Satellite time-series processing with FORCE in CSC-Taito environment

FORCE

Framework for Operational Radiometric Correction for Environmental Monitoring

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FORCE

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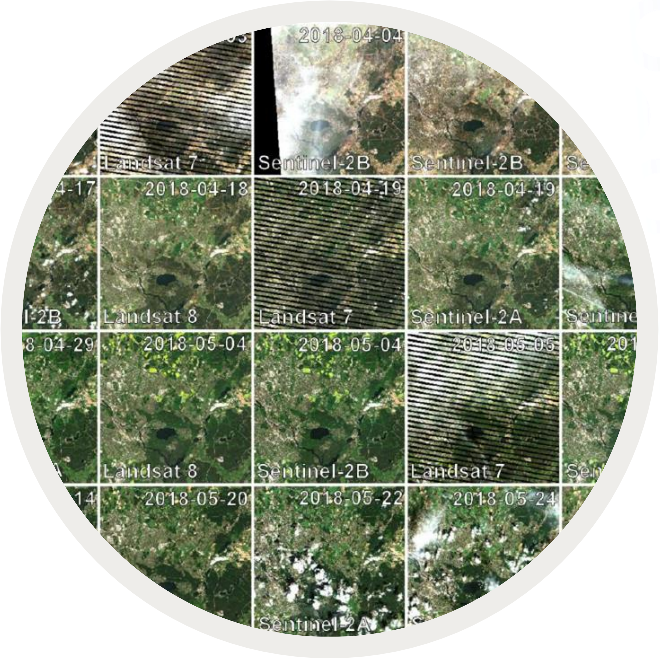
FORCE is a software project, which is intended to be a Landsat+Sentinel-2 'all-in-one solution' for generating atmospherically and topographically corrected, quality screened images, image composites and basic time series products tailored for large-area and multi-temporal applications.



Force homepage:

https://www.uni-trier.de/index.php?id=63673&L=0

S Y K E

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING

An Operational Radiometric Landsat Preprocessing Framework for Large-Area Time Series Applications

David Frantz, Achim Röder, Marion Stellmes, and Joachim Hill

ELSEVIER

Remote Sensing of Environment
Volume 190, 1 March 2017, Pages 331-347

Phenology-adaptive pixel-based compositing using optical earth observation imagery

David Frantz [a], Achim Röder [a], Marion Stellmes [a, b], Joachim Hill [a]

⊞ Show more

https://doi.org/10.1016/j.rse.2017.01.002

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Main features 1/3

- Written in C, parallelization with OpenMP API. Command-line!
- **Integration** of Landsat 4–8, and Sentinel-2 A/B as Virtual Constellation
- **Data management** of L4-8 and S2 Level 1 data, download
- Generation of **Analysis Ready Data** (ARD) a.ka Level2 data
  - Advanced cloud and cloud shadow detection (`modified` **`fmask`**)
  - Quality screening
  - Integrated atmospheric[1] and topographic[2] correction
  - Adjacency effect correction
  - BRDF reduction
  - Resolution merge of Sentinel-2 bands: 20m -> 10m
  - Data cubing: reprojection / gridding

[1]Radiative transfer model of Tanré et al 1990
[2]Modified c-correction of Kobayashi & Sanga-Ngoie 2008

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Pre-processing workflow (Level1 -> Level2)

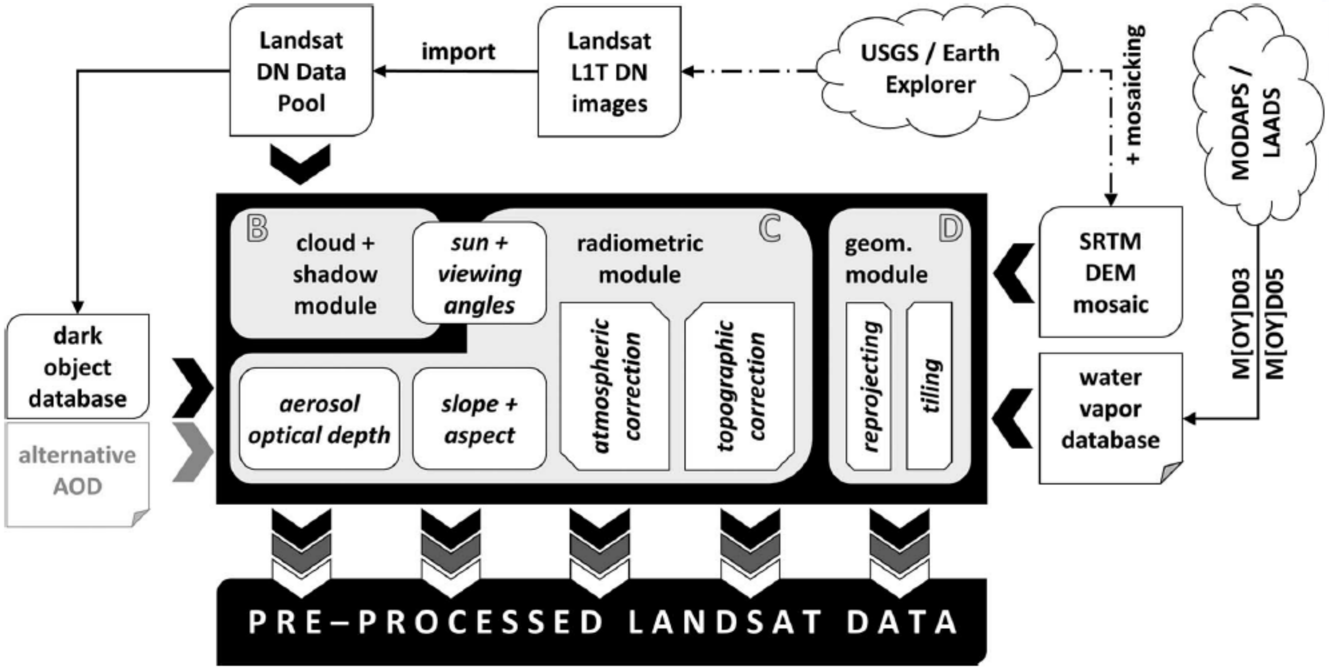

Fig. 3. Schematic workflow of the preprocessing framework. B, C, and D refer to the subsections of the methods section.

Frantz et al. 2015

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Main features 2/3

- Generation of **highly Analysis Ready Data** (hARD) a.ka Level3
  - Large area, Gap free
  - Best Available Pixel (BAP) composites
  - Phenology Adaptive Composites (PAC)
  - Spectral Temporal Metrics (STM) – min, max, mean, range, quantiles…
- Generation of **highly Analysis Ready Data plus** (hARD+).
  - Time Series generation: spectral bands, spectral indices, Spectral Mixture Analysis (SMA)
  - Time series folding
  - Time series interpolation
  - Time series statistics
  - Trend analysis
  - Change, Aftereffect, Trend (CAT) analysis
  - Land Surface Phenology (LSP)

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Main features 3/3

- Detailed **data mining** of the **Clear Sky Observation** (CSO) availability
- **Data Fusion**. Improving spatial resolution of coarse continuous fields:
  - MODIS LSP -> medium resolution LSP.
  - Improving spatial resolution of lower resolution ARD using higher resolution ARD: 30m Landsat -> 10m using Sentinel-2 targets

FORCE in Taito

- Installed to Taito in December 2018 (v2.1)
- Load modules:

```
module load force gnu-parallel
```

- List available commands:

```
ls -l /appl/earth/force/v2.1/bin
```

- Note, some commands have `.sh` extension some don't!

```
[pjhurska@c308 kili]$ ls -l /appl/earth/force/v2.1/bin
total 4828
-rwxrwxr-x 1 ejarvine csc   8568 Dec  4 16:22 force
-rwxrwxr-x 1 ejarvine csc 475864 Dec  4 16:22 force-cso
-rwxrwxr-x 1 ejarvine csc 477344 Dec  4 16:22 force-improphe
-rwxrwxr-x 1 ejarvine csc 479128 Dec  4 16:22 force-l2imp
-rwxrwxr-x 1 ejarvine csc 474992 Dec  4 16:22 force-l2ps
-rwxrwxr-x 1 ejarvine csc  11018 Dec  4 16:22 force-level1-landsat.sh
-rwxrwxr-x 1 ejarvine csc   6767 Dec 10 10:49 force-level1-sentinel2-long.sh
-rwxrwxr-x 1 ekkylli  csc   8211 Dec 12 12:53 force-level1-sentinel2_nv.sh
-rwxrwxr-x 1 ejarvine csc   8209 Dec 10 10:49 force-level1-sentinel2.sh
-rwxrwxr-x 1 ejarvine csc   4717 Dec 19 09:03 force-level2.sh
-rwxrwxr-x 1 ejarvine csc 481408 Dec  4 16:22 force-level3
-rwxrwxr-x 1 ejarvine csc 474120 Dec  4 16:22 force-lut-modis
-rwxrwxr-x 1 ejarvine csc   2450 Dec  4 16:22 force-mosaic.sh
-rwxrwxr-x 1 ejarvine csc  11480 Dec  4 16:22 force-parameter-cso
-rwxrwxr-x 1 ejarvine csc  11256 Dec  4 16:22 force-parameter-improphe
-rwxrwxr-x 1 ejarvine csc  11096 Dec  4 16:22 force-parameter-l2imp
-rwxrwxr-x 1 ejarvine csc  12000 Dec  4 16:22 force-parameter-level2
-rwxrwxr-x 1 ejarvine csc  14584 Dec  4 16:22 force-parameter-level3
-rwxrwxr-x 1 ejarvine csc  13992 Dec  4 16:22 force-parameter-tsa
-rwxrwxr-x 1 ejarvine csc 476096 Dec  4 16:22 force-qai-inflate
-rwxrwxr-x 1 ejarvine csc   1970 Dec  4 16:22 force-quicklook-level2.sh
-rwxrwxr-x 1 ejarvine csc   2472 Dec  4 16:22 force-quicklook-level3.sh
-rwxrwxr-x 1 ejarvine csc 477872 Dec  4 16:22 force-tabulate-grid
-rwxrwxr-x 1 ejarvine csc 472936 Dec  4 16:22 force-tile-finder
-rwxrwxr-x 1 ejarvine csc 478408 Dec  4 16:22 force-tsa
[pjhurska@c308 kili]$
```

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FORCE L1AS - Level 1 Archiving Suite

- Assists in organizing and maintaining a clean and consistent Level 1 data pool
- Automatic downloading of Sentinel-2 data (not for Landsat)
- TIP: Use **force-level1-sentinel2-nv.sh** – a script modified by Kylli Ek /CSC which shows real time download info

Module	|	force-level1-landsat
Usage	|	force-level1-landsat from Level-1-datapool queue cp/mv [dry]

Module	|	force-level1-sentinel2 + force-level1-sentinel2-long
Usage	|	force-level1-sentinel2 Level-1-datapool queue boundingbox starttime endtime min-cc max-cc

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Example: Download 3+ years of S2 images from Kilimanjaro, Tanzania

Module	|	force-level1-sentinel2 + force-level1-sentinel2-long
Usage	|	force-level1-sentinel2 Level-1-datapool queue boundingbox starttime endtime min-cc max-cc

- `force-level1-sentinel2-nv.sh /wrk/pjhurska/kili level1.pool "37.841/-3.58,36.97/-3.58,36.97/-2.805,37.841/-2.805,37.841/-3.58" 2016-01-01 2019-02-01 0 85`
- Downloads all available sentinel-2 images from the area of interest, from 1 Jan 2016 until 2 Feb 2019, allowed cloud coverage 0-85%
- You need user account at scihub.copernicus.eu (user name and password in a hidden file '`.scihub`' in your home directory)

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Example: Download 3+ years of S2 images from Kilimanjaro, Tanzania

- Downloaded images will be saved in the folder defined as the **level-1 datapool** (1st argument), under subfolders (compressed)
- The **file queue** (2nd argument) is a text file which simply lists all images and its processing status

```
[pjhurska@c308 ~]$ module load force
FORCE 2.1 is now in use
-------------------------------------------------------------------------------
  Setting up new environment, removing all currently loaded modules
-------------------------------------------------------------------------------
  Loading new modules:
    gcc/6.2.0    mkl/17.0.1

The following have been reloaded with a version change:
  1) mkl/11.3.0 => mkl/17.0.1

[pjhurska@c308 ~]$ cd /wrk/pjhurska
[pjhurska@c308 pjhurska]$ force-level1-sentinel2_nv.sh /wrk/pjhurska/kili level1.pool "37.841/-3.58,36.97/-3.58,36.97/-2.805,37.841/-2.805,37.841/-3.58" 2016-12-01 2019-02-01 0 85
2019-01-24 18:47:17 URL:https://scihub.copernicus.eu/dhus/search?q=filename:S2?_MSIL1C*%20AND%20footprint:%22Intersects(POLYGON((37.841%20-3.58,36.97%20-3.58,36.97%20-2.805,37.841%20-2.805,37.841%20-3.58)))%22%20AND%20orbitdirection:Descending%20AND%2
eginposition:[2016-12-01T00:00:00.000Z%20TO%202019-02-01T00:00:00.000Z]%20AND%20cloudcoverpercentage:[0%20TO%2085]&rows=100&start=0 [301931] -> "/wrk/pjhurska/kili/query.html" [1]
2019-01-24 18:47:13 - Found 100 S2A/B files.
2019-01-24 19:03:54 URL:https://scihub.copernicus.eu/dhus/odata/v1/Products('c856e542-e011-43fa-b2b2-376166d1c721')/$value [787544752/787544752] -> "/wrk/pjhurska/kili/T37MCS/S2B_MSIL1C_20190124T074219_N0207_R092_T37MCS_20190124T095535.zip" [1]
2019-01-24 19:12:41 URL:https://scihub.copernicus.eu/dhus/odata/v1/Products('7dfad035-9527-4822-972d-b421d5df6a57')/$value [834562485/834562485] -> "/wrk/pjhurska/kili/T37MCT/S2B_MSIL1C_20190124T074219_N0207_R092_T37MCT_20190124T095535.zip" [1]
2019-01-24 19:21:32 URL:https://scihub.copernicus.eu/dhus/odata/v1/Products('2a1fc31a-cd3f-4a18-937c-acecce1f0765')/$value [746471381/746471381] -> "/wrk/pjhurska/kili/T37MCS/S2B_MSIL1C_20181115T074159_N0207_R092_T37MCS_20181115T094839.zip" [1]
2019-01-24 19:49:36 URL:https://scihub.copernicus.eu/dhus/odata/v1/Products('ef60f5ee-decf-42ab-9733-22e4b01b9680')/$value [802250628/802250628] -> "/wrk/pjhurska/kili/T37MCT/S2B_MSIL1C_20181016T073859_N0206_R092_T37MCT_20181016T113522.zip" [1]
2019-01-24 20:02:06 URL:https://scihub.copernicus.eu/dhus/odata/v1/Products('00538166-bc4b-49f9-8088-534a74f07fce')/$value [774546846/774546846] -> "/wrk/pjhurska/kili/T37MBS/S2A_MSIL1C_20180901T073611_N0206_R092_T37MBS_20180901T095754.zip" [1]
2019-01-24 20:02:32 URL:https://scihub.copernicus.eu/dhus/search?q=filename:S2?_MSIL1C*%20AND%20footprint:%22Intersects(POLYGON((37.841%20-3.58,36.97%20-3.58,36.97%20-2.805,37.841%20-2.805,37.841%20-3.58)))%22%20AND%20orbitdirection:Descending%20AND%2
eginposition:[2016-12-01T00:00:00.000Z%20TO%202019-02-01T00:00:00.000Z]%20AND%20cloudcoverpercentage:[0%20TO%2085]&rows=100&start=100 [284688] -> "/wrk/pjhurska/kili/query.html" [1]
2019-01-24 20:02:27 - Found 100 S2A/B files.
```

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The file queue

- If the file queue file does not exist, it will be created.
- If it exists, new imports are appended to this file.
- This queue is needed also for Level 2 processing; all images with ‘QUEUED’ status are downloaded but not yet processed to Level2
- After L2-processing the status is set to ‘DONE’.

```
/wrk/pjhurska/kili/T37MCS/S2A_MSIL1C_20161110T075212_N0204_R092_T37MCS_20161110T075514.SAFE/GRANULE/L1C_T37MCS_A007239_20161110T075514 QUEUED
/wrk/pjhurska/kili/T37MCS/S2A_MSIL1C_20161021T075212_N0204_R092_T37MCS_20161021T075353.SAFE/GRANULE/L1C_T37MCS_A006953_20161021T075353 QUEUED
/wrk/pjhurska/kili/T37MBS/S2A_MSIL1C_20161021T075212_N0204_R092_T37MBS_20161021T075353.SAFE/GRANULE/L1C_T37MBS_A006953_20161021T075353 QUEUED
```

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FORCE L2PS - Level 2 Processing System

- Generates harmonized, standardized and radiometrically consistent Level 2 products (ARD: Analysis Ready Data) based on Level 1 data.
- Cloud and cloud shadow detection, radiometric correction, data cubing.
- Only one parameter file needed for all images and sensors!
- First step: create a skeleton parameter file which you can modify:

```
force-parameter-level2 /wrk/pjhurska/kili
```

Module	force-parameter-level2
Usage	force-parameter-level2 dir

- Rename: `mv level2-skeleton.prm level2.prm`
- Edit: `emacs level2.prm`

SYKE

Level 2 Parameter File, essential parameters

- Files and directories
  - `FILE_QUEUE, DIR_LEVEL2, DIR_TEMP, FILE_DEM`
- Spatial properties
  - `DO_REPROJ, DO_TILE, TILE_SIZE, RESOLUTION, ORIGIN_LAT / LON, PROJECTION`
- Radiometric correction options
  - `DO_TOPO, DO_ATMO, DO_BRDF, DO_AOD`
- Cloud detection options
  - `MAX_CLOUD_COVER_FRAME, MAX_CLOUD_COVER_TILE, CLOUD_THRESHOLD, SHADOW_THRESHOLD`

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force-level2 – mass processing of level1 images

Module	force-level2
Usage	force-level2 par-file ncpu delay

- 2nd step: run the actual level2 processing **as a batch job**
- Arguments: (1) name of the parameter file, (2) number of CPUs used for parallel processing, (3) delay in seconds between image processing
- Each image enqueued in the file queue is processed to Level 2 according to the specifications in the parameter file
- After processing, the image is dequeued -> if you need to reprocess your images, you can `sed -i ‘s/DONE/QUEUED/’ level1.pool`
- The processed images and a logfile are written to output dir

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Example of a SLURM batch file – run-level2.sh

```bash
#!/bin/bash -l
# created: Dec 16, 2018 11:13 PM
# author: pjhurska
#SBATCH -J run-level2
#SBATCH --constraint="snb|hsw"
#SBATCH -o level2.out
#SBATCH -e level2.err
#SBATCH -p serial
#SBATCH -N 1
#SBATCH -n 1
#SBATCH --cpus-per-task=10
#SBATCH -t 08:00:00
#SBATCH --mem=120000
#SBATCH --mail-type=END
#SBATCH --mail-user=pekka.hurskainen@helsinki.fi

srun force-level2.sh level2.prm 10 20

# This script will print some usage statistics to the
# end of file: level2.out
# Use that to improve your resource request estimate
# on later jobs.
used_slurm_resources.bash

```

TIP: More info about SLURM batch files:
https://research.csc.fi/taito-constructing-a-batch-job-file

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Run the batch file

- Schedule the batch job for processing:
  - `sbatch run-level2.sh`
- Check the status of your batch queue
  - `squeue –u pjhurska`
- You will be notified by email after the job is done, or crashed in an error (settings for that in the SLURM batch file)

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Example of a SLURM "standard output"

```
87 images enqueued. Start processing with 10 CPUs
Job ID: 37779858
Cluster: csc
User/Group: pjhurska/pjhurska
State: RUNNING
Nodes: 1
Cores per node: 10
CPU Utilized: 19:10:10
CPU Efficiency: 81.77% of 23:26:40 core-walltime
Memory Utilized: 109.89 GB
Memory Efficiency: 93.77% of 117.19 GB
Job consumed 140.67 CSC billing units based on memory reservation multiplier
WARNING: Efficiency statistics may be misleading for RUNNING jobs.
```

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About projection and tiling in FORCE

- You can either use the original UTM projection and zone, or reproject to any projection supported by GDAL
- After reprojection, the data can be **tiled to an arbitrary grid** -> highly recommended and necessary for all higher-level FORCE operations (>Level2)
- Final mosaicking to one single image can be done as last processing step.

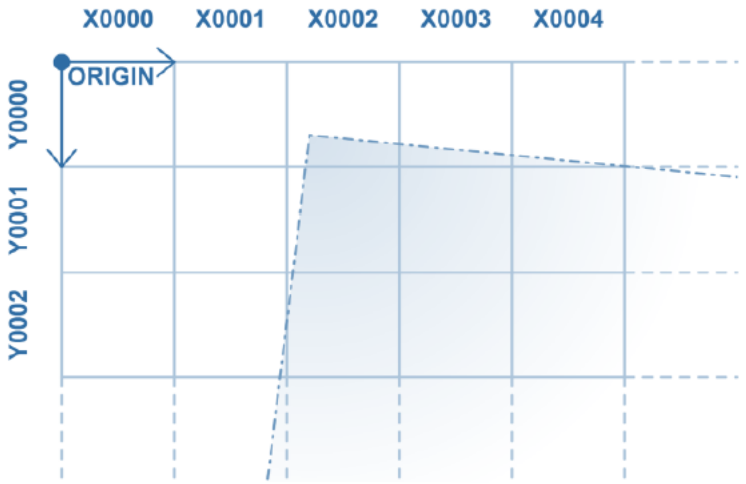

Fig. 12. Level 2 Gridding.
The image is intersected with the arbitrary grid and the chips are extracted. Tile X0000_Y0000, pixel 0/0 starts at ORIGIN_LON/ORIGIN_LAT. The tiles are square, the tile size is given by TILE_SIZE in output map units. TILE_SIZE must be a multiple of RESOLUTION.

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Export tile grid as shapefile

Module	force-tabulate-grid
Usage	force-tabulate-grid datacube bottom top left right

- *force-tabulate-grid* can be used to extract the processing grid as ESRI shapefile, e.g. for visualization purposes
- Parameters: 1) folder containing a data cube definition file 2-5) approximate bounding box of your study area in decimal degrees
  - `force-tabulate-grid /wrk/pjhurska/kili/level2 -3.58 -2.805 36.97 37.841`
- Output: shapefile ‘`datacube-grid.shp`’ stored in the same directory as the data cube.

X0000_Y0000	X0001_Y0000	X0002_Y0000
X0000_Y0001	X0001_Y0001	X0002_Y0001
X0000_Y0002	X0001_Y0002	X0002_Y0002

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Structure of the Level2 Data Cube 1/2

- Each datacube has the following components created automatically:
  - Subfolders for each tile (e.g. X0000_Y0000, X0000_Y0001, … Xnnnn_Ynnnn). Under each subfolder, output images for each tile and for each image that was processed.
  - Available output products, in GeoTIFF or ENVI format:

BOA	Bottom-of-Atmosphere Reflectance (standard output, scale: 10000, nodata: -9999)
TOA	Top-of-Atmosphere Reflectance (secondary standard output, scale: 10000, nodata: -9999)
QAI	Quality Assurance Information (standard output, bit coding, nodata: 1)
AOD	Aerosol Optical Depth (550 nm, optional output, scale: 1000, nodata: -9999)
CLD	Cloud / Cloud shadow distance (optional output, scale: 10000, nodata: -9999)
WVP	Water vapor (optional output, scale: 1000, nodata: -9999)
VZN	View zenith (optional output, scale: 100, nodata: -9999)
HOT	Haze Optimized Transformation (optional output, scale: 10000, nodata: -9999)

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Structure of the Level2 Data Cube 2/2

- Each datacube has the following components created automatically:
  - Spatial Data Cube Definition file '`datacube-definition.prj`' with following parameters each in a separate line: (1) projection as WKT string, (2) Lon origin of the tile system, (3) Lat origin of the tile system, (4) projected X origin of the tile system, (5) projected Y origin of the tile system, and (6) width of the tiles in projection units.

```
PROJCS["Arc 1960 / UTM zone 37S",GEOGCS["Arc 1960",DATUM["Arc_1960",SPHEROID["Clarke 1880 (RGS)",6378249.145,293.465,AUTHORITY["EPSG","7012"]],AUTHORITY["EPSG","6210"]],PRIMEM["Greenwich",0,AUTHORITY["EPSG","8901"]],UNIT["degree",0.0174532925199 4328,AUTHORITY["EPSG","9122"]],AUTHORITY["EPSG","4210"]],UNIT["metre",1,AUTHORITY["EPSG","9001"]],PROJECTION["Transverse_Mercator"],PARAMETER["latitude_of_origin",0],PARAMETER["central_meridian",39],PARAMETER["scale_factor",0.9996],PARAMETER["false_easting",500000],PARAMETER["false_northing",10000000],AUTHORITY["EPSG","21037"],AXIS["Easting",EAST],AXIS["Northing",NORTH]]
36.799999
-2.800000
255329.156250
9690586.000000
30000.000000
```

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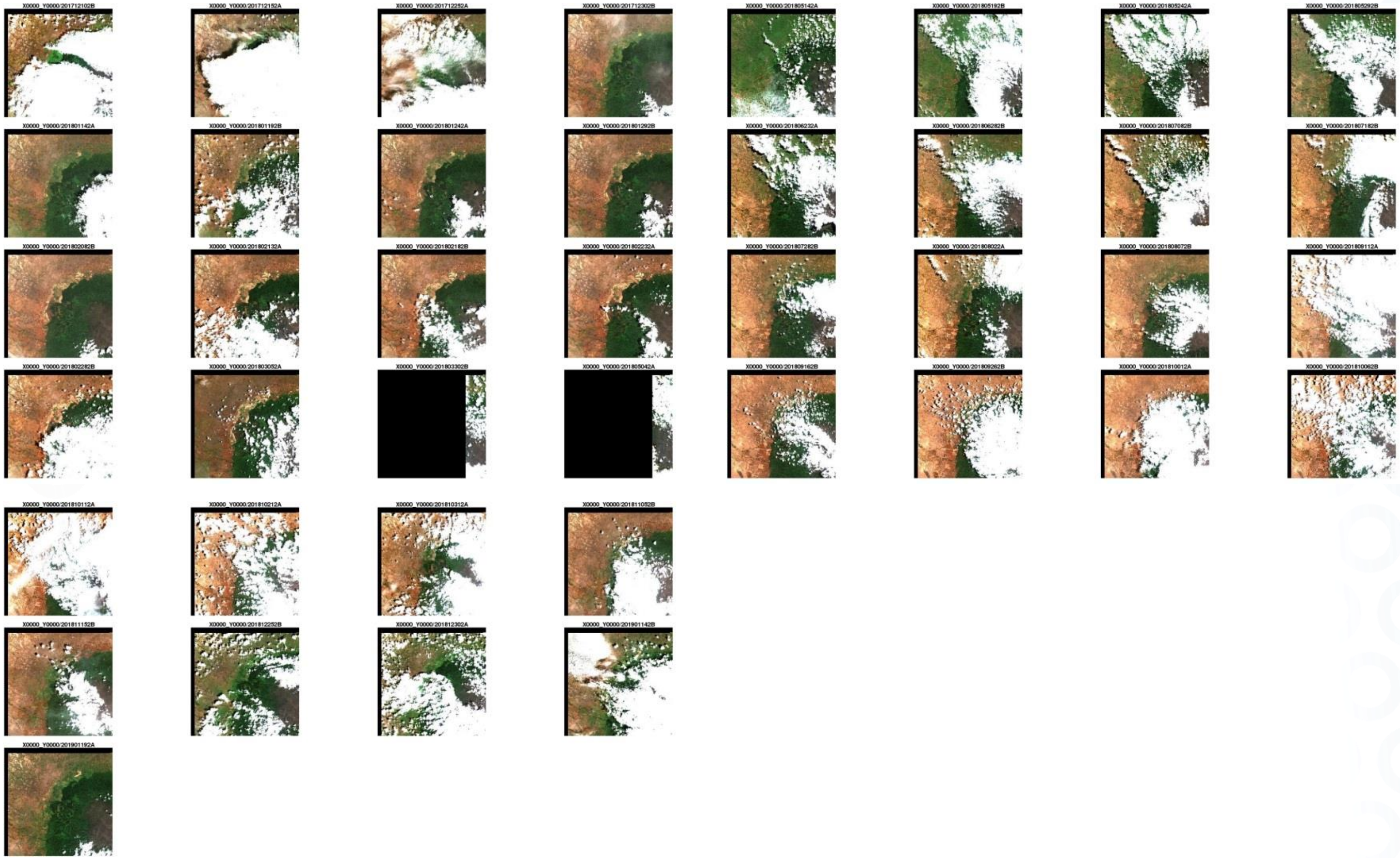
Create quicklooks of Level2 images

Module	force-quicklook-level2
Usage	force-quicklook-level2 L2-archive QUICKLOOK-archive maxval

- Create a new directory and generate quicklooks:
  - `mkdir /wrk/pjhurska/kili/level2/quicklook`
  - `force-quicklook-level2.sh /wrk/pjhurska/kili/level2 /wrk/pjhurska/kili/level2/quicklook 1500`
- Output: One JPG with fixed size 256x256 px for each image.
- The true color quicklooks have a fixed stretch from 0–maxval (3rd argument).
- The upper limit of the stretch needs to be given in scaled reflectance (scaling factor 10,000), e.g. 1500. This value can be decreased/increased for very dark/bright landscapes.

Quicklooks of one tile, 14 months observations



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FORCE L3PS - Level 3 Processing System

- Generates **temporal aggregations** of Level 2 data to provide seamless, gap free, and highly Analysis Ready Data (hARD)
  - Spectral temporal statistics (e.g. average reflectance within compositing period)
  - Pixel-based composites, static or phenology-adaptive (latter requires additional seasonal parameters SOS, POS, EOS)
- First step: create a skeleton parameter file which you can modify:

Module	|	force-parameter-level3
Usage	|	force-parameter-level3 dir

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Example of a SLURM batch file – run-level3.sh

```
#!/bin/bash -l
# created: Dec 16, 2018 11:13 PM
# author: pjhurska
#SBATCH -J run-level3
#SBATCH --constraint="snb|hsw"
#SBATCH -o level3.out
#SBATCH -e level3.err
#SBATCH -p serial
#SBATCH -N 1
#SBATCH -n 1
#SBATCH --cpus-per-task=16
#SBATCH -t 04:00:00
#SBATCH --mem=100000
#SBATCH --mail-type=END
#SBATCH --mail-user=pekka.hurskainen@helsinki.fi

srun force-level3 level3.prm

# This script will print some usage statistics to the
# end of file: s2test_out
# Use that to improve your resource request estimate
# on later jobs.
used_slurm_resources.bash
```

- Schedule the batch job for processing:
  - `sbatch run-level3.sh`

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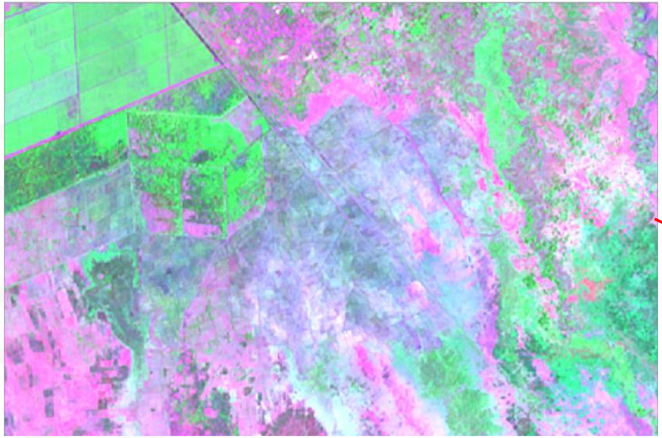
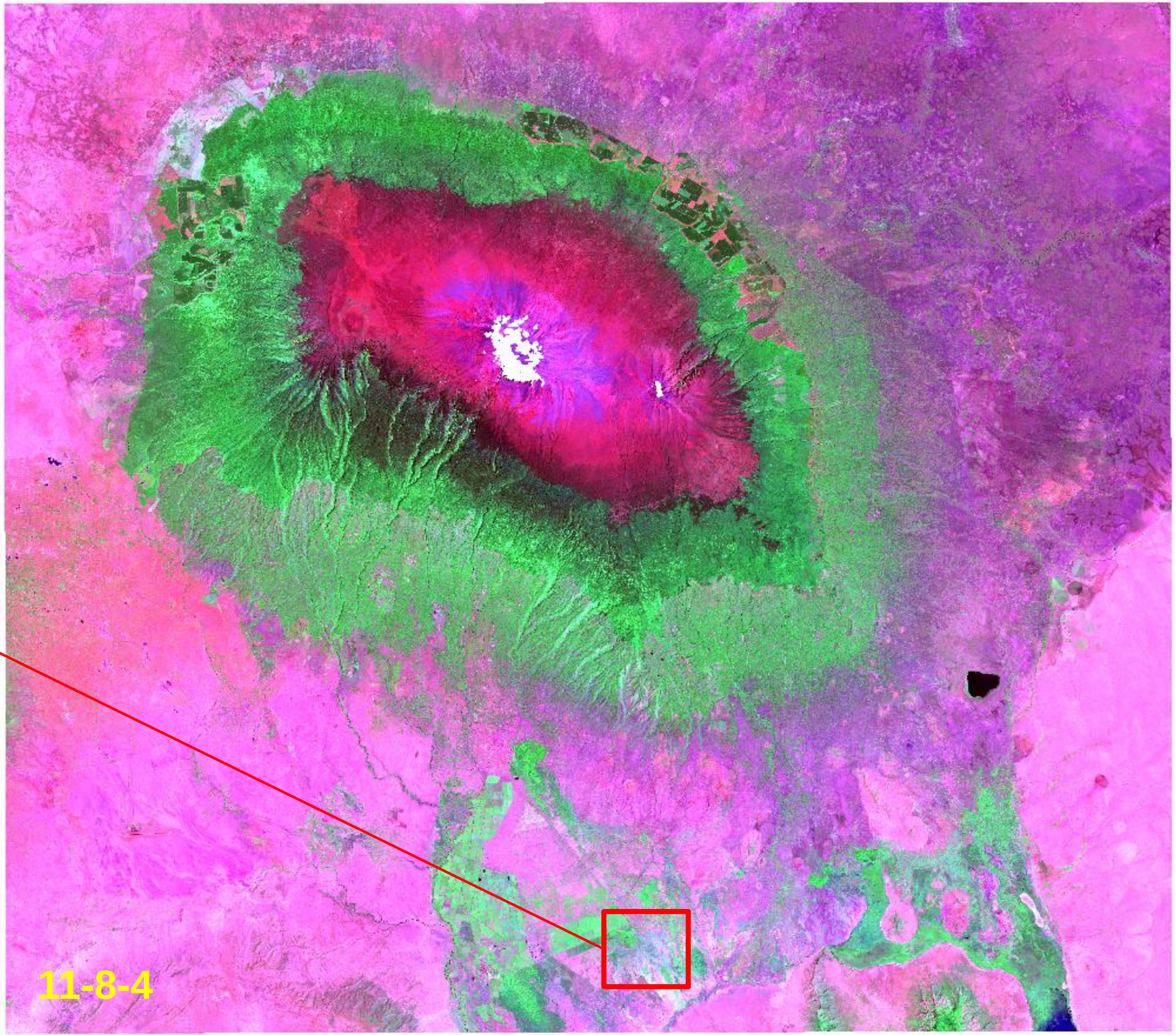
Level 3 outputs

BAP	Best Available Pixel composite (optional output, scale: 10000, nodata: -9999)
INF	Compositing Information (optional output, nodata: 1/-9999)
SCR	Compositing Scores (optional output, scale: 10000, nodata: -9999)
AVG	Temporal Average (optional output, scale: 10000, nodata: -9999)
STD	Temporal Standard Deviation (optional output, scale: 10000, nodata: -9999)
MIN	Temporal Minimum (optional output, scale: 10000, nodata: -9999)
MAX	Temporal Maximum (optional output, scale: 10000, nodata: -9999)
RNG	Temporal Range (optional output, scale: 10000, nodata: -9999)
SKW	Temporal Skewness (optional output, scale: 10000, nodata: -9999)
KRT	Temporal Kurtosis (optional output, scale: 10, nodata: -9999)
Q25	Temporal 0.25 Quantile (optional output, scale: 10000, nodata: -9999)
Q50	Temporal 0.50 Quantile (optional output, scale: 10000, nodata: -9999)
Q75	Temporal 0.75 Quantile (optional output, scale: 10000, nodata: -9999)
IQR	Temporal Interquartile Range (optional output, scale: 10000, nodata: -9999)

- Temporal average surface reflectance 01/2016 – 01/ 2019
- All composites in 10m pixel size





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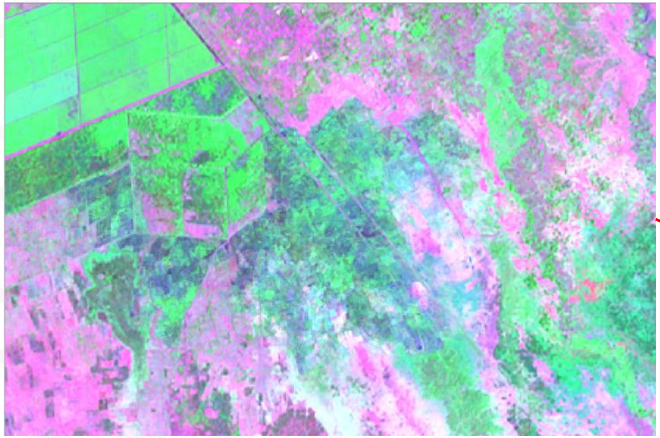
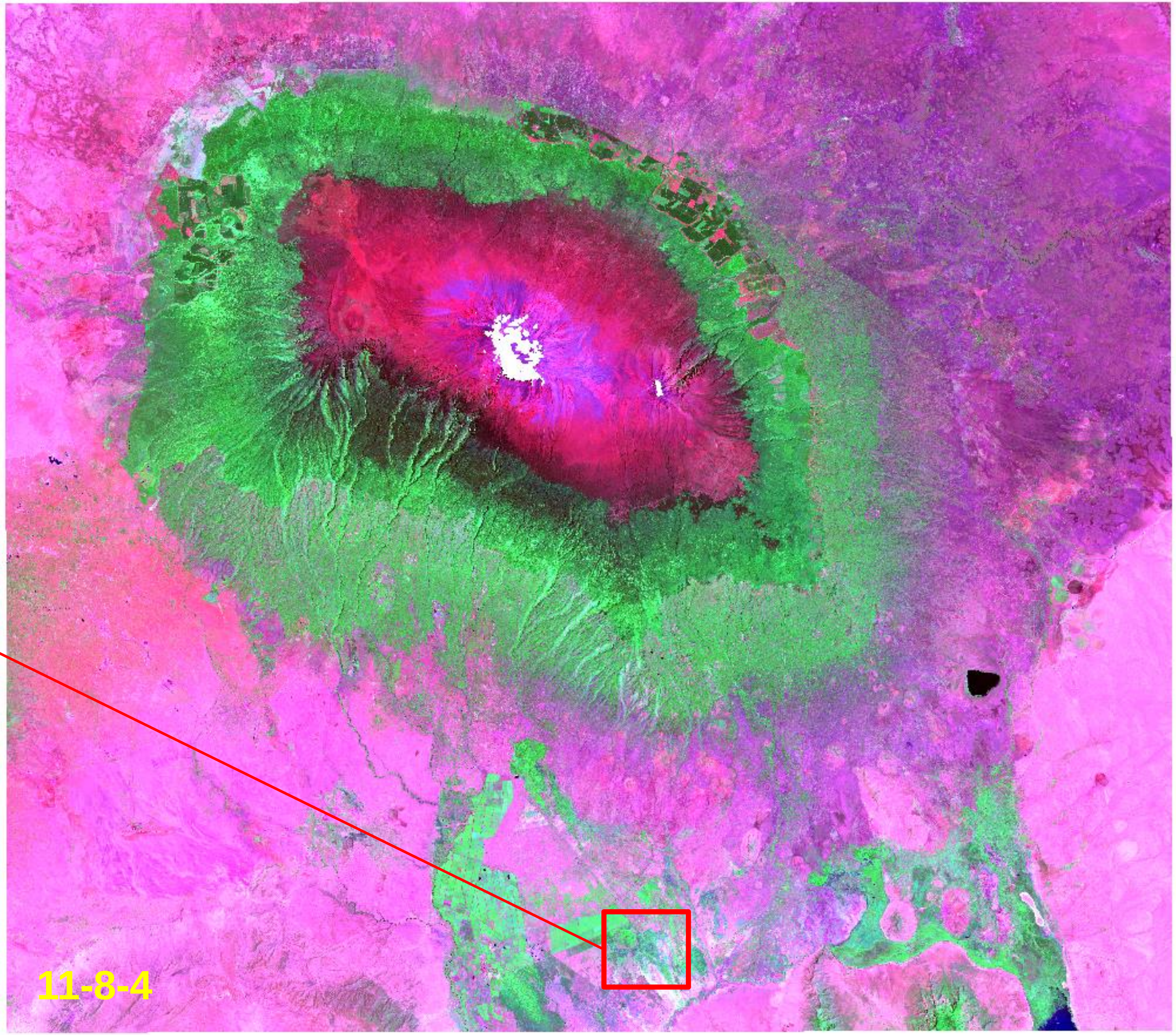
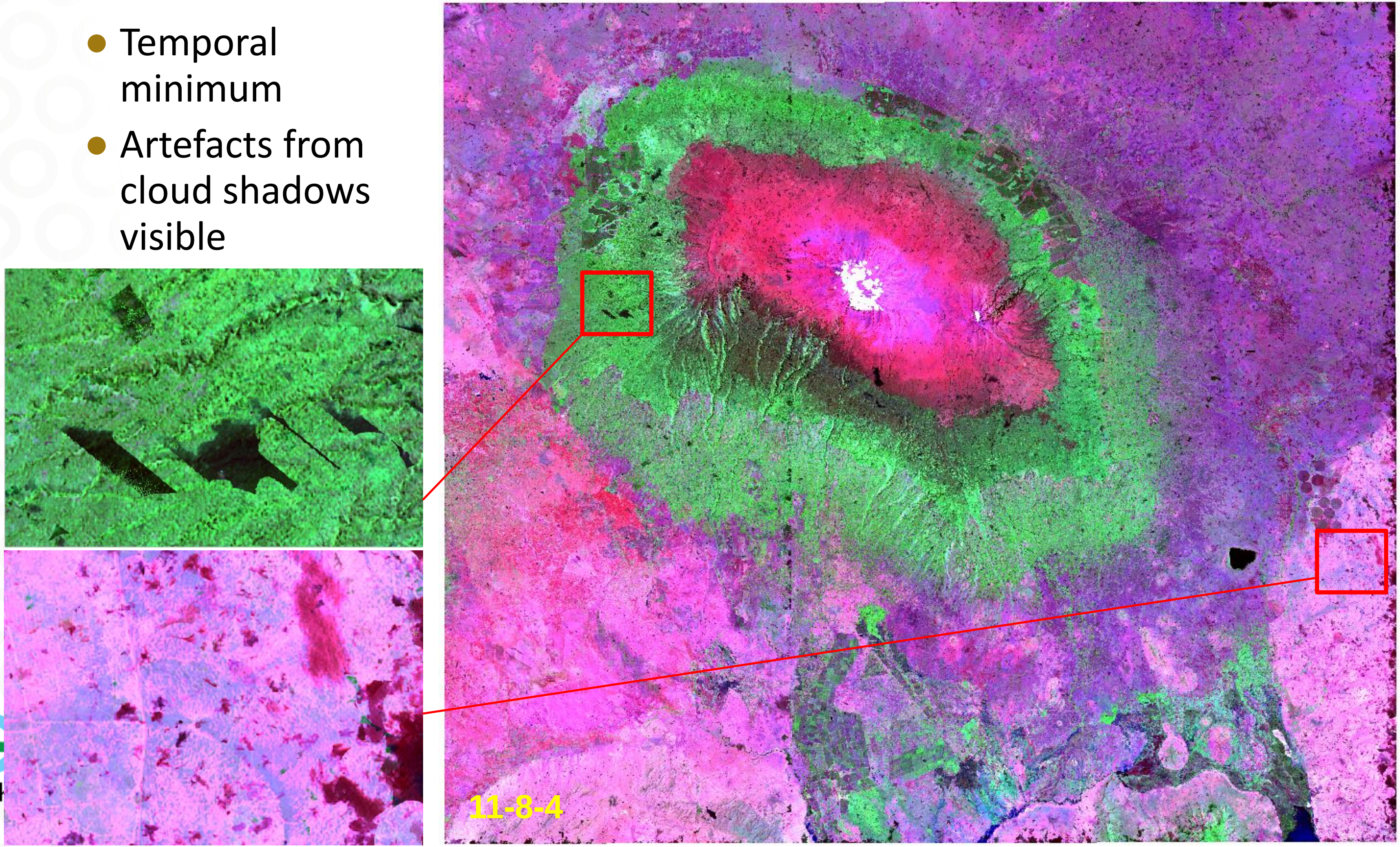
- Temporal median surface reflectance 01/2016 – 01/ 2019
- At first look, appears very similar to average



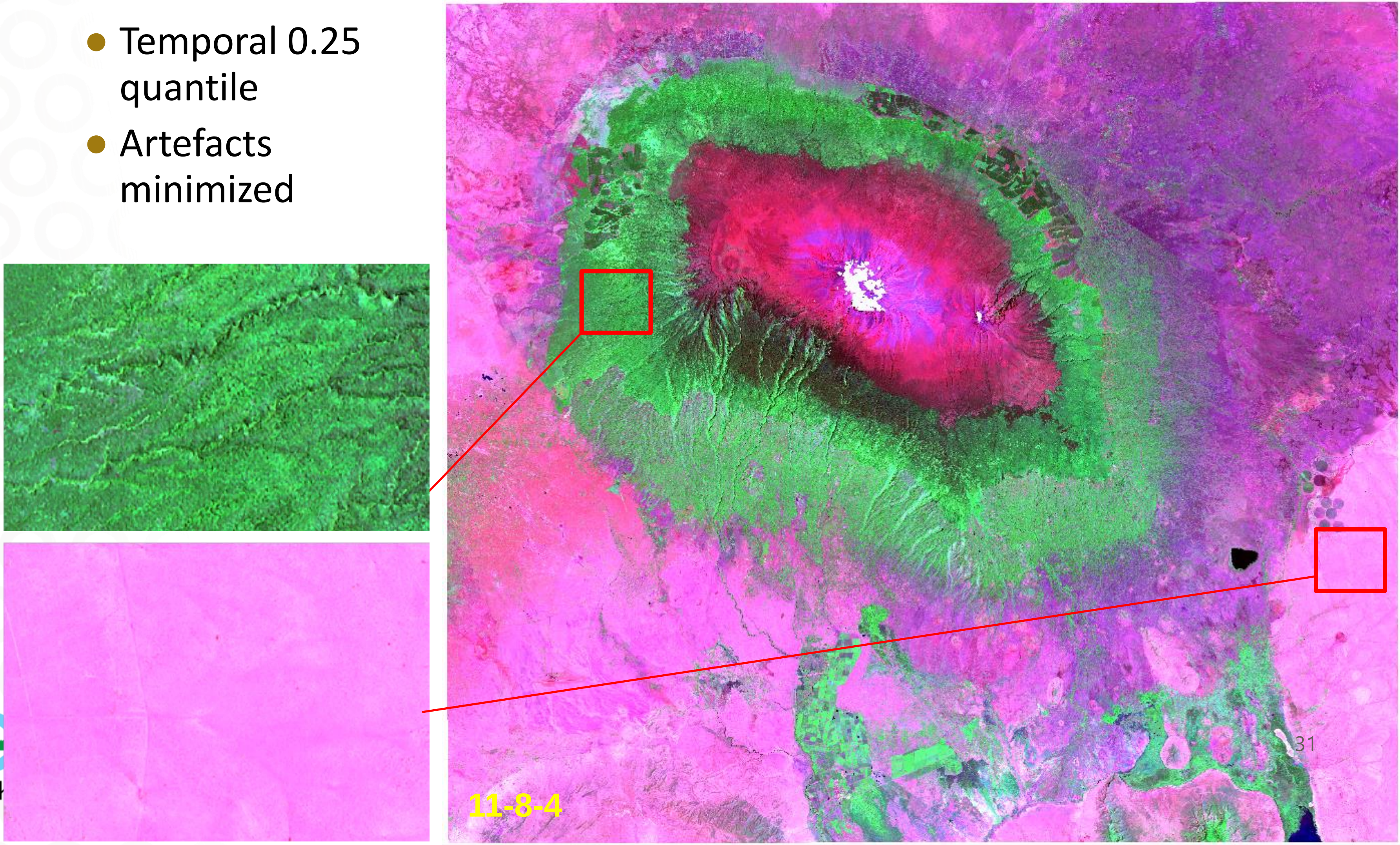


SYKE

- Temporal minimum
- Artefacts from cloud shadows visible

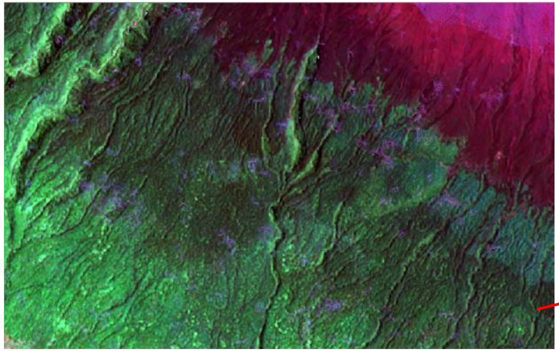


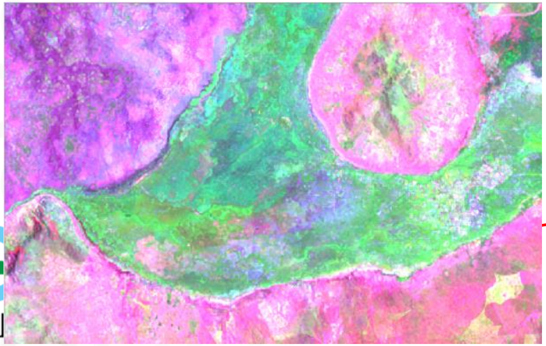
- Temporal 0.25 quantile
- Artefacts minimized

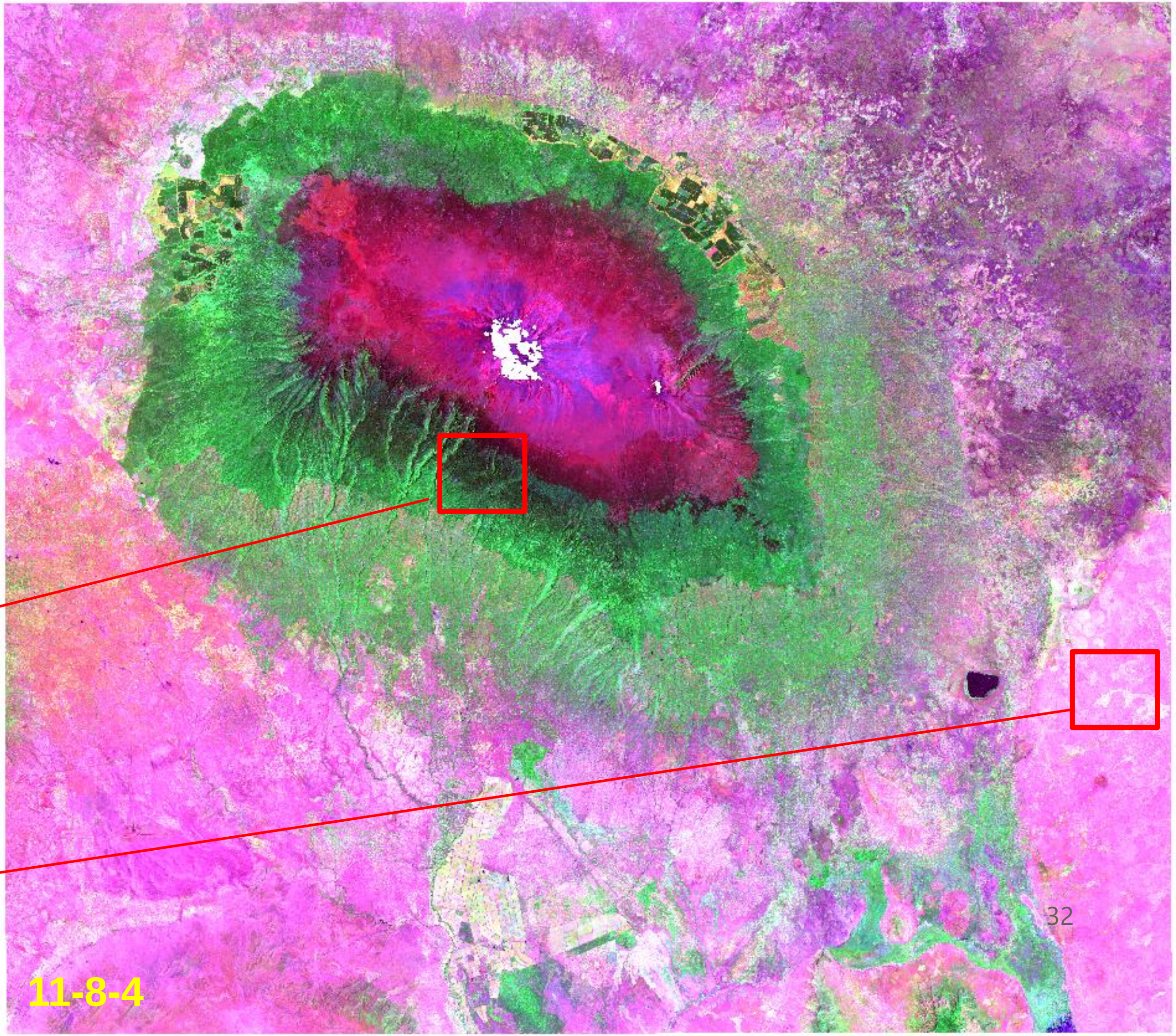


S Y K

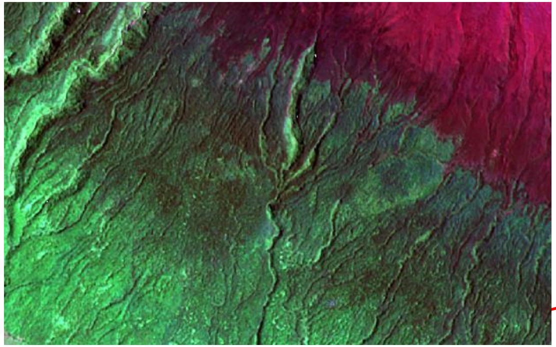
- Temporal maximum
- Cloud artefacts visible

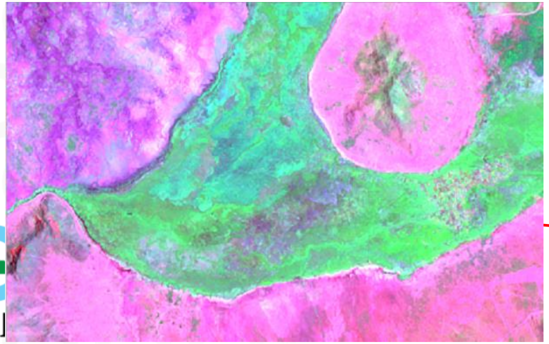


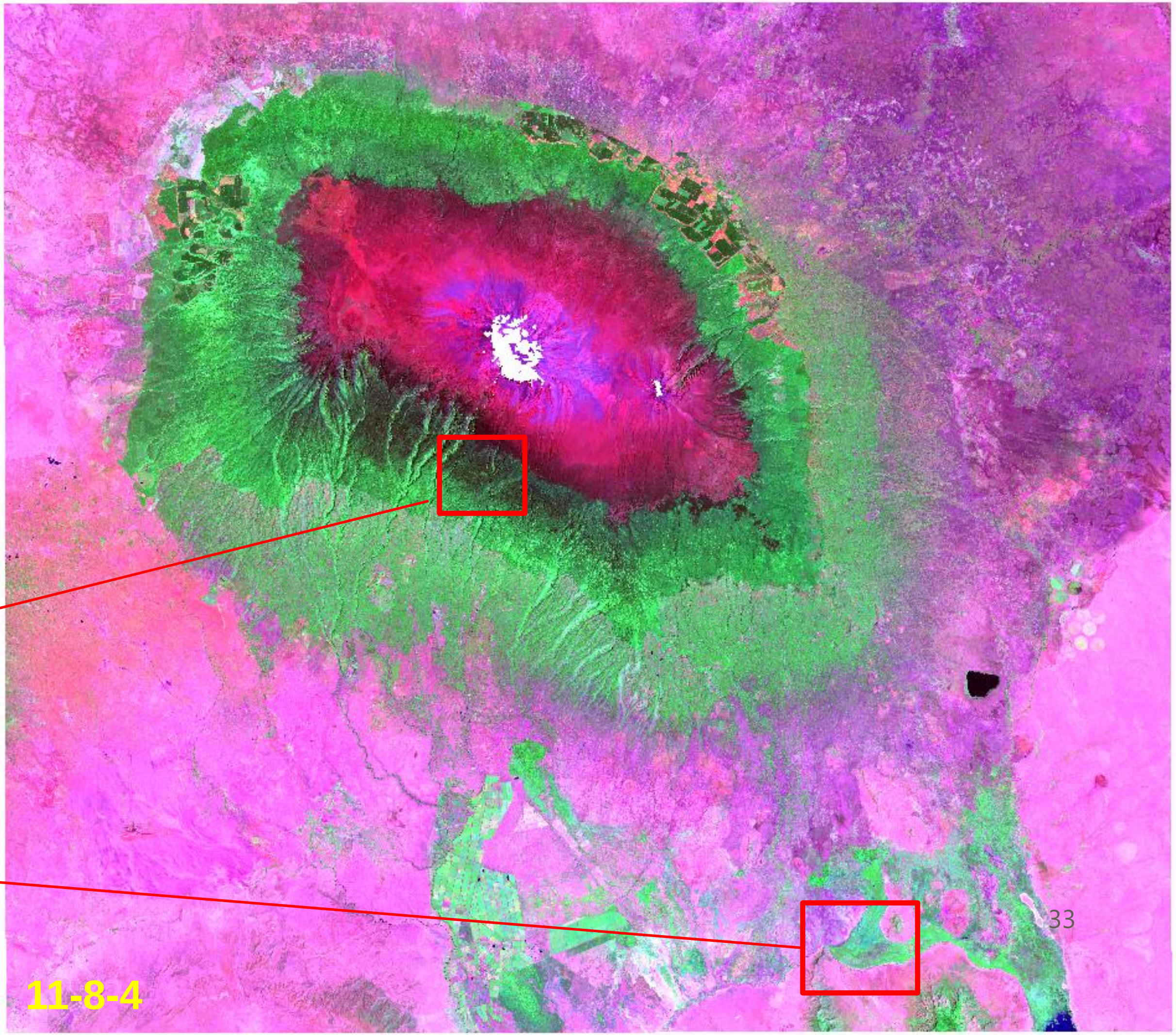




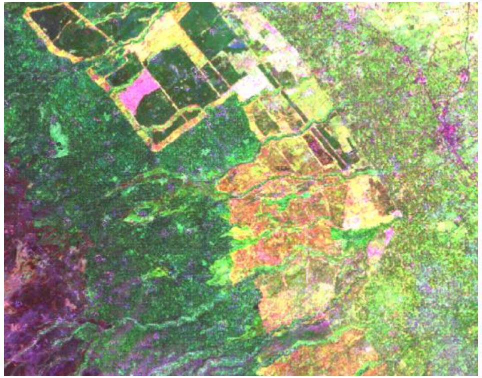
- Temporal 0.75 quantile
- Artefacts minimized

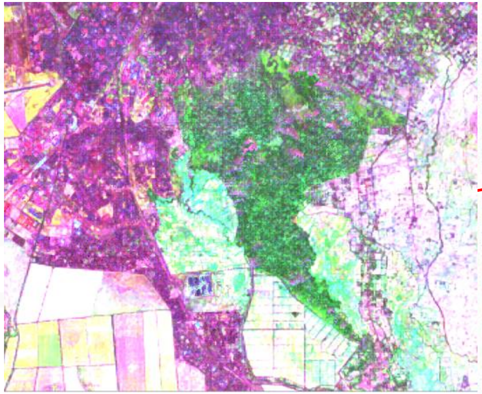


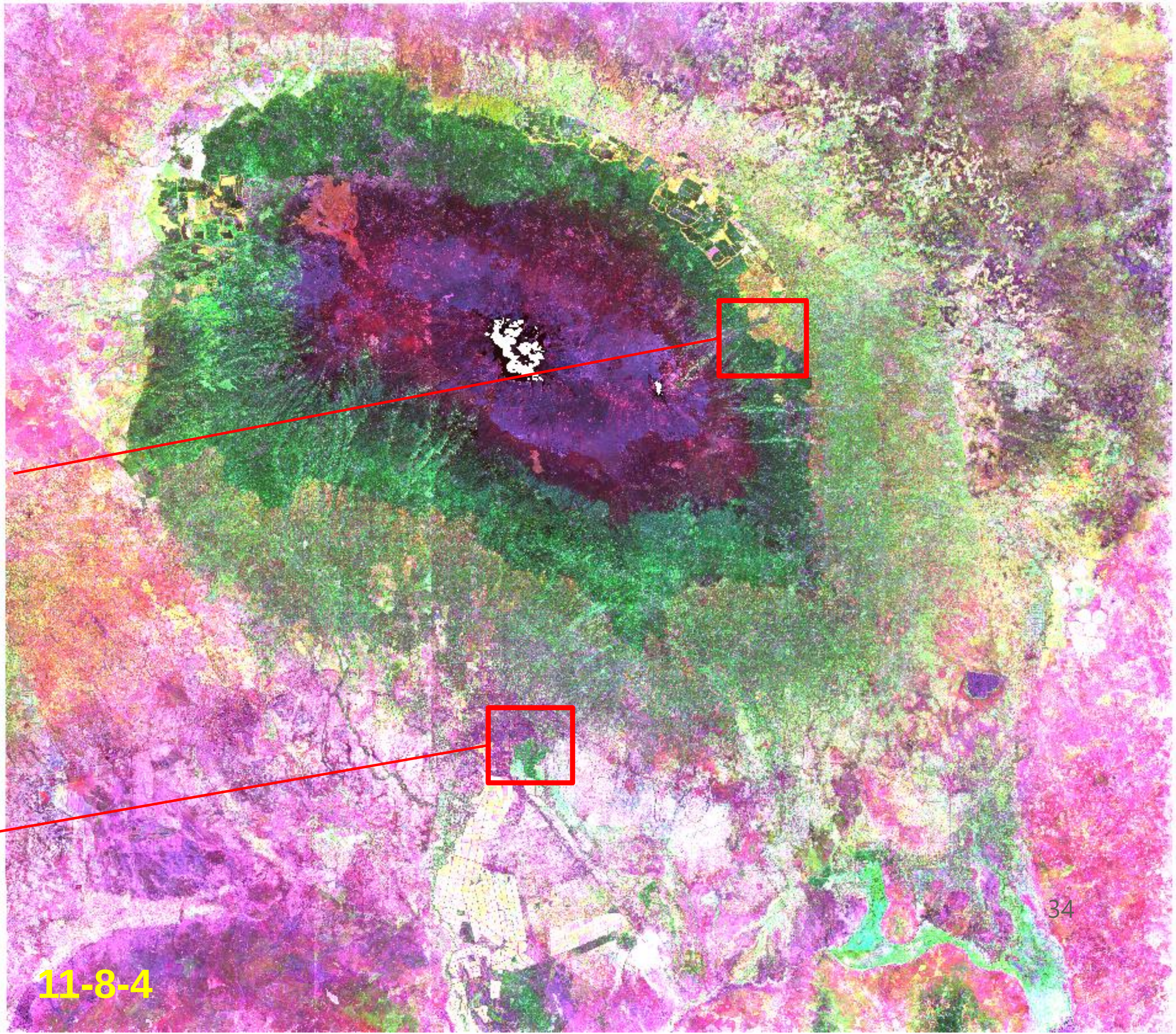




- Temporal range
- Artefacts visible (better to use interquartile range
- Reveals spectral variance

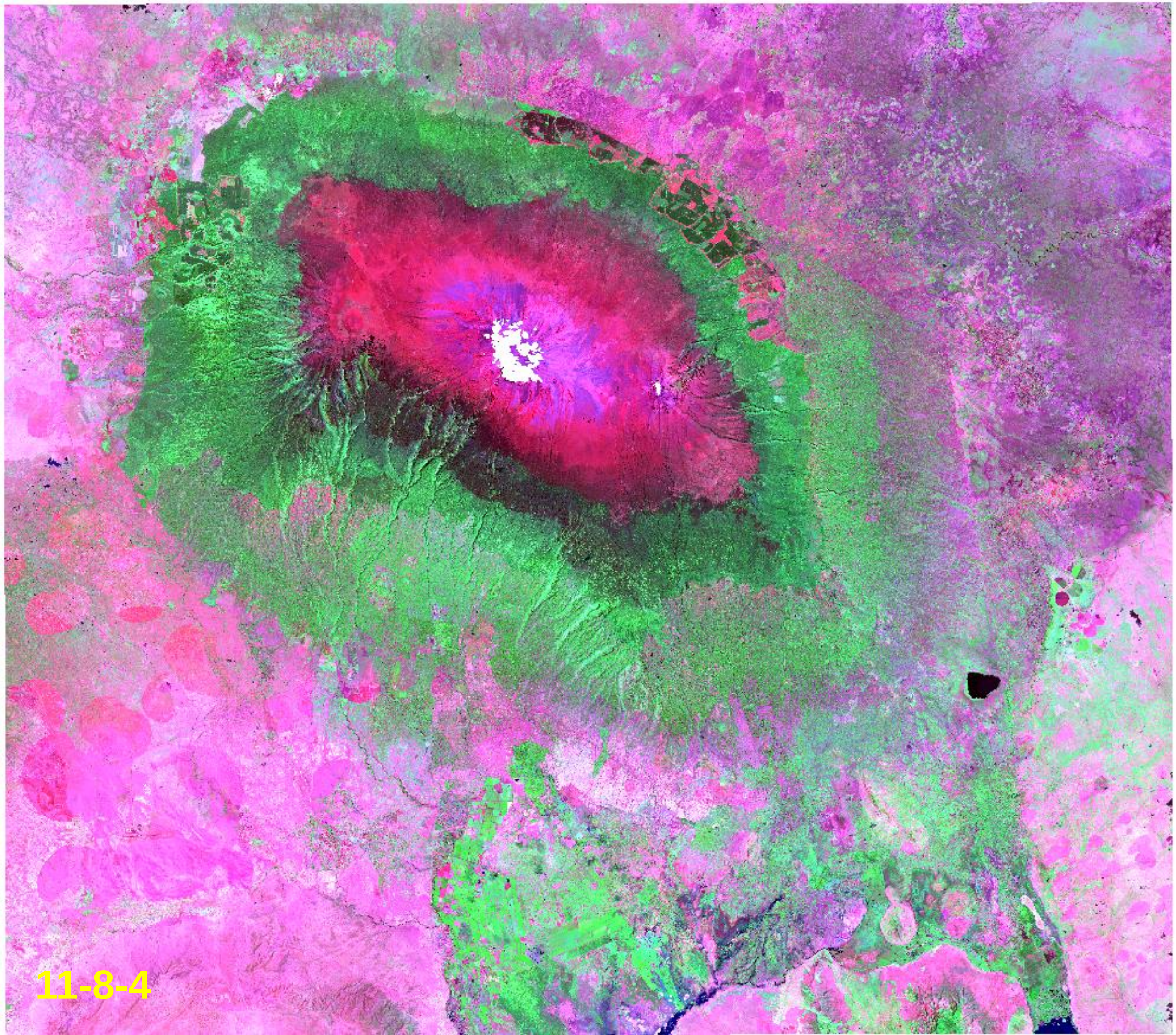






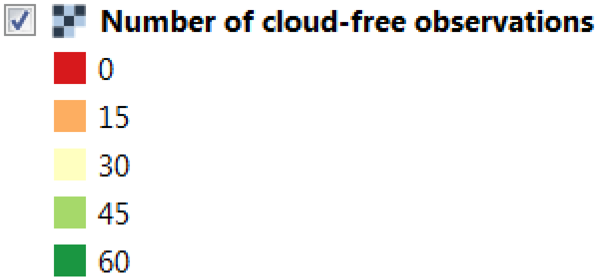
SYKE

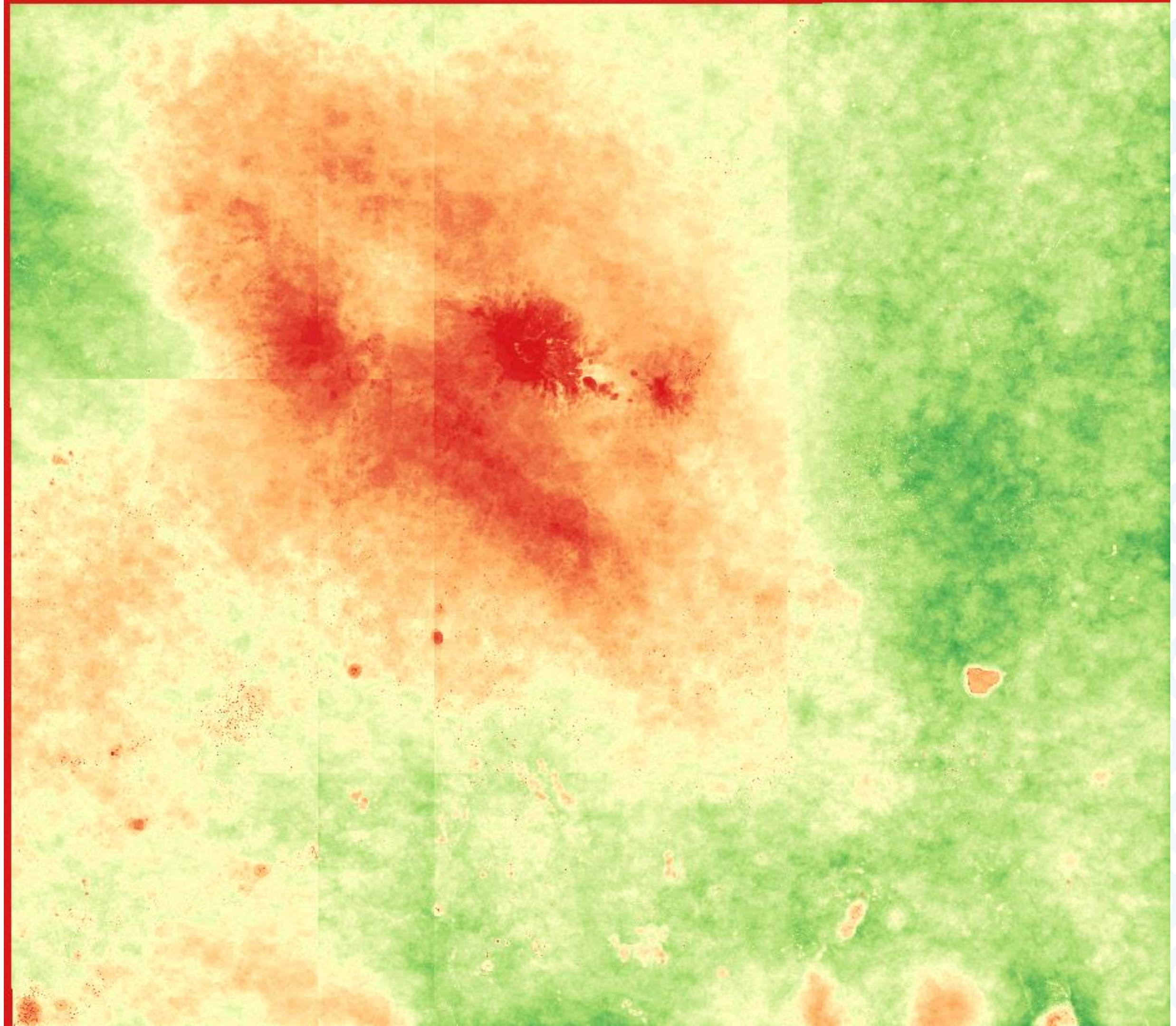
- Best Available Pixel composite
- This example is not usable due to high phenological variance and three years of observations
- Tuning of the compositing scores is also critical



SYKE

- Number of cloud-free observations in compositing period





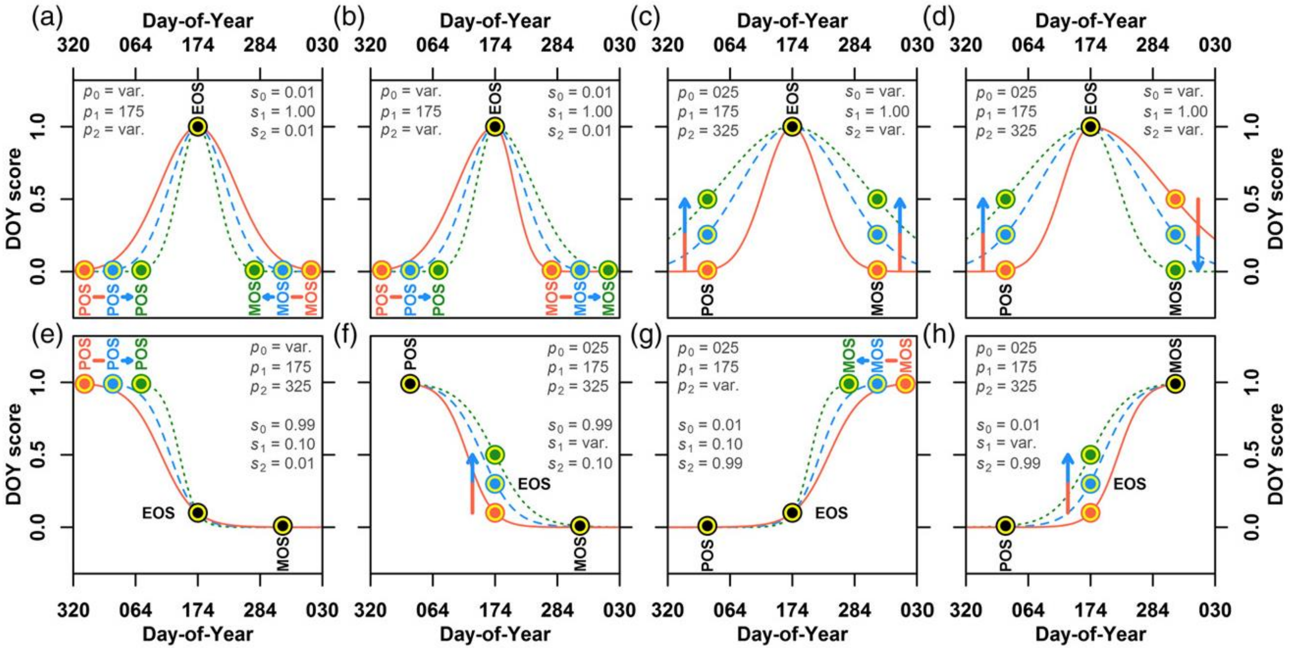
S Y K E

Temporal compositing scores: LSP-adaptive DOY scoring functions

Frantz et al. 2017

Gaussian, [0,1]
$S_0 < S_1 > S_2$

Logistic, [0,1]
$1 \geq s_0 > s_1 > s_2 \geq 0$
(*descending sigmoid*)
$0 \leq s_0 < s_1 < s_2 \leq 1$
(*ascending sigmoid*)



p_0, p_1, p_2 Land Surface Phenology (LSP) metrics
s_0, s_1, s_2 Function values for the LSP metrics

SYKE

Temporal compositing scores: Y-factor Y_f

D. Frantz et al. / Remote Sensing of Environment 190 (2017) 331–347

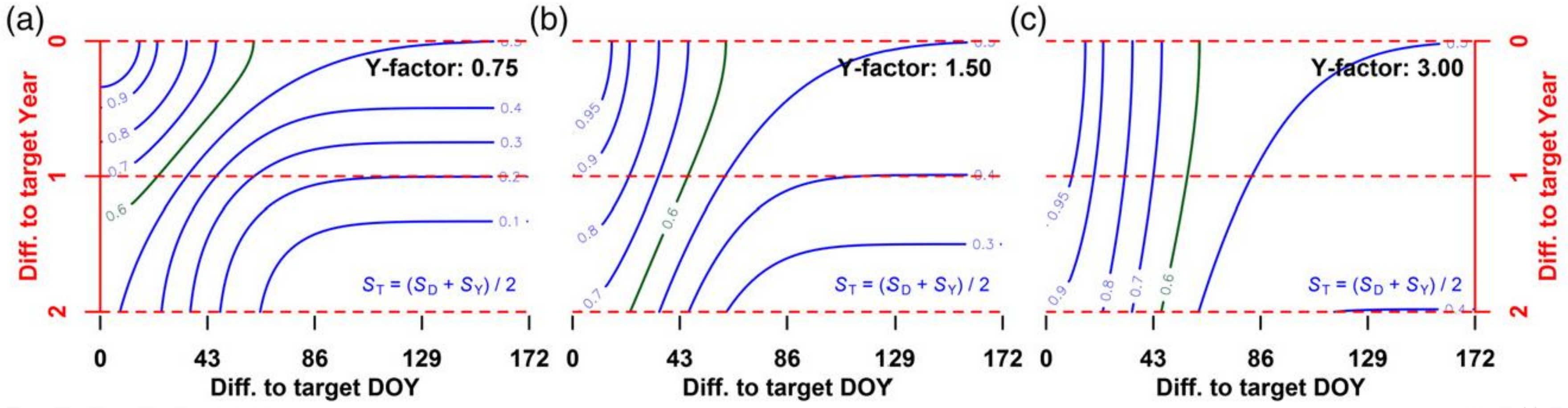


Fig. 5. Illustration of the Y-factor Y_f for an arbitrary example. The figure shows isolines of the total score S_T, drawn with a dependence on ΔY and ΔD. The right tail Gaussian type was chosen and two years around the target year are allowed; i.e. $y = 2$. The total score was computed as a combination of the Year score S_Y and the DOY. The higher Y_f, the higher is S_Y – and the smaller is the influence of ΔY on S_T.

SYKE

Auxiliary compositing scores, 1/3

- **Cloud distance score**, devaluates pixels in close proximity to a cloud or cloud shadow
  - uses modified *fmask* code, with $\mathbf{d_{req}}$ parameter (distance in meters beyond which the sky is assumed to be clear)
- **Haze score**, devaluates hazy observations using *Haze Optimized Transformation* (HOT) (Zhang et al. 2002, Zhu & Woodcock 2012)

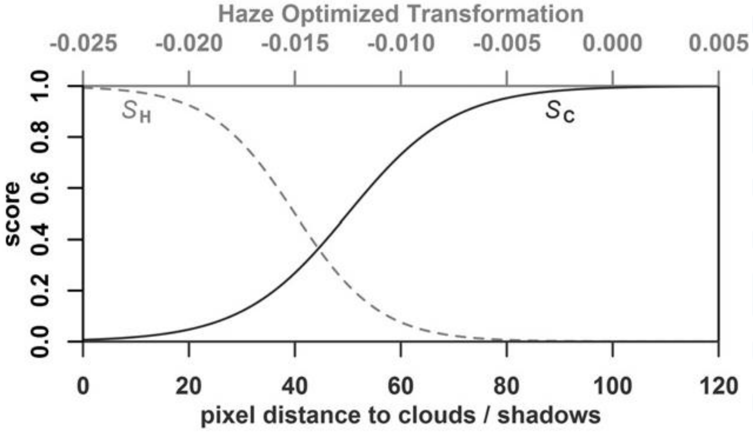


Fig. 6. Cloud distance and haze scoring functions; d_{req} was set to 100 pixels.

Auxiliary compositing scores, 2/3

- **Correlation score**, a general criterion to account for outlier-induced noise not detected previously
  - data artifacts,
  - residual misregistration,
  - undesired phenomena e.g. fires, missed clouds or shadows
- Correlates one pixel observation with other observations -> **Computationally expensive!**

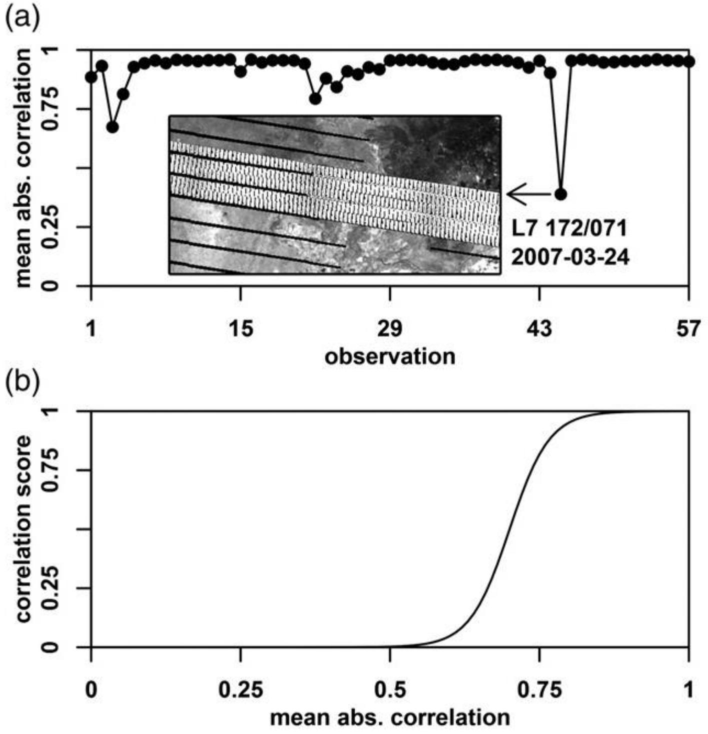


Fig. 7. Exemplary illustration of the spectral stability assessment and correlation scoring function. (*a*): mean absolute correlation derived from all spectra within the compositing period, and Landsat-7 NIR image (Path/Row 172/072) affected by sensor anomalies. (*b*): correlation scoring function.

Auxiliary compositing scores, 3/3

- **View angle score** – devaluates off-nadir pixels on the basis of view zenith angle (e.g. for MODIS data)

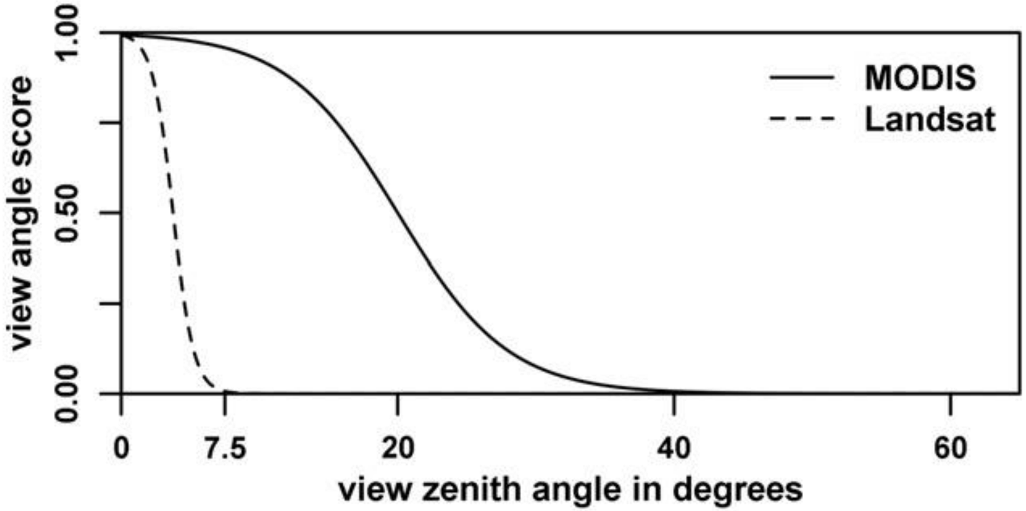


Fig. 8. View zenith angle scoring function; θ_{req} was set to 40° and 7.5° for MODIS and Landsat, respectively.

S Y K E

Weighting parameters W

- You can also give weights [0,1] for each compositing score S (DOY, Year, Cloud, Haze, Correl, Vzen)
- Weight = 0 disables the score entirely

SYKE

FORCE TSA – Time Series Analysis

- Extracts quality-controlled time series with a number of aggregation and interpolation techniques
  - TS on spectral bands, vegetation indices, spectral mixture analysis
  - Annual Land Surface Phenology metrics
- Change and trend analyses can be done on any of the TS
- TSA needs Level 2 ARD as input!

SYKE

Phenology-based CAT-analysis

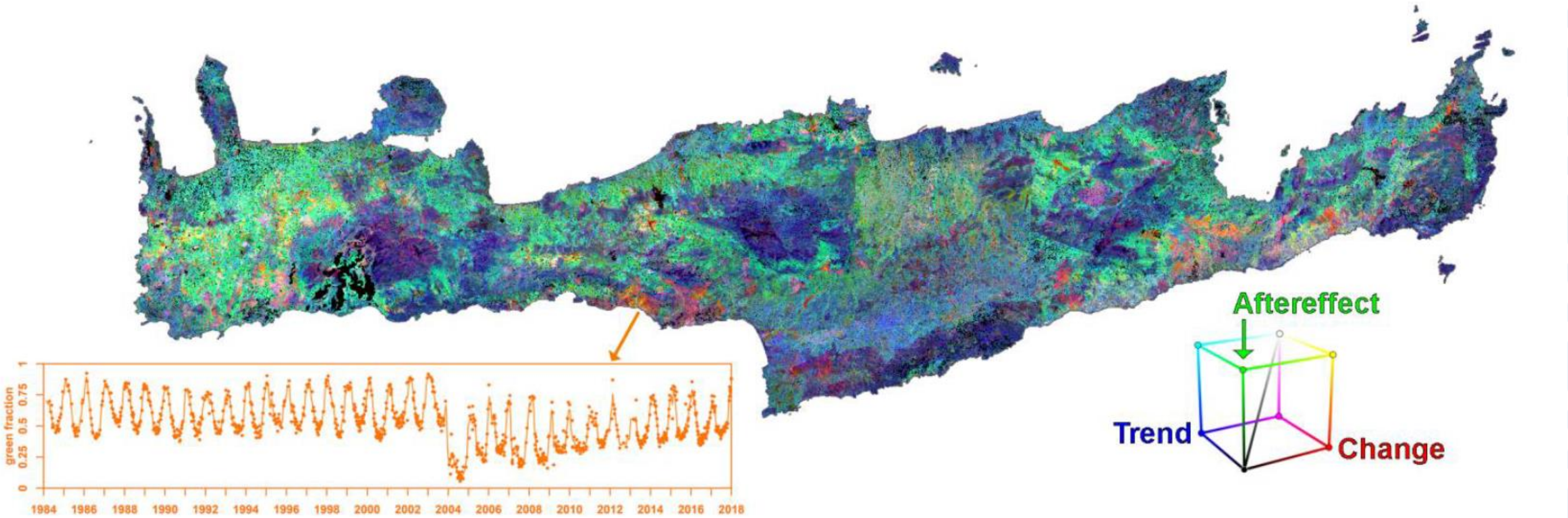


Fig. 4. Phenology-based change and trend analysis.
Change, Aftereffect, Trend transformation (CAT) showing both long-term (30+ years) gradual and abrupt changes over Crete, Greece. The CAT transform was applied to the Value of Base Level (VBL) annual time series, which was itself derived by inferring Land Surface Phenology (LSP) metrics from dense time series of green vegetation abundance derived from linear spectral mixture analysis (SMA).
[All this was done in one step using force-tsa; then mosaicked using force-mosaic]

S Y K

ImproPhe – Improve spatial resolution of LSP

- Data fusion tool to developed to refine LSP metrics from MODIS using Landsat or S2

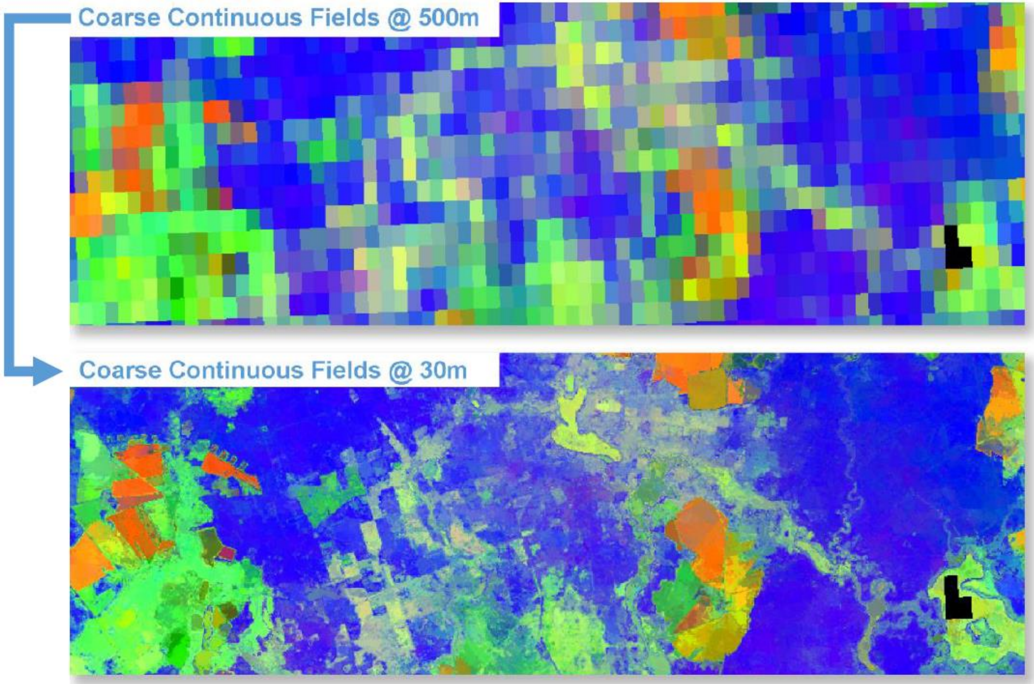


Fig. 8. Coarse resolution (500m) and ImproPhed (30m) LSP metrics.
Rate of Maximum Rise (R), Integral of Green Season (G), and Value of Early Minimum (B) phenometrics for a study site in Brandenburg, Germany. Using the ImproPhe algorithm, the LSP metrics were improved to 30m spatial resolution using Landsat and (degraded) Sentinel-2 targets.
[Data were fused using force-improphe]

S Y K E

ImproPhe – Improve spatial resolution of LSP

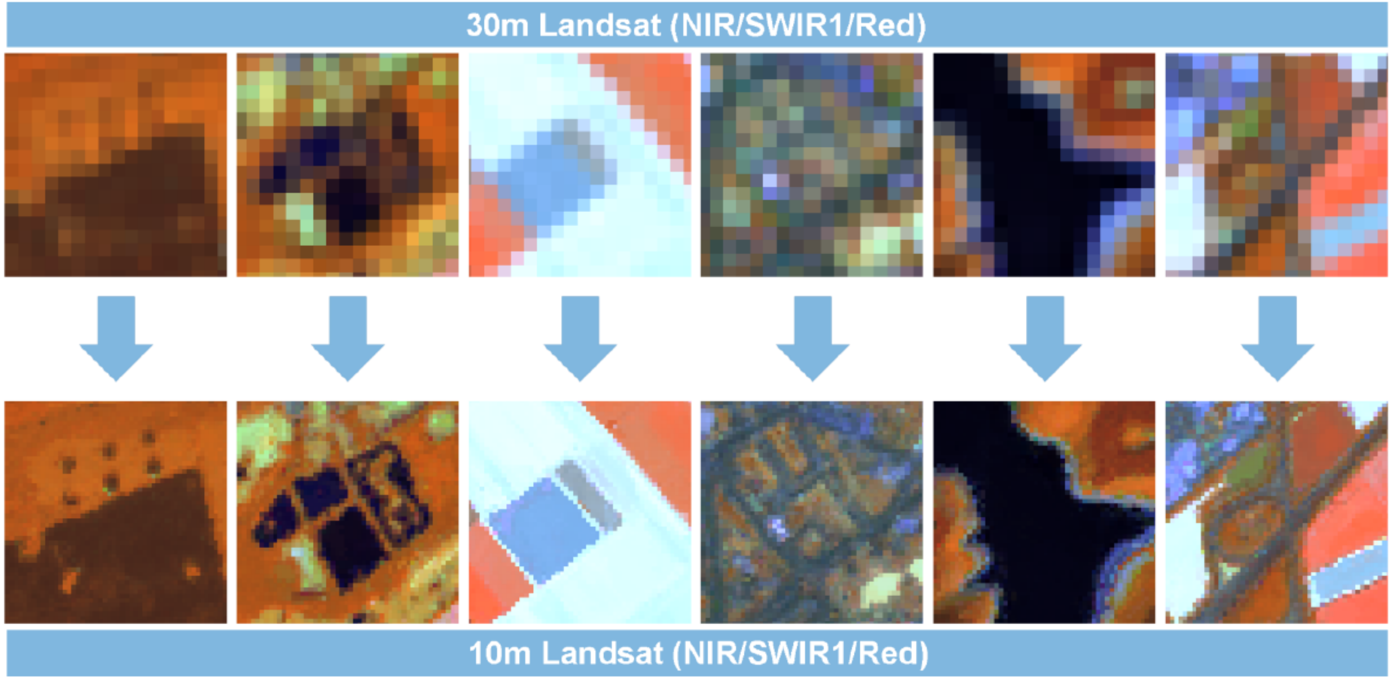


Fig. 9. 30m Landsat ARD, and ImproPhed 10m Landsat ARD.
The figure shows image subsets from North Rhine-Westphalia, Germany. Using the ImproPhe algorithm, the spatial resolution was improved to 10m using multi-temporal Sentinel-2 A/B high-res bands as prediction targets.
[Data were fused using force-l2imp]

SYKE