11th Advanced Training Course on Land RS

Biophysical variables retrieval and time series smoothing

- Sentinel-2 Surface Reflectance
- Noise and gap-filling: temporal compositing, Smoothing and Gap-filling
- Value-Added Products: Leaf Area Index

Teacher: Francesco Vuolo
with contributions from our team

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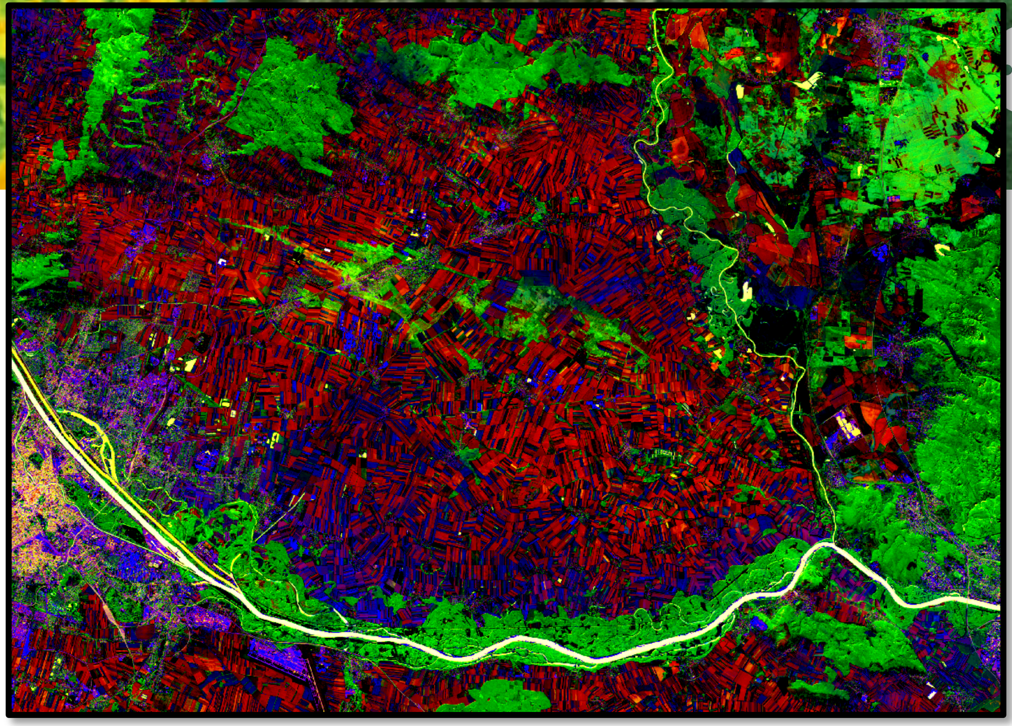
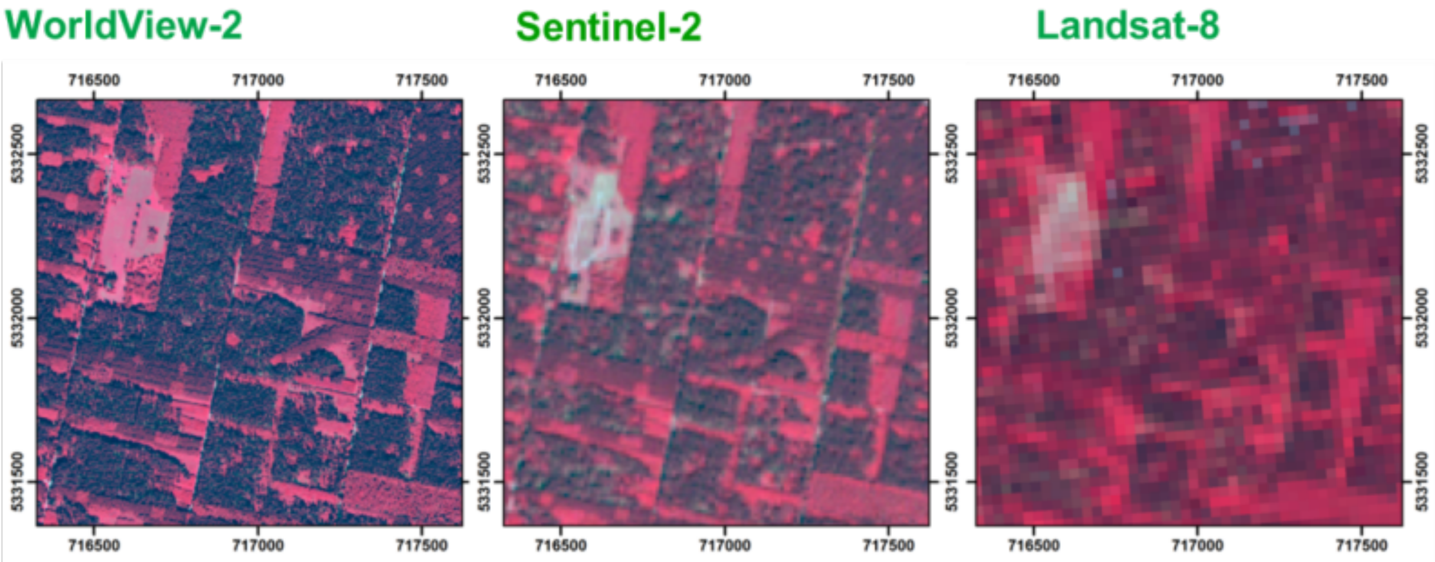
Department of Landscape, Spatial and Infrastructure Sciences
Institute of Geomatics

sentinel-2

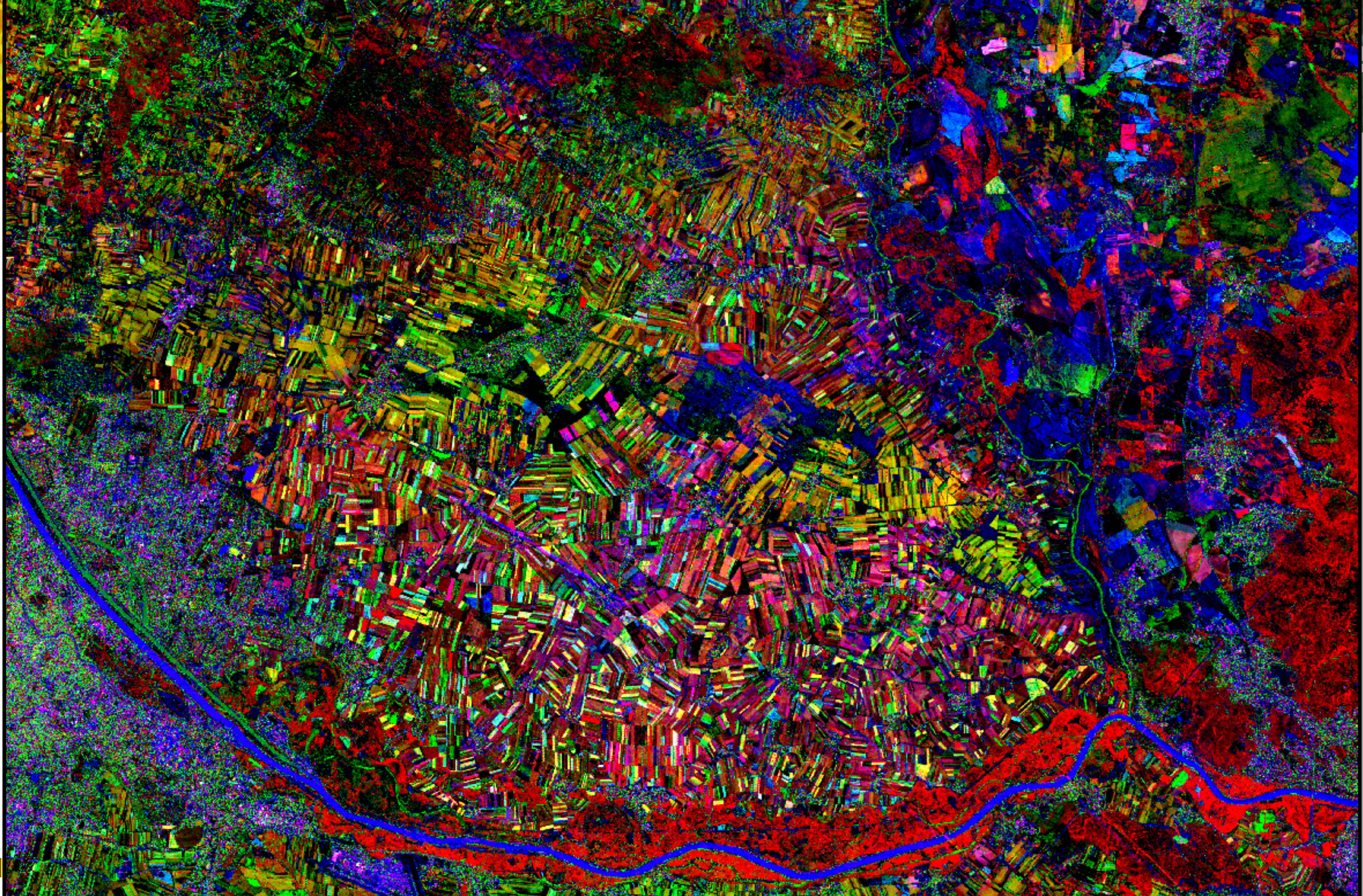
- Sentinel-2
  - 10 spectral bands (+3)
  - 10-20 m spatial resolution
  - wide swath width (290 km)
  - high revisit time (~5 days)



PCs: 1-2-3: 30/08/2015



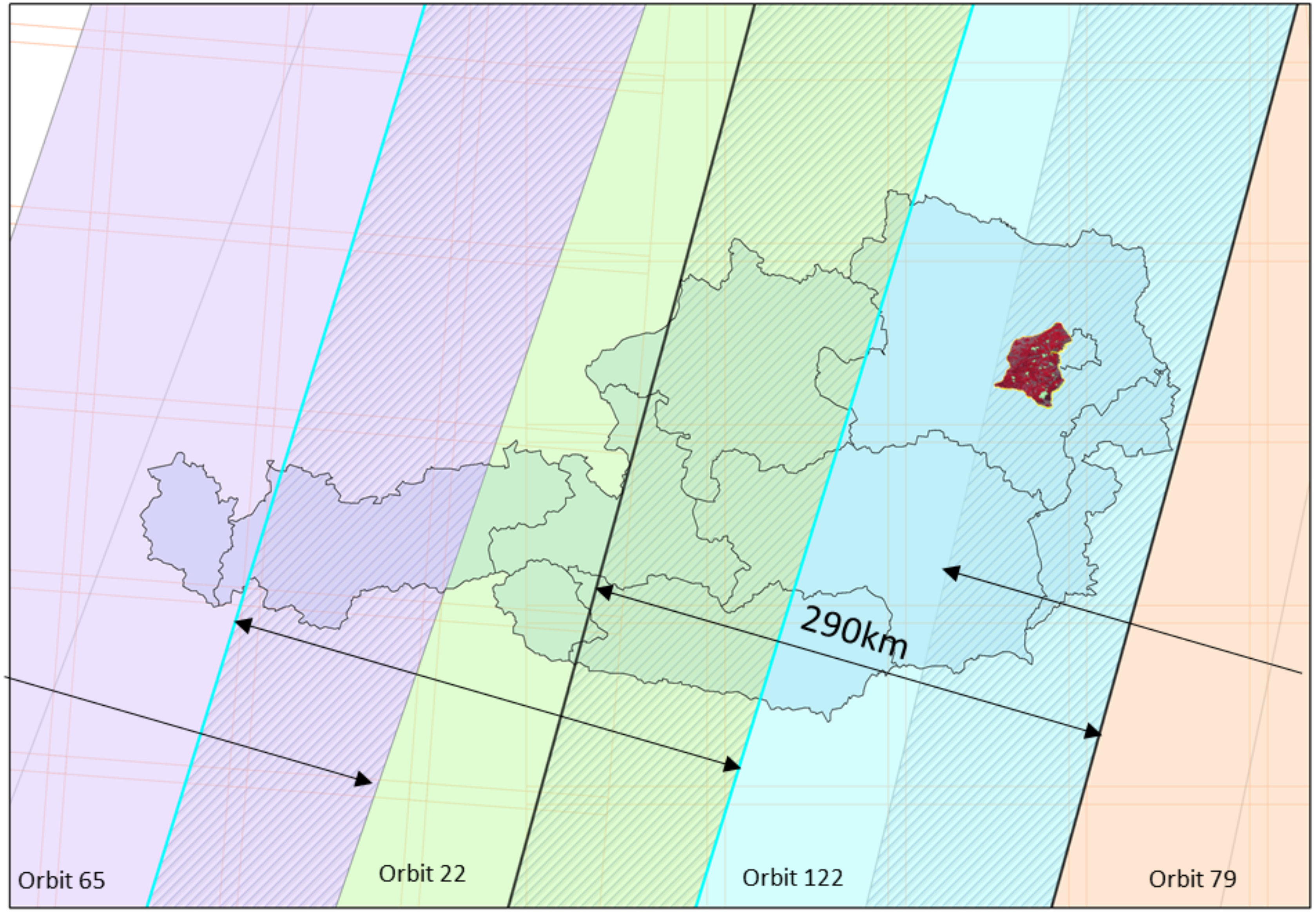
PCs: 1-2-3: 30/08/2015

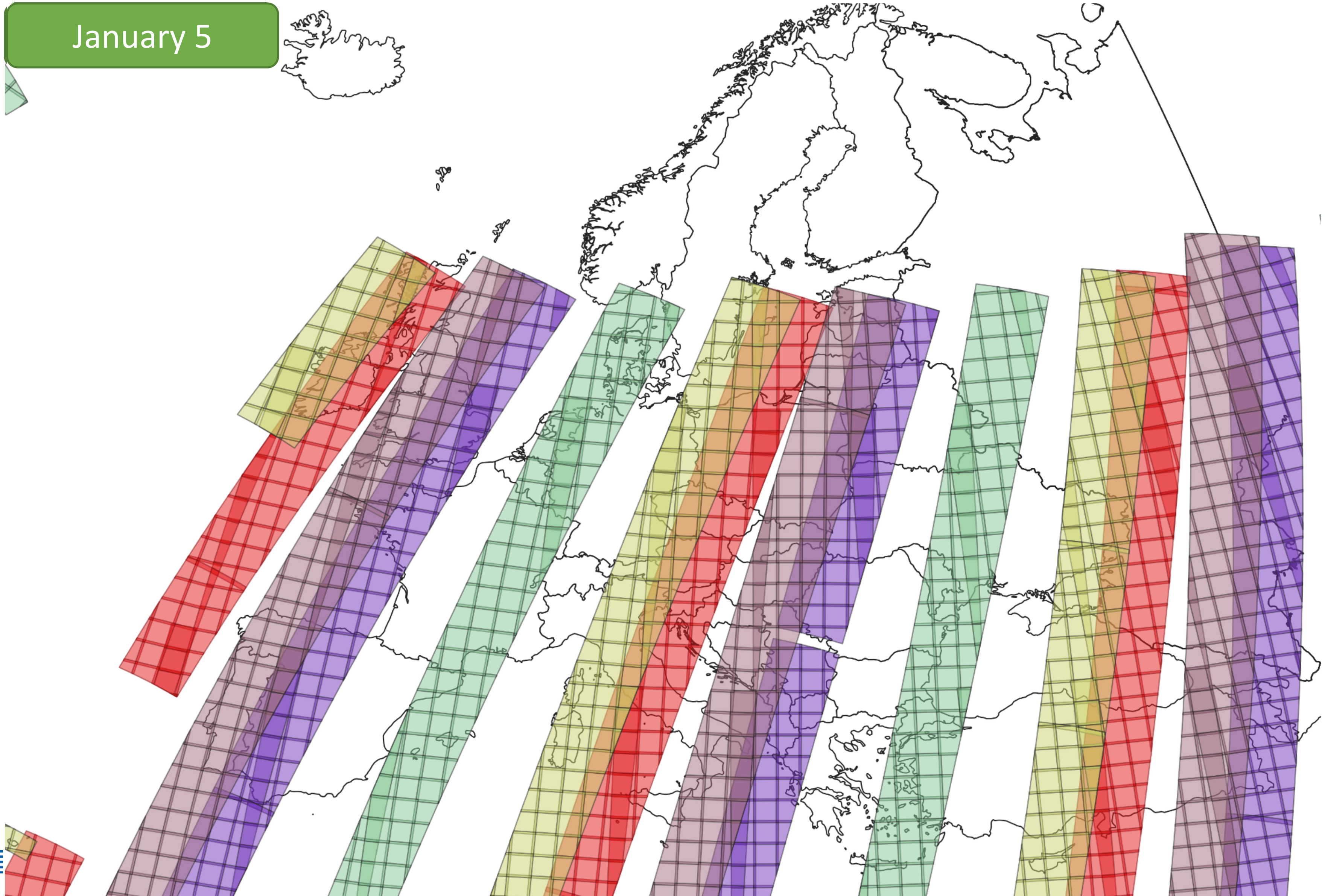


PCs: 5-6-7: 30/08/2015

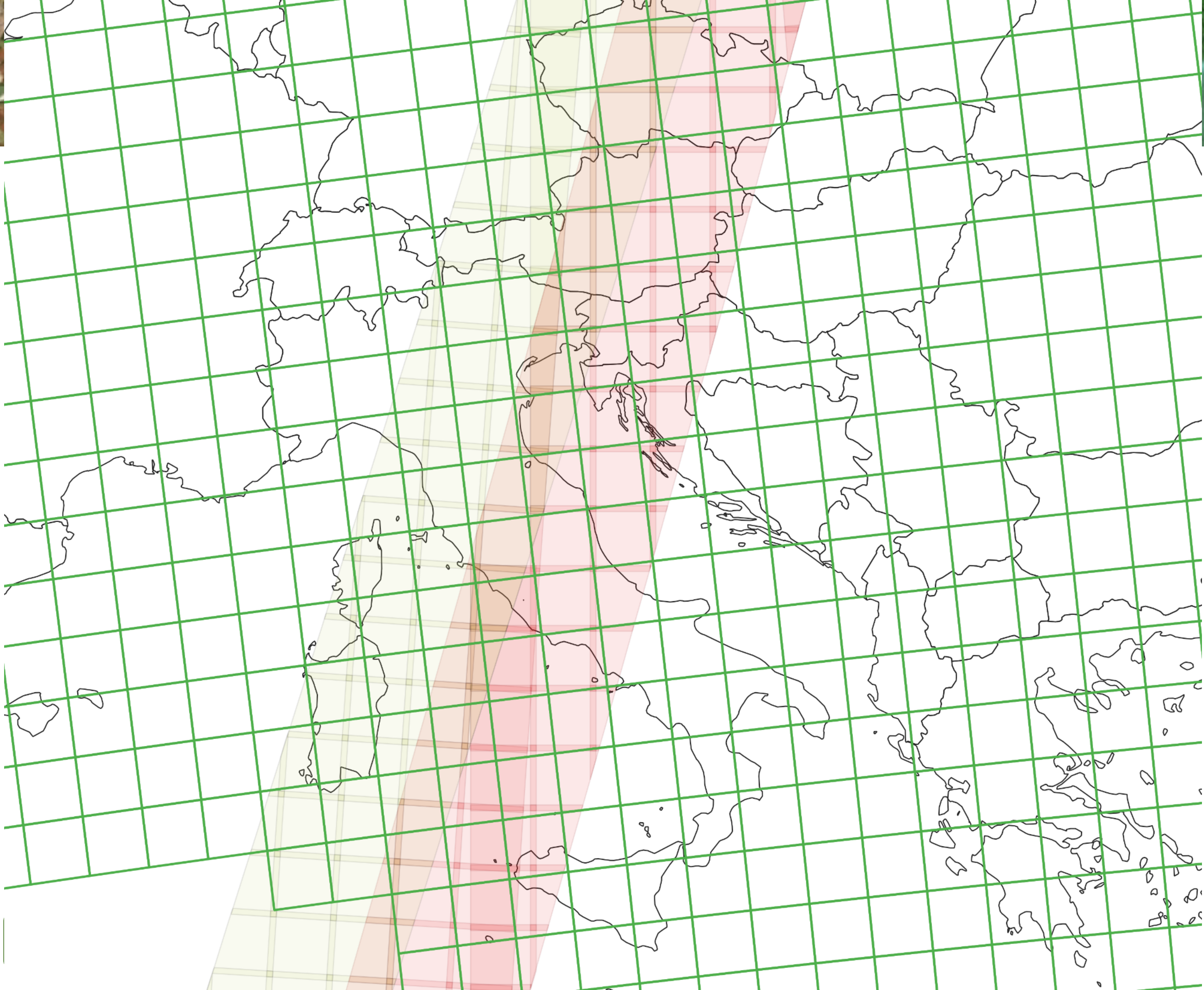
Challenge 1: data granularity
spatially and temporally fragmented EO data

facilitate the exploitation of multi-temporal and multi-satellite datasets





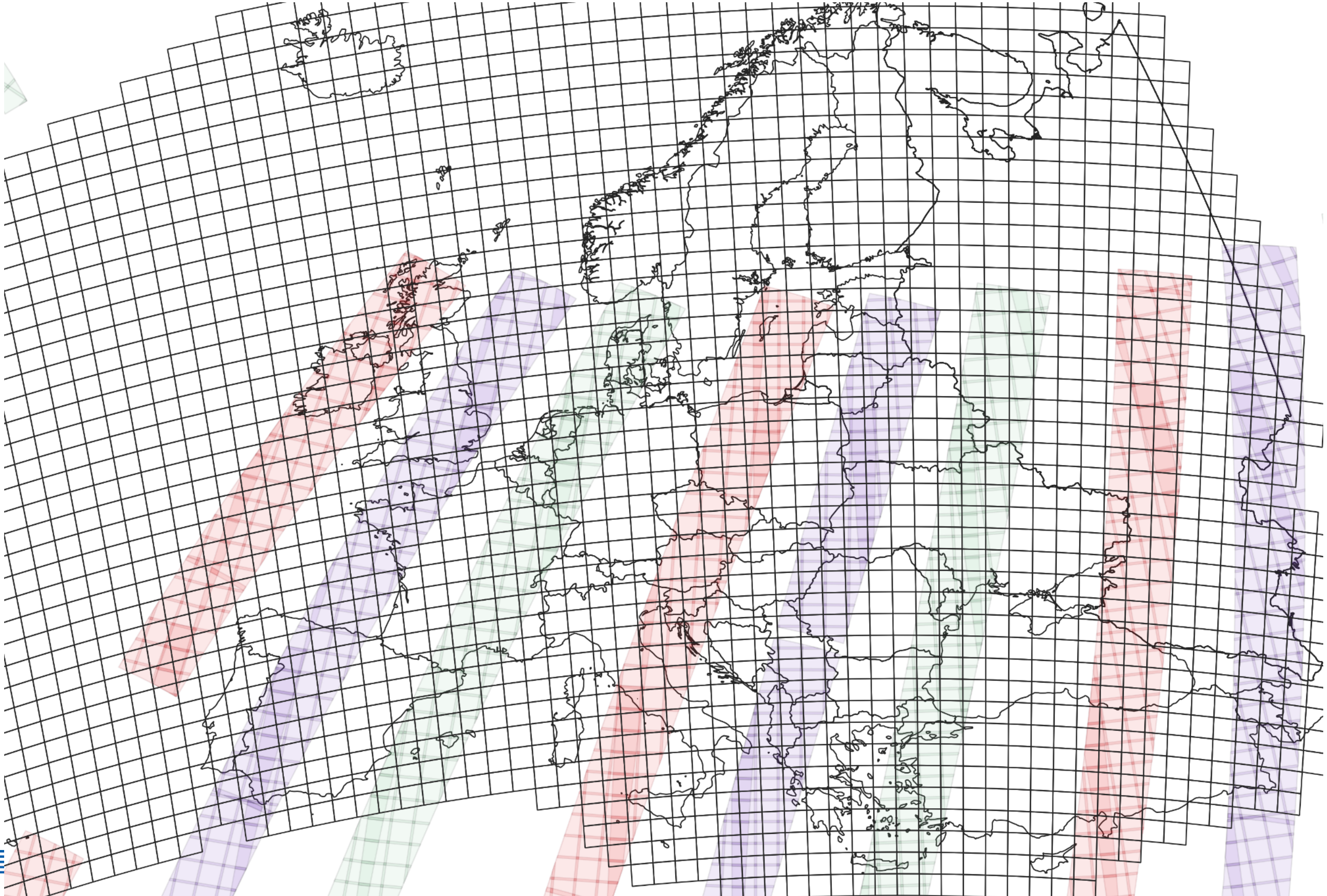
All observations,
only 1 of the 2 S-2
missing



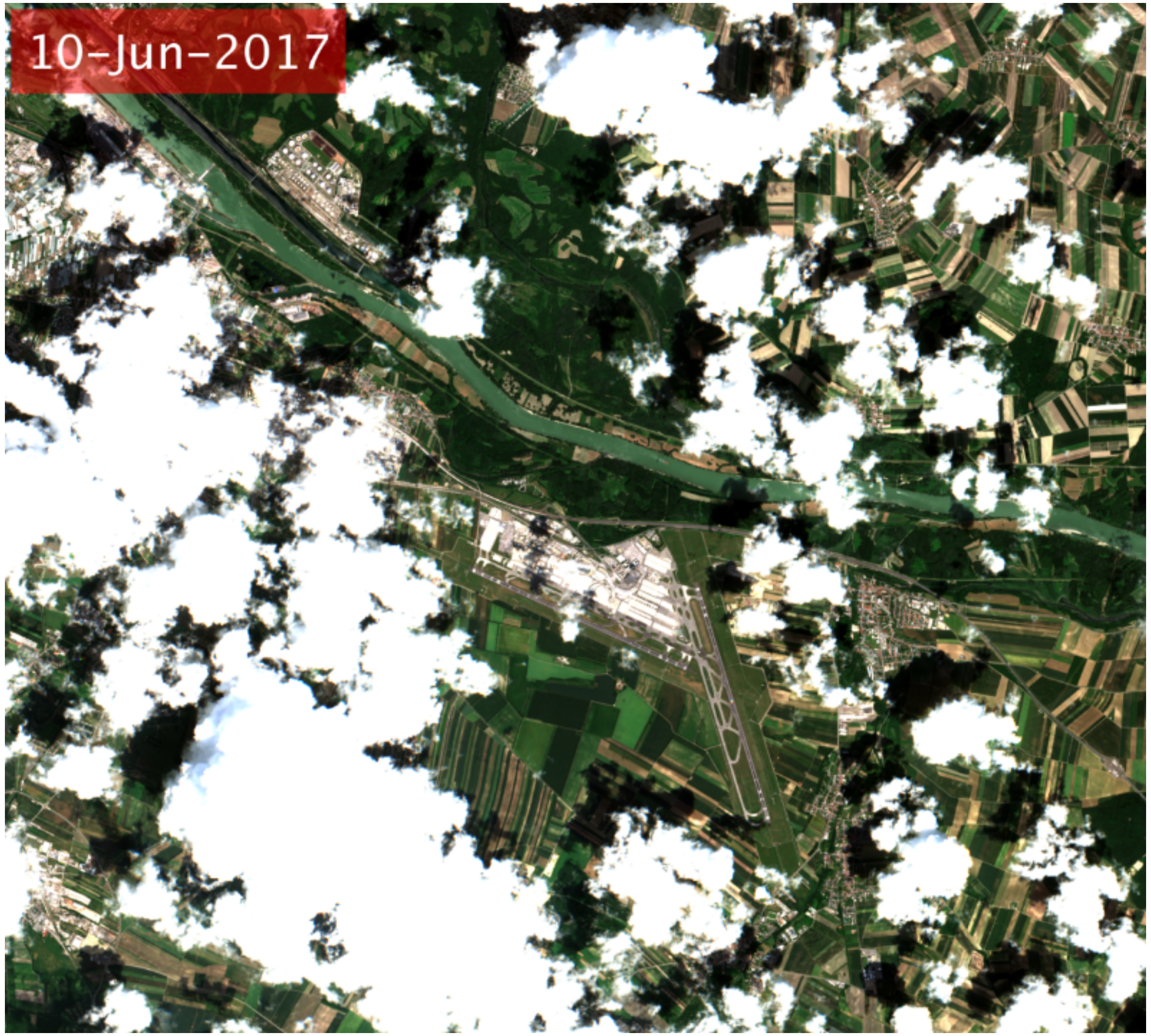
Re-project to
Equi7Grid

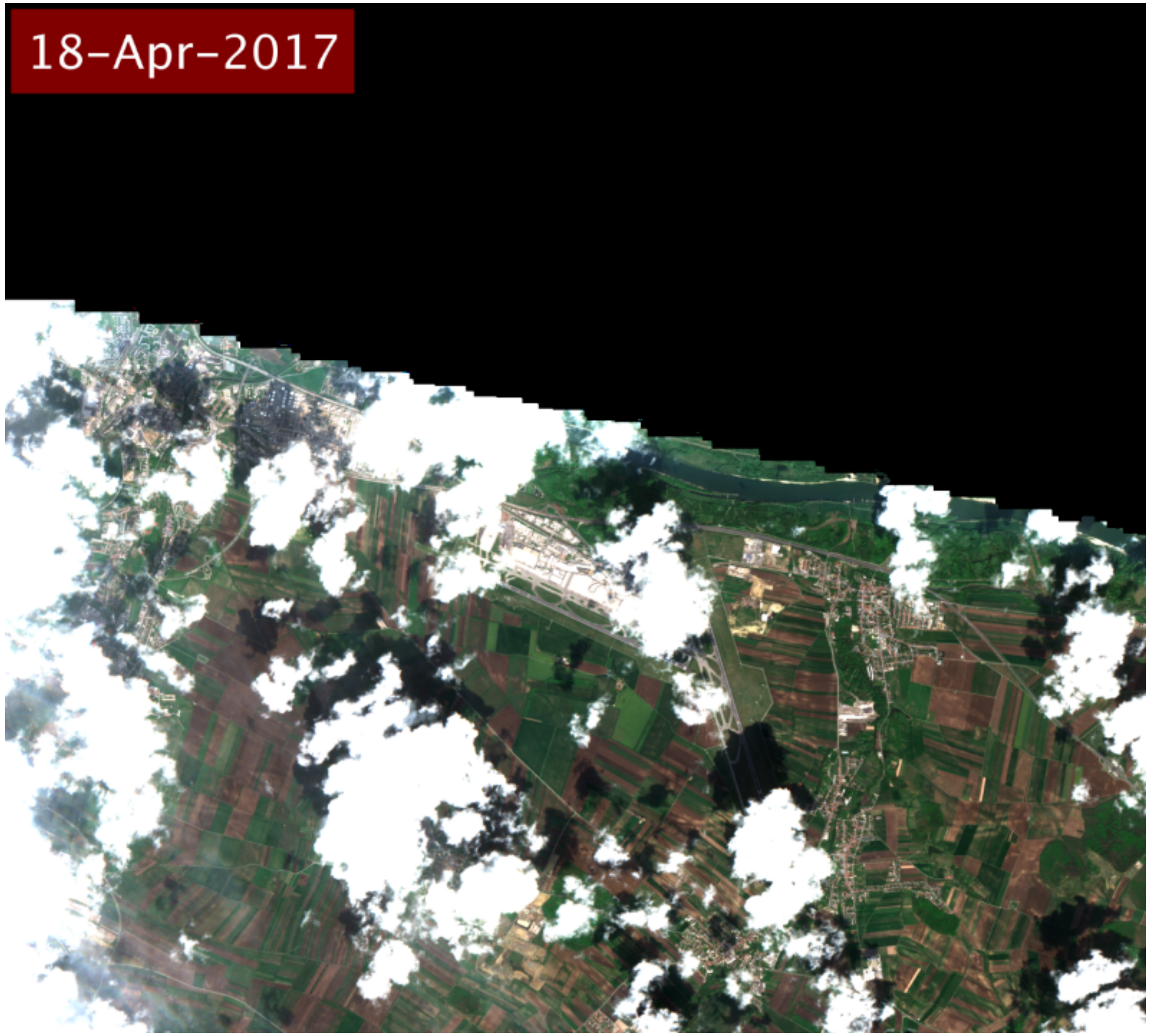
Equi7Grid European Coverage

Compatible with other available data cubes (S-1)

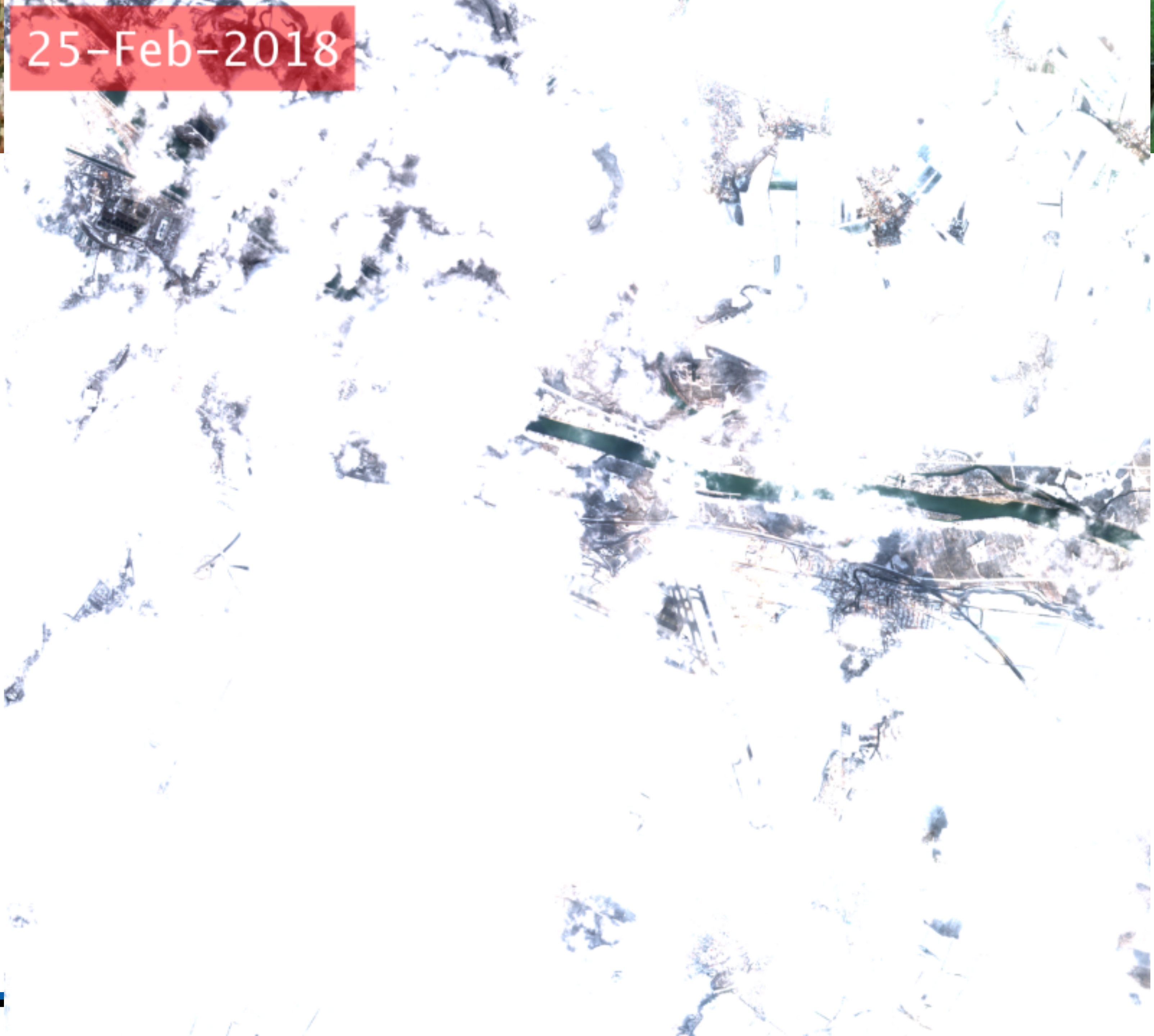


Challenge 2: Noise and data gaps






15-Feb-2018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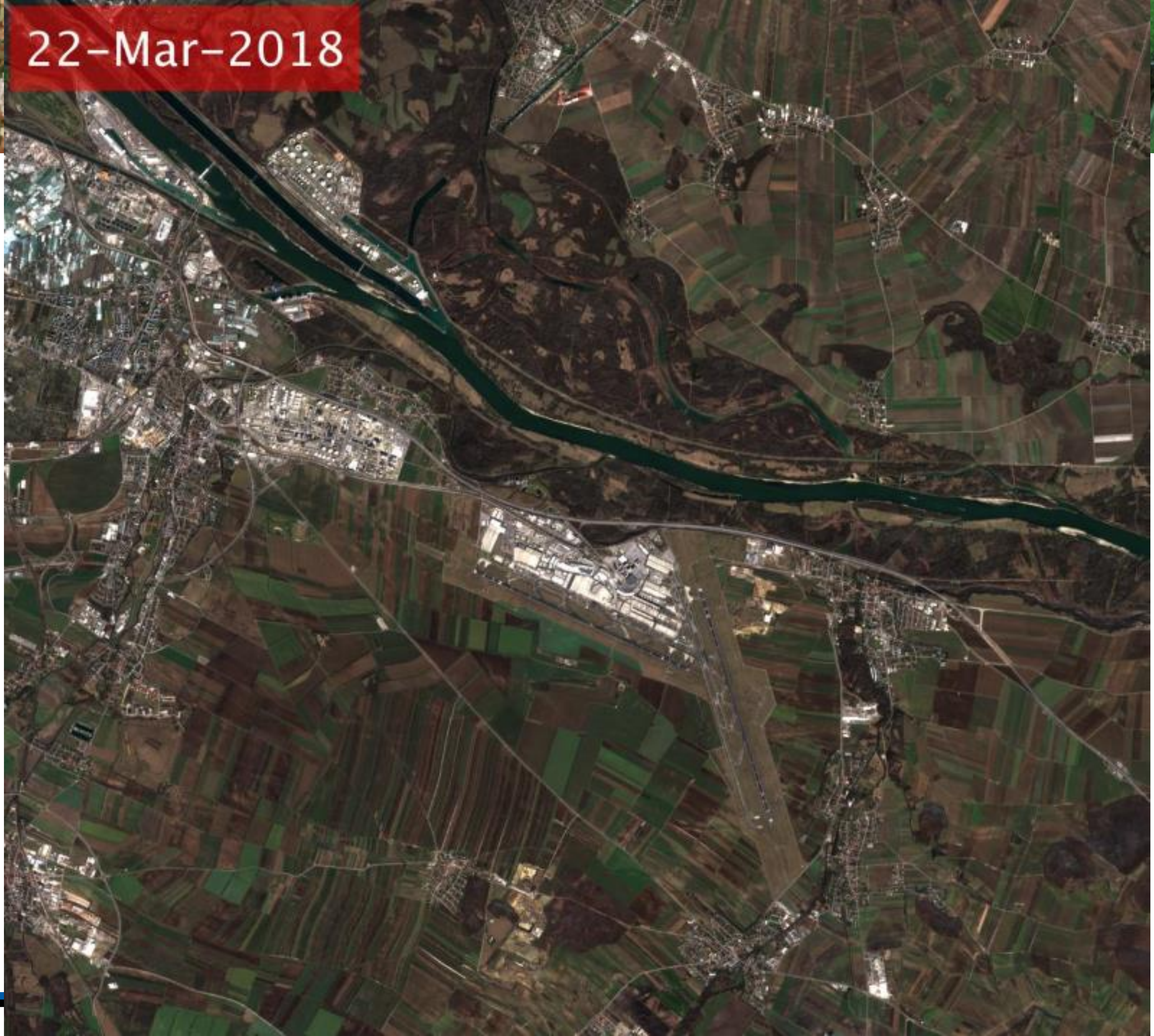
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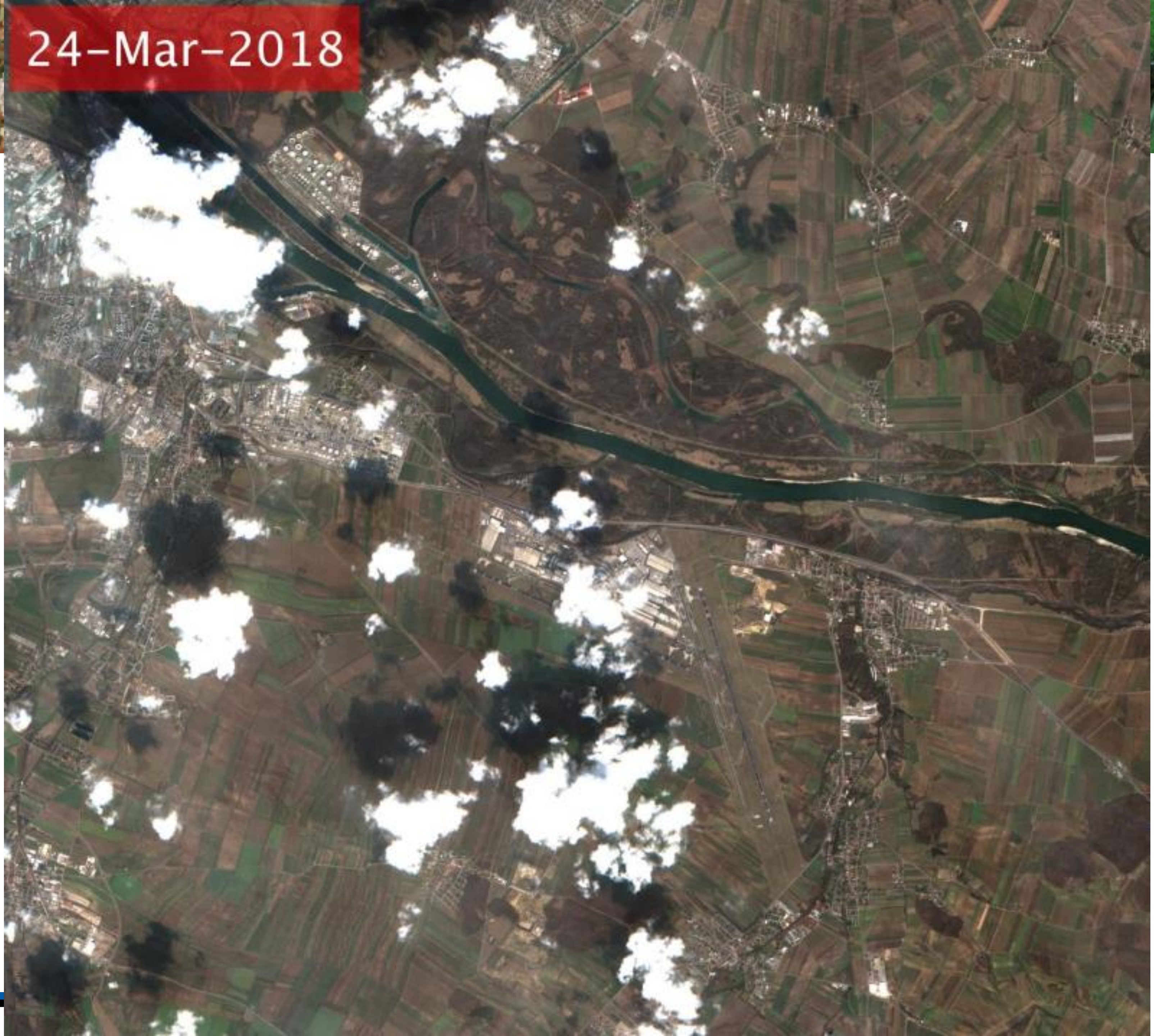
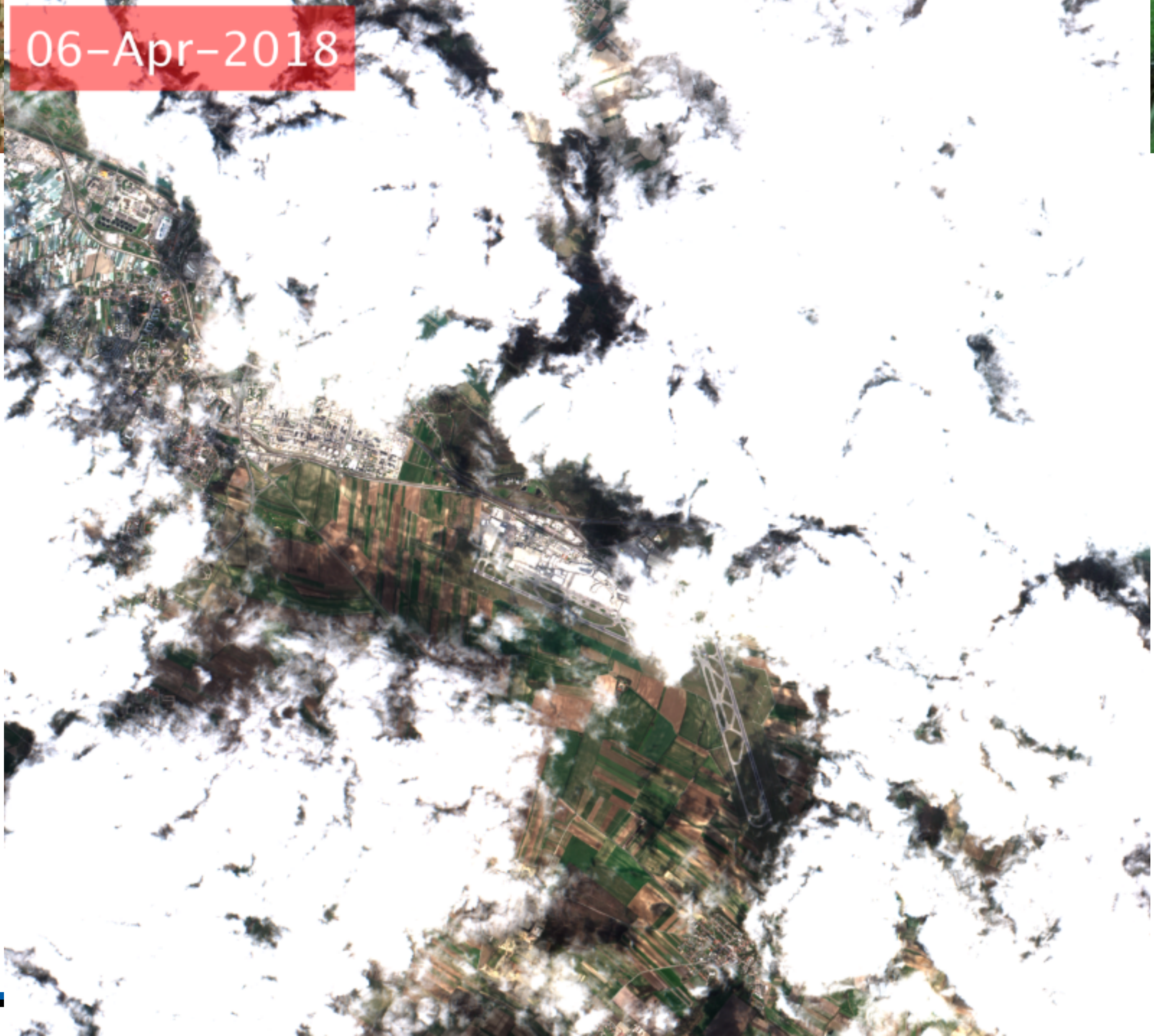
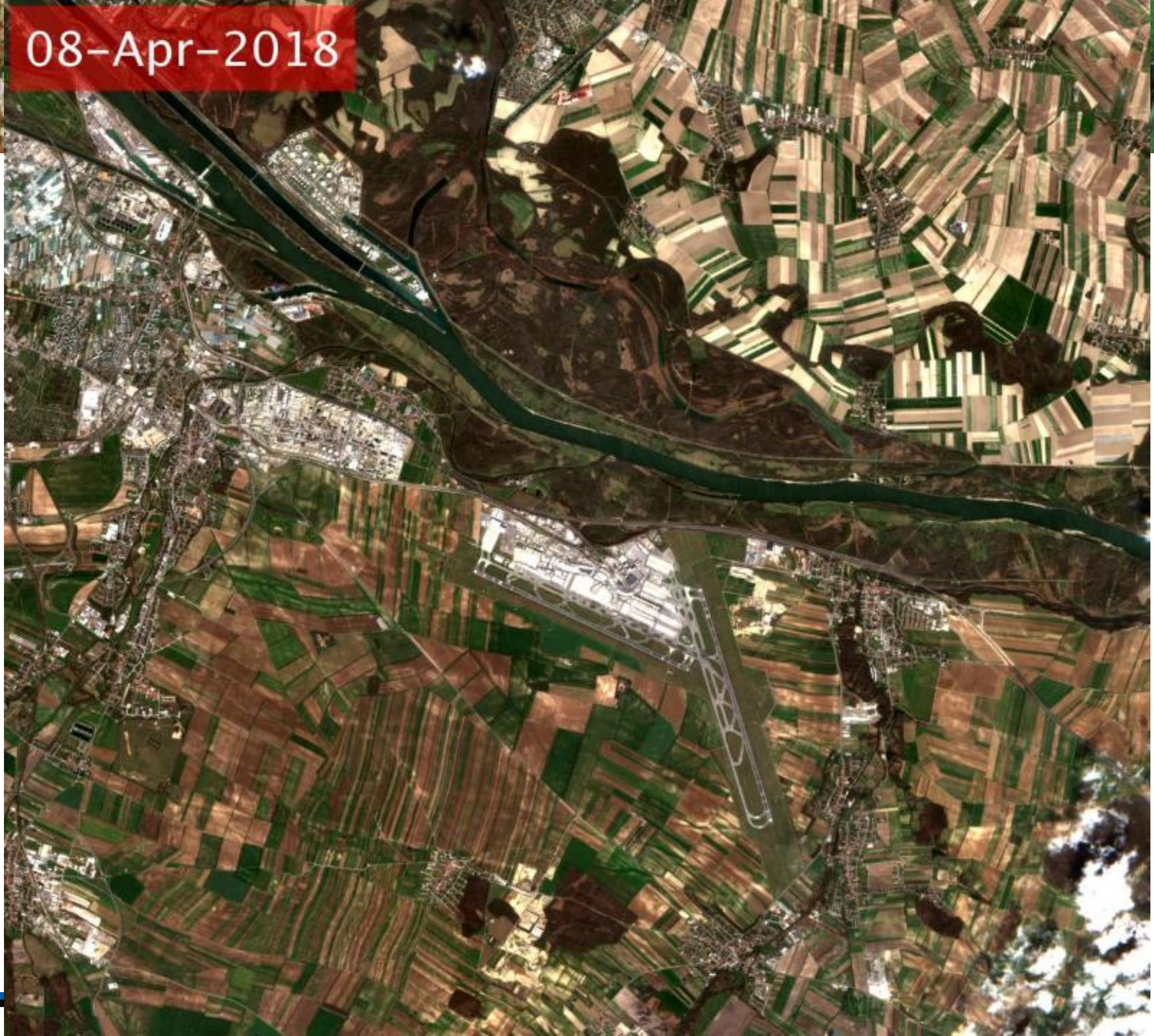
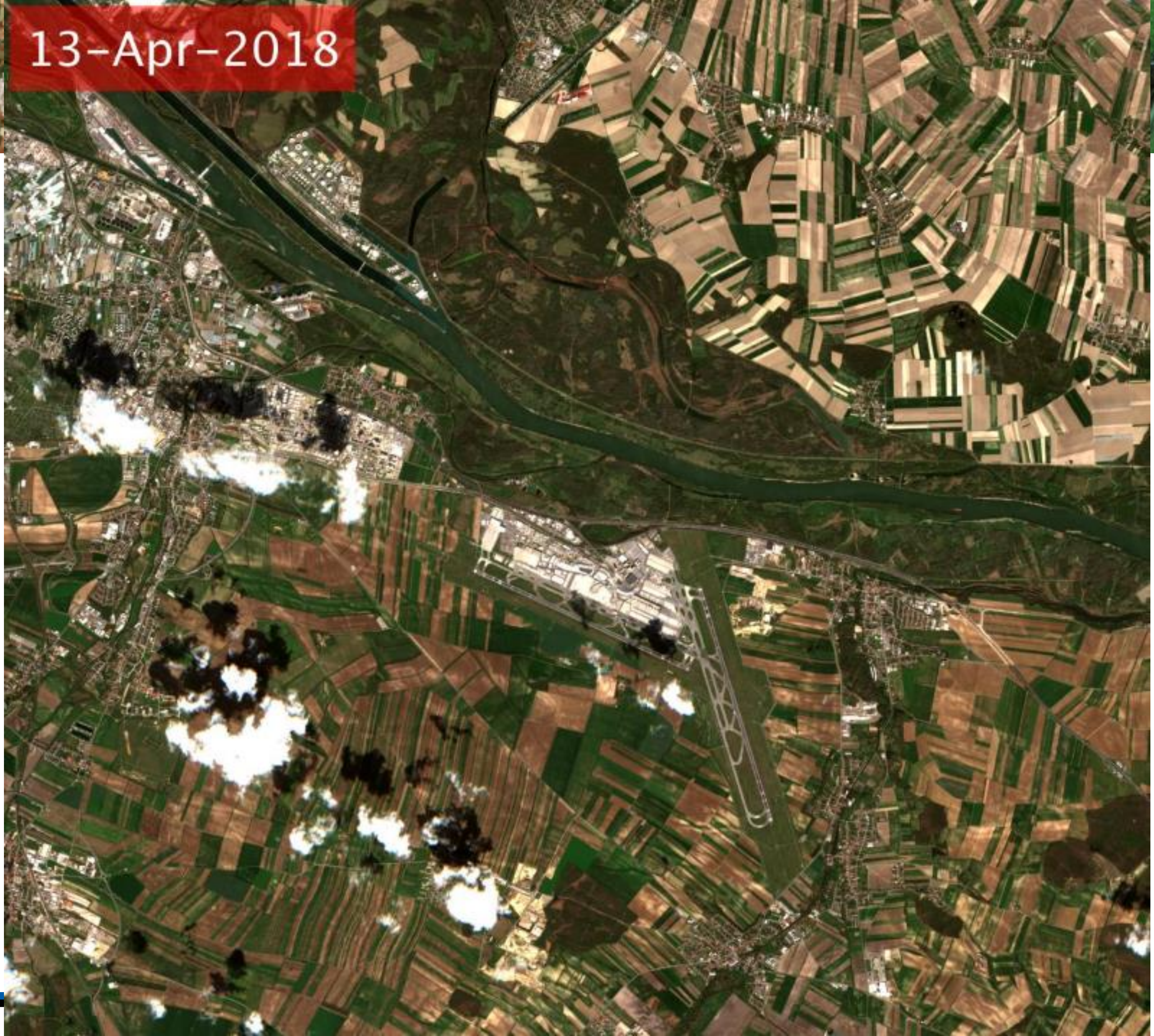
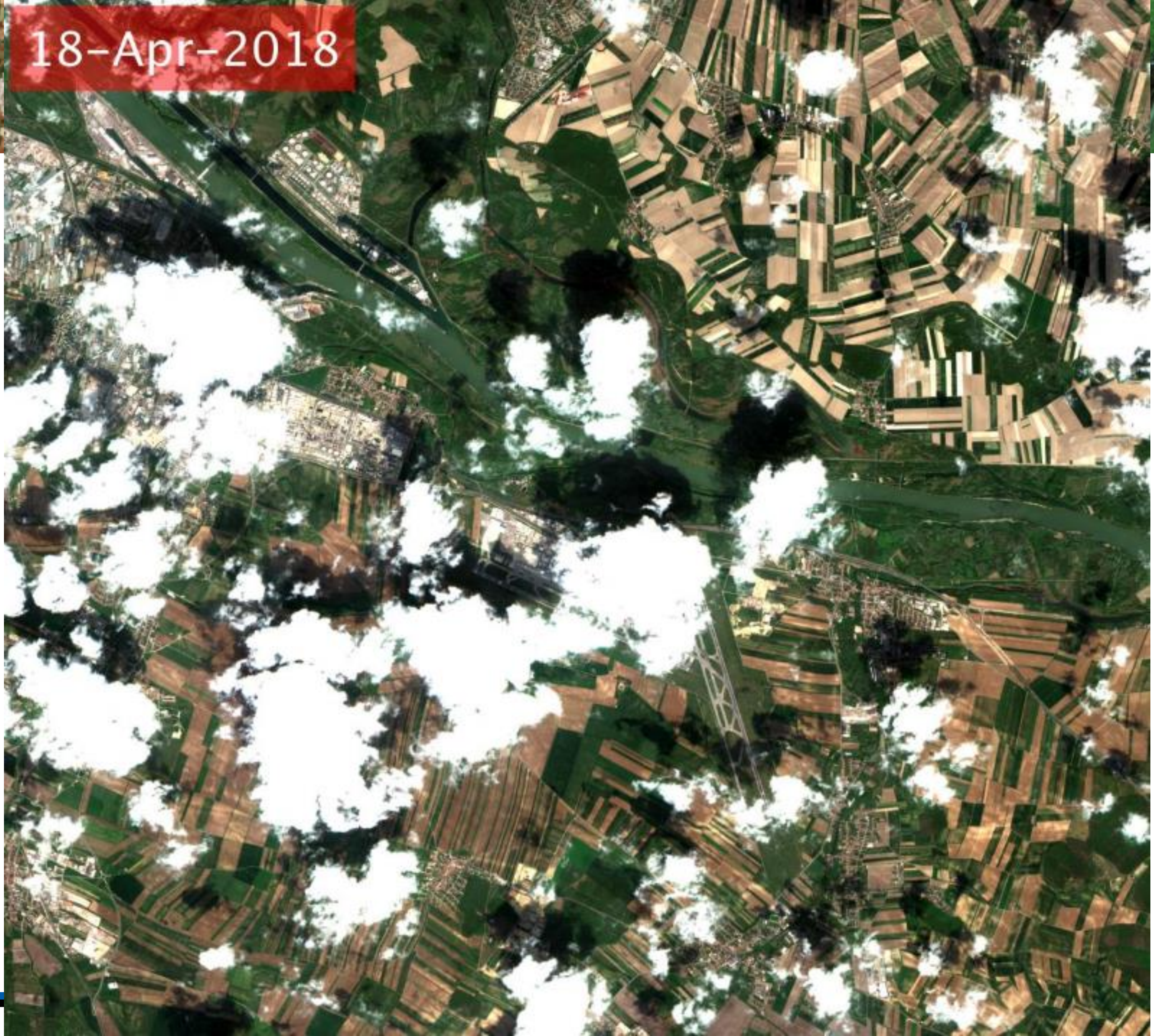

24-Mar-2018


03-Apr-2018


06-Apr-2018


08-Apr-2018


13-Apr-2018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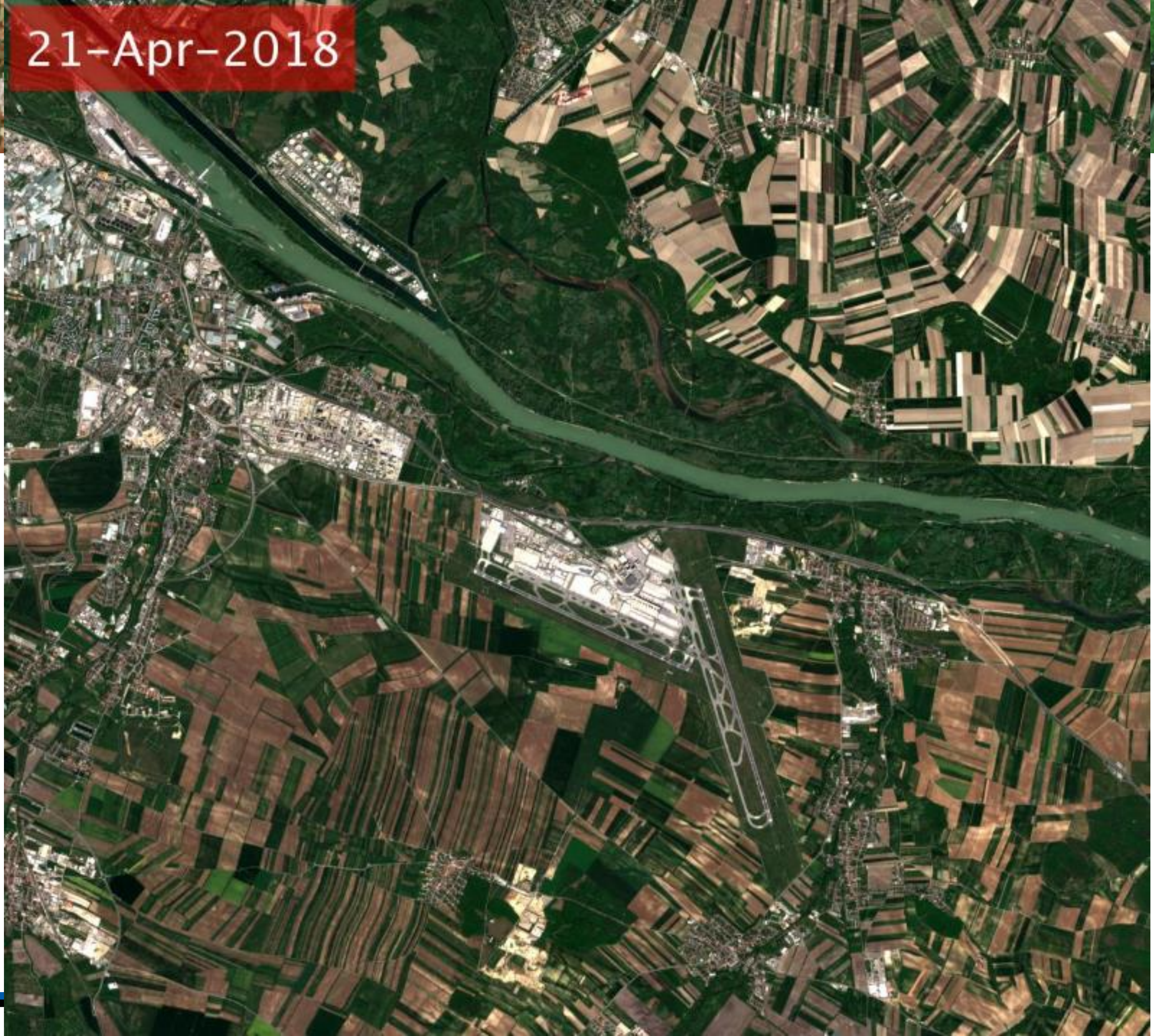
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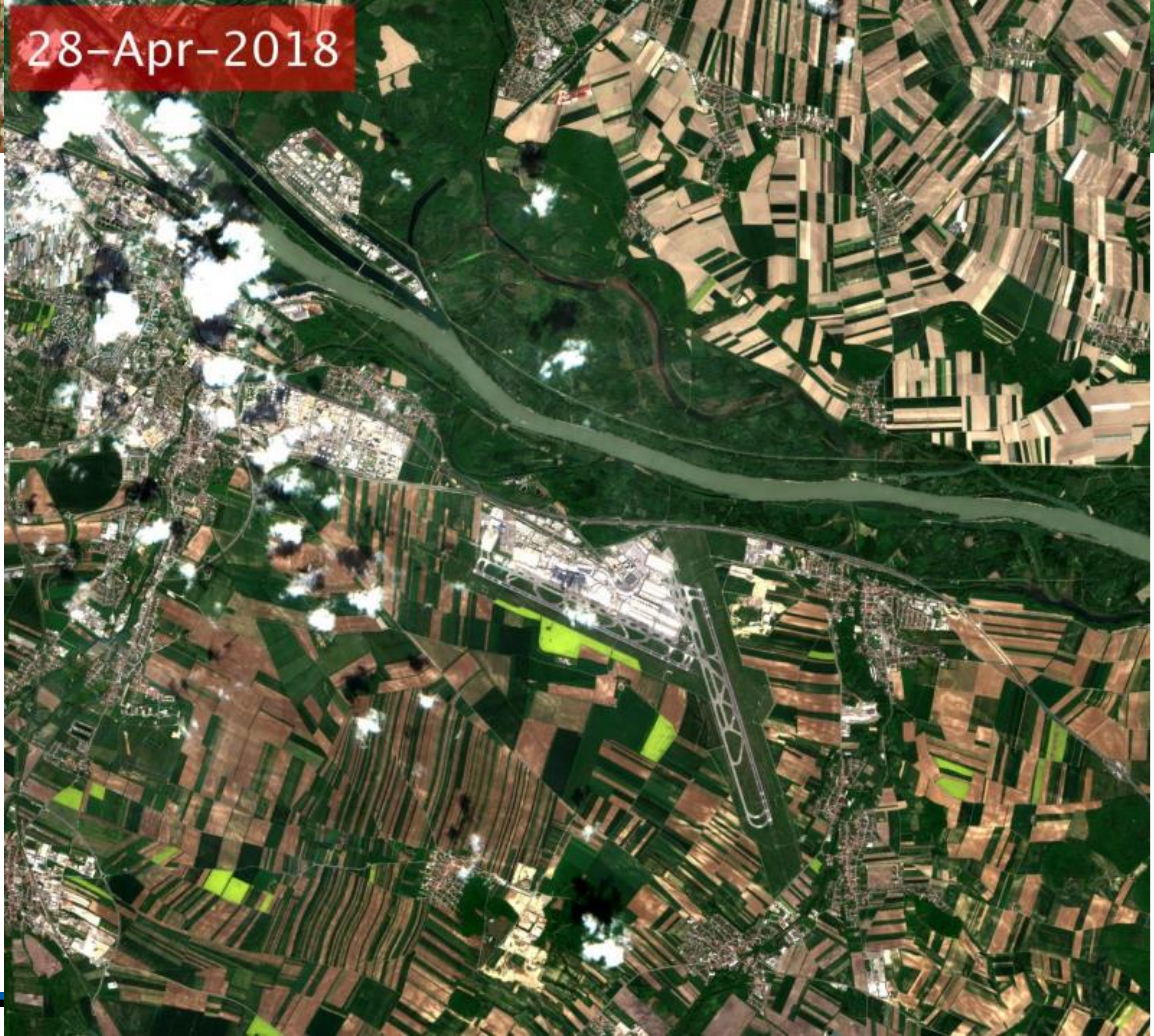
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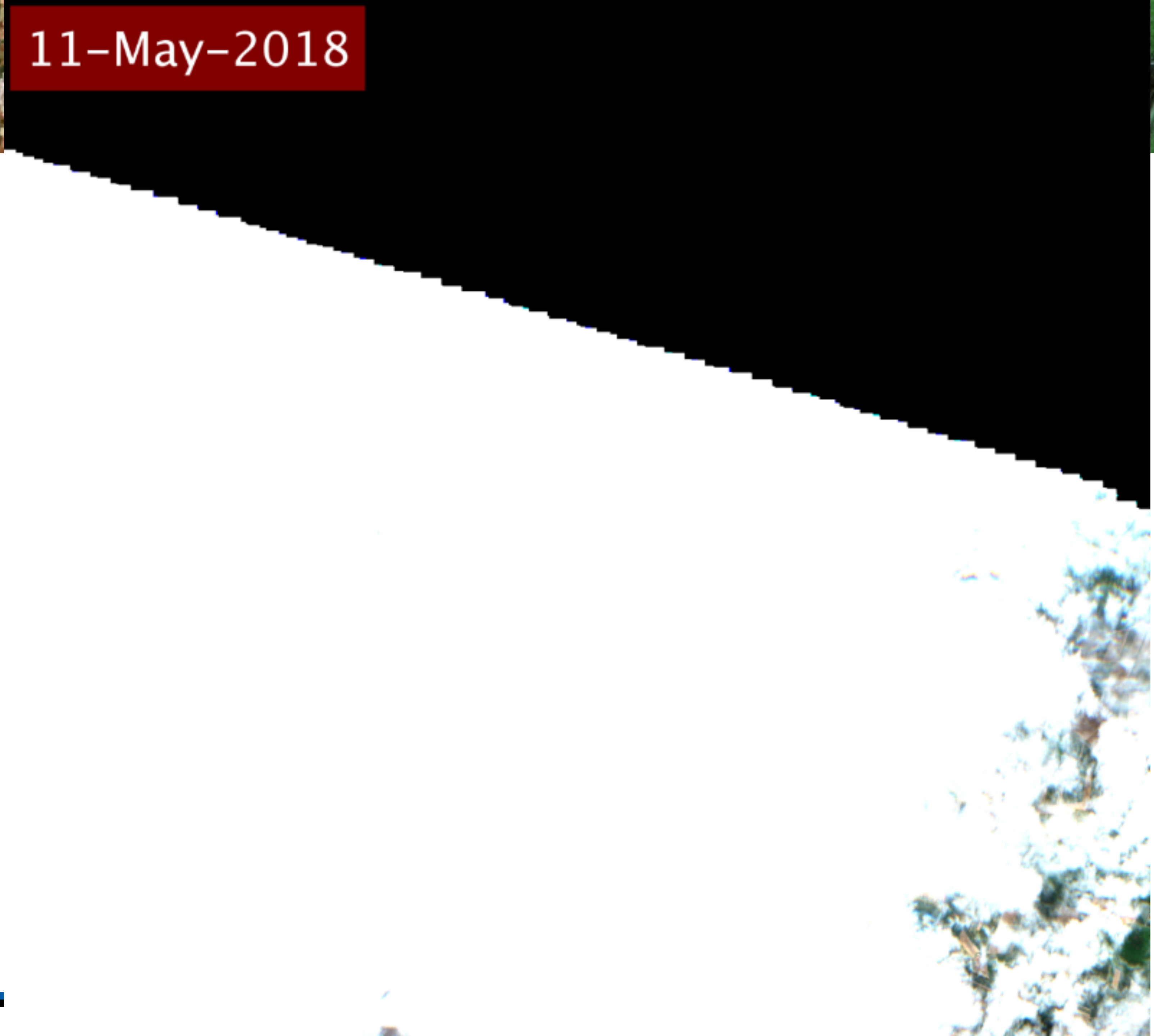
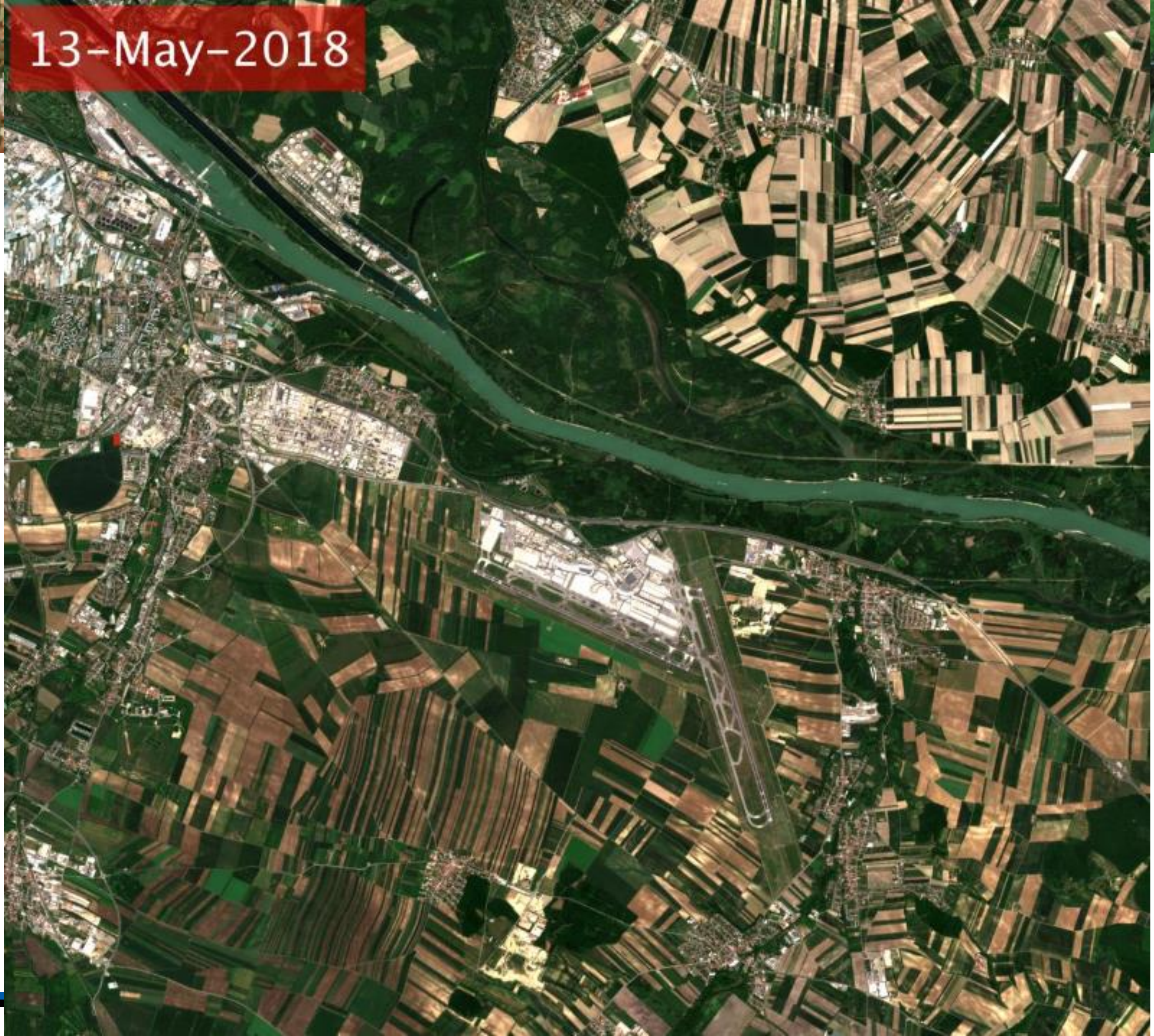
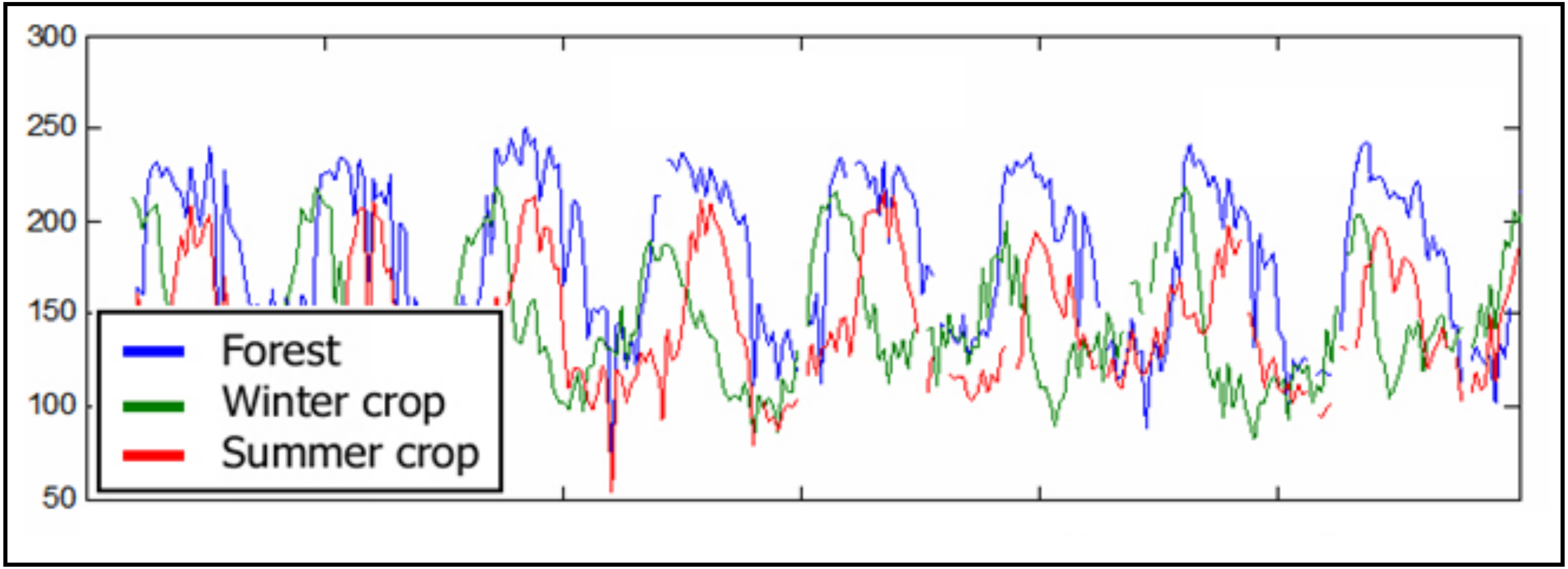
06-May-2018


08-May-2018

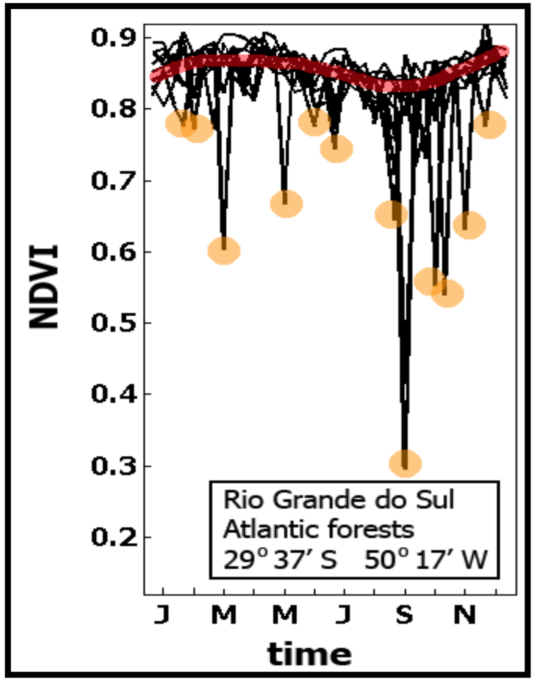

11-May-2018


13-May-2018

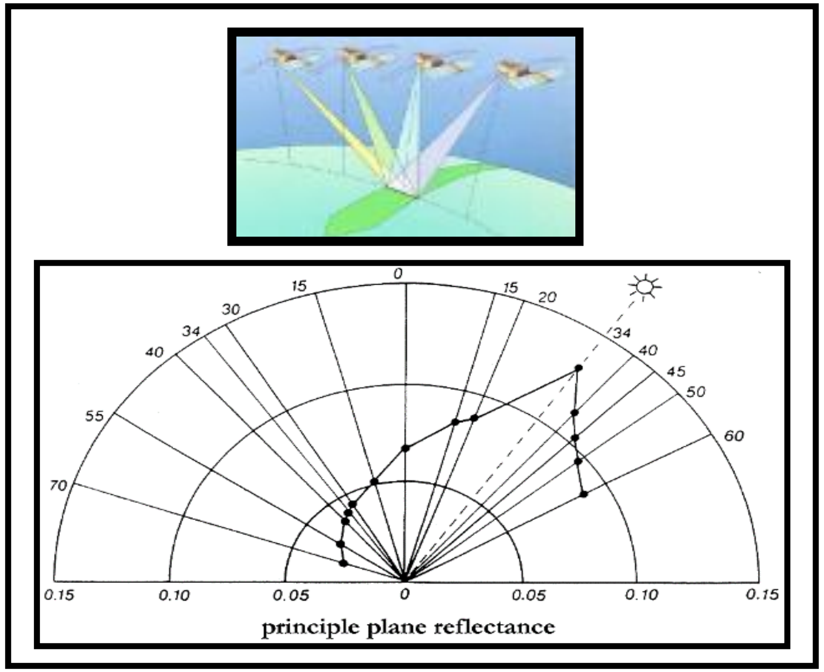
Noise and data gaps



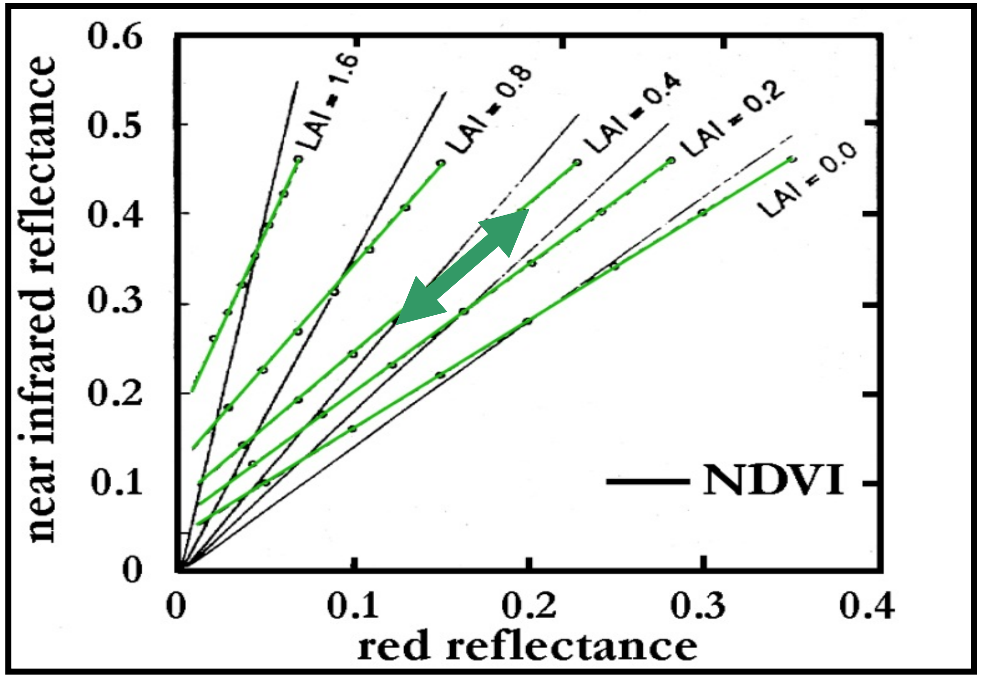
Noise and data gaps



Atmosphere

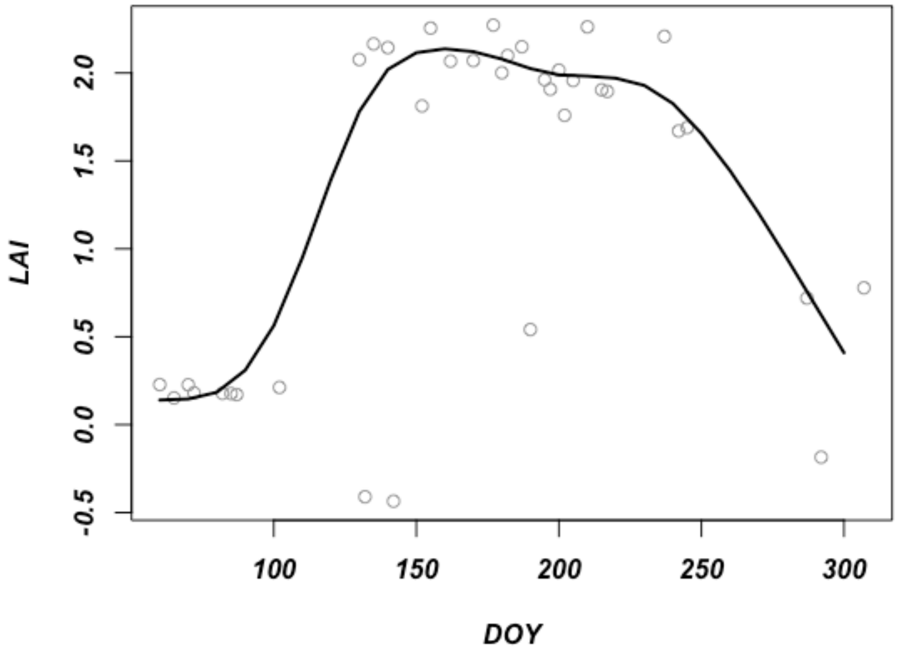


BRDF effects



Soil brightness variability

Definitions of „smoothing“ & „filtering“

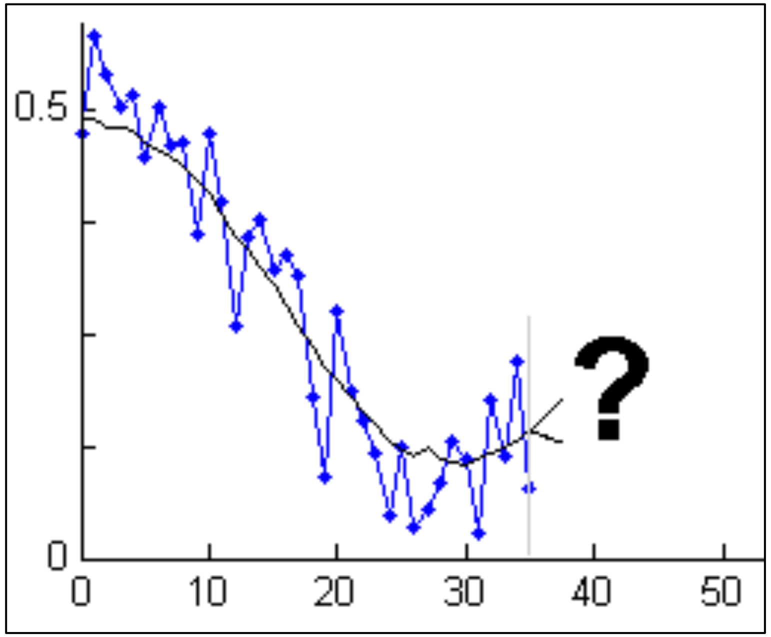


Sedano et al. (2014)

Smoothing applies in a post hoc sense, where there is a need to optimally interpolate past events in a time series.

Smoothing estimates a state based on data from both previous and later times.

Definitions of „smoothing“ & „filtering“



Filtering is relevant in an online learning sense, in which current conditions are to be estimated by the currently available data.

Filtering involves calculating the estimate of a certain state based on a partial sequence of inputs.

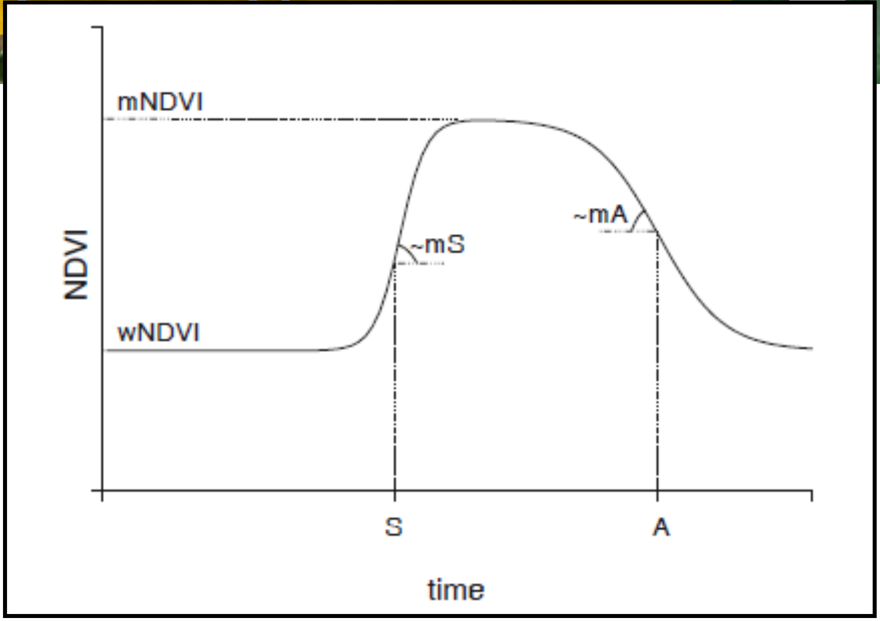
Noise removal & gap filling

Type of filter	Prominent examples
Harmonic Series, e.g., fast and discrete Fourier transform (HS)	*Hermance*, 2007; *Bradley* et al., 2007; *Roerink* et al., 2000; *Jakubauskas* et al., 2001; *Moody & Johnson*, 2001; *McCloy & Lucht, 2004*
Double logistic (DL)	*Beck* et al., 2006; *Zhang* et al., 2003
Asymmetric Gaussian (AG)	*Jönsson & Eklundh*, 2002; *Jönsson & Eklundh*, 2004
Savitzky-Golay (SG)	*Chen* et al., 2004; *Joensson & Eklundh*, 2004
Wavelets (WL)	*Sakamoto* et al., 2005; *Li & Kafatos*, 2000
Weighted least squares windowed regression (SWETS)	*Swets* et al., 1999
Running medians (4253H)	*Velleman*, 1980
Best Index Slope Extraction (BISE)	*Viovy* et al., 1992; *Lovell & Graetz*, 2001
Mean Value Iteration (MVI)	*Ma & Veroustraete*, 2006

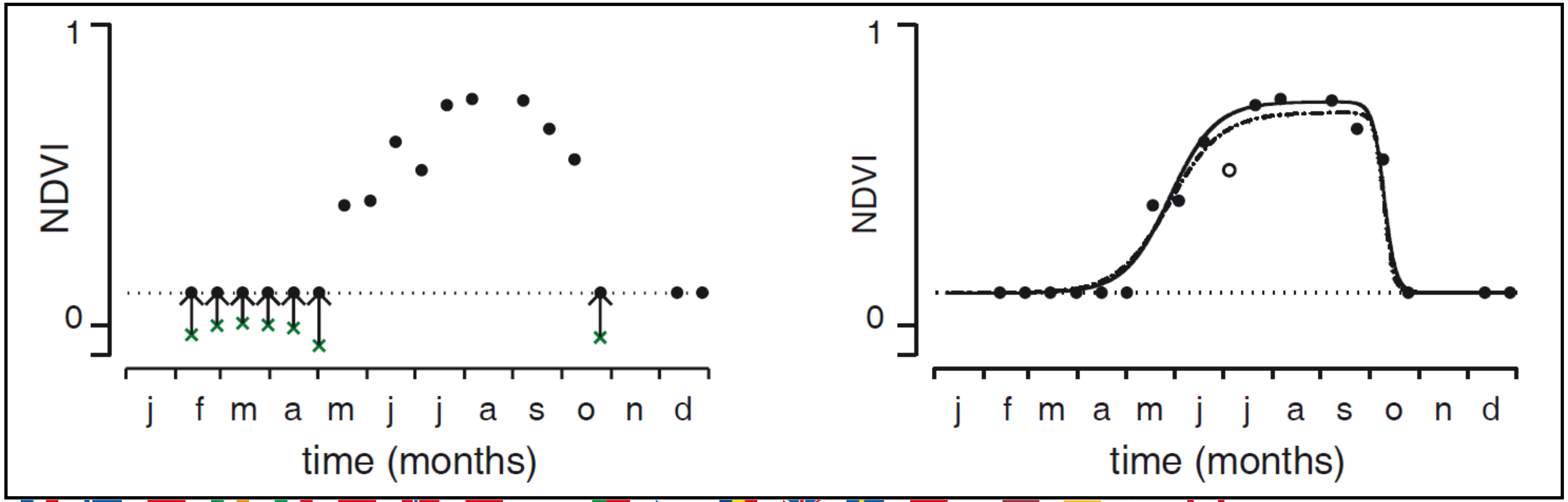
Atzberger & Eilers, 2011

Noise removal & gap filling

$$\mathrm{NDVI}(t) = w\mathrm{NDVI} + (m\mathrm{NDVI} - w\mathrm{NDVI}) \times \left(\frac{1}{1 + \exp(-mS \times (t - S))} + \frac{1}{1 + \exp(mA \times (t - A))} - 1 \right)$$



Principle of a curve fitting procedure based on a double logistic function (Beck et al., 2006)



Whittaker smoother (Eilers, 2003)

Smoothing data by striking a balance between fidelity to the data and smoothness of the fitted curve:

$$Q = S + \lambda \cdot R$$

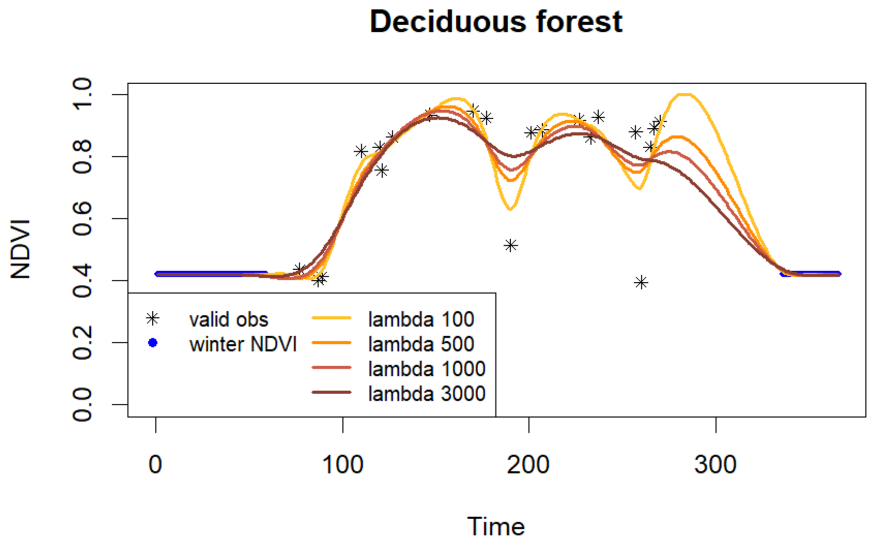
- **Fidelity of curve** is measured by the sum of squares of deviations where yi = observed time series and zi = smoothed time series

$$S = \sum_i (y_i - z_i)^2$$

- **Roughness of data** can be expressed with differences, e.g. 1st, 2nd, 3rd

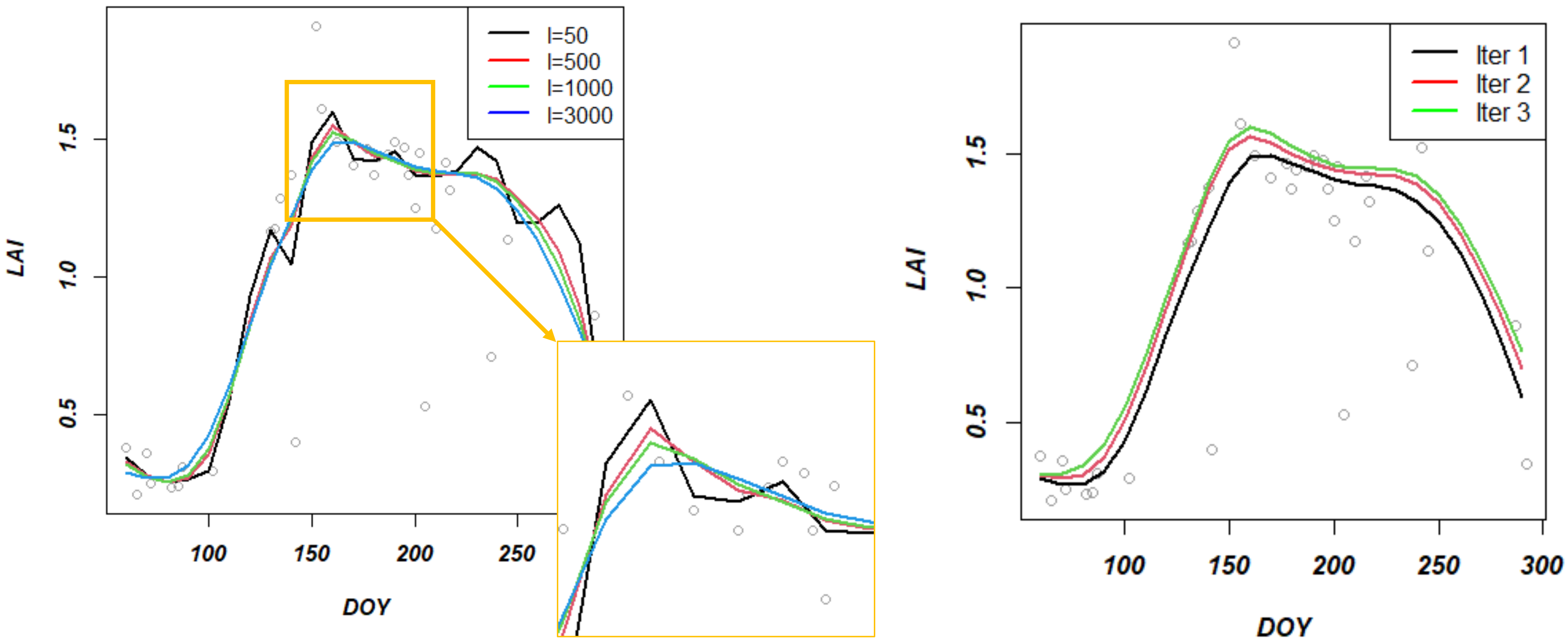
$$R = \sum_i ((z_i - z_{i-1}) - (z_{i-1} - z_{i-2}))^2$$

- λ (lambda) is a number chosen by the user
- Find z_i (= smoothed time series) by minimising Q for a given lambda
- Effect of Lambda:
  - the larger λ
  - the stronger the influence of roughness R
  - the smoother z will be
  - at the cost of the fit of the data getting worse



- ✓ No periodicity assumed (e.g., Fourier/ Wavelets)
- ✓ Data points can be irregularly spaced
- ✓ Only one smoothing parameter
- ✓ Interpolates automatically
- ✓ No boundary effects
- ✓ Fast leave-one-out cross validation

Impact of λ and number of iterations



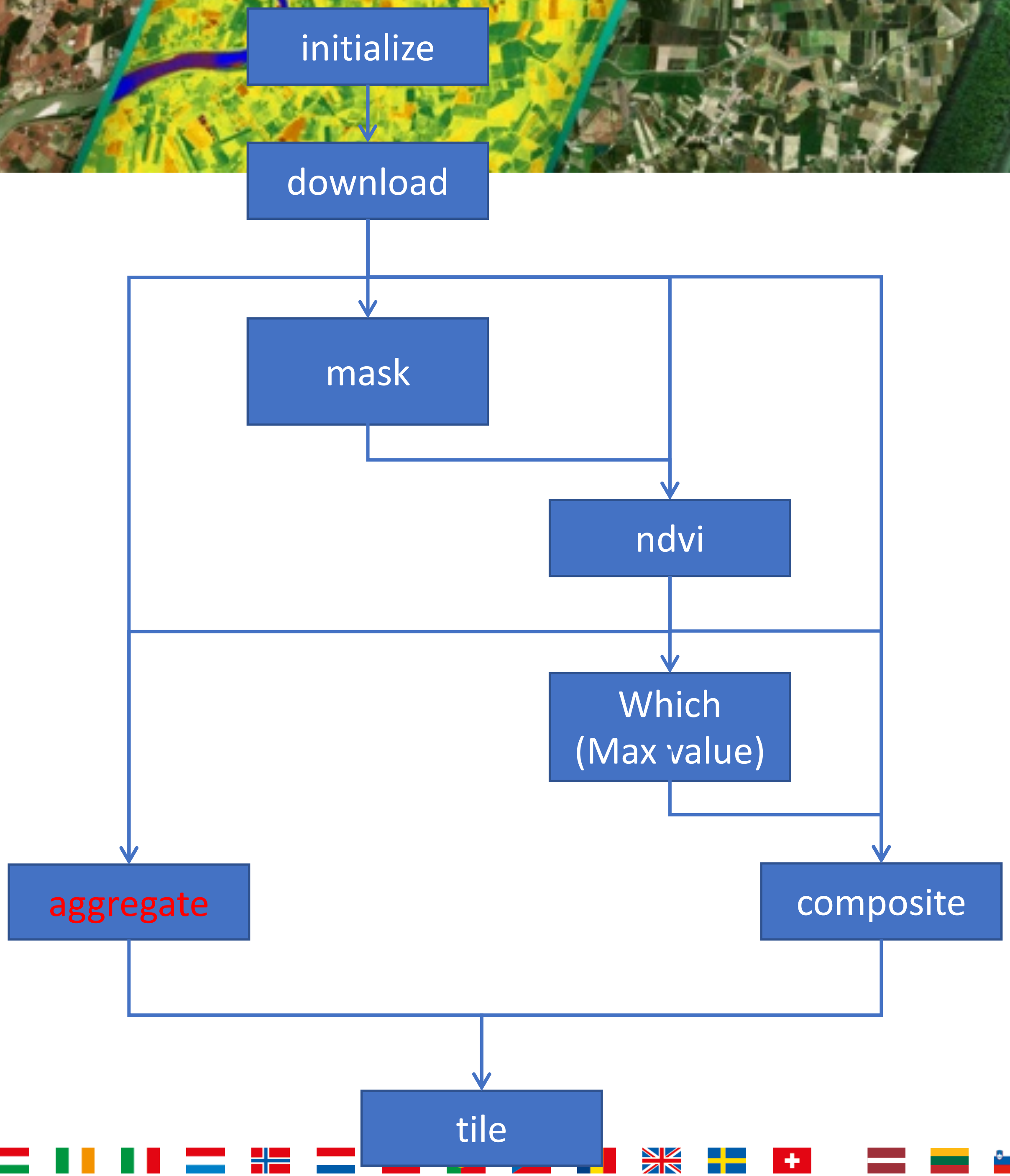
Temporal compositing workflow

No smoothing or filtering

Data acquisition & atmospheric correction → Cloud detect. & masking → Temporal composite (7,10, 30-day) → DATACUBE of EO products → Application

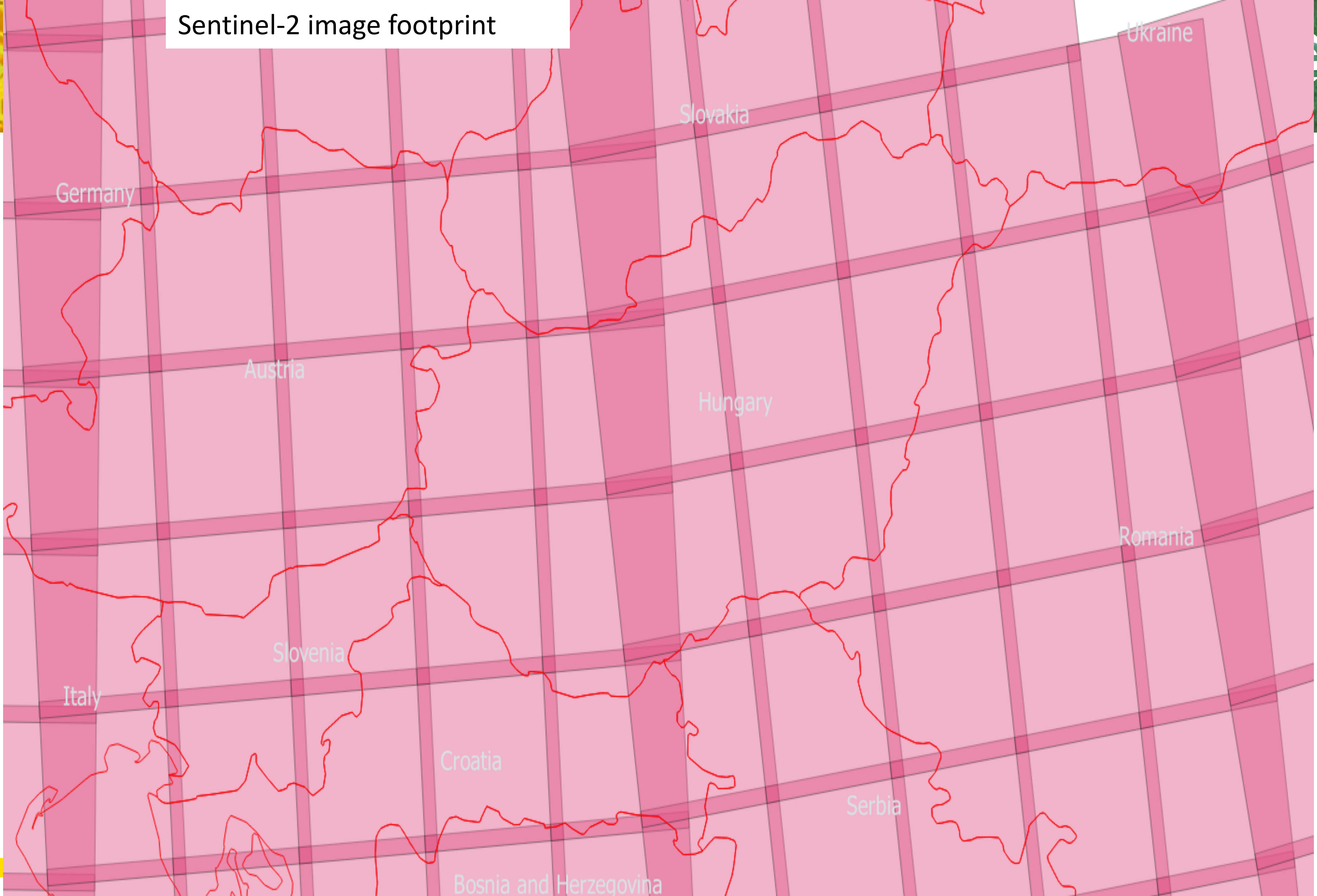
Microservices built on the datacube

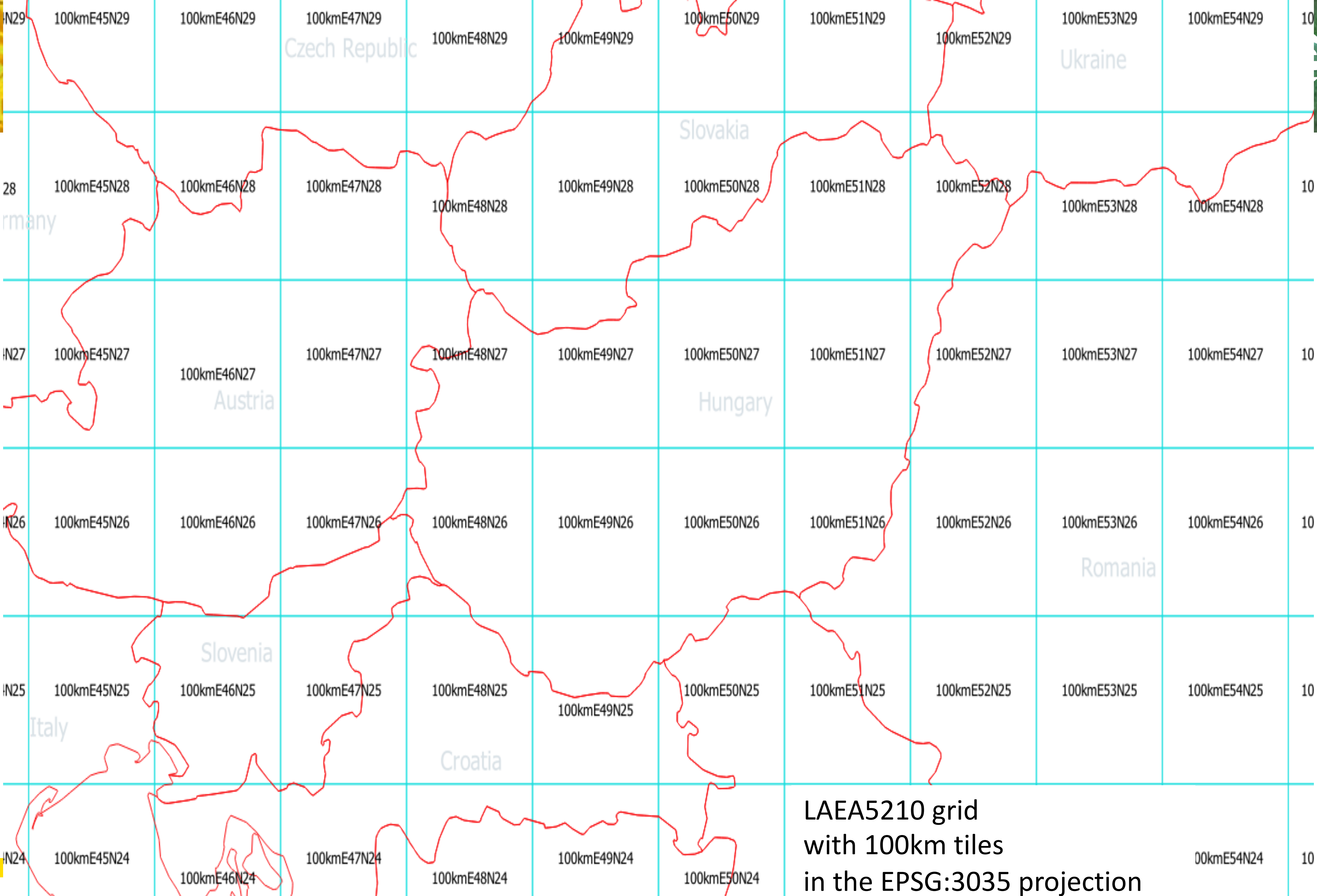
Example workflow




Czech Republic
Ukraine
Slovakia
Germany
Austria
Hungary
Romania
Slovenia
Italy
Croatia
Serbia
Bosnia and Herzegovina

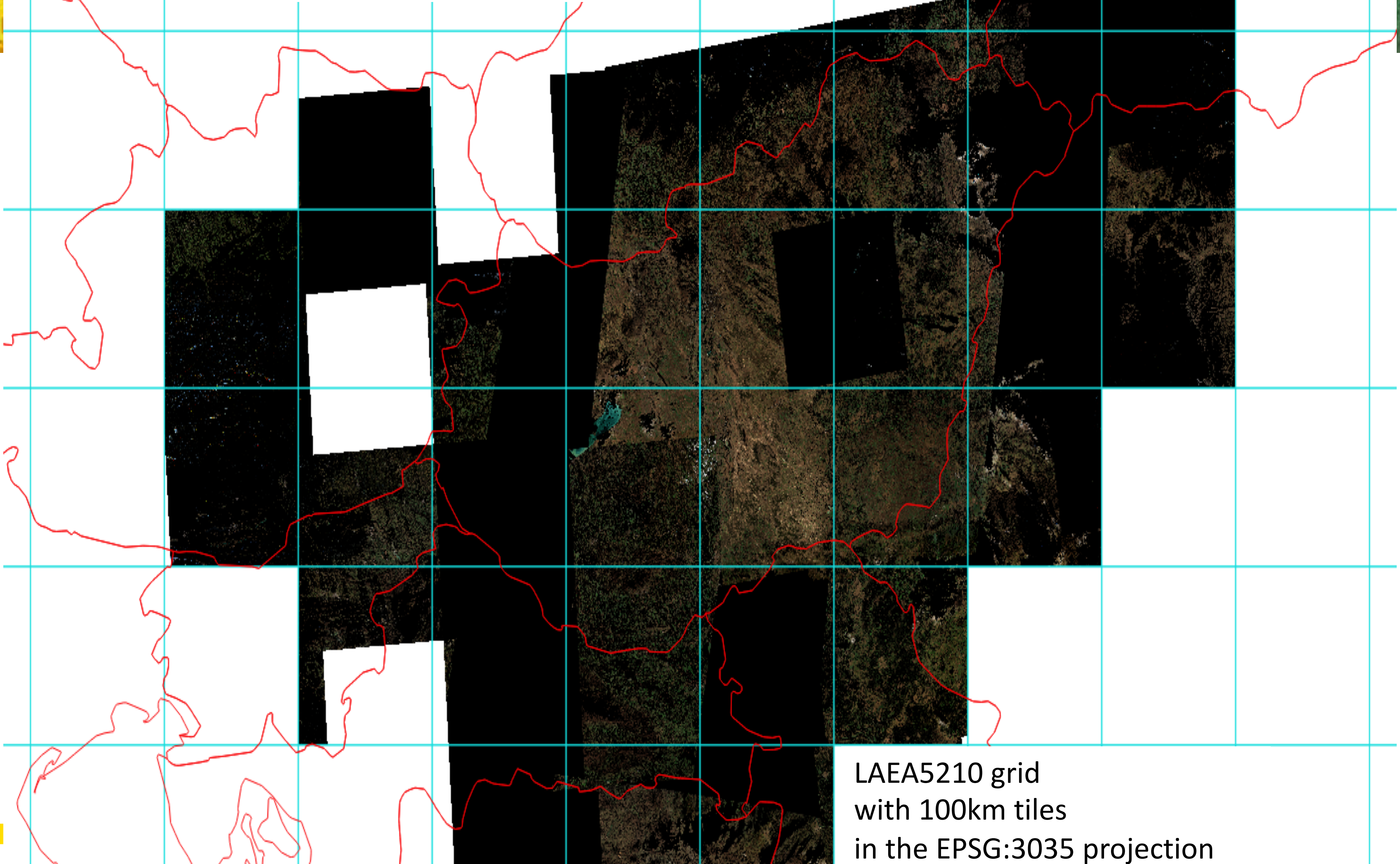
Sentinel-2 image footprint





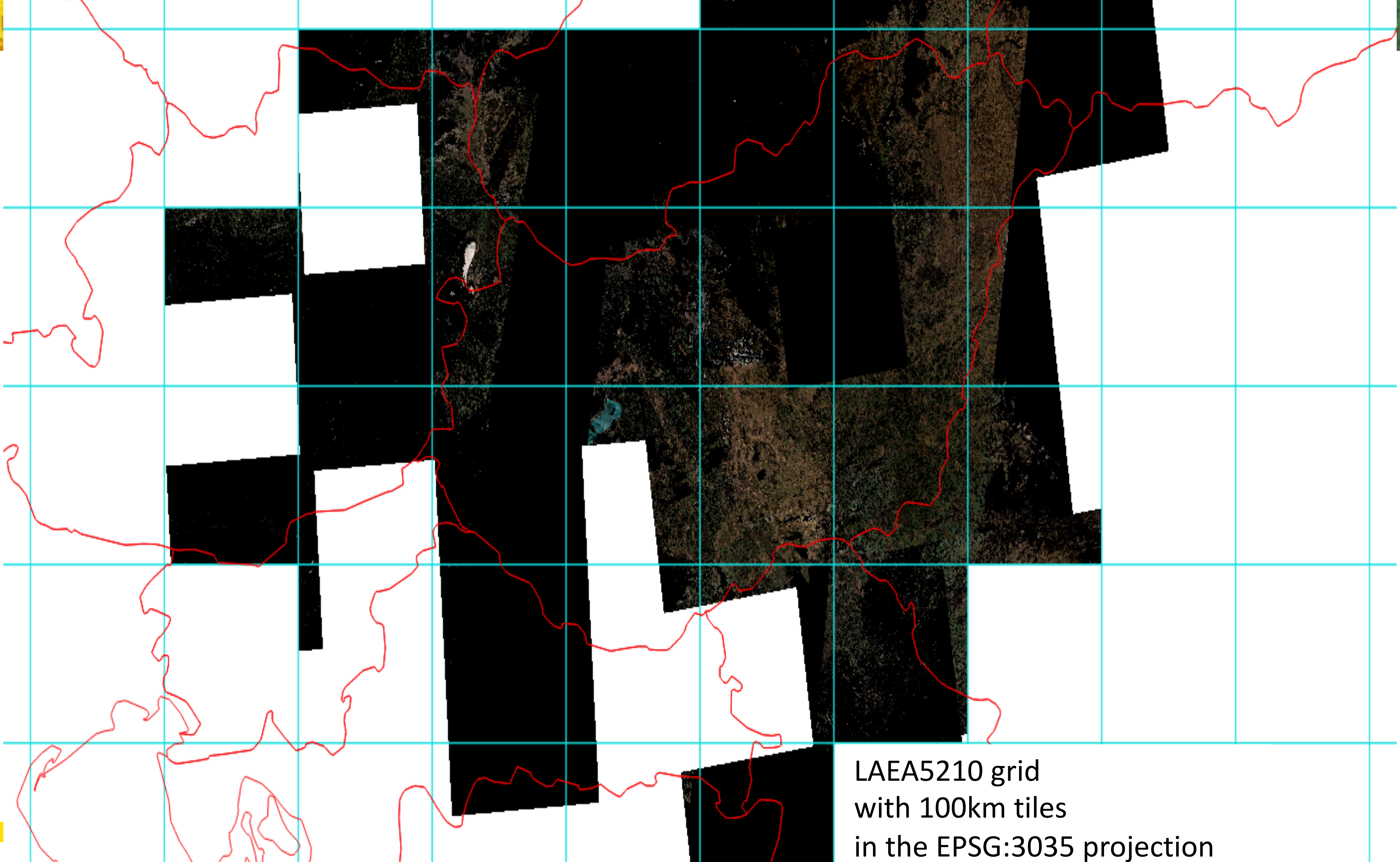
LAEA5210 grid
with 100km tiles
in the EPSG:3035 projection

True Color Image January 2018
Monthly composite



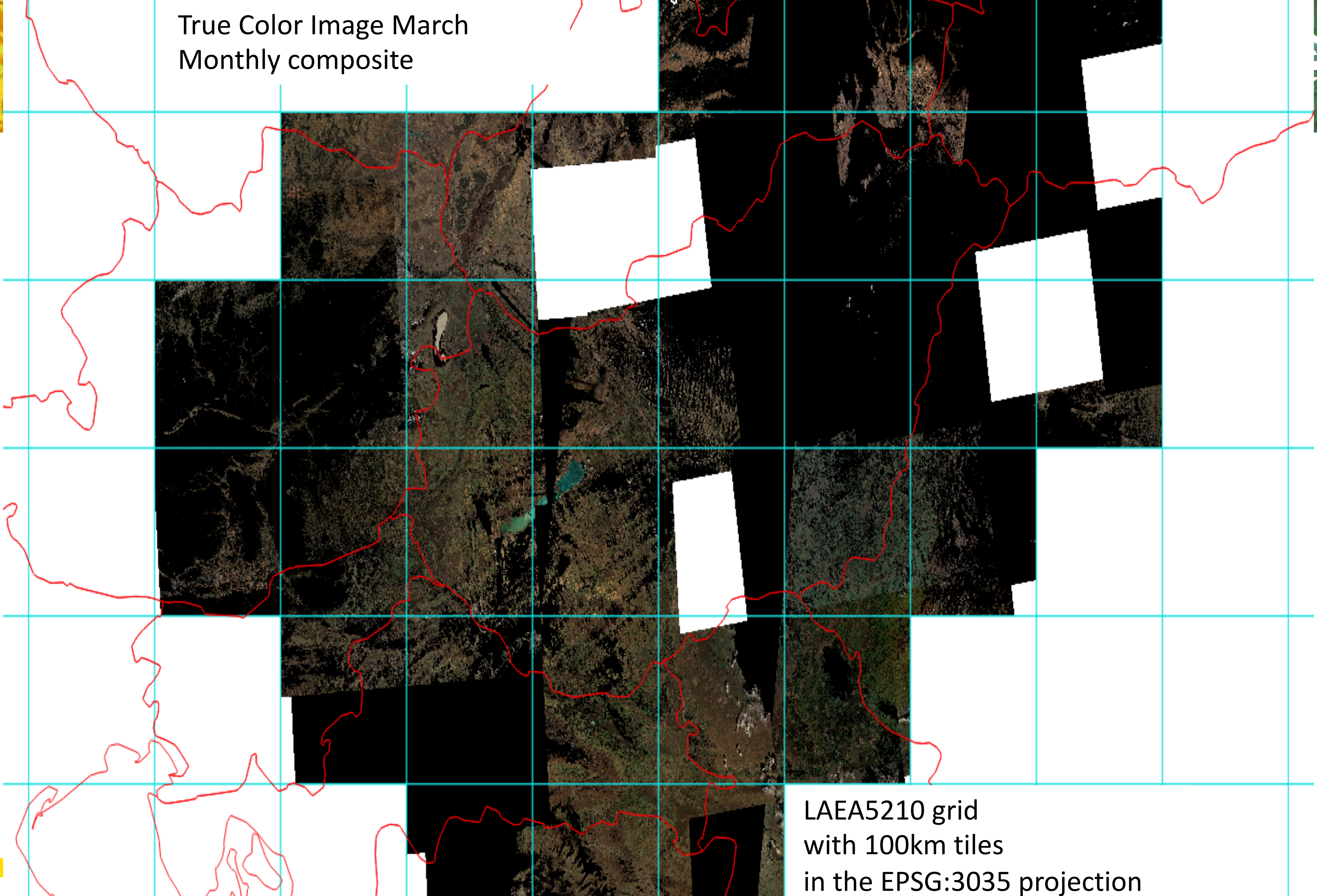
LAEA5210 grid
with 100km tiles
in the EPSG:3035 projection

True Color Image February
Monthly composite



LAEA5210 grid
with 100km tiles
in the EPSG:3035 projection

True Color Image March
Monthly composite



LAEA5210 grid
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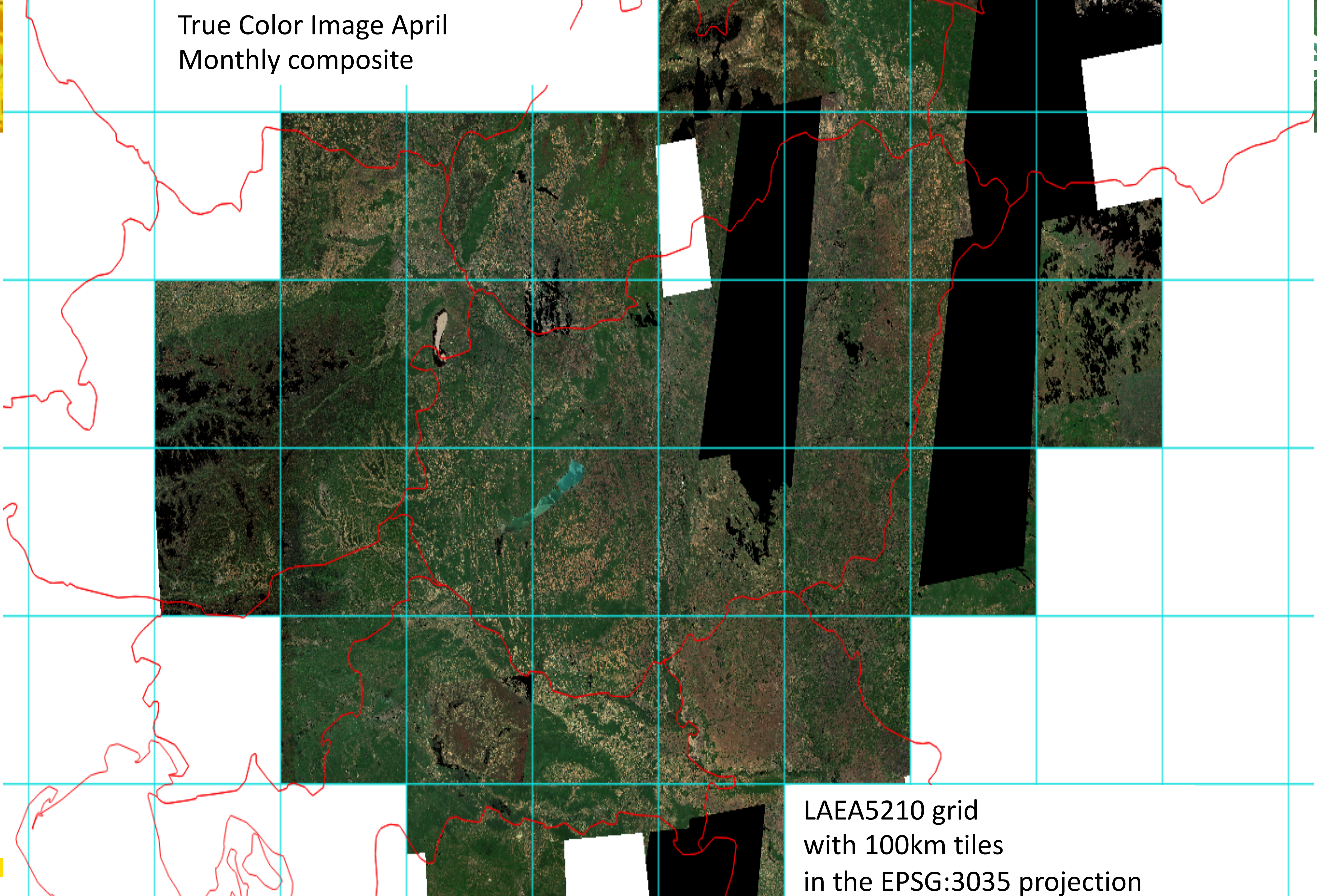
in the EPSG:3035 projection

True Color Image April
Monthly composite



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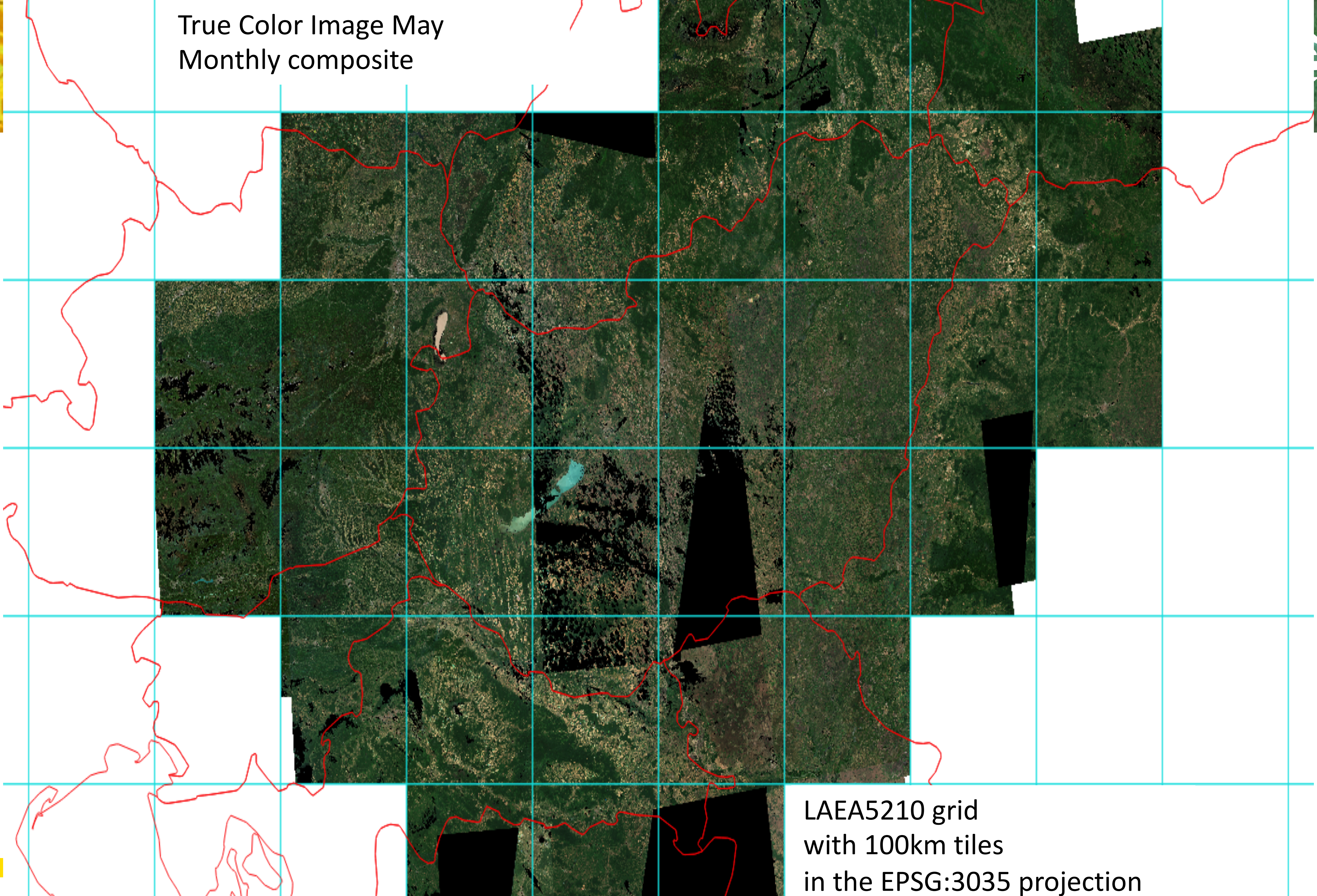
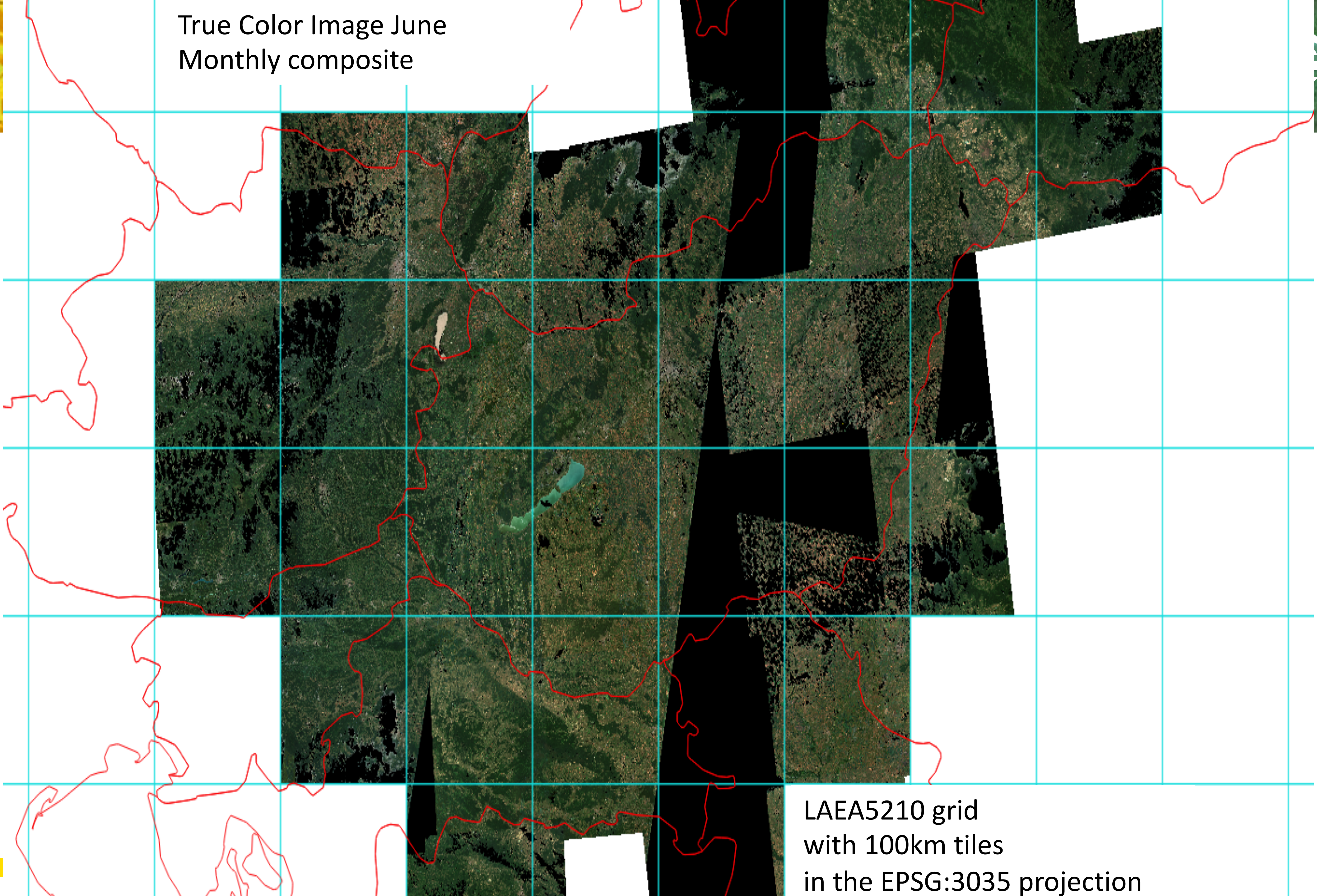
True Color Image May
Monthly composite



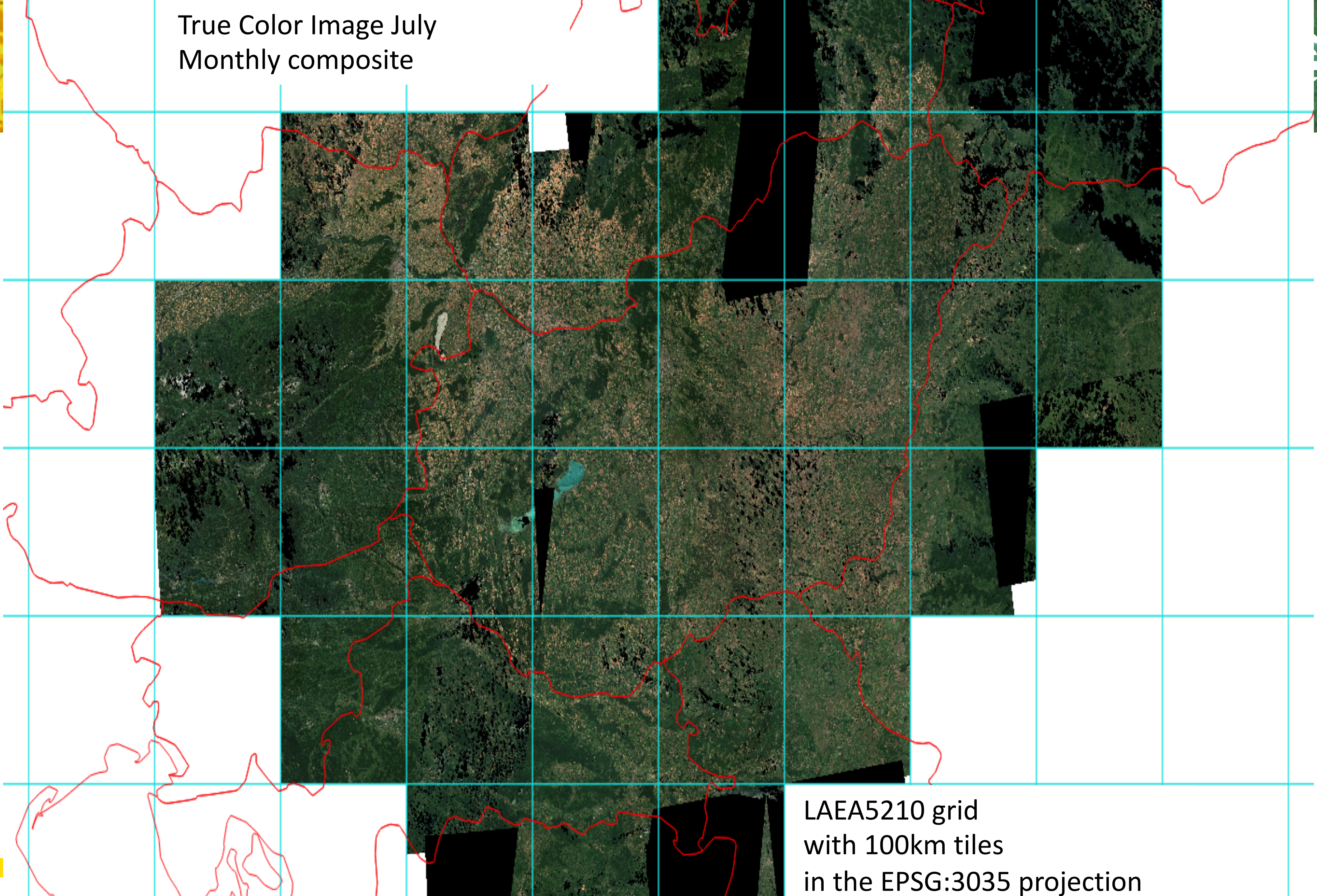
LAEA5210 grid
with 100km tiles
in the EPSG:3035 projection

True Color Image June
Monthly composite



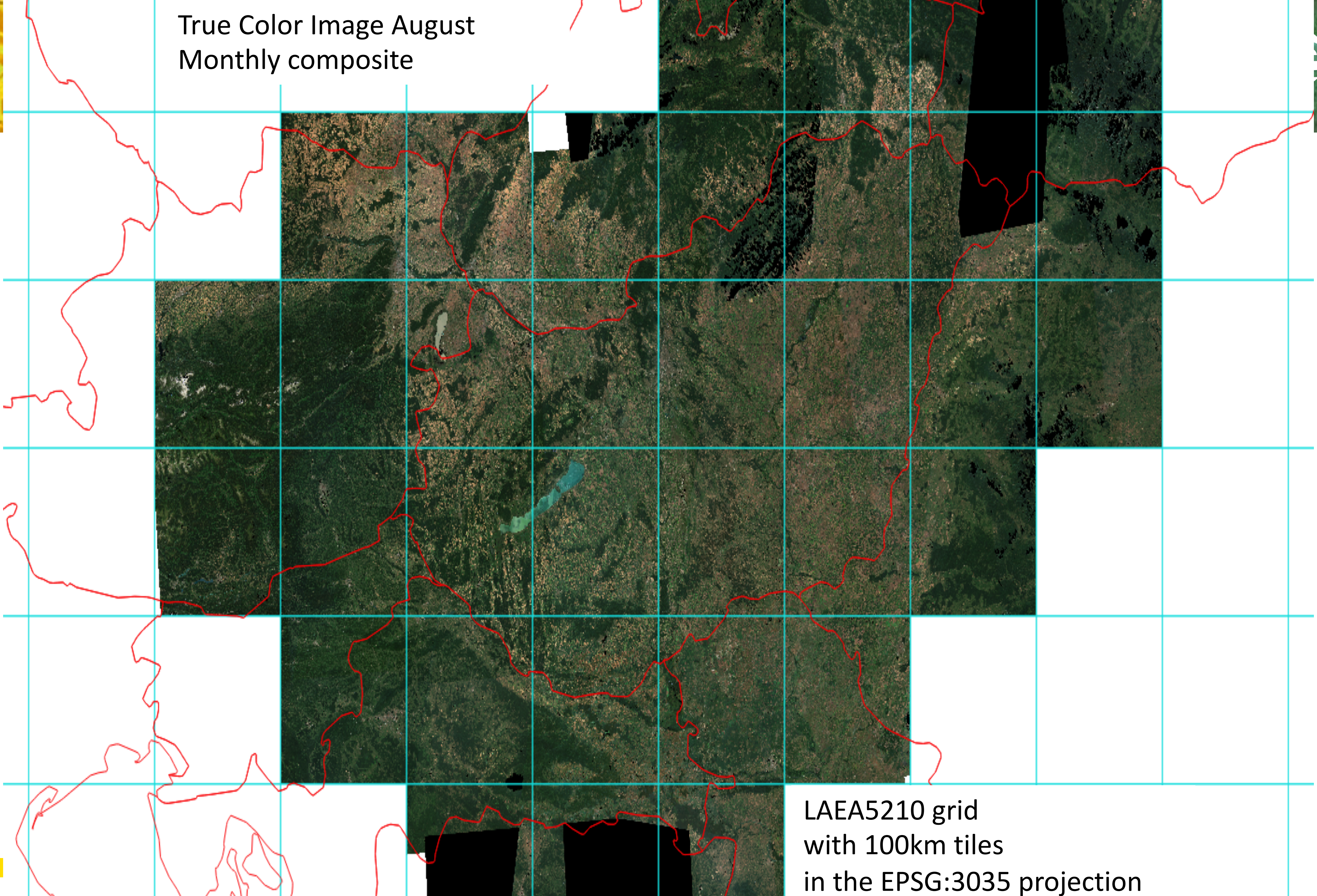
LAEA5210 grid
with 100km tiles
in the EPSG:3035 projection

True Color Image July
Monthly composite



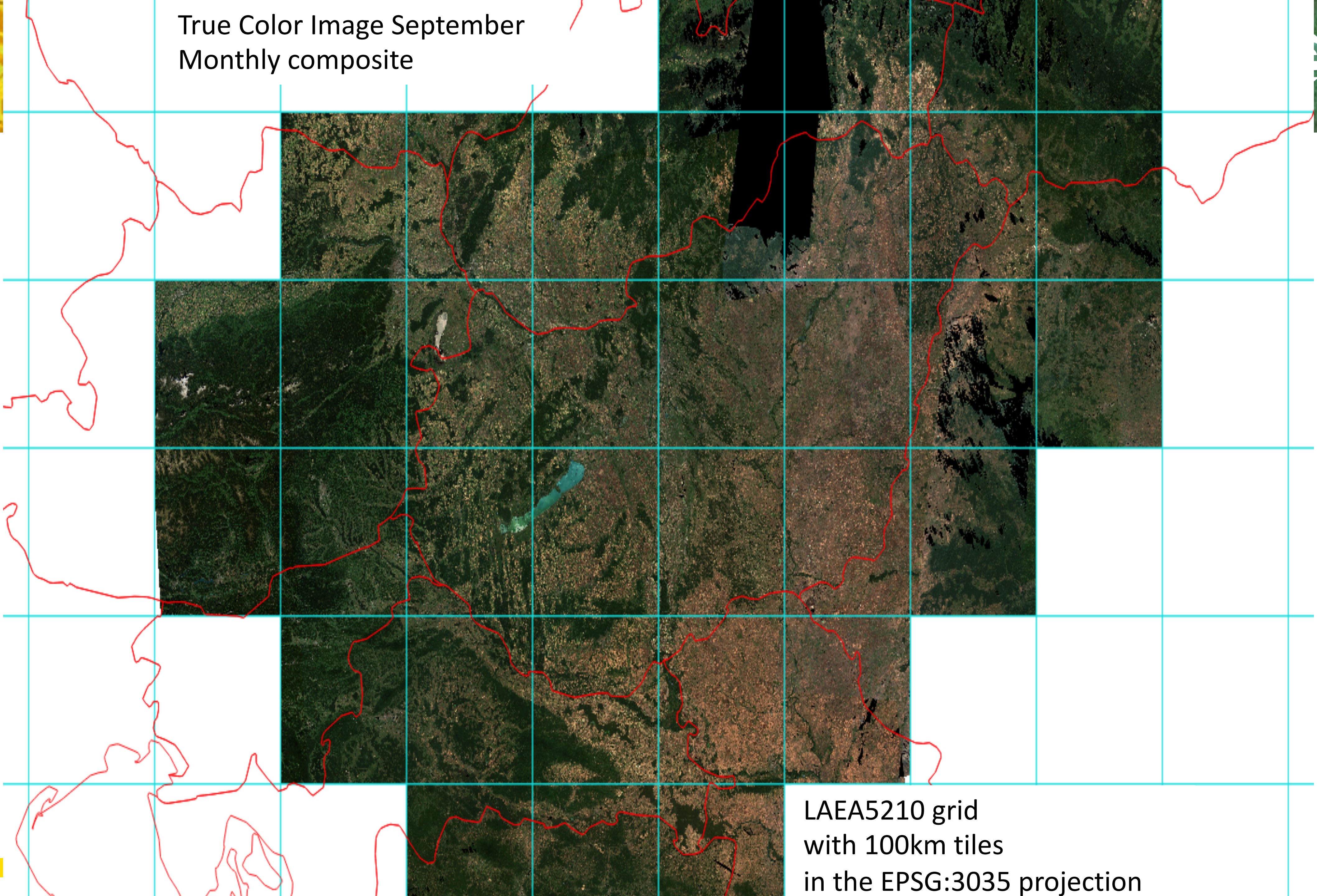
LAEA5210 grid
with 100km tiles
in the EPSG:3035 projection

True Color Image August
Monthly composite



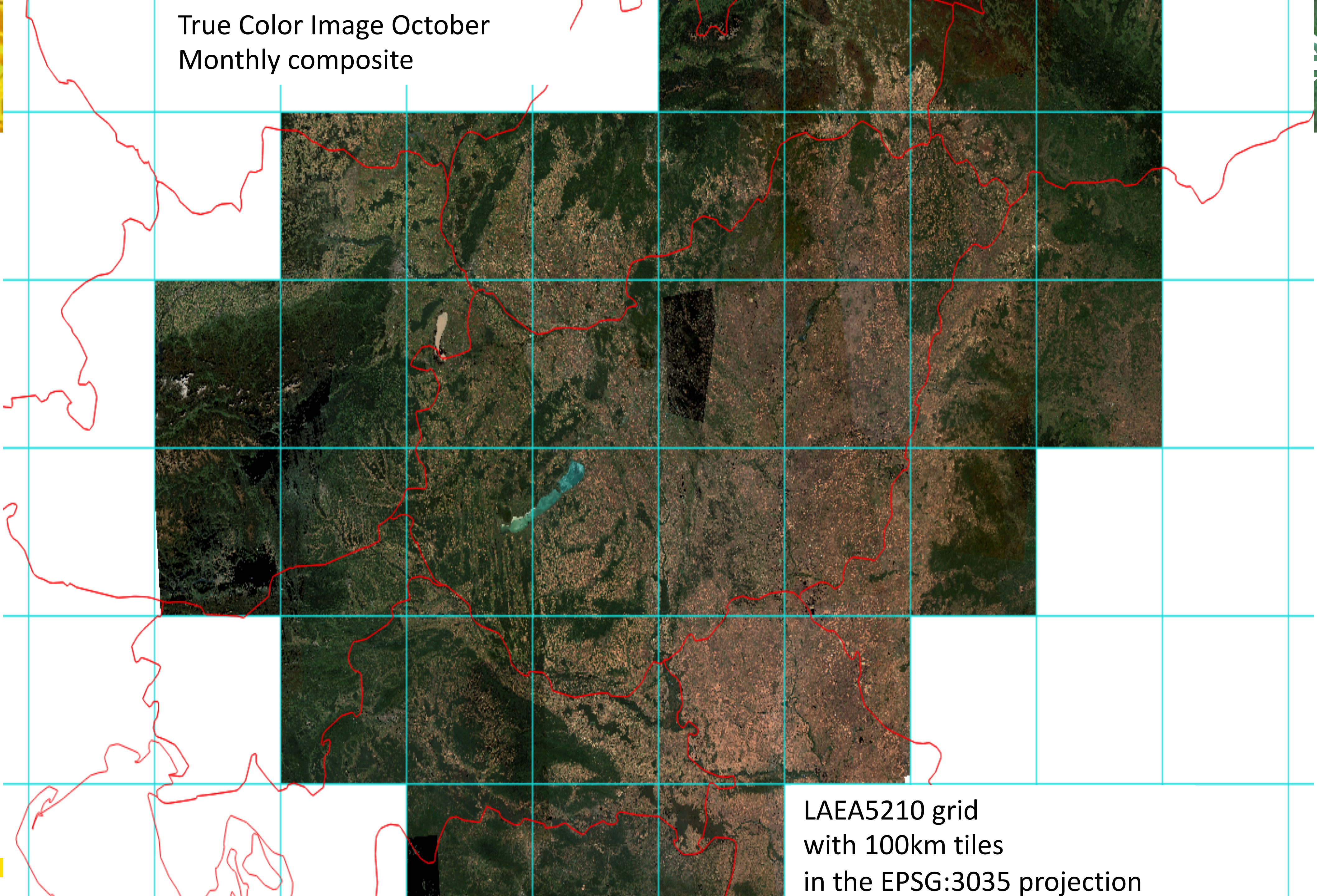
LAEA5210 grid
with 100km tiles
in the EPSG:3035 projection

True Color Image September
Monthly composite



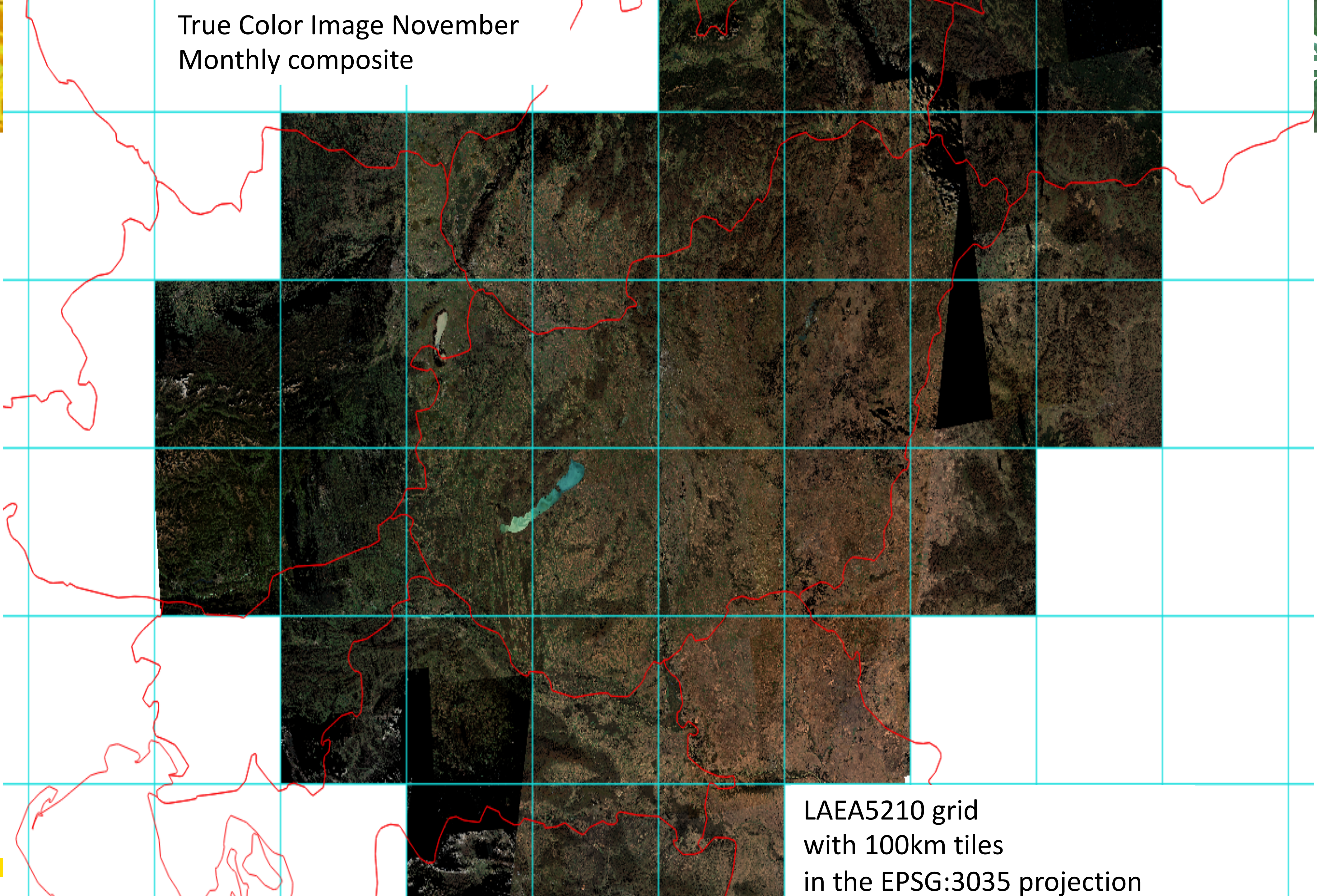
LAEA5210 grid
with 100km tiles
in the EPSG:3035 projection

True Color Image October
Monthly composite



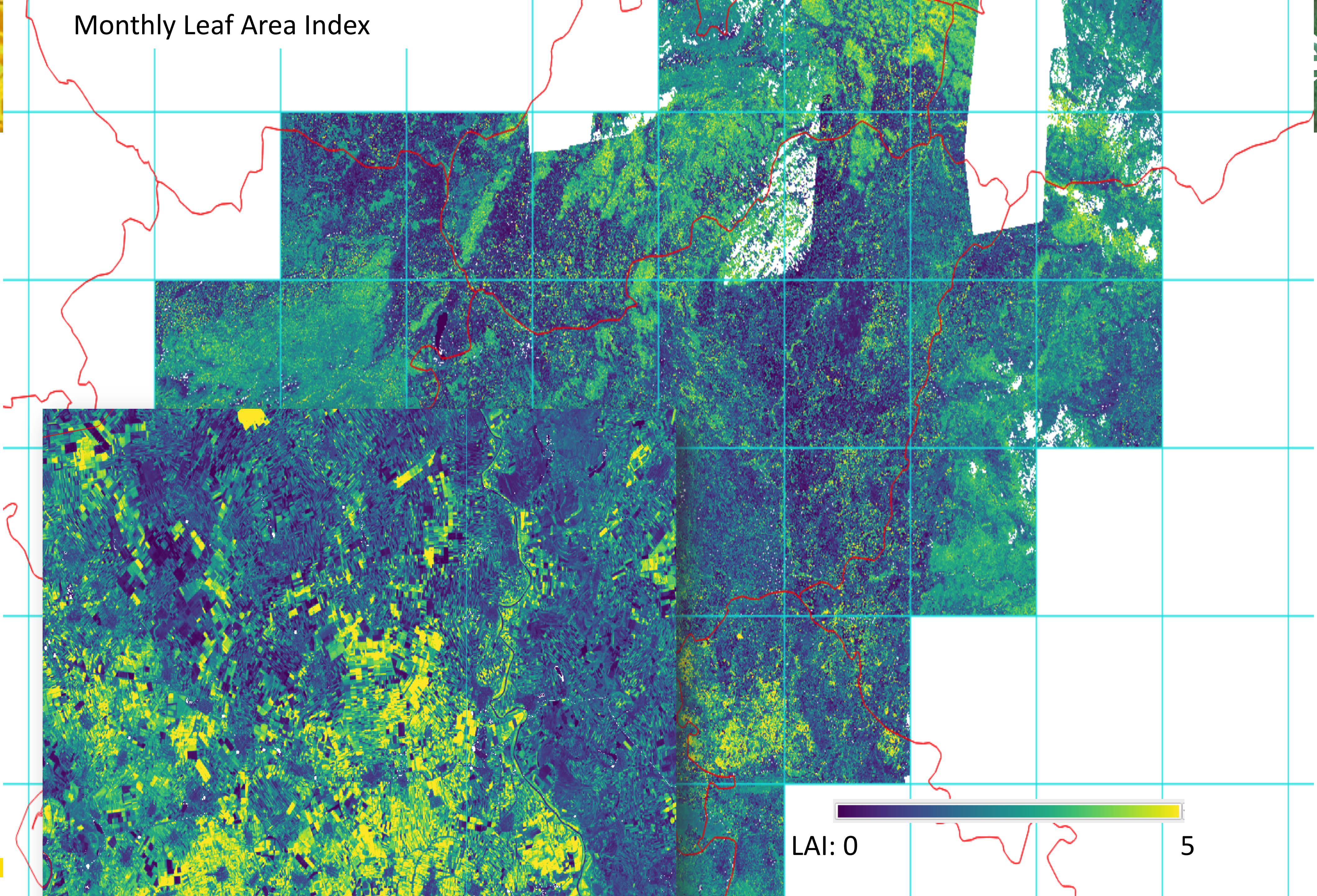
LAEA5210 grid
with 100km tiles
in the EPSG:3035 projection

True Color Image November
Monthly composite



LAEA5210 grid
with 100km tiles
in the EPSG:3035 projection

Monthly Leaf Area Index



Smoothing and gap-filling workflow

Data acquisition & atmospheric correction

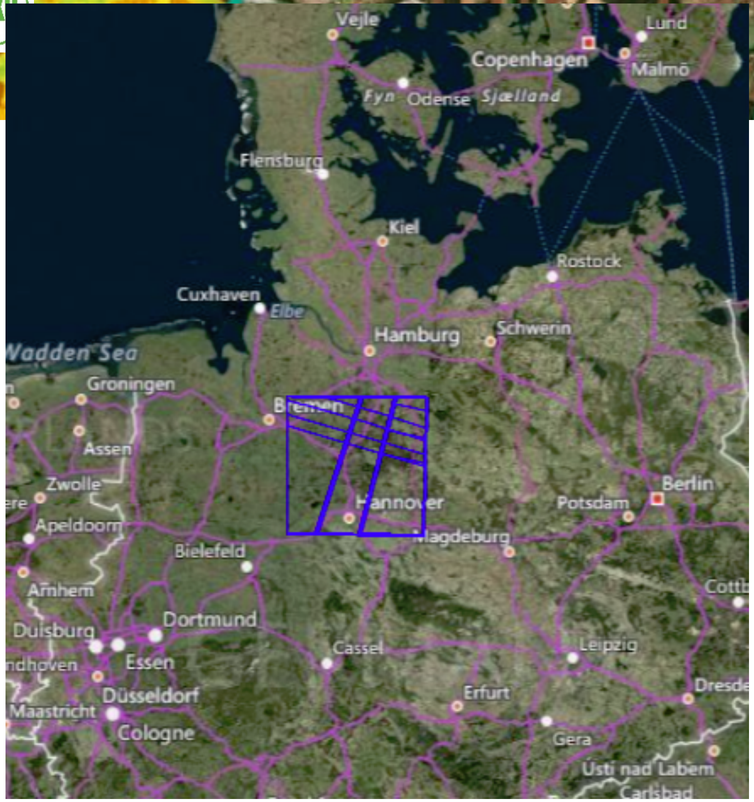
Cloud detect. & masking

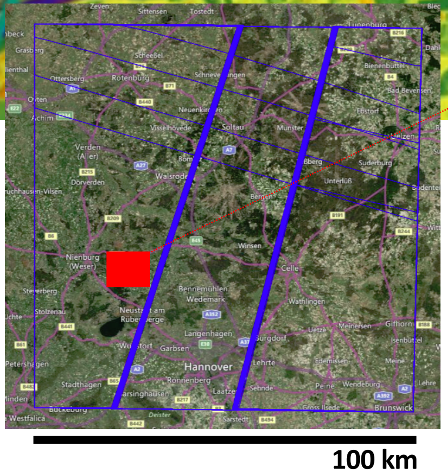
Function fitting

DATACUBE of EO products

Application

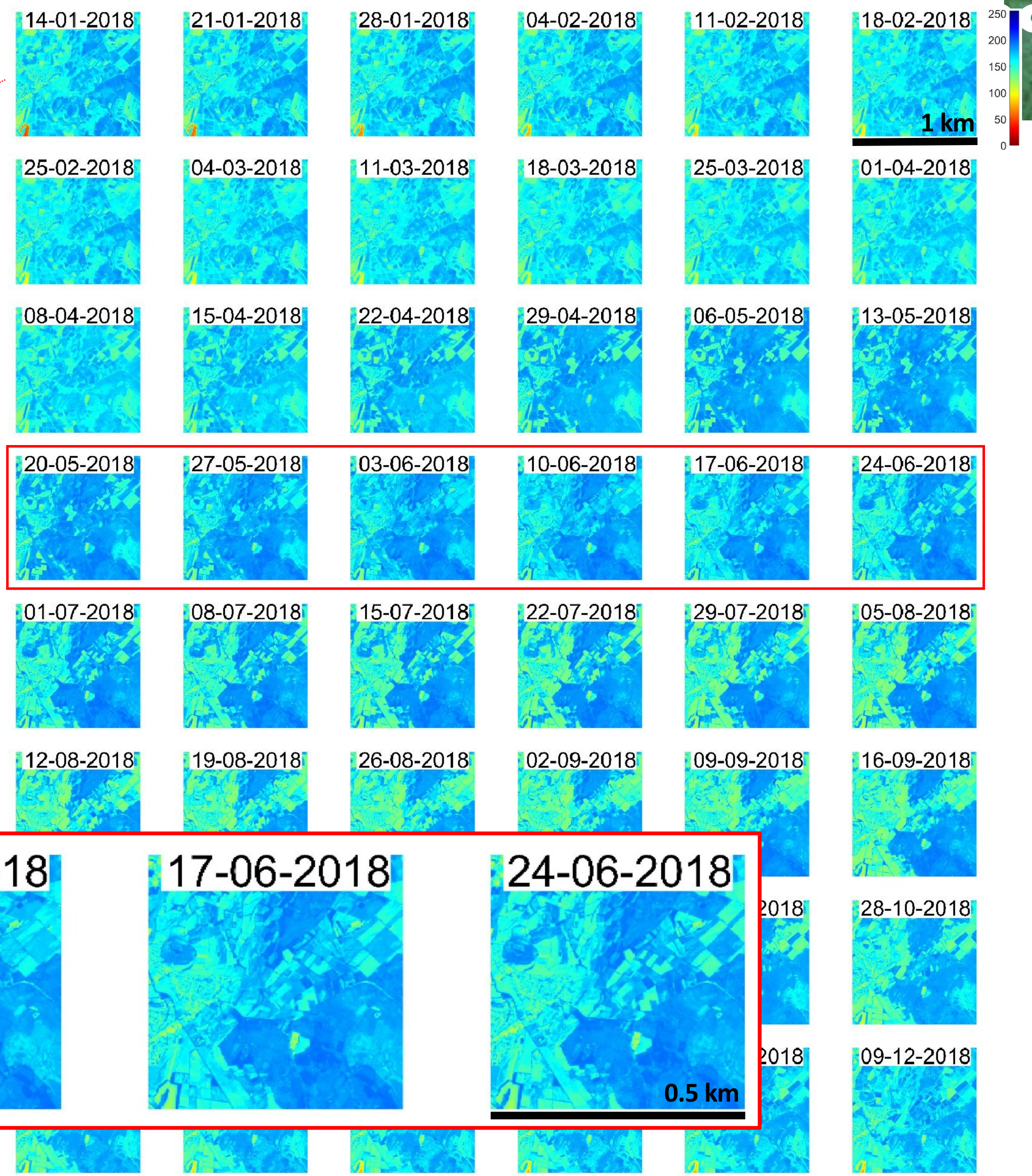
Microservices built on the datacube

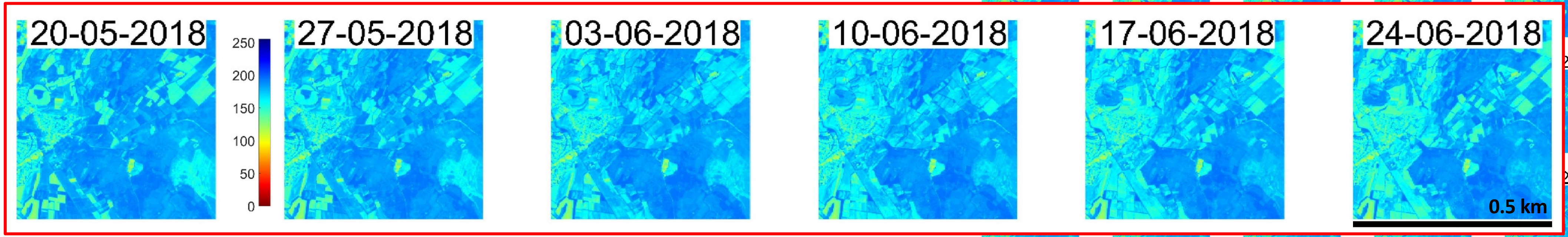




Sentinel-2 granule "32UND"
Time series
- starting **01-01-2018**
- ending **31-12-2018**

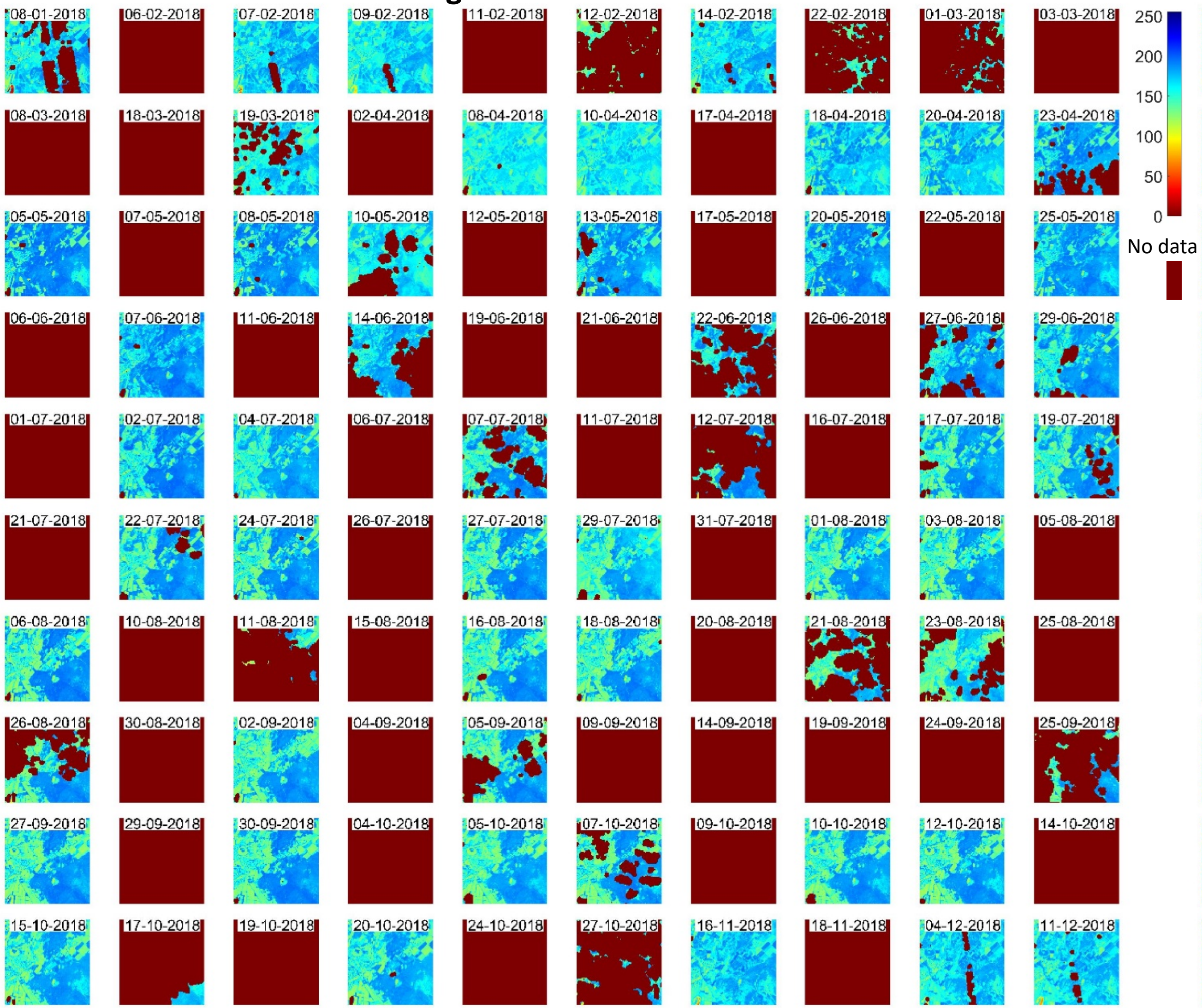
Cloud cover max **50%**





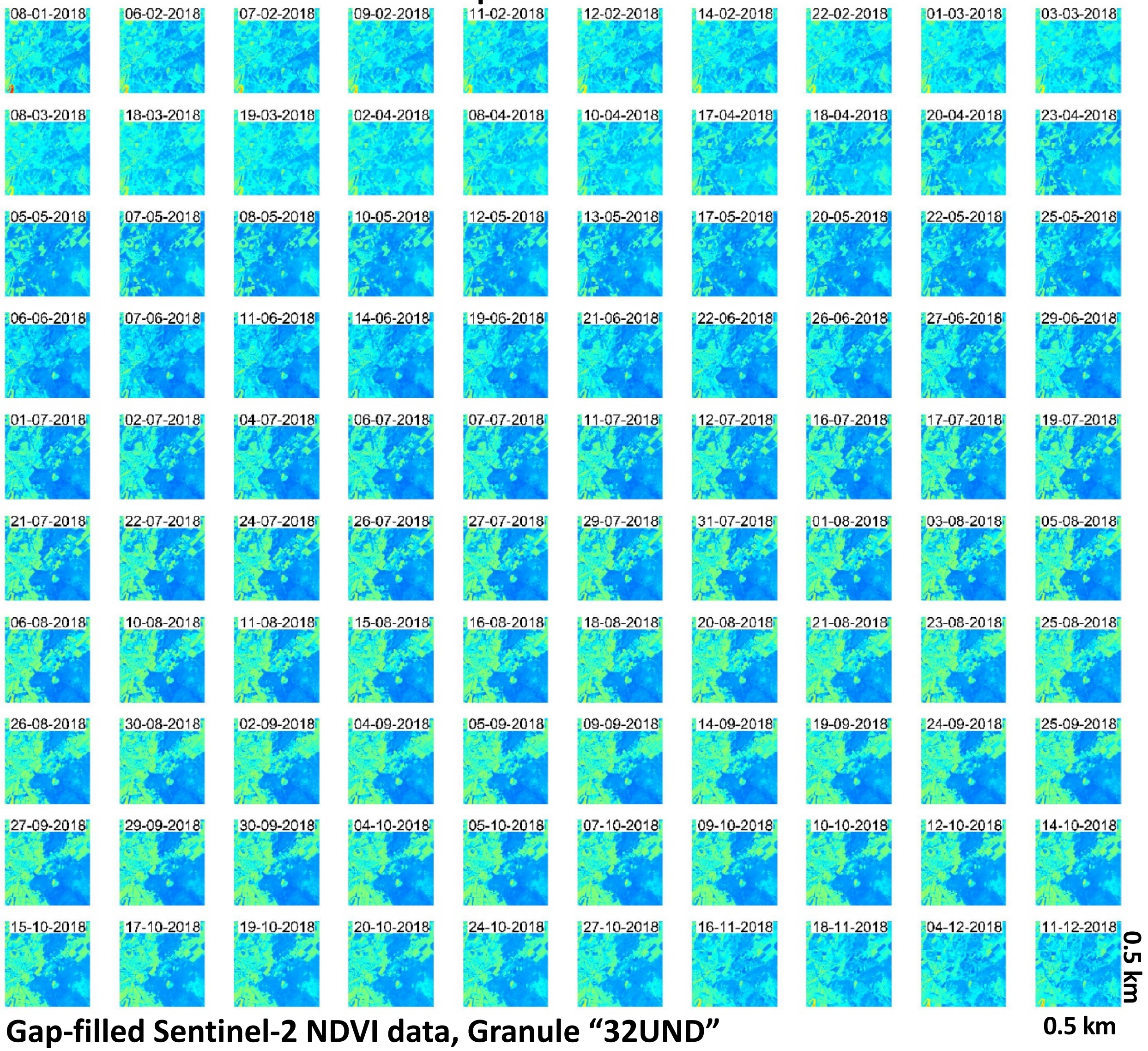
Smoothed and gap-filled NDVI time series – regularly spaced "Every Sunday"

Original data



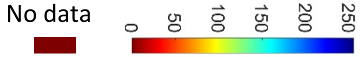
Original Sentinel-2 NDVI data, Granule “32UND”
starting **01-01-2018 -** ending **31-12-2018** Cloud cover max **50%**

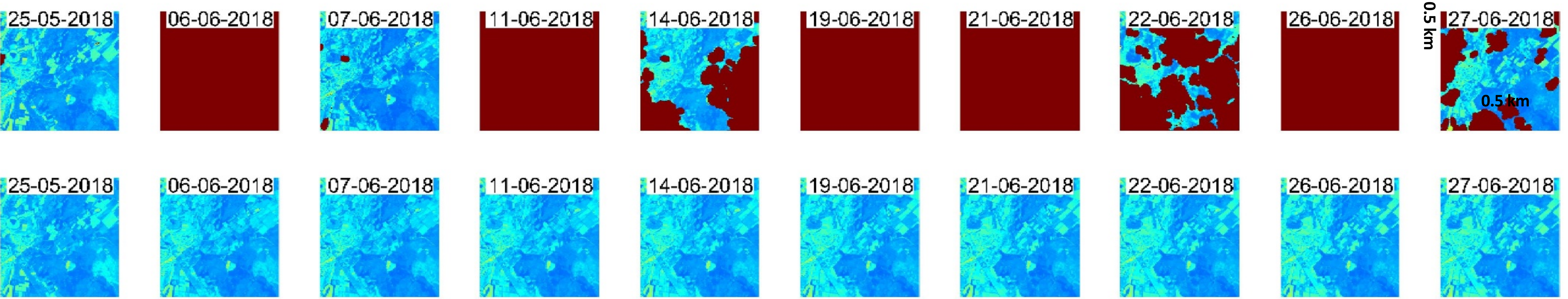
Gap-filled data



Gap-filled Sentinel-2 NDVI data, Granule “32UND”
starting **01-01-2018 -** ending **31-12-2018**

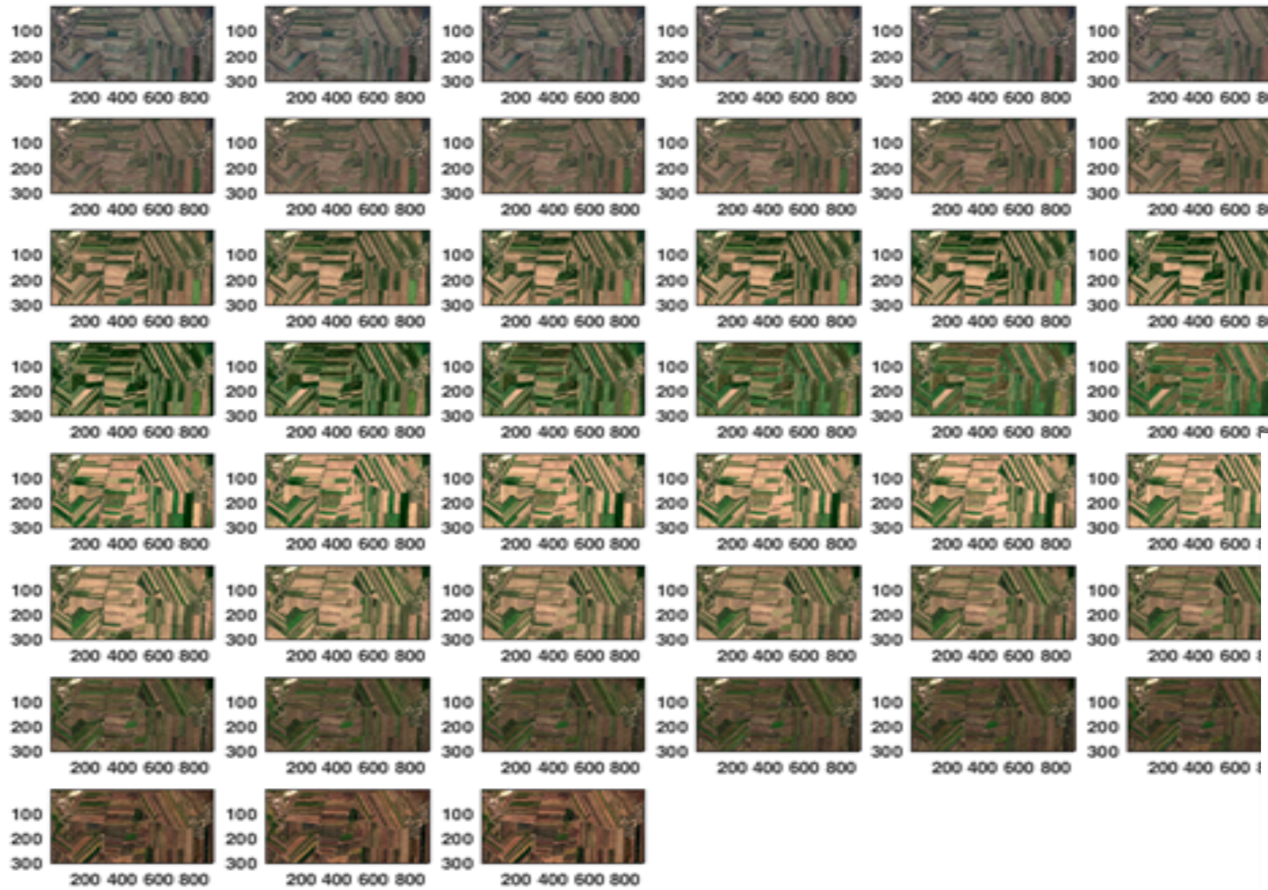
Original Sentinel-2 NDVI data, Granule “32UND”
starting **01-01-2018 -** ending **31-12-2018** Cloud cover max **50%**

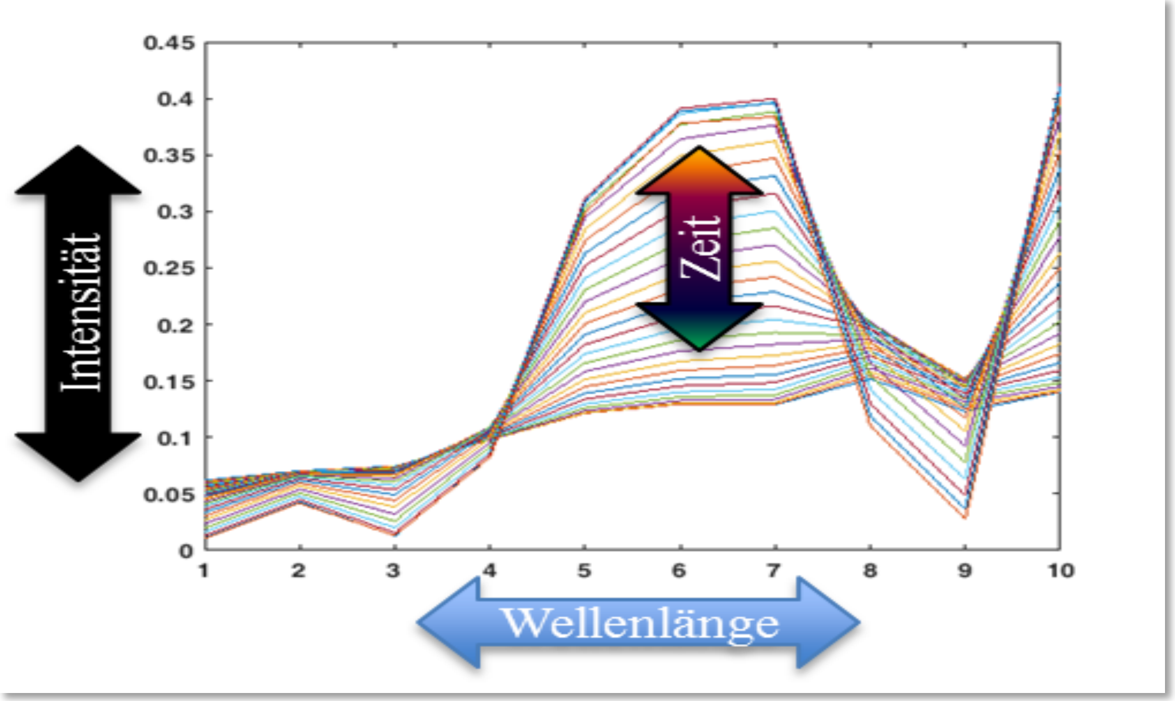




Gap-filled Sentinel-2 NDVI data, Granule “32UND”
starting **01-01-2018 -** ending **31-12-2018**

Data Cube: Spectro-temporal Features…





5-daily (gap-filled) images

Sentinel-2 Level 2-A processor (2016)

Open Access | Technical Note

Data Service Platform for Sentinel-2 Surface Reflectance and Value-Added Products: System Use and Examples

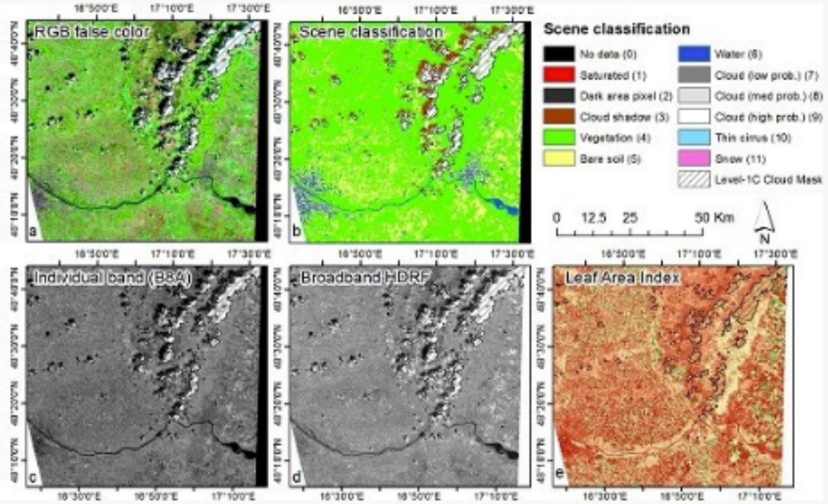
by Francesco Vuolo, Mateusz Żółtak, Claudia Pipitone, Luca Zappa, Hannah Wenng, Markus Immitzer, Marie Weiss, Frederic Baret and Clement Atzberger

Remote Sens. **2016**, *8*(11), 938; https://doi.org/10.3390/rs8110938
Received: 1 August 2016 / Revised: 12 October 2016 / Accepted: 6 November 2016 / Published: 11 November 2016

Abstract This technical note presents the first Sentinel-2 data service platform for obtaining atmospherically-corrected images and generating the corresponding value-added products for any land surface on Earth. Using the European Space Agency's (ESA) *Sen2Cor* algorithm, the platform processes ESA's Level-1C top-of-atmosphere reflectance to atmospherically-corrected [...] Read more.

(This article belongs to the Special Issue First Experiences with European Sentinel-2 Multi-Spectral Imager (MSI))

▼ Figures



Graphical abstract

First data processing infrastructure for Sentinel-2 data

Sentinel-2 Level 2-A processor (2017)

Sentinel2 Data Portal Wiki

- **2019-03-12 Service maintenance**
- 2018-12-13 Ndvi endpoint added
- 2018-11-26 Service maintenance
- 2018-10-25 Data loss
- 2018-10-16 Scheduled m
- 2018-10-16 Normal opera resumed
- 2018-08-15 EODC infras problems
- 2018-10-11 Topographic
- 2018-10-08 Granules de
- 2018-08-14 EODC Maint
- 2018-06-22 New DEMs

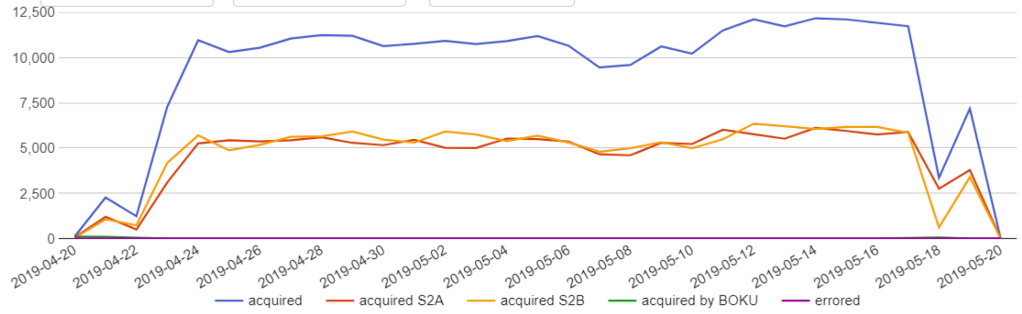
As RSS feed

⚠ 2019-03-12 Service maintenance

Due to our infrastructure provide maintenance the service will be down between 12th March 5pm and 13th Match 8pm.

Granules provided by EODC

from 04/20/2019 to 05/20/2019 by acquisition date



Last check: 2019-05-20 20:05:00

Angle

download	OK	0.481476 s
getCollection	OK	0.318161 s
getCollectionFilters	OK	16.510115 s

Calc

granuleNdvi	OK	527.190824 s
granuleNdviTransform	OK	15.011104 s

Granule

download	OK	0.322291 s
getCollection	OK	1.35662 s

DATA ACCESS

Need a single Sentinel-2A image ?

Use our web-interface after a one-step registration proces

https://s2.boku.eodc.eu

Need bulk Sentinel-2A data access ?

Get our **sentinel2 R package** on github.com

https://github.com/IVFL-BOKU/sentinel2

Need more flexibility?

Explore our application programming interface (API):

Wiki API https://s2.boku.eodc.eu/wiki/

Sentinel-2 Level 2-A processor (2018)

Define region of interest

For the given period and cloud threshold this corresponds to **251** new granule(s) and consumes **246** out of **-267** credit you have.

Out of **251** granule(s) covered by the region **241** are ready and **10** will be added to the processing queue.

User	francesco.vuolo@gmail.com
Region name	EODC FORUM
Start date	01/01/2019
End date	05/20/2019
Cloud coverage threshold	10
albedo	☐
LAI	☐
FAPAR	☐
FCOVER	☐
gap filling	☑

Close Save

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

ELSEVIER

Smoothing and gap-filling of high resolution multi-spectral time series: Example of Landsat data

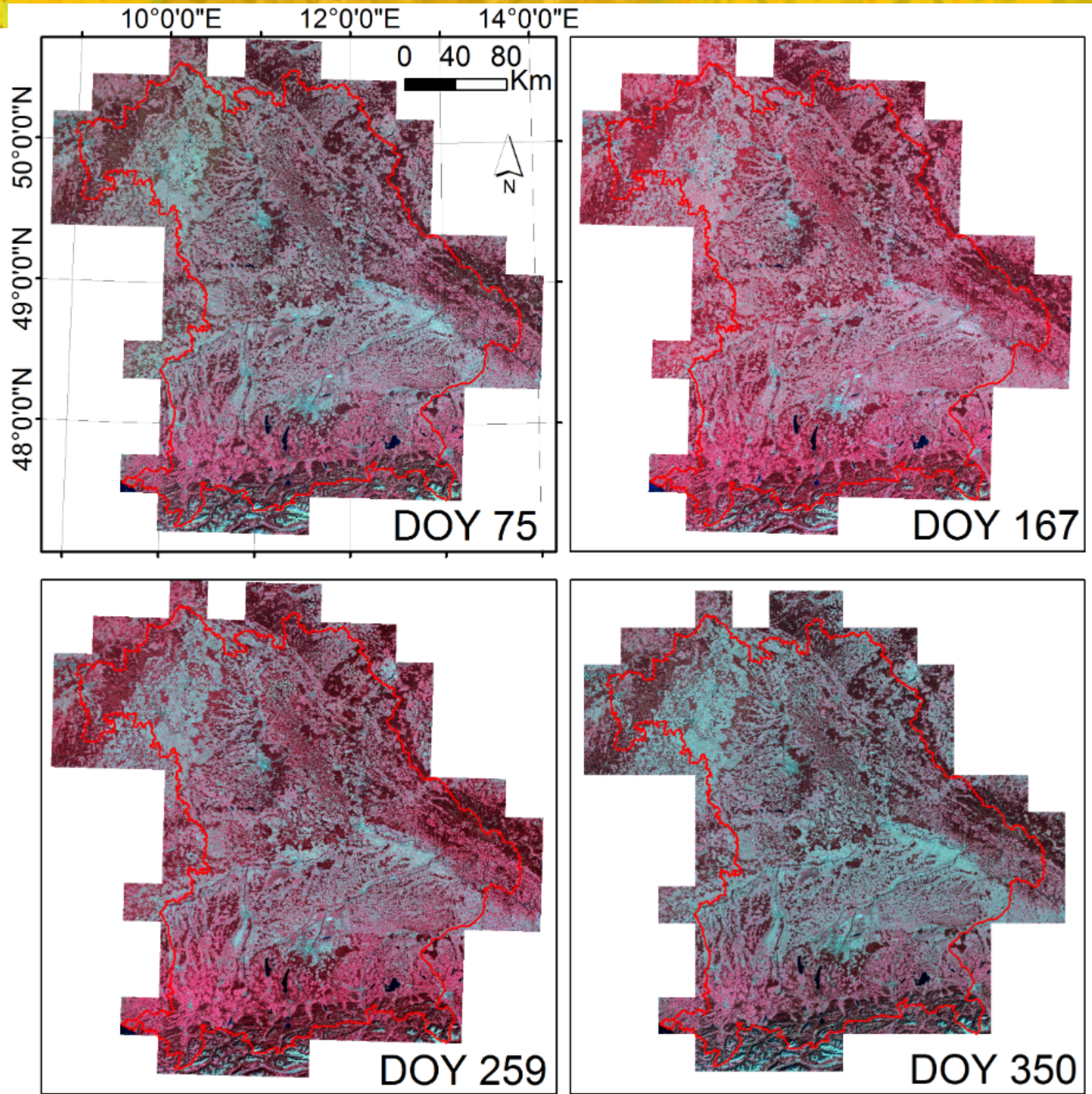
CrossMark

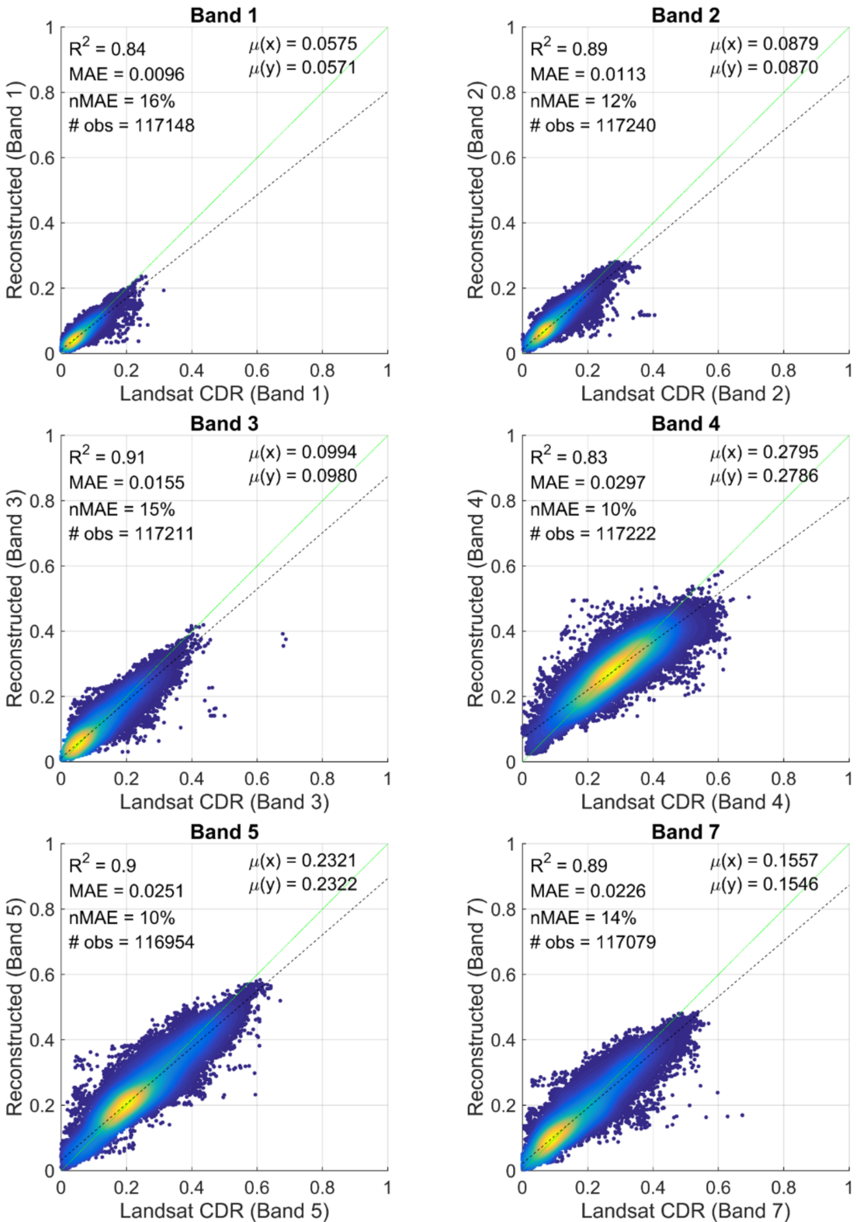
Francesco Vuolo*, Wai-Tim Ng, Clement Atzberger

On-demand

smoothing and gap-filling

Sentinel-2 Level 2-A processor (2018)





Sentinel-2 Level 2-A processor (2016-2018)

Near real time access

Essential Climate Terrestrial Variables

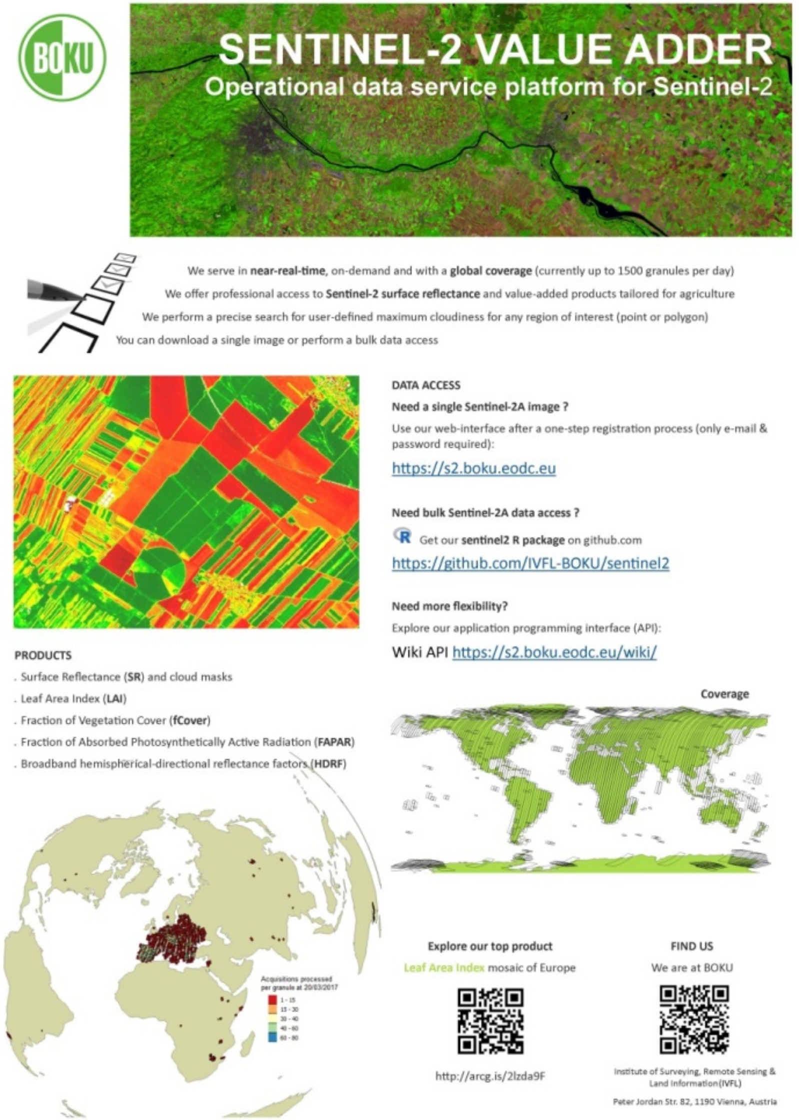
Richest metadata catalogue

Global coverage

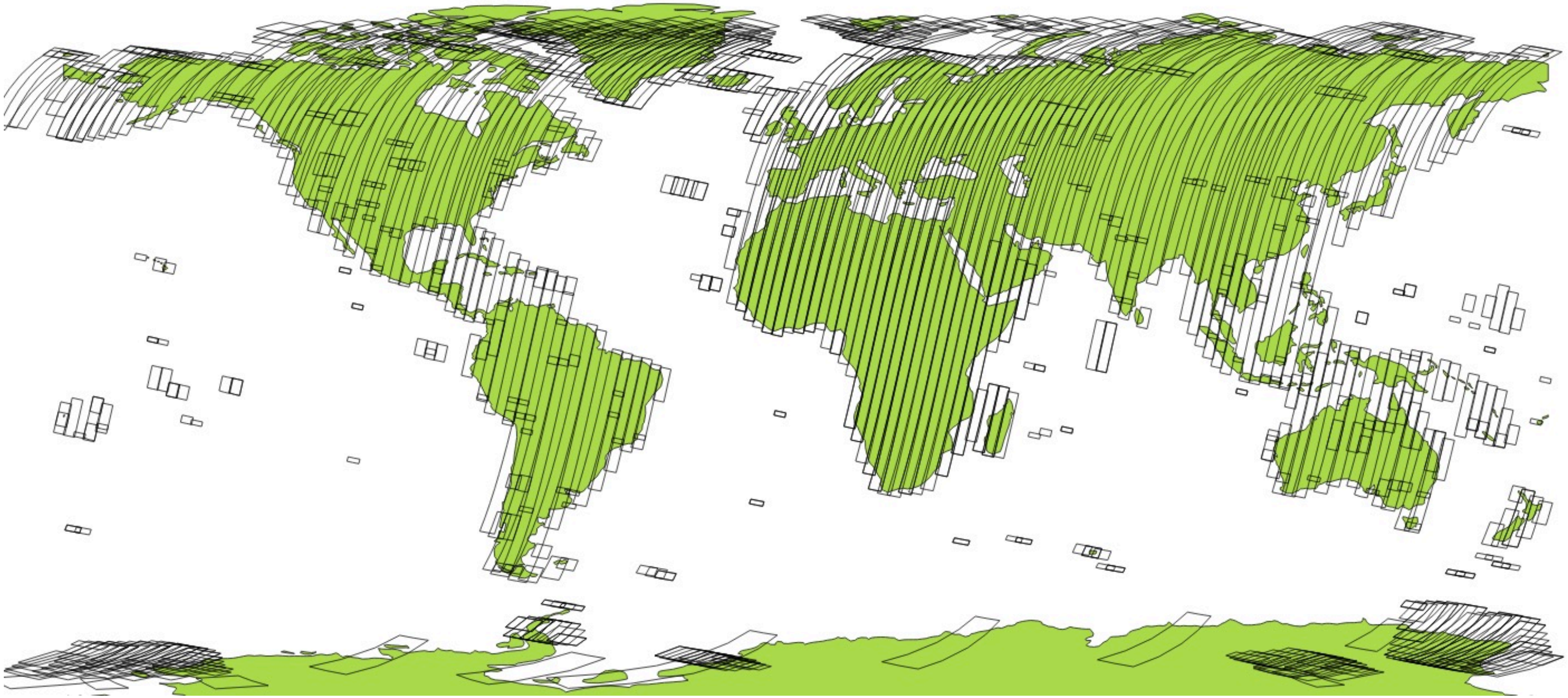
1500+ per day

Regular processing of EU

pre-DIAS example



Global coverage



Operational (24/7)

List of products

Layers	Short name	Source/Model	Packaging	Format	Resolutions	Geolocation accurac	Application note
L1C, TOA Reflectance	BXX				10,20,60 m		DN 0-10000, representative of ref
L2A, BOA Reflectance	BXX	Sen2Cor v 2.4			10,20,60 m		0 to 1, R = DN / 10000
True Color Image	TCI				10,20,60 m		Red=B4; Green=B3; Blue=B2; 0-
Scene classification	SCL		Individual bands of entire tile or a spatial subset		20,60 m		See Sen2Cor documentation for
Aerosol optical thickness (550 nm)	AOT			jp2	10,20,60 m	as L1C, TOA Refl.	0-1, AOT = DN / 1000
Water vapor	WVP				10,20,60 m		0.4-5.5 cm, WVP = DN / 1000
Quality Indicators for cloud probability	CLD				20,60 m		0-100
Quality Indicators for snow probability	SWM				20,60 m		0-100
Visibility	VIS				20 m		
Customised RGB image	RGB			tif	any resampling possible		
Time series (smoothed and gap-filled)	BXX_TS	BOKU		tif			DN 0-10000, representative of ref 0 to 1, SR = DN / 10000
Bio-physical indicators							
Broadband hemispherical-directional reflectance factor	HDRF	Weighted sum of the L2A data					Valid for all pixels, DN 0-1000 albe
Leaf area index	LAI	PROSAIL &			10 m (bands at 20 m are resampled to 10 m)		Valid for cropland, DN 0-8000 LAI
Fraction of Vegetation Cover	FCOVER	Neural Network		tif			Valid for cropland, DN 0-1000 FC
Fraction of Absorbed Photosynthetically Active Radiation	FAPAR						Valid for cropland, DN 0-1000 FA
Vegetation indices	VI	Raster calculator					A list of pre-defined indices is und
Auxiliary Data							
Digital elevation model	DEM	CGIAR 90 m		jp2	10,20,60 m		Elevation = DN - 10000
Metadata							
L2A processing parameters	GIP_TL.xml	/granule/granuleId/AUX_DATA					
Level 2A Tile metadata XML file	Directly exposed via the data portal and APIs						

Remote sensing of the Earth surface

- Land surfaces can be characterized by:
  - *Categorical variables* (e.g., land cover, …)
    - RS application: land cover and use and change mapping
  - *Continuous variables* (e.g., leaf area index, albedo, …)
    - RS application: hydrology, climatic modelling

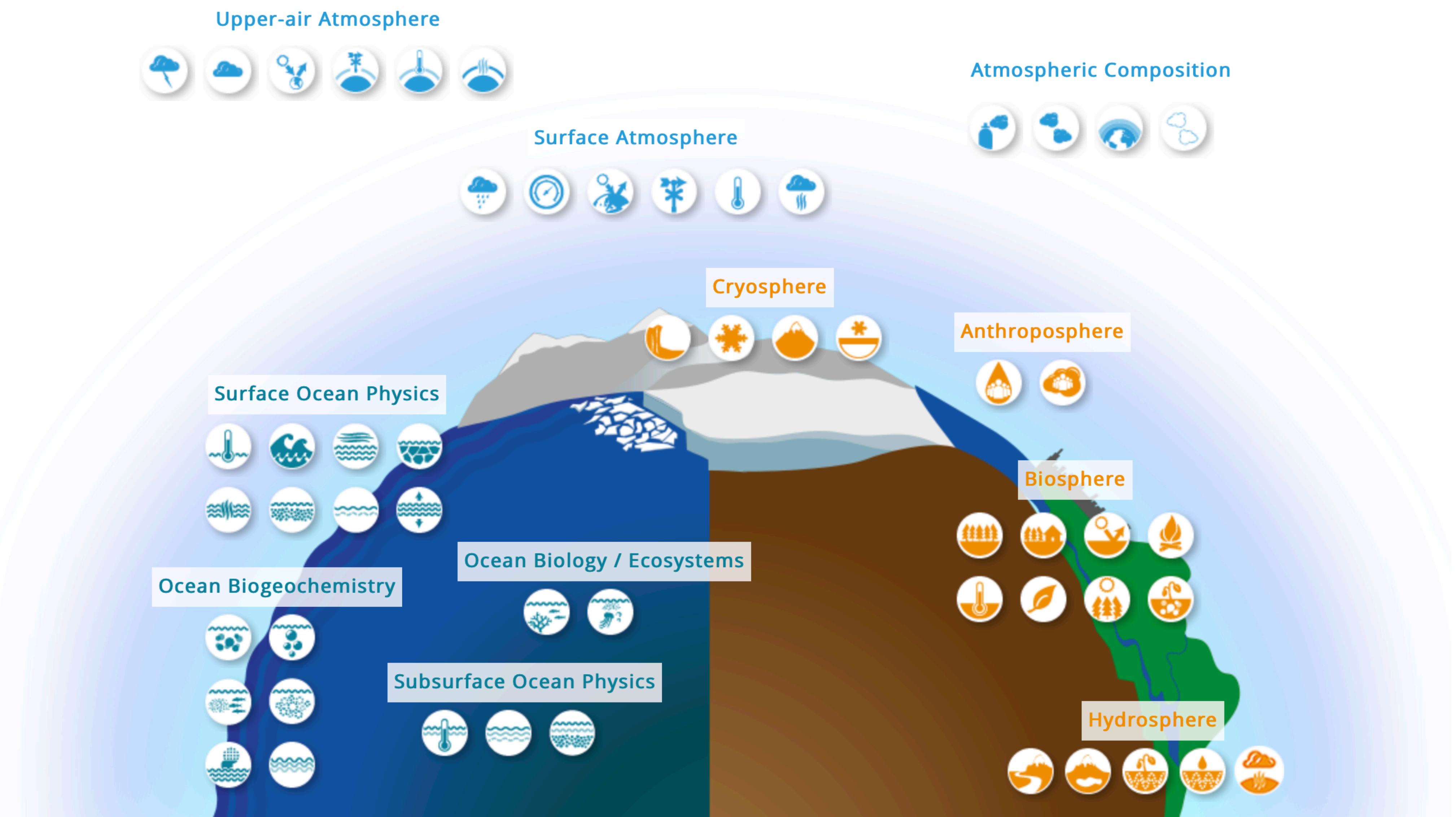
Global Climate Observing System

https://gcos.wmo.int/en/essential-climate-variables/

Essential Climate Variables

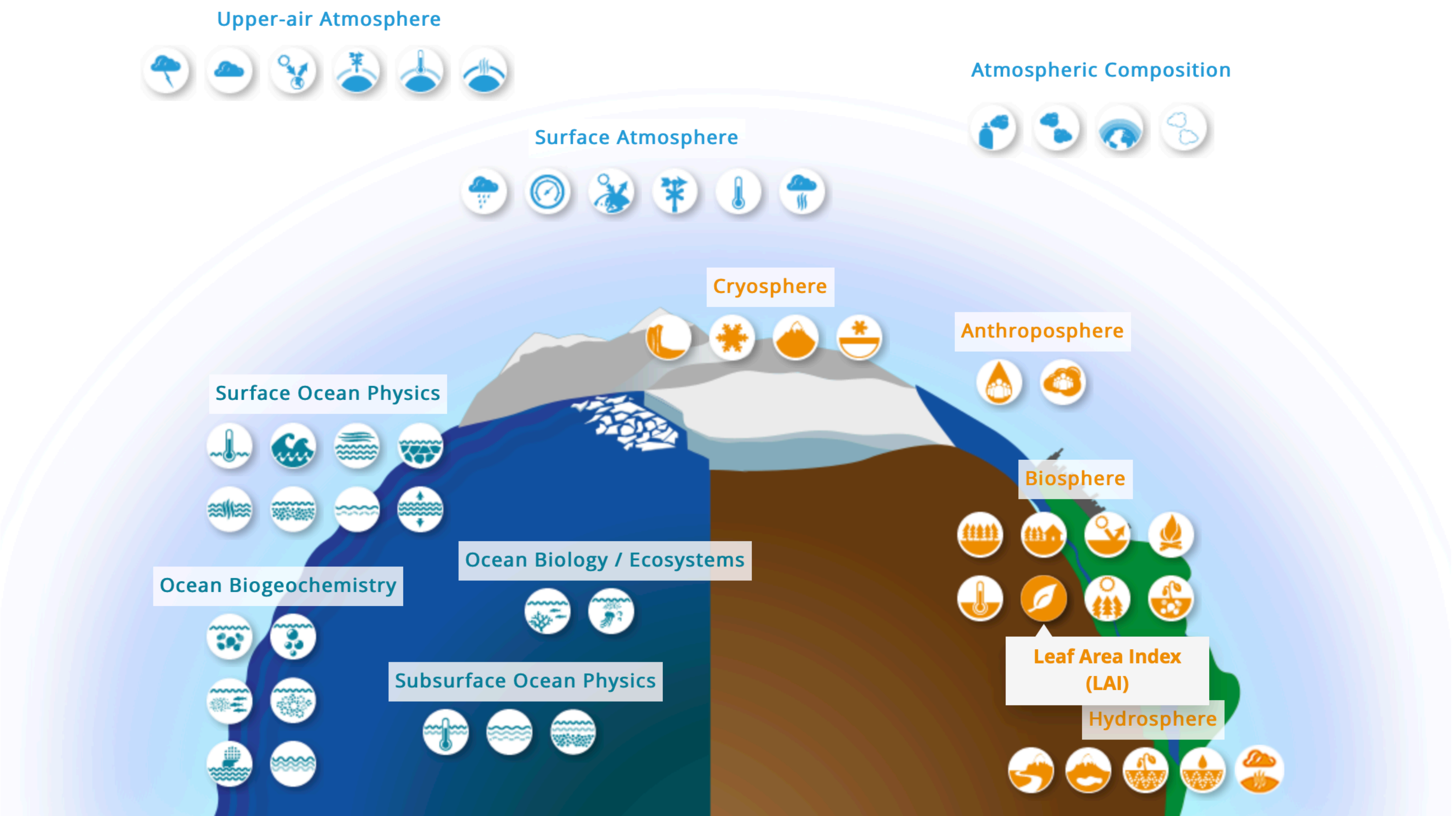
For table version click here

What are Essential Climate Variables (ECVs)?



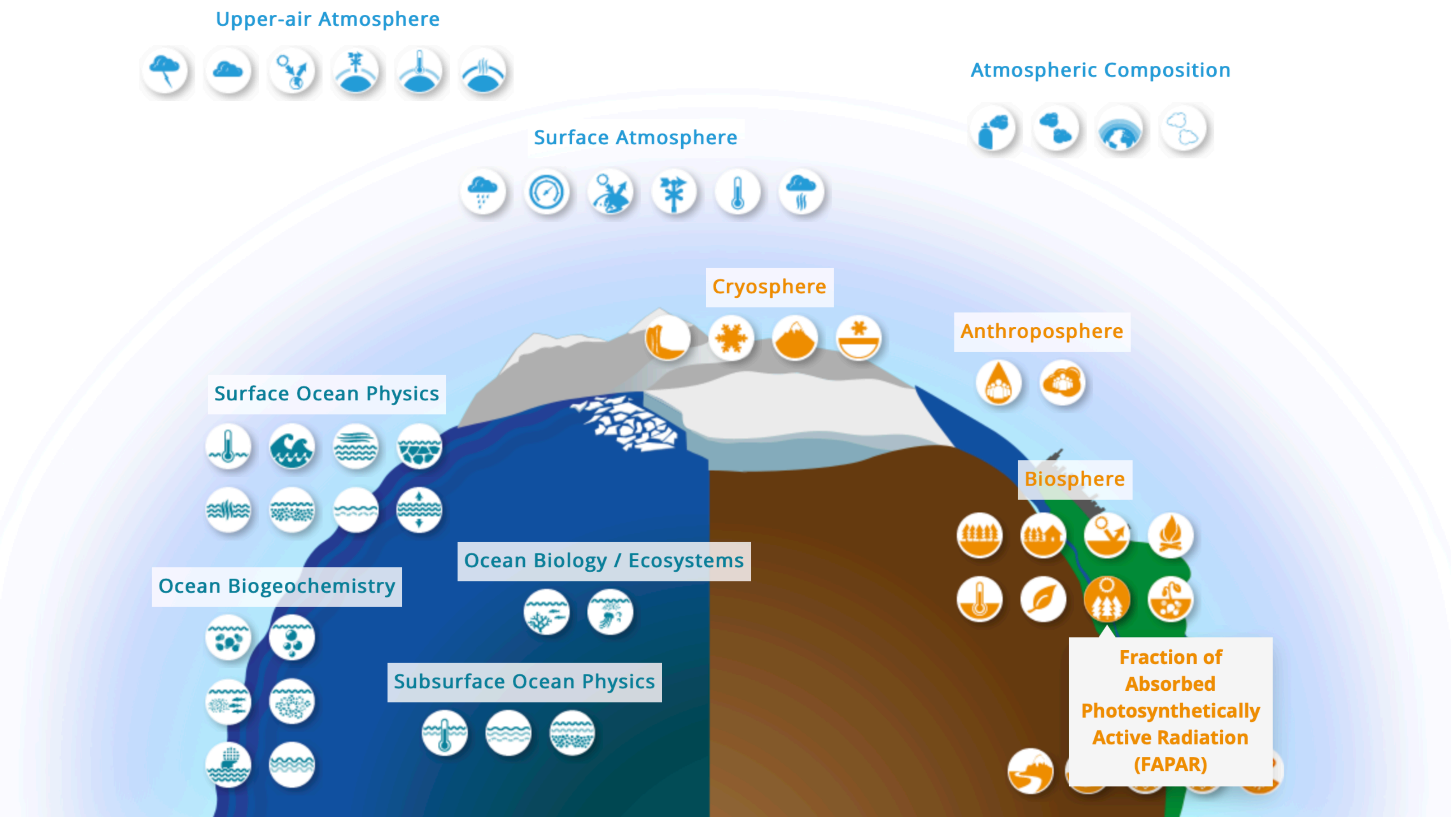
Essential Climate Variables

For table version click here
What are Essential Climate Variables (ECVs)?



Essential Climate Variables

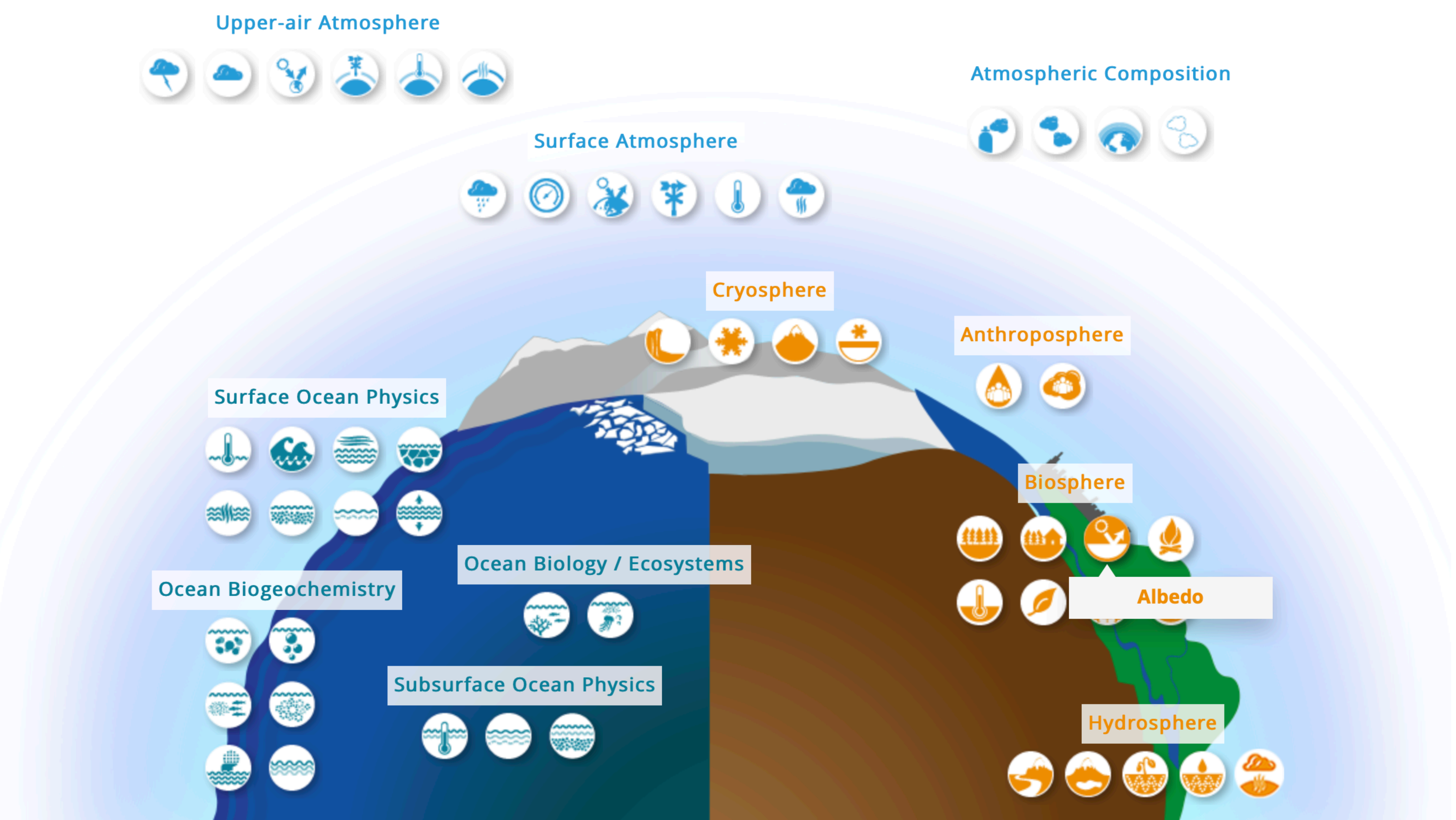
For table version click here
What are Essential Climate Variables (ECVs)?



Essential Climate Variables

[For table version click here](#)

[What are Essential Climate Variables (ECVs)?](#)



For graphical version click here
What are Essential Climate Variables (ECVs)?

Atmosphere

Surface

- Precipitation
- Pressure
- Radiation budget
- Temperature
- Water vapour
- Wind speed and direction

Upper-air

- Earth radiation budget
- Lightning
- Temperature
- Water vapor
- Wind speed and direction

Atmospheric Composition

- Aerosols
- Carbon dioxide, methane and other greenhouse gases
- Clouds
- Ozone
- Precursors for aerosols and ozone

Land

Hydrosphere

- Groundwater
- Lakes
- River discharge

Cryosphere

- Glaciers
- Ice sheets and ice shelves
- Permafrost
- Snow

Biosphere

- Above-ground biomass
- Albedo
- Evaporation from land
- Fire
- Fraction of absorbed photosynthetically active radiation (FAPAR)
- Land cover
- Land surface temperature
- Leaf area index
- Soil carbon
- Soil moisture

Anthropospehere

- Anthropogenic Greenhouse gas fluxes
- Anthropogenic water use

Ocean

Physical

- Ocean surface heat flux
- Sea ice
- Sea level
- Sea state
- Sea surface currents
- Sea surface salinity
- Sea surface stress
- Sea surface temperature
- Subsurface currents
- Subsurface salinity
- Subsurface temperature

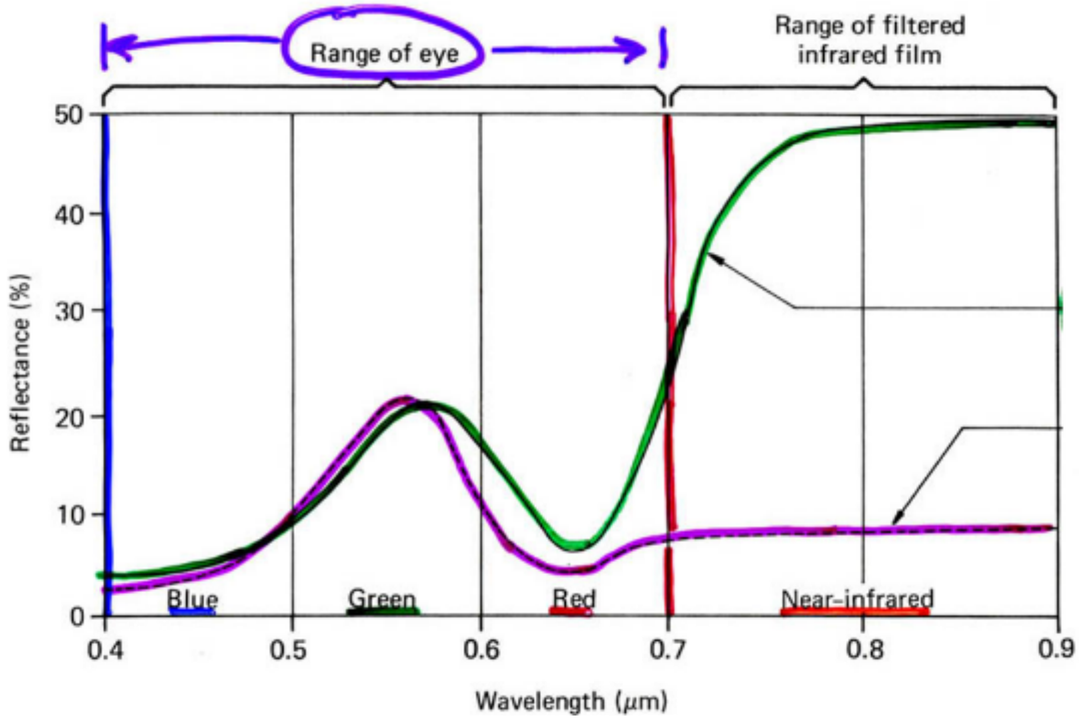
Biogeochemical

- Inorganic carbon
- Nitrous oxide
- Nutrients
- Ocean colour
- Oxygen
- Transient tracers

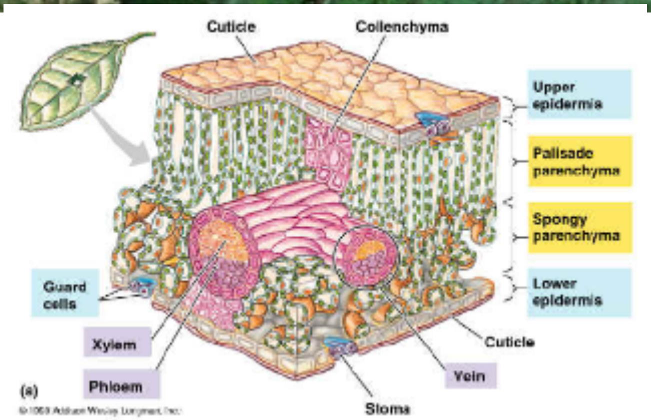
Biological/ecosystems

- Marine habitats
- Plankton

Spectral signature of land surface objects

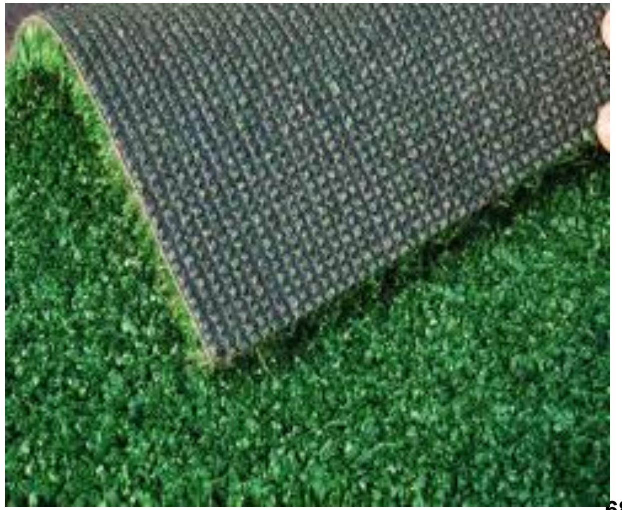


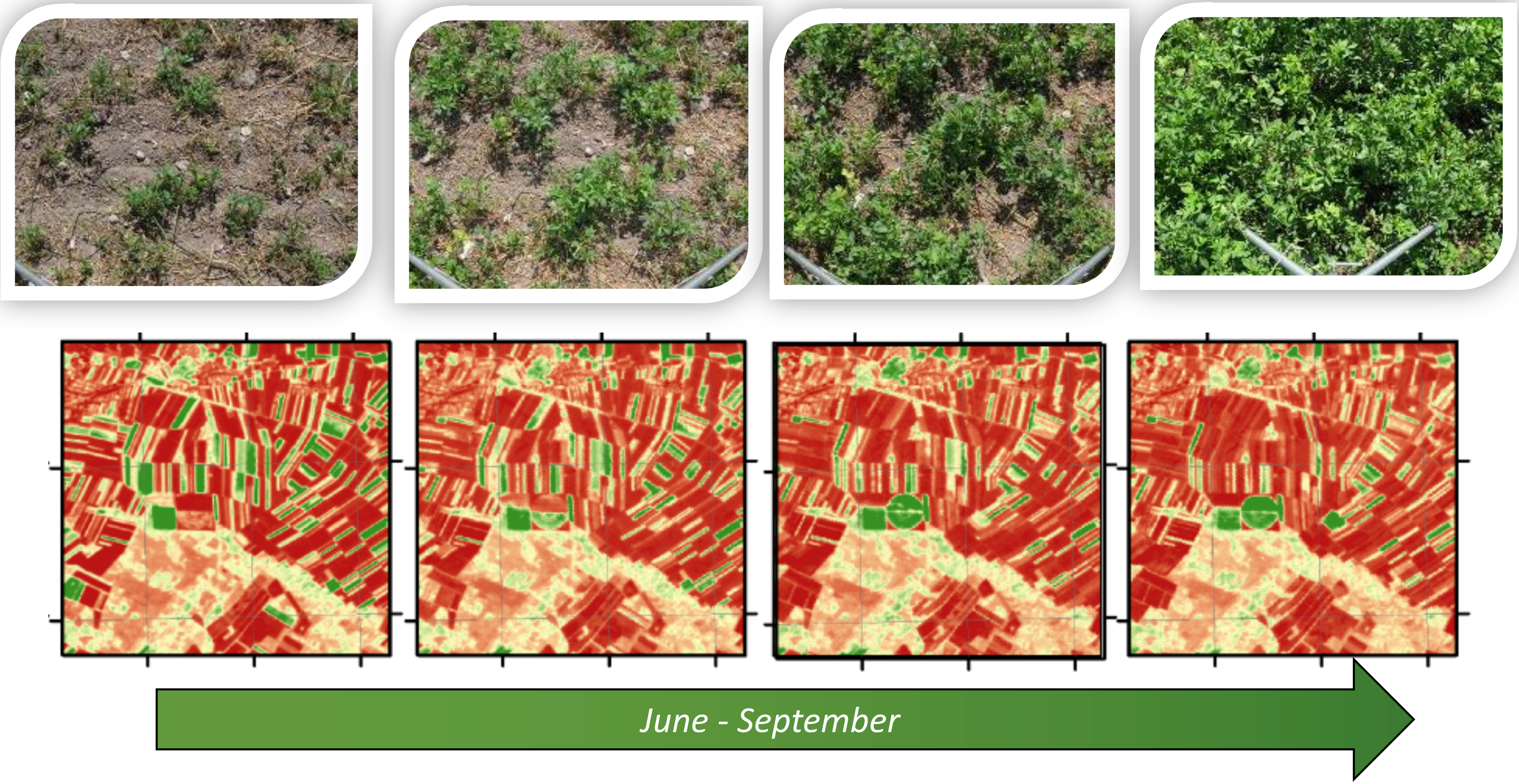
Credit: University of Maryland



Real

Artificial

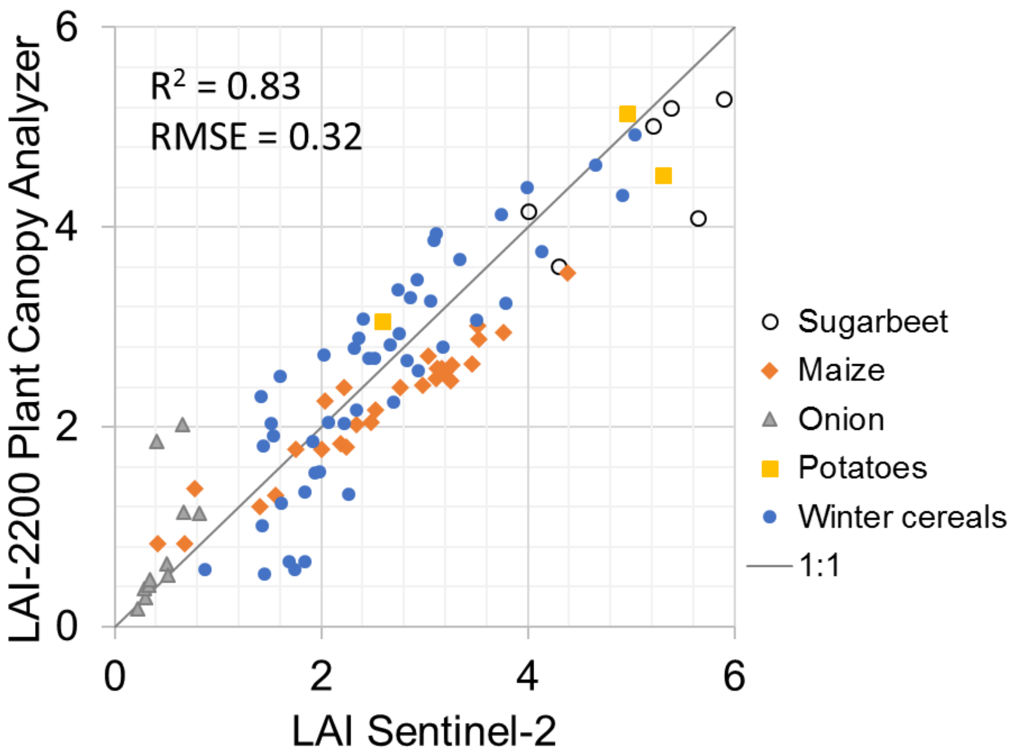



June - September

Leaf Area Index measurements

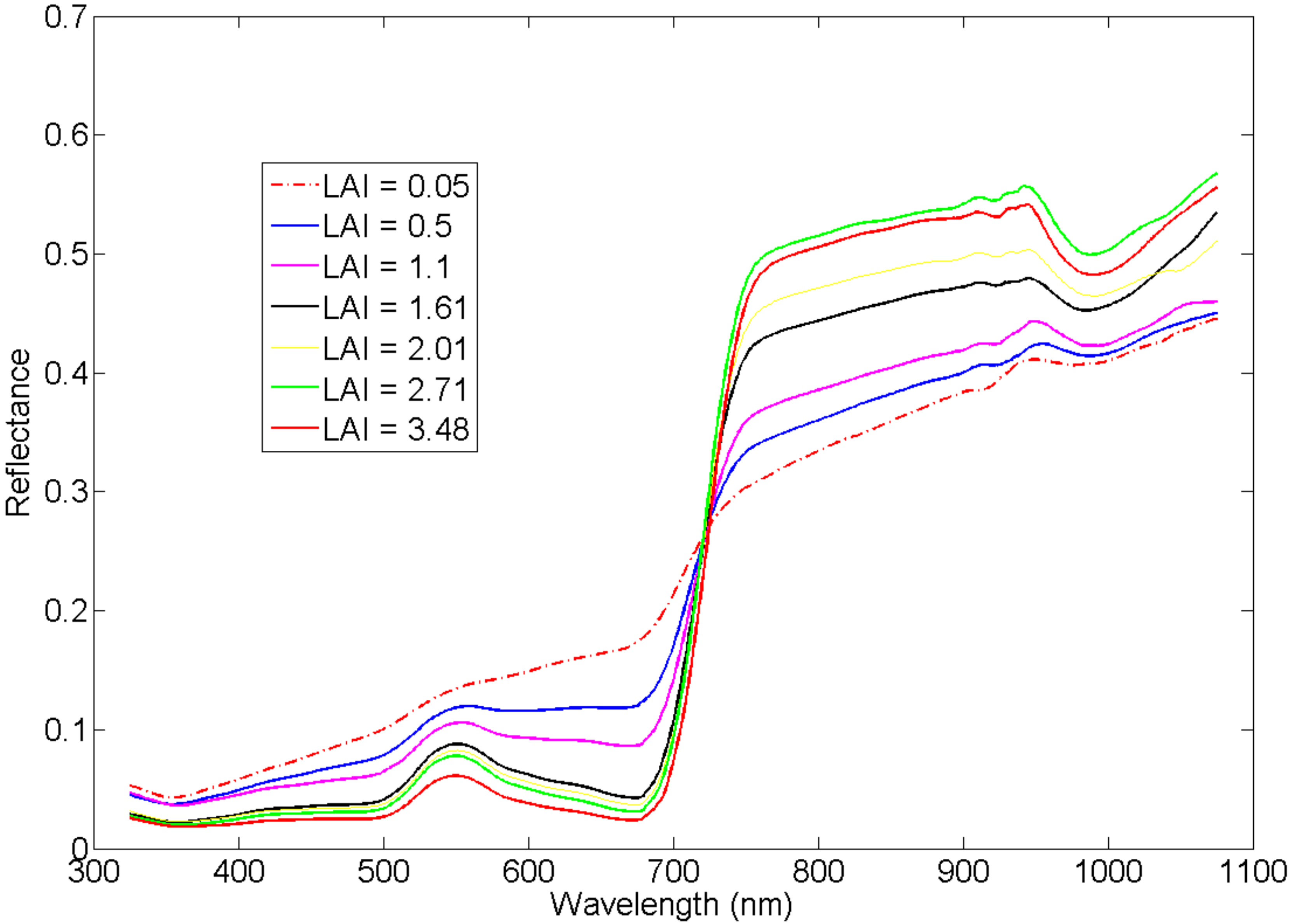
https://www.licor.com/env/support/LAI-2200C/videos/measuring-lai.html

Field observations vs Sentinel-2 LAI



sentinel-2

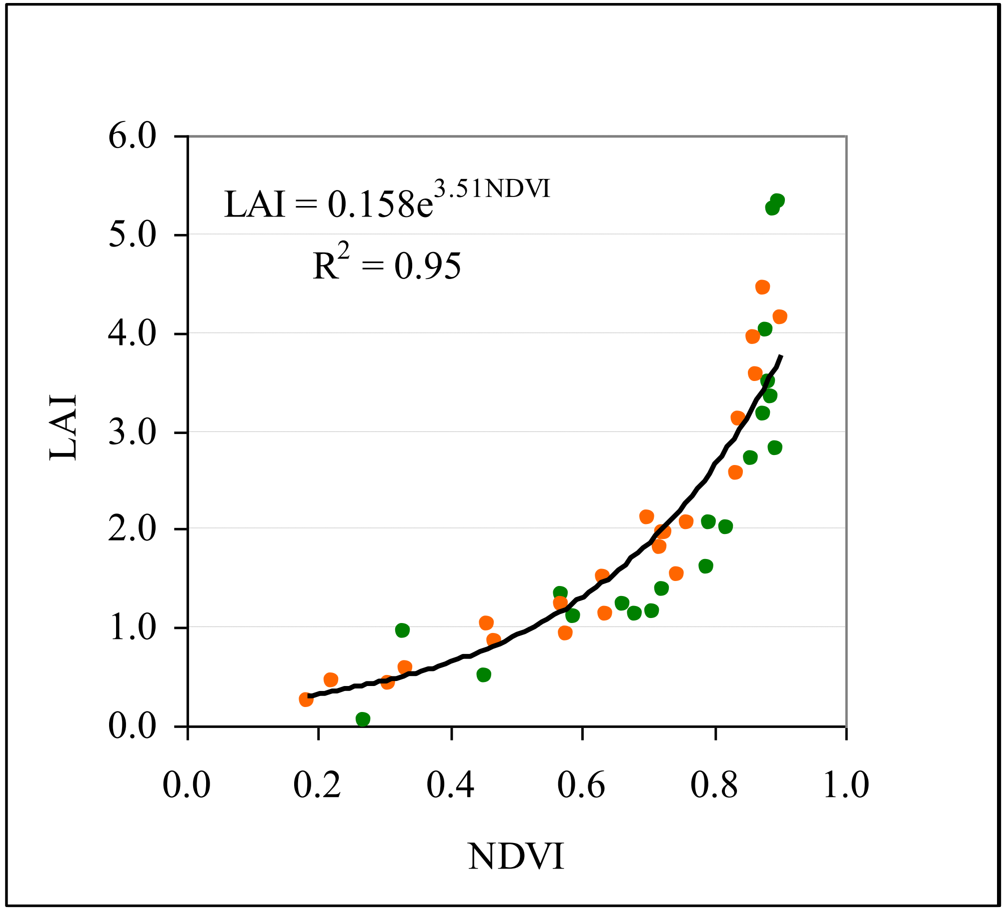
Reflectance – LAI 18/07 – 05/08



How can we estimate LAI from remote reflectance measures?

$$NDVI = \frac{r_i - r_r}{r_i + r_r}$$

$$LAI = 0.158e^{3.51NDVI}$$



Estimation of Leaf Area Index from the Weighted Difference Vegetation Index

$$WDVI = r_i - r_r \frac{r_{s\,i}}{r_{s\,r}}$$

$$LAI = -\frac{1}{\alpha}\ln\left(1 - \frac{WDVI}{WDVI_\infty}\right)$$

Calibration required!

Clevers, J.G.P.W. Application of a weighted infrared-red vegetation index for estimating leaf Area Index by Correcting for Soil Moisture. *Remote Sens. Environ* **1989**, *29*, 25–37.

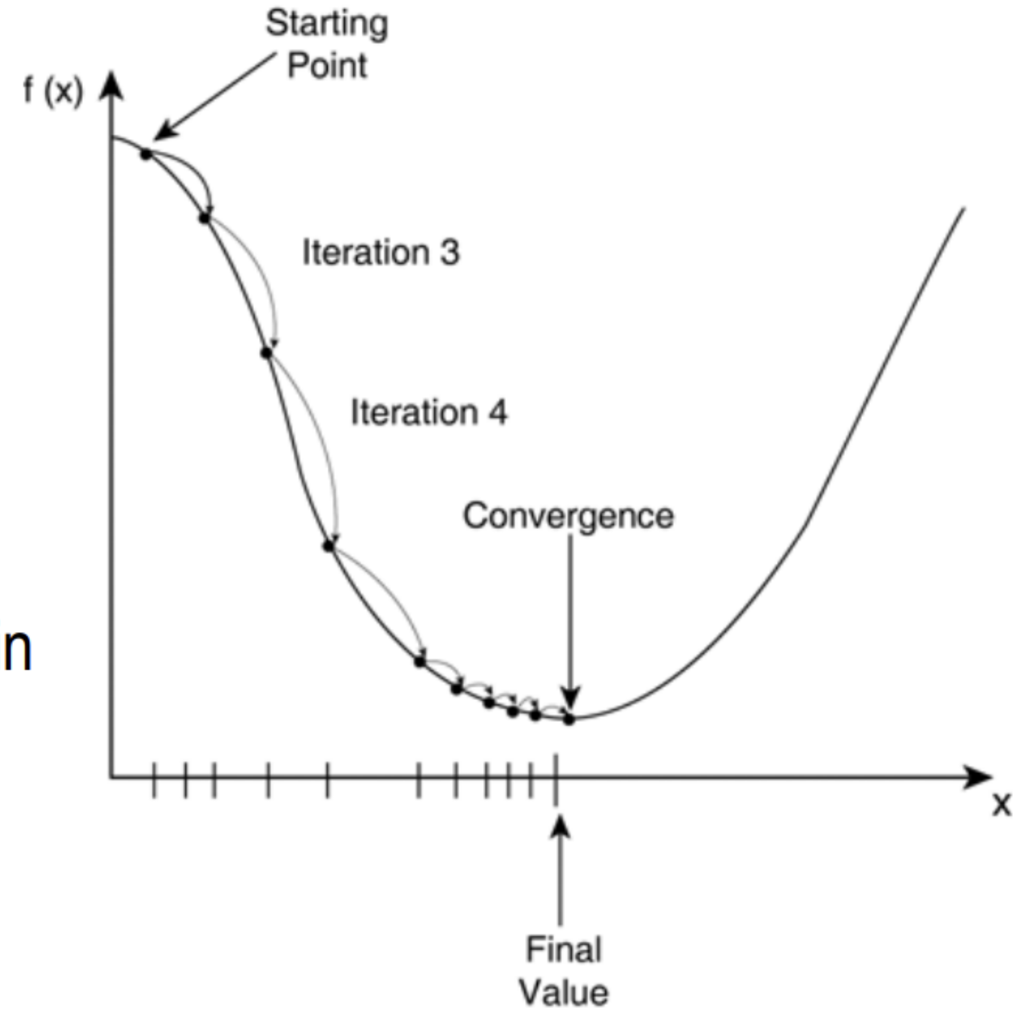
Iterative optimization

$$LAI = -\frac{1}{\alpha}\ln\left(1 - \frac{WDVI}{WDVI_{\infty}}\right)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=i}^{N}(LAI_{in-situ,i} - LAI_{estimates,i})^2}{N}}$$

PROBLEM: FIND MINIMUM RMSE by changing α

Iterative optimization



https://towardsdatascience.com/machine-learning-fundamentals-via-linear-regression-41a5d11f5220

Model parameters: α

$$LAI = -\frac{1}{\alpha}\ln\left(1 - \frac{WDVI}{WDVI_{\infty}}\right)$$

α is a combination of extinction and scattering coefficients.
It describes the rate with which the function runs to its asymptotic value, and $WDVI_{\infty}$ as the asymptotic limiting value for the WDVI.

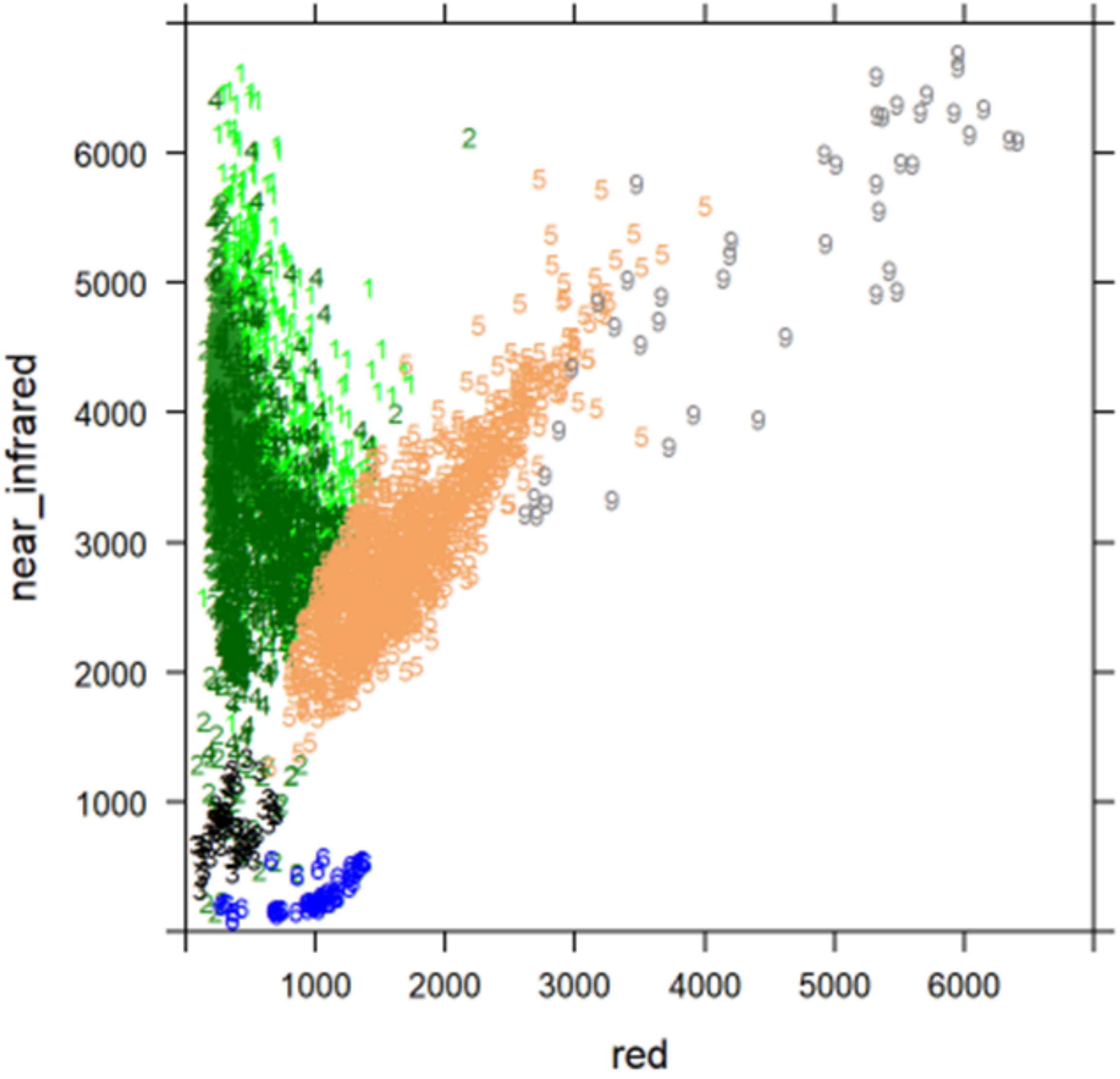
$WDVI_{\infty}$ is the asymptotical value of WDVI for $LAI \rightarrow \infty$

The exponential relationship between WDVI and LAI means that LAI estimates will be less accurate when approximating the asymptotic value of WDVI ($WDVI_{\infty}$)

```
# Invert the LAI CLAIR model to find alfa. This is written in the form of a function that we can optimise in R.
  alfa_search <- function(alfa) sqrt(sum((y - ((-log(1-(WDVI/WDVI_inf)))*(1/alfa)))^2)/length(y))

# Search the interval from lower to upper for a minimum in the function alfa_search
  a<-optimise(f = alfa_search,lower = 0.1, upper = 1)
```

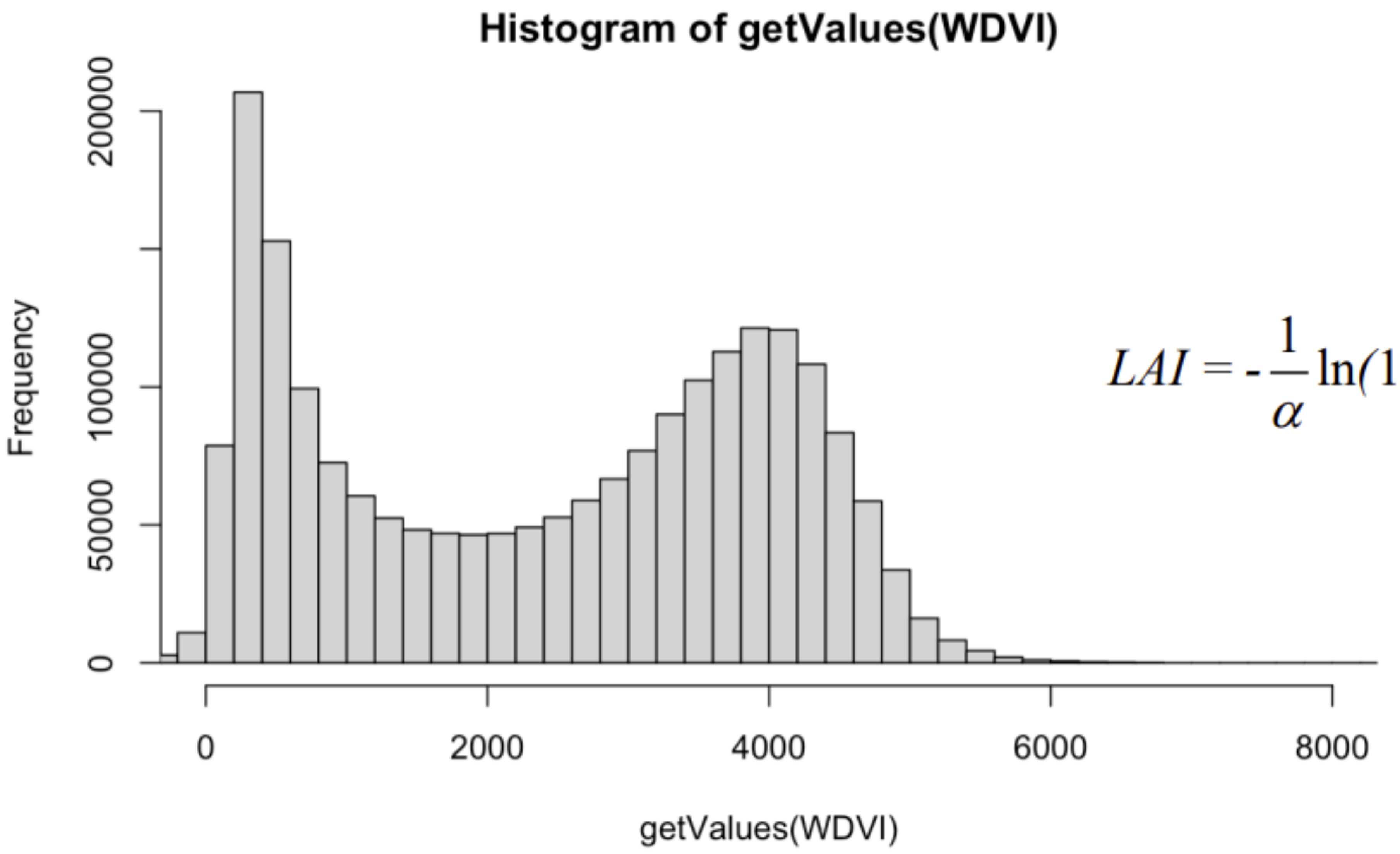
Soil line slope



$$WDVI = r_i - r_r \frac{r_{s\,i}}{r_{s\,r}}$$

Model parameters: $WDVI_{\infty}$

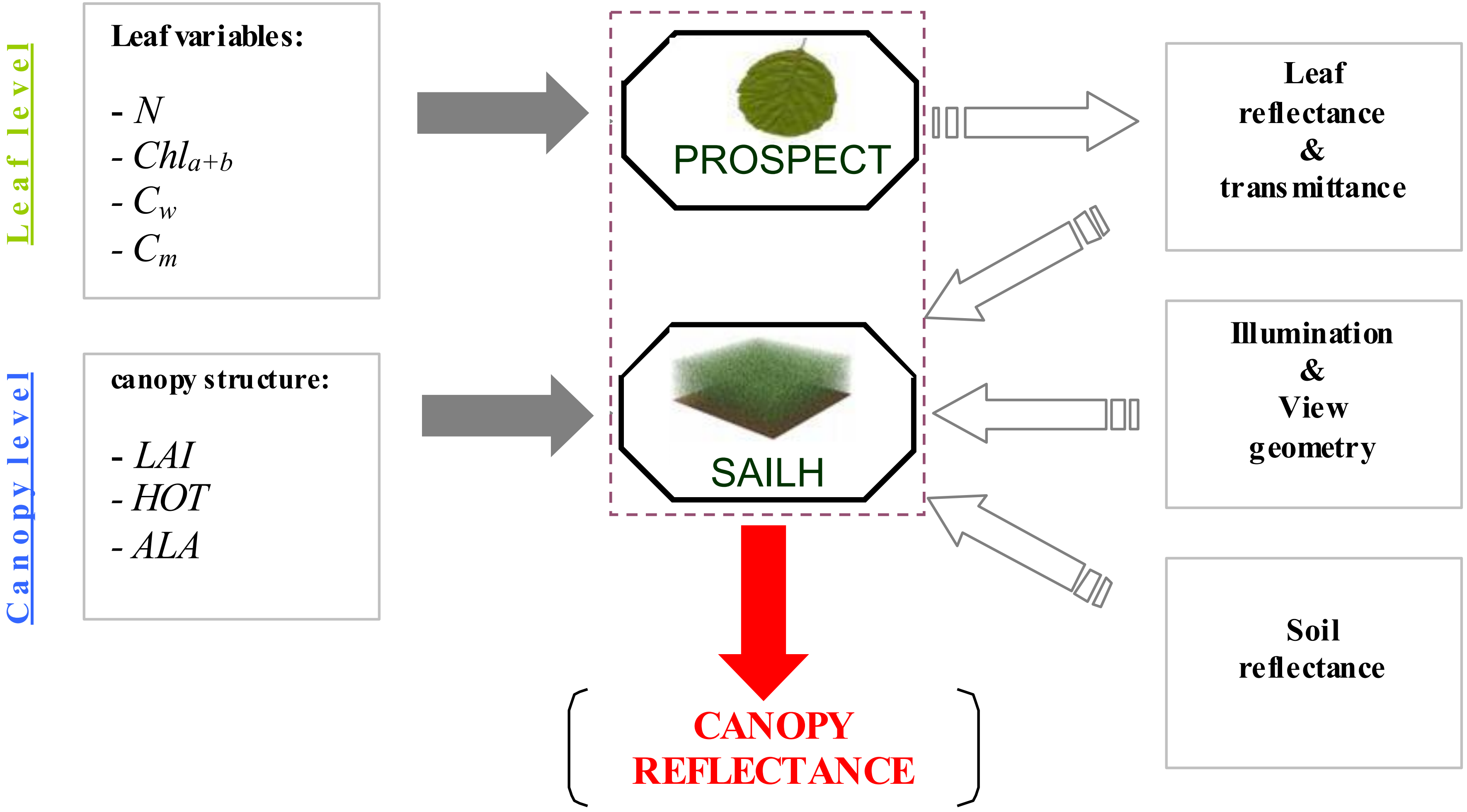
$WDVI_{\infty}$ is the asymptotical value of WDVI for LAI$\rightarrow\infty$



$$LAI = -\frac{1}{\alpha}\ln\left(1 - \frac{WDVI}{WDVI_{\infty}}\right)$$

Radiative Transfer Model

PROSPECT+SAILH („PROSAILH“) Model (Jacquemoud & Baret, 1990; Verhoef, 1984)

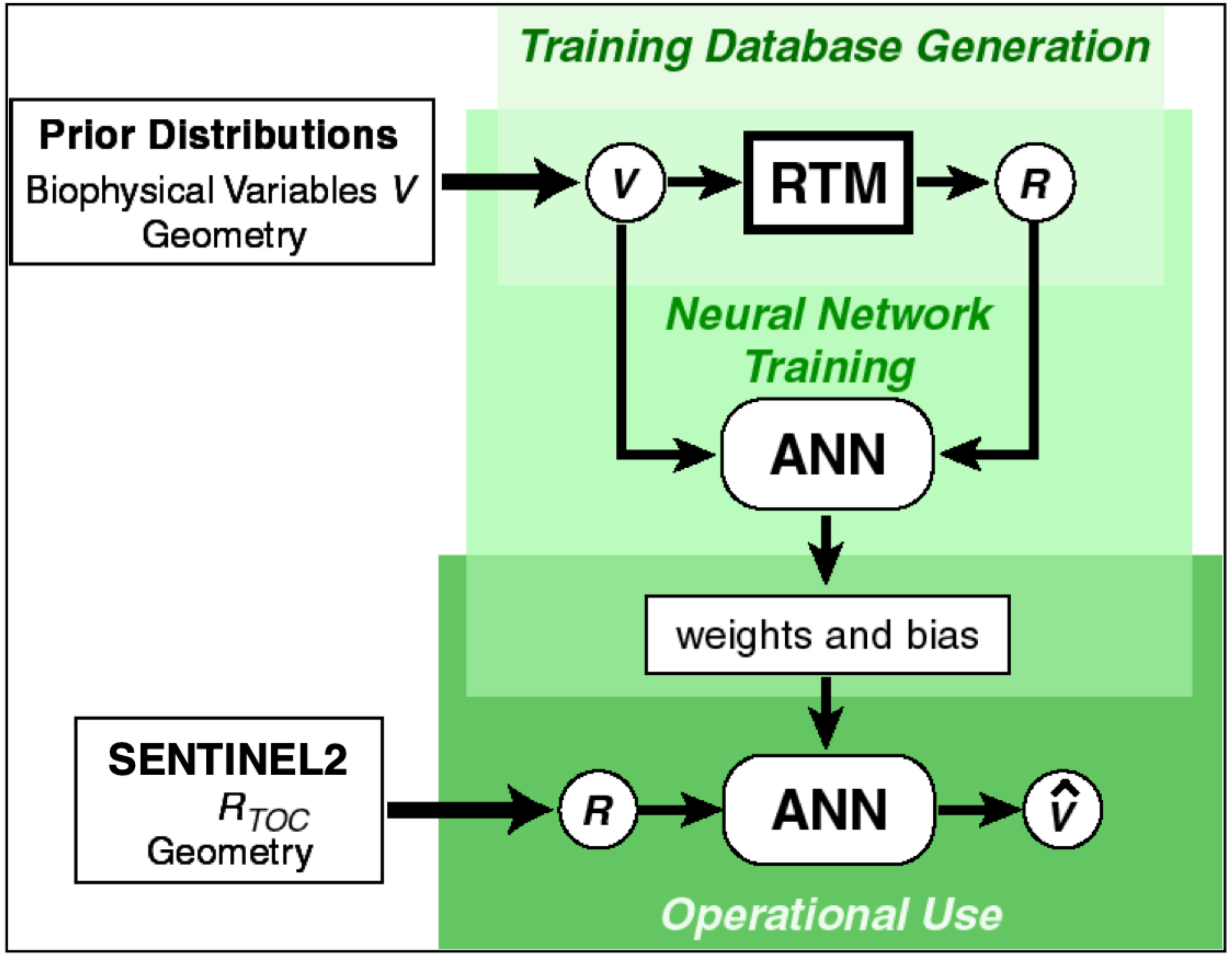


ESA SNAP Sentinel-2 L2 Biophysical processor

	Variable	Minimum	Maximum	Mode
Canopy	LAI	0.0	15.0	2.0
	ALA (°)	30	80	60
	Hot	0.1	0.5	0.2
Leaf	N	1.20	1.8	1.50
	Cab ($\mu g.m^{-2}$)	20	90	45
	Cdm (g.m-2)	0.0030	0.0110	0.005
	Cw_Rel	0.60	0.85	0.75
	Cbp	0.00	2.00	0.00
Soil	Bs	0.50	3.50	1.20

Table 5. Distribution of the input variables of the radiativ data base. Truncated Gaussian, log-normal or uniform di mode, the standard deviation (s), and minimum and max variable is presented (Nb_Class).

[Source: ATBD_S2ToolBox (esa.int)]



ESA SNAP Sentinel-2 Toolbox

ATBD_S2ToolBox (esa.int)

Supported Products

- Sentinel-2 L1B, L1C, L2A and L3, Landsat-8, Spot 1 to Spot 7, Spot4 Take5, Spot5 Take5, RapidEye, Deimos

Processors

- Sen2Cor for Atmospheric Correction
- Sen2Three level-3 processor for Spatio-Temporal Synthesis of bottom of atmosphere corrected Sentinel-2 level 2a images
- L2B biophysical processor (LAI, fAPAR, …) from this ATBD
- Reflectance to Radiance Processor
- Radiometric Indices
  - Vegetation indices : DVI, RVI, PVI, IPVI, WDVI, TNDVI, GNDVI, GEMI, ARVI, NDI45, MTCI, MCARI, REIP, S2REP, IRECI, PSSRa
  - Soil indices : SAVI, TSAVI, MSAVI, MSAVI2, BI, BI2, RI, CI
  - Water indices : NDWI, NDWI2, MNDWI, NDPI, NDTI
- MCI Processor: Maximum Chlorophyll Index by exploiting the height of a measurement over a specific baseline.
- OTB tools: MultivariateAlterationDetector, Pansharpening-bayes, Pansharpening-lmvm, Pansharpening-rcs, Rasterization-image, Rasterization-manual, Segmentation-cc, Segmentation-meanshift, Segmentation-mprofiles, Segmentation-watershed and SFSTextureExtraction

Thank you for your attention

Universität für Bodenkultur Wien

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& team contribution

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