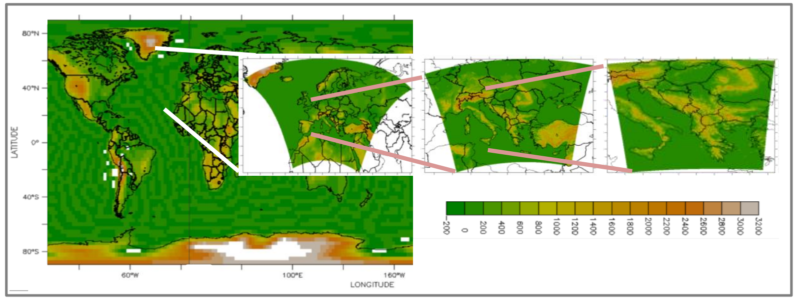
Outline

1) Global and regional **sulfur dioxide** (SO_2) **emissions**

2) SO_2 observations and modeling activities in the vicinity of two **coal-fired power plants** in Serbia and Bosnia-Herzegovina
   - 2.1) **Airborne research campaign** METHANE-To-Go-Europe
   - 2.2) Sentinel-5 Precursor (S5P) with **TROPOMI** instrument
   - 2.3) **Ground-based** measurement **network**
   - 2.4) Global/regional **nested chemistry climate model** MECO(n)
   - 2.5) Regional online coupled **meteorology-atmospheric chemistry model** WRF-Chem

3) First **results**
   - 3.1) Serbia mission flight
   - 3.2) Bosnia mission flight

4) Summary and Outlook



1) Global and regional sulfur dioxide (SO_2) emissions

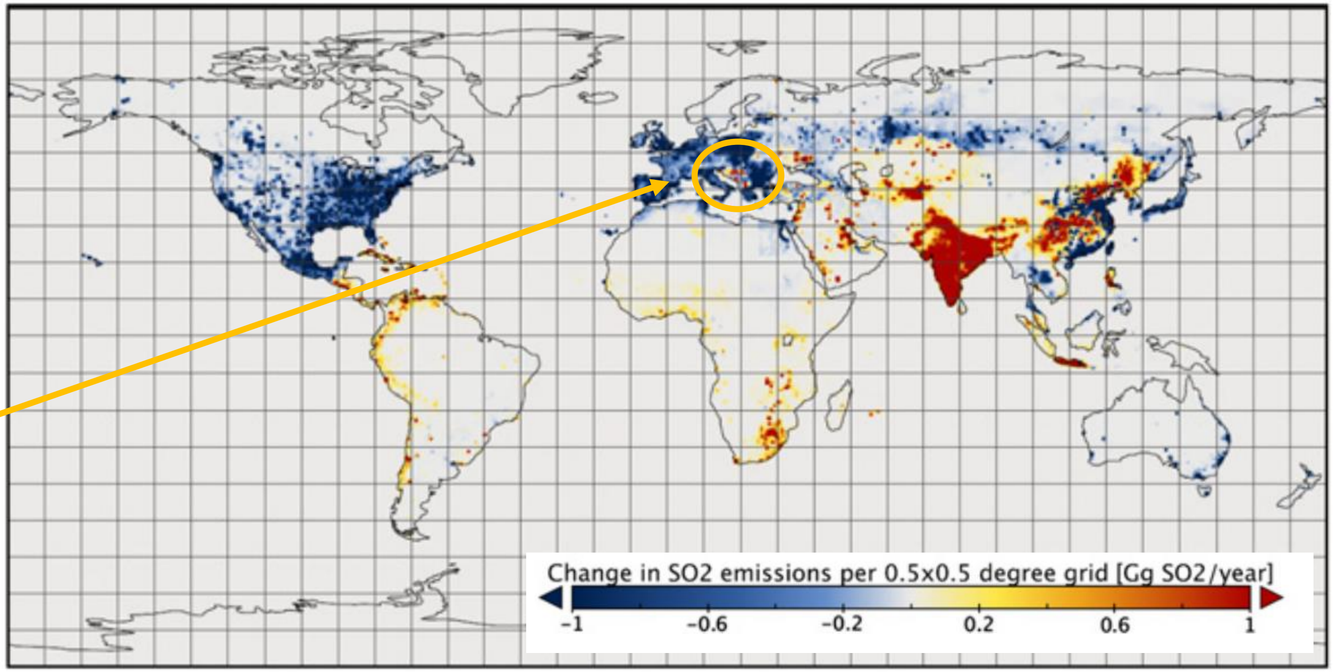
1) Global SO_2 emissions

- Globally **~2/3rd** of SO_2 are directly emitted by **anthropogenic activities**, mainly by **combustion of sulfur-rich fossil fuels**; ~1/3rd is indirectly emitted (sulfur containing gases) by natural sources and oxidized to SO_2 (Theys et al., 2015)

- Shutdown of older power plants, switching from coal to natural gas and/or installation of flue gas desulfurization systems led to severe **reductions in western Europe**, throughout northern America and Russia (Klimont et al., 2013)

- **SO_2 emissions increased** in Europe in the **Balkan region**, as well as in India and eastern China

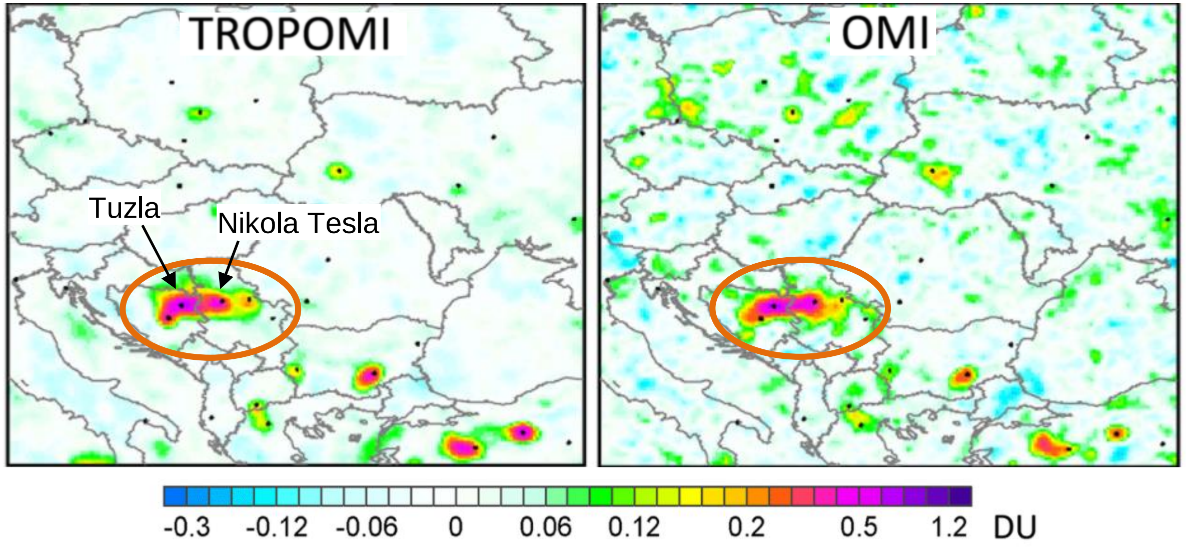
Change in anthropogenic land based SO_2 emissions between 2010 and 2005 (Klimont et al., 2013)



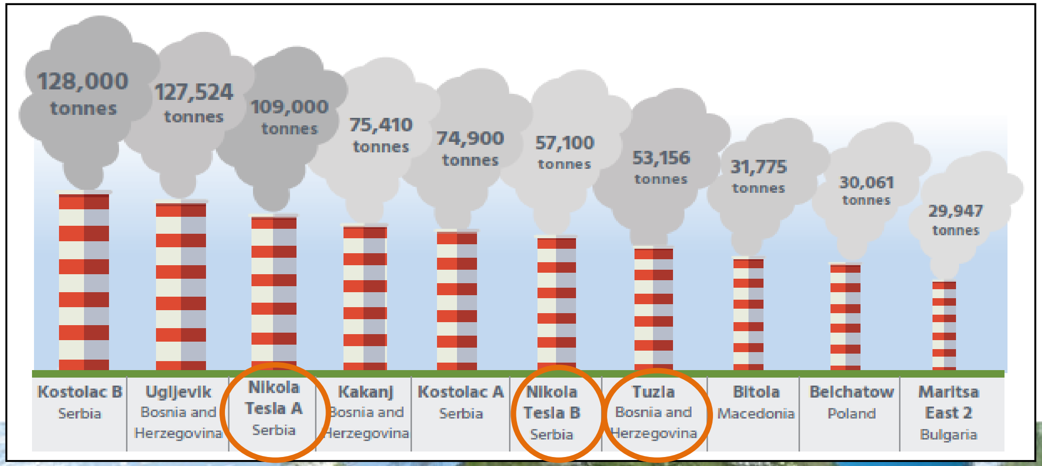
1) Regional SO_2 emissions in the Balkan

- **SO_2 emission hotspot** in **Serbia** and **Bosnia-Herzegovina** was recently also observed from space by **TROPOMI** and **OMI** (Fioletov et al., 2020)
- The two coal-fired power plants **Nikola Tesla** (Serbia) and **Tuzla** (Bosnia), with no or incomplete SO_2 removal, belong to the **ten strongest SO_2 emitters in Europe** (Chronic Coal Pollution)
- According to the World Health Organization, both countries are among the most polluted ones in Europe
- Tuzla and surrounding cities are also among the ten most polluted cities in Europe based on PM2.5 (www.NZZ.ch)

TROPOMI and OMI mean SO_2 (April 2018 to March 2019) smoothed by oversampling/pixel averaging with R=30 km. Black dots indicate SO_2 emissions sources. (Fioletov et al., 2020)



Top 10 largest SO_2 emitters among power plants in 2016 (Chronic Coal Pollution)

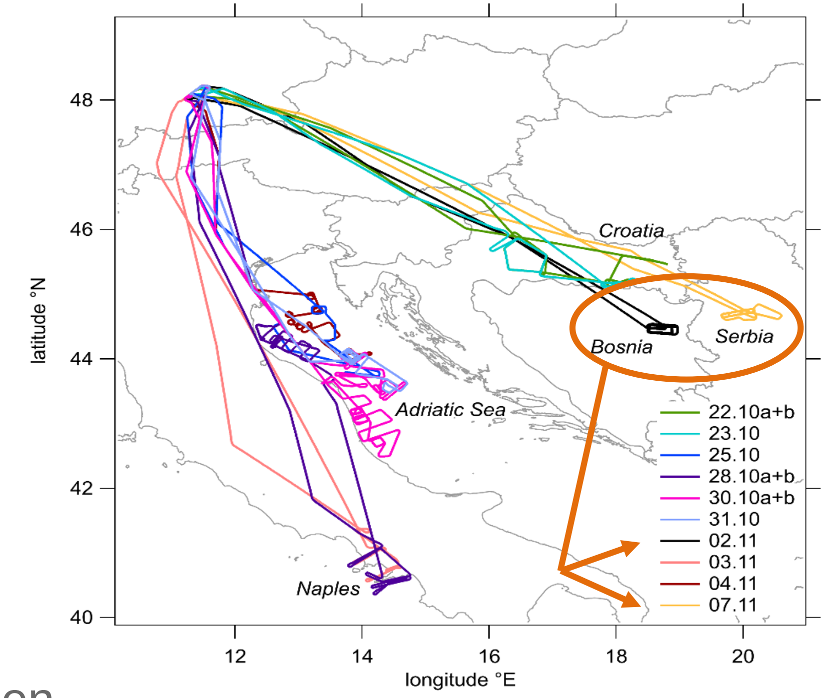


TROPOMI = TROPOspheric Monitoring Instrument;
OMI = Ozone Monitoring Instrument

2) SO_2 observations and modeling activities in the vicinity of two coal-fired power plants in Serbia and Bosnia-Herzegovina

2.1) Airborne research campaign METHANE-To-Go-Europe

- DLR Falcon 20 aircraft performed 13 flights from October 22nd to November 7th, 2020



- In situ instrumentation:
  - isotopically on-line calibrated **Chemical Ionization Ion Trap Mass Spectrometer** (CI-ITMS) for **SO_2**
  - complemented by greenhouse gas (CO_2, CH_4), aerosol number concentration, and other short-lived pollutant (CO, NO, NO_y) measurements

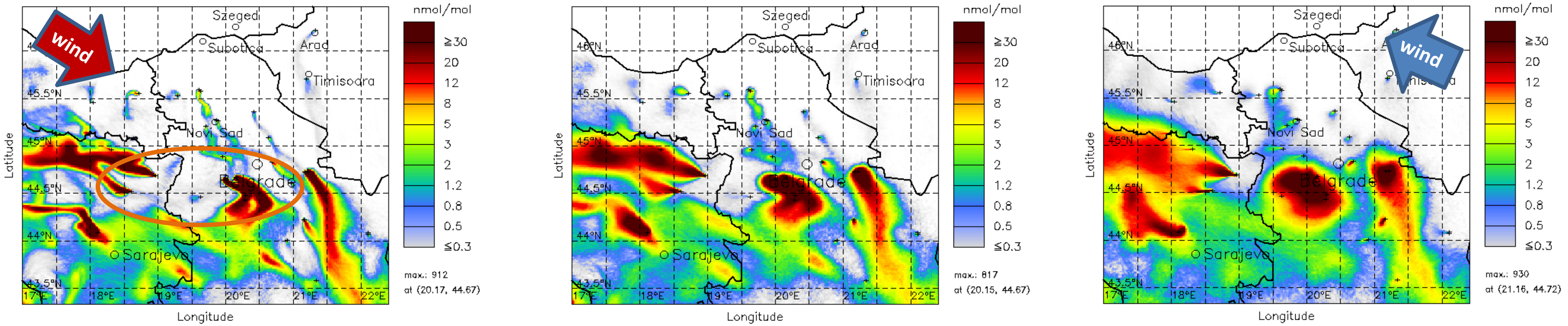
- Two flights, on **November 2nd and 7th**, focused on characterizing the pollution plumes downwind of **Tuzla** (Bosnia) and **Nikola Tesla** (Serbia)

2.1) Airborne research campaign METHANE-To-Go-Europe

- **Challenges** during flights to the Balkan region:
  - No stopover to refuel due to Covid-19 → limited measurement time
  - Low-flight permit difficult in Balkan → performance of „**low approach**“ at nearby airports
  - Target region has to be **cloud free** for satellite validation
  - Changing wind **forecasts** hamper SO_2 pollution plume forecast by HYSPLIT
  - Extreme **high pollutant volume mixing ratios** (VMR)

HYSPLIT forecast: SO_2 (mean VMR) from selected point sources

07.11.2020, 10 UTC 12 UTC 15 UTC

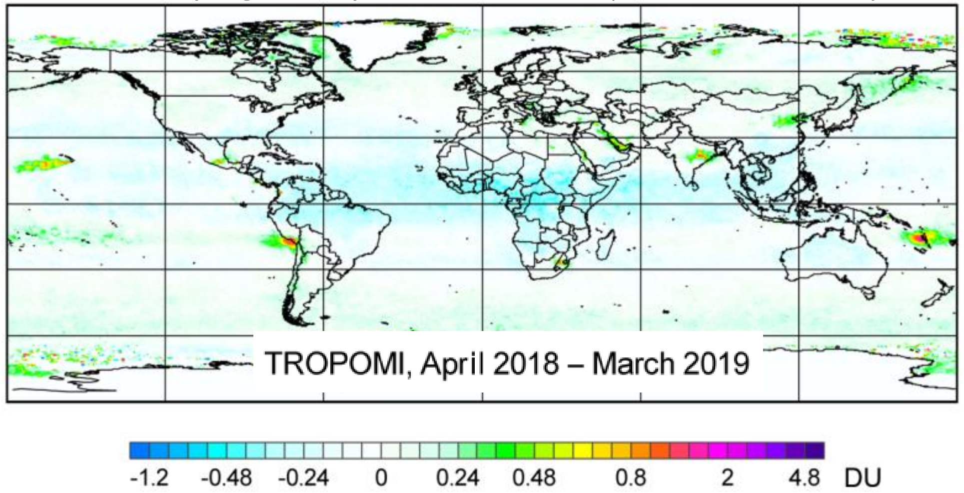


HYSPLIT= Hybrid Single-Particle Lagrangian Integrated Trajectory model

2.2) Sentinel-5 Precursor (S5P) with TROPOMI instrument

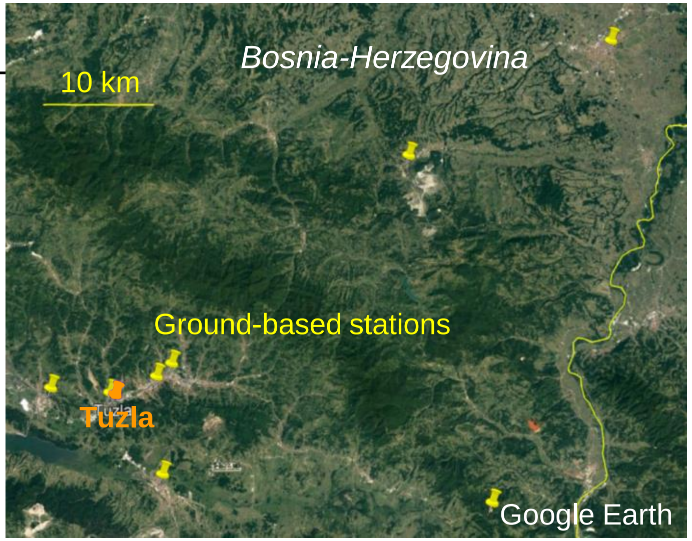
- ESA satellite **Sentinel-5P** launched in October 2017
  -multichannel spectrometer **TROPOMI** (UV-VIS-NIR, SWIR)
  -measuring **Vertical Column Density** (VCD) of O_3, NO_2, HCHO, **SO_2**, CO_2, CH_4, aerosols and clouds
- Specifications
  -polar orbit, 14-15 Orbits / day
  -equator passing: **13:30 h (local)**
  -swath: 2600 km wide → daily global coverage
  -pixel resolution: **5.5 x 3.6 km^2** (at the beginning: 7 x 3.5 km^2)
- SO_2 Retrieval
  -band 3 (310-405 nm)
  -besides TROPOMI operational product also **COBRA** product which improves low SO_2 VCDs (< ~0.25 DU)
  -VCD via air mass factor (AMF), knowledge on the SO_2 vertical profile needed

TROPOMI mean SO_2 (April 2018 to March 2019) smoothed by oversampling techniques with R=30 km. (Fioletov et al., 2020)

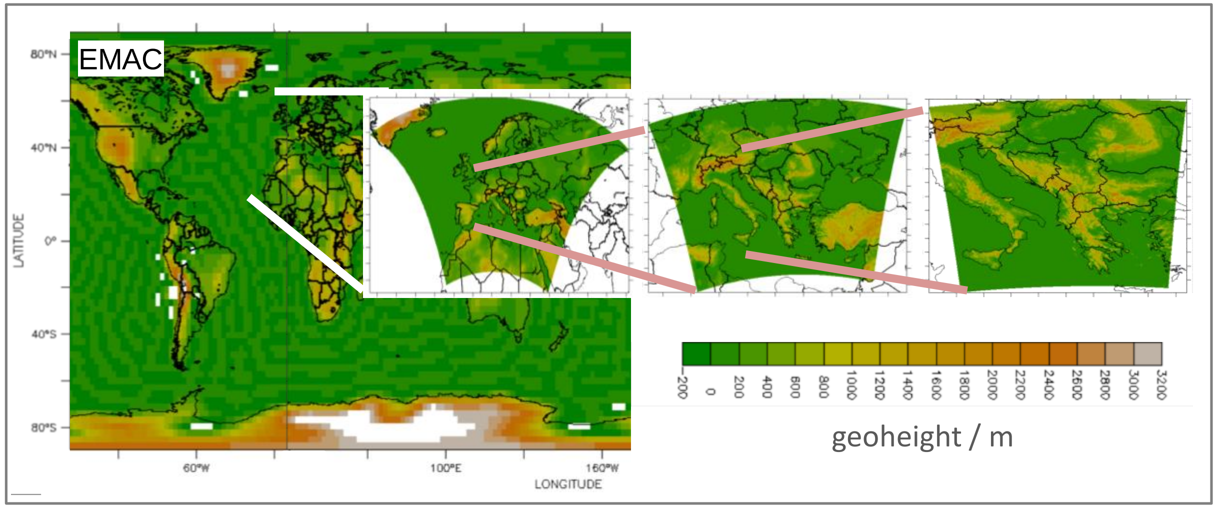


2.3) Ground-based measurement network

Country	Location	Lat °N	Lon °E	Measured species
Bosnia-Herzgewonia				
	Caparde (Zvornik)	44.3986	19.0089	SO_2
	Bijeljina	44.7568	19.2185	SO_2
	Ugljevik	44.6840	18.9696	NO, NO_2, NOx, PM10
	Skver Tuzla	44.5408	18.6733	SO_2, NO, CO, O_3, PM2.5
	BKC Tuzla	44.5319	18.6547	SO_2, NO, CO, O_3, PM2.5
	Bukinje Tuzla	44.5236	18.6003	SO_2, NO, CO, O_3, PM2.5
	Lukavac	44.5333	18.5349	SO_2, NO, CO, O_3, PM2.5
	Živinice	44.4539	18.6483	SO_2, NO, CO, O_3, PM2.5
Serbia				
	Obrenovac	44.6595	20.2045	SO_2, PM10, NO_2, CO
	Kostolac	44.7175	21.1734	SO_2, NO_2

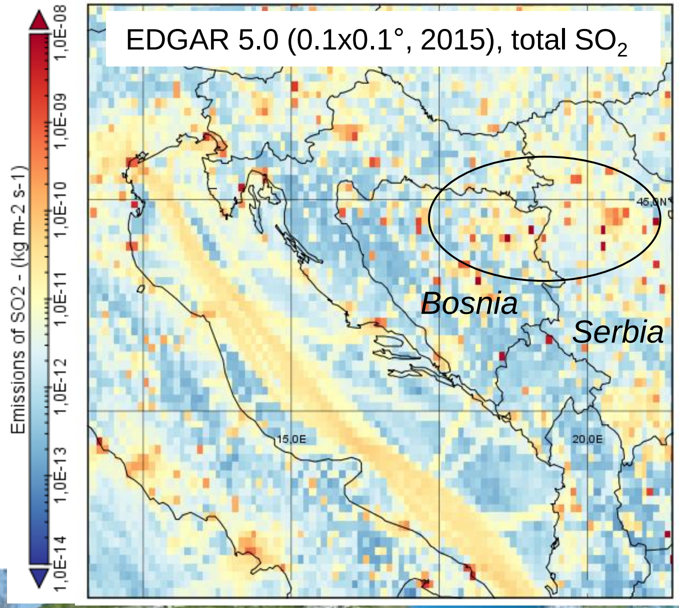


2.4) Global/regional nested chemistry climate model MECO(n)



- On-line coupling of the global CCM EMAC with regional CCM COSMO-CLM/MESSy → **regional refinement** (e.g. Hofmann et al., 2012; Kerkweg and Jöckel, 2012a and 2012b; Mertens et al., 2016)
  - EMAC
    - nudging (operational ECMWF)
    - horizontal resolution ~280 km, 90 vertical levels
    - time step 720 s
  - 3 COSMO-CLM/MESSy nests
    - nudging (optional)
    - horizontal resolution 50 / 12 / 2 km, 50 vertical levels
    - time step 240 / 60 / 30 s

- Simulation of **various anthropogenic SO_2 emissions**
  - P-SO2: modified point source emissions from **E-PRTR** (2016)
  - E-SO2: **EDGAR** v5.0 gridded inventory (2015)
  - O-SO2: **OMI-HTAP** v2.2 gridded inventory (2010)



CCM = chemistry-climate model; MECO(n) = MESSy-field ECHAM and COSMO models nested n times; EMAC = ECHAM/MESSy Atmospheric Chemistry; COSMO-CLM/MESSy =COSMO model in CLimate Mode / Modular Earth Submodel System; E-PRTR=European Pollutant Release and Transfer Register; EDGAR=Emissions Database for Global Atmospheric Research; OMI-HTAP=OMI-based and HTAP emission inventory

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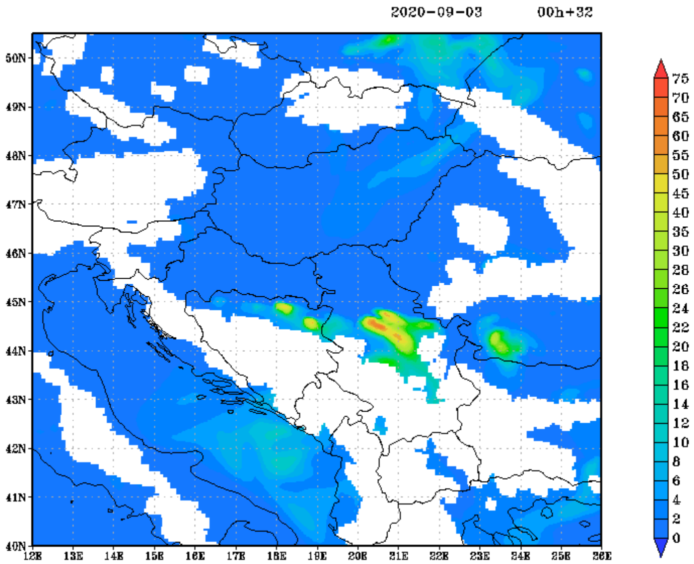
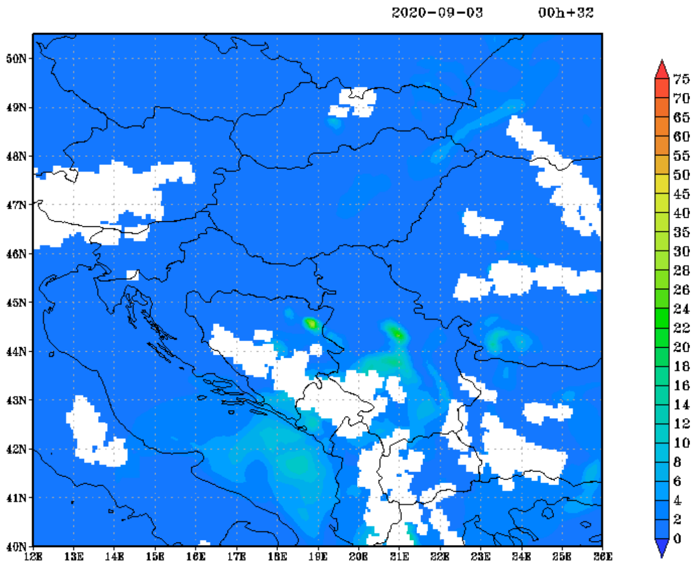
2.5) Regional online coupled meteorology-atmospheric chemistry model WRF-Chem

- High model **resolution of 10 x 10 km** and 151 × 151 grid points
- Center of domain: 45.25°N and 19.85°E
- NOx, **SOx**, PM2.5, PM10 and NH_3 **emissions from EMEP** (10x10 km) for all anthropogenic SNAP sectors
- Used as **forecast and analysis simulation**

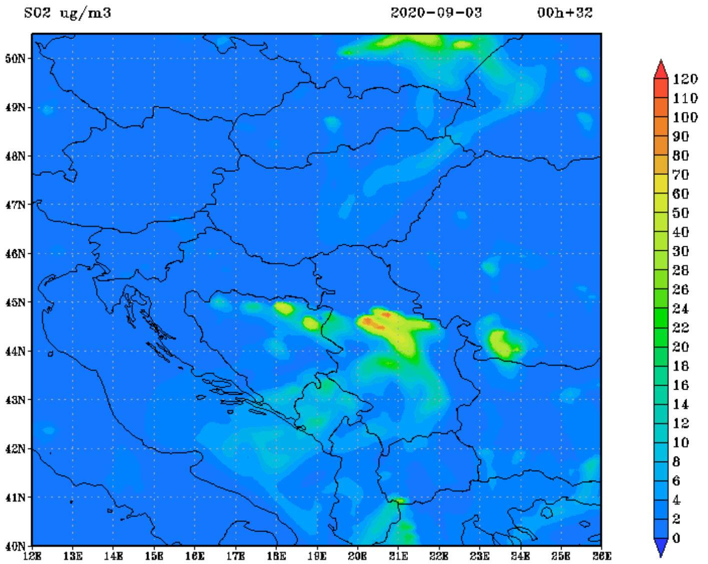
WRF SO_2 (µg m^{-3}) 950 hPa



900 hPa



surface



EMEP = European Monitoring and Evaluation Programme,
SNAP = selected nomenclature for reporting of air pollutants

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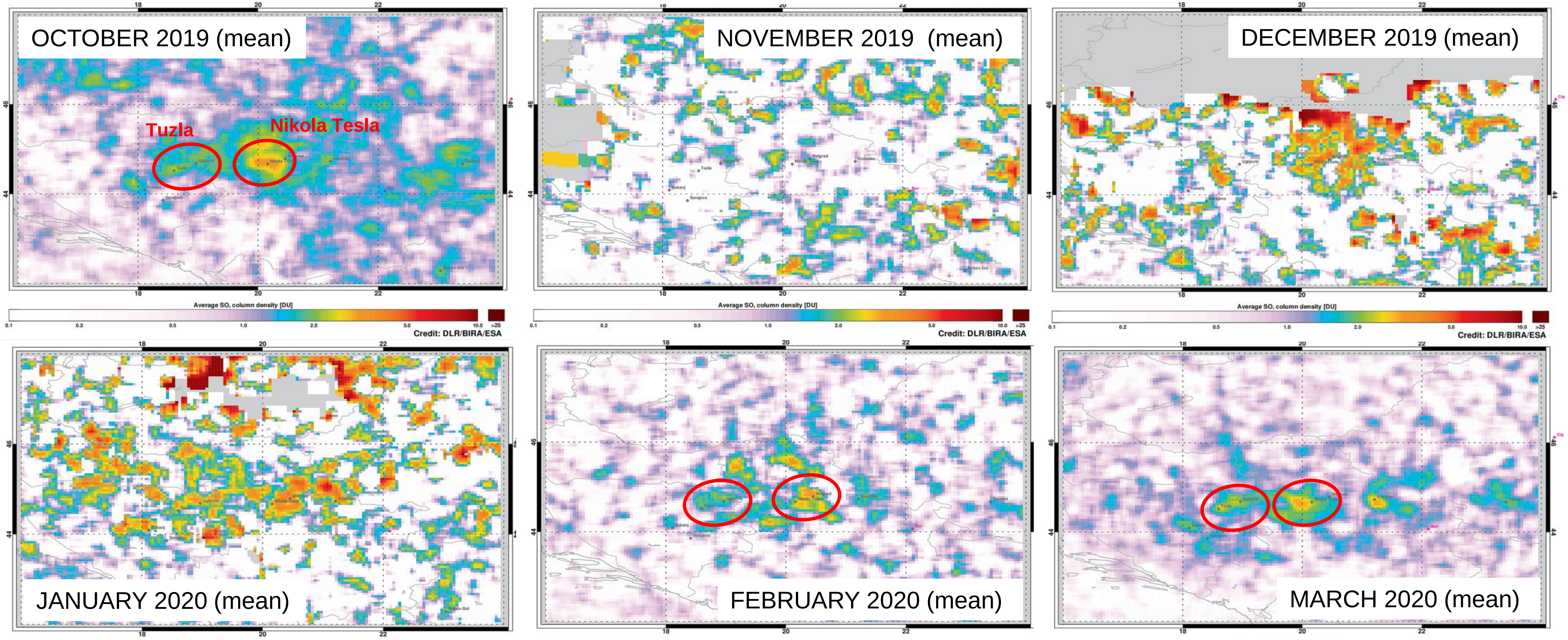
3) First results

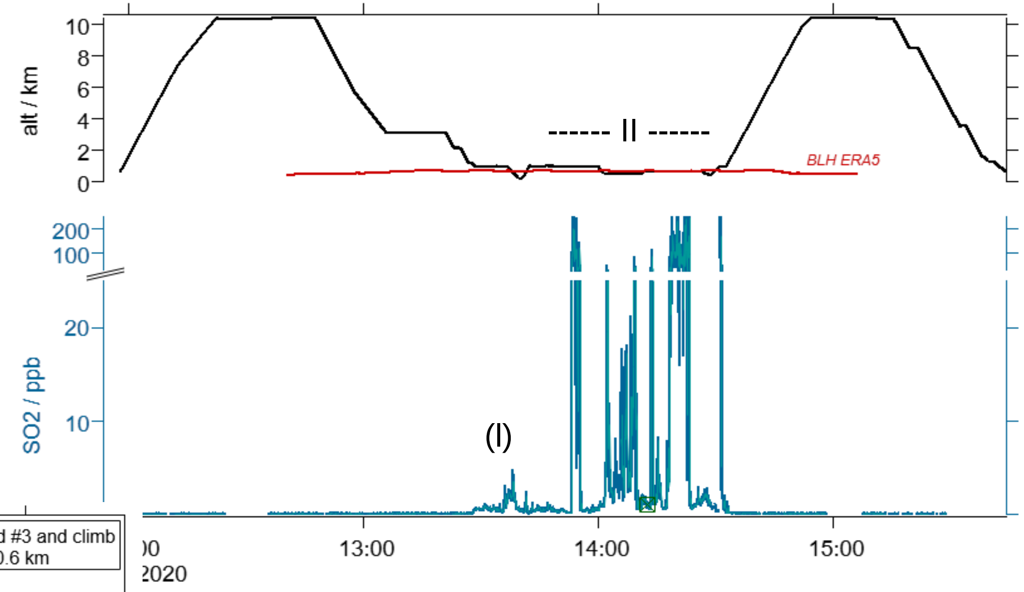
3) Effect of low sun position and smoke aerosols on TROPOMI products

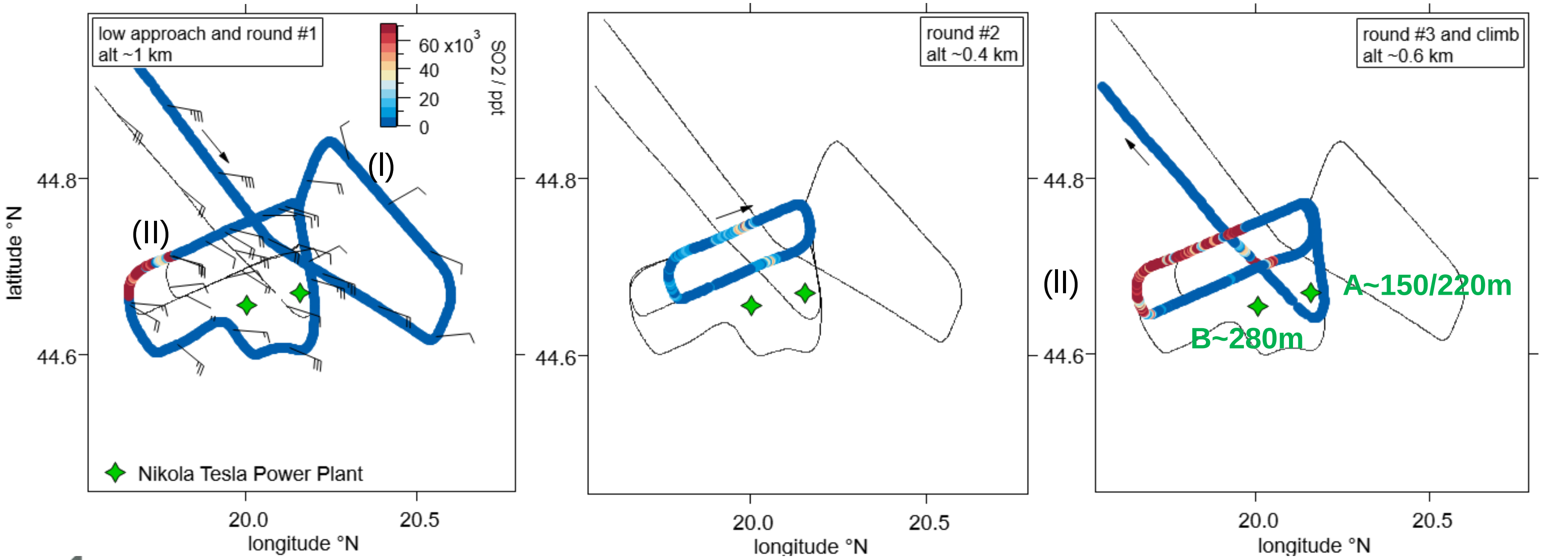


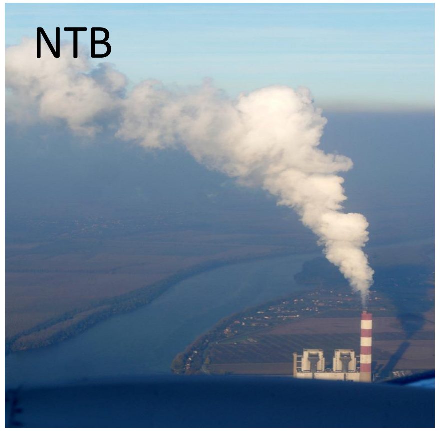
November to January: very noisy (ground-based smog due to usage of low quality coal) → hampers validation

3.1) Falcon flight downwind of Nikola Tesla (Serbia)

- Flight pattern on November 7th, 2020
  - low approach at Belgrade airport (I)
  - „box“ at different heights (1, 0.4, 0.6 km; II), detecting **SO_2 enhancements of up to 200 ppb**
- **Separate emission plumes** of both chimneys (Nikola Tesla A and B) are distinguishable at different heights

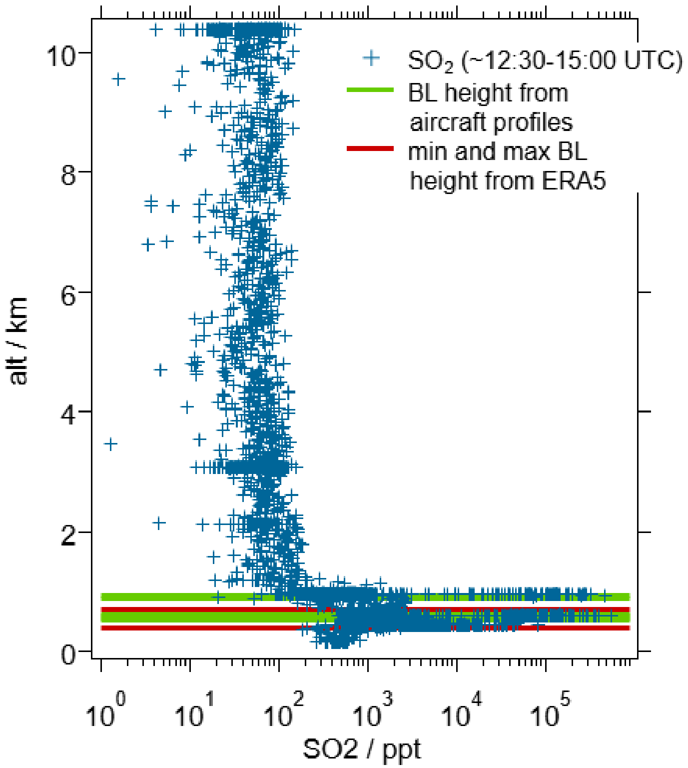


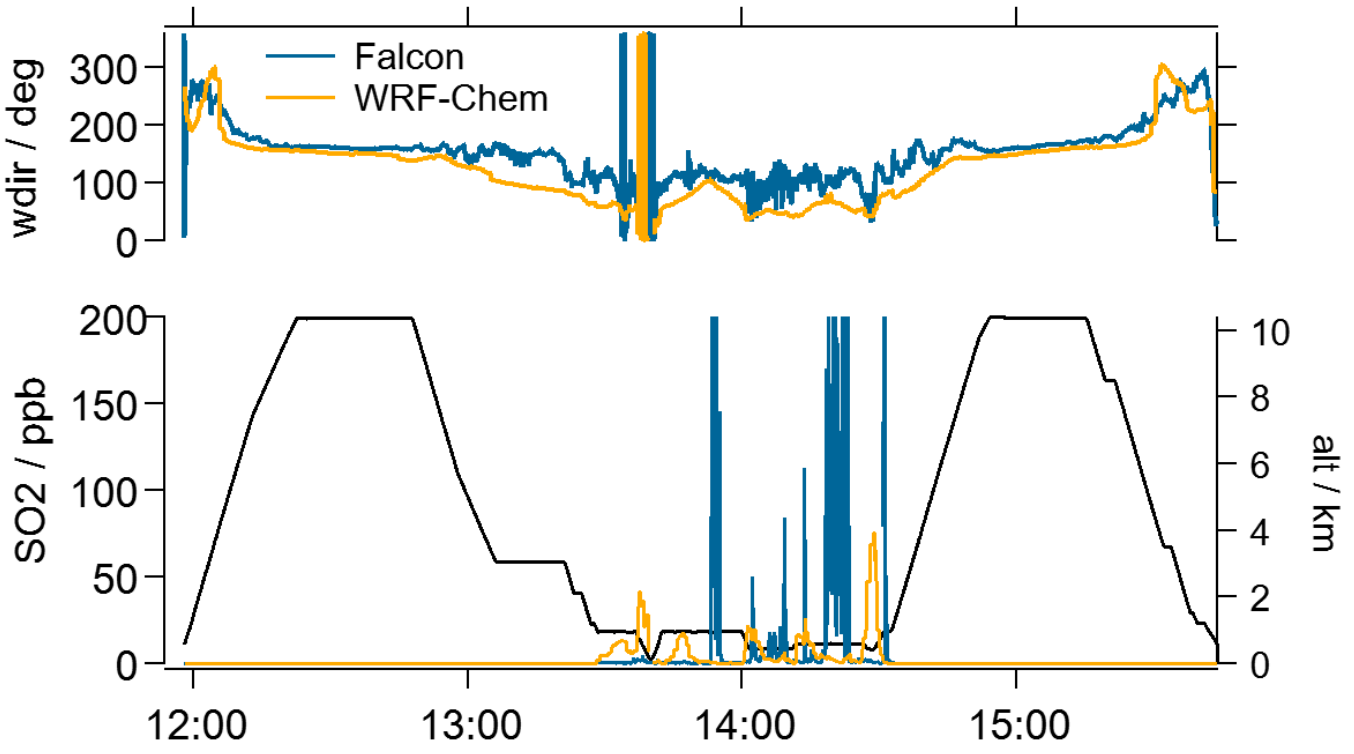




3.1) Falcon flight downwind of Nikola Tesla (Serbia)

- **Detailed vertical profile** indicates that SO_2 is mainly located in boundary layer (BL) → important knowledge for VCD calculation
- First **comparison with WRF-Chem** indicates more easterly wind (-25°) and lower SO_2 mixing ratios

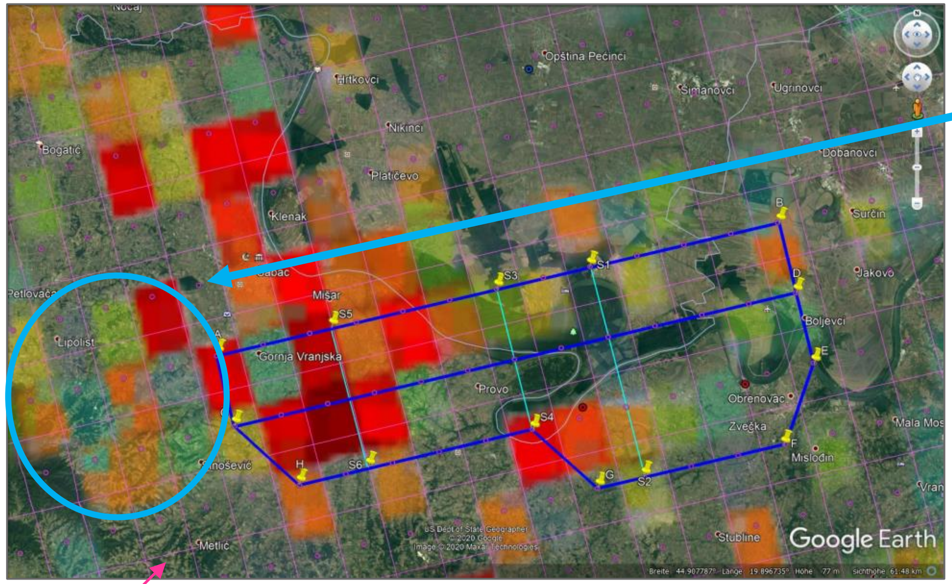




3.1) Operational TROPOMI and COBRA products around Nikola Tesla (Serbia)

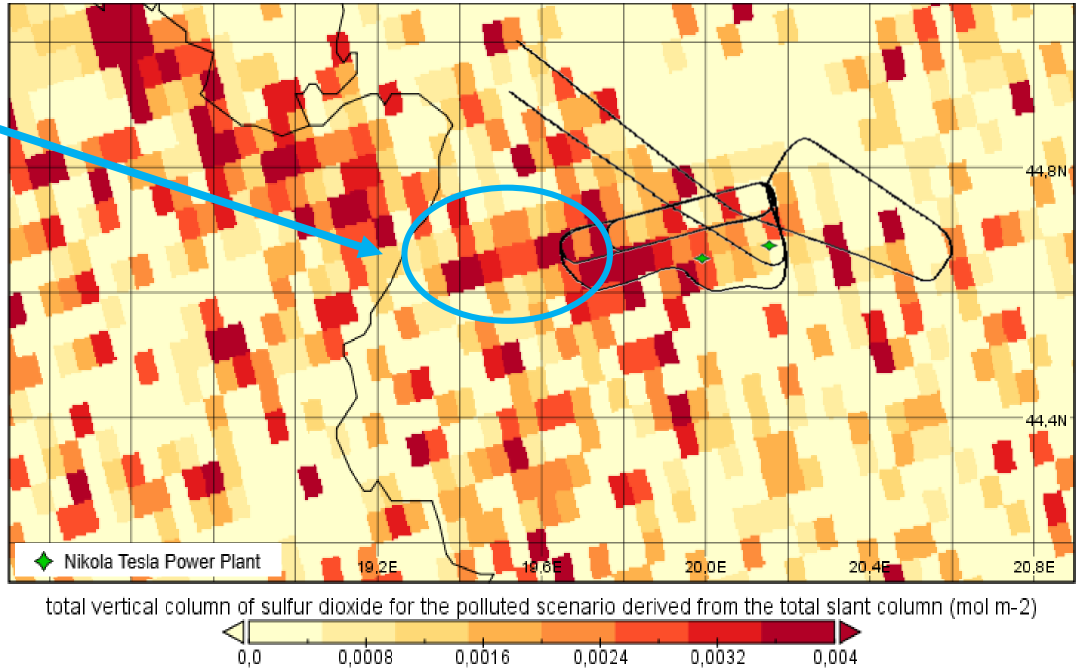
- **Operational and COBRA products** are **different** → challenging for validation with airborne measurements
- Flight track was designed to allow for satellite evaluation in space and time; due to fog the flight was delayed by two hours and took place from ~13:30 to 14:30 UTC

Operational product (orbit at 11:38 UTC)



Different plume detection

COBRA* (orbit at 11:38 UTC)



*COBRA is mostly meant to improve the low SO_2 VCDs (< ~0.25DU) and therefore not performing the retrievals for the alternative windows (325-335 nm and 360-390nm) as in the operational algorithm

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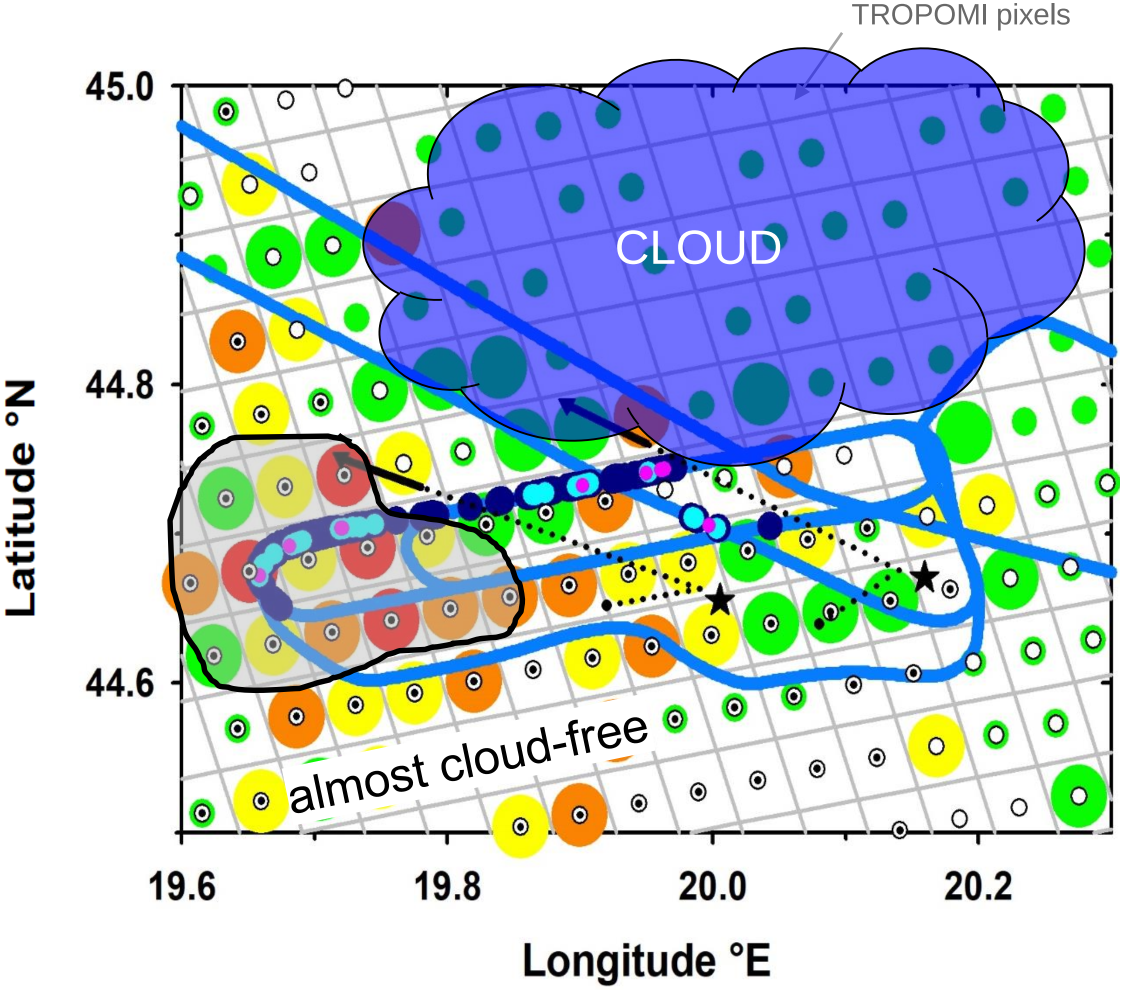
3.1) Combination of Falcon flight & TROPOMI around Nikola Tesla (Serbia)



Selecting reliable TROPOMI **COBRA** pixels

VCD SO_2 [mol m^{-2}] x1000
- 0-2
- 2-5
- 5-10
- 10-15
- >15

Falcon SO_2 [ppb]
- 100-200
- >200

★ Two chimneys of Nikola Tesla power plant

○ Cloud product quality assurance (QA >= 0.50)

⊙ Cloud product cloud fraction (CF <= 0.10)

Wind measured aboard Falcon

→ More **reliable TROPOMI SO_2 pixels on left side** (cloud on right side)

Potential steps for validation of emission plume (left chimney):

- Estimate VCD-SO_2 from Falcon
- Combine with simulated SO_2 to determine total VCD-SO_2 in designated area indicated by “ ”
- Compare with VCD-SO_2 from TROPOMI

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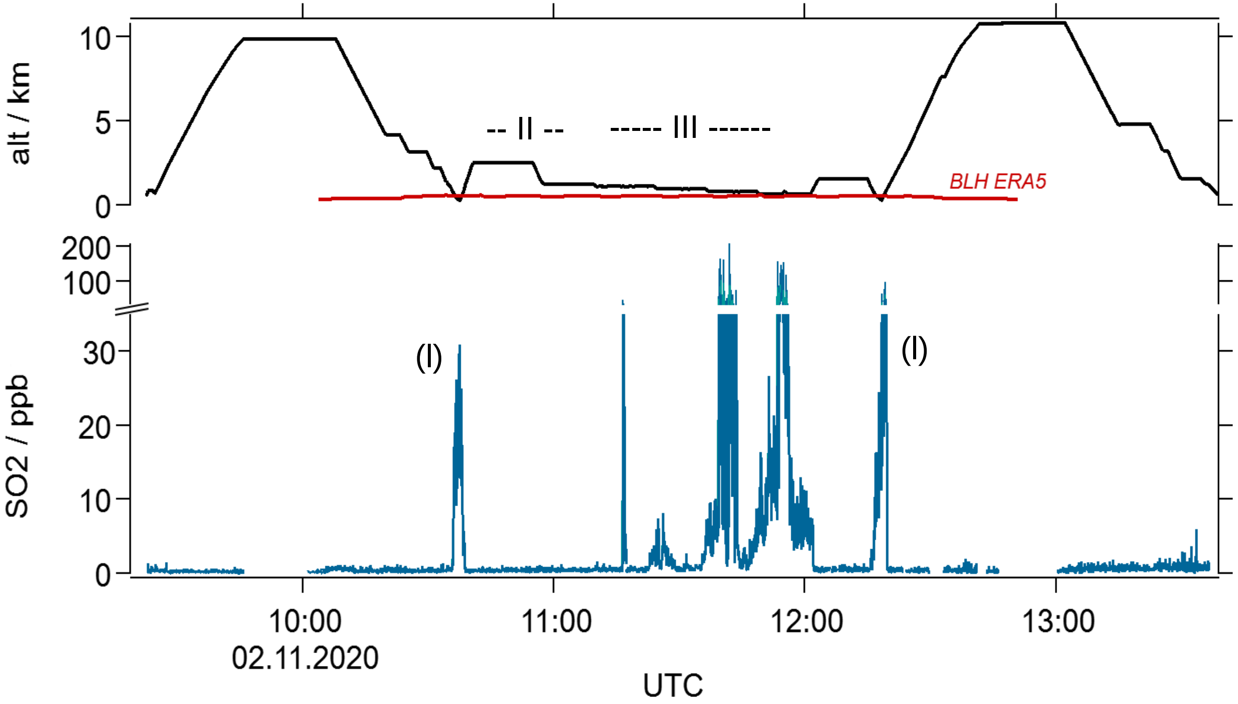
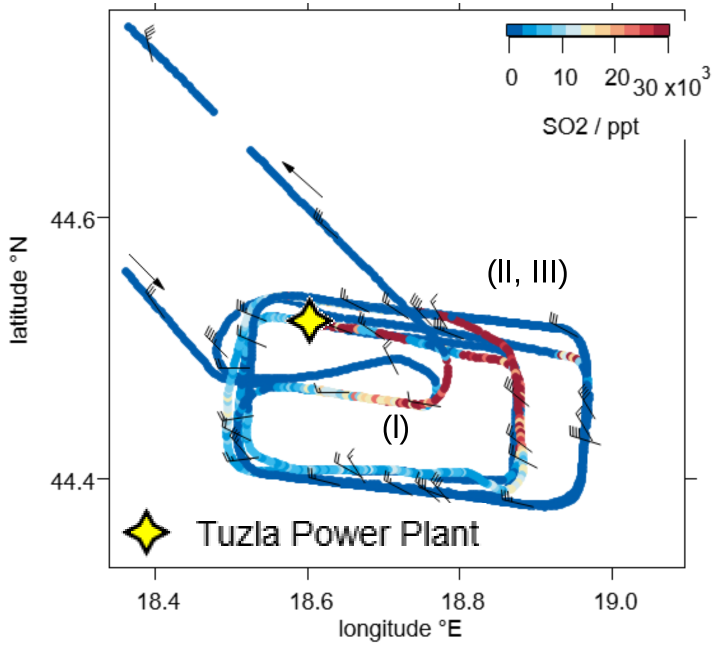
3.2) Falcon flight downwind of Tuzla (Bosnia)

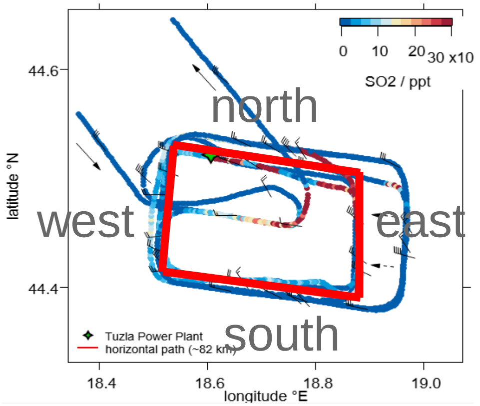
- Flight pattern on November 2nd, 2020
  - low approach at Tuzla airport (I)
  - „box“ at different heights without (2.5, 1.2 km; II) and with (1.1, 0.9, 0.8, 0.6 km; III)

  SO_2 enhancements of up to 100 ppb





3.2) Falcon flight downwind of Tuzla (Bosnia)

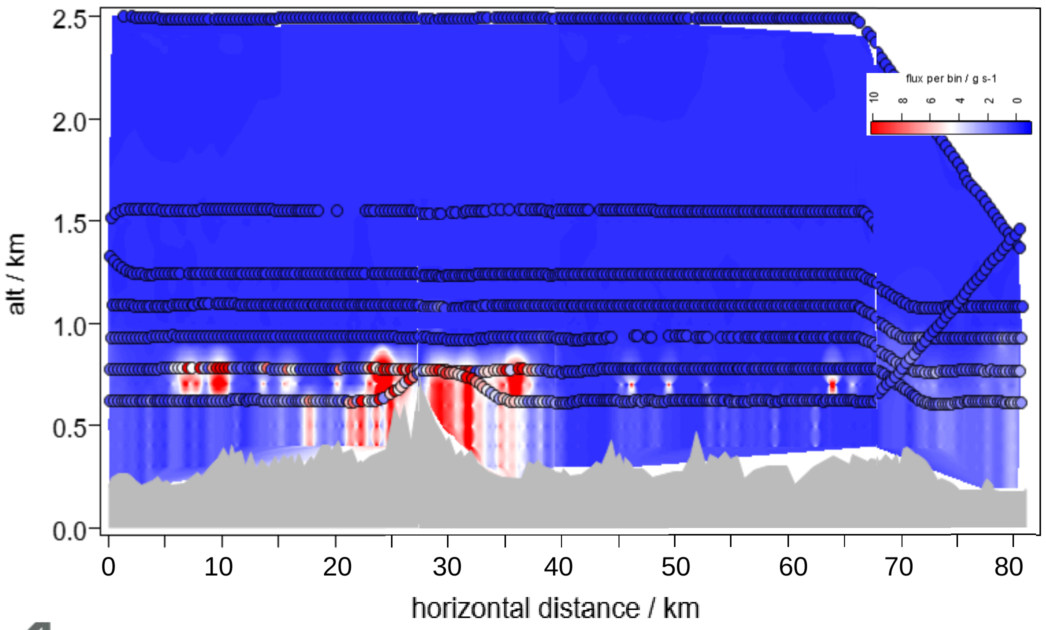


- **Mass balance** for rectangle (in red) to calculate **instantaneous SO_2 flux** [kg s^{-1}]
- Airborne measurements grouped into bins of 300 x 100 m (horiz. x vert.), interpolated between flight legs, lowest flight leg valid down to ground

$$F = \int\int \vec{U}(\theta, z)\sin(\alpha)\cdot(C(\theta, z) - C_{bg})L\,d\theta dz,$$

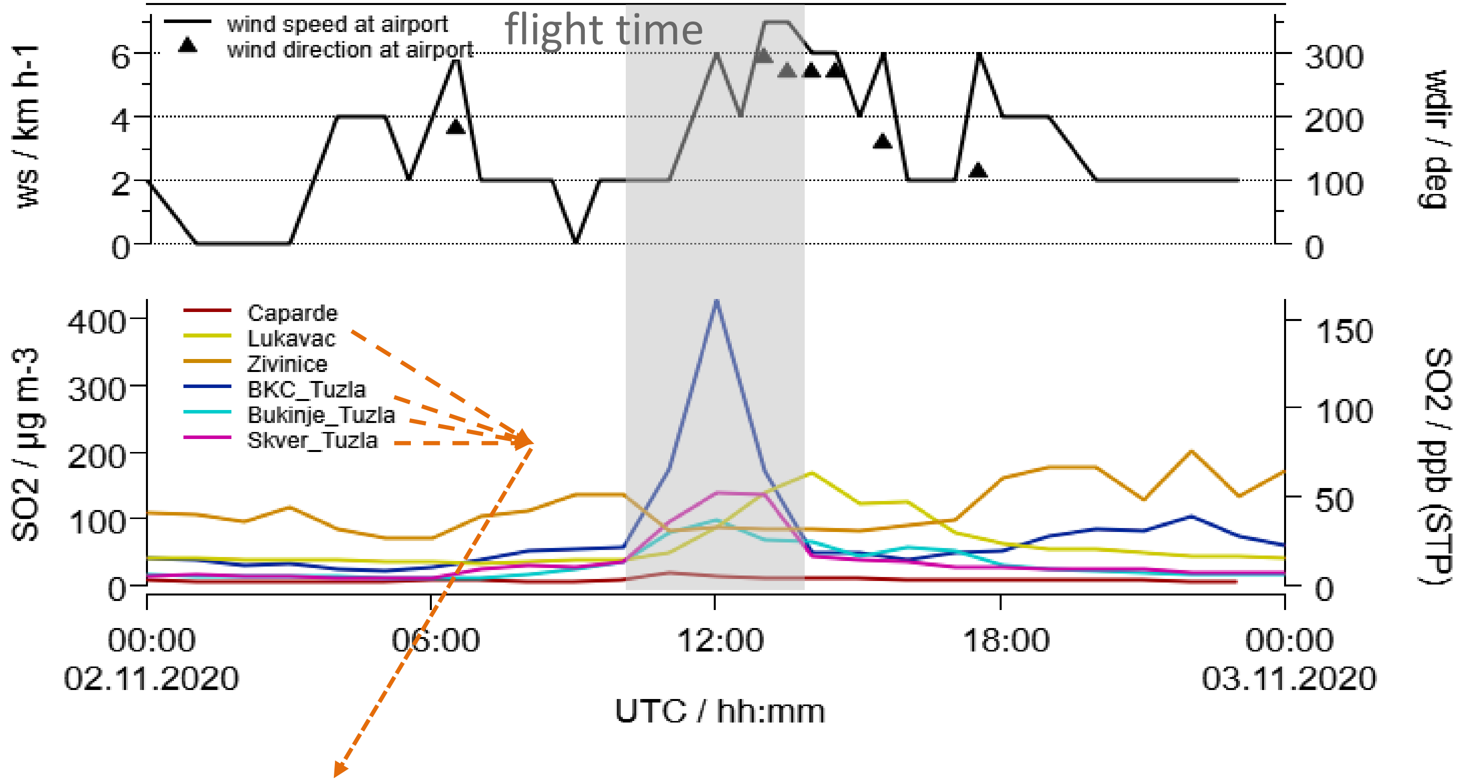
ppb to g m^{-3} by ideal gas law; integrated in horizontal and vertical; L=difference between two points on regular grid of 300x100 m, U=wind speed, α=wind angle

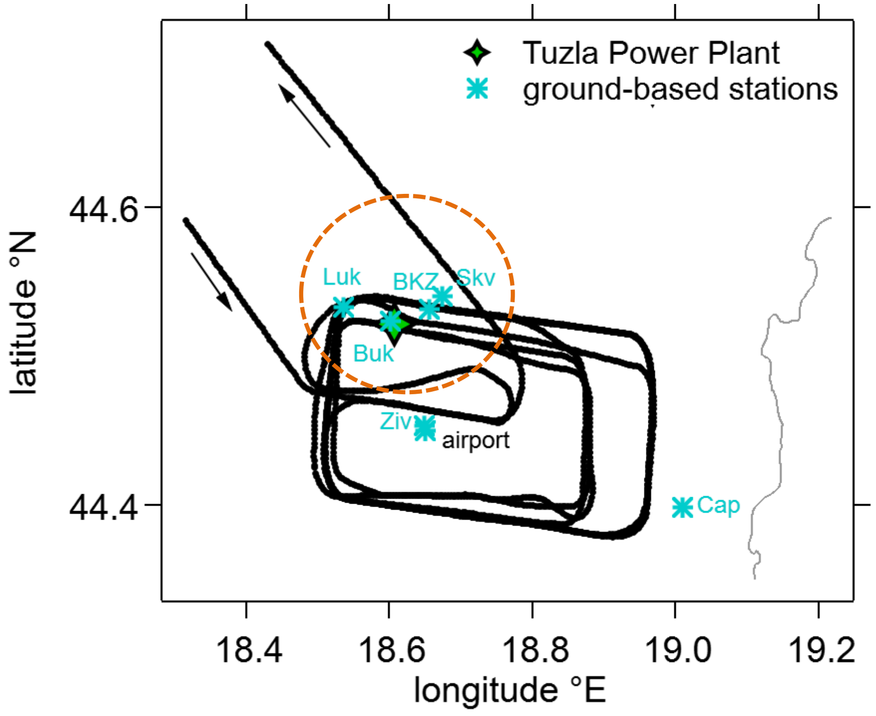
Interpolated measurements along red line: from north to east, south and west



- **Preliminary flux ~3.8 kg s^{-1}**, which is a **factor ~2 higher** than average emissions from EDGAR, OMI HTAP and E-PRTR of 1.8 kg s^{-1}

3.2) Ground-based measurements at Tuzla (Bosnia)



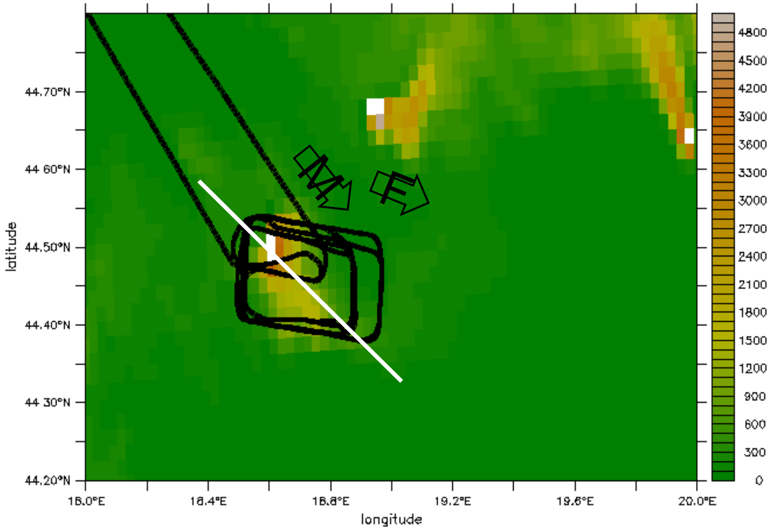


- „Cluster“ detects **SO_2 mixing ratios at similar magnitude** as observed aboard Falcon
- Lukavac latest in time, but wind direction changes during the day

STP=standard conditions for temperature and pressure

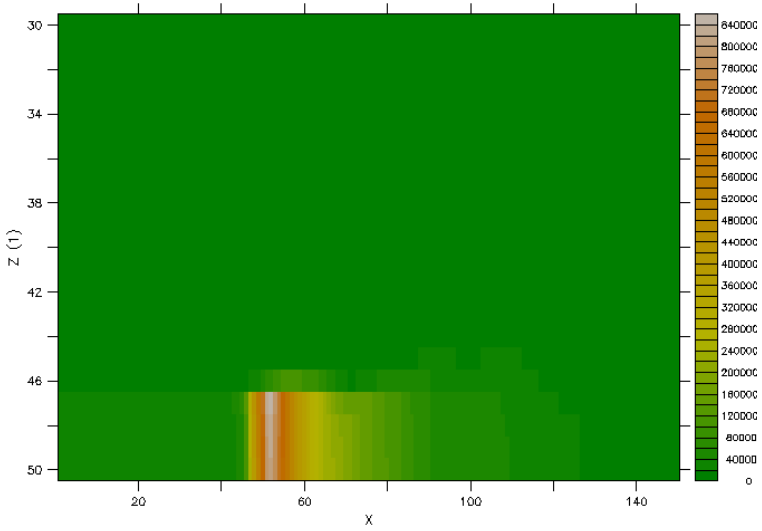
3.2) MECO(n) simulations of Tuzla (Bosnia)

P-SO_2 column (ppt) at 12 UTC



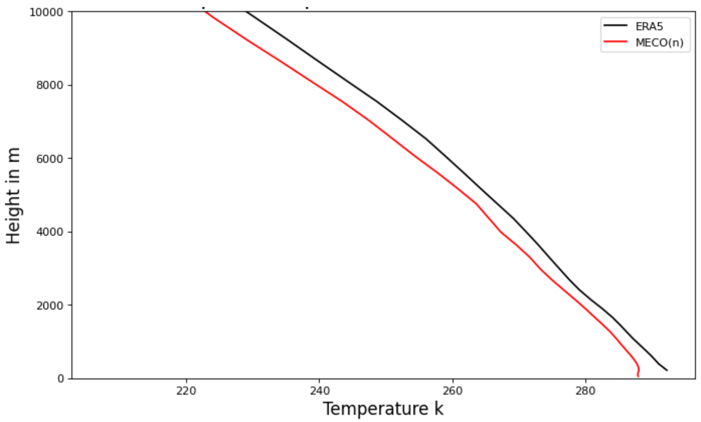
(mean wind direction of M=MECO(n), F=Flight)

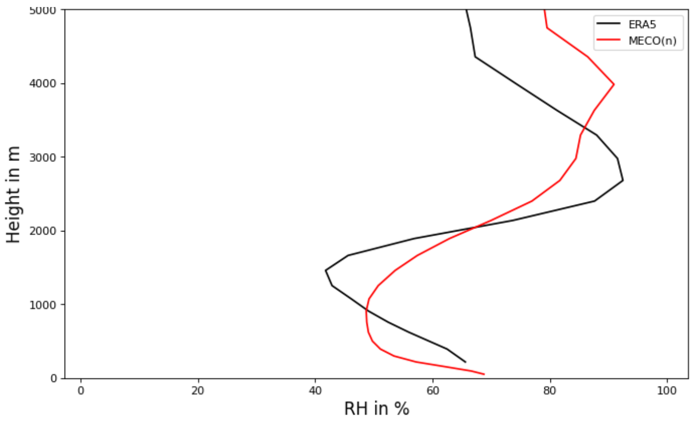
P-SO_2 (ppt) vertical section along white line



- Clean inflow
- **Uniform vertical P-SO_2 distribution** in boundary layer → consistent with mass balance assumption

- Ongoing **effort to minimize model bias** in temperature, relative humidity and wind direction

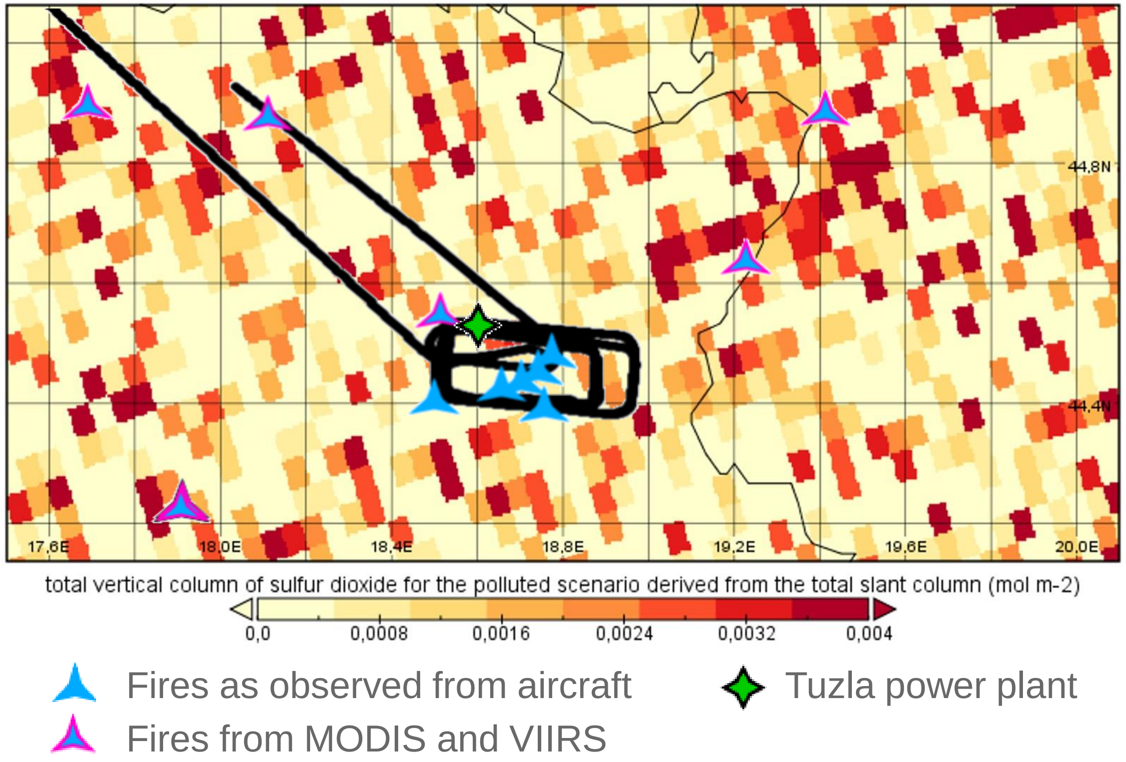




3.2) COBRA product around Tuzla (Bosnia)

- Both, COBRA and the operational product, are **noisy** (lots of smaller fires which influence the sensitivity due to enhanced amount of aerosol)
- Useful **validation** needs to be **further examined**

COBRA (orbit at 11:32 UTC)



4) Summary and Outlook

4) Summary and Outlook

- **Airborne in situ SO_2** measurements were for the first time **successfully conducted** downwind of two **major coal-fired power plants** in Serbia and Bosnia-Herzegovina
- Two **TROPOMI underpass validation flights** were conducted and revealed important lessons learned for future flights
- Validation of **TROPOMI-SO_2 with Falcon-SO_2** looks promising for the flight in Serbia
- **Mass Balance estimate** of Falcon-SO_2 looks promising for the flight in Bosnia

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- Improvements on Falcon-SO_2 **data quality** of extreme high SO_2 mixing ratios
- **Ongoing refinements** on mass balance estimation, MECO(n) and WRF-Chem model simulations
- Comparison of **SO_2 Vertical Column Densities** over designated areas using TROPOMI and combined Falcon-MECO(n)-SO_2 data
- **Future TROMOPI-SO_2 validation flights** envisaged within the framework of METHANE-To-Go

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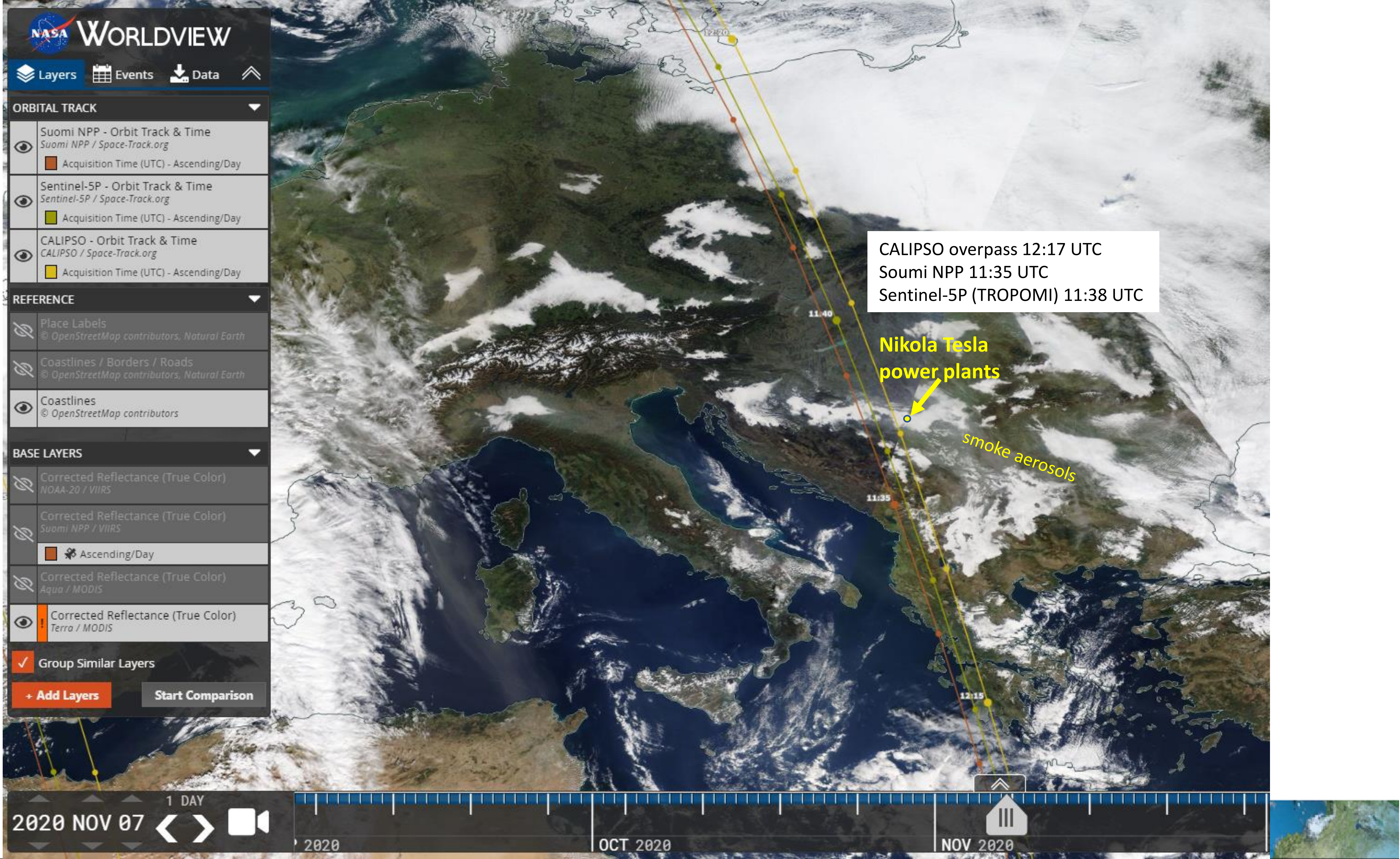
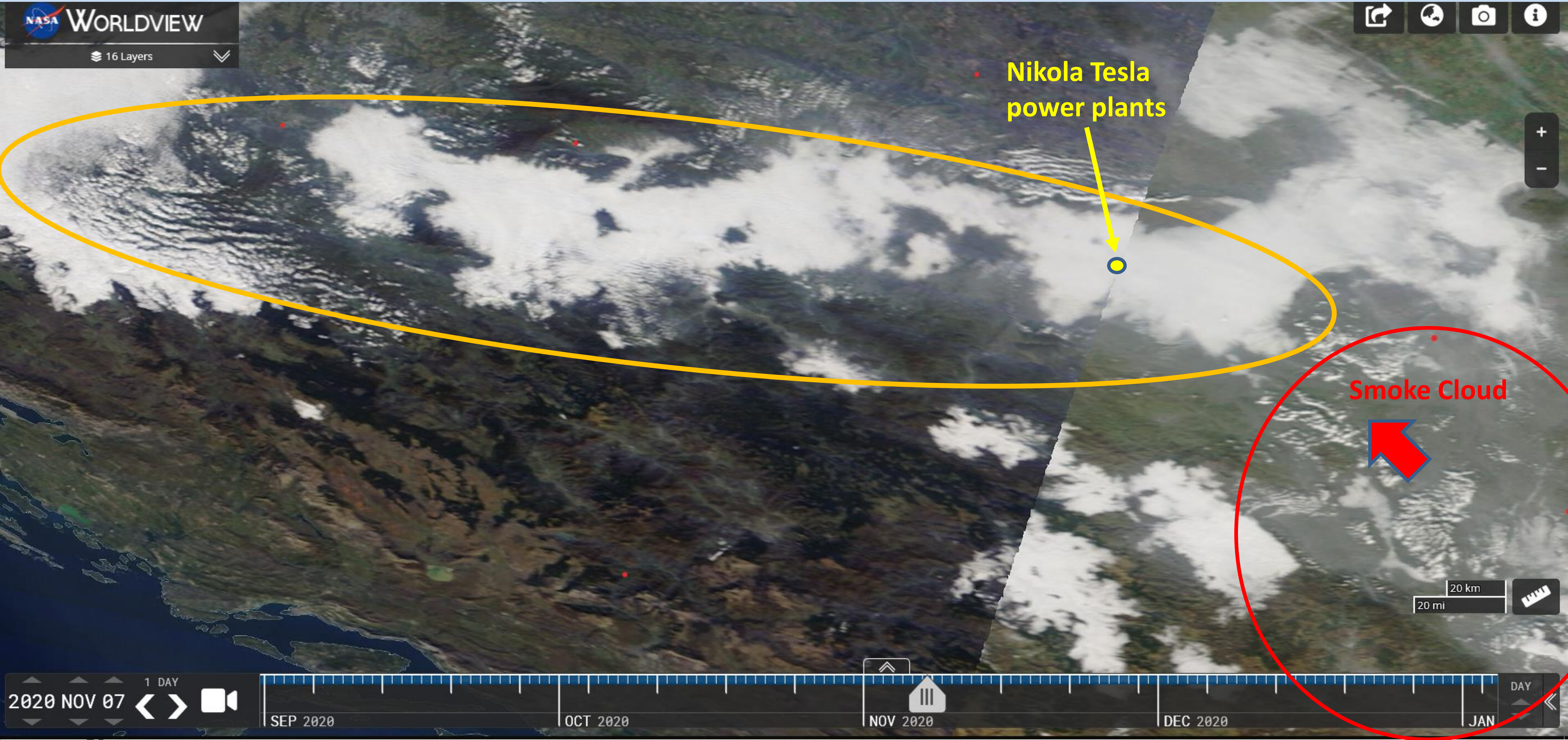
- www.NZZ.ch: Bosnien: https://www.nzz.ch/international/bosnien-kohlekraftwerke-verpesten-die-luft-ld.1538169 (last access 09.04.2021)

Additional slides



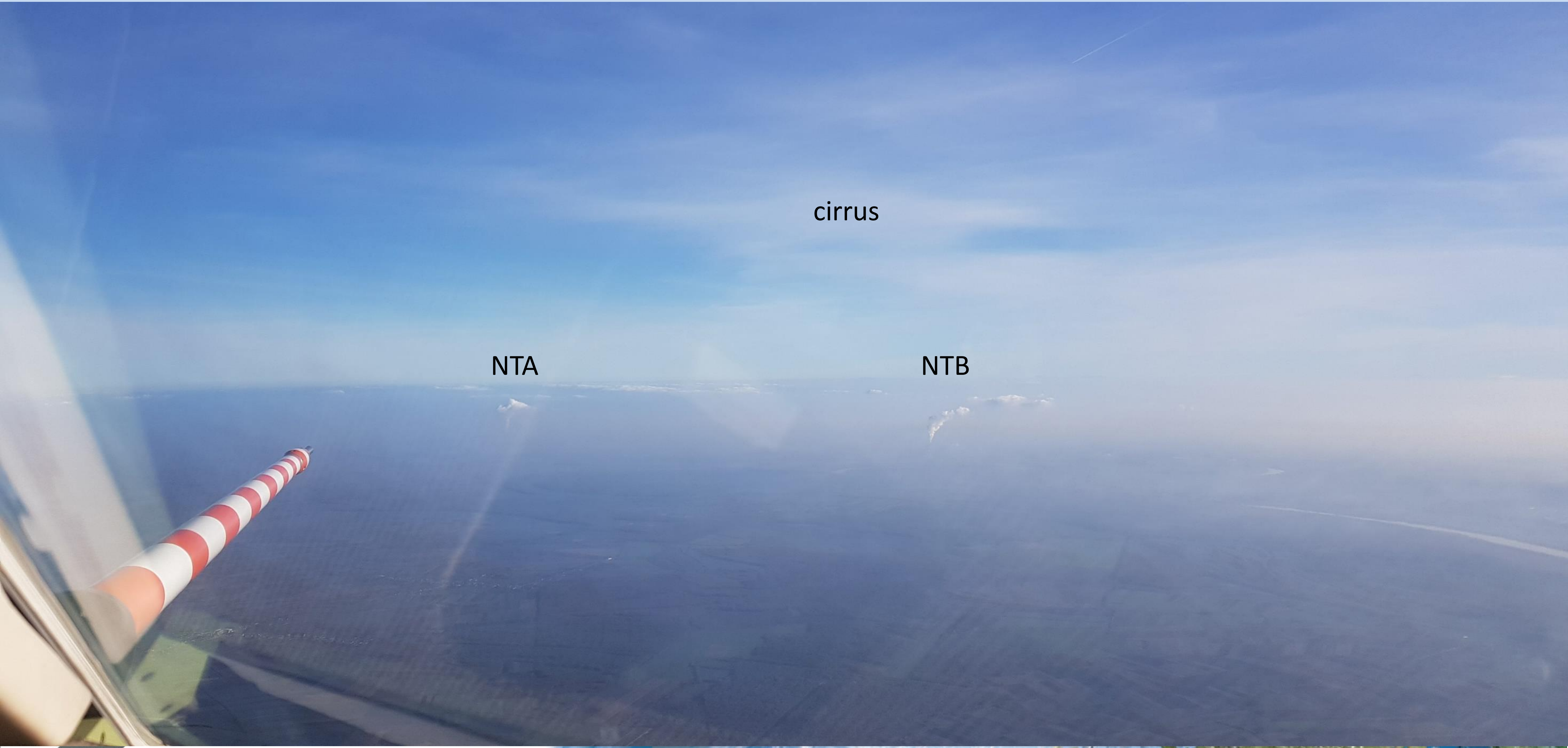
WORLDVIEW
Layers
Events
Data
ORBITAL TRACK
Suomi NPP - Orbit Track & Time
Suomi NPP / Space-Track.org
Acquisition Time (UTC) - Ascending/Day
Sentinel-5P - Orbit Track & Time
Sentinel-5P / Space-Track.org
Acquisition Time (UTC) - Ascending/Day
CALIPSO - Orbit Track & Time
CALIPSO / Space-Track.org
Acquisition Time (UTC) - Ascending/Day
REFERENCE
Place Labels
© OpenStreetMap contributors, Natural Earth
Coastlines / Borders / Roads
© OpenStreetMap contributors, Natural Earth
Coastlines
© OpenStreetMap contributors
BASE LAYERS
Corrected Reflectance (True Color)
NOAA-20 / VIIRS
Corrected Reflectance (True Color)
Suomi NPP / VIIRS
Ascending/Day
Corrected Reflectance (True Color)
Aqua / MODIS
Corrected Reflectance (True Color)
Terra / MODIS
Group Similar Layers
+ Add Layers
Start Comparison
CALIPSO overpass 12:17 UTC
Soumi NPP 11:35 UTC
Sentinel-5P (TROPOMI) 11:38 UTC
Nikola Tesla power plants
smoke aerosols
11:40
11:35
12:15
2020 NOV 07
1 DAY
2020
OCT 2020
NOV 2020

Cloud Situation in the morning over Croatia, Bosnia & Serbia – 7 November 2020

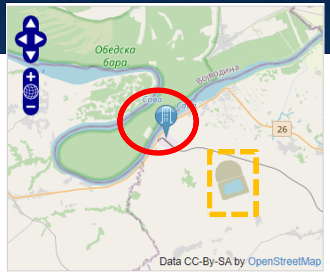


DLR

Flight to Nikola Tesla A (left) & B (right) – 7 November 2020 at 13:23 UTC (lat 44.89°N, lon 19.76°E)

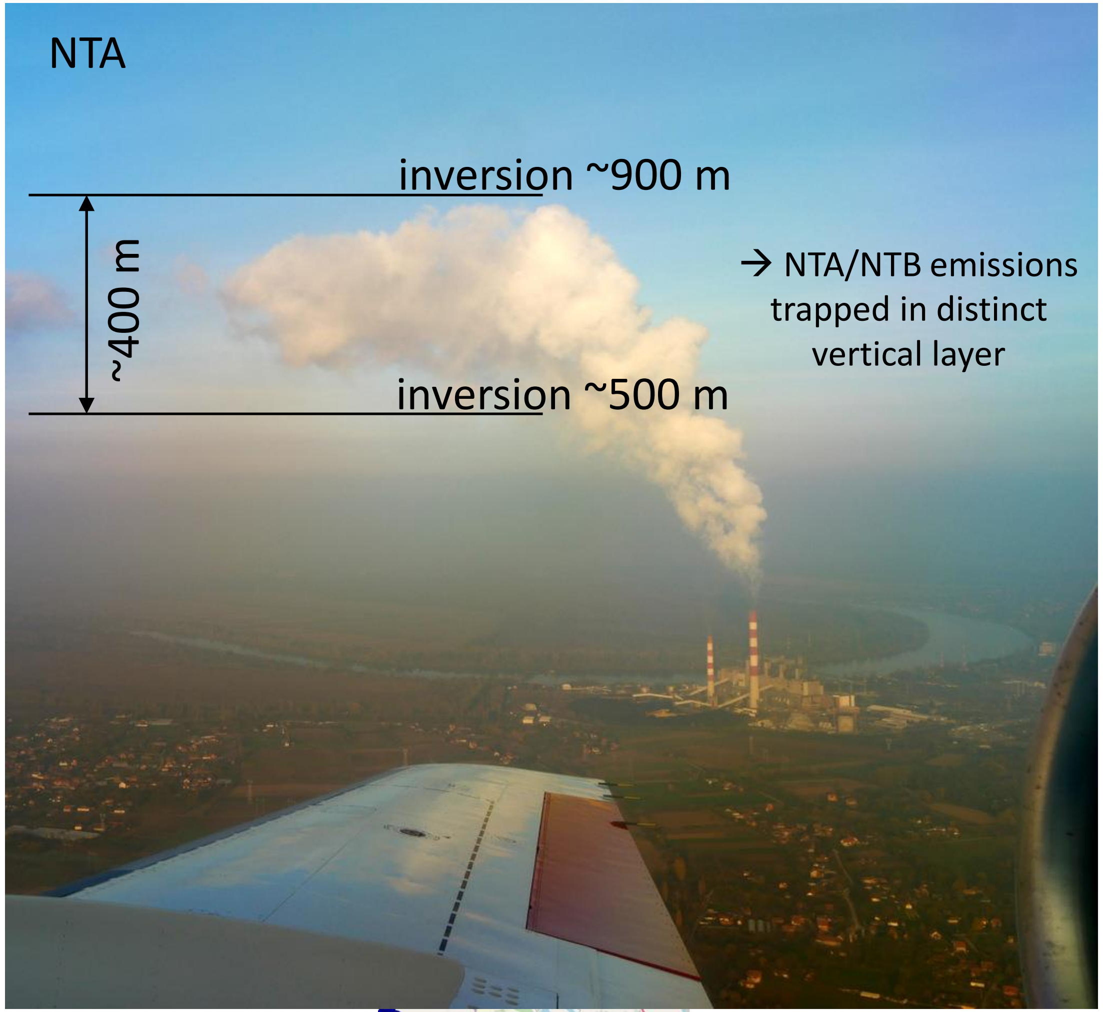


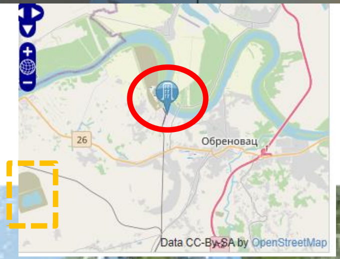
Flight to Nikola Tesla A (right) & B (left) – 7 November 2020



N

S





DLR