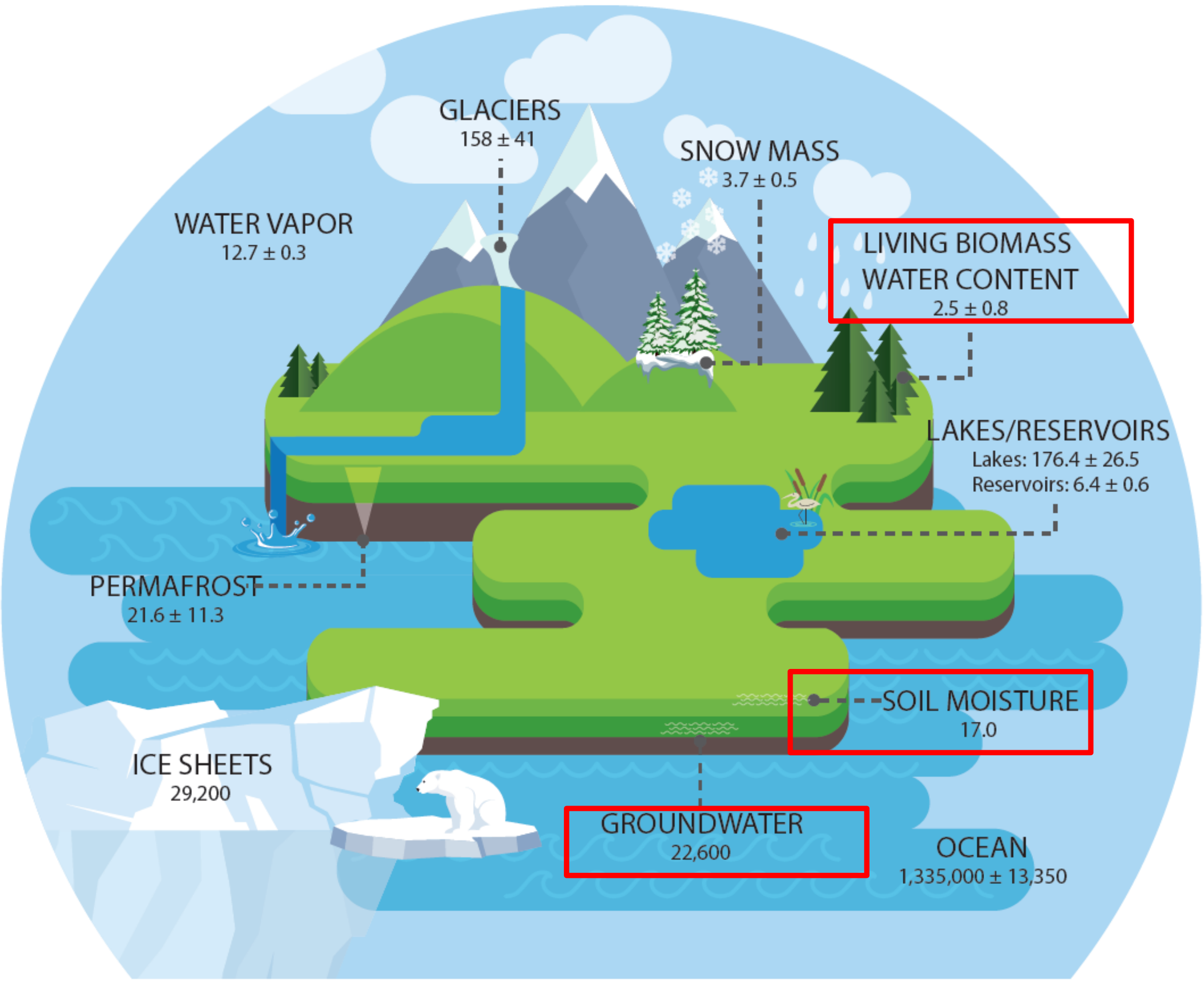
ESA Land Training course ´22

Drought monitoring and forecasting

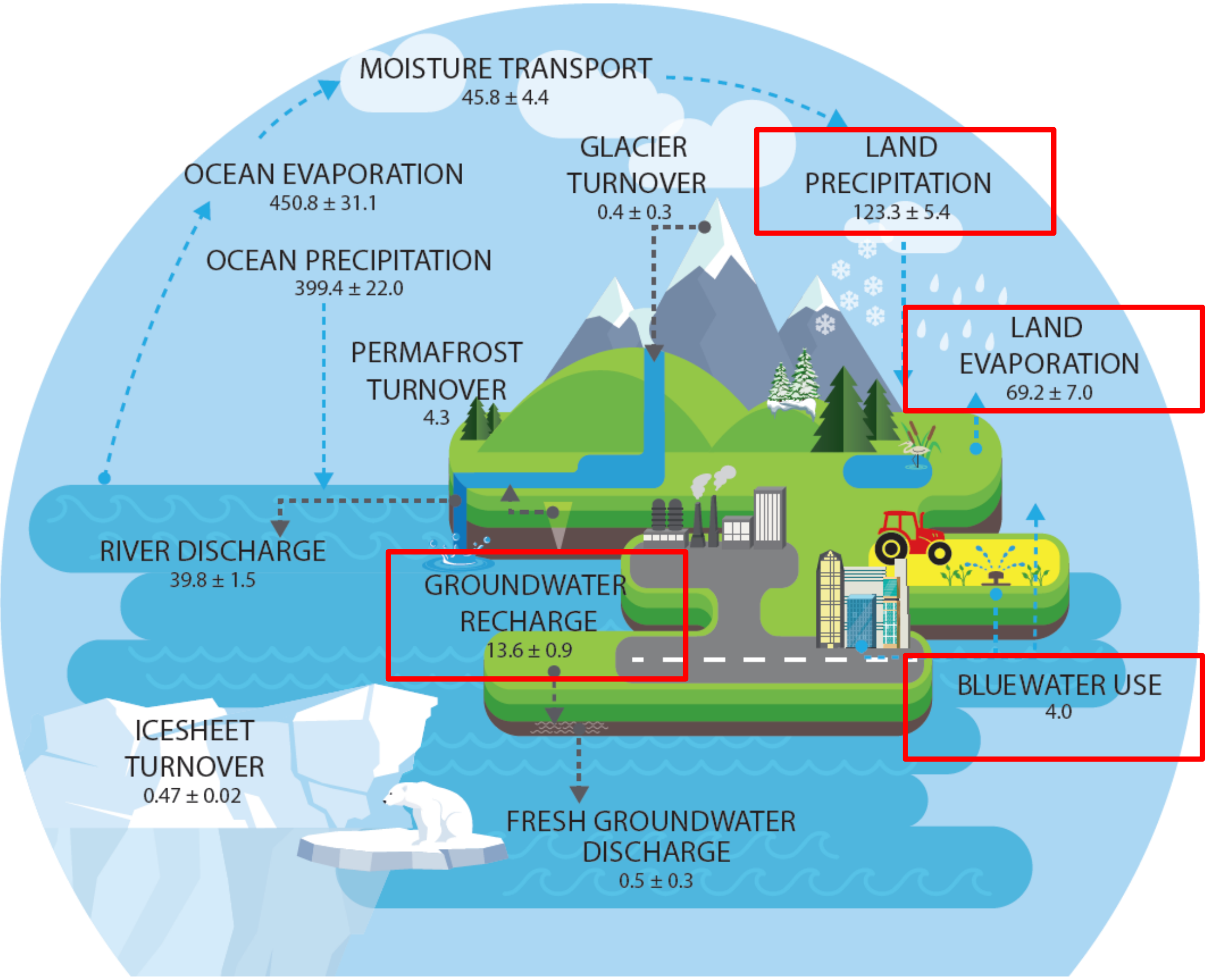
Wouter Dorigo, Wolfgang Preimesberger, Mariette Vreugdenhil

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

Global water stores and yearly fluxes

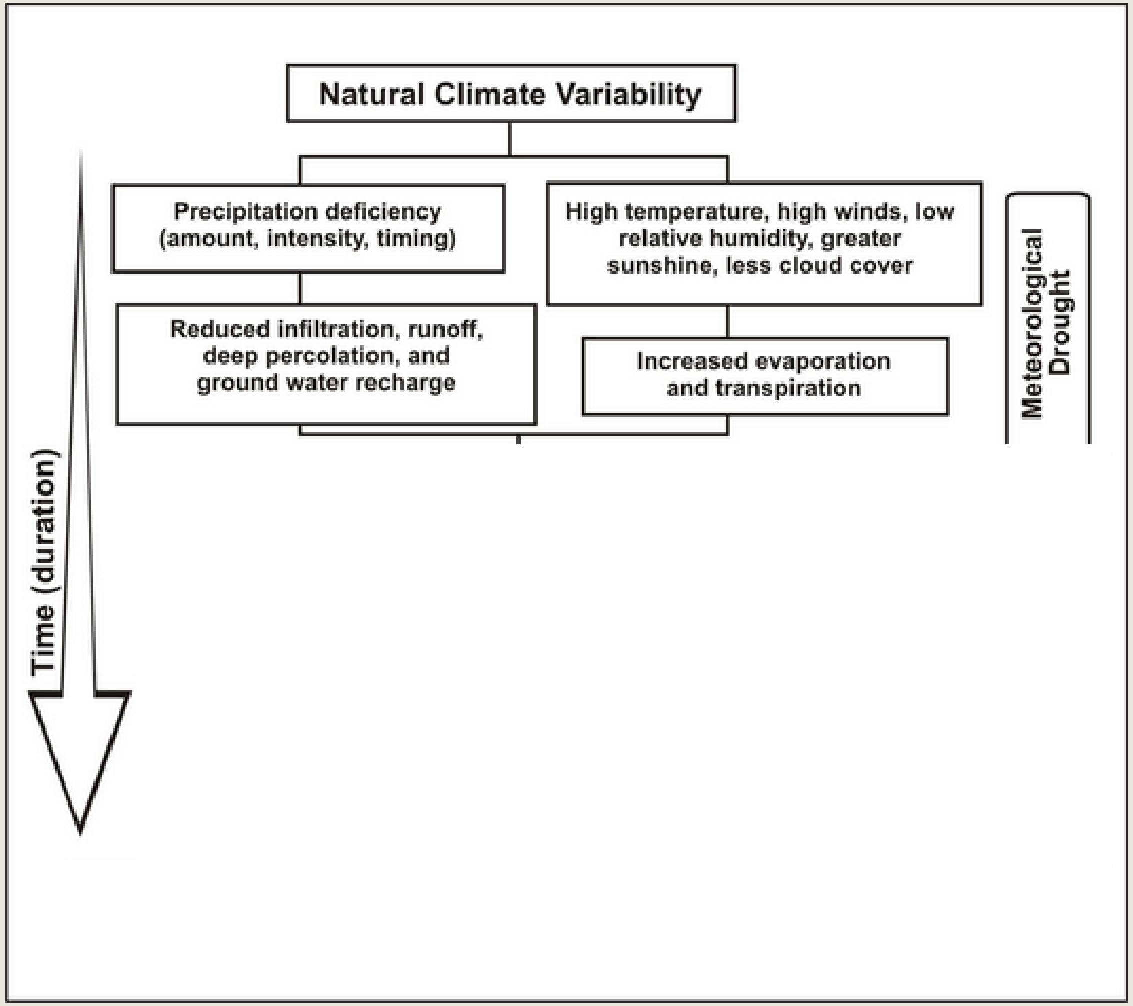


GLOBAL WATER STORAGES
[10^3 km^3]



GLOBAL WATER CYCLE FLUXES
[10^3 km^{3}y^{-1}] [Dorigo et al., 2021]

What is drought?

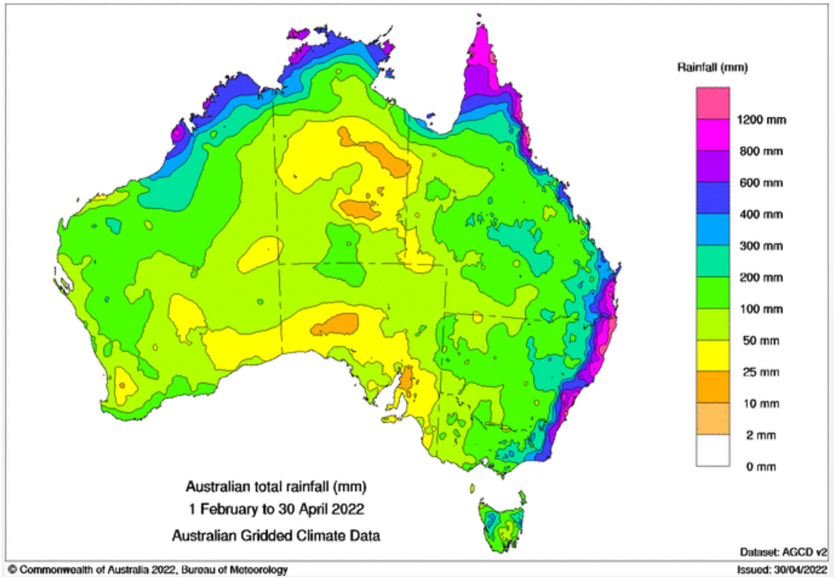


Sequence of drought occurrence and impacts for commonly accepted drought types. All droughts originate from a deficiency of precipitation or meteorological drought but other types of drought and impacts cascade from this deficiency. (Source: National Drought Mitigation Center, University of Nebraska-Lincoln,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

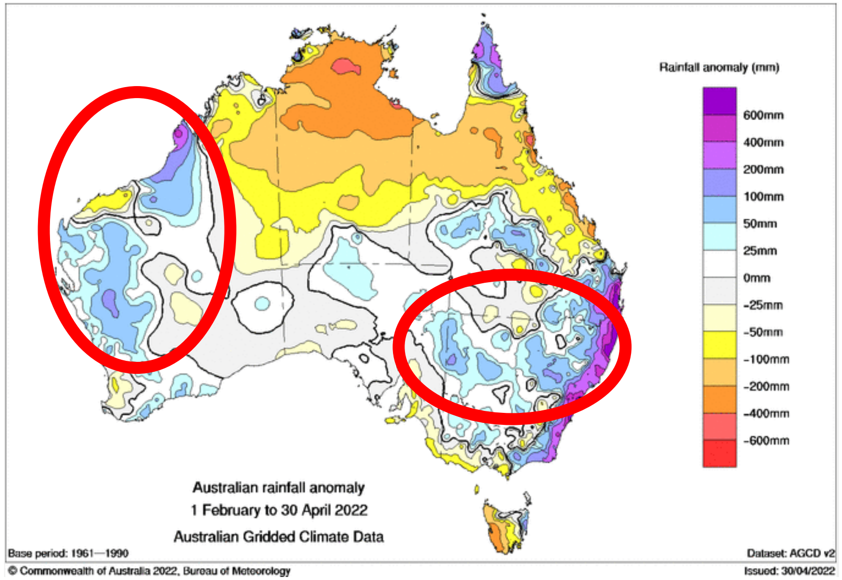
How do we quantify drought?

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

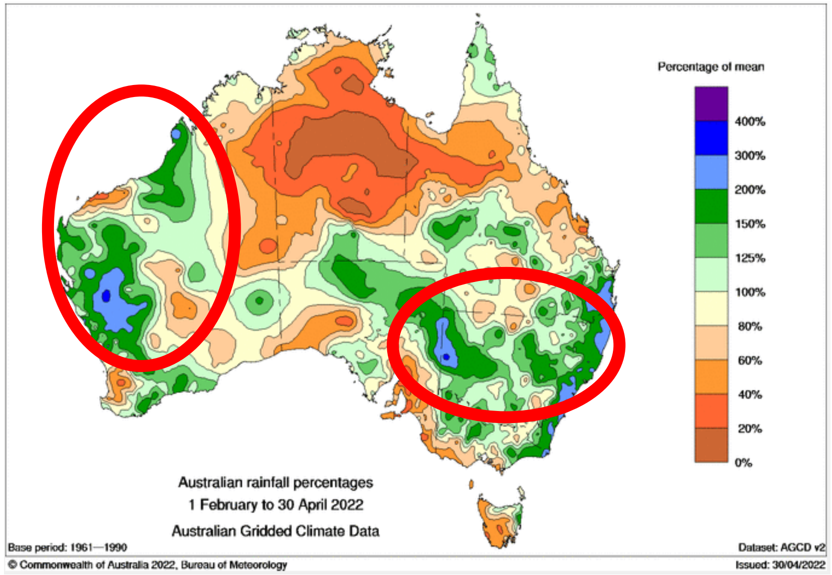
Rainfall January-April 2022 [mm]



Anomaly from long-term mean rainfall [mm]



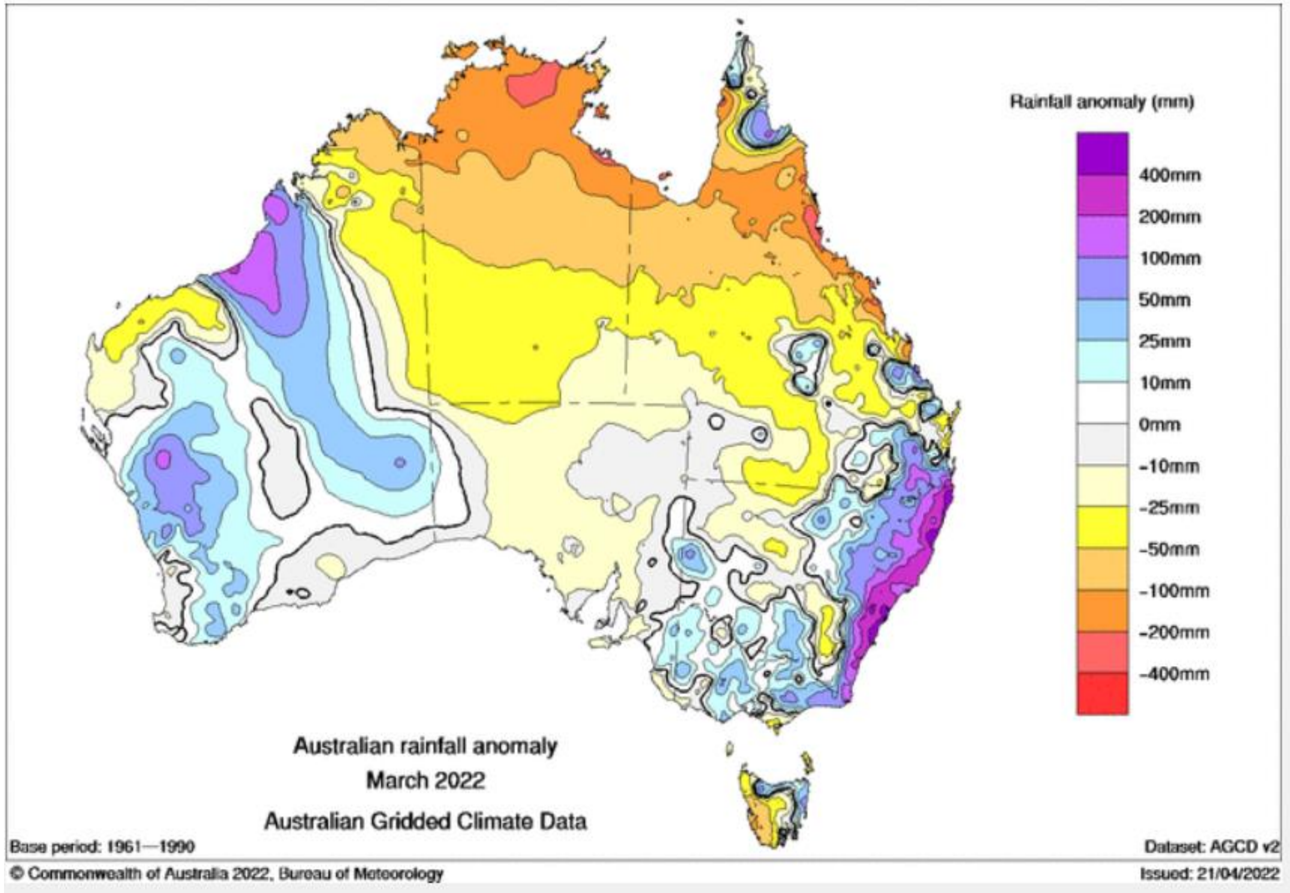
Percentages of long-term mean rainfall [mm]

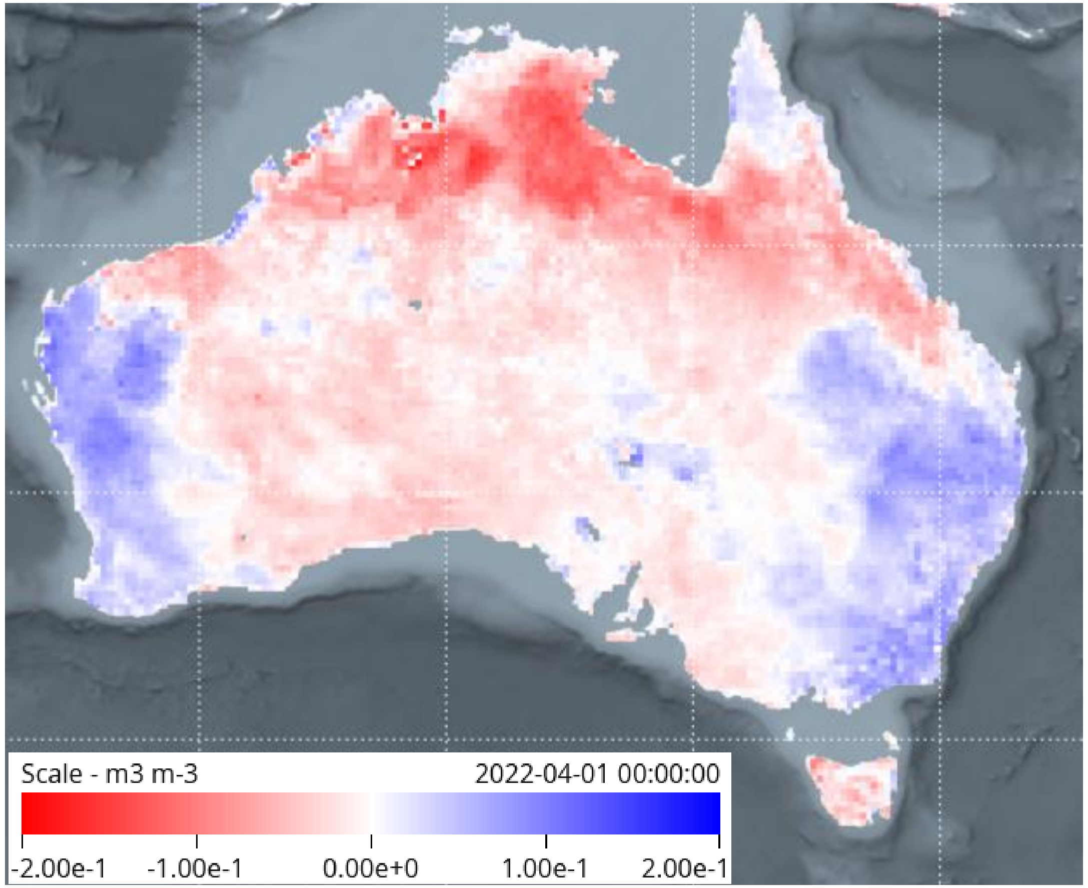


http://www.bom.gov.au/climate/maps/rainfall/?variable=rainfall&map=totals&period=3month&region=nat&year=2022&month=03&day=31

How do we quantify drought?

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



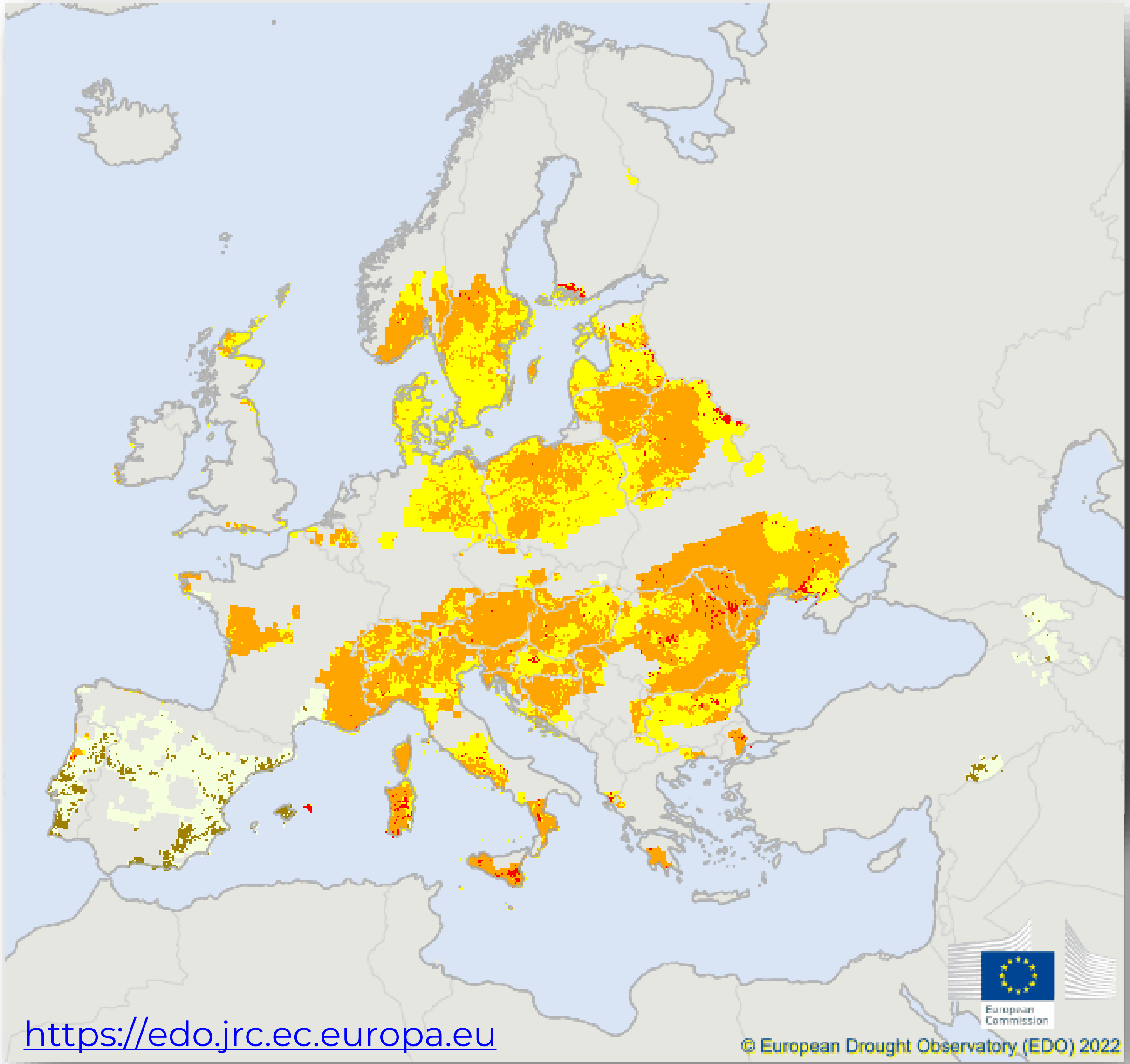


https://dataviewer.geo.tuwien.ac.at/

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

European Drought Observatory

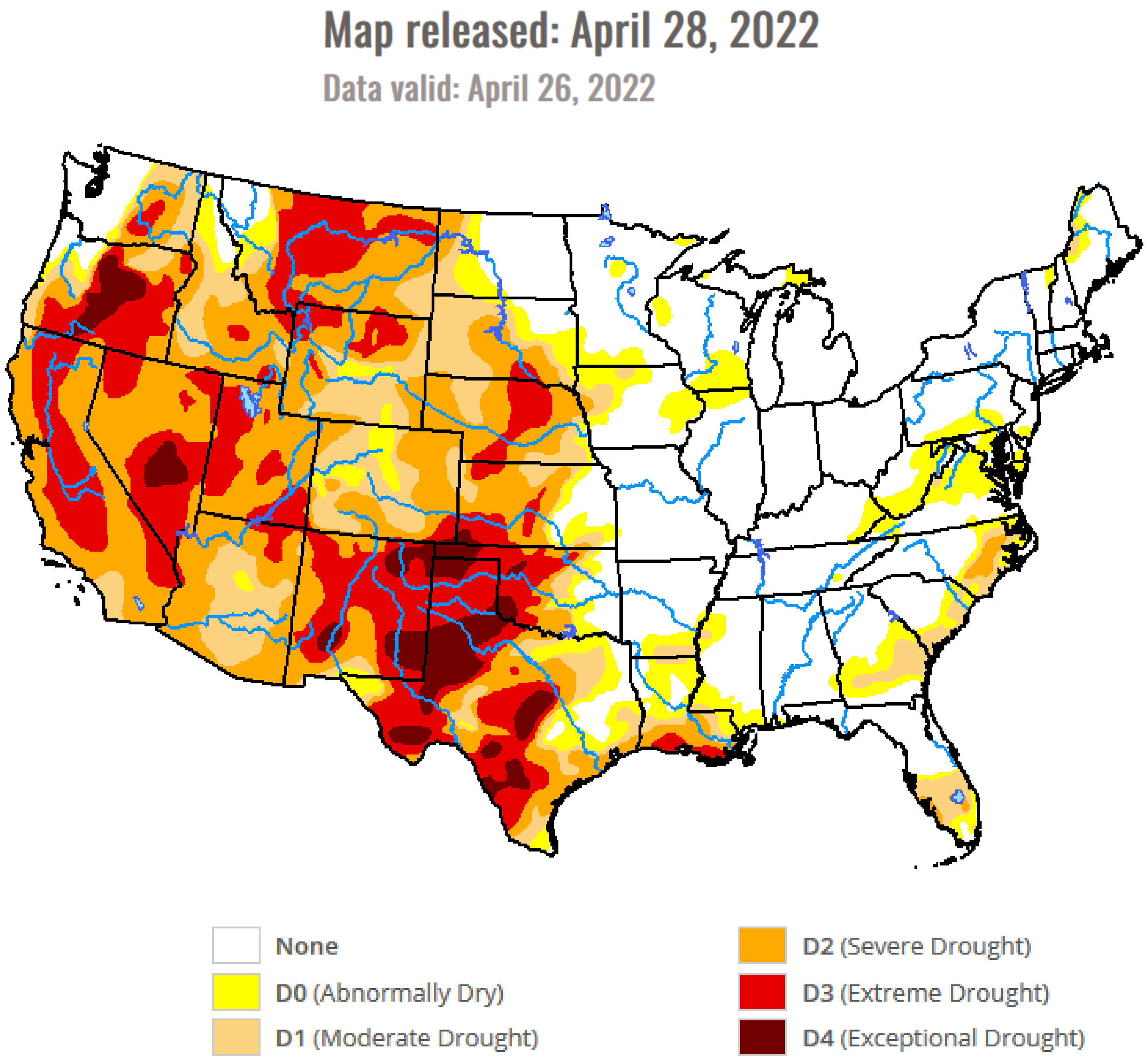
- Drought indicators:
  - **Soil Moisture Anomaly** (SMA)
  - **Standardized Precipitation Index** (SPI)
  - **Anomaly of Vegetation Condition** (FAPAR Anomaly)
  - **Low-Flow Index** (LFI)
  - **Heat and Cold Wave Index** (HCWI)
  - **Combined Drought Indicator** (CDI): Integrates information on anomalies 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.



https://edo.jrc.ec.europa.eu

Drought indices

- Drought is commonly expressed as an index, and fed with (Earth) observations
- Indices can be used to measure severity and duration
- 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…

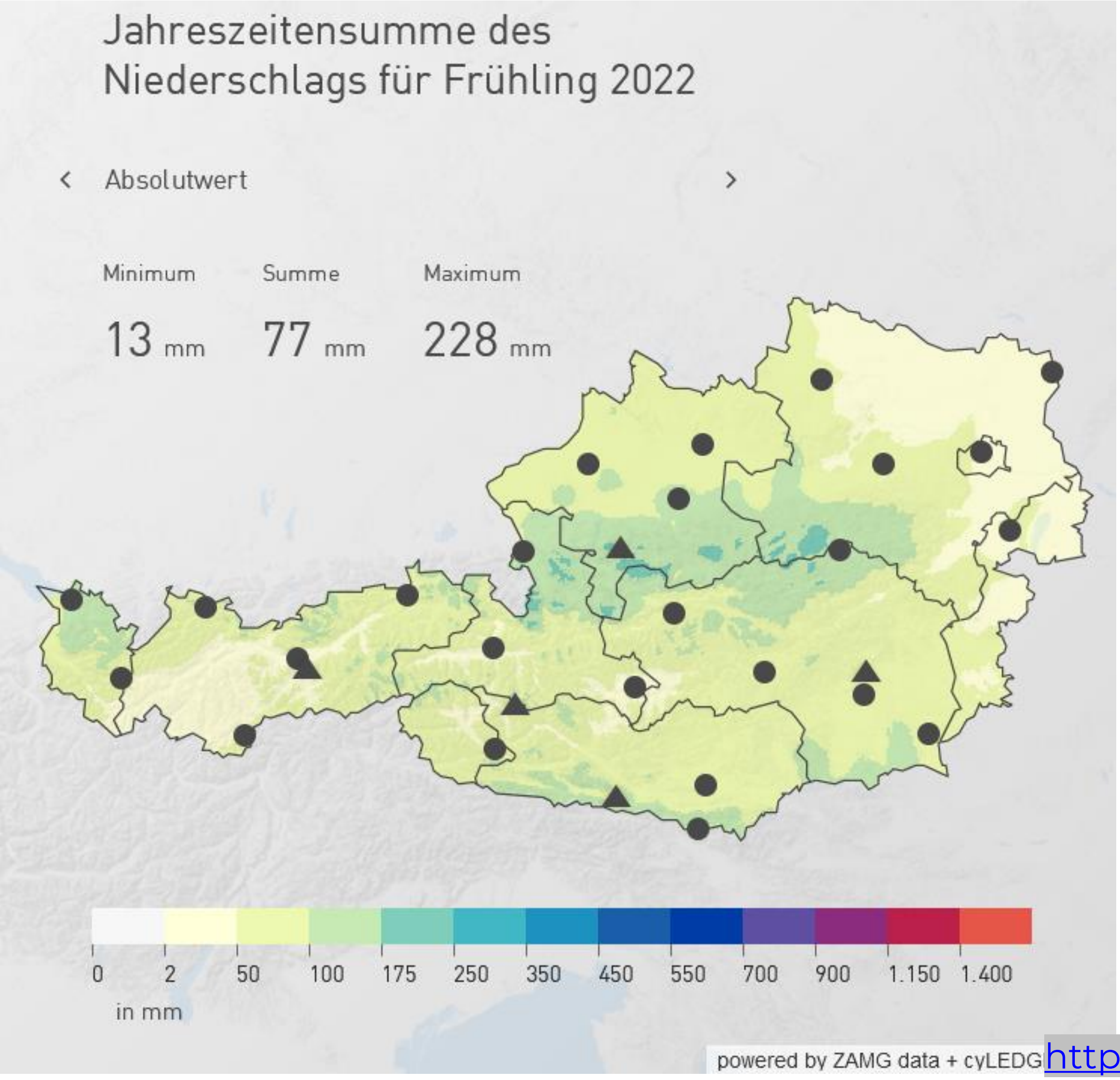


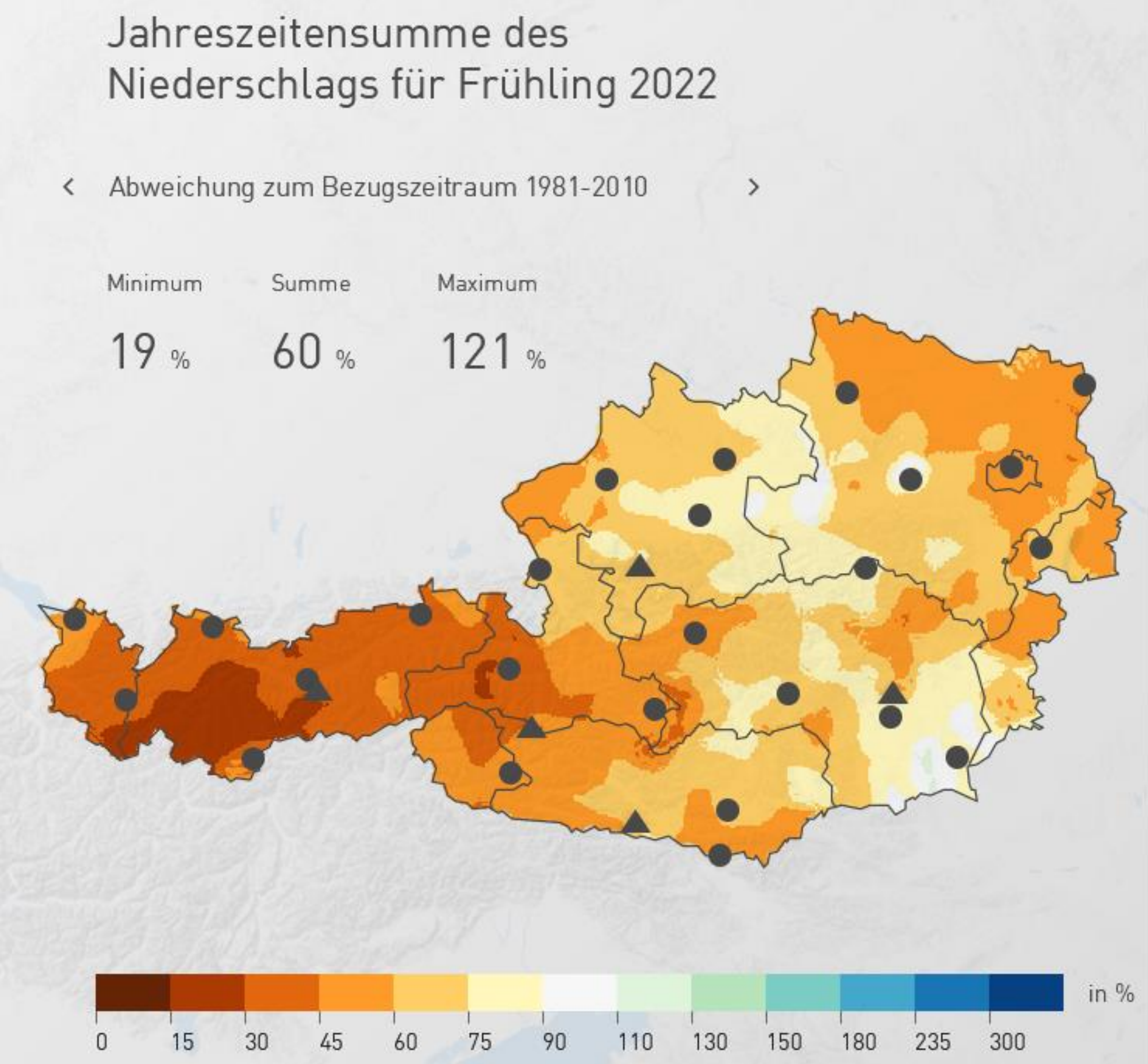
Drought indices

- 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

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

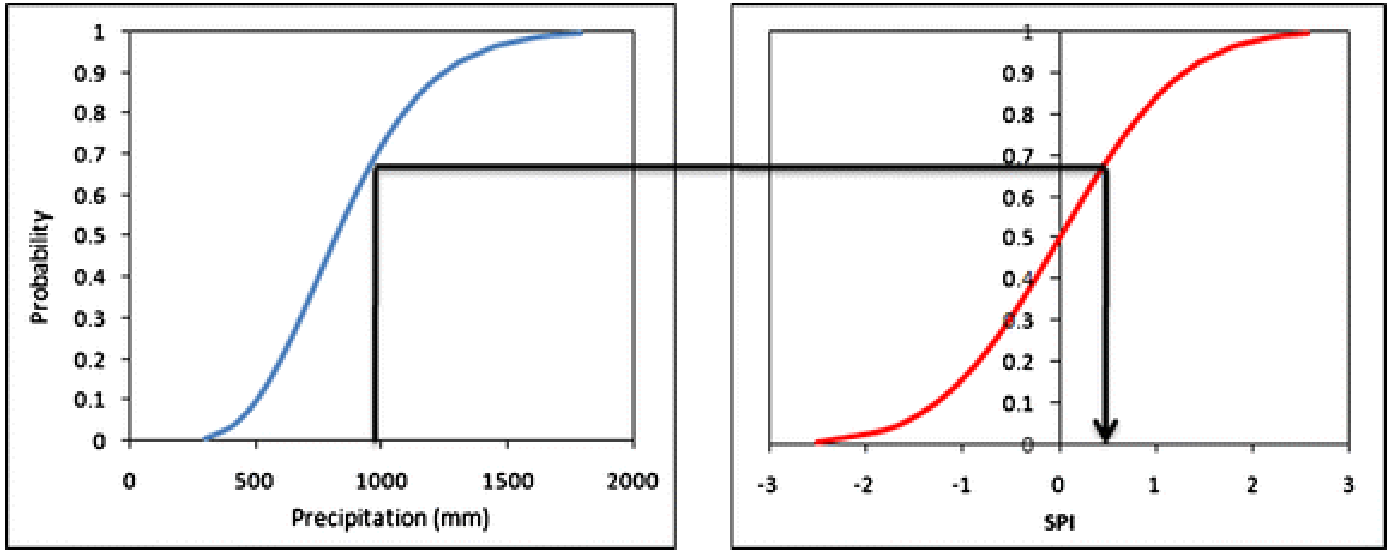
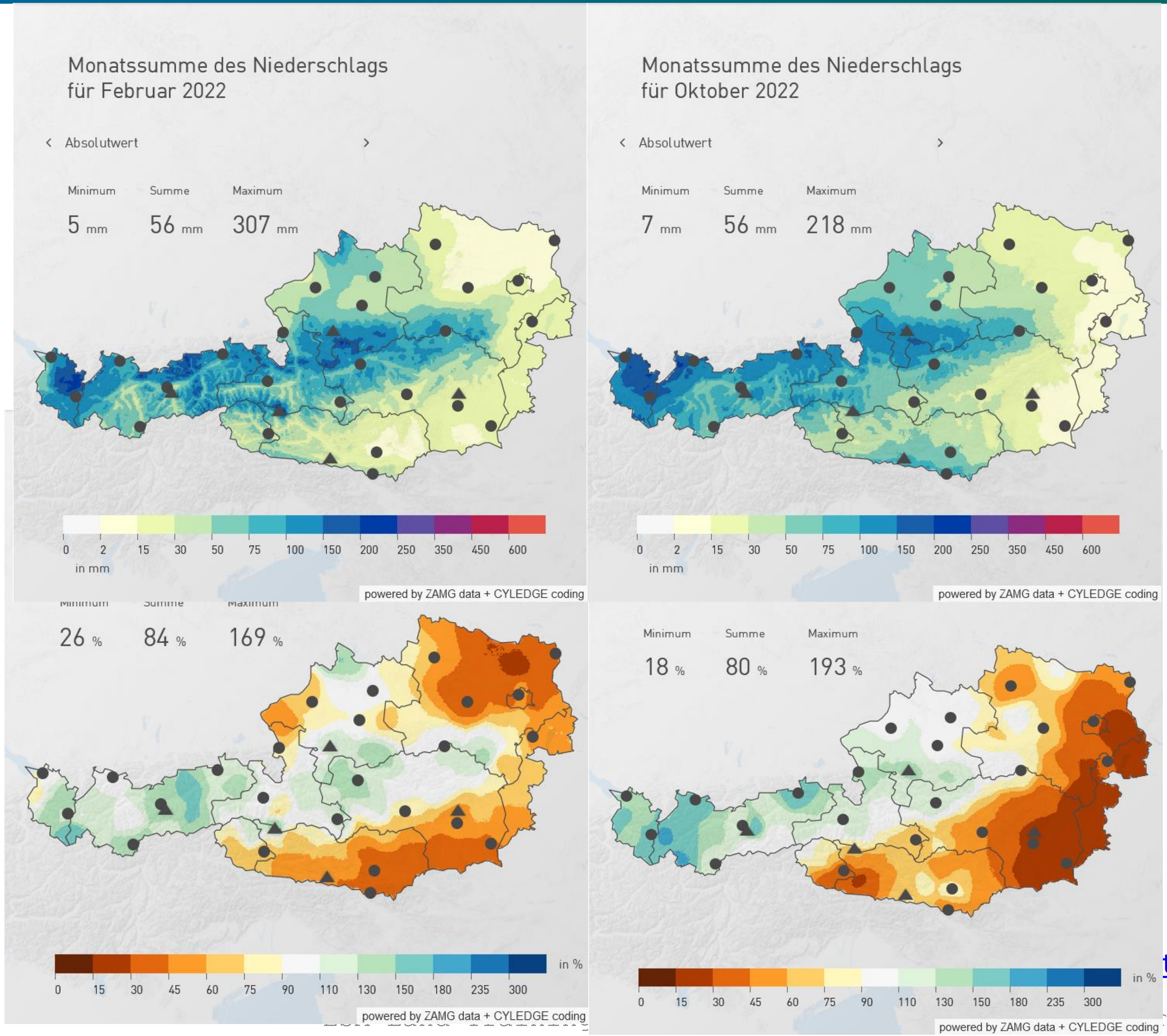


Table 1. SPI values

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

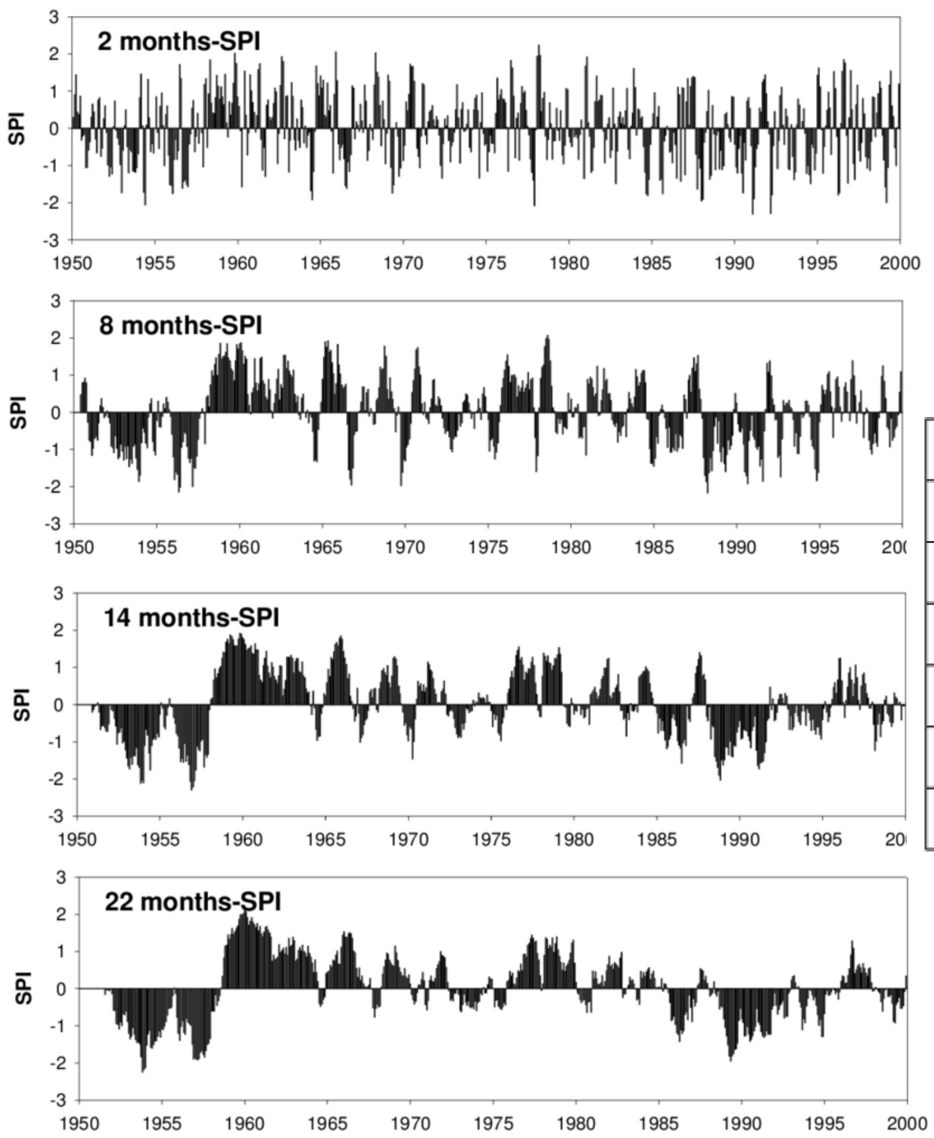


- Individual distribution needs to be fitted for each season individually

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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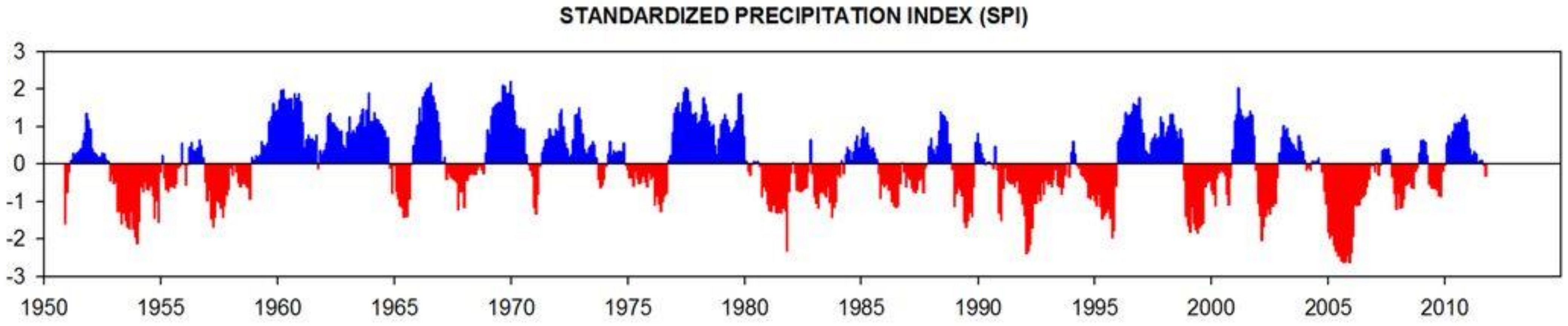
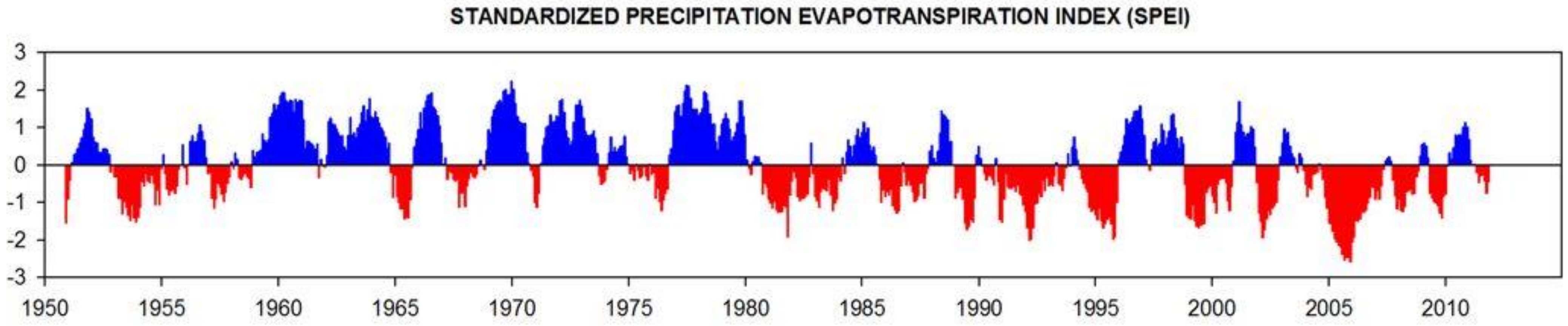
[Vicente-Serrano, 2005]

Standardised Precipitation minus Evaporation index

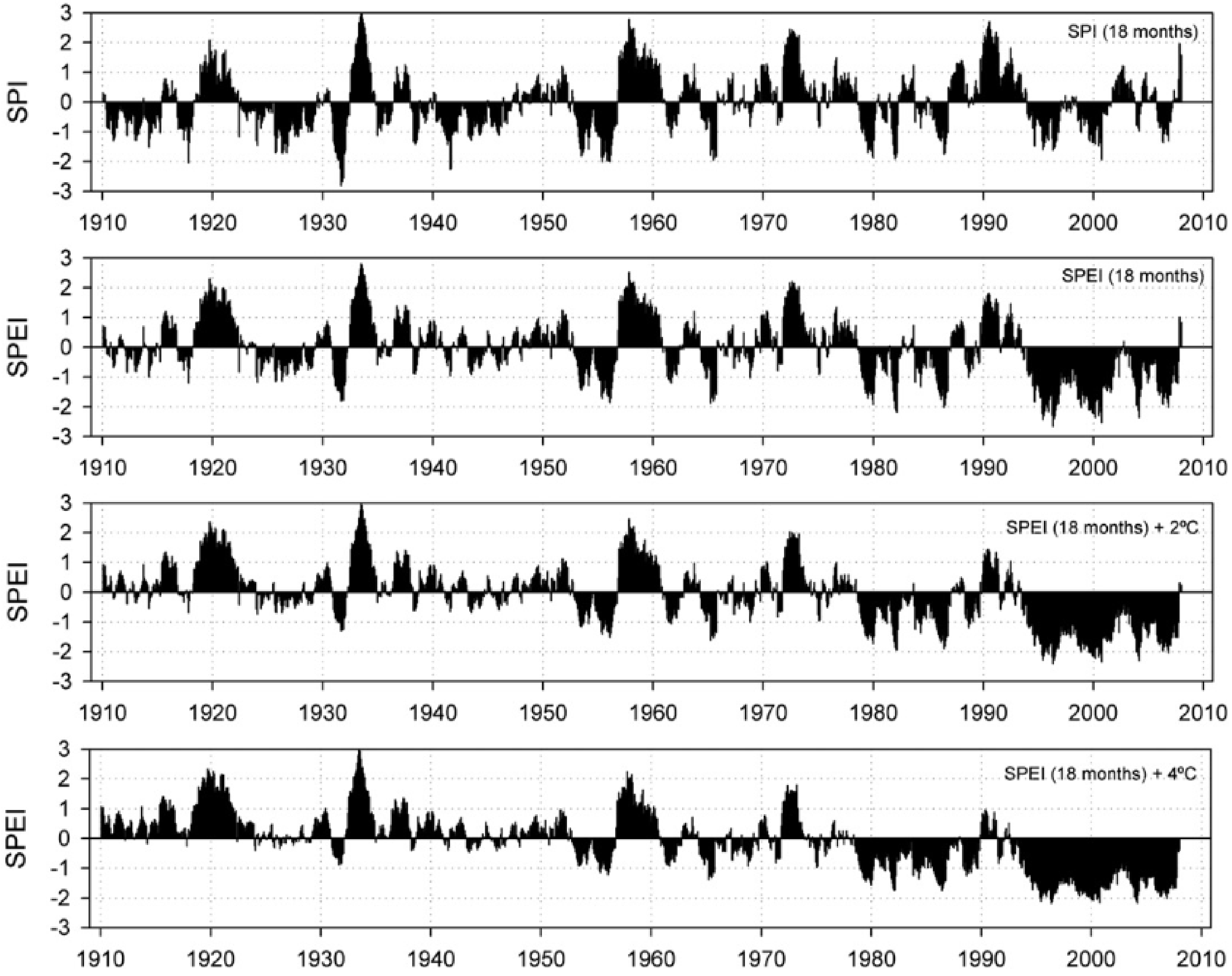
- Climatic water balance (precipitation minus evapotranspiration)
  - Includes the impact of (rising) temperature





SPEI

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

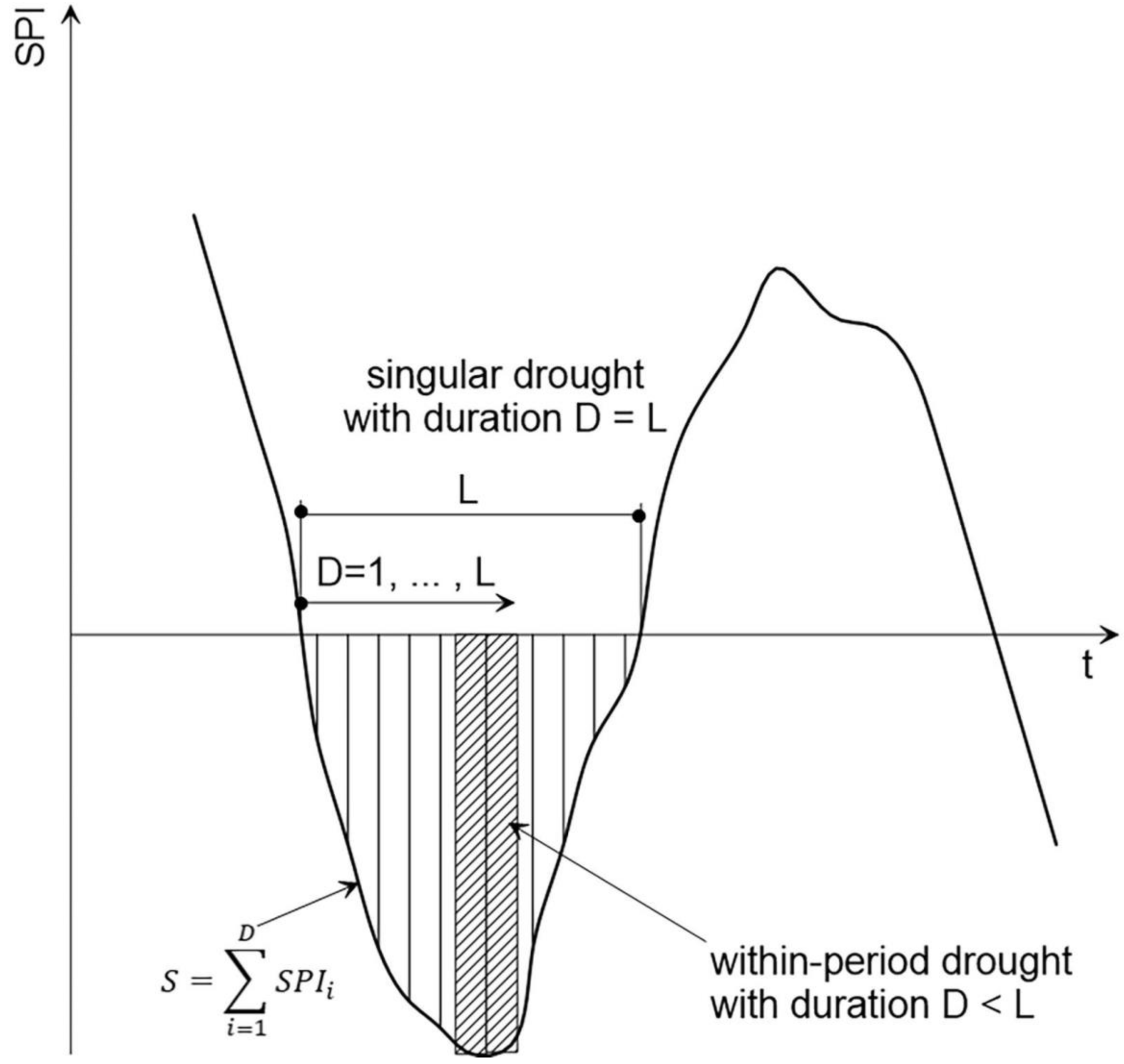


[Vicente-Serrano, 2010]

How severe is a drought?

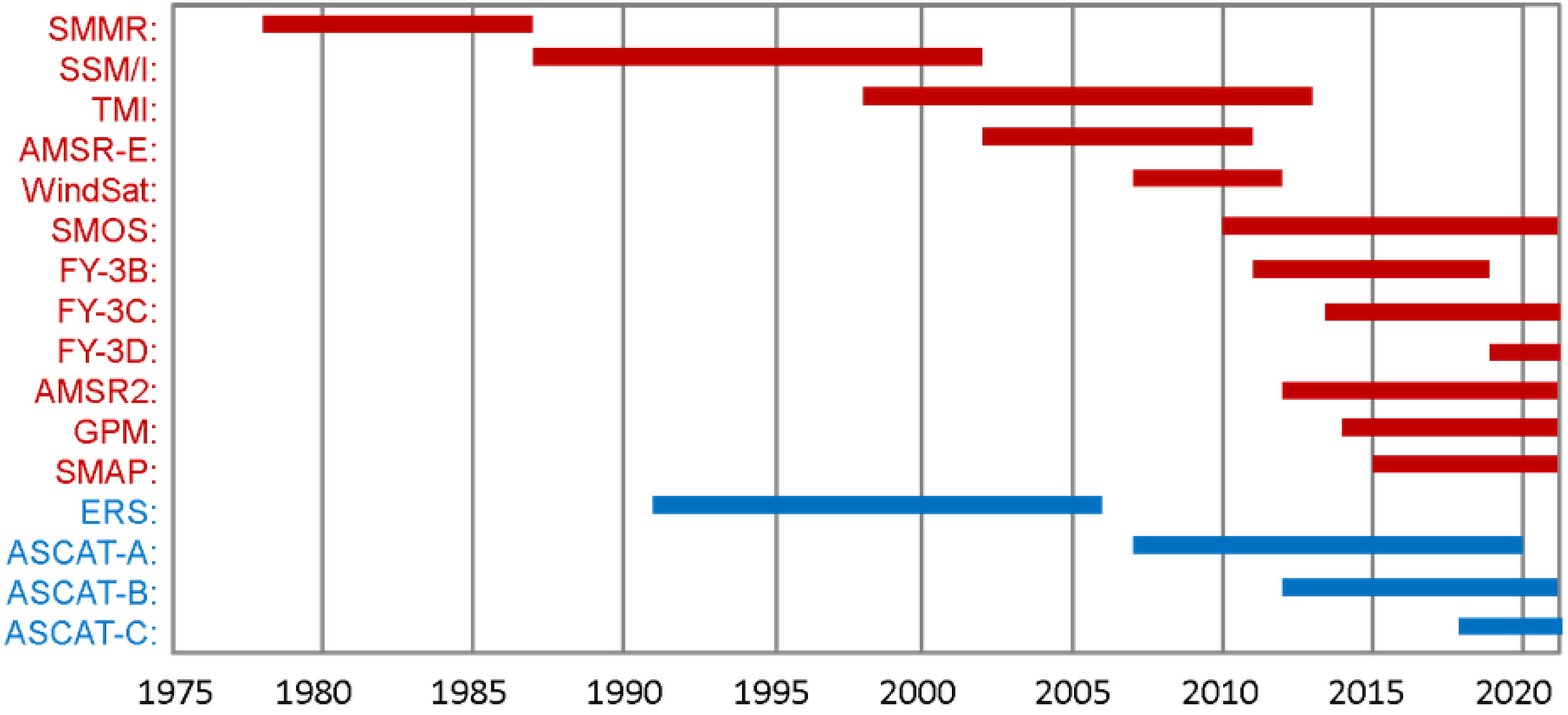
- ***Drought duration (D)*:** Number of sonsecutive days with index <0
- ***Drought severity (S)***: The accumulation of negative index (e.g. SPI) values preceded and followed by positive SPI values is called severity.
- ***Drought intensity (I)***: The intensity is obtained by dividing the severity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

[Cavus and Aksoy, 2020]



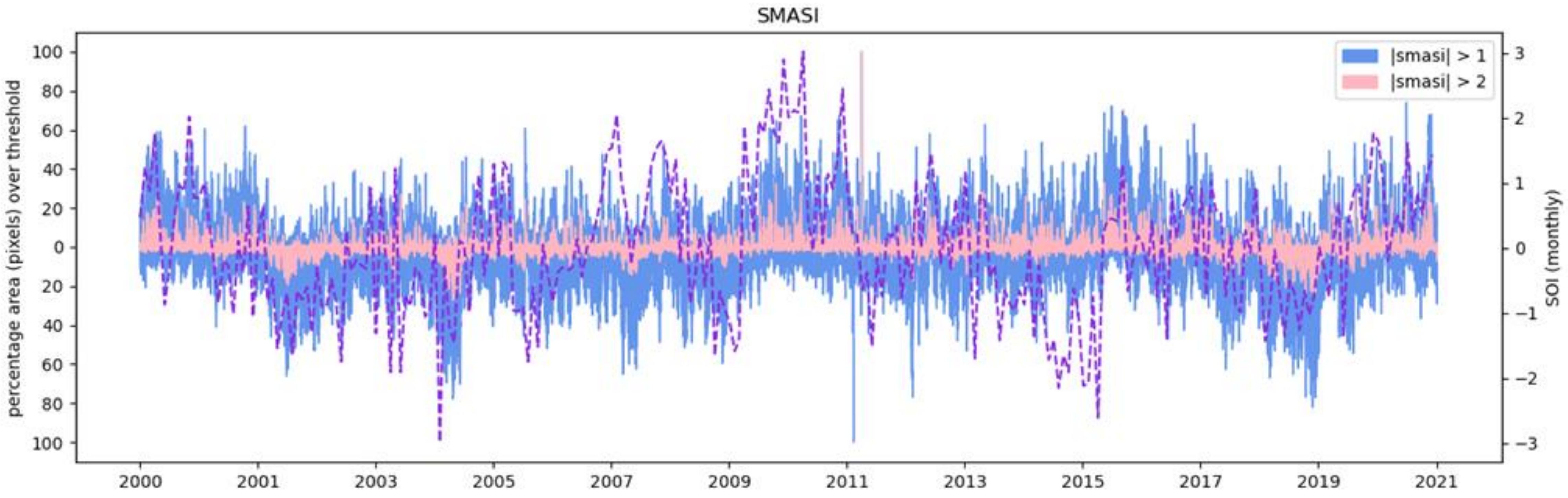
SMASI - A drought index for soil moisture

- Z-scores can in principle be computed for any dataset of sufficient length
- Use of multiple satellite missions (e.g., ESA CCI SM) allows for a more robust assessment over longer time periods

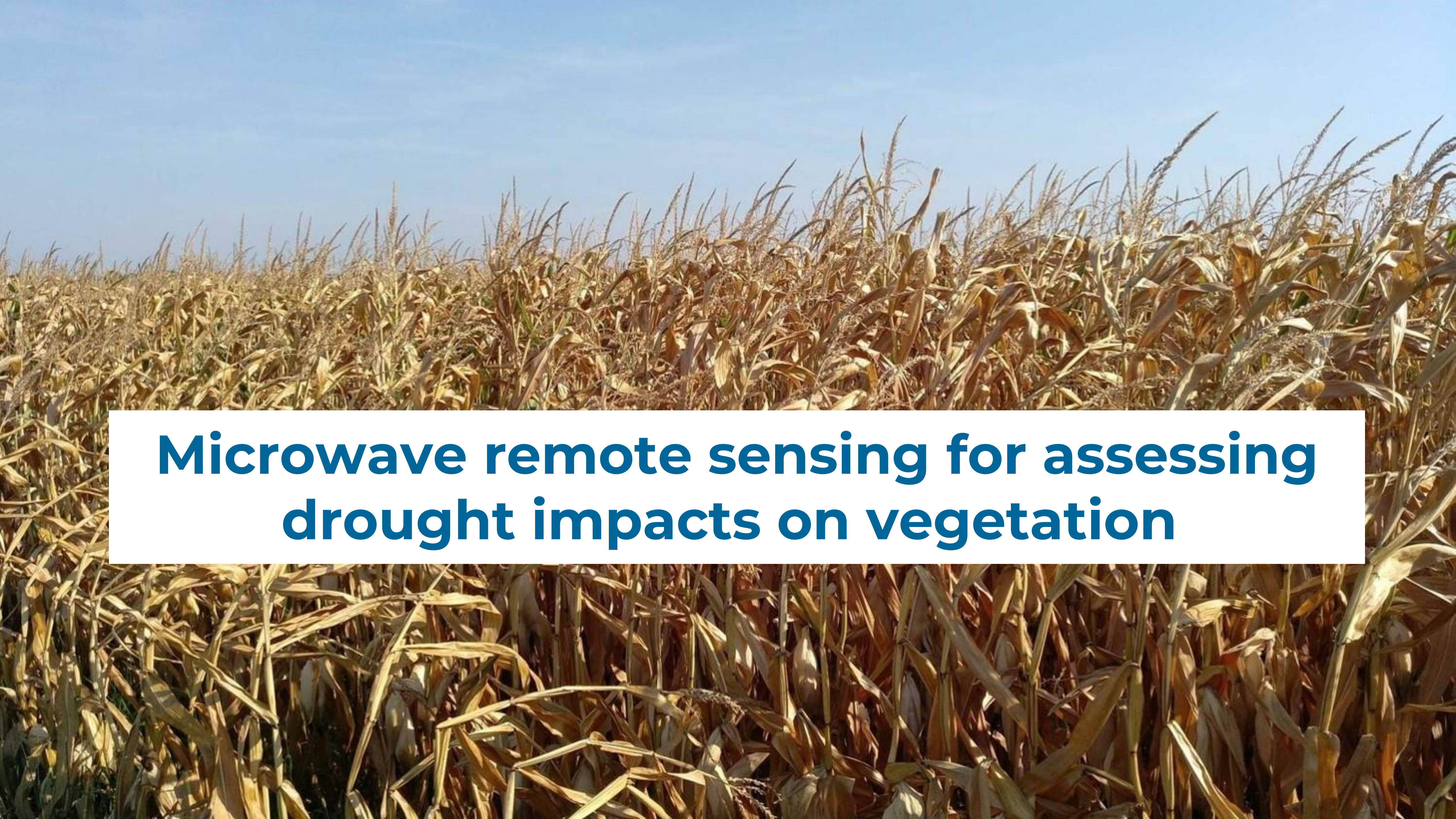


SMASI - A drought index for soil moisture

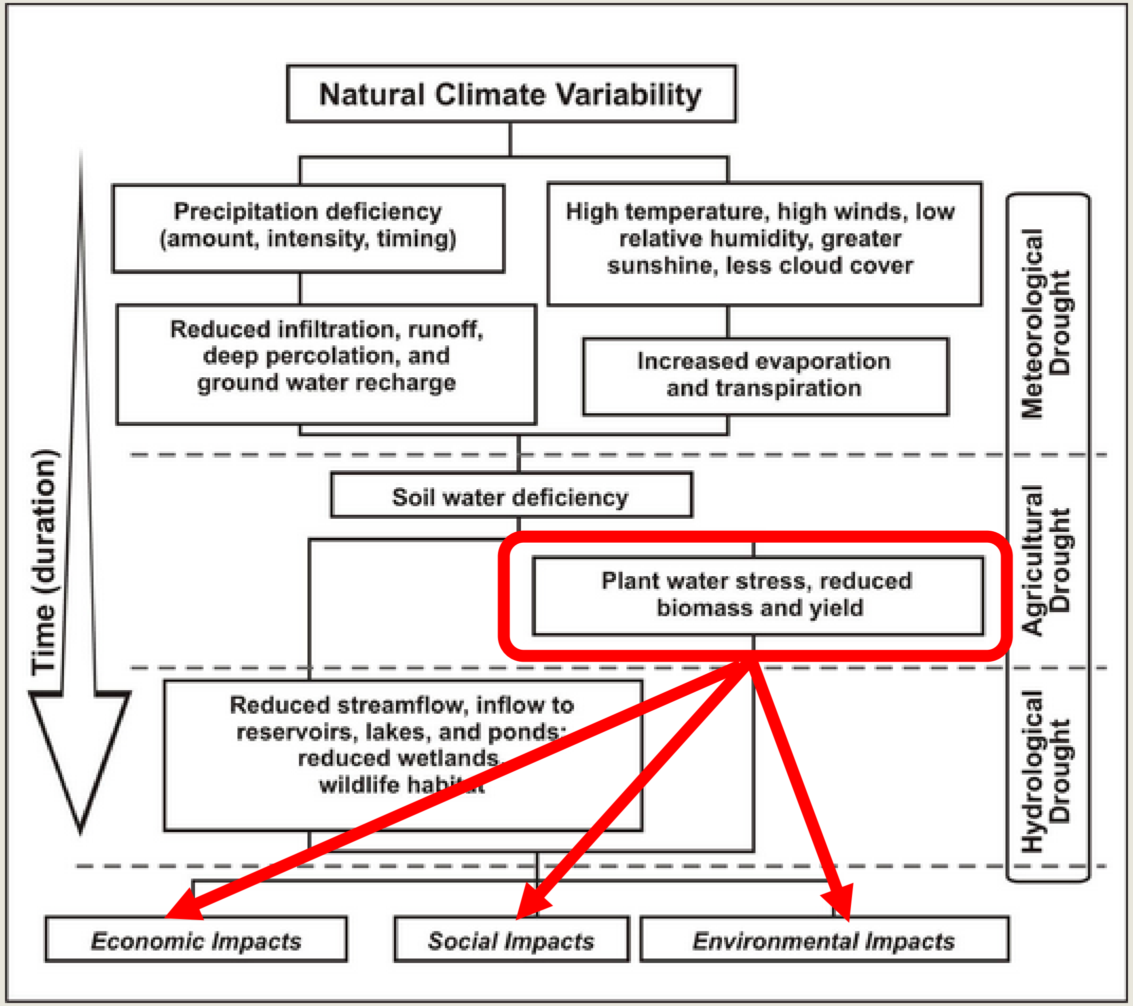
- Soil Moisture Anomaly Standardised Index shows severity of anomalies
  - Example for Australia, where moisture is strongly driven by El Nino Southern Oscillation (ENSO), as indicated by the Southern Oscillation Index (SOI)



Microwave remote sensing for assessing drought impacts on vegetation

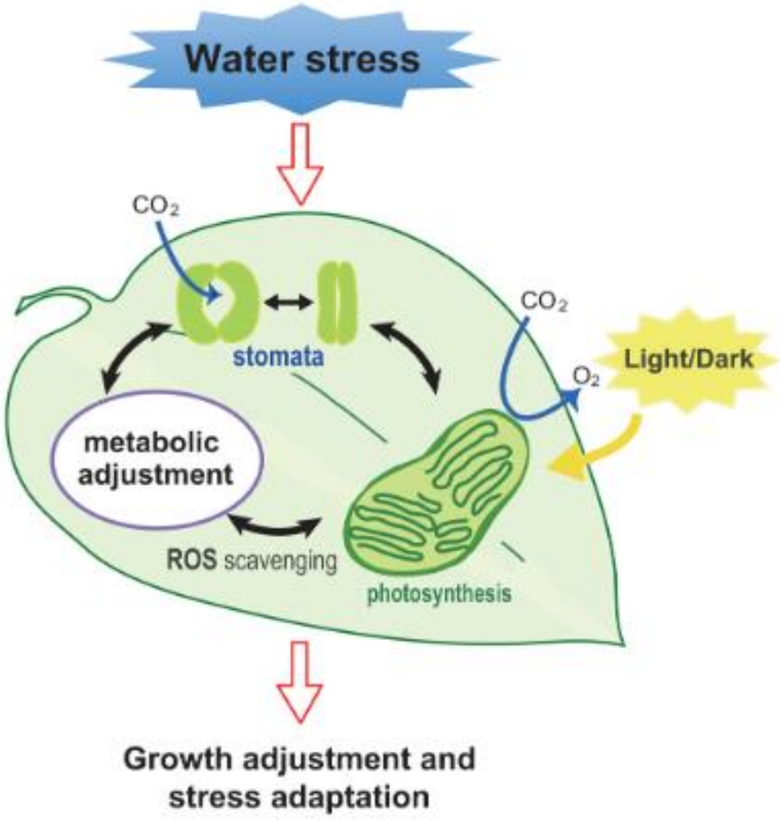


Impacts on vegetation



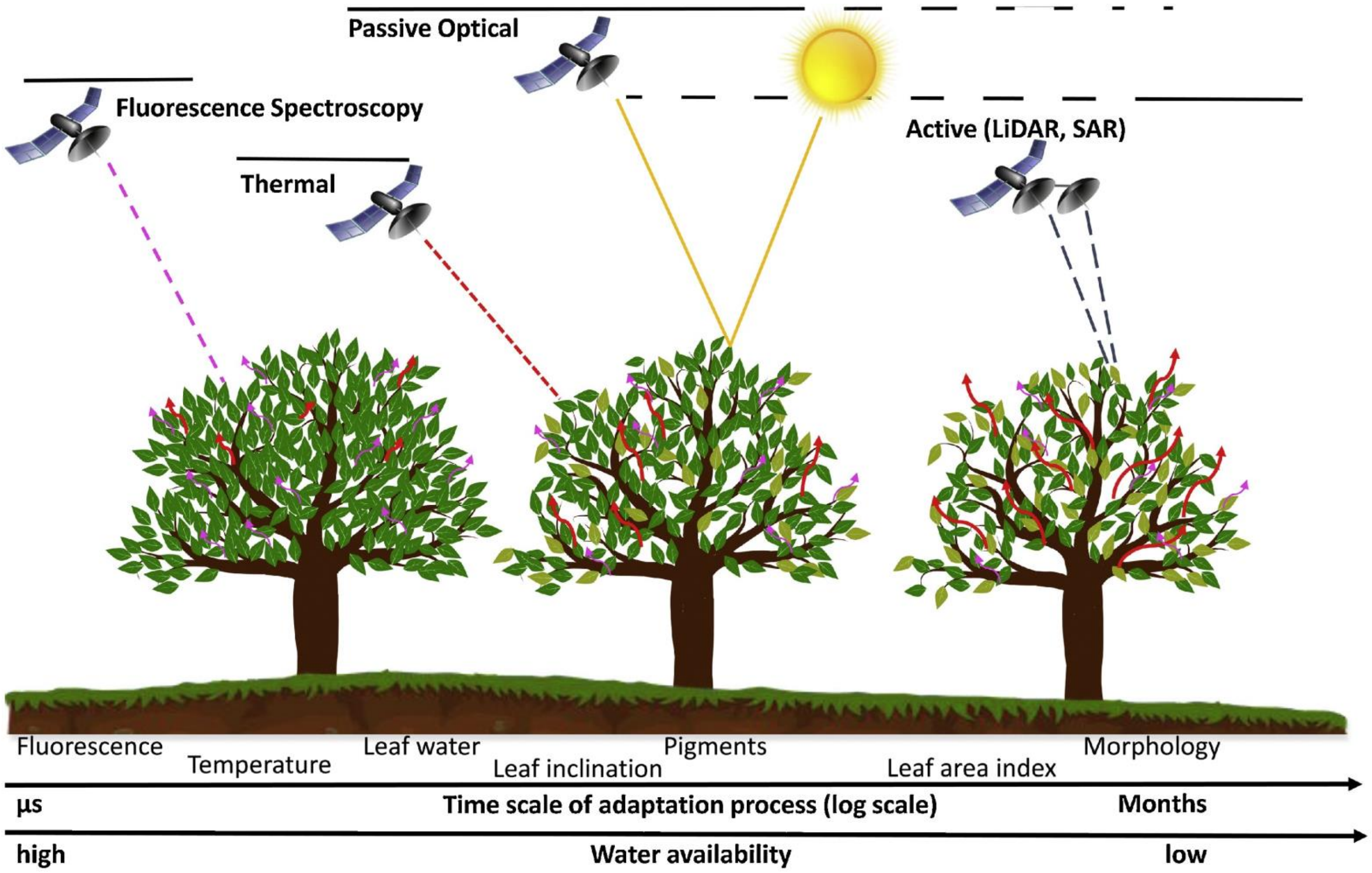
Sequence of drought occurrence and impacts for commonly accepted drought types. All droughts originate from a deficiency of precipitation or meteorological drought but other types of drought and impacts cascade from this deficiency. (Source: National Drought Mitigation Center, University of Nebraska-Lincoln,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

A plant's reaction to water stress



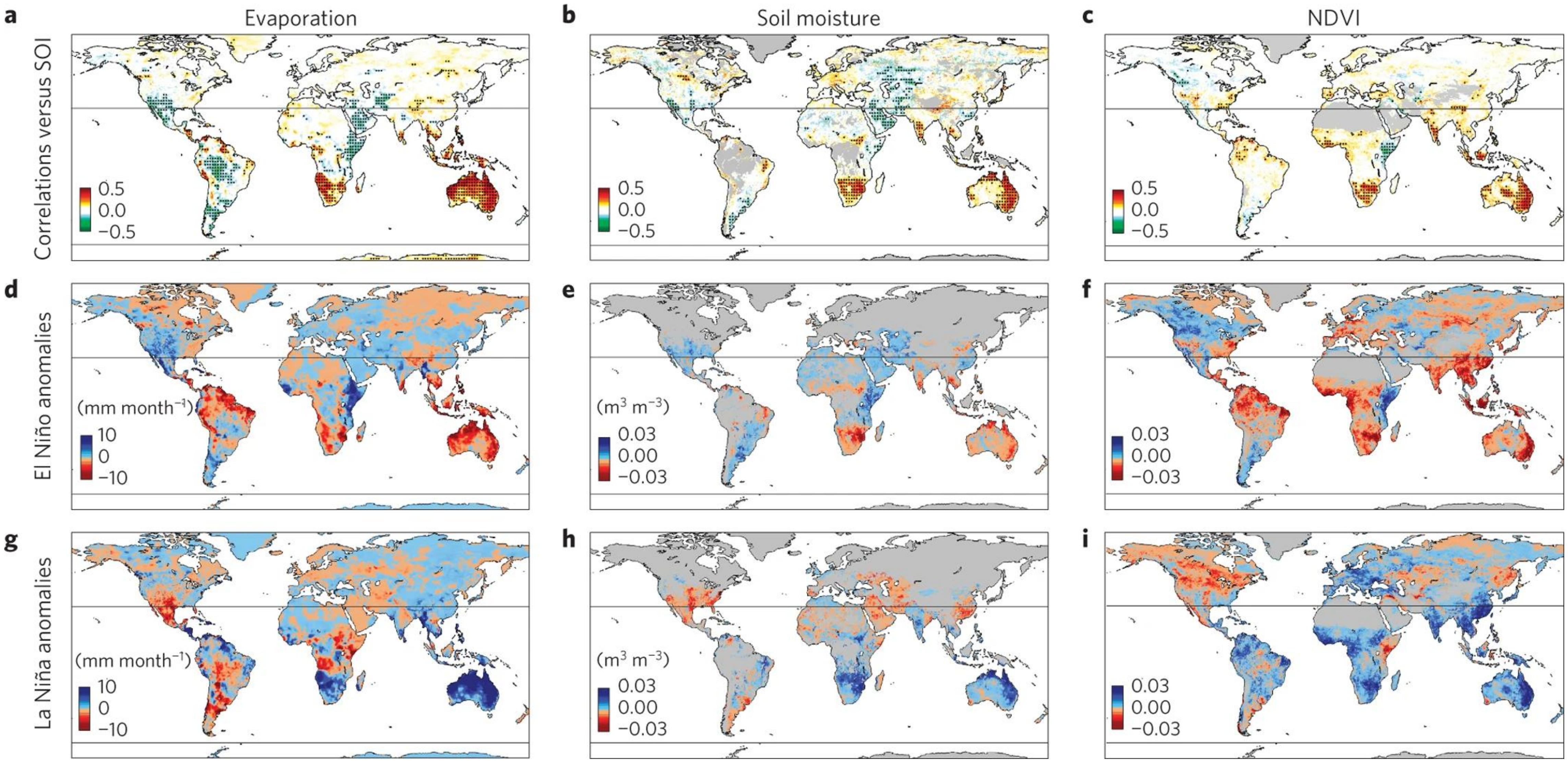
[Osakabe et al. 2014]

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



[Damn et al. 2018]

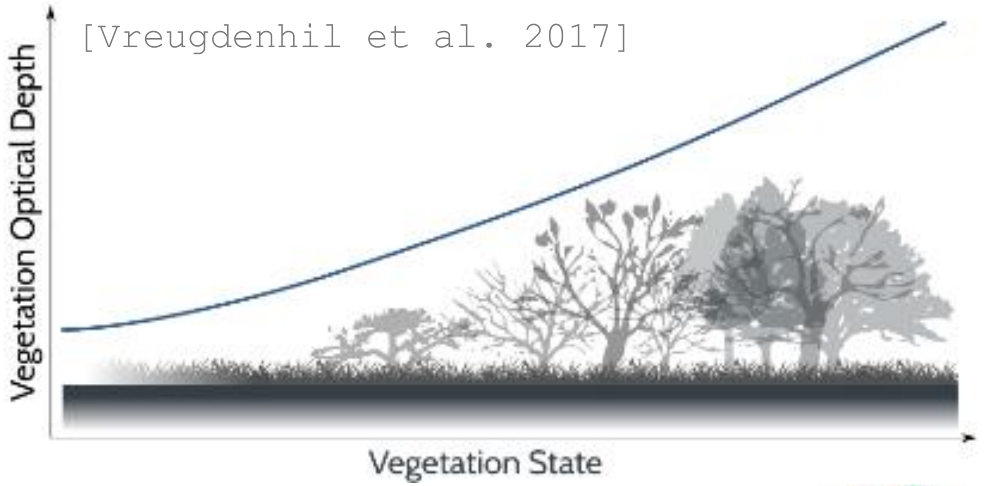
Linking moisture to vegetation activity

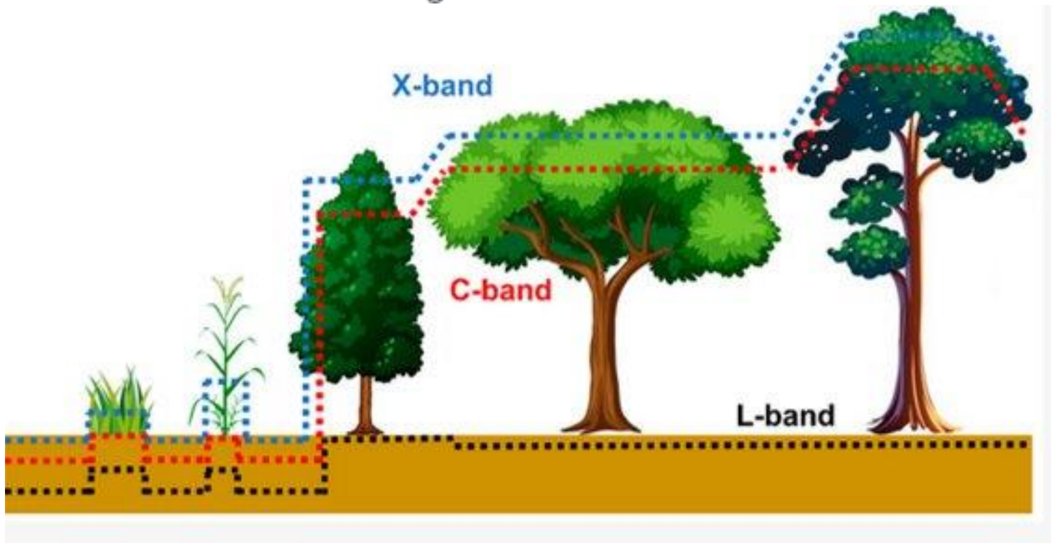


[Miralles et al. 2014]

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 Vreugdenhil LTC22)
  - Land Parameter Retrieval Model (VU/NASA/VanderSat/Planet) for radiometer data



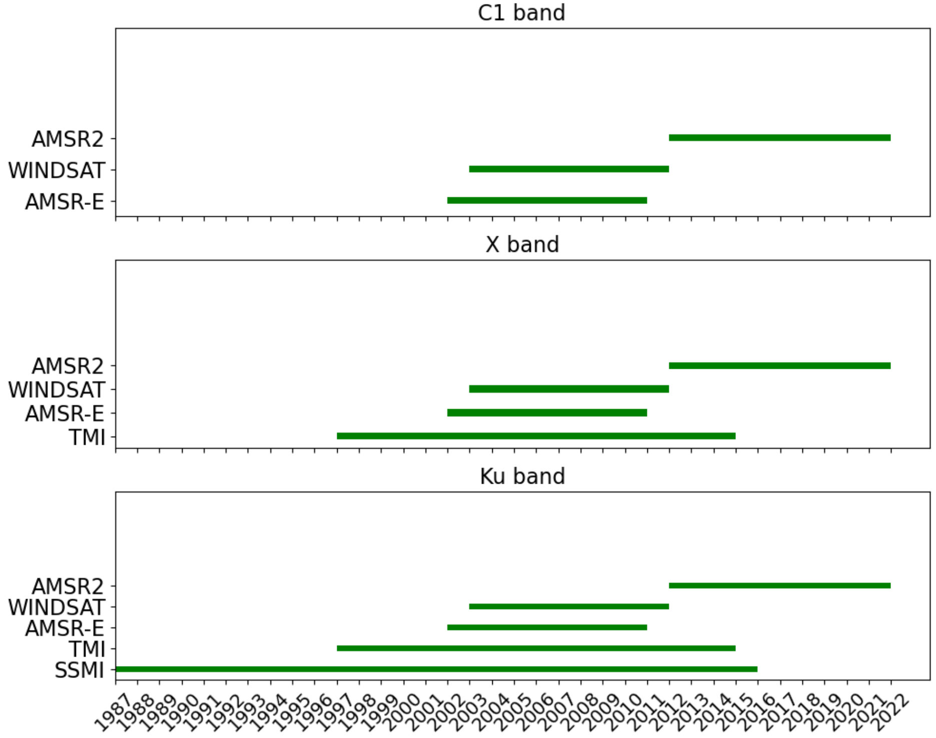


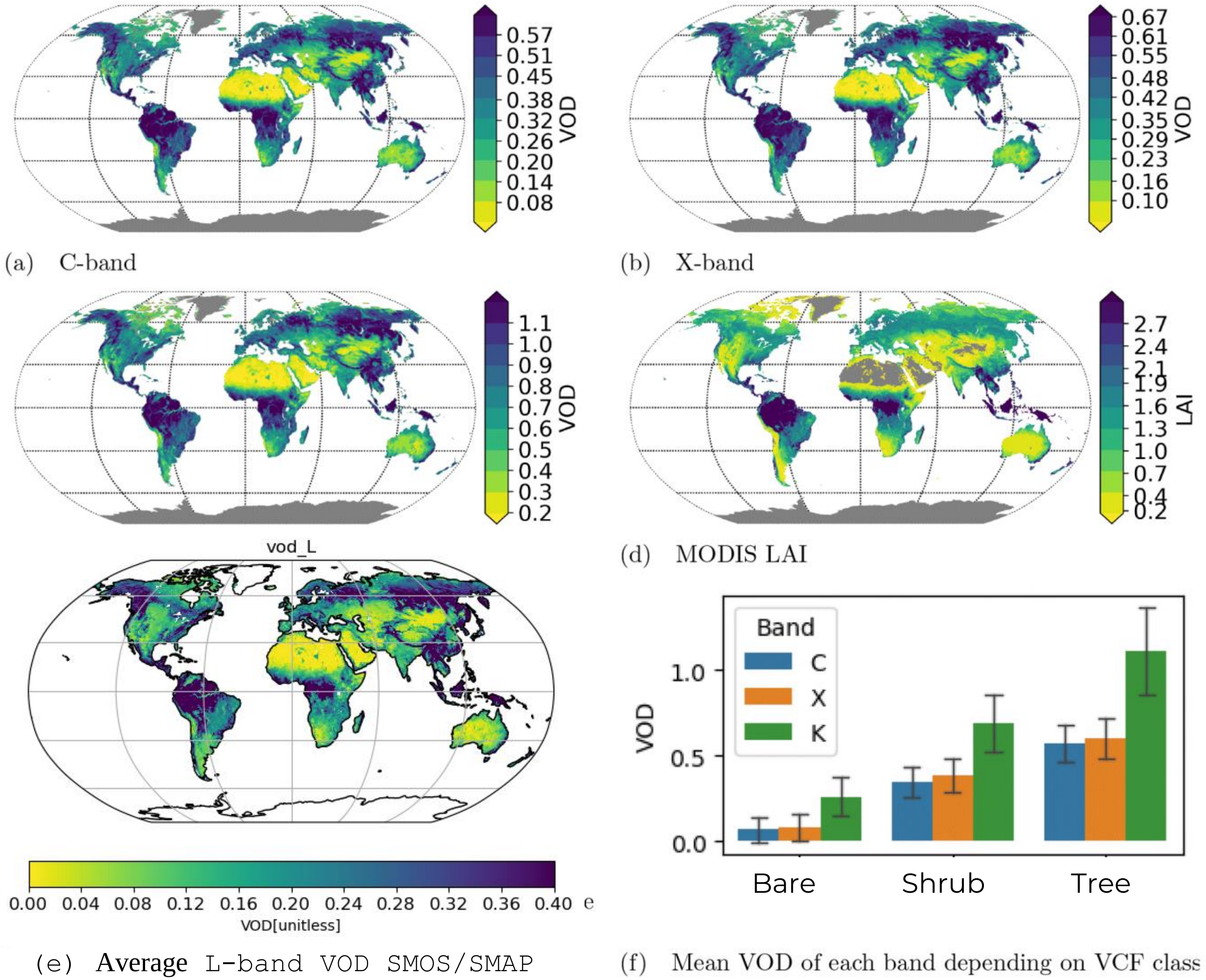
[Frappart et al. 2020]

VODCA - The VOD Climate Archive

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

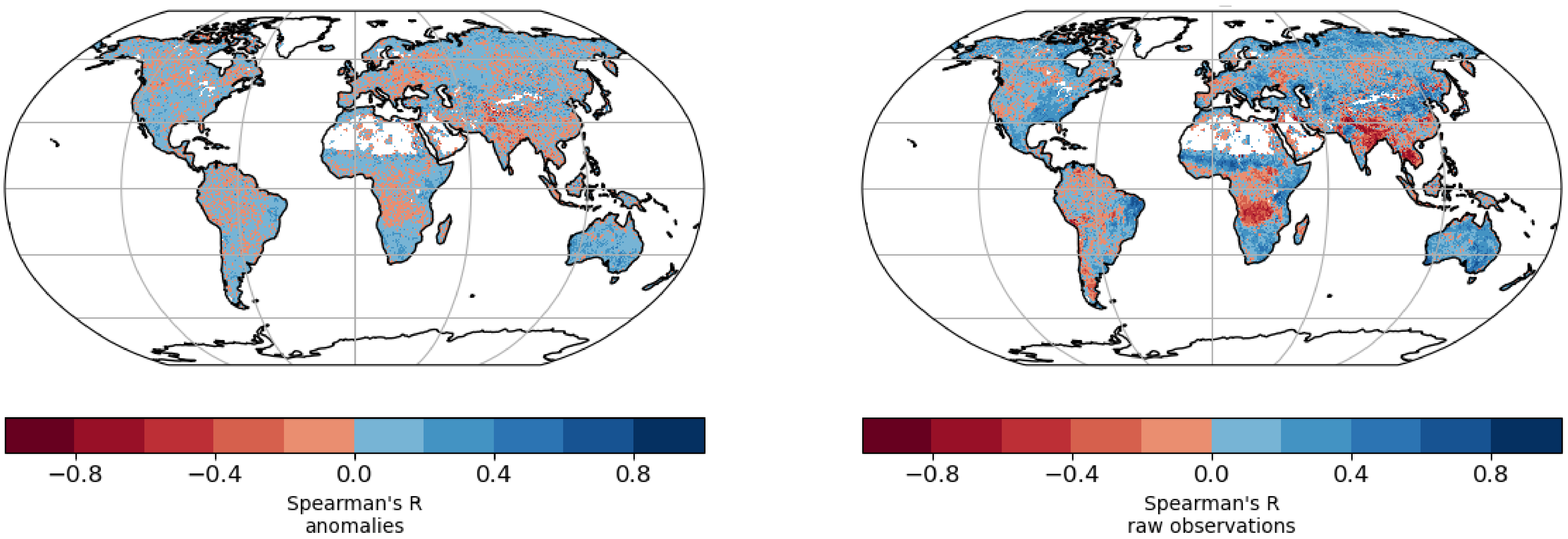
- Separate VODCA products for C-, X-, Ku-band
- 0.25° spatial sampling
- Daily, 1987 - 2021
- https://doi.org/10.5281/zenodo.2575599





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

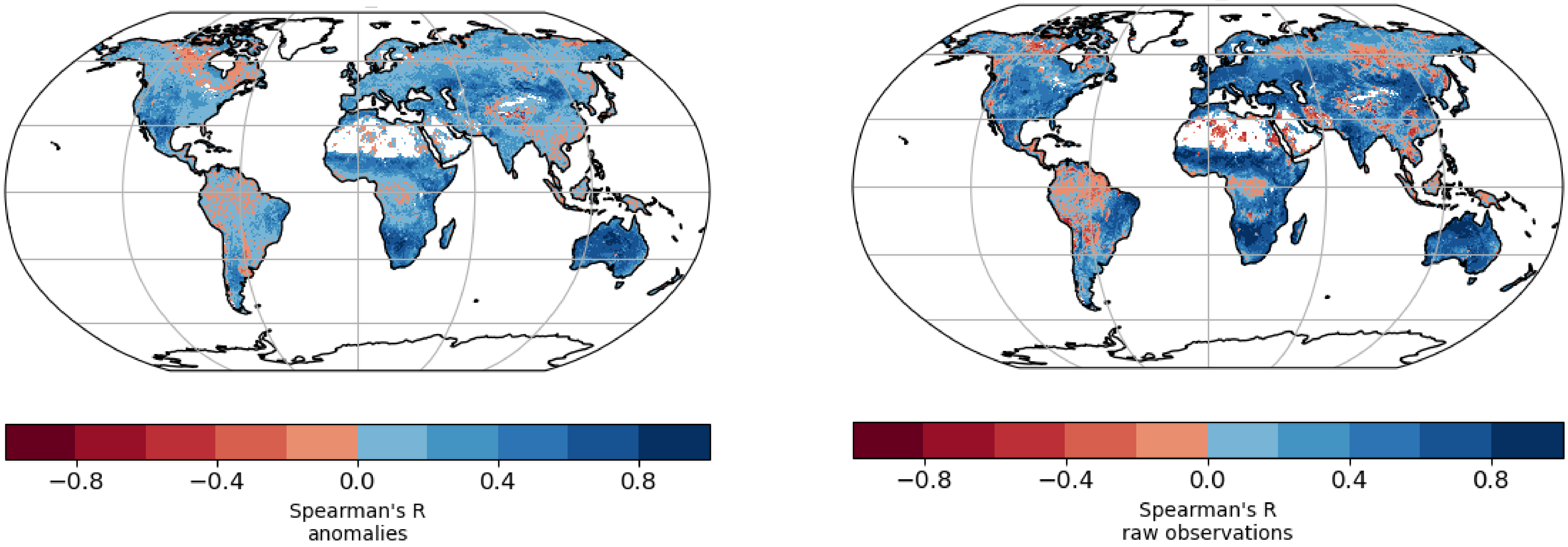
L-VODCA correlation with LAI



(2010-2019)

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

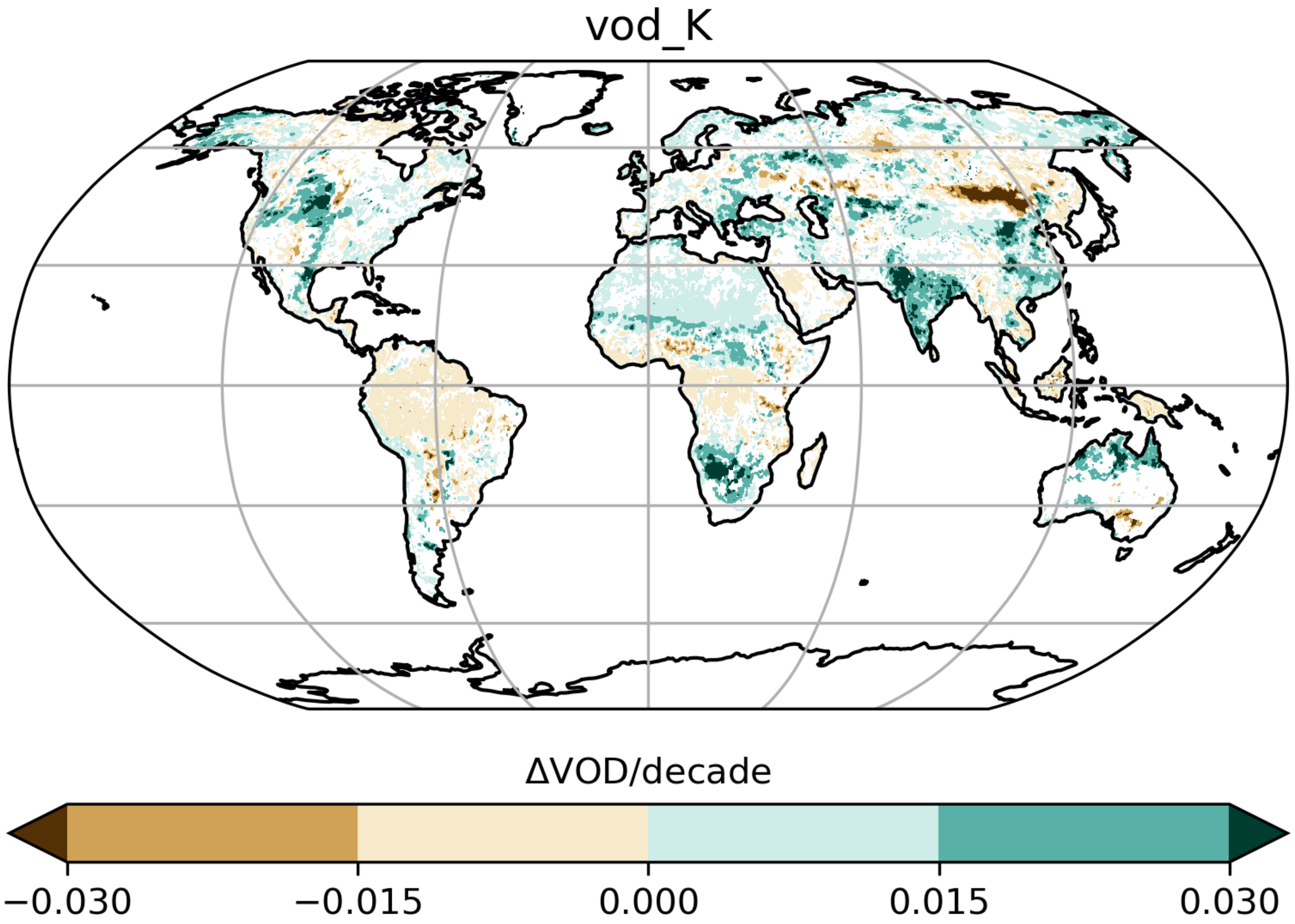
Ku-VODCA correlation with LAI



(2002-2017)

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

Ku-VODCA Trends (1987-2021)

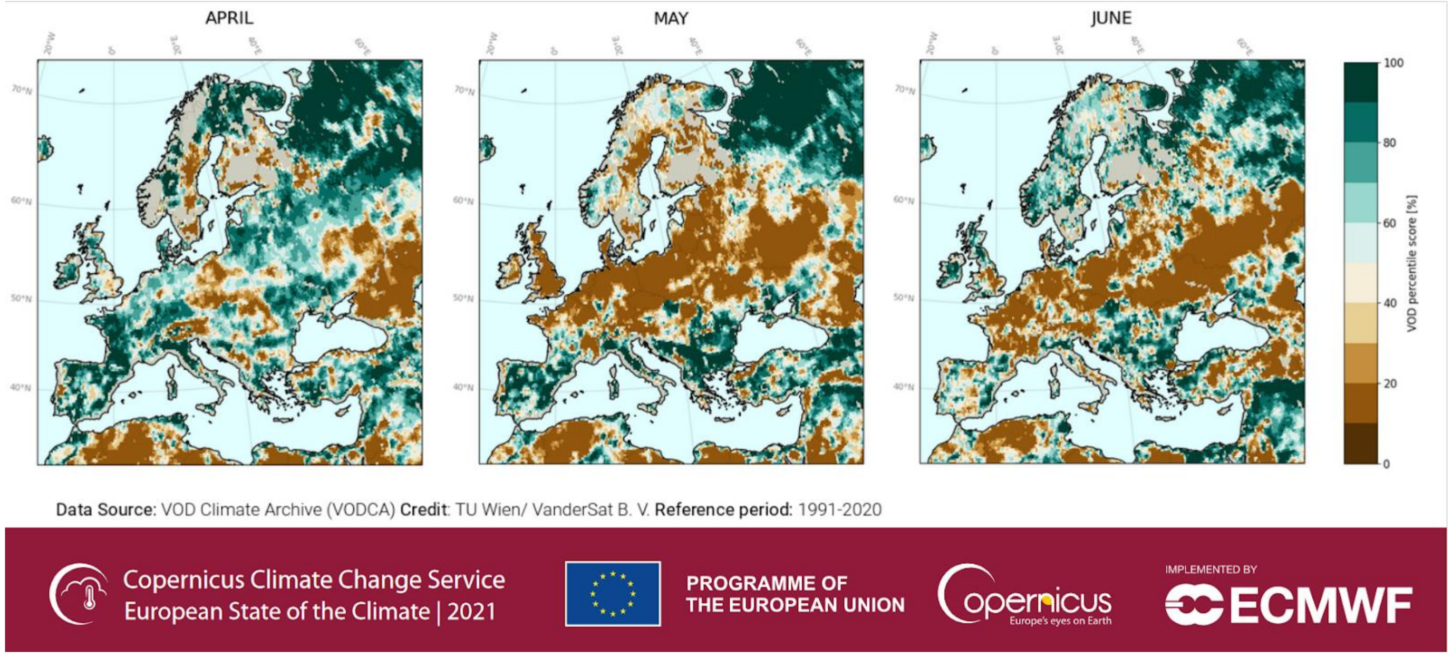


[Moesinger et al., 2020; 10.5194/essd-12-177-202]

VODCA - State of the Climate

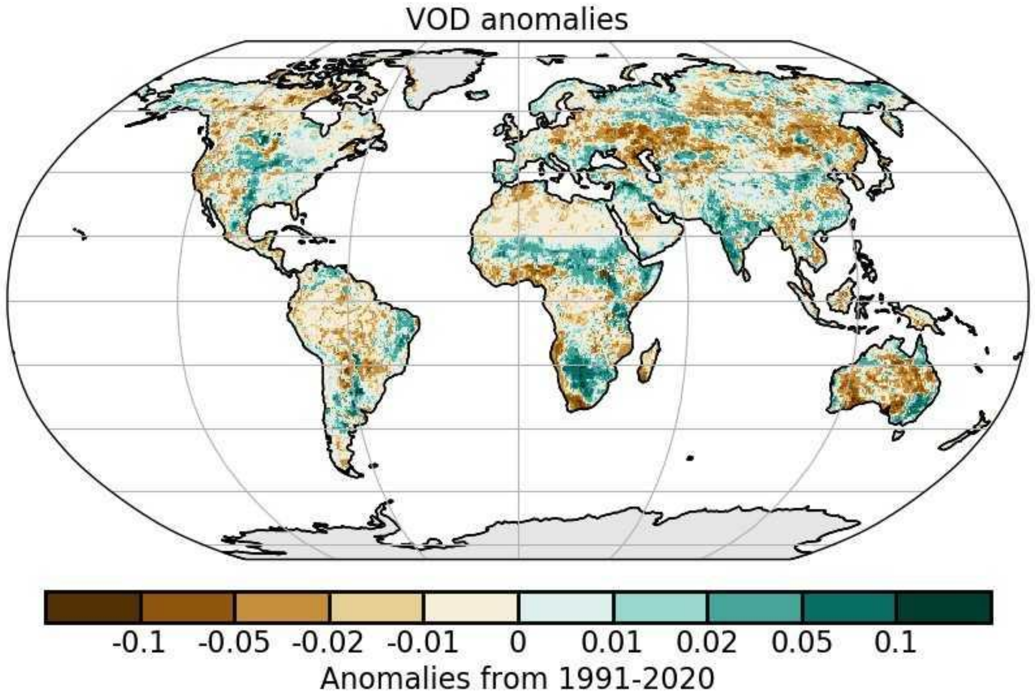
C3S European State of the Climate 2021

- Impact of late spring frost on vegetation



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

NOAA/BAMS State of the Climate 2021

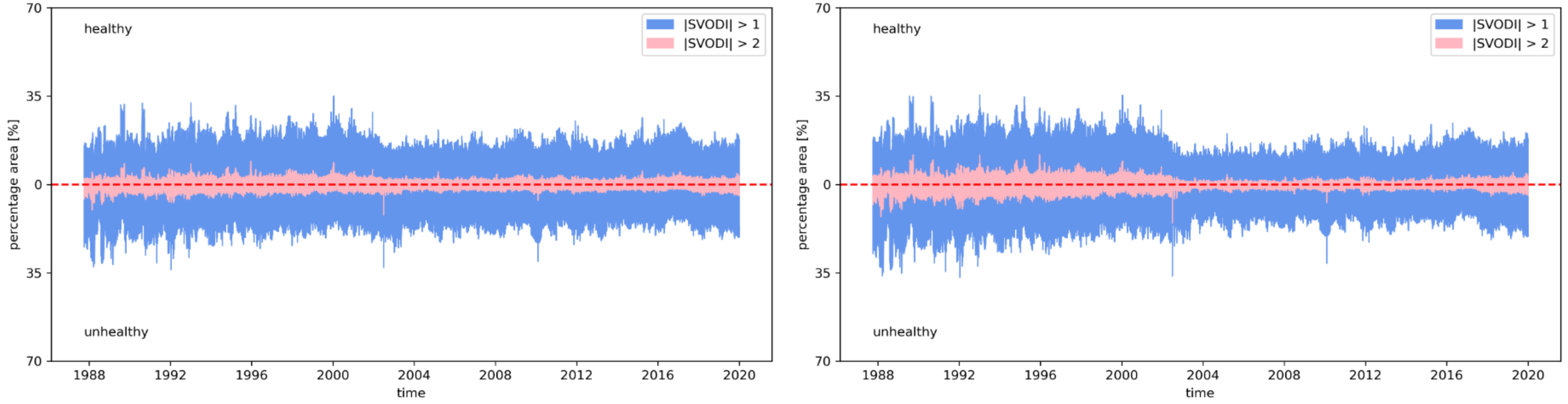


[Dorigo et al., 2021]

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

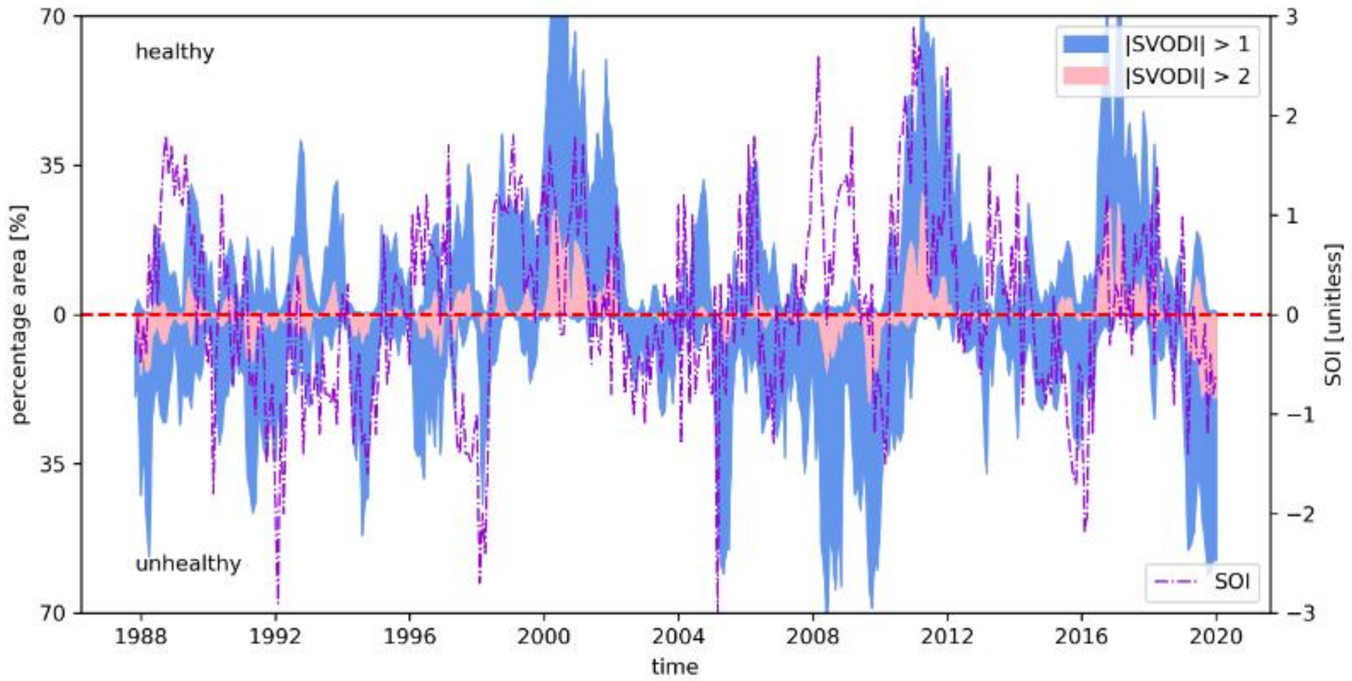
- Improves spatio-temporal sampling
- Uses a probabilistic merging method to deal with the varying instrument noise and sampling density of the data, similar as for SMASI



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

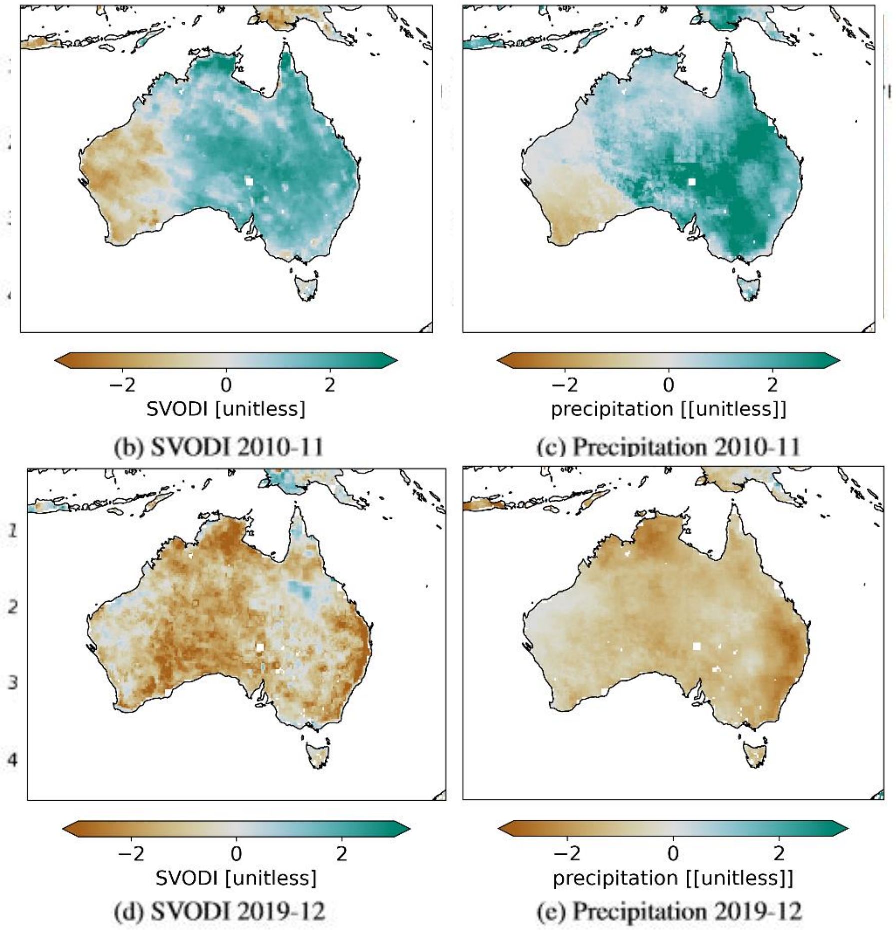
[Moesinger et al., 2022; 10.5194/bg-2021-360]

Standardised VOD Index



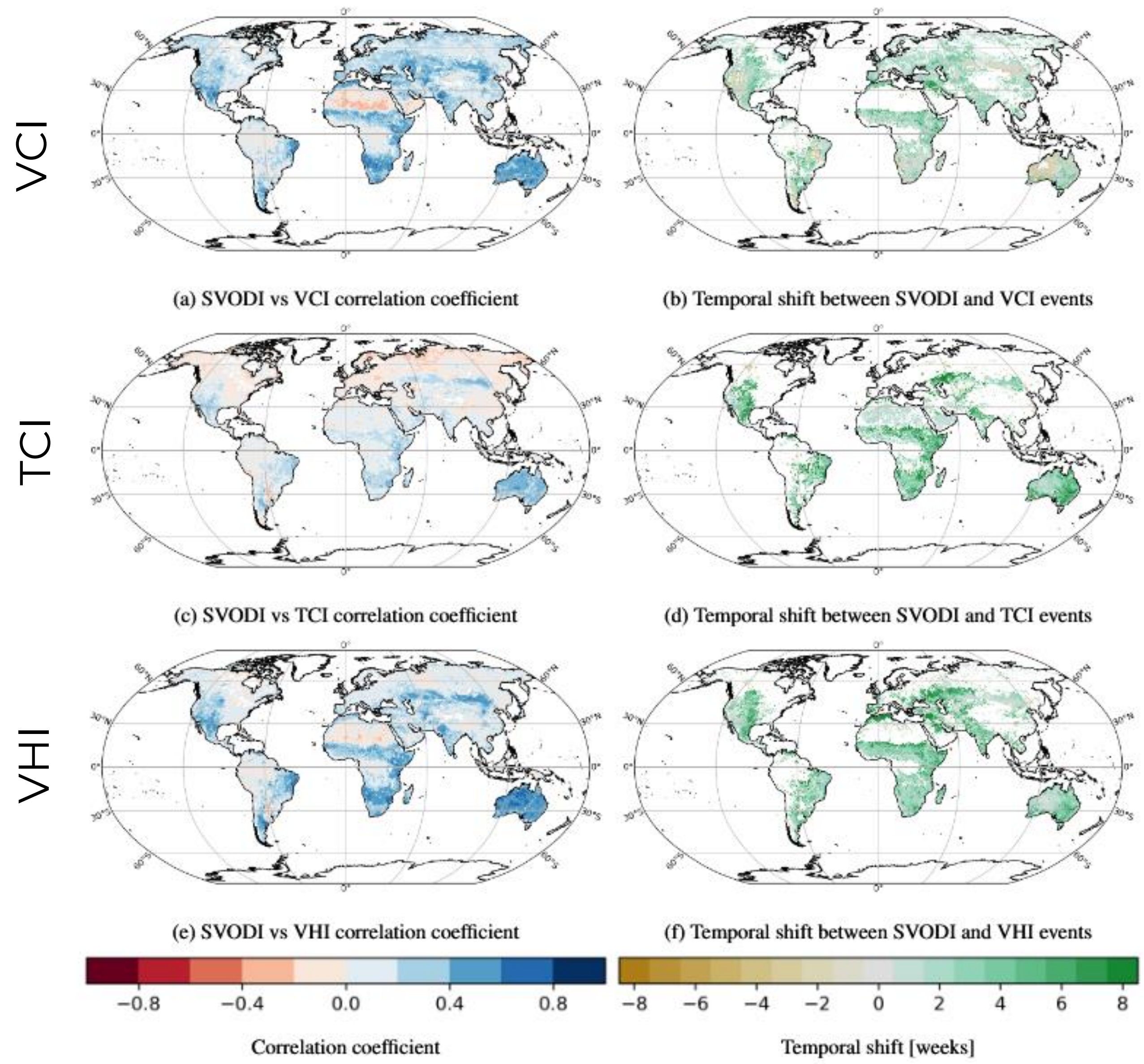
Fraction of percentage area of |SVODI| > 1 > 2 for central Australia along with Southern Oscillation Index

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



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

SVODI



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

- Vegetation Condition Index (VNIR)
- Temperature Condition Index (thermal)
- Vegetation Health Index (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)

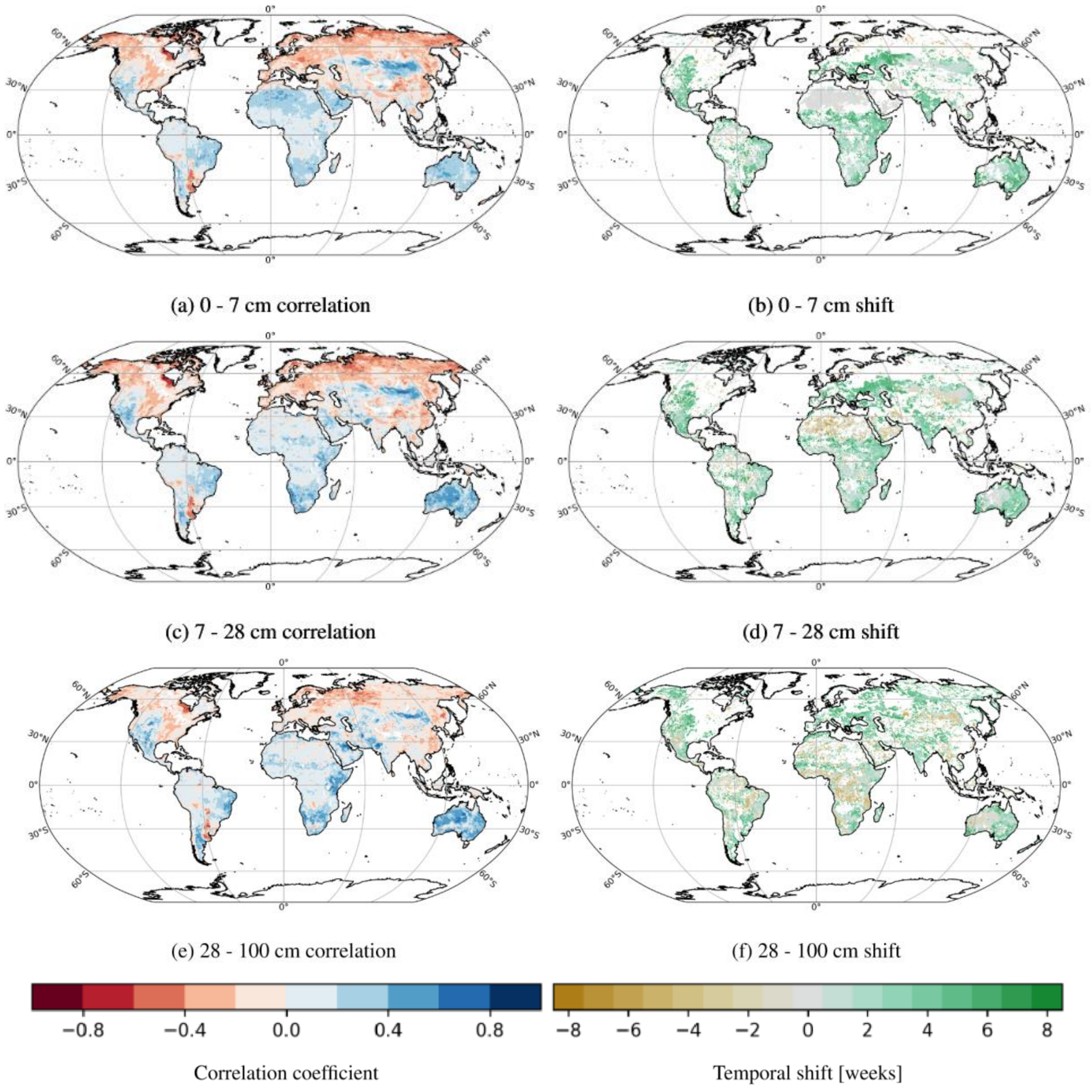
[Moesinger et al., 2022; 10.5194/bg-2021-360]

SVODI

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



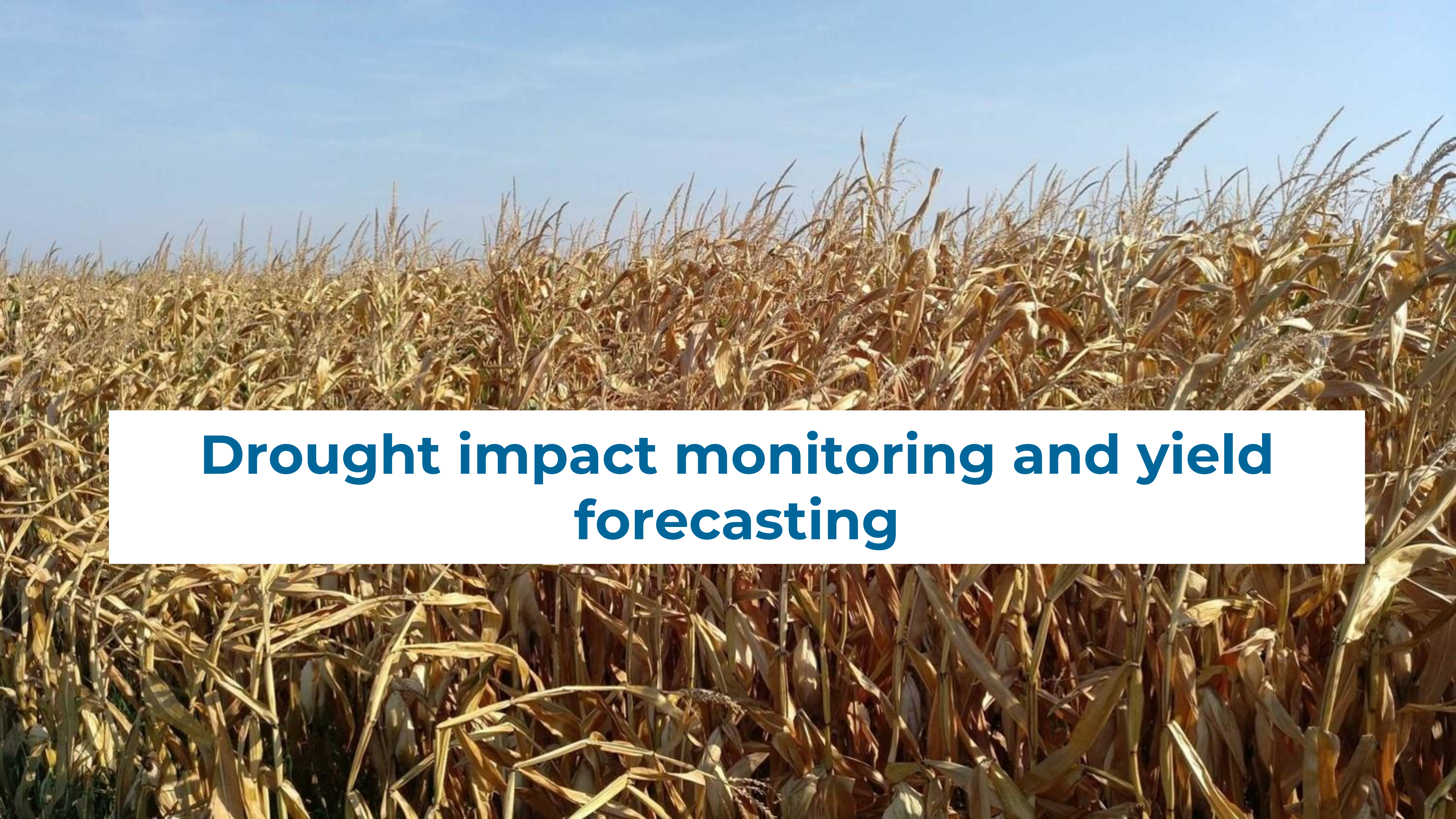
[Moesinger et al., 2022; 10.5194/bg-2021-360]

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

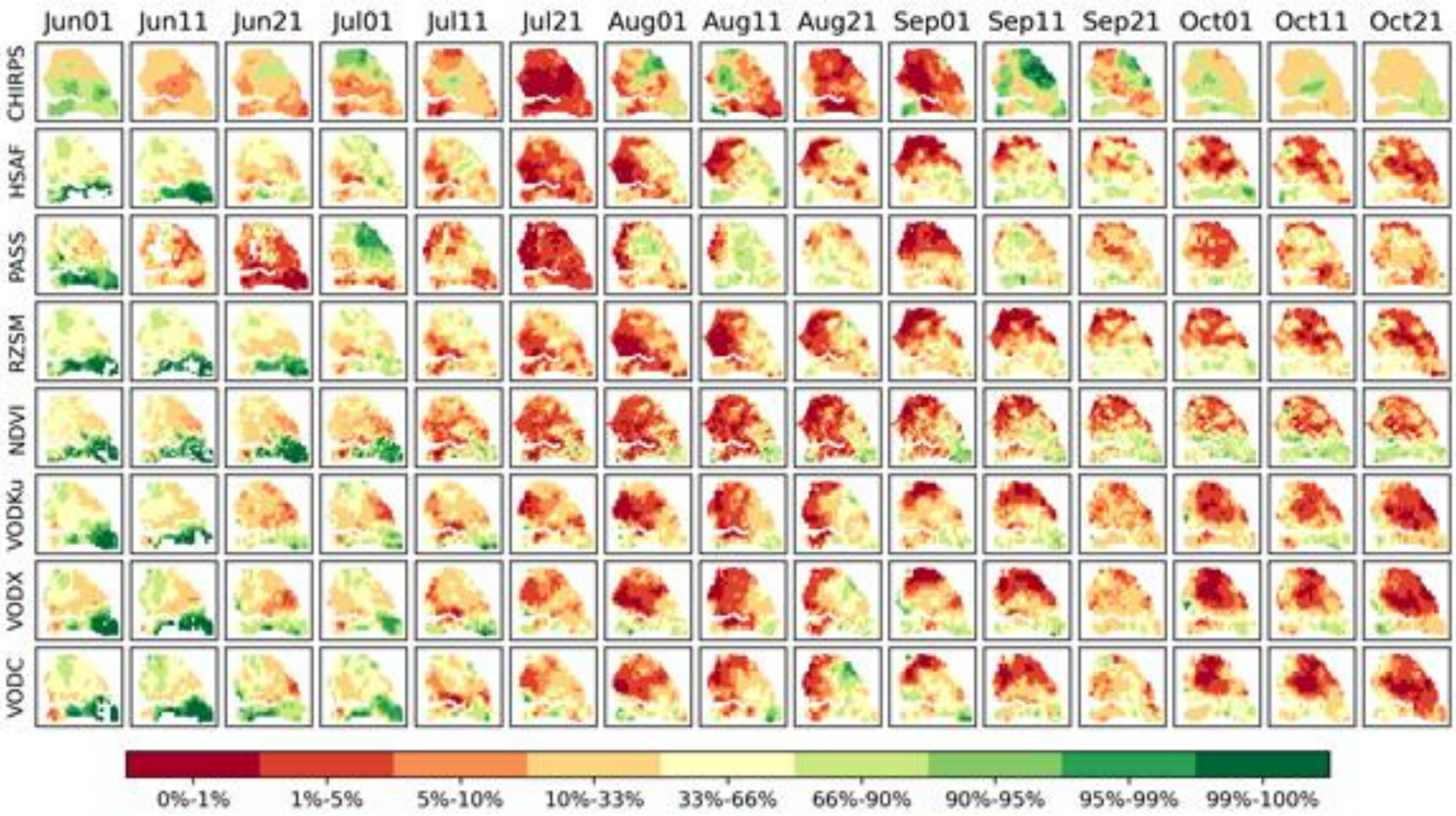
- **SVODI** allows to assess the impact of extreme events and water cycle variability on global vegetation dynamics



Drought impact monitoring and yield forecasting

Senegal 2014 drought

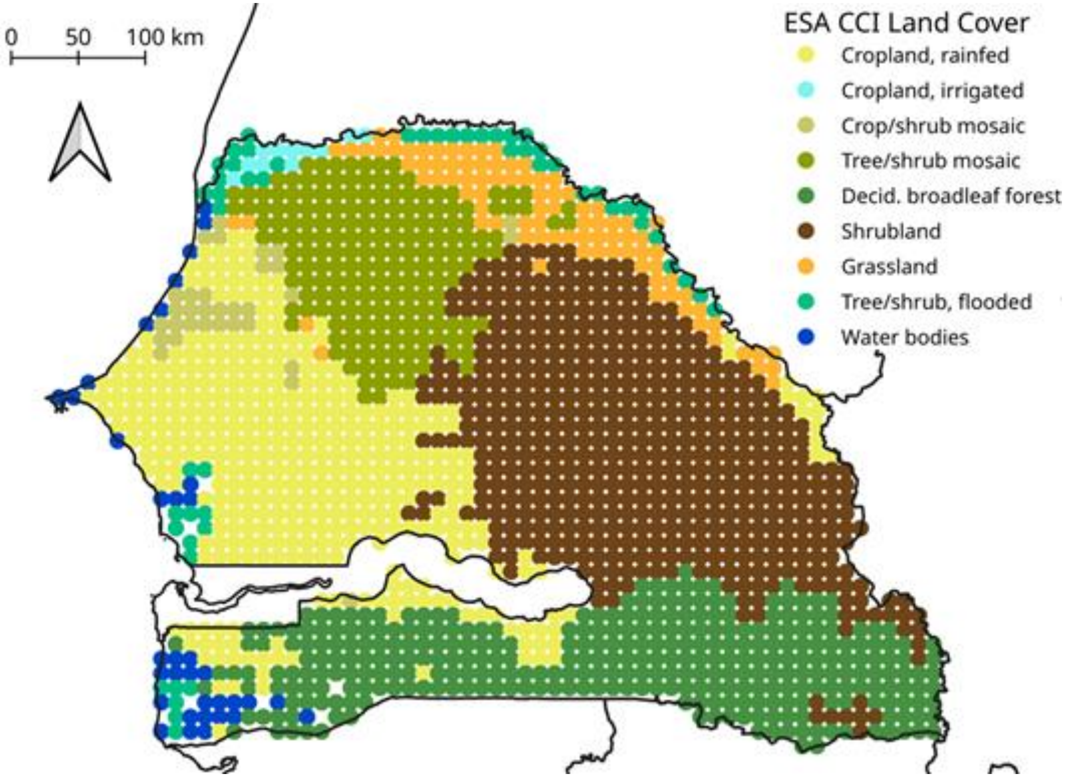
- Impact in multiple indicators
- Strongly water-limited region

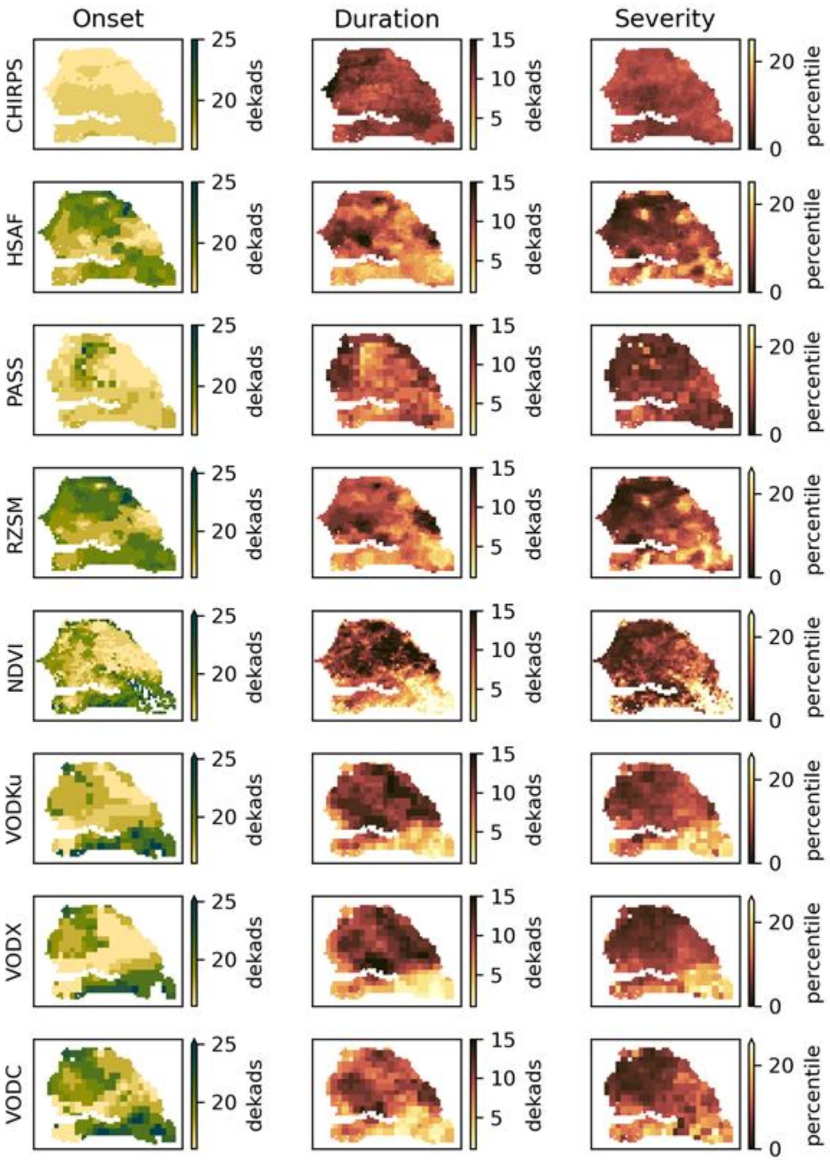


[Vreugdenhil, Pfeil et al., 2022]

Senegal 2014 drought

- Drought impact carries the signature of land cover





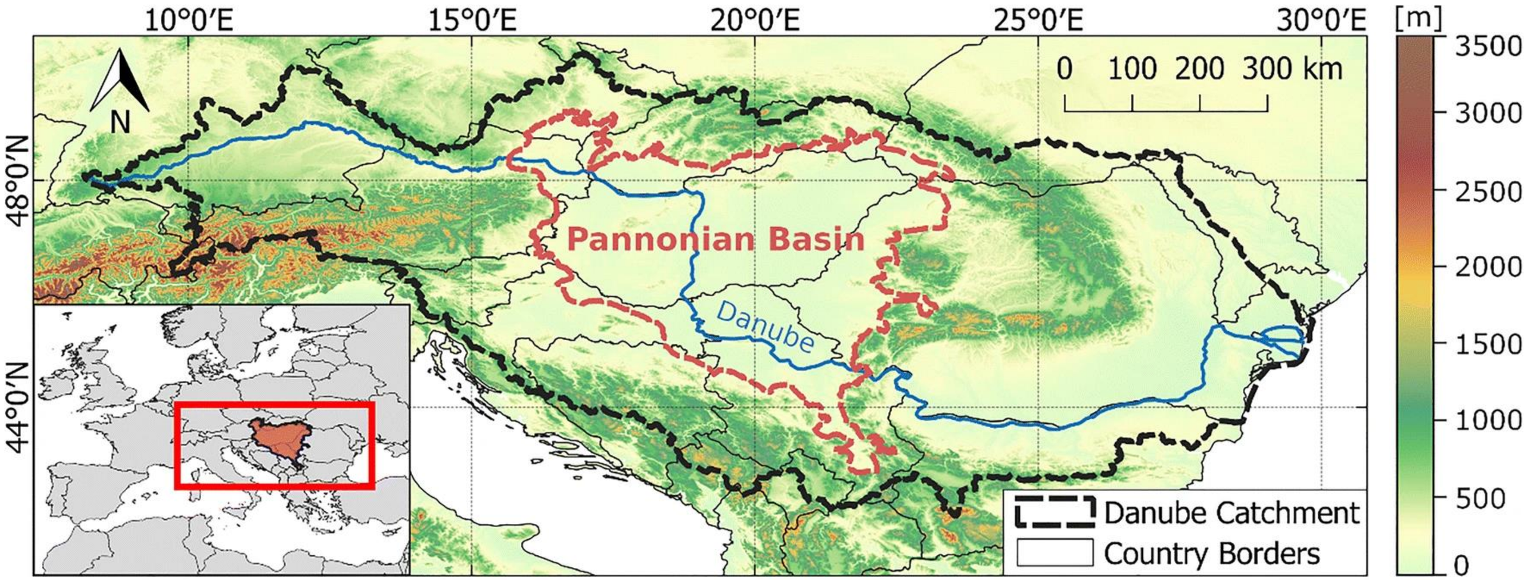
[Vreugdenhil, Pfeil et al., 2022]

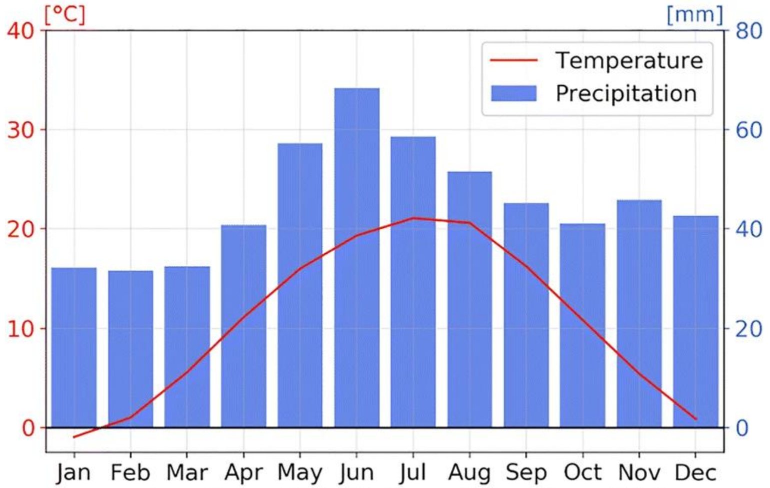
Drought in the Pannonian Basin

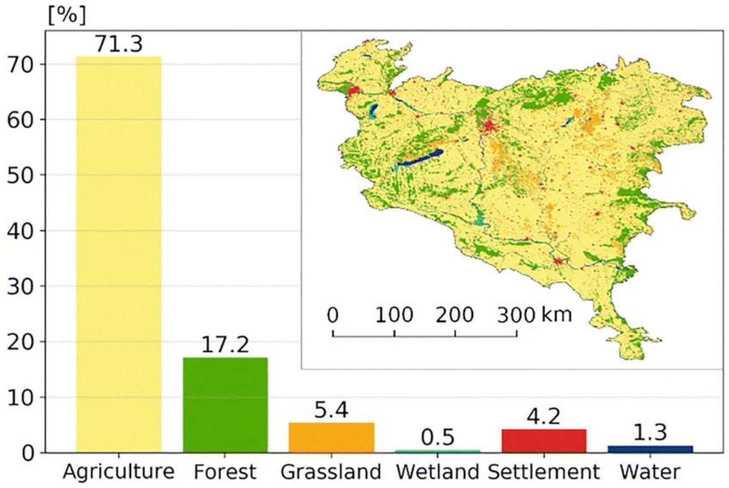
Sheltered, with relatively low levels of precipitation (< 600 mm/year)

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

Mainly rain-fed



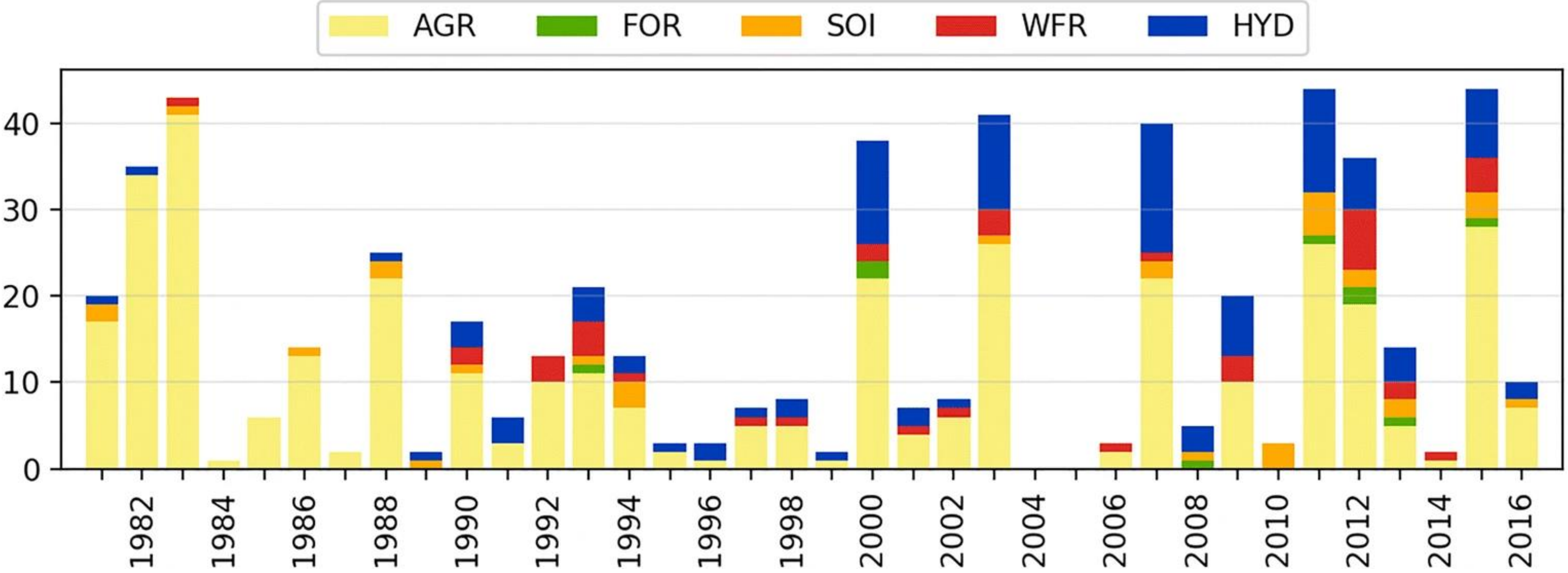




[Crocetti et al., 2020]

Drought impacts in the Pannonian Basin

Reported by various media

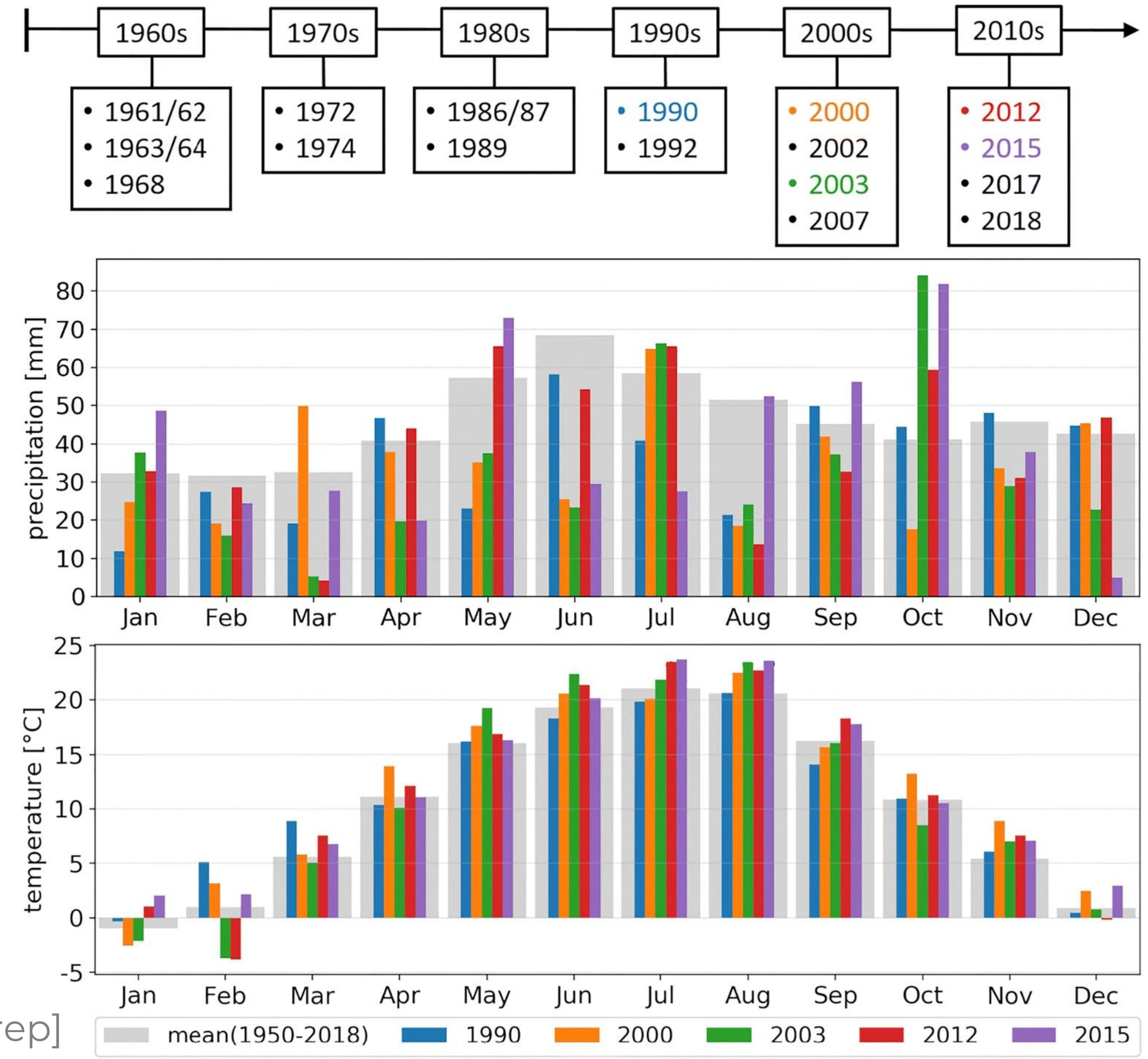


AGR|Agriculture - FOR|Forests - SOI||Soils – WFR|Wildfires – HYD|Hydrology

[Crocetti et al., 2020]

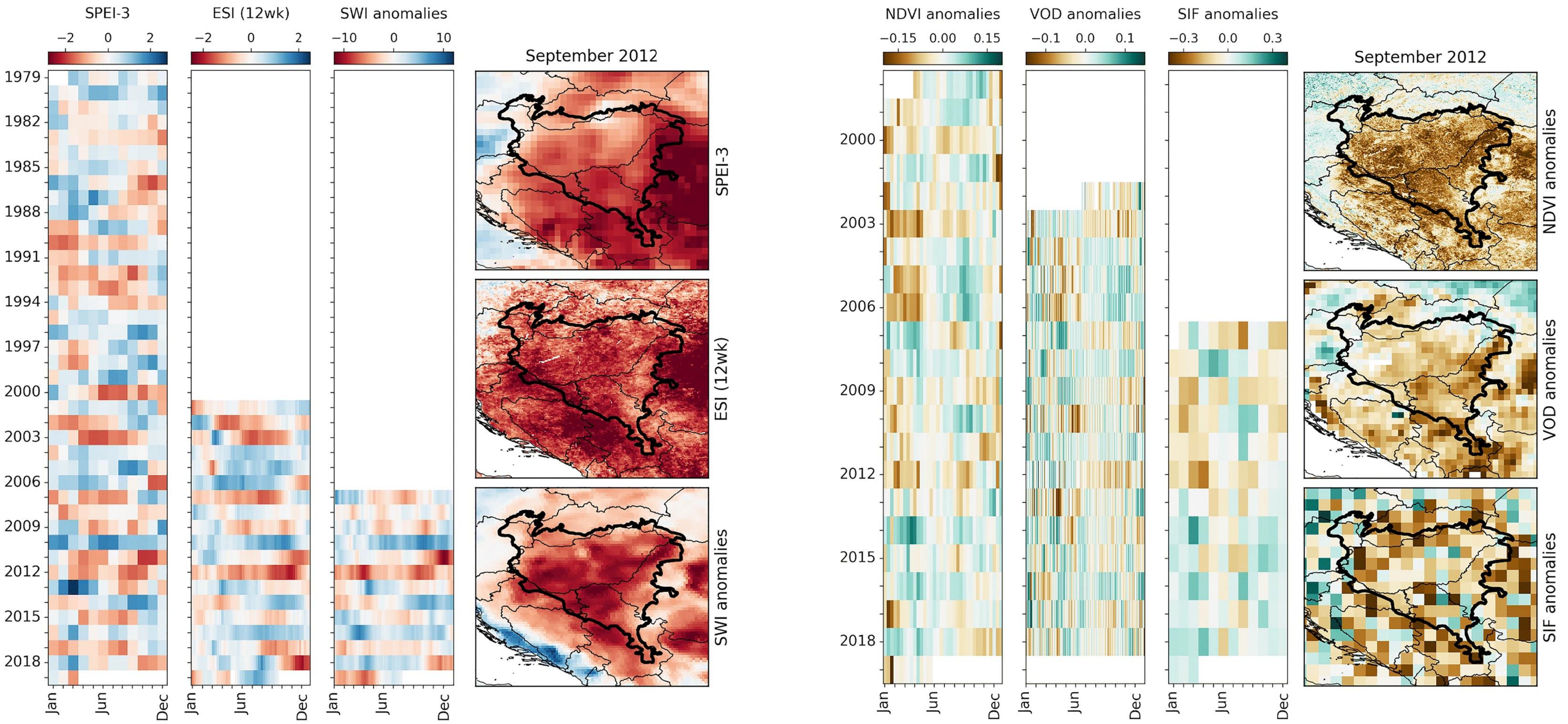
Climatological conditions and yield loss

- 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., in prep]

Earth observation for yield forecasting



[Crocetti et al., 2020]

Can we predict yield losses?

- Numerous EO-based crop yield models have been developed and applied
  - Process-based
  - Machine learning

- Application over large areas possible using EO data, reanalysis and meteorological observations

- Extreme weather conditions complicate accurate crop yield forecasts

The ARYA crop yield forecasting algorithm: Application to the main wheat exporting countries

B. Franch [a,b,*], E. Vermote [c], S. Skakun [b,c], A. Santamaria-Artigas [b,c], N. Kalecinski [b,c], J.-C. Roger [b,c], I. Becker-Reshef [b], B. Barker [b], C. Justice [b], J.A. Sobrino [a]

Towards regional grain yield forecasting with 1 km-resolution EO biophysical products: Strengths and limitations at pan-European level

Raúl López-Lozano [a,*], Gregory Duveiller [a,b], Lorenzo Seguini [a], Michele Meroni [a], Sara García-Condado [a], Josh Hooker [a], Olivier Leo [a], Bettina Baruth [a]

Statistical modelling of crop yield in Central Europe using climate data and remote sensing vegetation indices

Anikó Kern [a], Zoltán Barcza [b,c,d,*], Hrvoje Marjanović [e], Tamás Árendás [f], Nándor Fodor [f], Péter Bónis [f], Péter Bognár [a], János Lichtenberger [a,g]

In-season performance of European Union wheat forecasts during extreme impacts

glar, S. Garcia Condado, S. Karetsos, R. Lecerf,
) & M. van den Berg

Seasonal weather forecasts for crop yield modelling in Europe

Pierre Cantelaube & Jean

Statistical modelling of drought-related yield losses using soil moisture-vegetation remote sensing and multiscalar indices in the south-eastern Europe

Vera Potopová [a,*], Miroslav Trnka [b,c], Pavel Hamouz [a], Josef Soukup [a], Tudor Castraveţ [d]

Yield estimation and forecasting for winter wheat in Hungary using time series of MODIS data

Péter Bognár [a], Anikó Kern [a], Szilárd Pásztor [a], János Lichtenberger [b], Dávid Koronczay [a] and Csaba Ferencz [a]

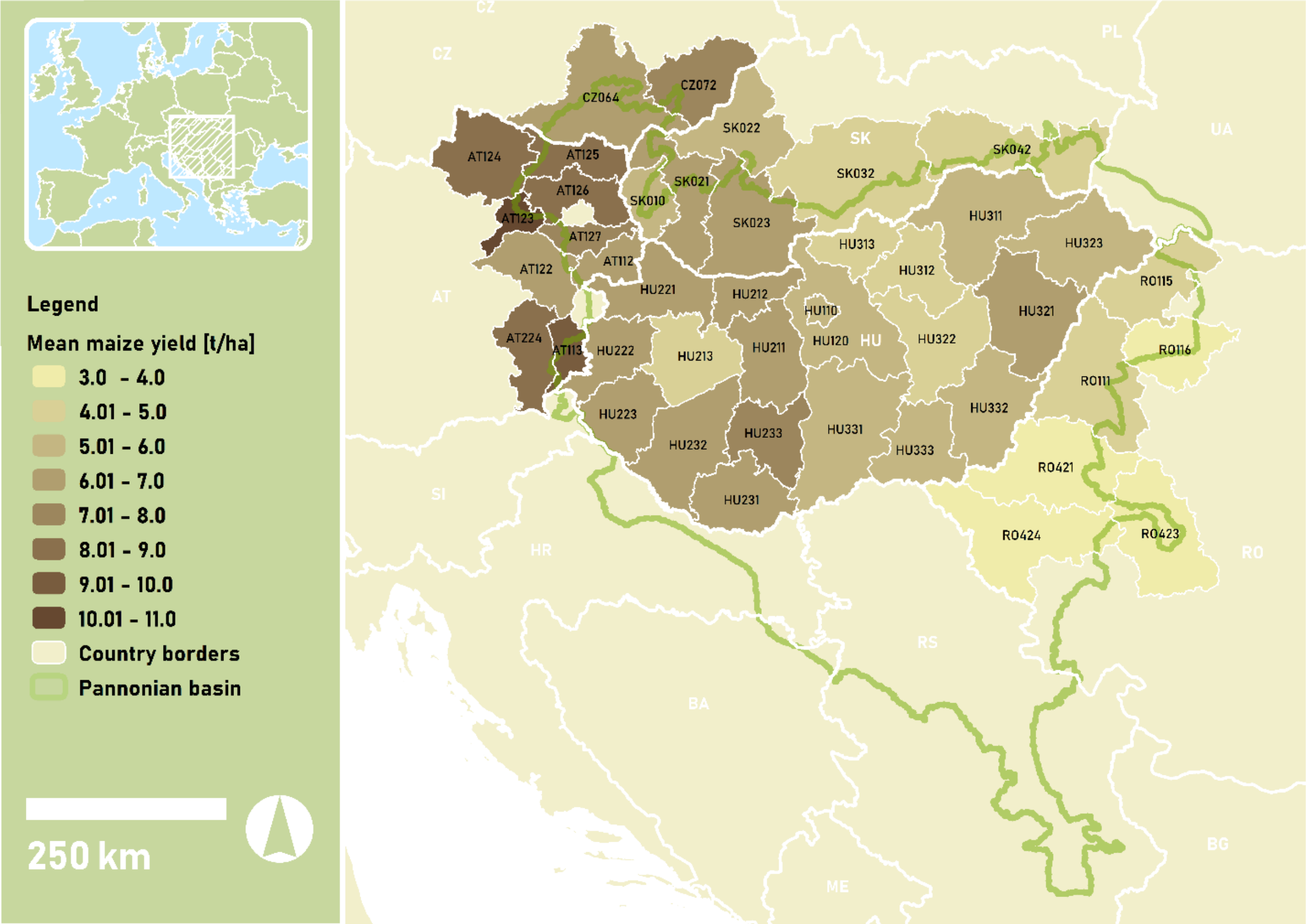
Can we predict yield losses?

- 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



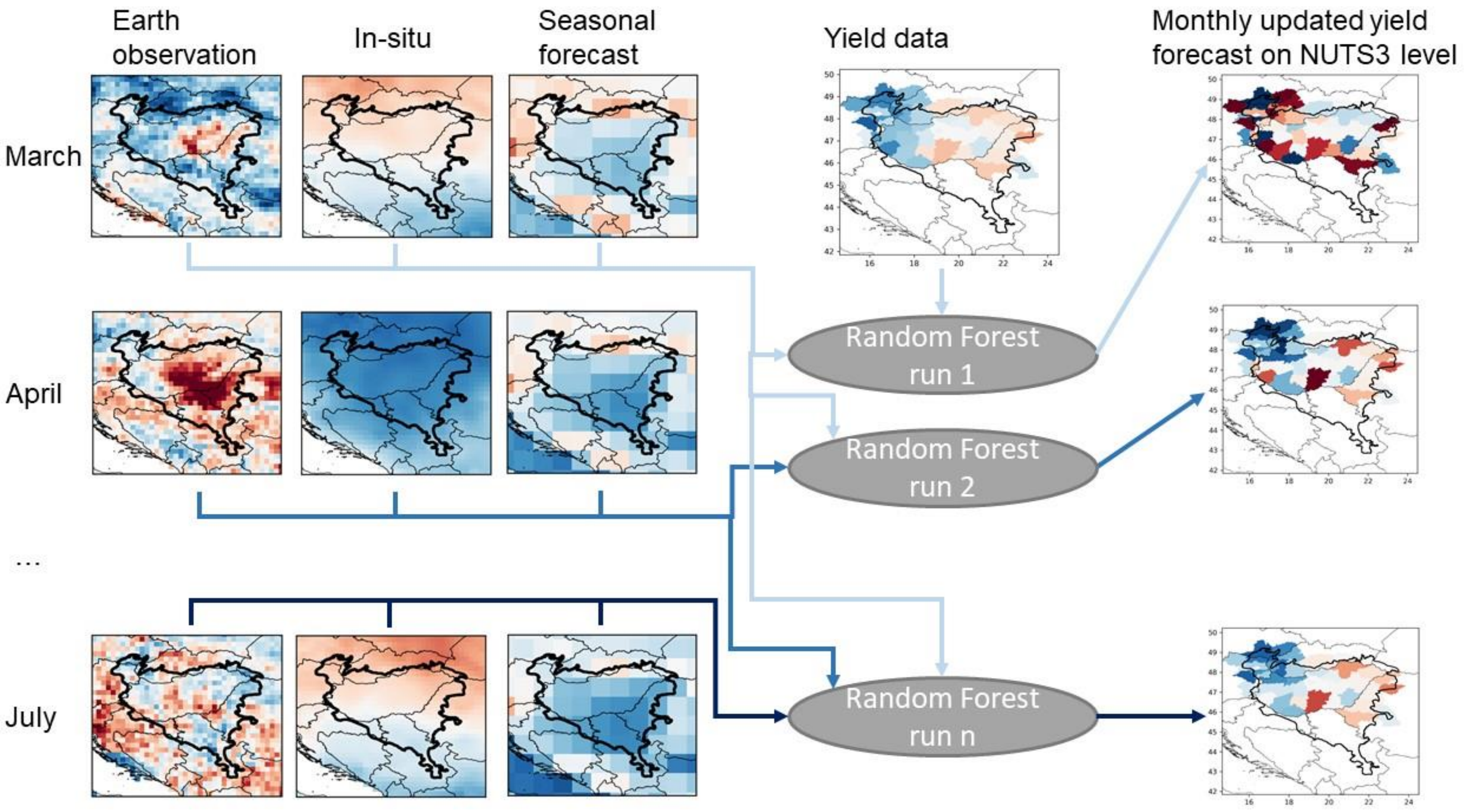
Predictor data

- 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
Earth Observation			
Soil Moisture	ESA CCI	0.25°	daily
Soil Water Index	ESA CCI	0.25°	daily
VOD Ku-Band	VODCA	0.25°	daily
NDVI	CGLS	0.01°	10-daily
LAI	CGLS	0.01°	10-daily
ESI (1 and 3 months)	MODIS	0.05°	weekly
Reanalysis			
Temperature	ERA5-Land	0.1°	daily
Growing Degree Days	ERA5-Land	0.1°	monthly
SPEI (1 and 3 months)	ERA5	0.25°	monthly
Seasonal forecasts			
Precipitation	ECMWF	1°	monthly
Temperature	ECMWF	1°	monthly
In situ data			
Temperature	E-OBS	0.25°	daily
Precipitation	E-OBS	0.25°	daily
Fraction of wet days	E-OBS	0.25°	monthly

Random forests

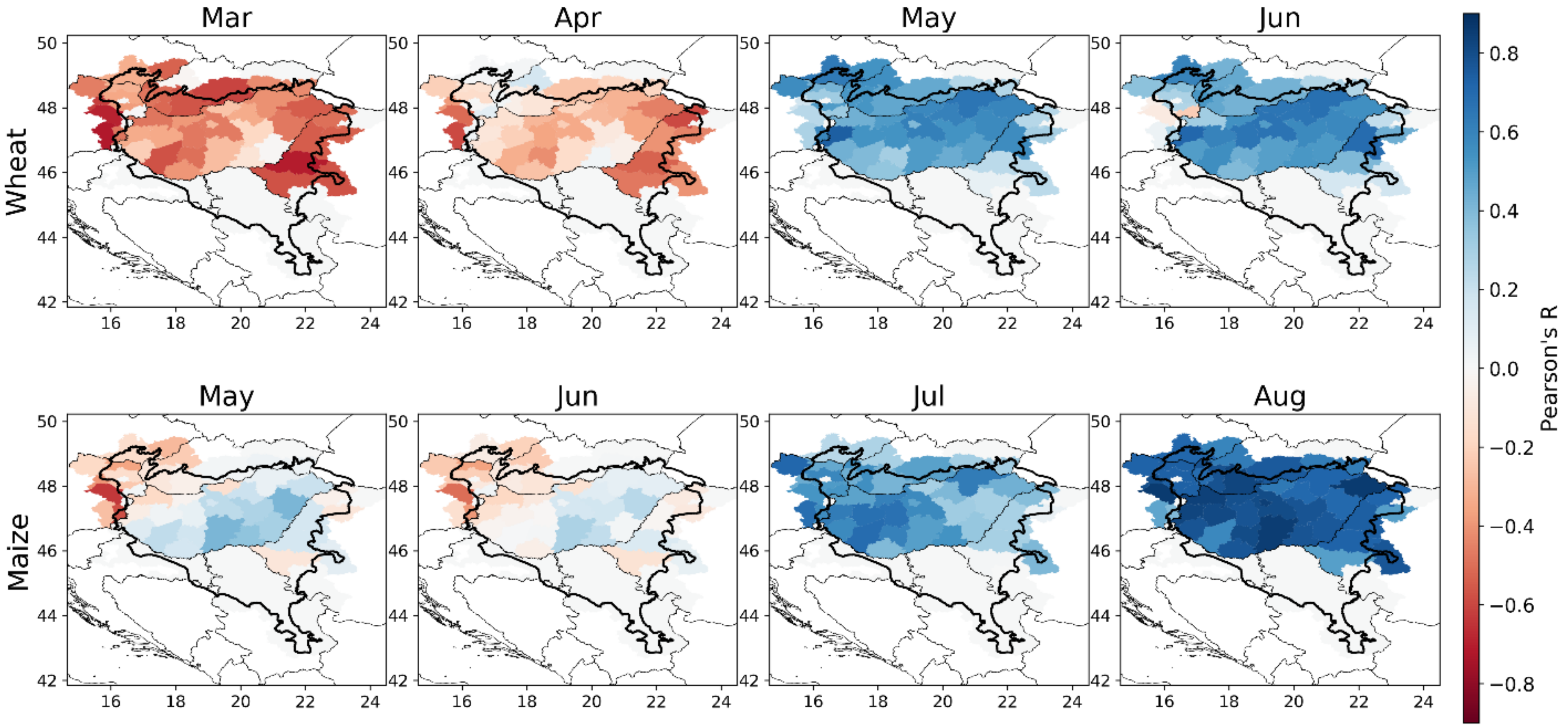
- Crop yield forecasts with lead times up to 4 months before harvest
- Feature importance to assess impact of predictors
- Monthly updated with latest data
- Cross-validation leaving 3 years out in blocked periods



[Bueechi et al., in prep

Skill per NUTS3 region

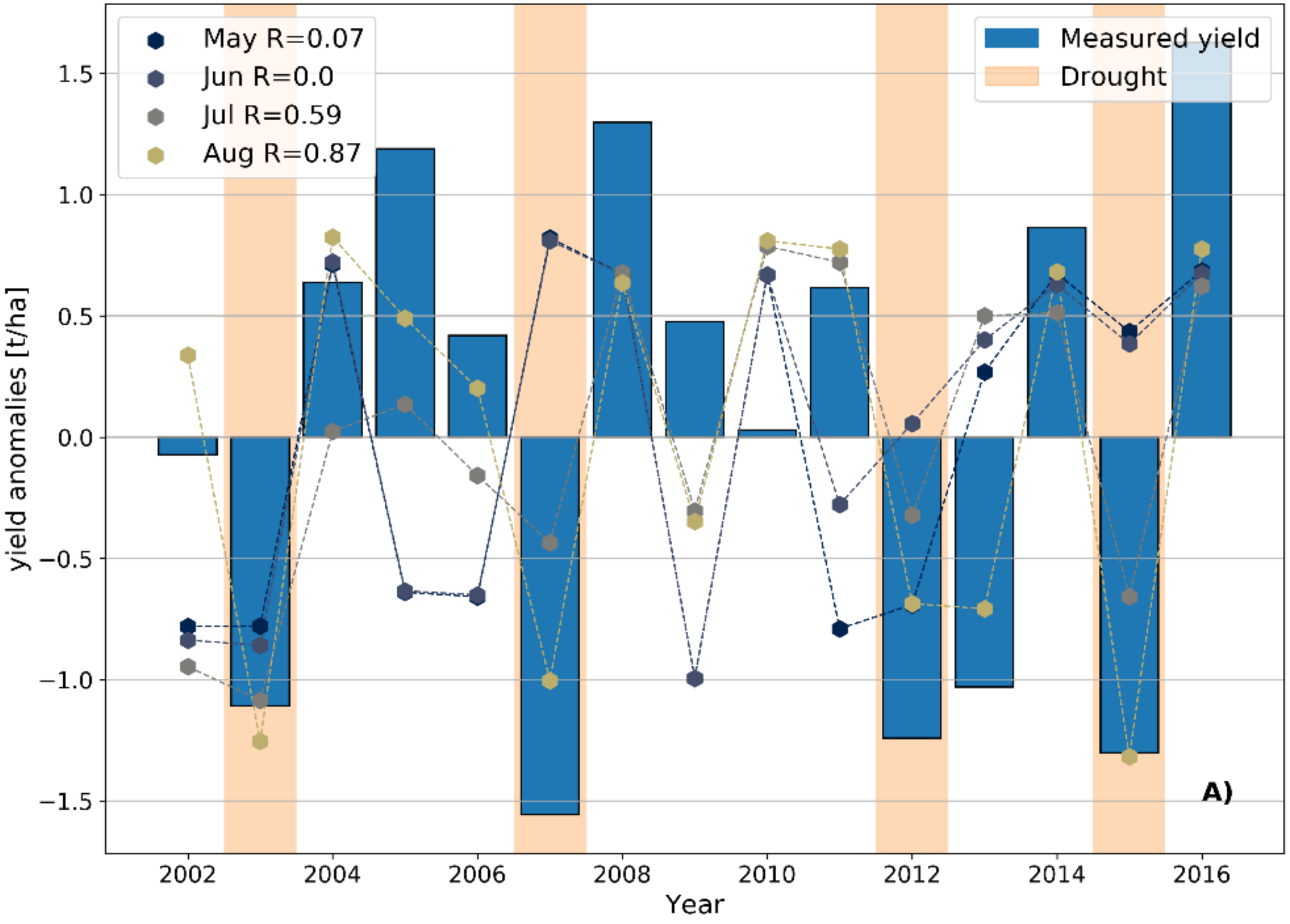
- For all regions, predicted and observed yields have high correlations 2 months before harvest (NUTS3 and mean of Pannonian basin)



[Bueechi et al., in prep

Performance in drought years

- Highest correlations to predict Pannonian basin mean maize yield the month before harvest (R=0.87)
- Model detects negative anomalies in drought years from around 2 months prior to harvest

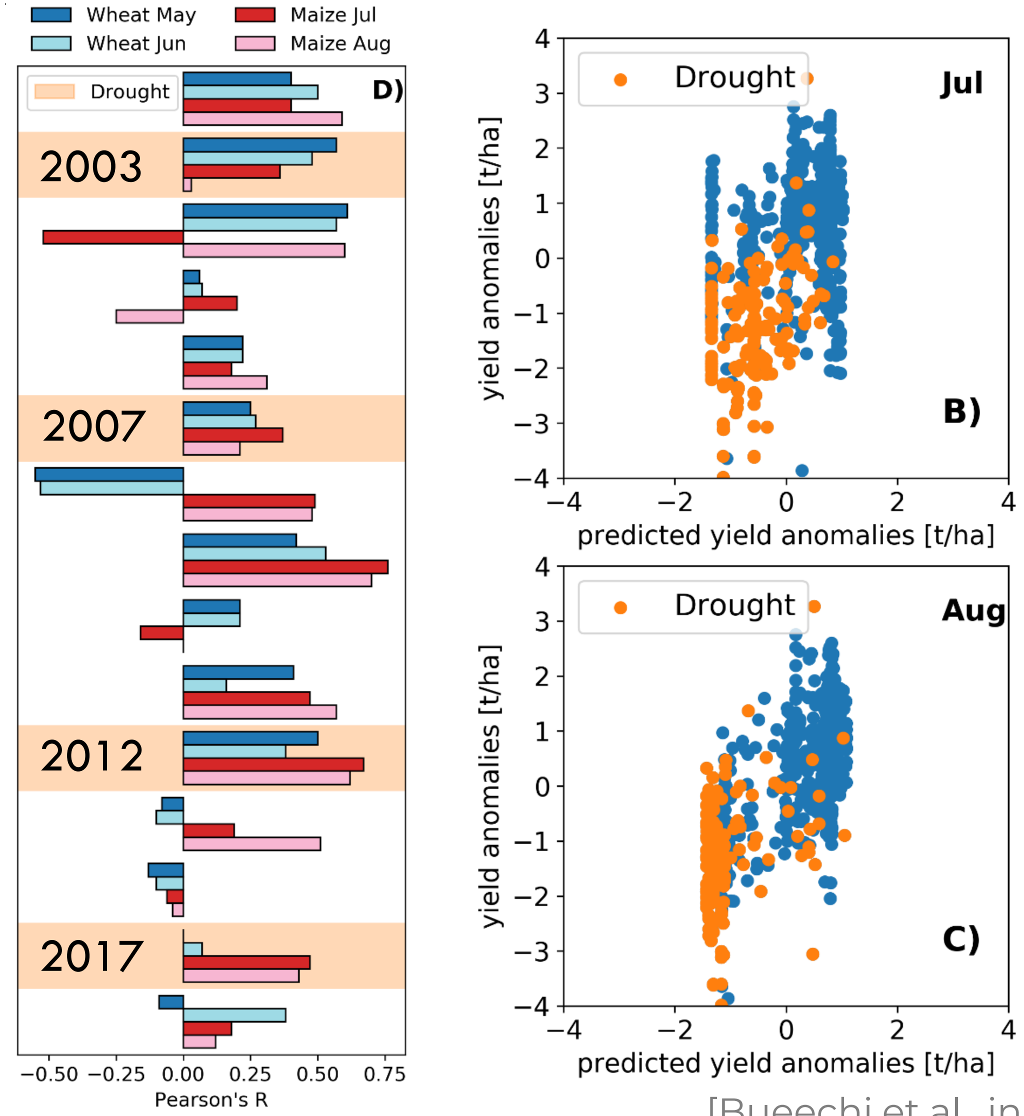


[Bueechi et al., in prep

Differentiation between NUTS3 regions

- Model is poor in distinguishing crop yields between different NUTS3 regions
  - Low yearly performance (spatial correlations)
  - High spatial correlations of yields and predictors
  - Coarse resolution of predictors

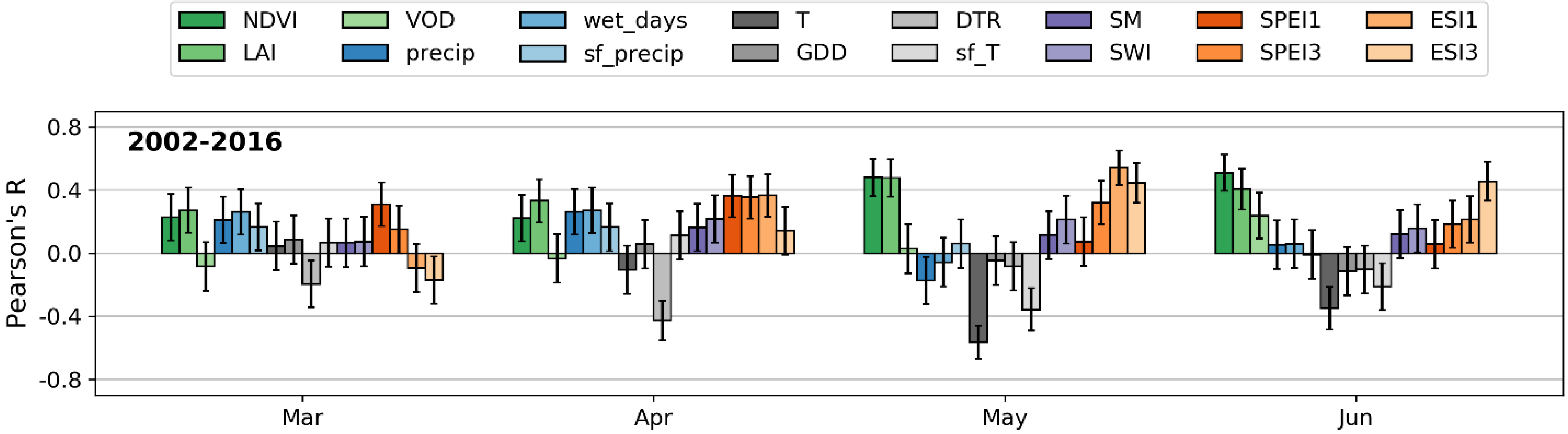
	Overall (R)	Drought (R)
Maize Jul	0.51	0.36
Maize Aug	0.67	0.33
Wheat May	0.41	0.47
Wheat Jun	0.47	0.44



[Bueechi et al., in prep

Predictor importances - wheat

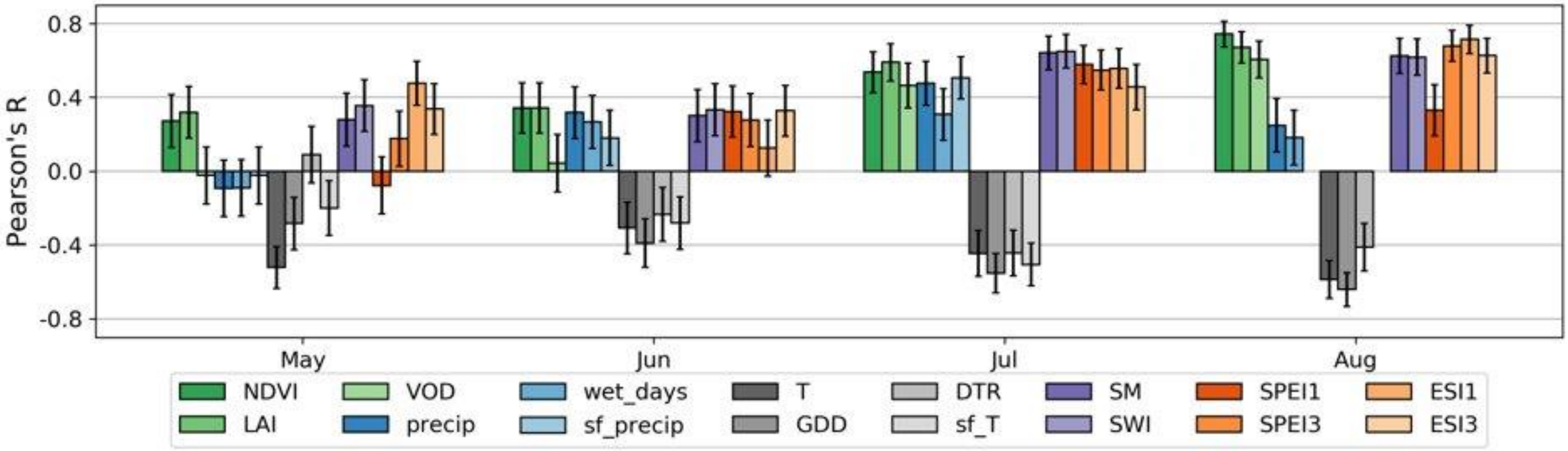
- Increase in correlation between predictors and wheat yields towards last two months
- Soil moisture little impact in addition to SPEI
- Crop condition most important predictor



[Bueechi et al., in prep

Predictor importances - maize

- Large increase in correlation between predictors and maize yields towards last two months
- Surface and root-zone soil moisture have highest correlations in July
- Crop indicators largest skill shortly before harvest



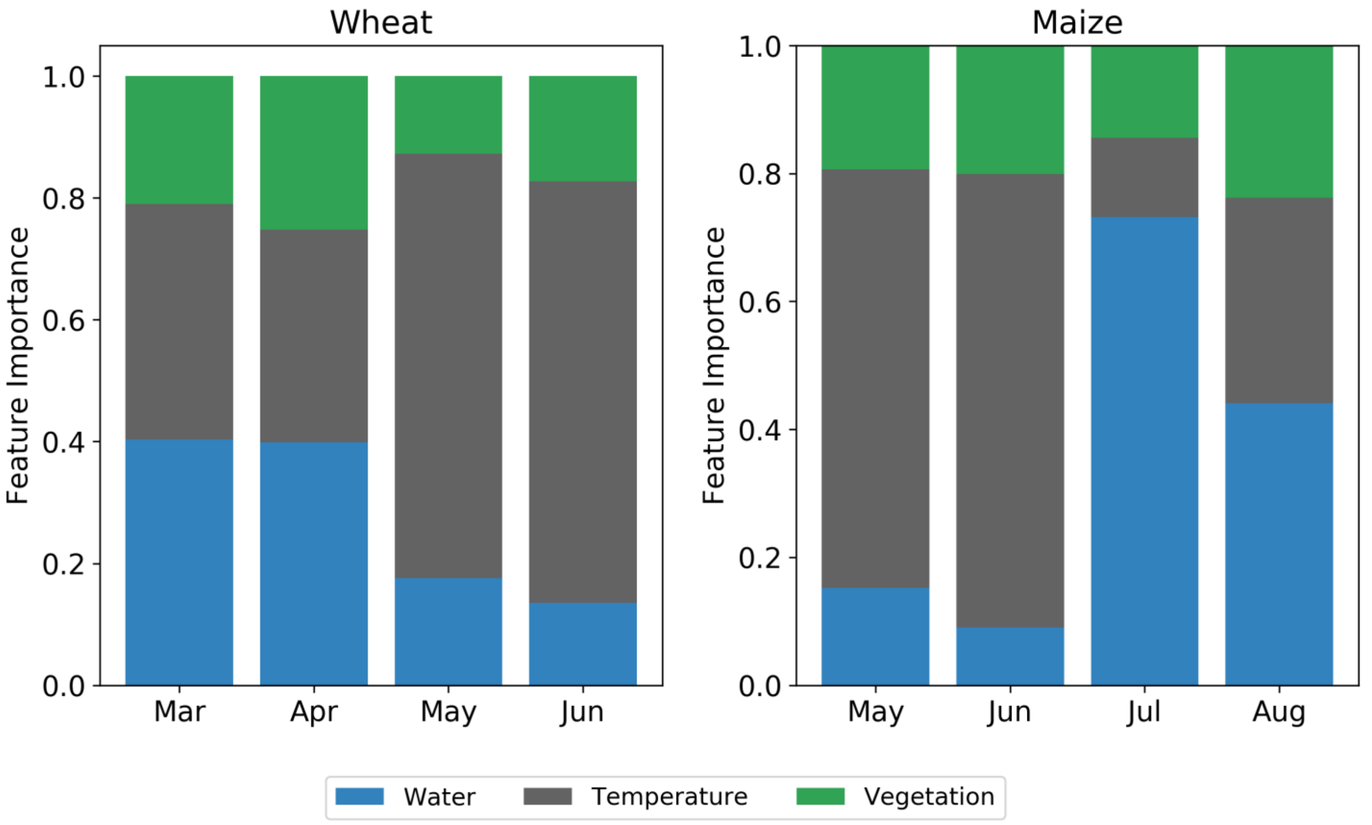
[Bueechi et al., in prep

Relative ´predictor importances

- Large changes of the feature importance from first to last two months

- Wheat
  - Temperature main control overall
  - Water (SPEI3 and soil moisture) mostly at beginning of growing season

- Maize
  - Temperature main control in first months
  - Water main control in last months



Conclusion EO for yield forecasting

- Wheat and maize yield forecasts show reasonable performance from around two months before harvest for interannual variabilities
  - Wheat is mainly dependent on the temperature - maize on water availability
  - Soil moisture and crop state provide key information during last two months before harvest
- Crop yield losses in years of severe drought underestimated - negative anomalies are correctly early detected
- 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; toward field-scale prediction
  - 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
- Dub-daily observations for better capturing of plant response to drought and heat stress?

TU Wien CLIMERS data products and services

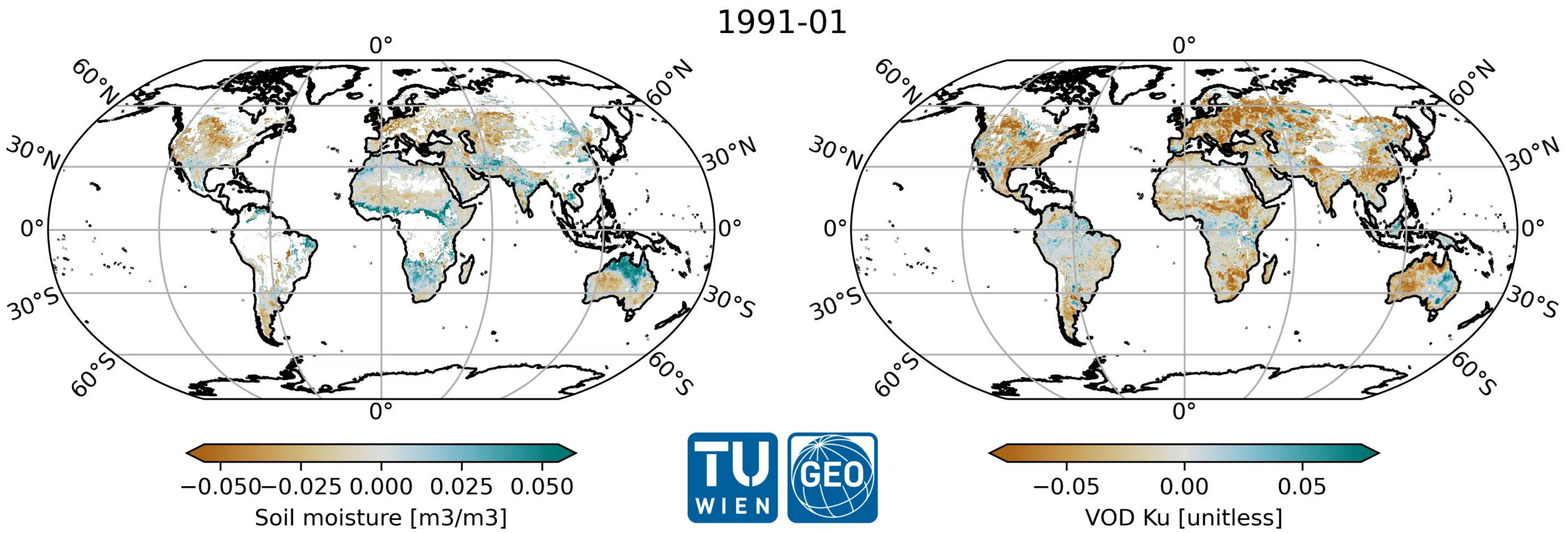
- **ESA CCI Soil Moisture**
  - climate.esa.int/en/odp/
- **C3S Soil Moisture**
  - cds.climate.copernicus.eu/
- **International Soil Moisture Network**
  - ismn.earth
- **Vegetation Optical Depth Climate Archive (VODCA)**
  - doi.org/10.5281/zenodo.2575599o
- **SVODI**
  - doi.org/10.5281/zenodo.7114654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

Climate Change Service

FFG Forschung wirkt.

climers.geo.tuwien.ac.at

Thank you!



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