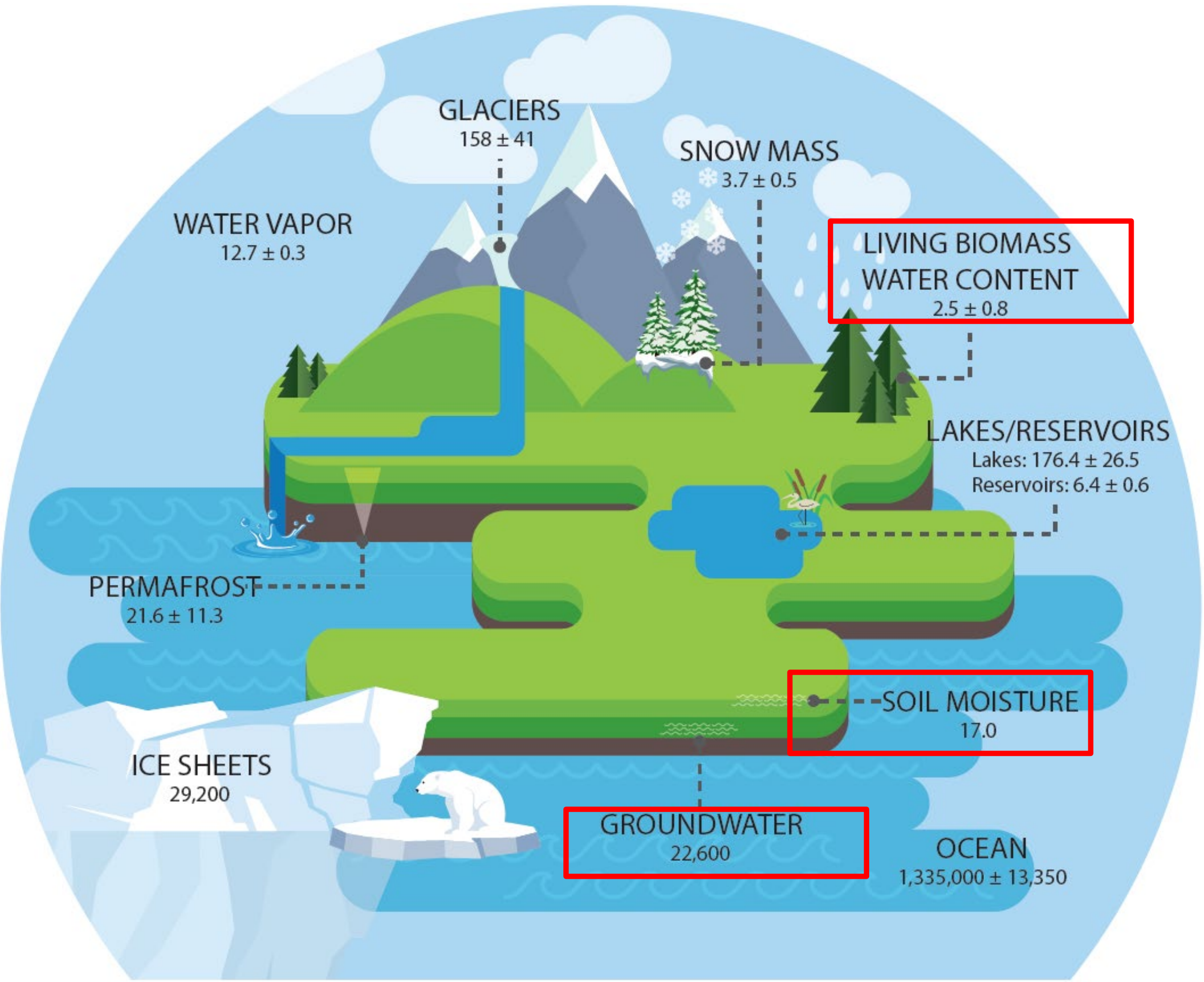
ESA Land Training course ´23

Drought monitoring and forecasting

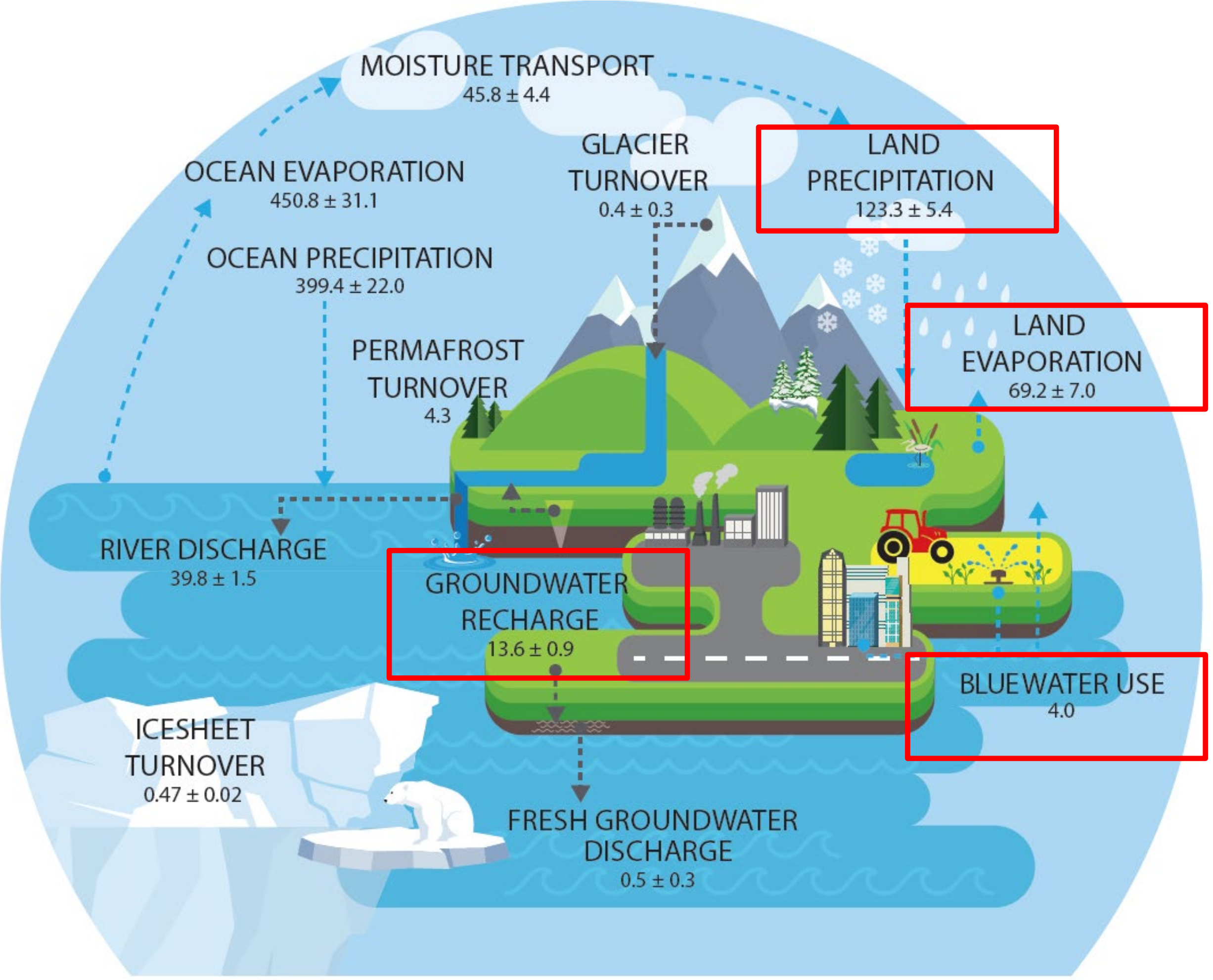
Wouter Dorigo, Pietro Stradiotti, Wolfgang Preimesberger

TU Wien
Department of Geodesy and Geoinformation
Climate and Environmental Remote Sensing

Global water stores and yearly fluxes

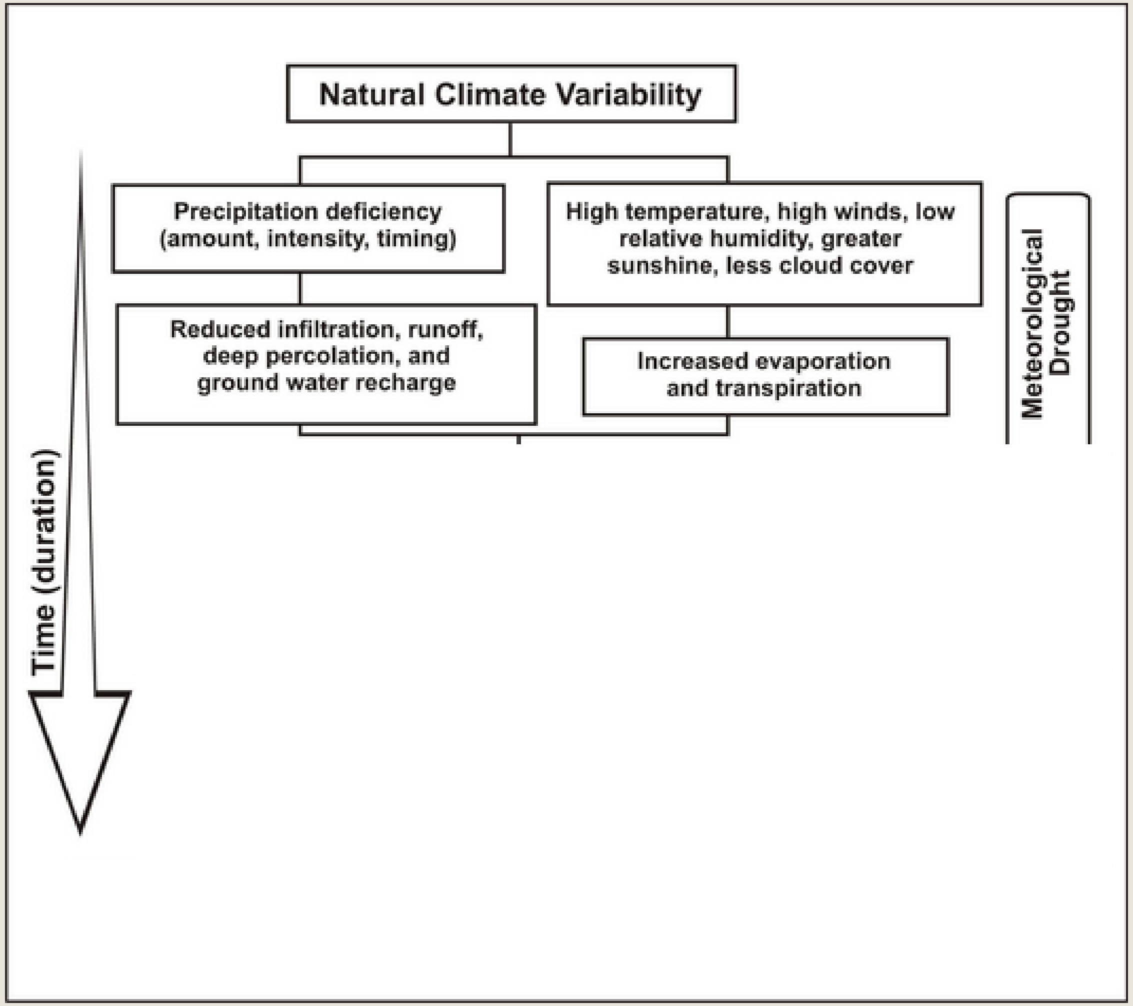


[10³ km³]



[10³ km³y⁻¹] [Dorigo et al., 2021]

What is drought?

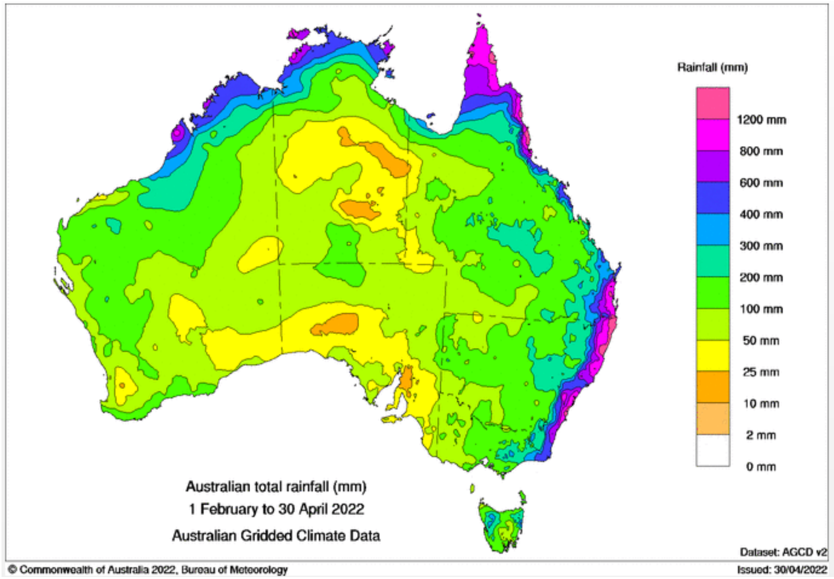


Sequence of drought occurrence and impacts for commonly accepted drought types. All droughts originate from a deficiency of precipitation or meteorological drought but other types of drought and impacts cascade from this deficiency. (Source: National Drought Mitigation Center, University of Nebraska-Lincoln, U.S.A.)

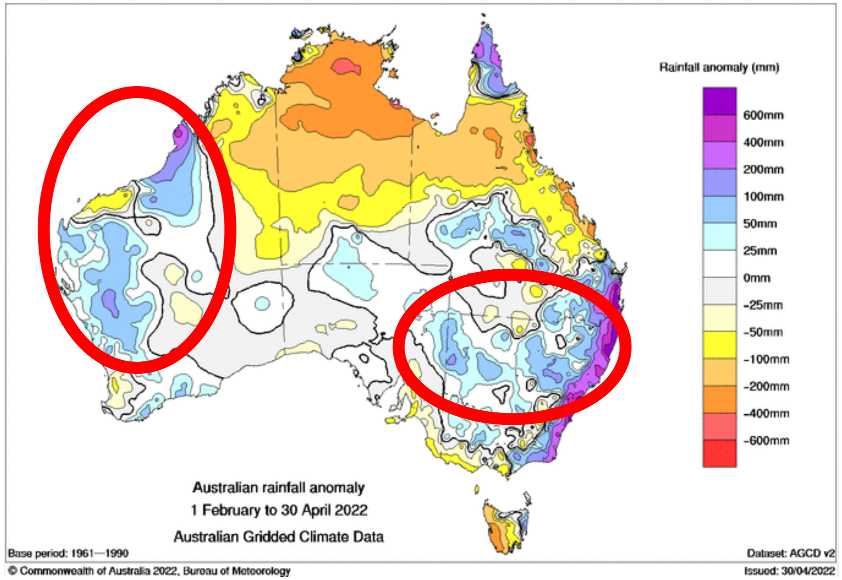
How do we quantify drought?

- Drought is not a physical variable but an indicator of deviating conditions, and can be expressed in various ways

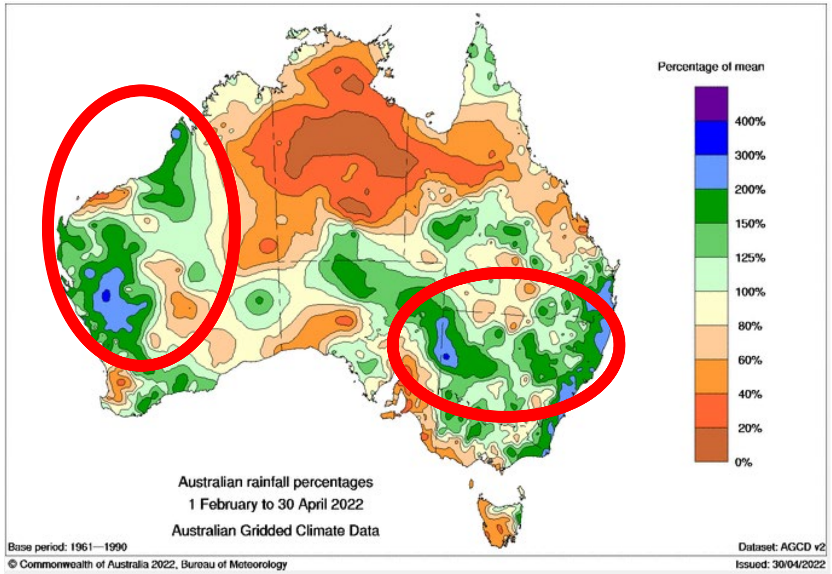
Rainfall January-April 2022 [mm]



Anomaly from long-term mean rainfall [mm]



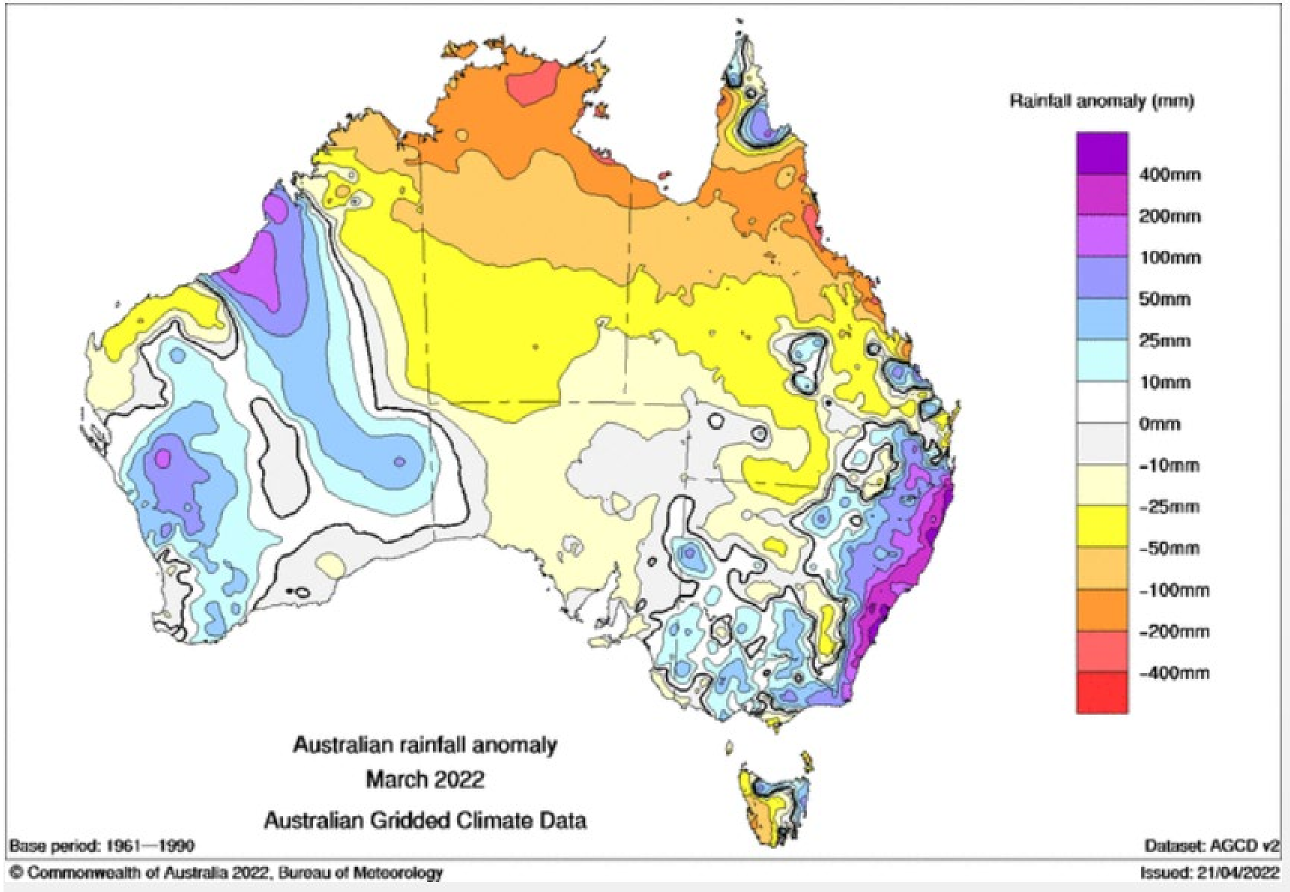
Percentages of long-term mean rainfall [mm]

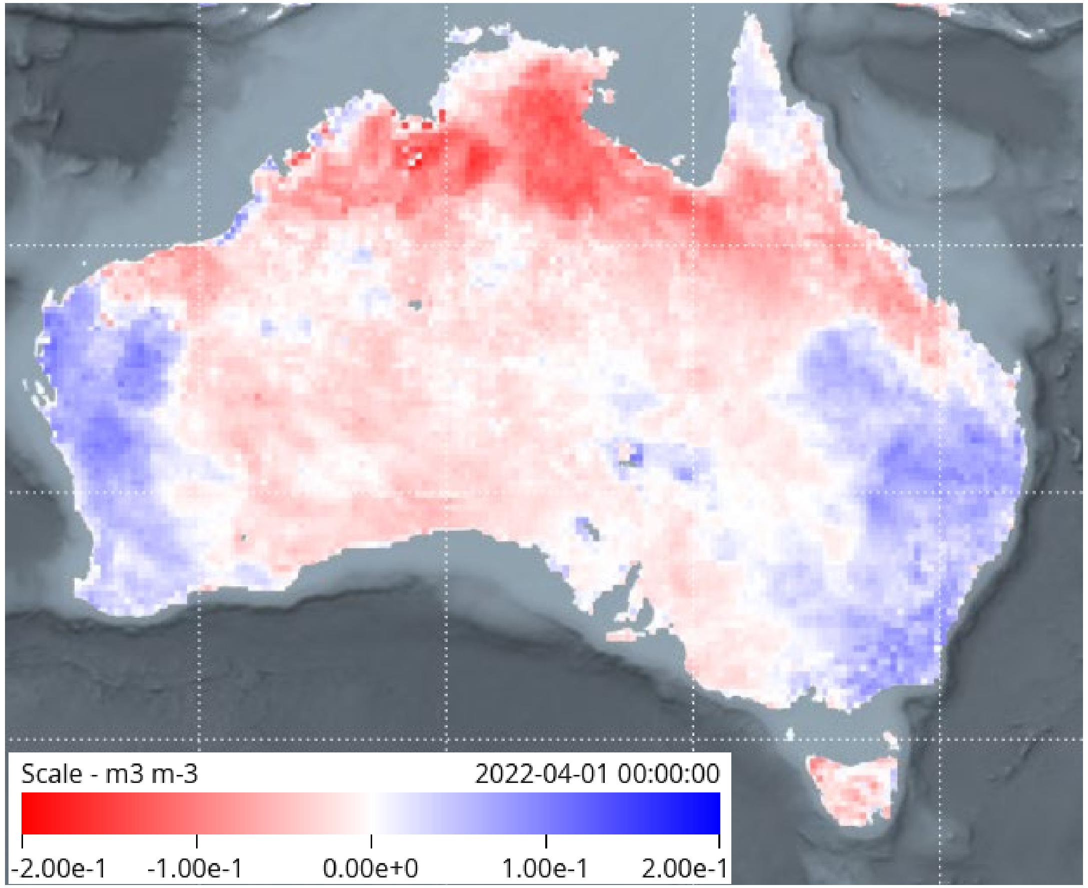


http://www.bom.gov.au/climate/maps/rainfall/?variable=rainfall&map=totals&period=3month&region=nat&year=2022&month=03&day=31

How do we quantify drought?

- Anomalies in precipitation and multi-satellite C3S soil moisture for March 2022

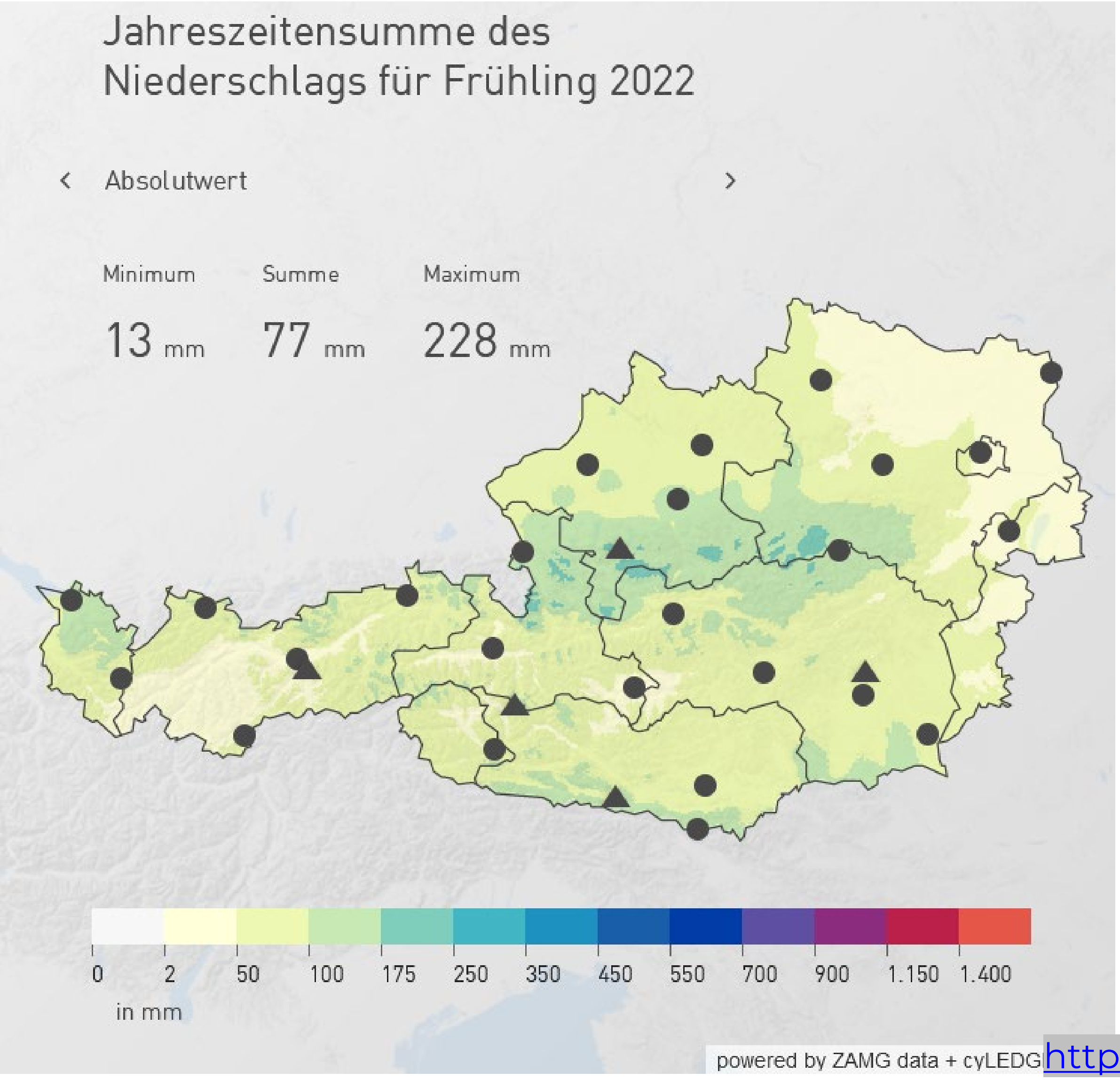


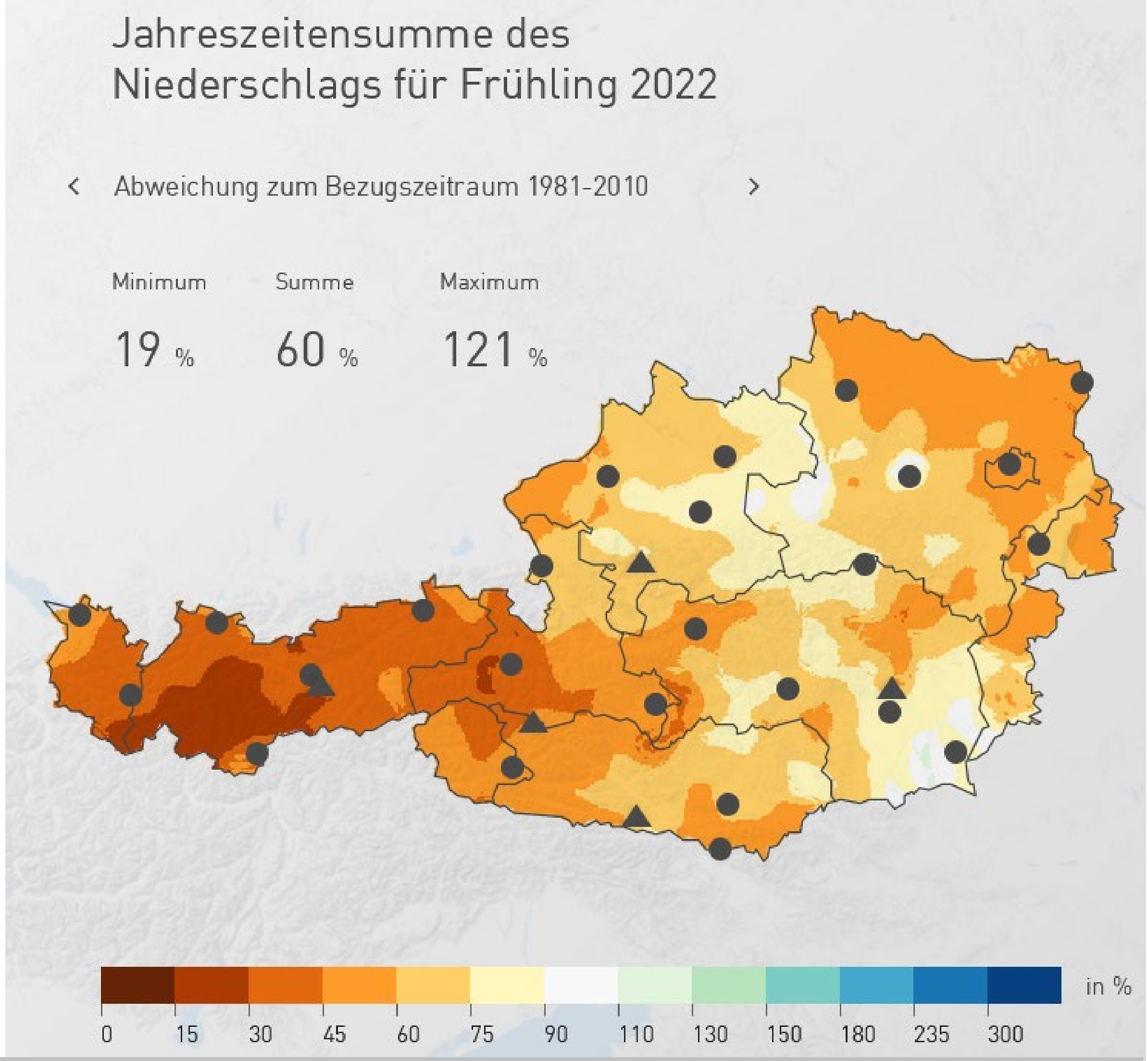


https://dataviewer.geo.tuwien.ac.at/

http://www.bom.gov.au/climate/maps/rainfall/

Drought indices "correct for" differences in climate



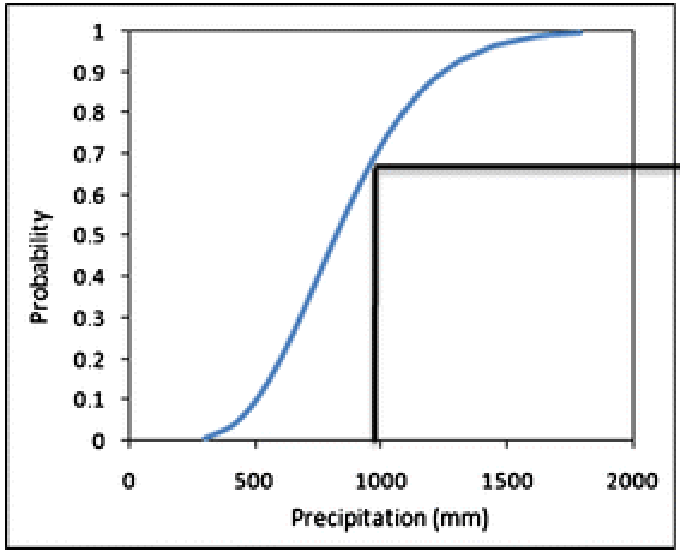


https://www.zamg.ac.at/cms/de/klima/klima-aktuell/klimamonitoring

Spring precipitation in Austria 2022 in comparison to 1981-2010 in %. 100% equals the long-term average.

Standardised Precipitation Index

SPI fits actual, long-term precipitation record to probability distribution (left), which is then transformed into a normal distribution (right) so that the mean SPI for the location and desired period is zero and the SPI is expressed by a z-score



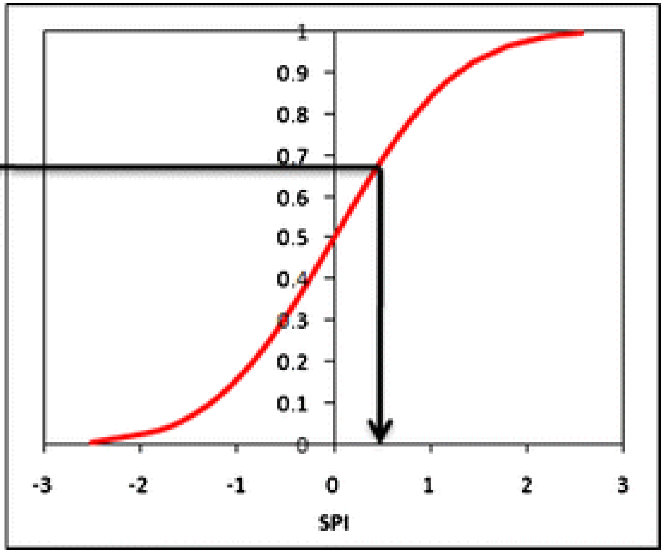
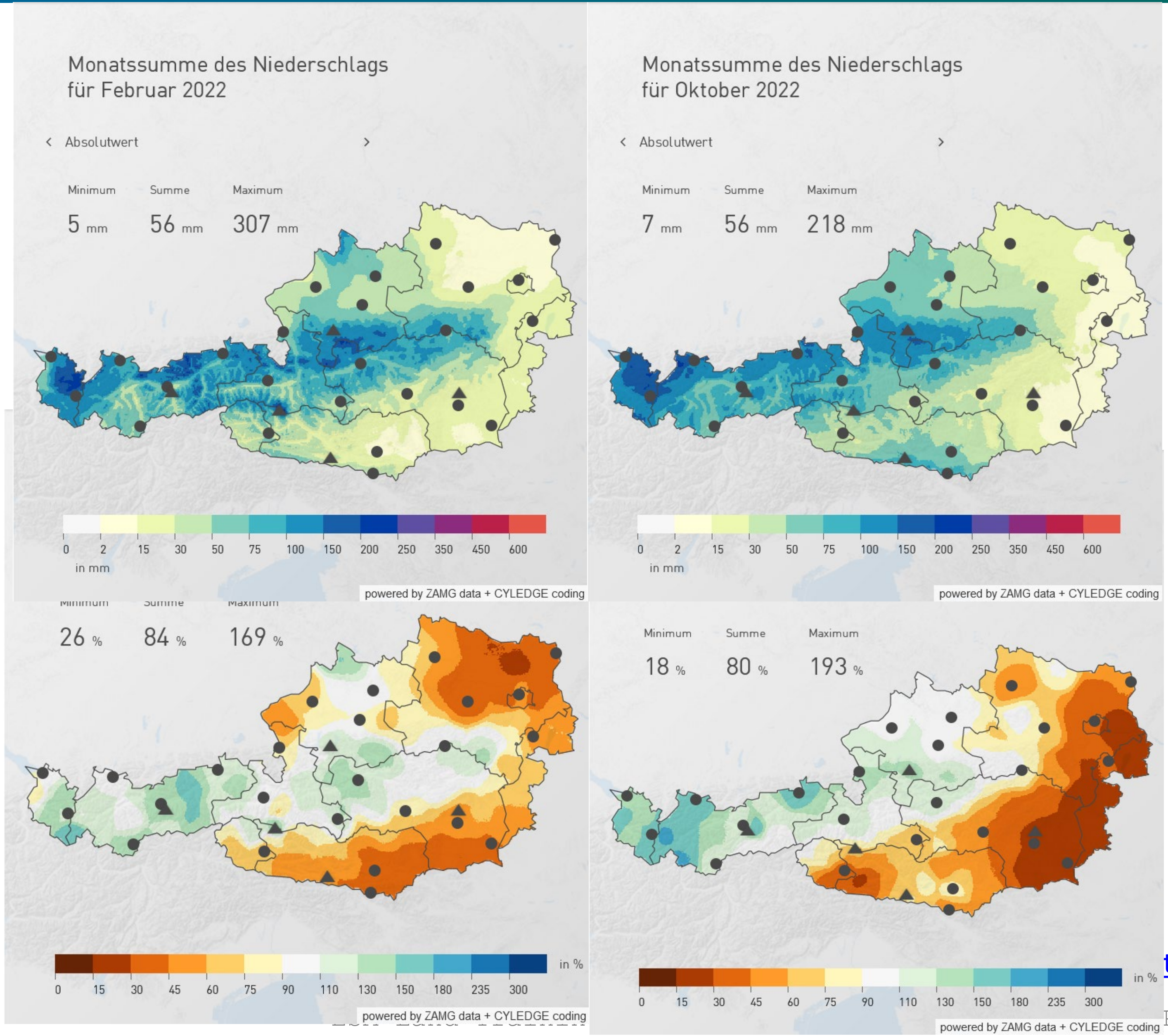


Table 1. SPI values

2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-.99 to .99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
-2 and less	extremely dry

- Two basic assumptions
  - Variability of precipitation is much higher than that of other variables, (e.g., T and ET_{pot})
  - Precipitation and other variables are stationary (i.e., they have no temporal trend)

Also seasonal differences need to be accounted for

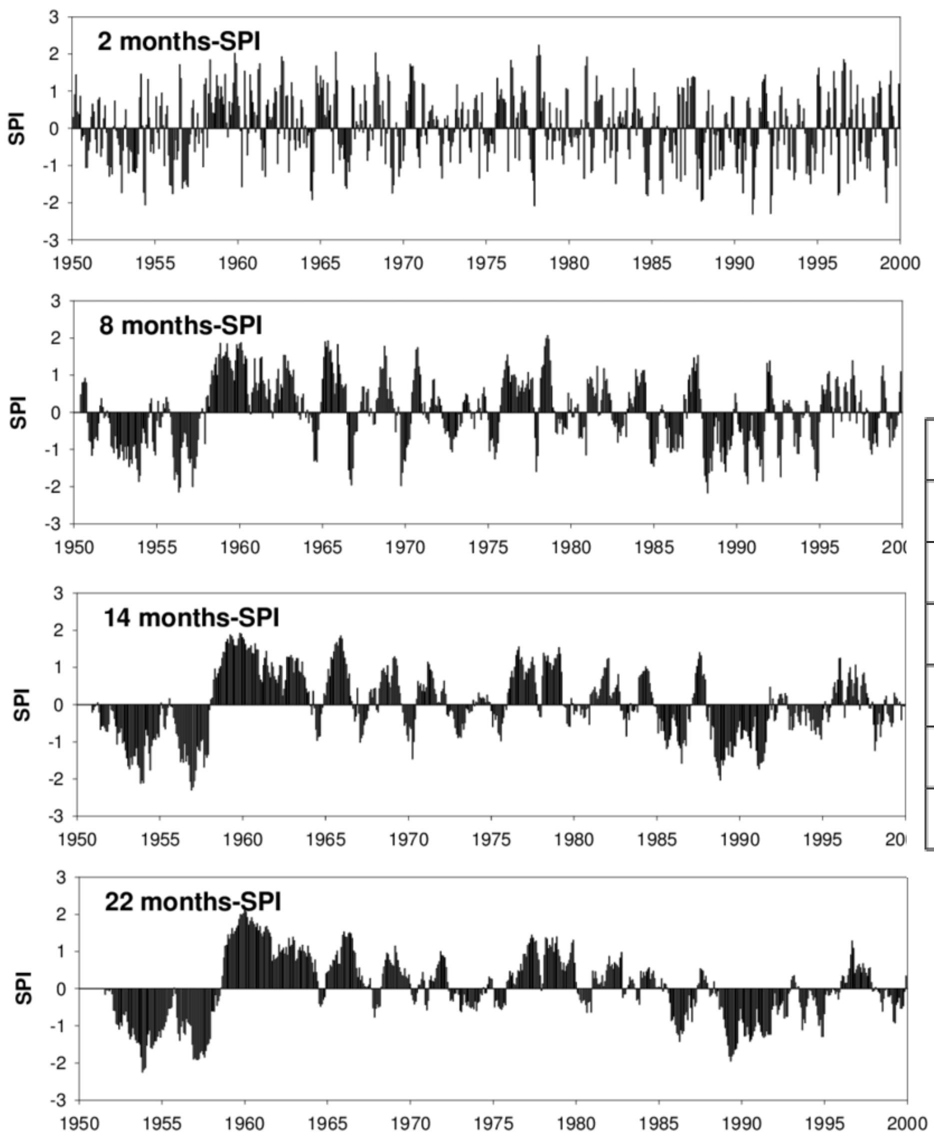


- Individual distribution needs to be fitted for each season individually

ttps://www.zamg.ac.at/cms/de/klima/klima-aktuell/klimamonitoring

Standardised Precipitation Index

- Can be computed at multiple time aggregates (1, 2, 3, 12 months etc) representing different process time scales



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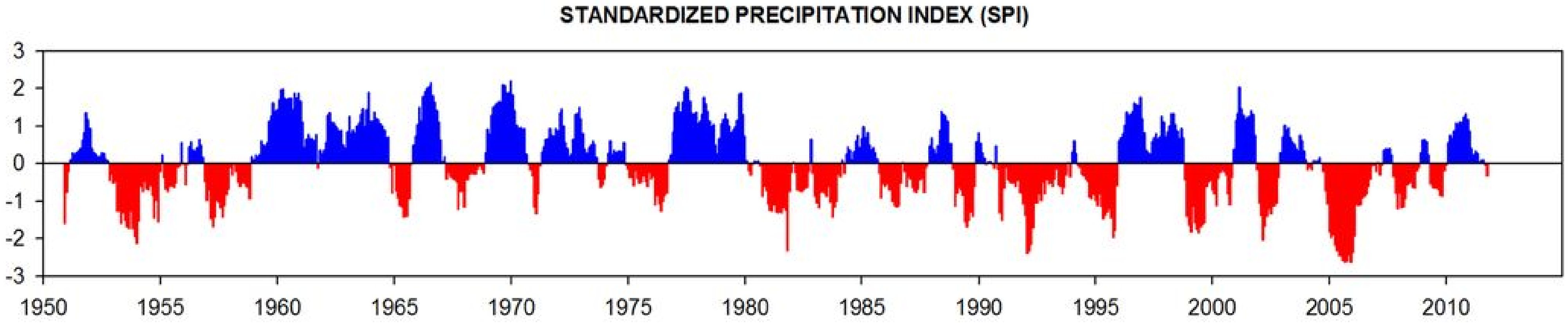
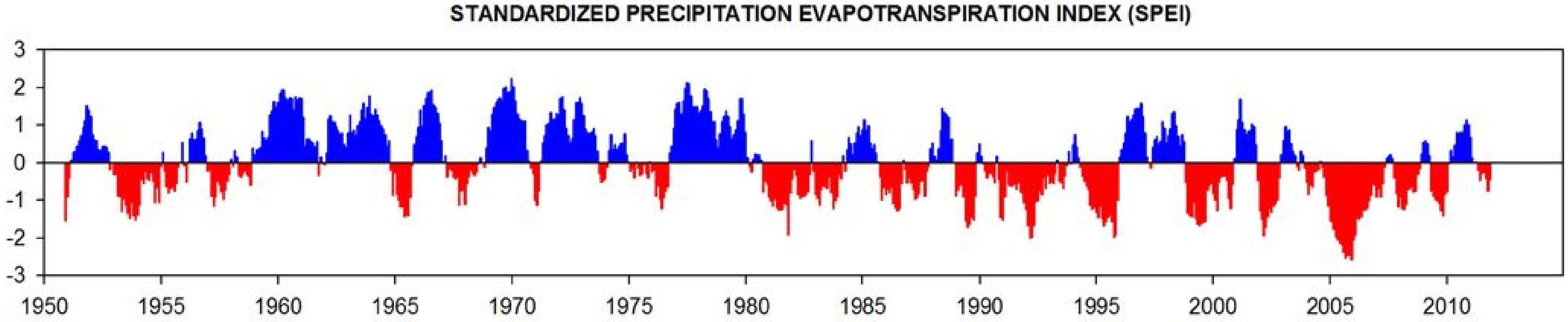
[Vicente-Serrano, 2005]

Standardised Precipitation minus Evaporation index

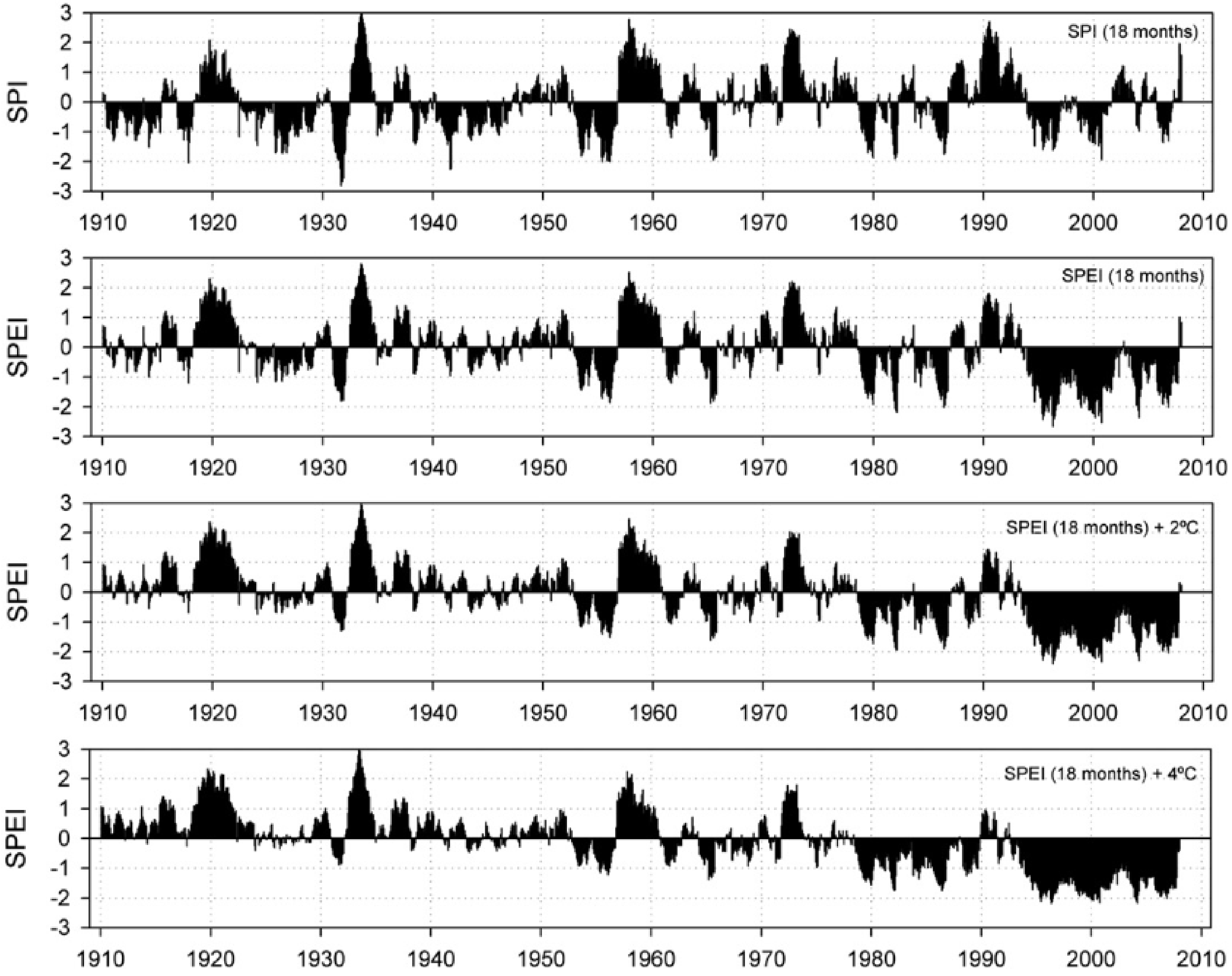
- Climatic water balance (precipitation minus potential evapotranspiration)
  - Considers what potentially evaporates again (in summer more than in winter)
  - Includes the impact of (rising) temperature





SPEI

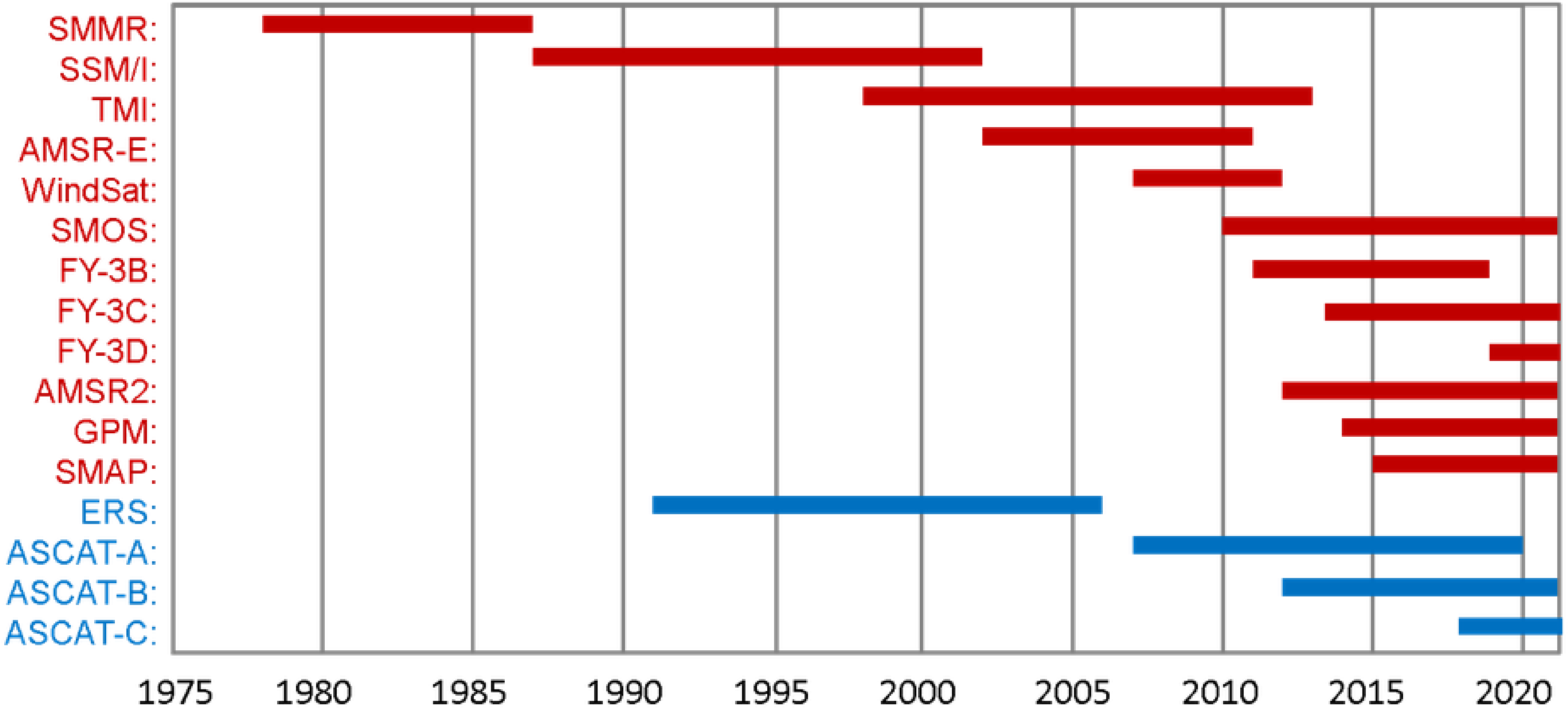
Impact of temperature under 2 °C and 4 °C global warming scenario



[Vicente-Serrano, 2010]

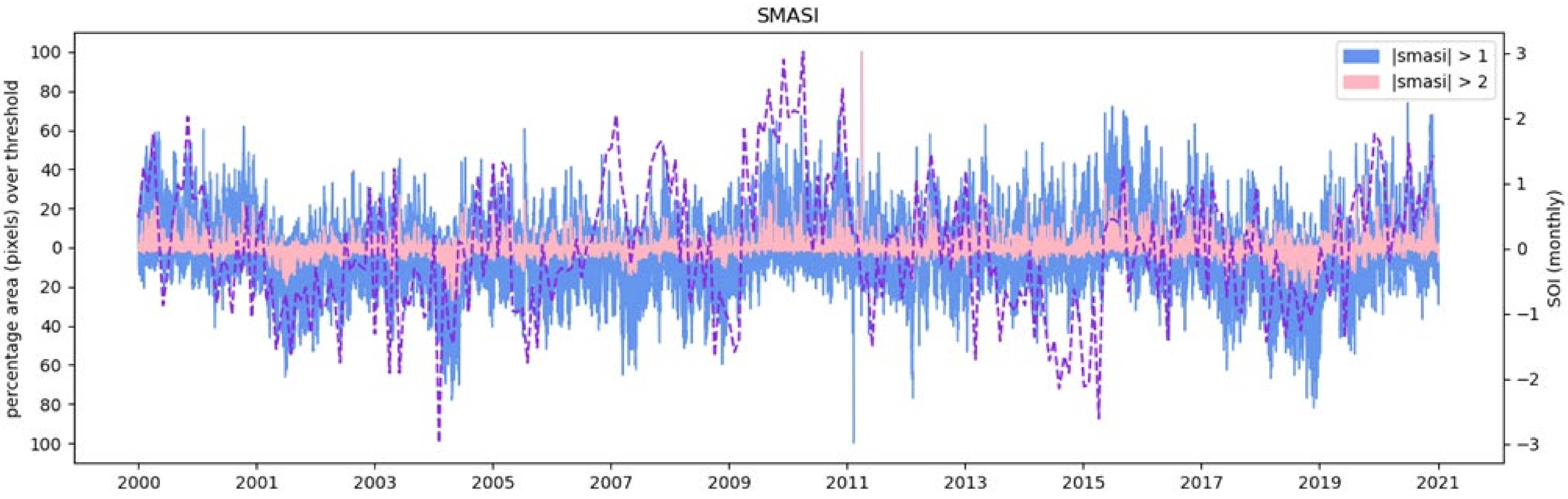
SMASI - A drought index for soil moisture

- Z-scores can in principle be computed for any dataset of sufficient length, not only from precipitation
- Use of multiple satellite missions (e.g., ESA CCI SM) allows for a more robust assessment over longer time periods



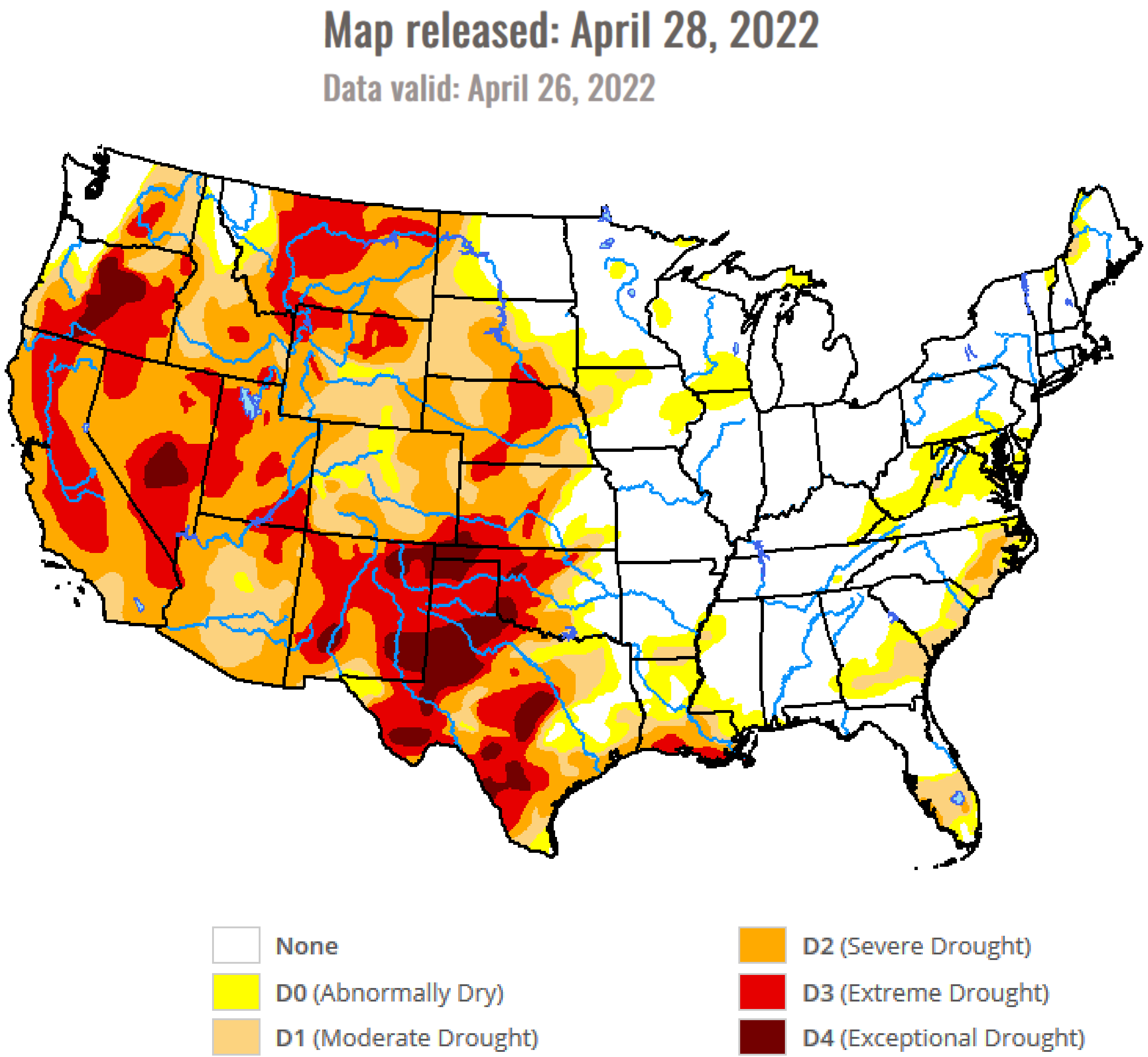
SMASI - A drought index for soil moisture

- Soil Moisture Anomaly Standardised Index shows severity of anomalies
  - Example for Australia, where moisture is strongly driven by El Nino Southern Oscillation (ENSO), as indicated by the Southern Oscillation Index (SOI)



Drought portals

- Drought is commonly expressed as an index, and fed with (Earth) observations
- Many variations have been developed
  - Standardized Precipitation Index (SPI), using Precipitation only
  - Standardised Precipitation-Evapotranspiration Index (SPEI), using P and potential ET
  - Palmer Drought Severity Index (PDSI), based on P and T
  - Self-calibrating PDSI
  - And many more…
- Indices can be used to measure severity and duration



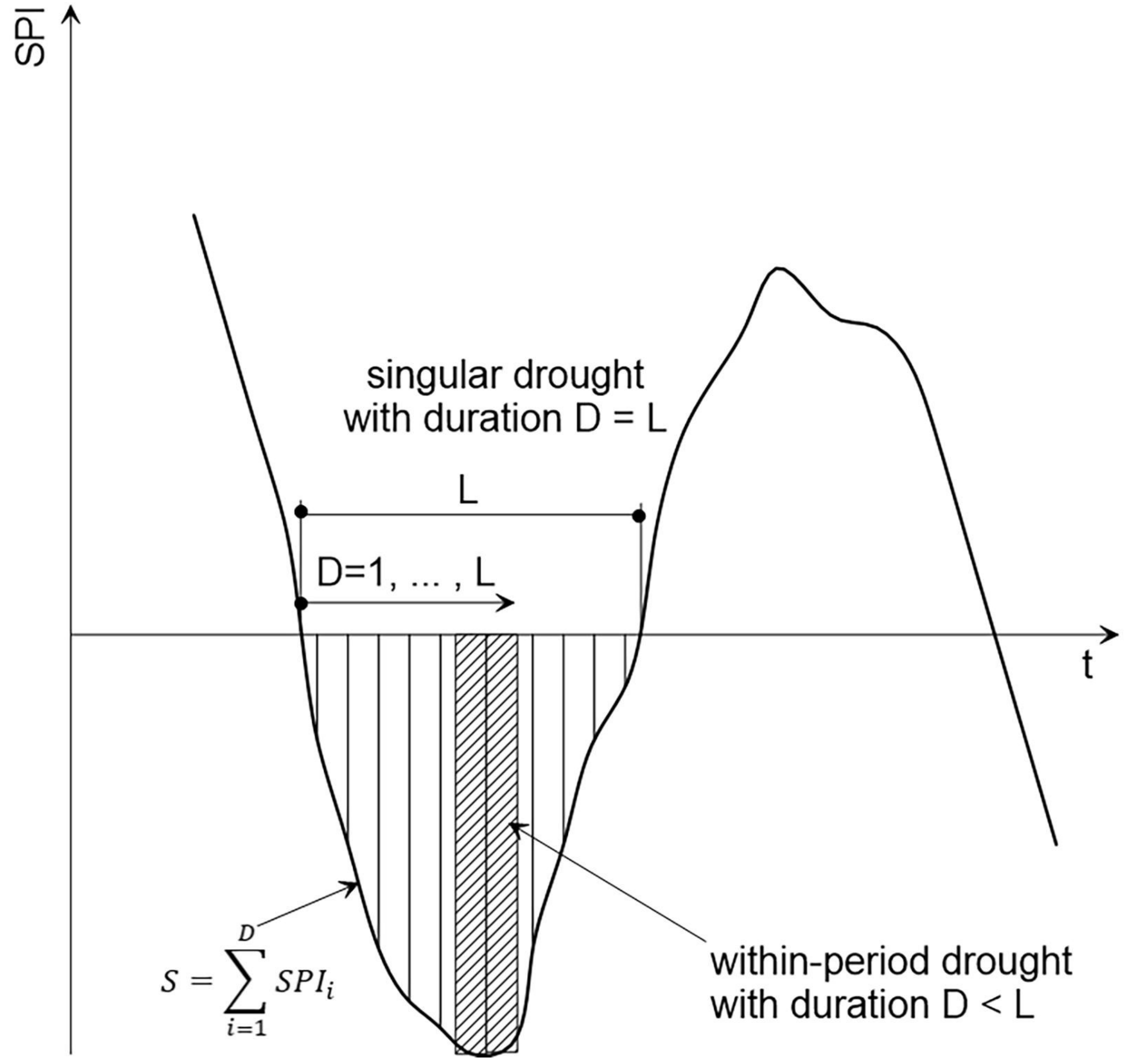
Drought indices

- Categorisation depends on index

Category	Description	Possible Impacts	Ranges: Palmer Drought Severity Index (PDSI)	Ranges: CPC Soil Moisture Model (Percentiles)	Ranges: USGS Weekly Streamflow (Percentiles)	Ranges: Standardized Precipitation Index (SPI)	Ranges: Objective Drought Indicator Blends (Percentiles)
D0	Abnormally Dry	Going into drought: ▪ short-term dryness slowing planting, growth of crops or pastures Coming out of drought: ▪ some lingering water deficits ▪ pastures or crops not fully recovered	-1.0 to -1.9	21 to 30	21 to 30	-0.5 to -0.7	21 to 30
D1	Moderate Drought	▪ Some damage to crops, pastures ▪ Streams, reservoirs, or wells low, some water shortages developing or imminent ▪ Voluntary water-use restrictions requested	-2.0 to -2.9	11 to 20	11 to 20	-0.8 to -1.2	11 to 20
D2	Severe Drought	▪ Crop or pasture losses likely ▪ Water shortages common ▪ Water restrictions imposed	-3.0 to -3.9	6 to 10	6 to 10	-1.3 to -1.5	6 to 10
D3	Extreme Drought	▪ Major crop/pasture losses ▪ Widespread water shortages or restrictions	-4.0 to -4.9	3 to 5	3 to 5	-1.6 to -1.9	3 to 5
D4	Exceptional Drought	▪ Exceptional and widespread crop/pasture losses ▪ Shortages of water in reservoirs, streams, and wells creating water emergencies	-5.0 or less	0 to 2	0 to 2	-2.0 or less	0 to 2

How severe is a drought?

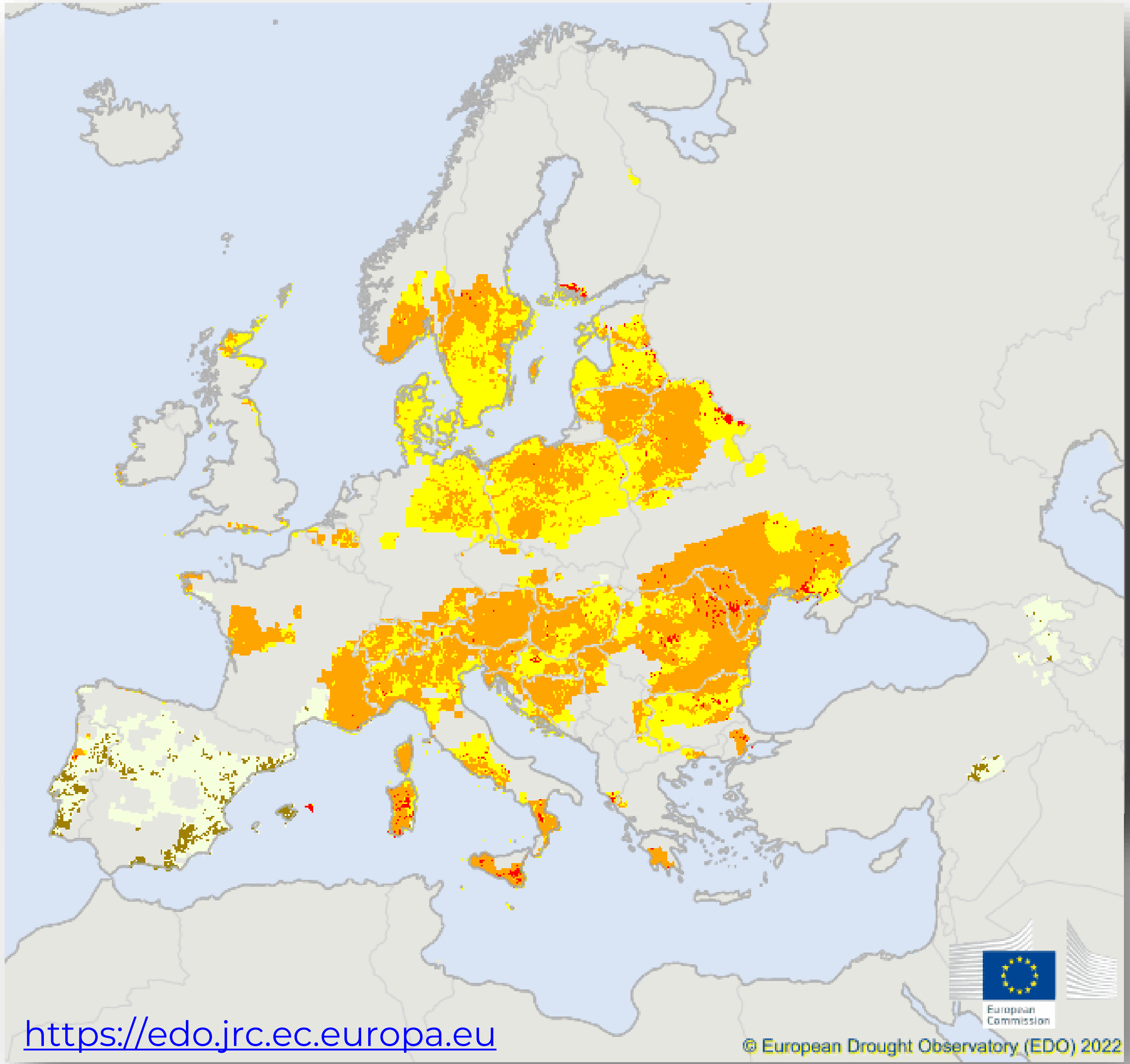
- ***Drought duration (D)*:** Number of sonsecutive days with index <0
- ***Drought severity (S)***: The accumulation of negative index (e.g. SPI) values preceded and followed by positive SPI values is called severity.
- ***Drought intensity (I)***: The intensity is obtained by dividing the severity to the drought duration



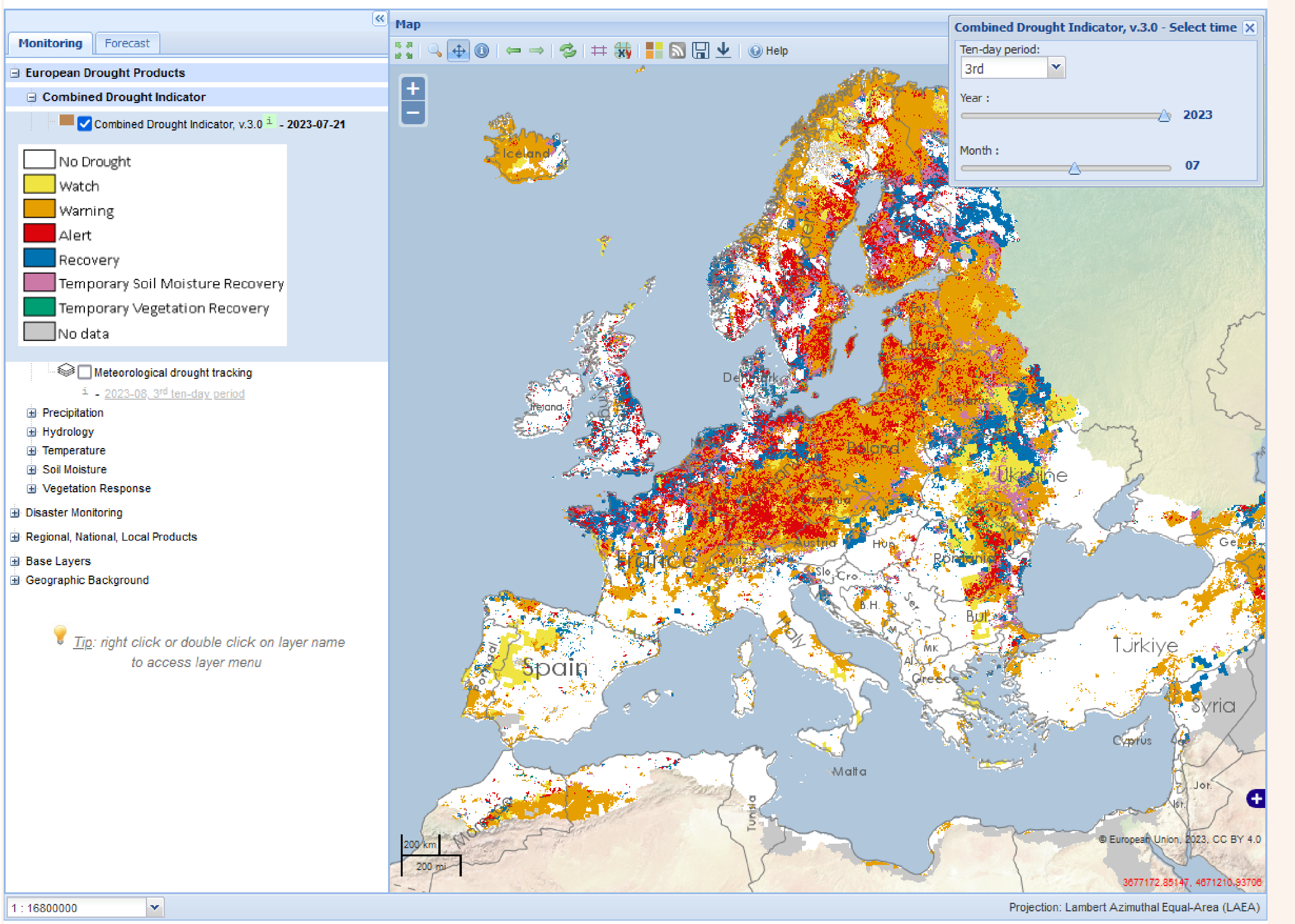
[Cavus and Aksoy, 2020]

European Drought Observatory

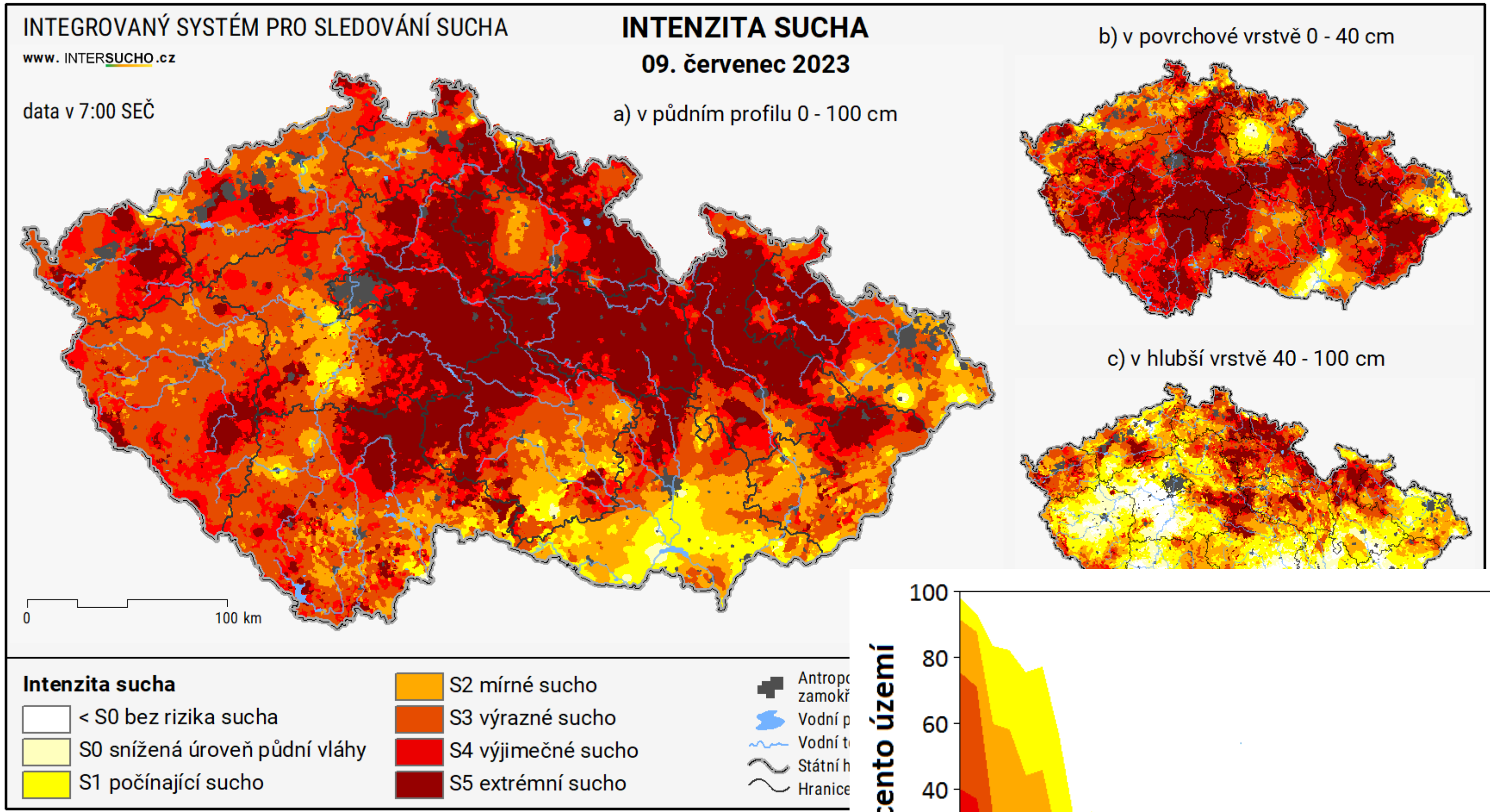
- Drought indicators:
  - **Soil Moisture Anomaly** (SMA)
  - **Standardized Precipitation Index** (SPI)
  - **Anomaly of Vegetation Condition** (FAPAR Anomaly)
  - **Low-Flow Index** (LFI)
  - **Heat and Cold Wave Index** (HCWI)
  - **Combined Drought Indicator** (CDI): Integrates information on anomalies of precipitation, soil moisture and satellite-measured vegetation condition into a single index that is used to monitor both the onset of agricultural drought and its evolution in time and space.

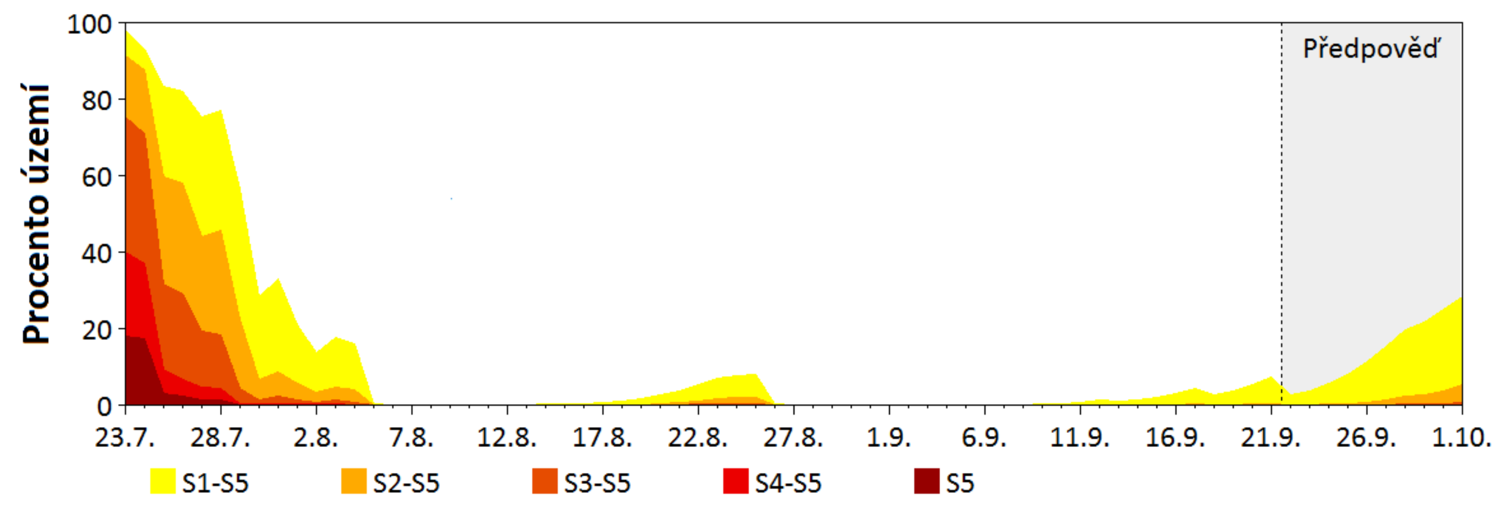


European Drought Observatory

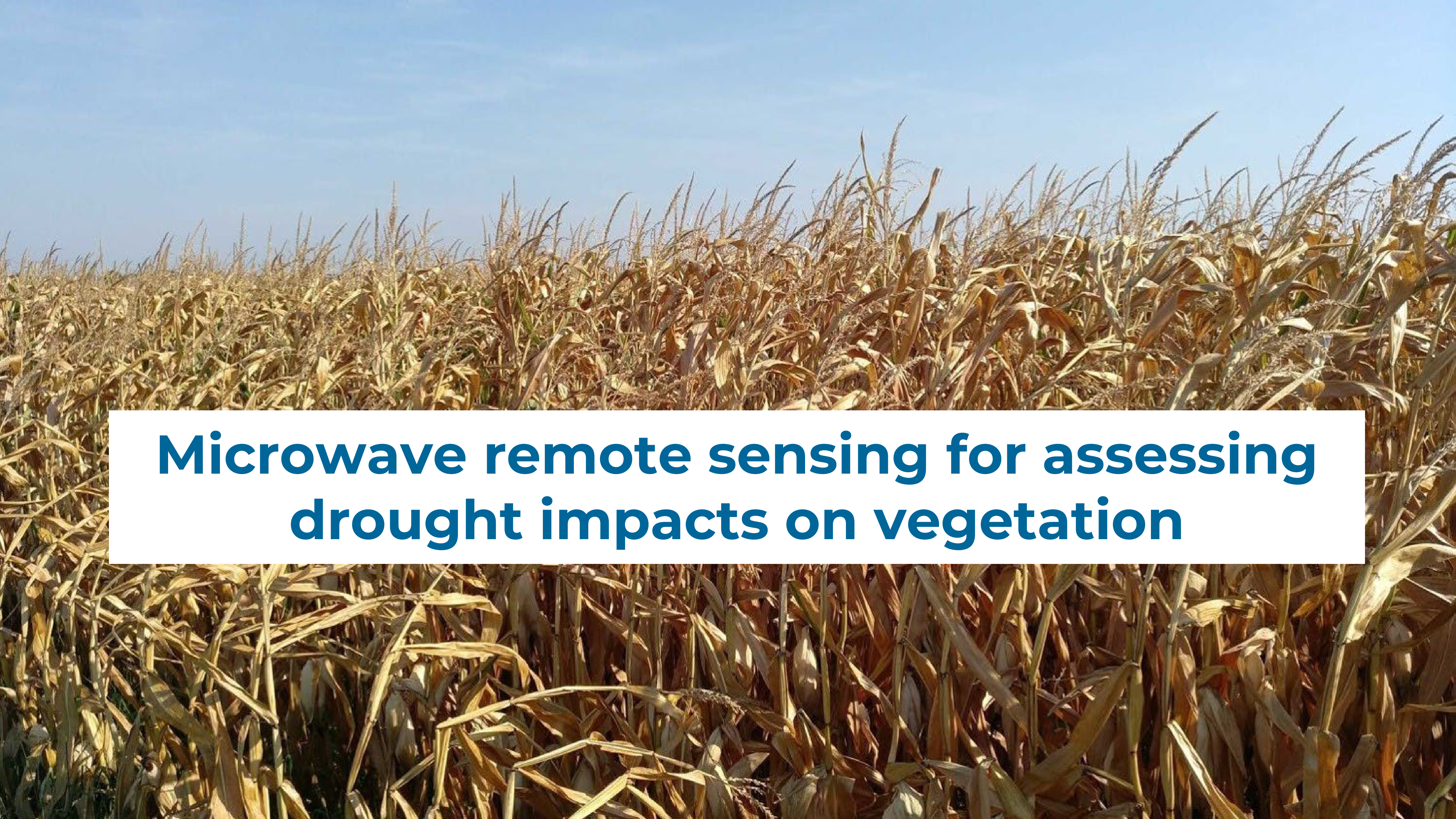


Intersucho.cz

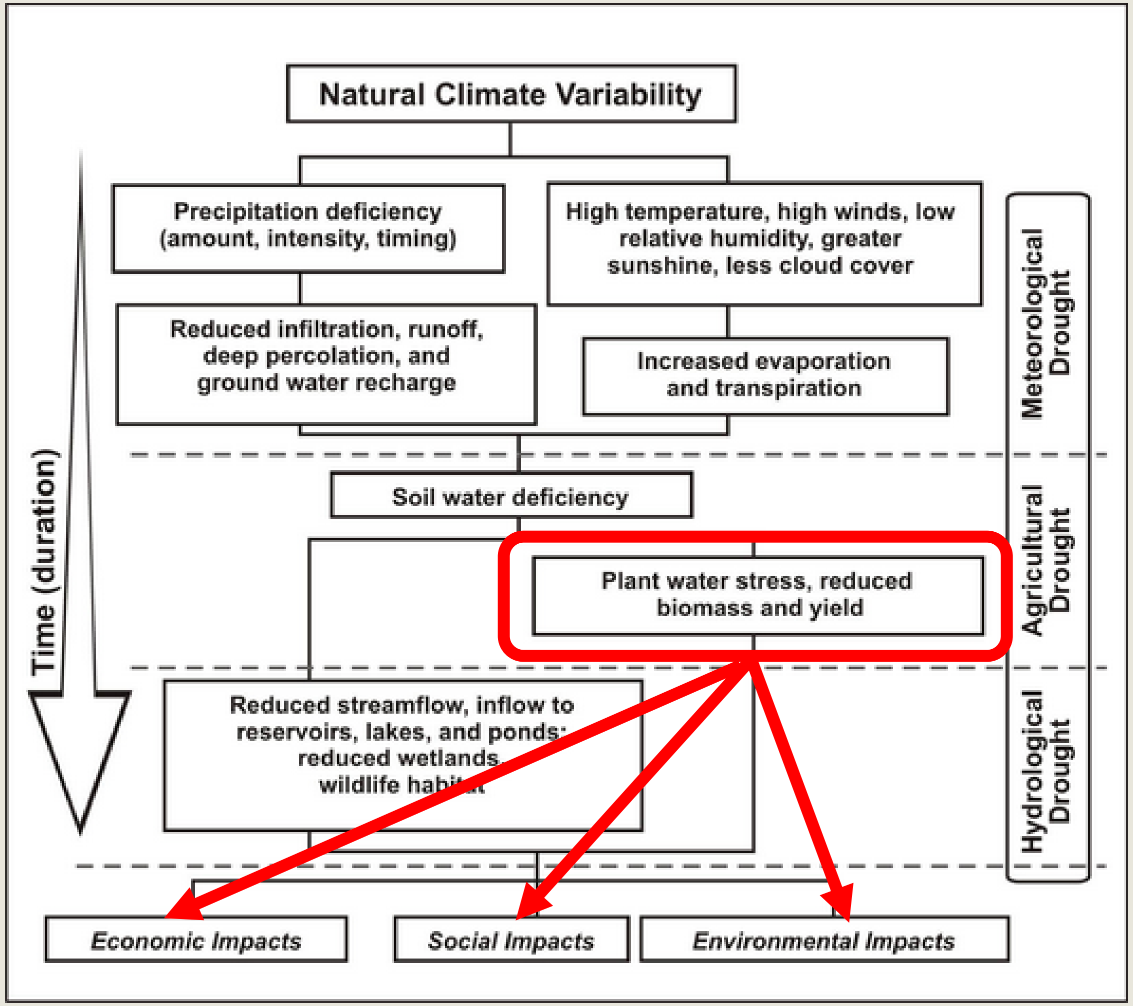




Microwave remote sensing for assessing drought impacts on vegetation

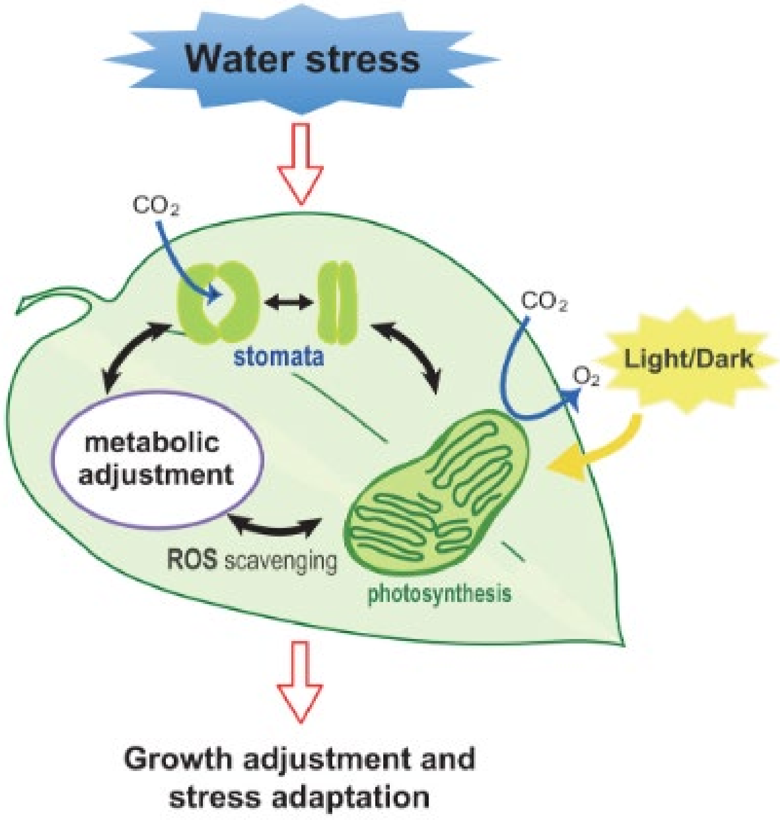


Impacts on vegetation



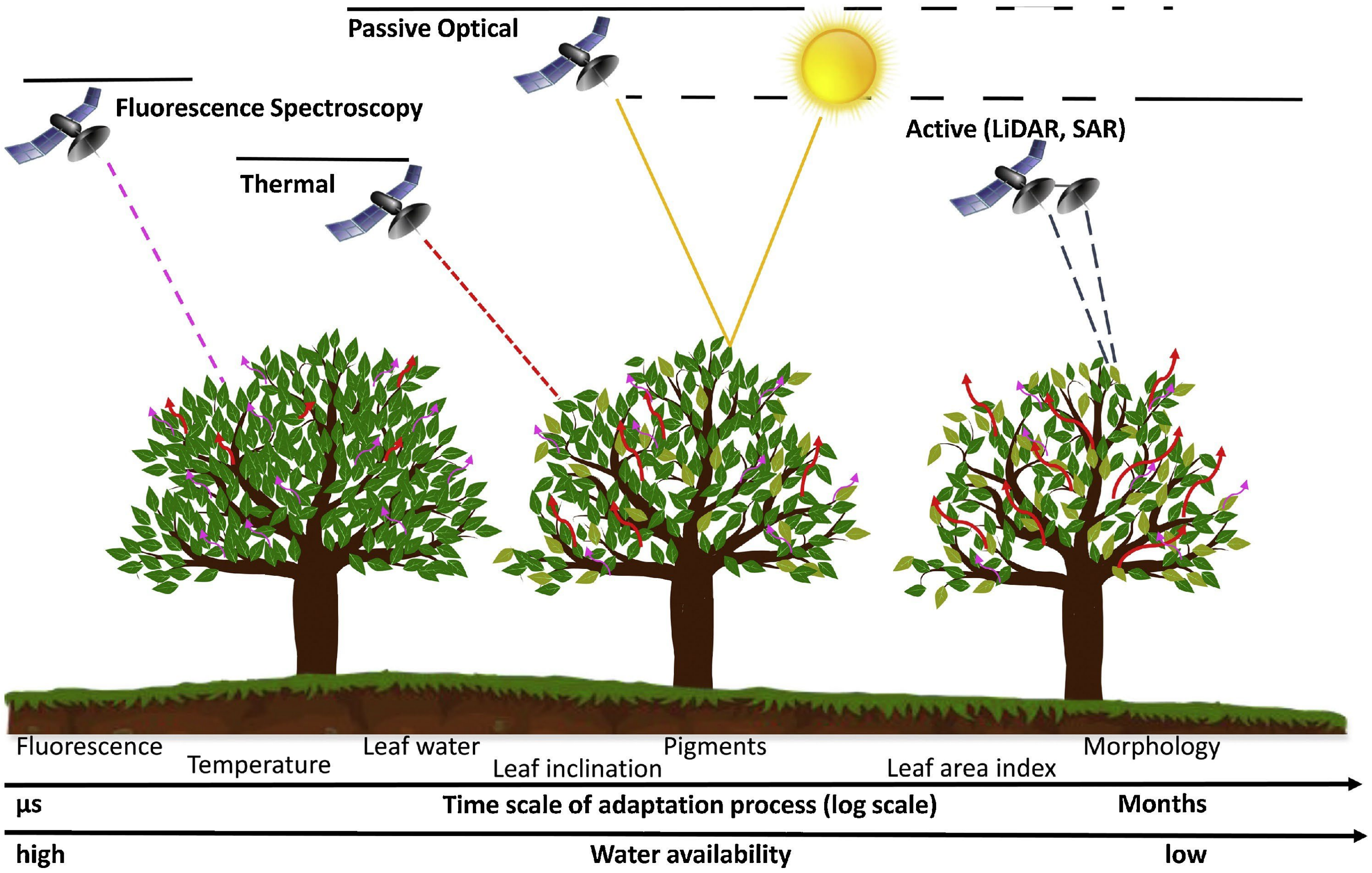
Sequence of drought occurrence and impacts for commonly accepted drought types. All droughts originate from a deficiency of precipitation or meteorological drought but other types of drought and impacts cascade from this deficiency. (Source: National Drought Mitigation Center, University of Nebraska-Lincoln, U.S.A.)

A plant's reaction to water stress



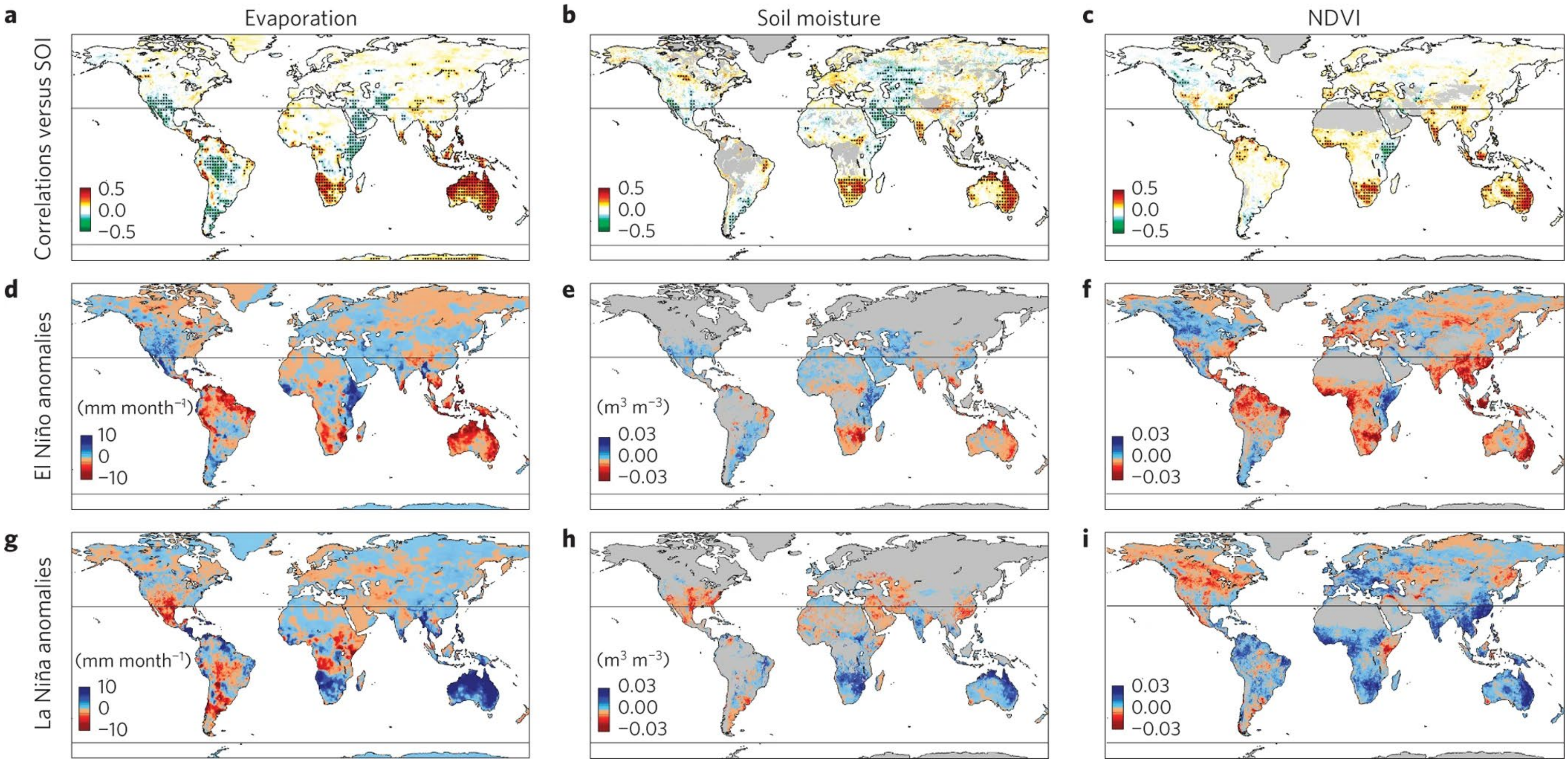
[Osakabe et al. 2014]

* Removal of Reactive Oxygen Species (ROS) released by changed metabolism



[Damn et al. 2018]

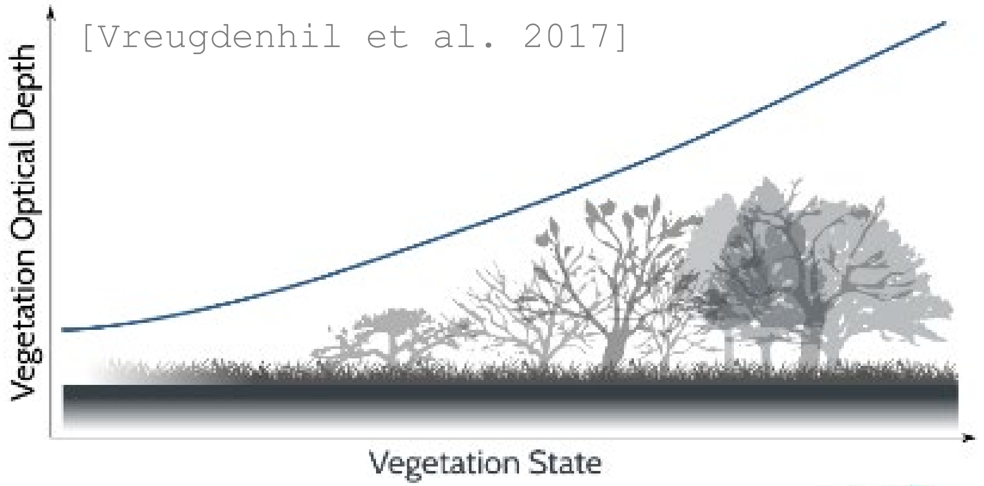
Linking moisture to vegetation activity

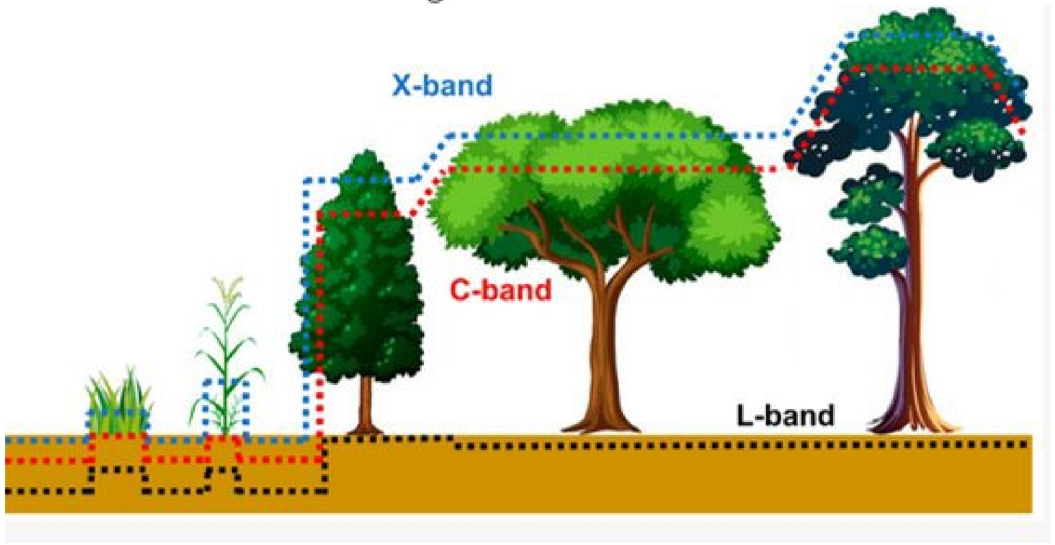


[Miralles et al. 2014]

Microwave remote sensing for vegetation dynamics

- Vegetation Optical Depth (VOD) quantifies the attenuation of (microwave) radiation by vegetation.
  - Related to vegetation water content and biomass
  - Signal depends on wavelength
  - Typically retrieved from L-, C-, X-, and Ku-band
- Retrieval algorithms seek to separate vegetation signal from soil signal, e.g.,
  - TU Wien method for radar observations (See Raml LTC23)
  - Land Parameter Retrieval Model (VU/NASA/VanderSat/Planet) for radiometer data



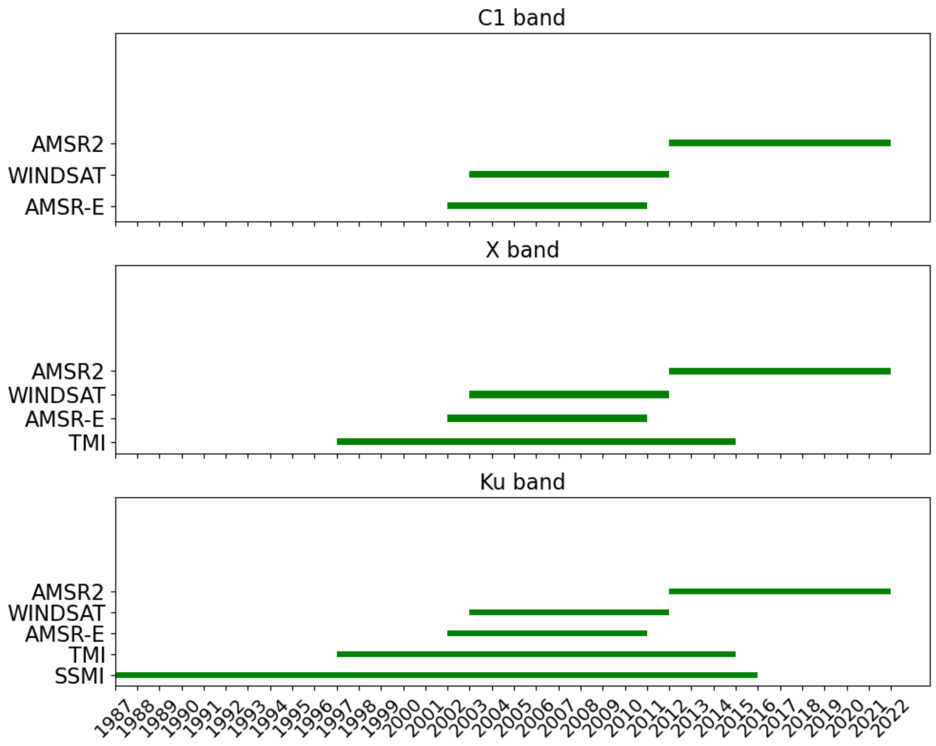


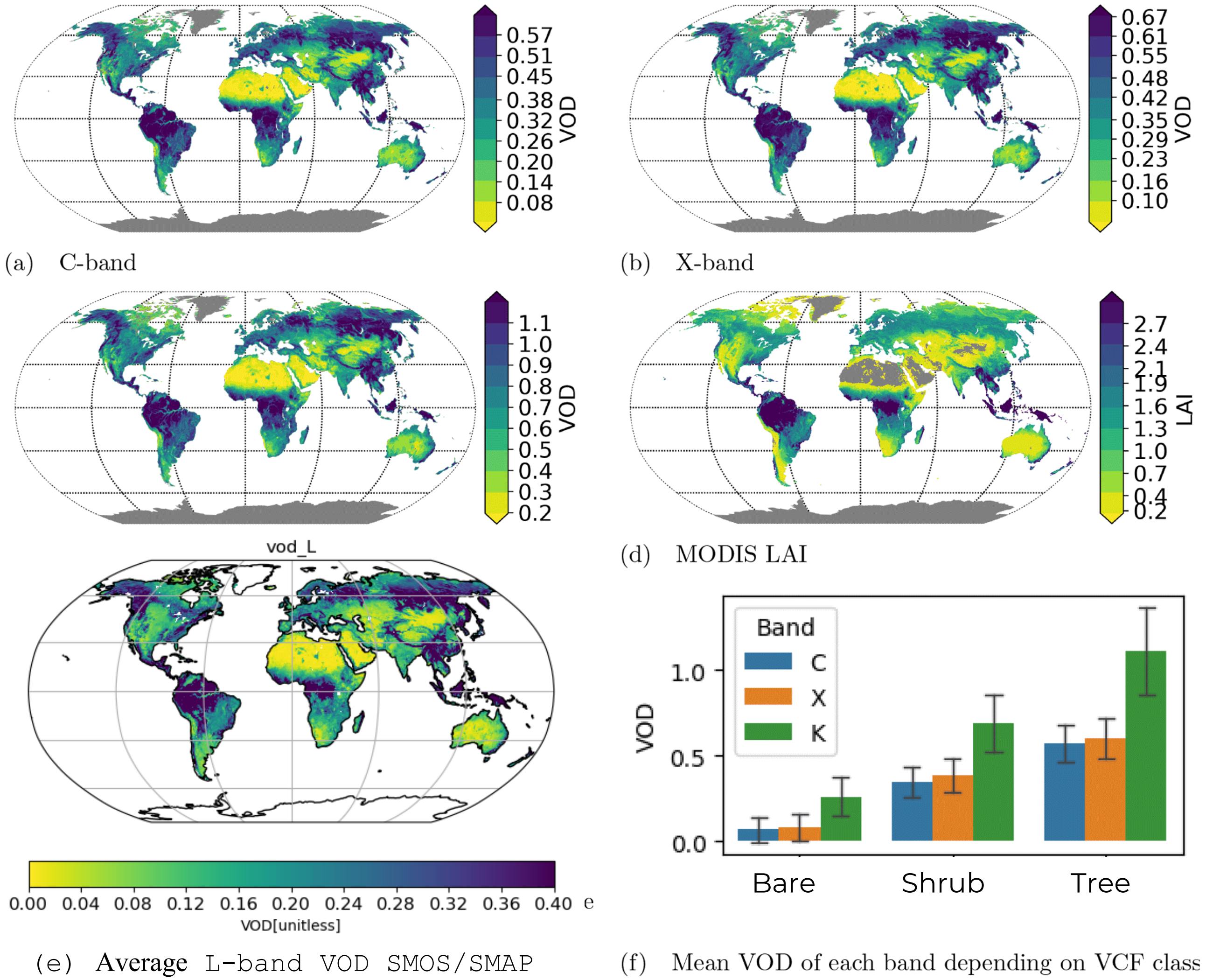
[Frappart et al. 2020]

VODCA - The VOD Climate Archive

Long-term, harmonized VOD, derived from multiple radiometer datasets

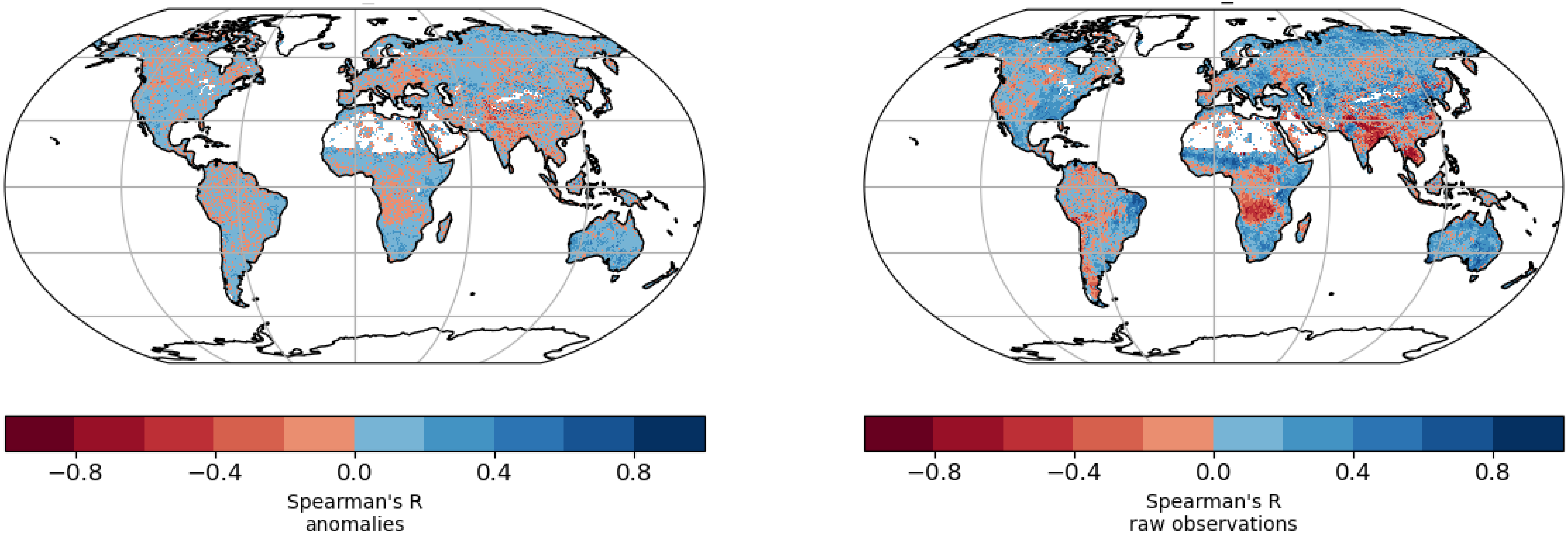
- Separate VODCA products for C-, X-, Ku-band
- 0.25° spatial sampling
- Daily, 1987 - 2021
- https://doi.org/10.5281/zenodo.2575599





[Moesinger et al. 2020; 10.5194/essd-12-177-202]

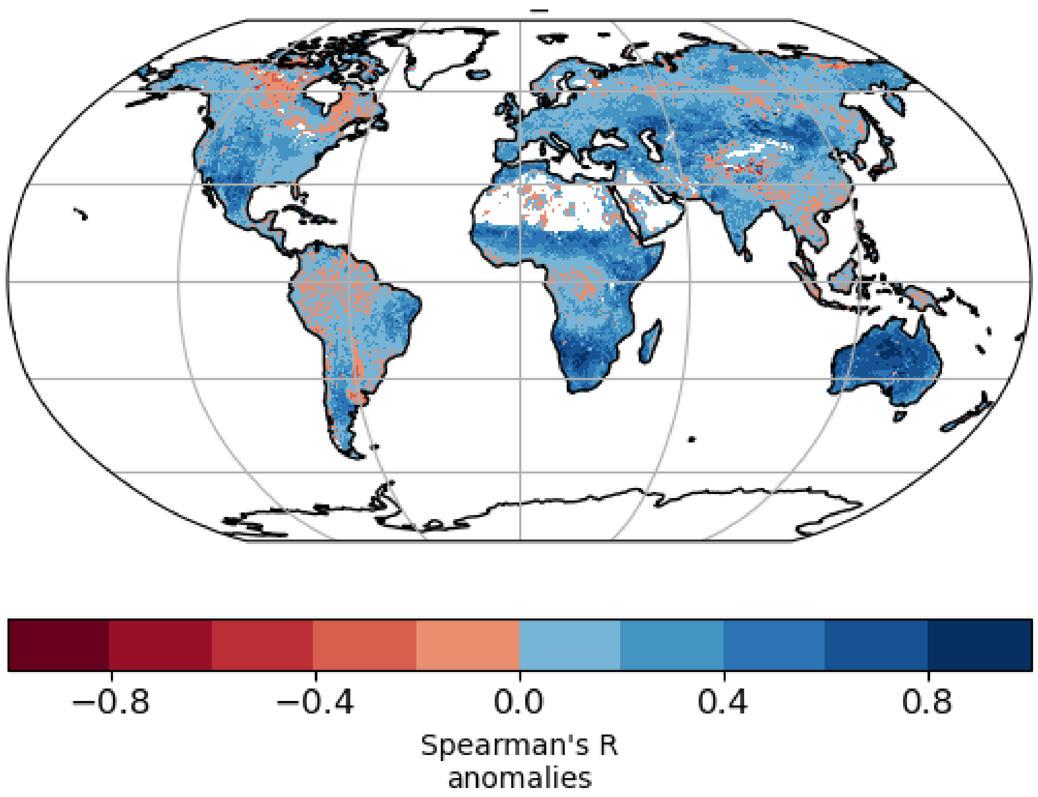
L-VODCA correlation with LAI

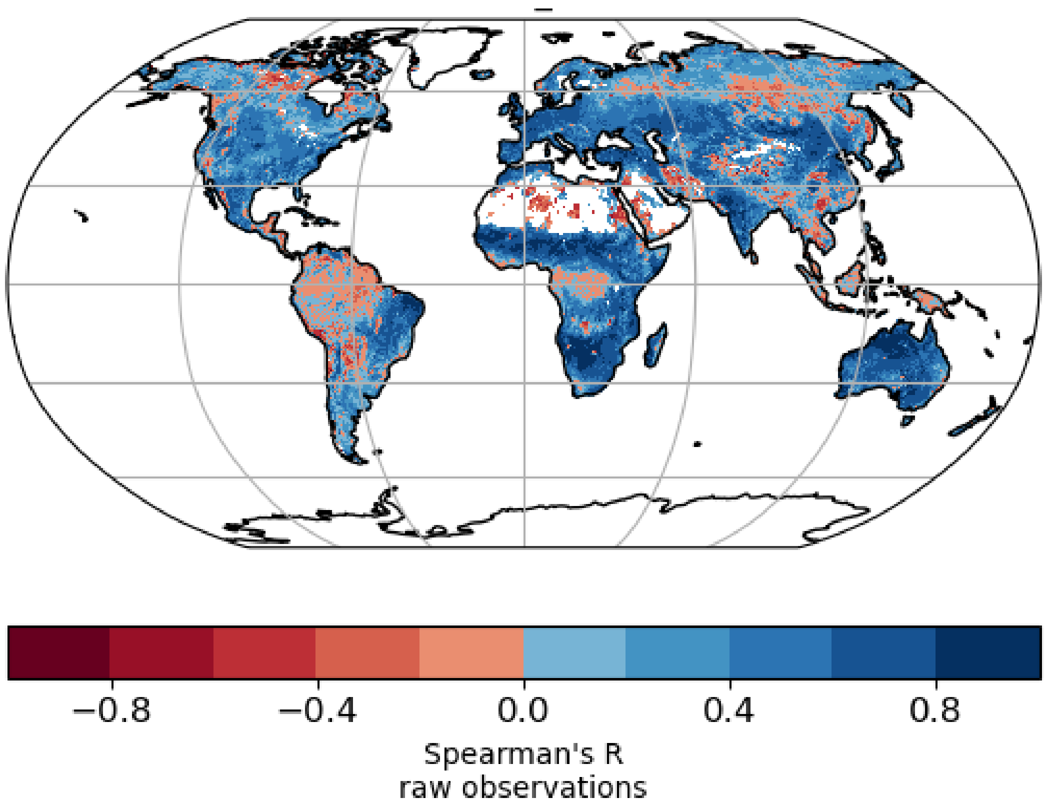


(2010-2019)

[Moesinger et al. 2020; 10.5194/essd-12-177-202]

Ku-VODCA correlation with LAI

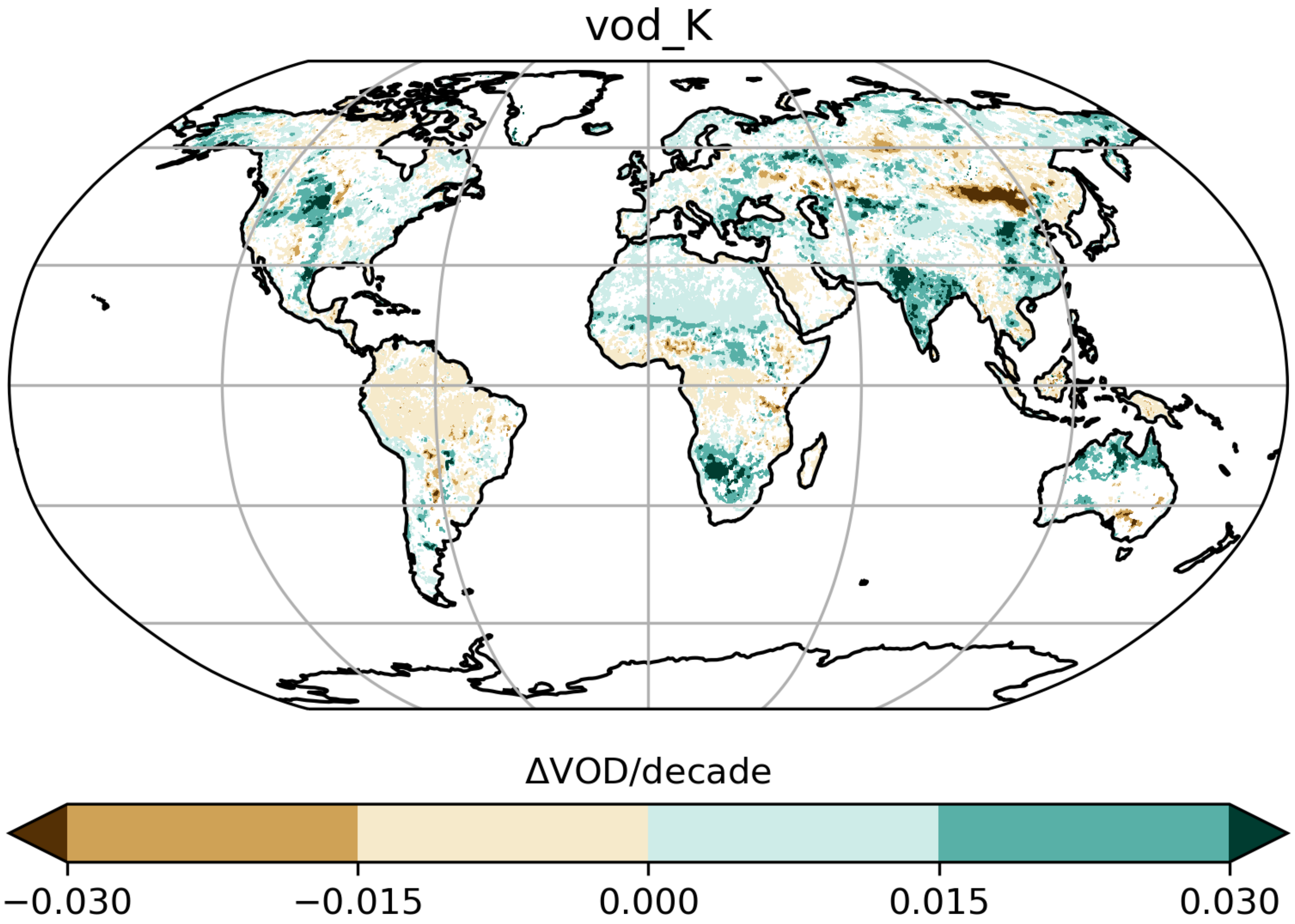




(2002-2017)

[Moesinger et al. 2020; 10.5194/essd-12-177-202]

Ku-VODCA Trends (1987-2021)

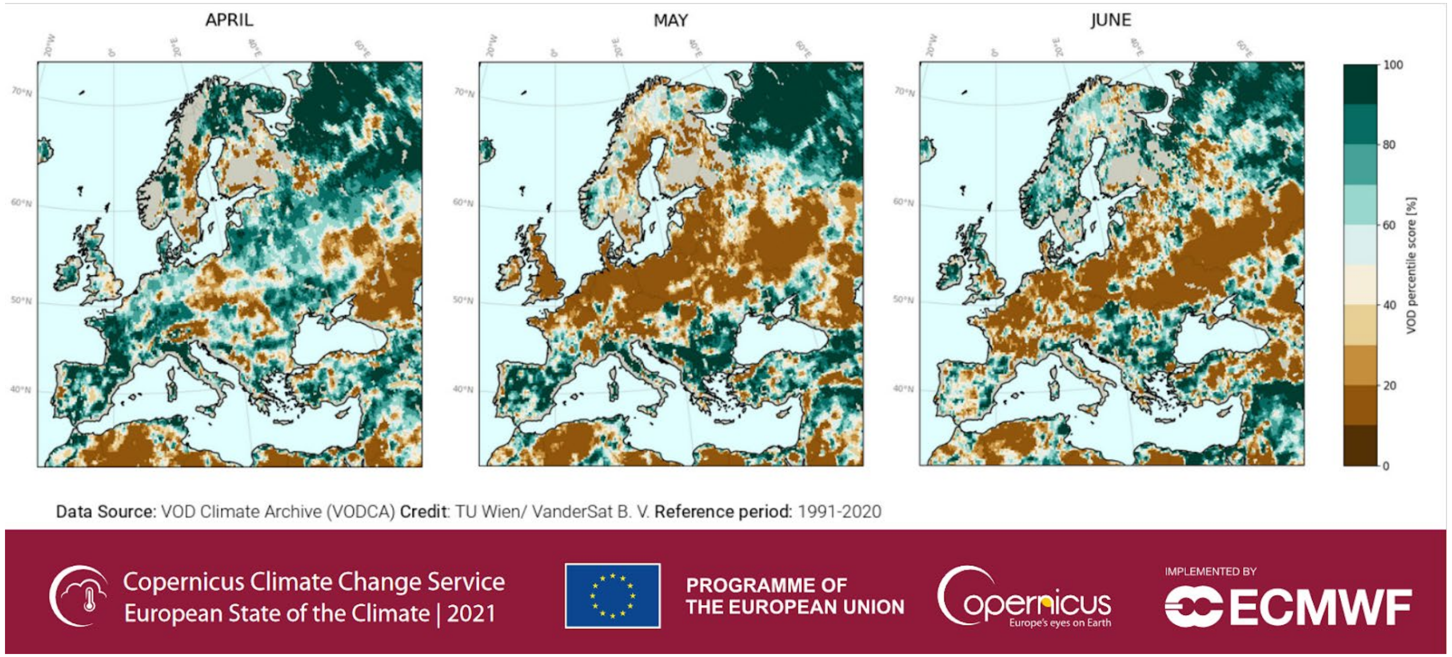


[Moesinger et al., 2020; 10.5194/essd-12-177-202]

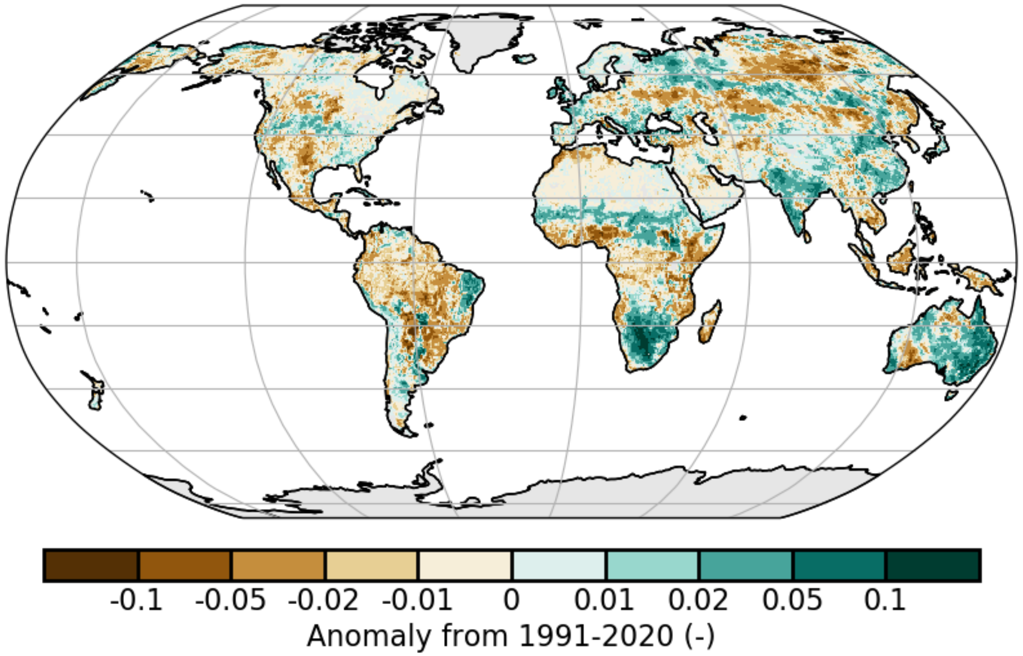
C3S European State of the Climate 2021

NOAA/BAMS State of the Climate 2022

- Impact of late spring frost on vegetation



Monthly ranking of VOD for April, May and June 2021, relative to 1991-2020, expressed in percentiles

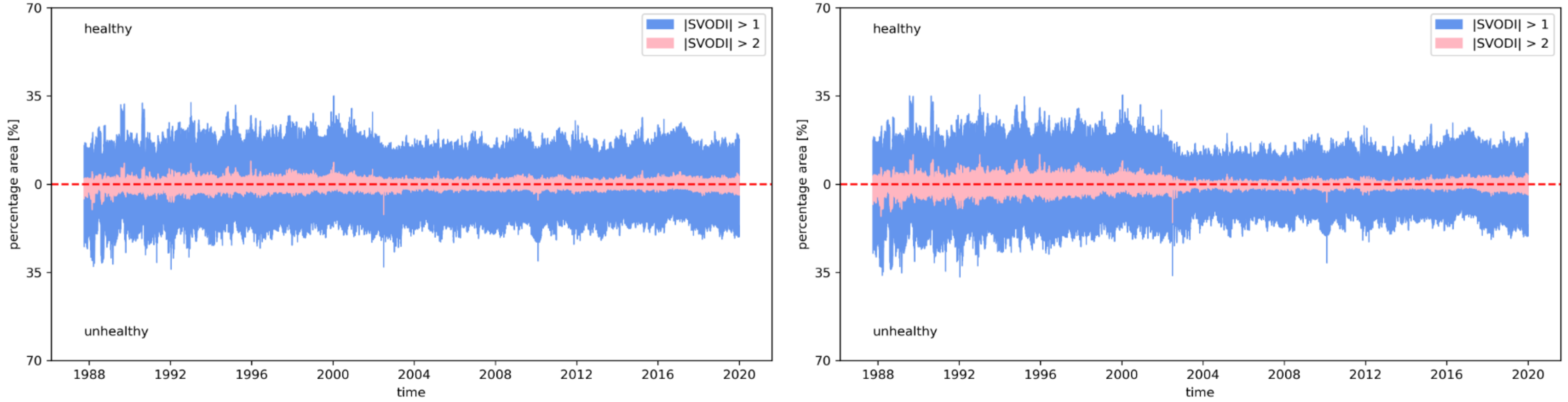


[Zotta et al., 2023]

Standardised VOD Index

SVODI is a long-term (1987 - present), daily, global vegetation condition monitoring dataset combining on C-, X- and Ku-band VOD from multiple sensors

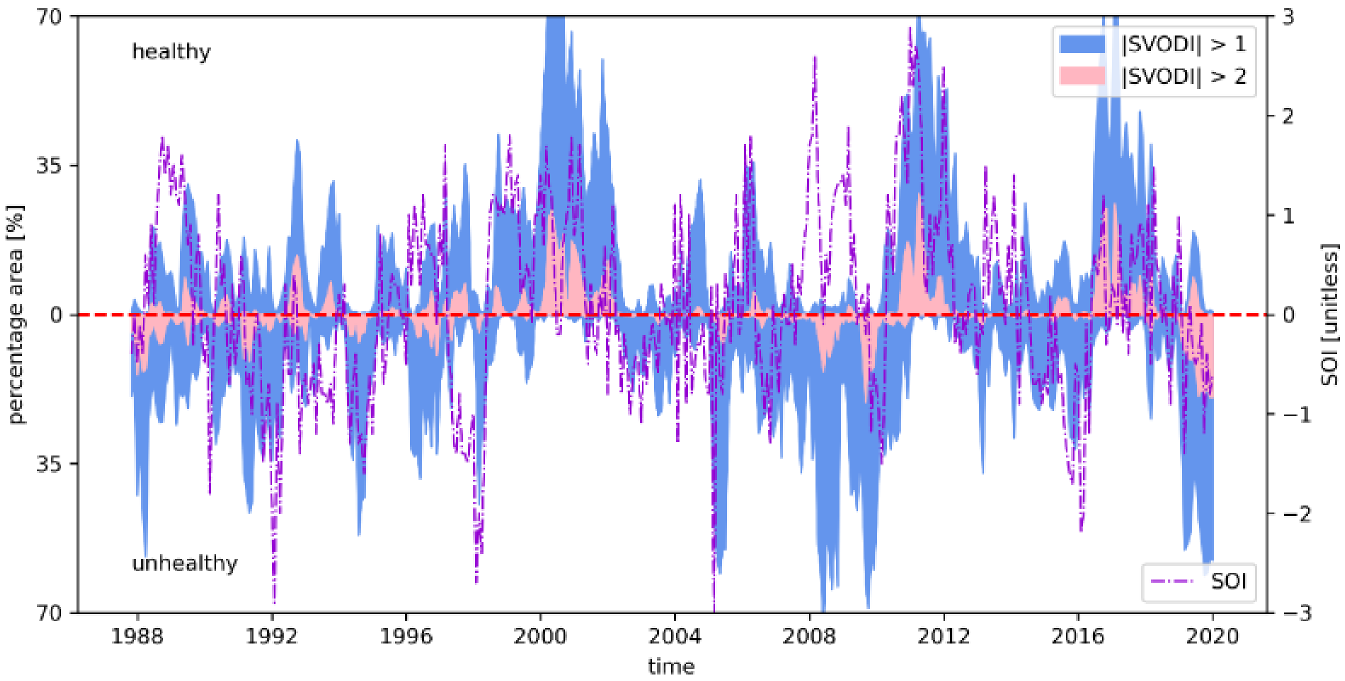
- Improves spatio-temporal sampling
- Uses a probabilistic merging method to deal with the varying instrument noise and sampling density of the data, similar as for SMASI



Example of abnormal and extreme counts for probabilitic (left) and non-probabilistic (right) merging

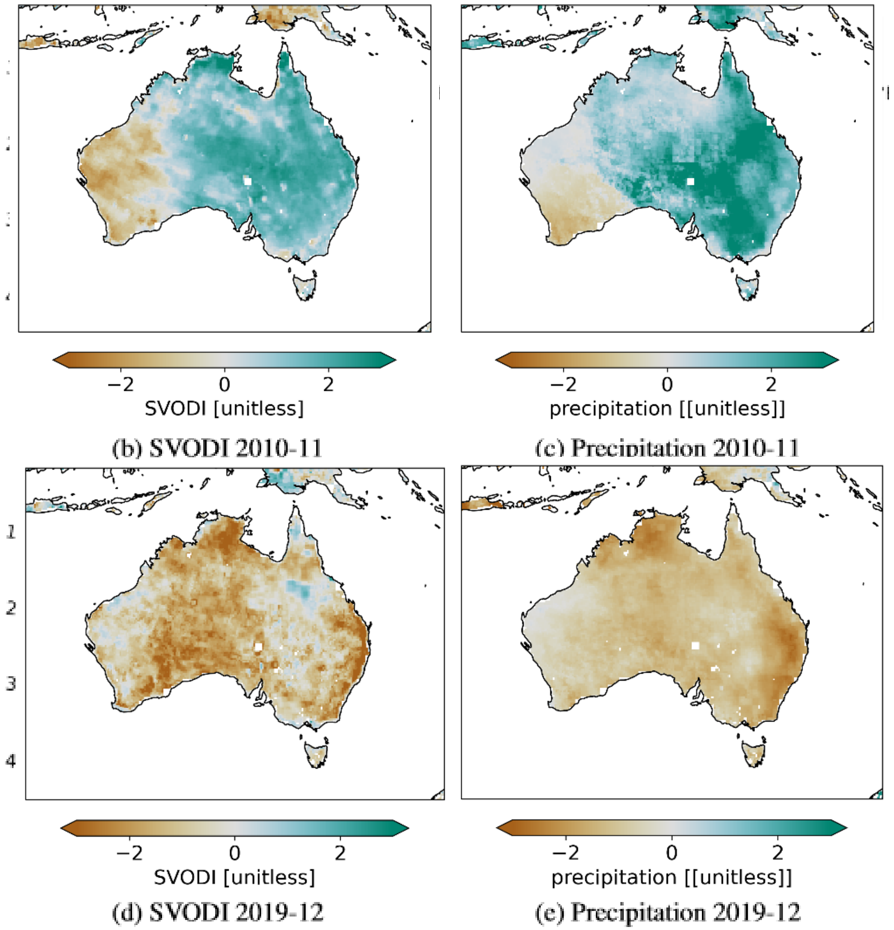
[Moesinger et al., 2022; 10.5194/bg-2021-360]

Standardised VOD Index

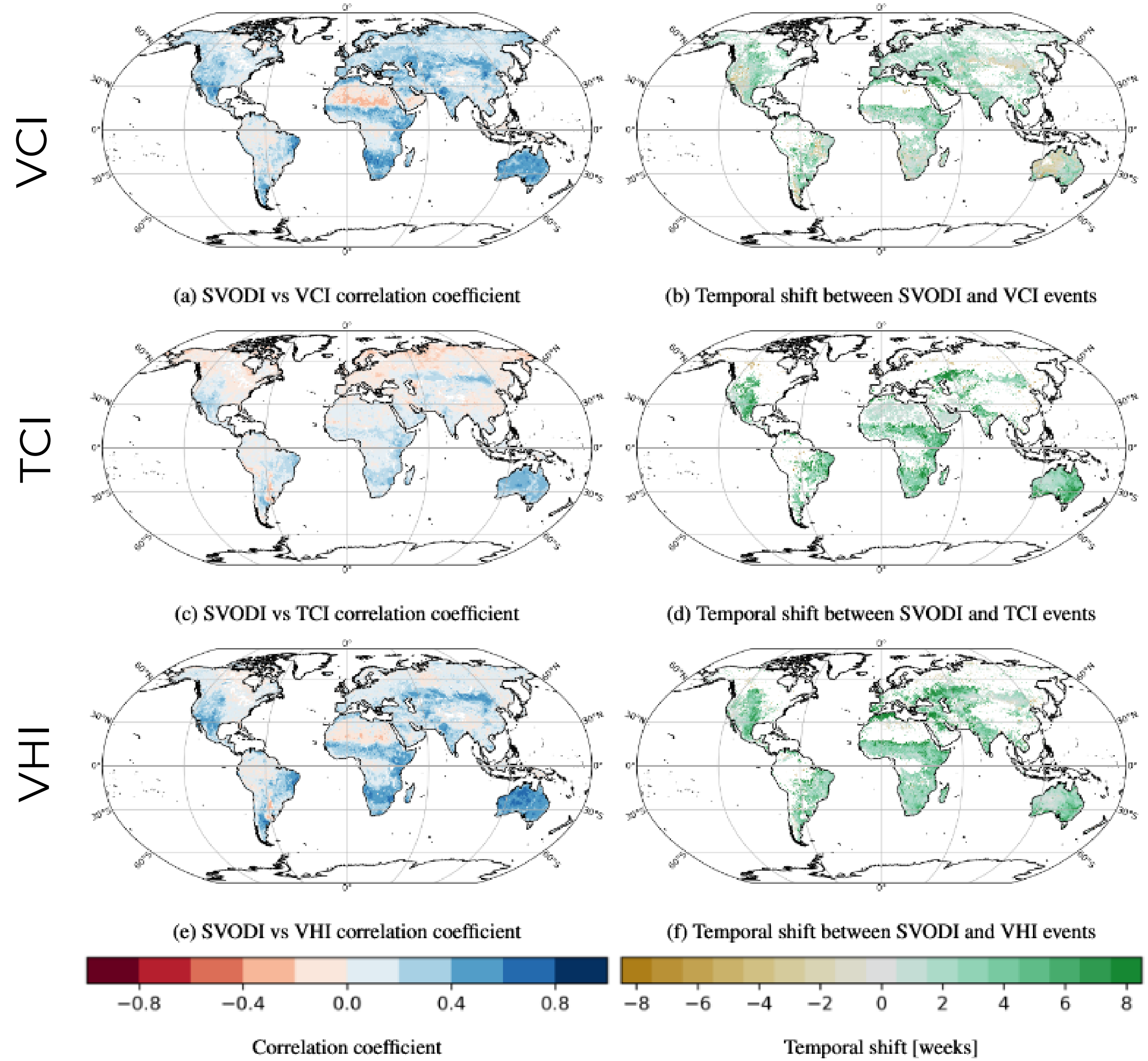


Fraction of percentage area of |SVODI| > 1 > 2 for central Australia along with Southern Oscillation Index

[Moesinger et al., 2022; 10.5194/bg-2021-360]



SVODI and standardized precipitation anomalies for 2010-11 and 2019-12



Correlation and temporal shift (in weeks) between SVODI and optical **vegetation indices**:

- **V**egetation **C**ondition **I**ndex (VNIR)
- **T**emperature **C**ondition **I**ndex (thermal)
- **V**egetation **H**ealth **I**ndex (optical + thermal)

SVODI anomalies usually **follow** those from optical data: Thermal > VNIR > Microwave

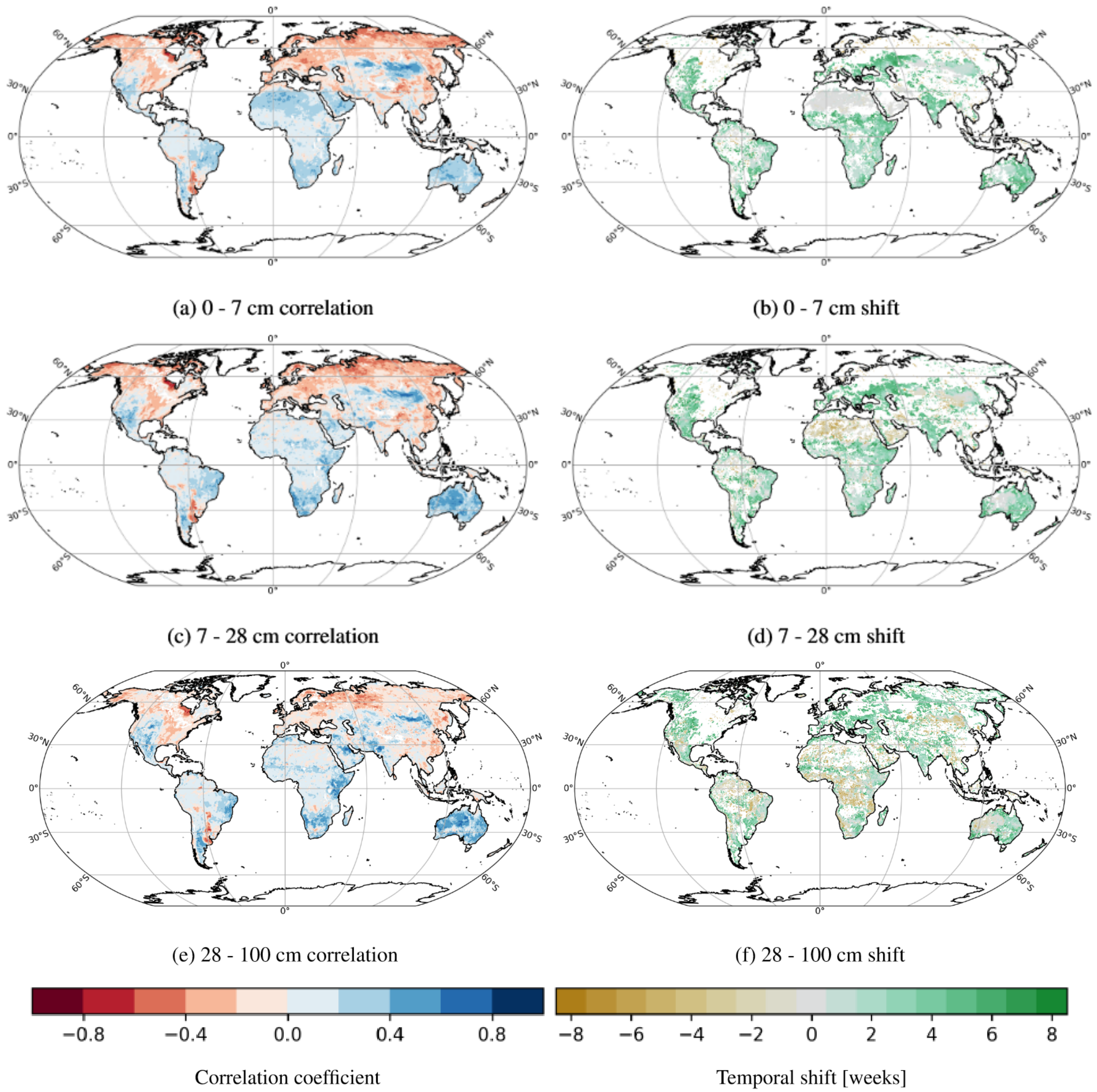
Sign of advanced vegetation stress (loss of vegetation water content, and stress in deeper soil layers)

[Moesinger et al., 2022; 10.5194/bg-2021-360]

Correlation and temporal shift (in weeks) between SVODI and ERA5 Soil Moisture:

- 0-7 cm
- 7-28 cm
- 28-100 cm

Apart from very dry regions, correlations generally increase with deeper layers



[Moesinger et al., 2022; 10.5194/bg-2021-360]

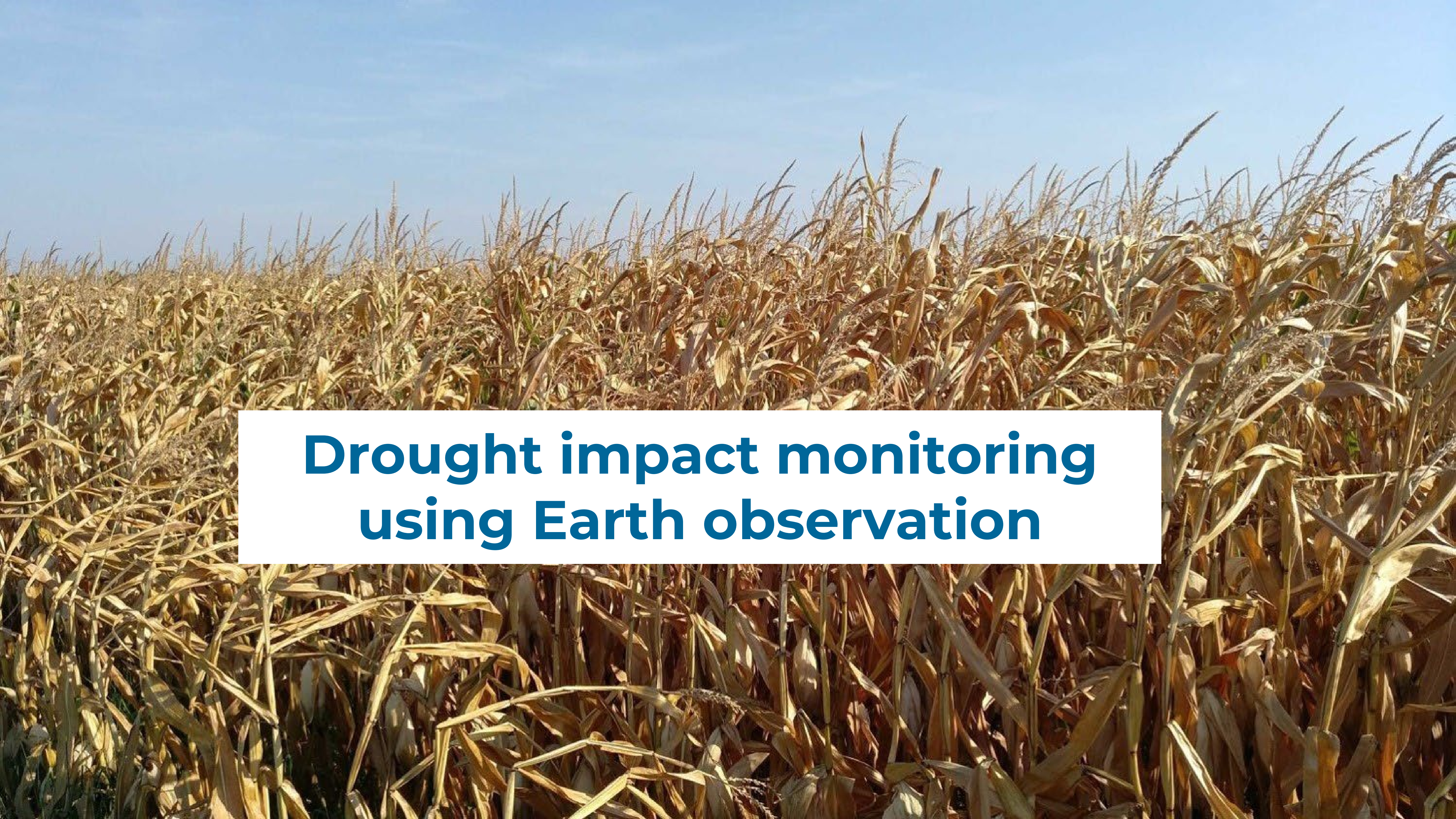
Summary VOD

- **VOD** profits from long heritage of high frequency (C-, X-, Ku) microwave missions, making it a powerful source to study climate (change) impacts on vegetation and plant hydraulics

- **VODCA** allows monitoring temporal and spatial dynamics in above-ground biomass
  - Ku-, X-, and C-band more sensitive to foliage biomass than L- and P-band
  - Particularly useful for drylands, agriculture, pastures

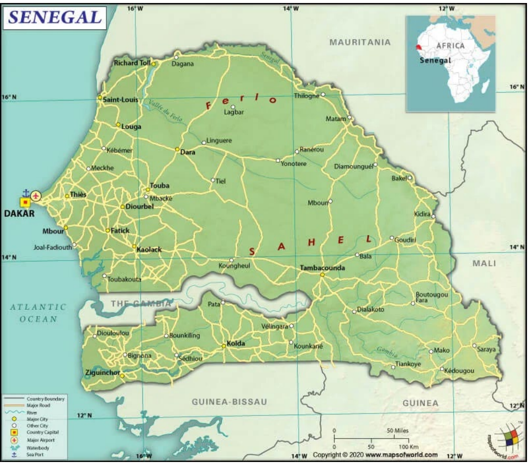
- **SVODI** allows to assess the impact of **droughts** on global vegetation dynamics

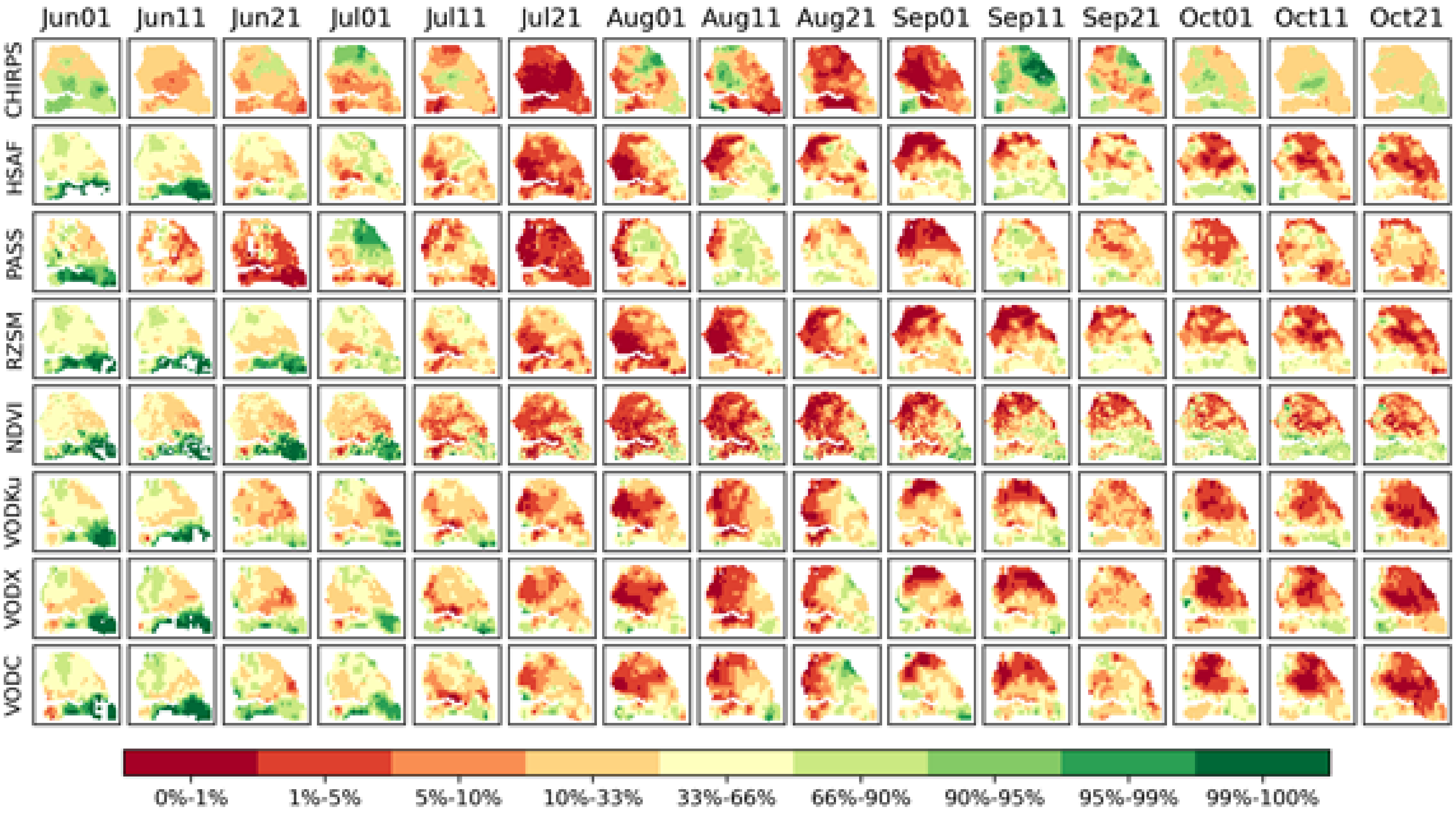
Drought impact monitoring using Earth observation



Senegal 2014 drought

- Impact in multiple indicators
- Strongly water-limited region

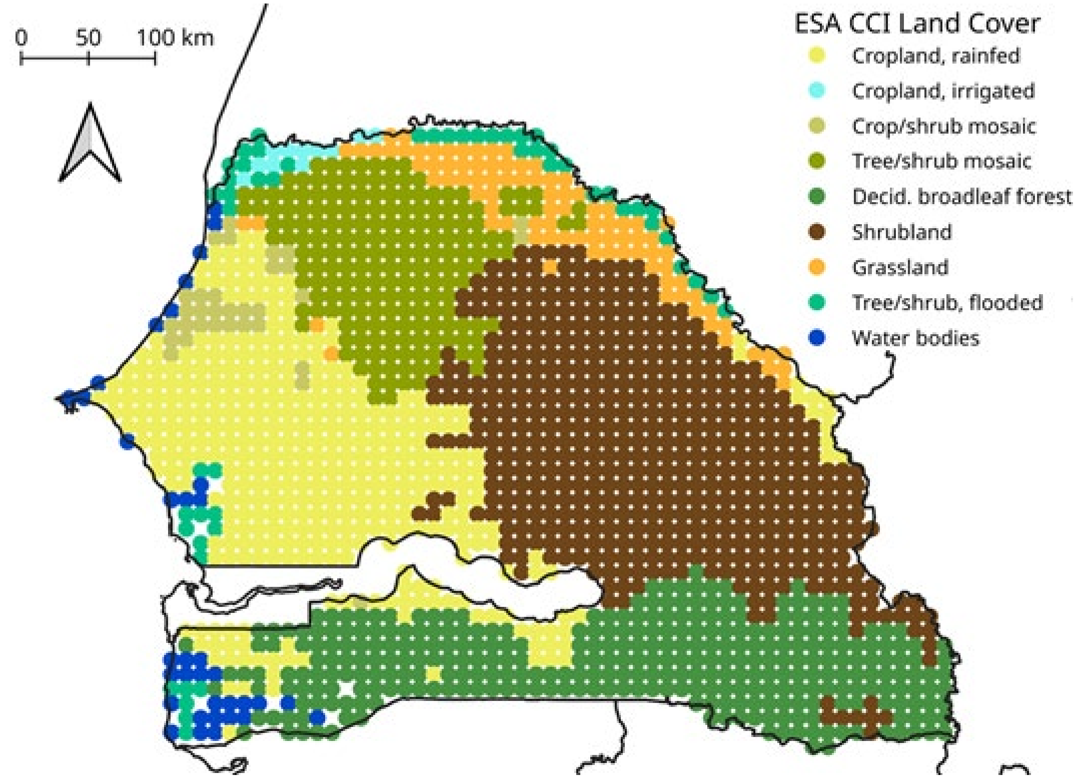


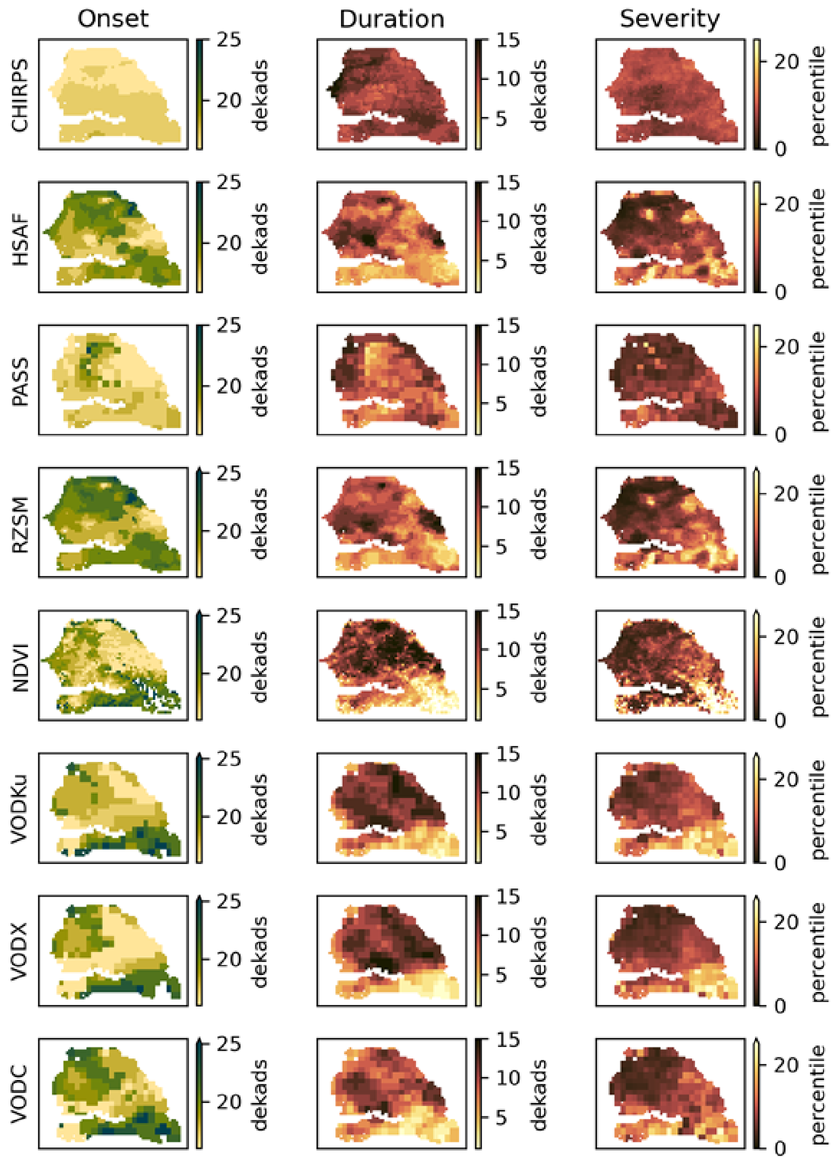


[Vreugdenhil, Pfeil et al., 2022]

Senegal 2014 drought

- Drought impact carries the signature of land cover





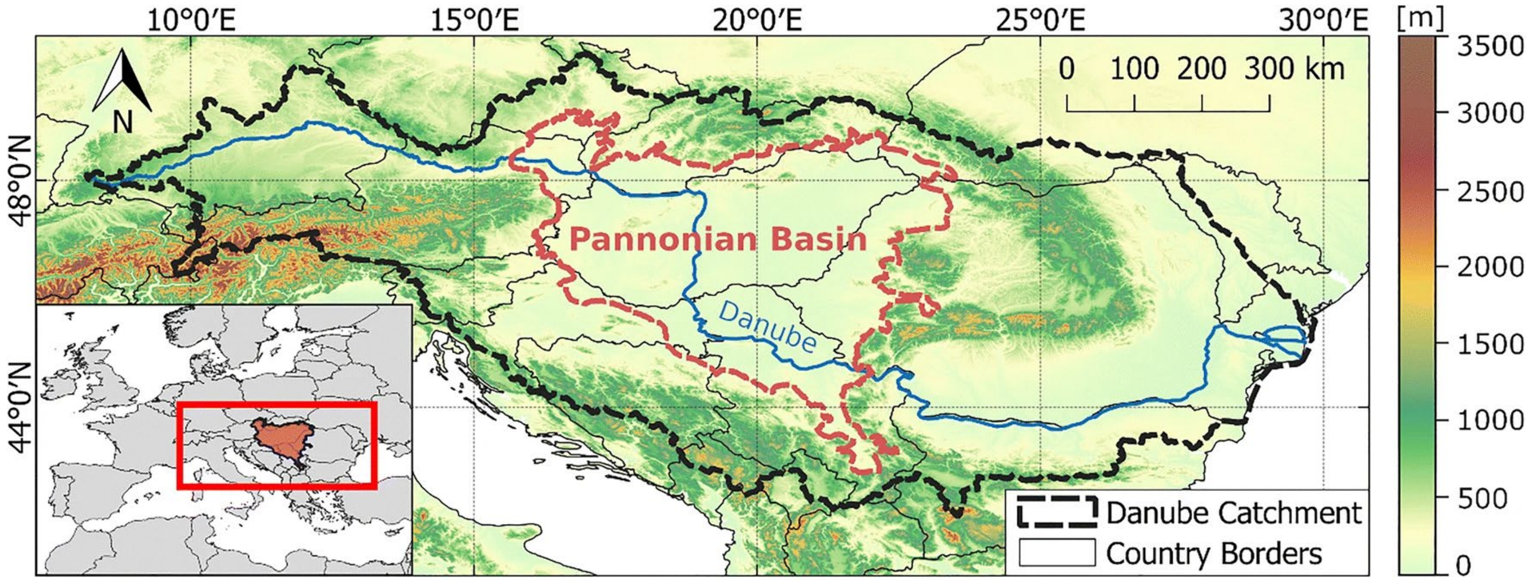
[Vreugdenhil, Pfeil et al., 2022]

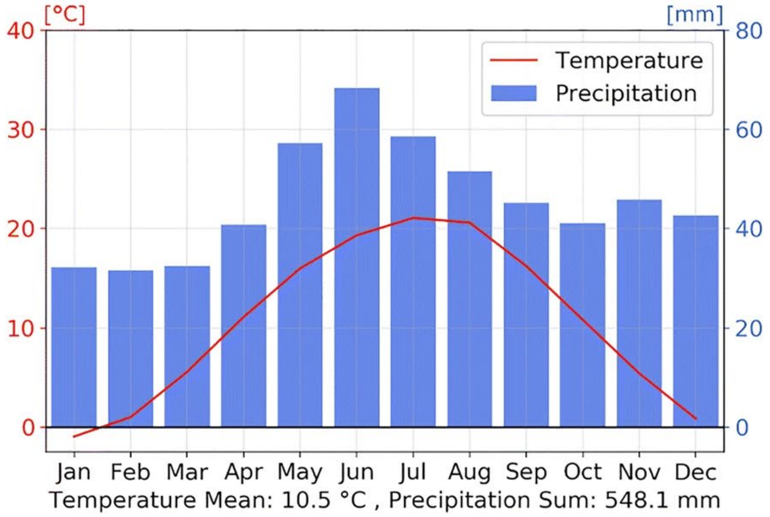
Drought in the Pannonian Basin

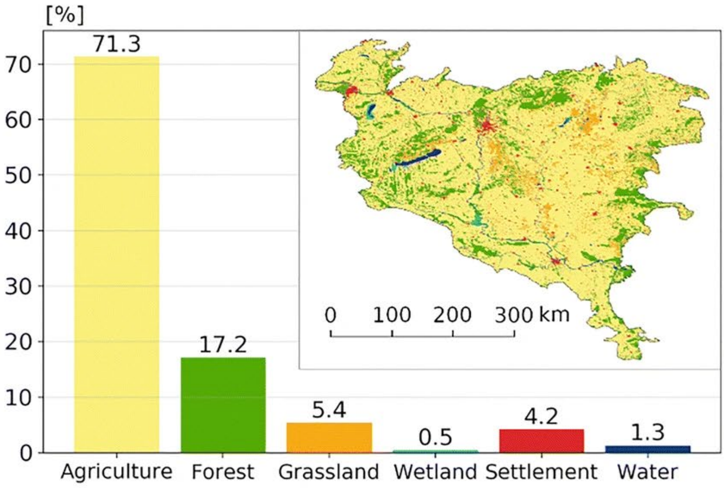
Sheltered, with relatively low levels of precipitation (< 600 mm/year)

High dependency of population on agriculture: 10-20% of population; >70% of area

Mainly rain-fed



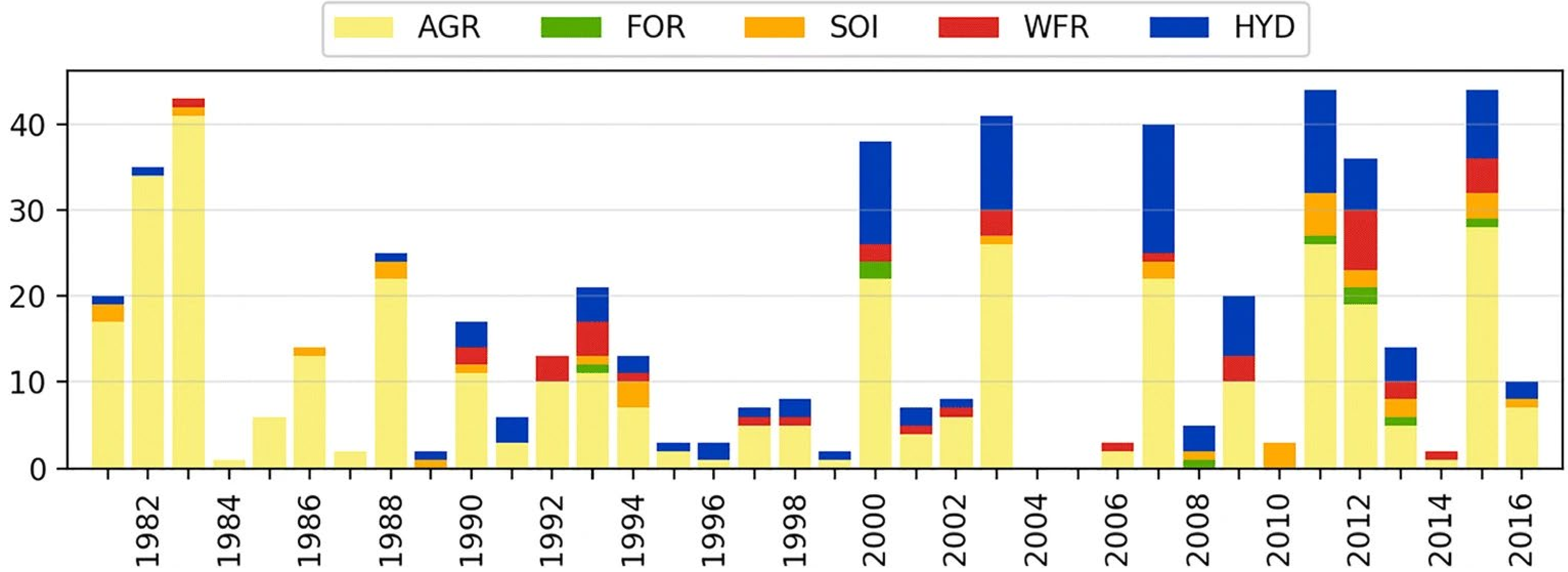




[Crocetti et al., 2020]

Drought impacts in the Pannonian Basin

Reported by various media

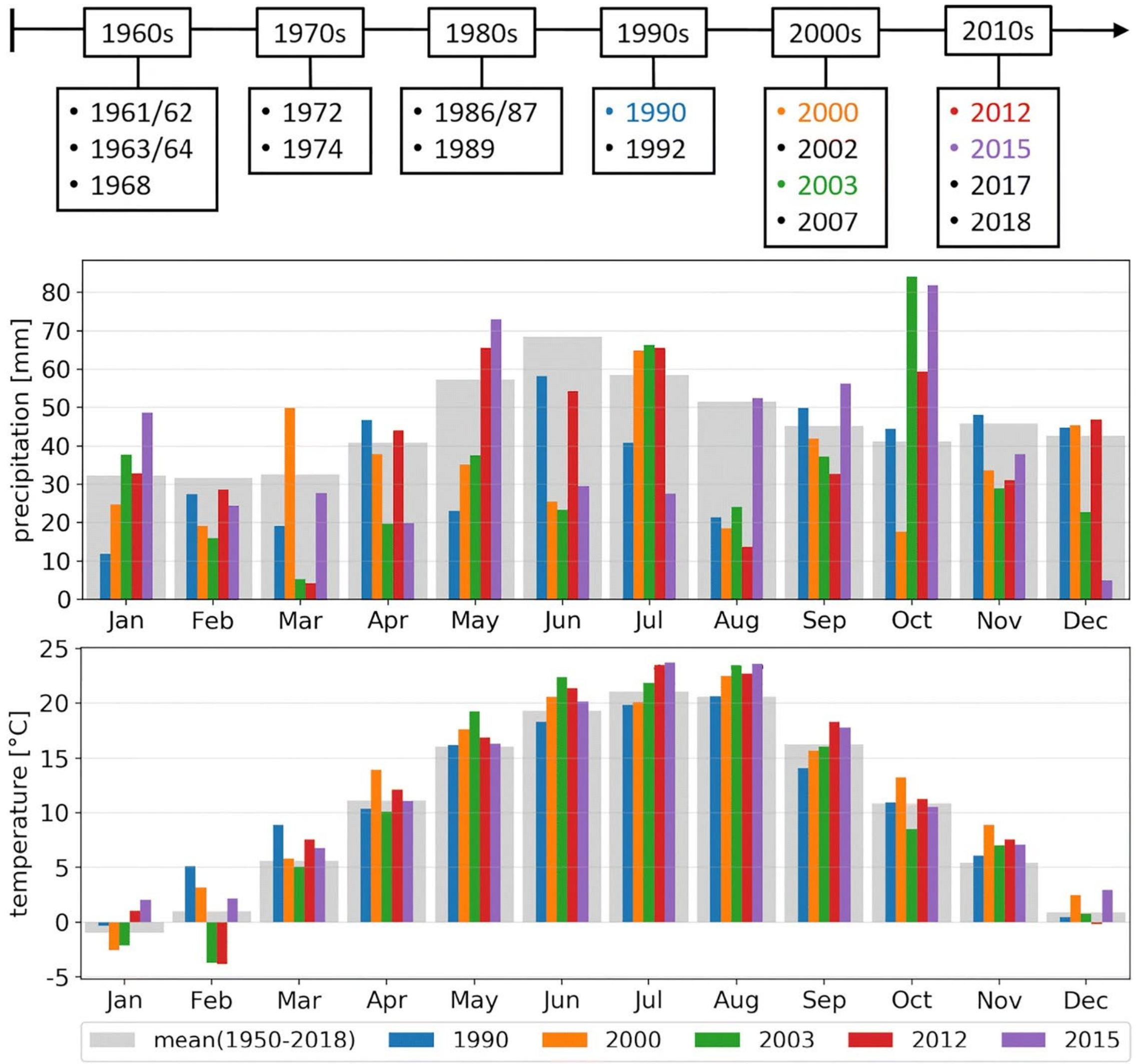


AGR|Agriculture - FOR|Forests - SOI||Soils – WFR|Wildfires – HYD|Hydrology

[Crocetti et al., 2020]

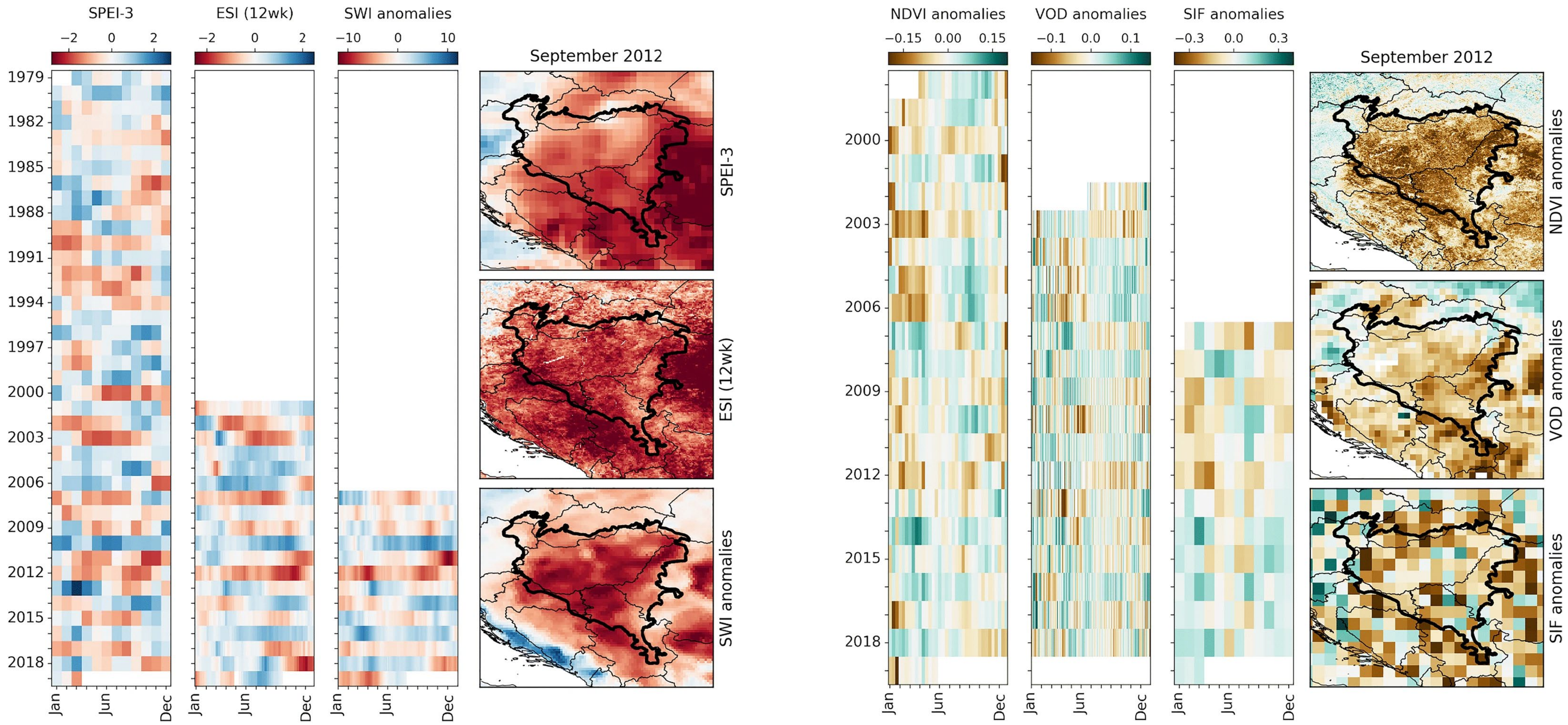
Climatological conditions and yield loss

- Several drought episodes in the last decades caused significant crop yield losses
  - 2003, 2007, 2012, 2015, 2017, 2018
- Mean yield loss of 20-30% for all regions
- Further exacerbated by climate change



[Bueechi et al., 2023]

Earth observation for yield forecasting



[Crocetti et al., 2020]

Predicting yield losses

- Develop a forecasting system based on random forests:
  - Wheat, harvested in July
  - Maize, harvested in September
- 41 NUTS3 regions
  - 2002-2016
- Assess its skill:
  - in normal years and
  - years of severe drought
- Assess the contribution of various drivers:
  - Per crop type
  - At different times during the growing season

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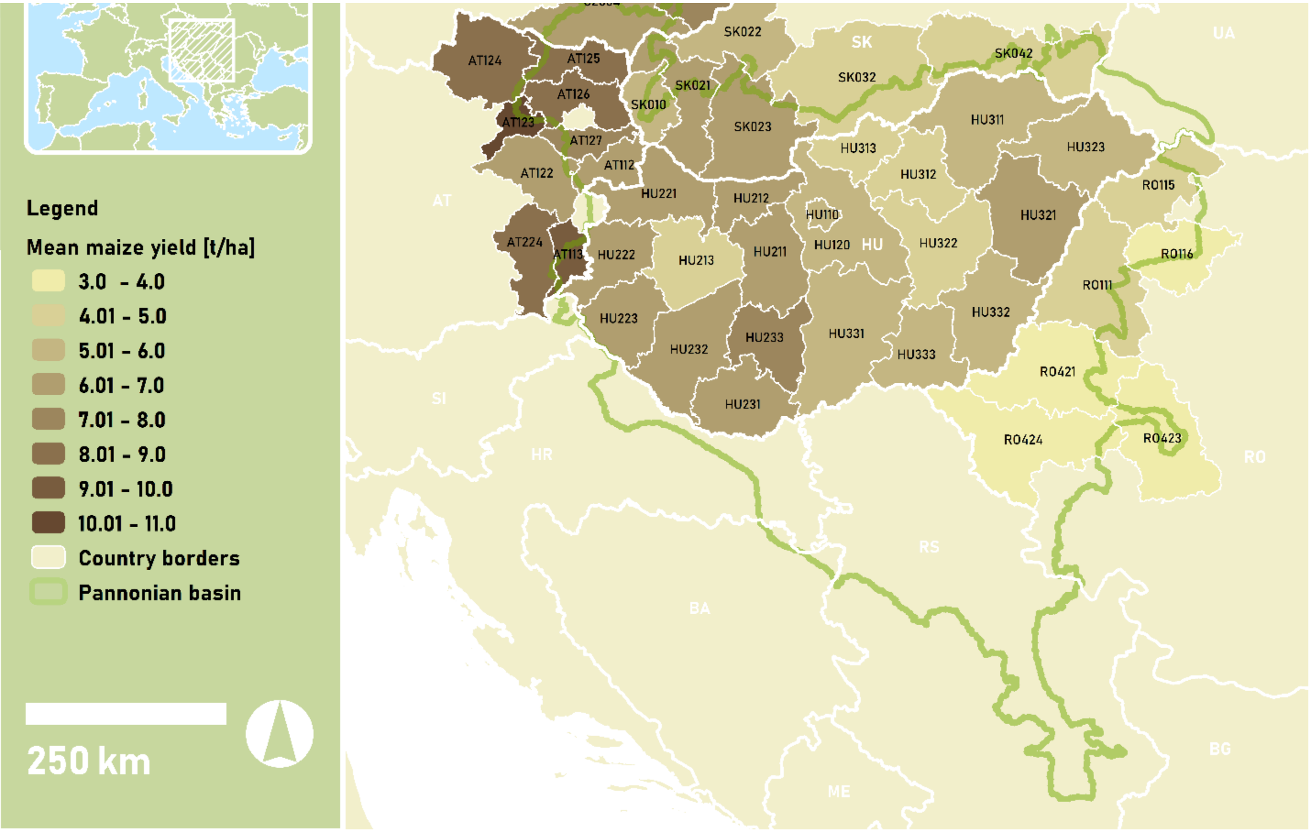
Crop yield anomaly forecasting in the Pannonian basin using gradient boosting and its performance in years of severe drought

E. Bueechi [a,*], M. Fischer [b], L. Crocetti [c], M. Trnka [b], A. Grlj [d], L. Zappa [a], W. Dorigo [a]

[a] Department of Geodesy and Geoinformation, TU Wien, Wiedner Hauptstraße 8-10, 1040 Vienna, Austria
[b] Global Change Research Institute CAS, CzechGlobe, Bělidla 986/4a, 603 00 Brno, Czechia
[c] Institute of Geodesy and Photogrammetry, ETH Zurich, Robert-Gnehm-Weg 15, 8093 Zurich, Switzerland
[d] SPACE-SI, Slovenian Centre of Excellence for Space Sciences and Technologies, Aškerčeva 12, 1000 Ljubljana, Slovenia



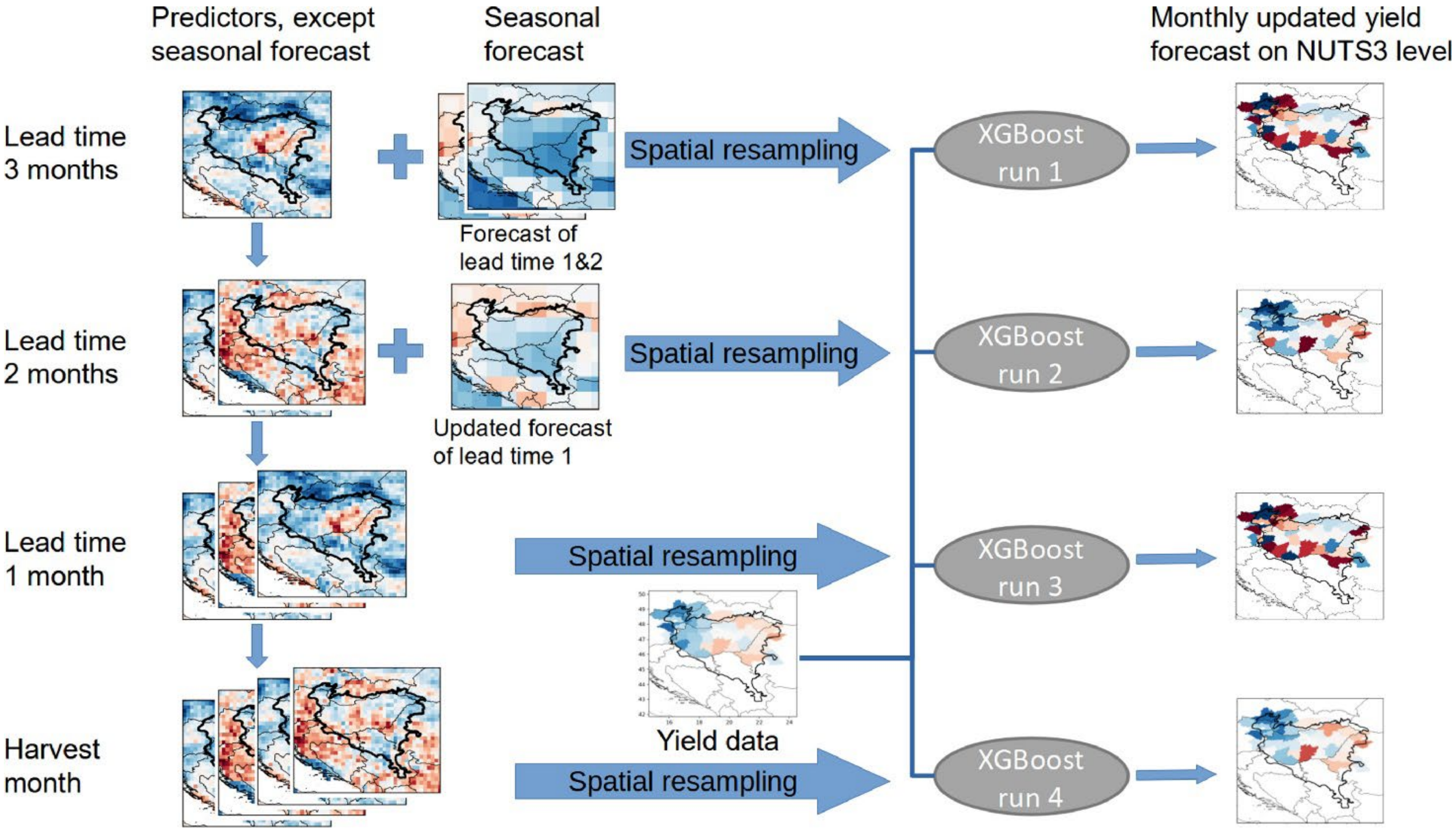
Predictor data

- Temperature
- Water availability
  - Precipitation
  - Soil moisture
  - Drought indices
- Crop status: VOD, NDVI, LAI
- Drought indices SPEI and ESI for specific drought information
- Seasonal forecasts of precipitation and temperature
- Detrended anomalies

Dataset	Source	Spatial Resolution	Temporal Resolution
Canopy status			
VOD Ku-Band	VODCA	0.25°	daily
NDVI	CGLS	0.01°	10-daily
LAI	CGLS	0.01°	10-daily
Meteorology			
Precipitation	E-Obs	0.25°	daily
Fraction of wet days	E-Obs	0.25°	daily
Seasonal P forecast	ECMWF	1°	monthly
Air Temperature	E-OBS	0.25°	daily
Diurnal temperature range	ERA5-Land	0.1°	monthly
Seasonal T forecast	ECMWF	1°	monthly
Surface radiation	ERA5	0.25°	daily
Soil water availability			
Surface soil moisture	ESA CCI	0.25°	Daily
Root-zone SM	ESA CCI	0.25°	Daily
In situ data			
SPEI (1 and 3 months)	ERA5	0.25°	monthly
ESI (1 and 3 months)	MODIS	0.05°	weekly

XGBoost

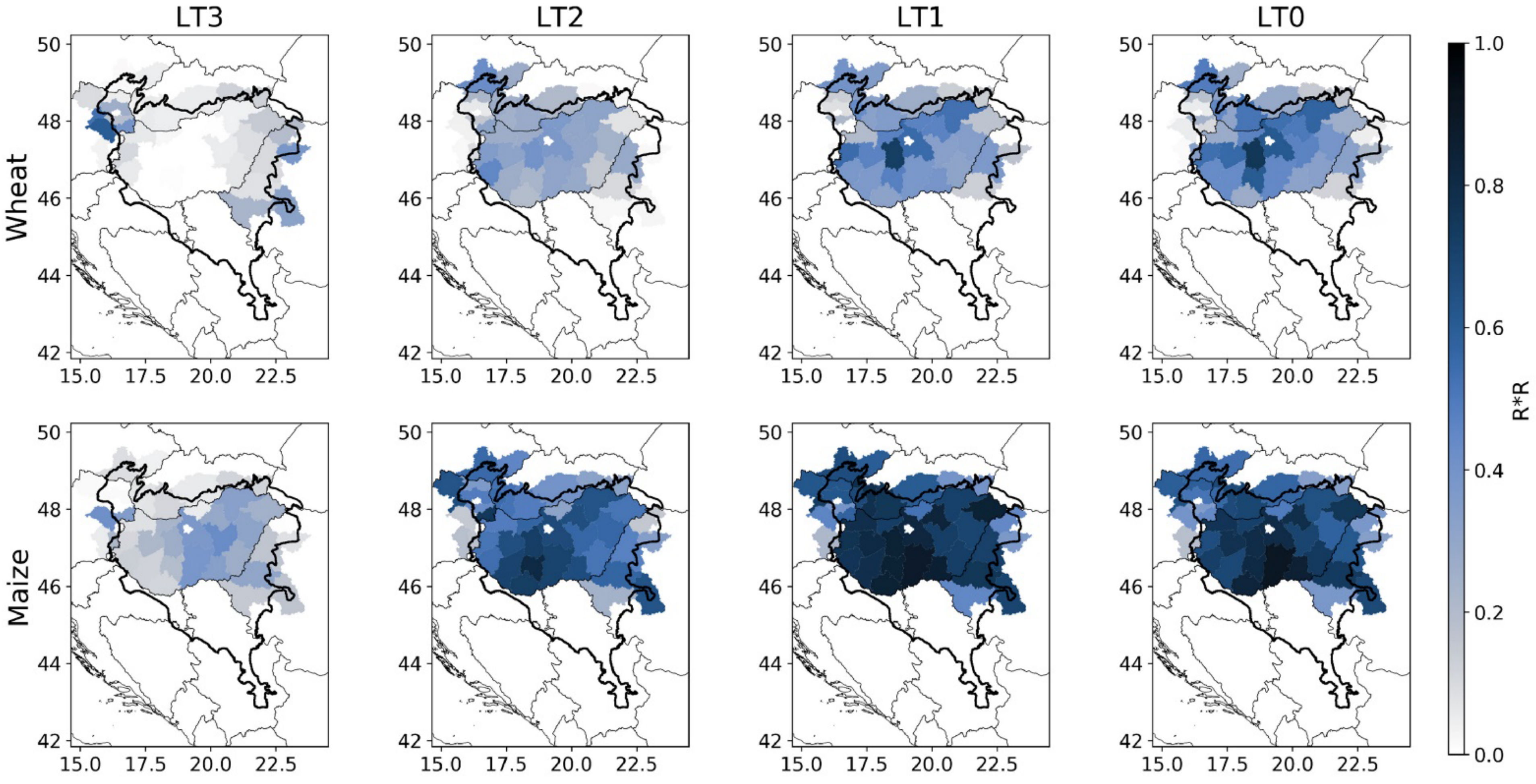
- Crop yield forecasts with lead times up to 4 months before harvest
- Feature importance to assess impact of predictors
- Monthly updated with latest data
- Cross-validation leaving 3 years out in blocked periods



[Bueechi et al., 2023]

Skill per NUTS3 region

- For all regions, predicted and observed yields have high correlations 2 months before harvest (NUTS3 and mean of Pannonian basin)

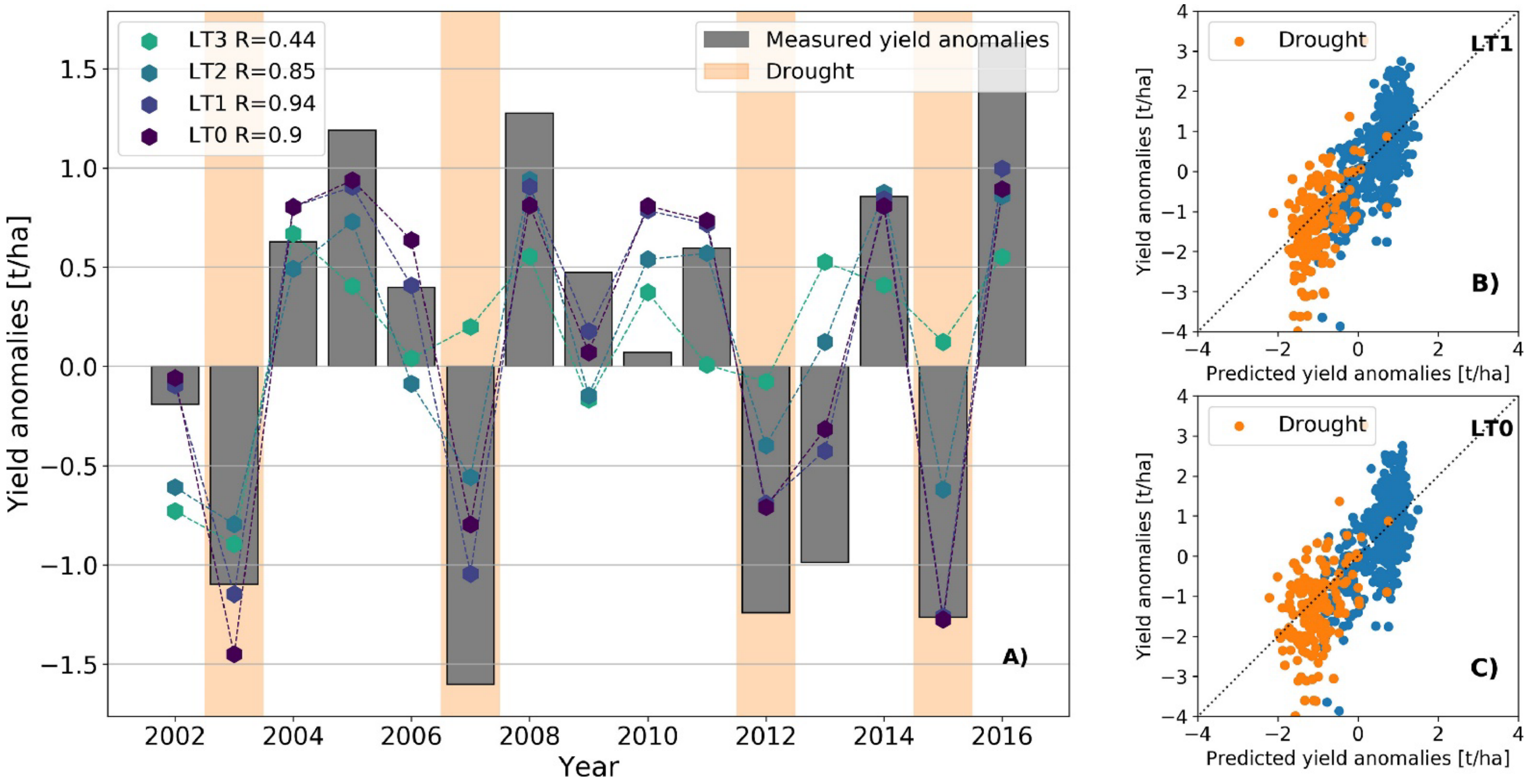


[Bueechi et al., 2023]

Performance in drought years

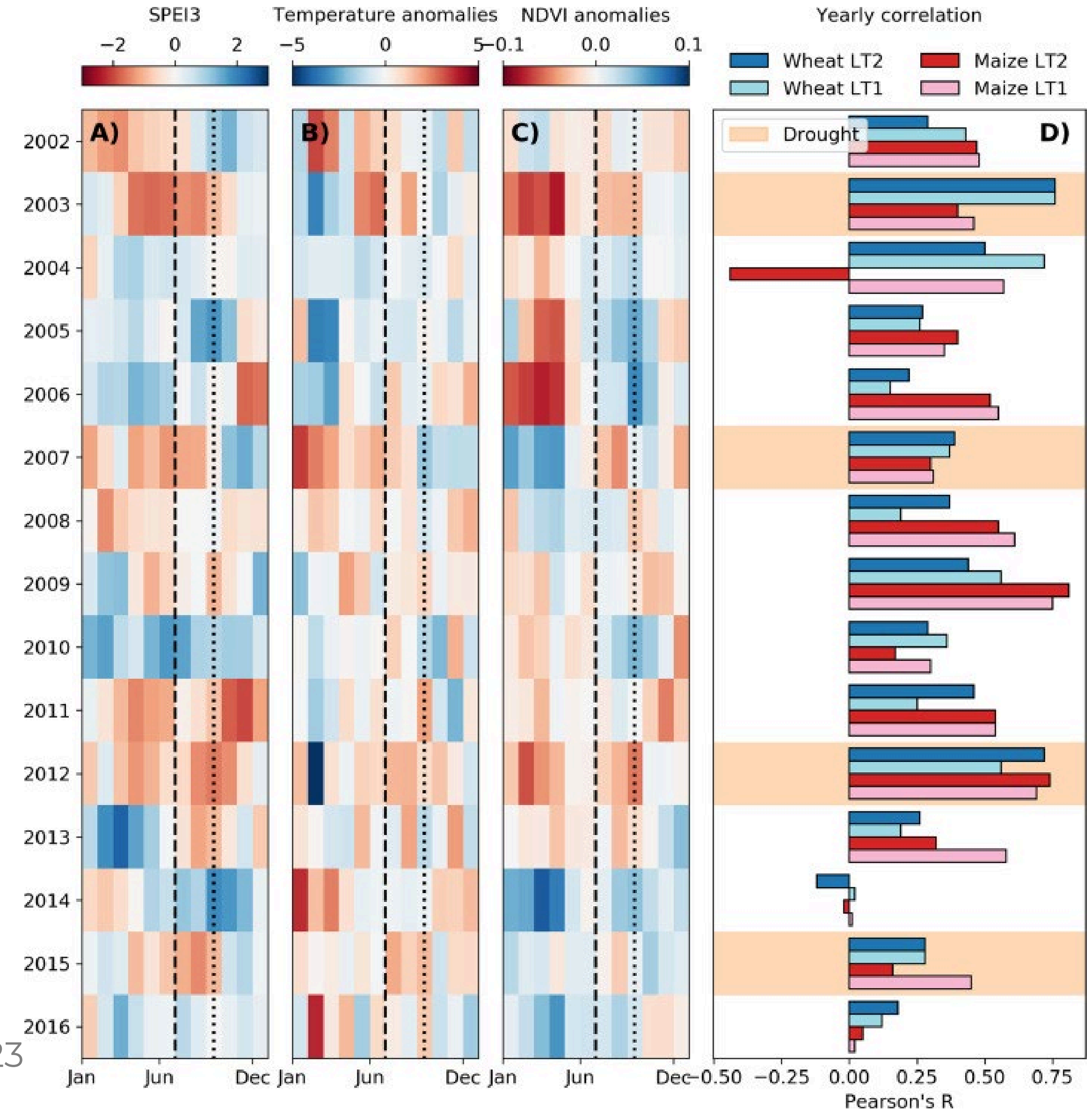
- Highest correlations to predict Pannonian basin mean maize yield the month before harvest (R=0.94)

- Model detects negative anomalies in drought years from around 2 months prior to harvest



[Bueechi et al., 2023]

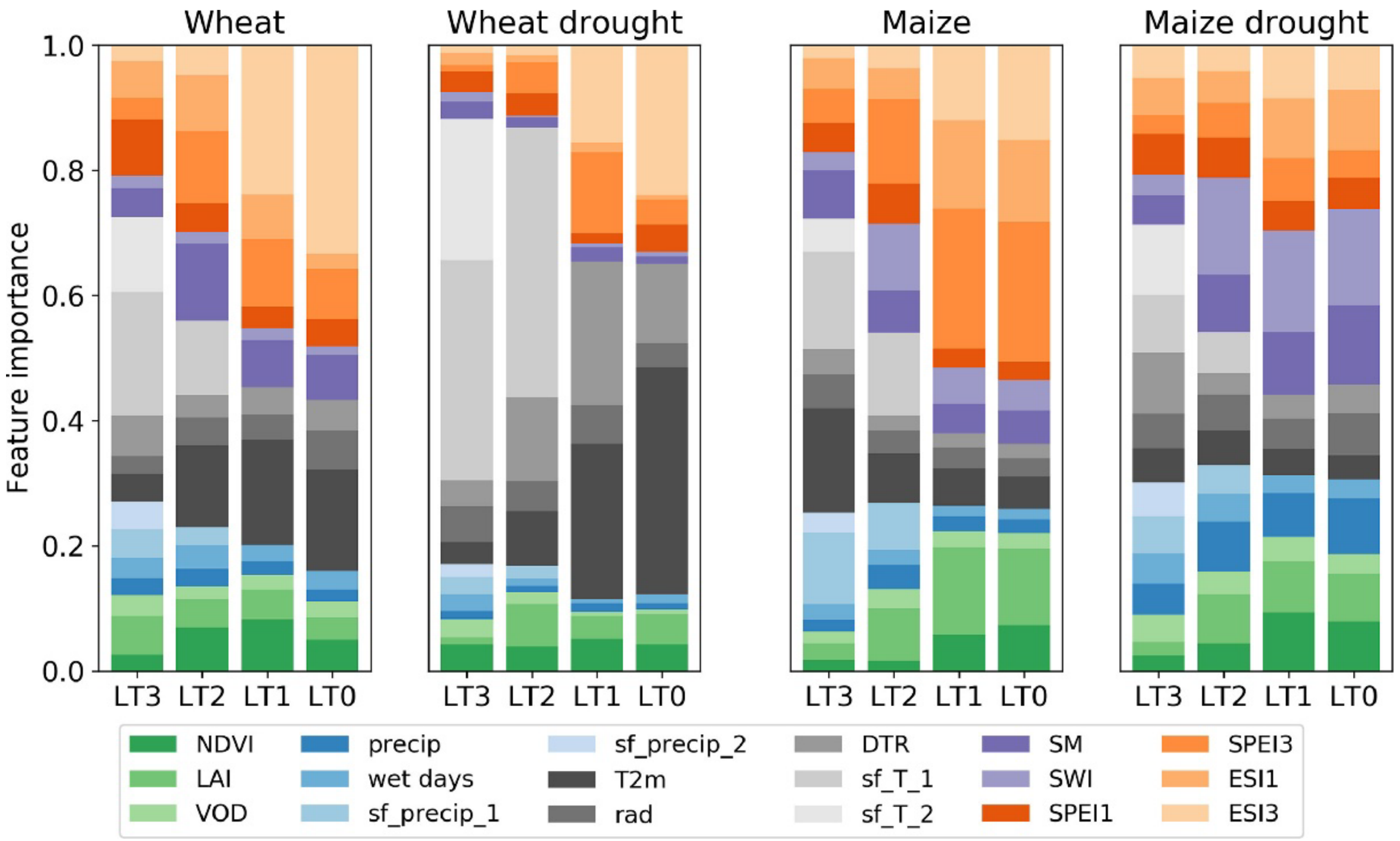
	Median error non-drought [t/ha]	Median error drought [t/ha]	T-test error non-drought and drought [p value]
Wheat_LT2	0.32	0.49	0.00
Wheat_LT1	0.34	0.43	0.01
Wheat_LT0	0.35	0.4	0.08
Maize_LT2	0.65	0.77	0.00
Maize_LT1	0.47	0.6	0.02
Maize_LT0	0.55	0.6	0.01



[Bueechi et al., 2023

Relative feature importances

- Wheat
  - › Temperature main control overall, especially in drought years
  - › Drought and stress indicators (SPEI, ESI) gain importance towards harvest
- Maize
  - › Temperature most important at long lead times
  - › Soil moisture and main control in last months

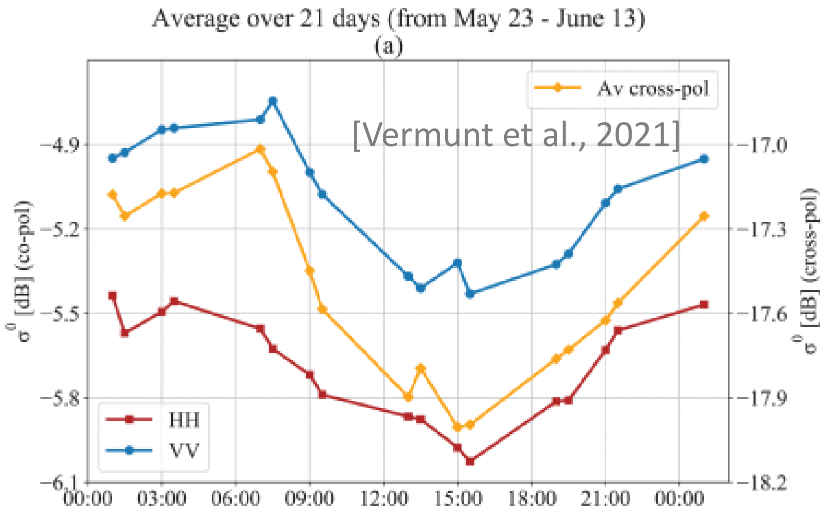


Conclusion EO for yield forecasting

- EO information (soil moisture, vegetation state, stress) provide key information for drought (impact) monitoring and prediction, but..
- Crop yield losses in years of severe drought underestimated
- High spatial autocorrelations make it difficult to distinguish between regions

What else do we need from satellites?

- Improving spatial and temporal resolutions to improve regional model performance and make field-scale predictions
  - Sentinel-1 soil moisture, Sentinel-2 crop variables
- Using novel EO datasets to better capture key variables like temperature and water availability
  - LSTM temperature, Fluorescence from FLEX
- Sub-daily observations for better capturing of plant response to dr and heat stress?



[Vermunt et al., 2021]

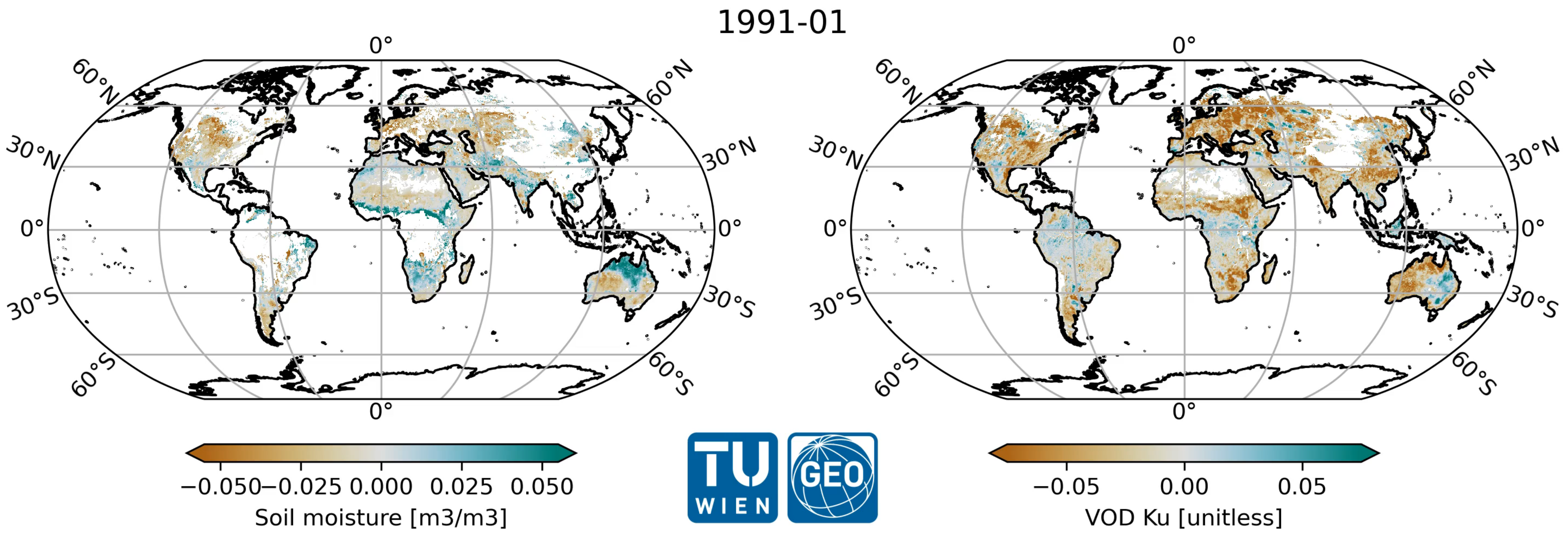
TU Wien CLIMERS data products and services

- **ESA CCI Soil Moisture**
  - climate.esa.int/en/odp/
- **C3S Soil Moisture**
  - cds.climate.copernicus.eu/
- **International Soil Moisture Network**
  - ismn.earth
- **Vegetation Optical Depth Climate Archive (VODCA)**
  - doi.org/10.5281/zenodo.2575599o
- **SVODI**
  - doi.org/10.5281/zenodo.7114654
- **VODCA2GPP**
  - doi.org/10.48436/1k7aj-bdz35
- **QA4SM**
  - qa4sm.eu
- **Data Viewer**
  - dataviewer.geo.tuwien.ac.at

Climate Change Service

climers.geo.tuwien.ac.at

Thank you!



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