

# Snow Drought Impacts on GPP Anomalies Across the Northern Hemisphere

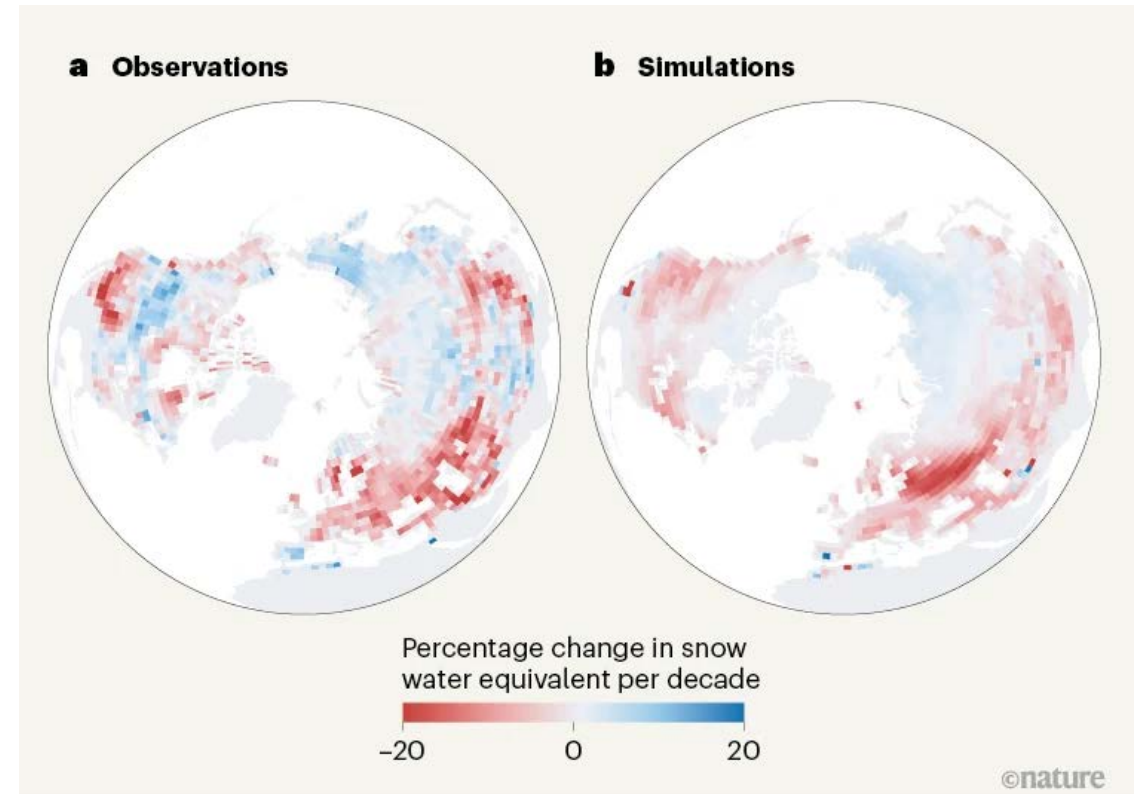
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Mariangela Varela, Franziska Koch and David Gampe



# Topic Relevance

- Snow is crucial for many ecological processes and serves as a natural water reservoir.
- Snowpack amount and duration is decreasing in most of the Northern Hemisphere (NH) due to global warming.
- **“Snow droughts”** are a growing threat to ecosystems that have evolved under stable winter snow conditions.
- The extent of snow droughts impacts on ecosystem productivity at a large scale is poorly understood.
- How the impact will evolve as temperatures continue to rise is also not known.

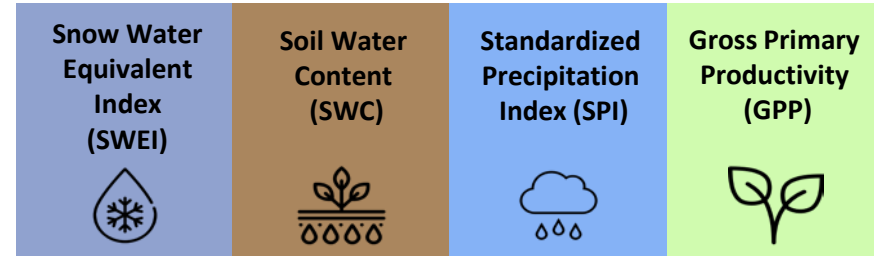


Pulliainen (2024)

# Methods

## Key variables

central to snow-ecosystem interactions



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**Model:** LPJmL Model Forced with ERA5L data

**Datasets:**



ERA5Land



FLUXCOM, VODCA2GPP, NIRv

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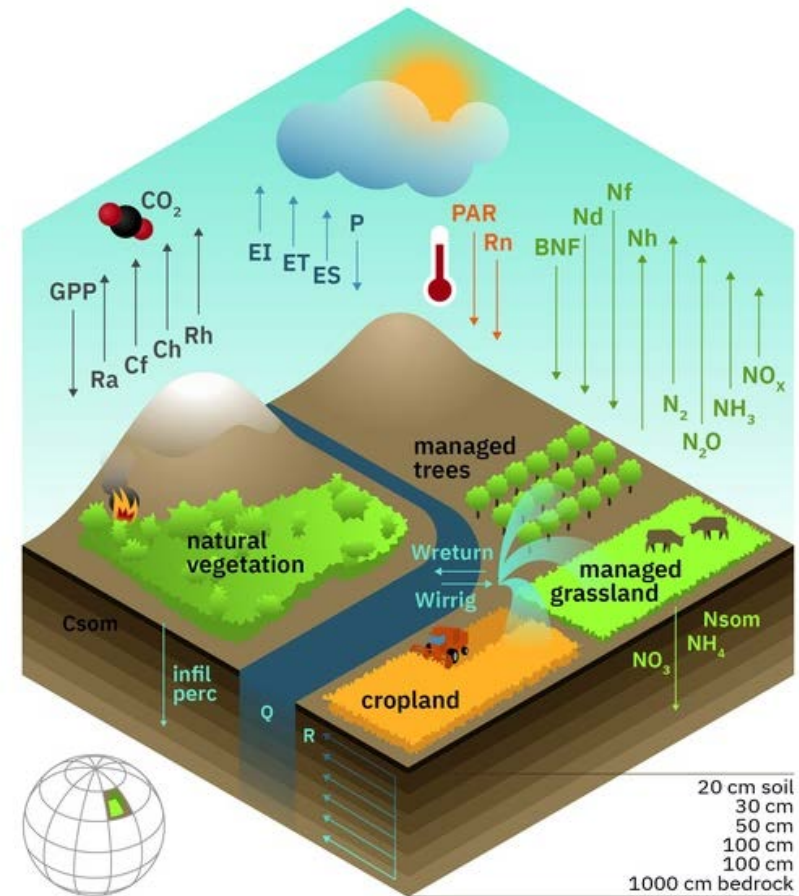
**Time frame:** 1988-2018 (monthly timestep)

**Scale:** Global (Northern Hemisphere)

**Resolution:** 0.5°x 0.5°

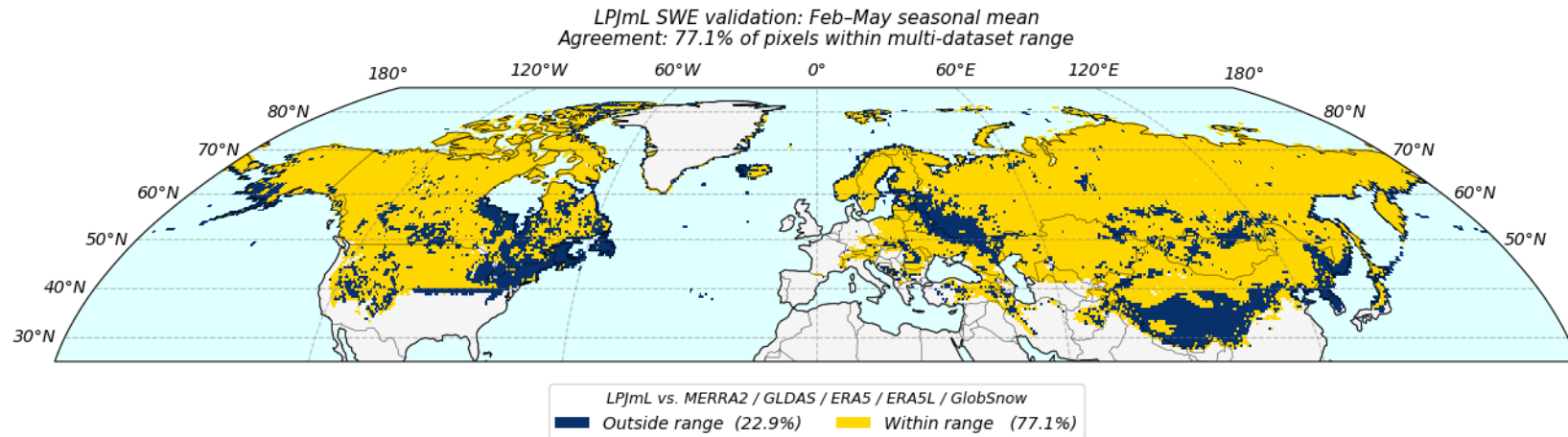
# Why LPJmL?

- Process-based Dynamic Global Vegetation (DGVM) model.
- Simulates coupled carbon, energy and water cycle processes.
- Mechanistic ecosystem response, can represent lag effects.
- Compensation studies and future projections.



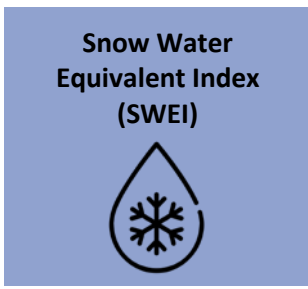
LPJmL – Lund-Potsdam-Jena managed Land, Potsdam Institute for Climate Impact Research

# Why LPJmL?



SWE datasets considered  
(period: 1950-2018):

- Globsnow
- GLDAS
- ERA5L
- Merra2
- ERA5



# Snow Water Equivalent Index (SWEI)

- A measure of how unusual the current snowpack is for a given location and time of year (Huning and AghaKouchak (2020)).
- Locally standardized, allowing fair comparison across regions.
- 3-month accumulation window.

- Event classification:

Snow drought:  $SWEI \leq -1.3$

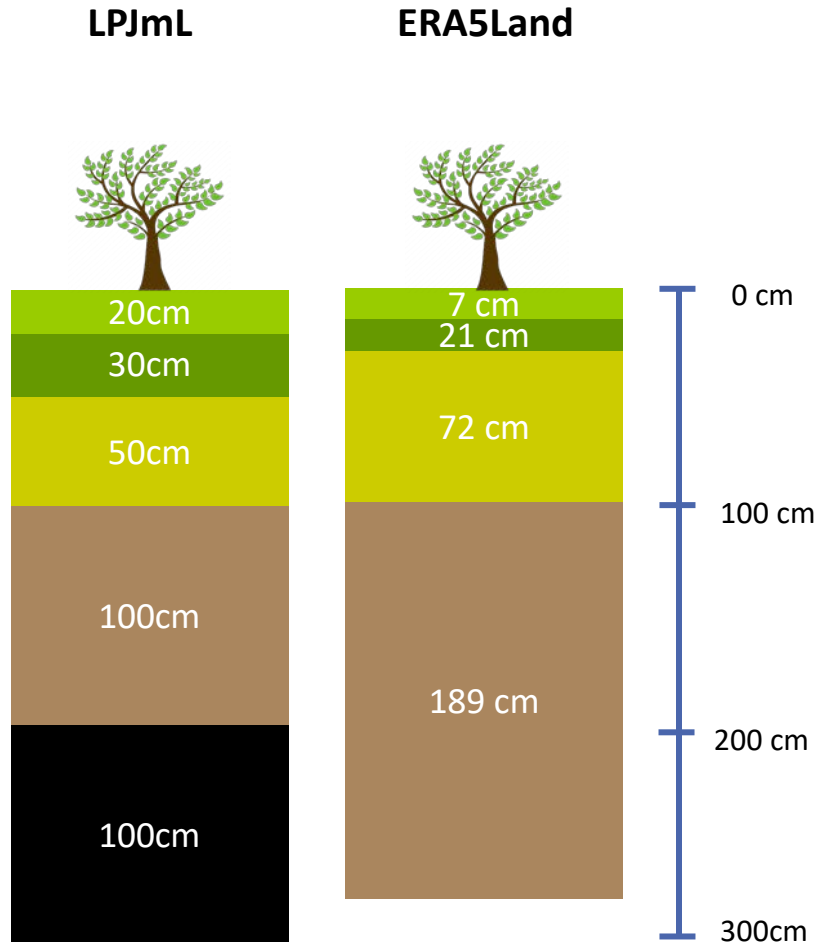
No snow drought:  $SWEI > -1.3$

**Table S1.** Drought and wet spell classifications.

Classification	Description	SWEI Values
D4	Exceptional Drought	$SWEI \leq -2.0$
D3	Extreme Drought	$-2.0 < SWEI \leq -1.6$
D2	Severe Drought	$-1.6 < SWEI \leq -1.3$
D1	Moderate Drought	$-1.3 < SWEI \leq -0.8$
D0	Abnormally Dry	$-0.8 < SWEI \leq -0.5$
NN	Near Normal*	$-0.5 < SWEI < +0.5$
W0	Abnormally Wet	$+0.5 \leq SWEI < +0.8$
W1	Moderate Wet Spell	$+0.8 \leq SWEI < +1.3$
W2	Severe Wet Spell	$+1.3 \leq SWEI < +1.6$
W3	Extreme Wet Spell	$+1.6 \leq SWEI < +2.0$
W4	Exceptional Wet Spell	$SWEI \geq +2.0$

Huning and AghaKouchak (2020)

# Soil Water Content (SWC)



- LPJmL: Layer 1.
- ERA5L: weighted sum of layer 1 and 2.

$$SWC_{\text{rootzone}} = \sum_{\text{layers}} \frac{SWC_{\text{layer}} \cdot d_{\text{layer}}}{d_{\text{total}}}$$

- We calculate anomalies.
- Event classification:

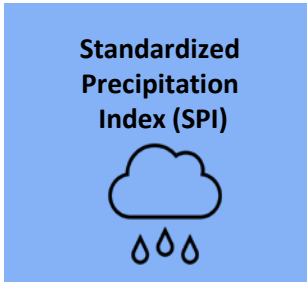
Dry:  $SWC < 25^{\text{th}}$  percentile

Normal:  $25^{\text{th}} \leq SWC \leq 75^{\text{th}}$

Wet:  $SWC > 75^{\text{th}}$  percentile



# Standardized Precipitation Index (SPI)



- Measures how unusual the current precipitation is for a given location and time of year.
- 3-month accumulation window.
- Event classification:

Low:  $SPI \leq -1.3$

Normal:  $-1.3 < SPI < 1.3$

High:  $SPI \geq 1.3$

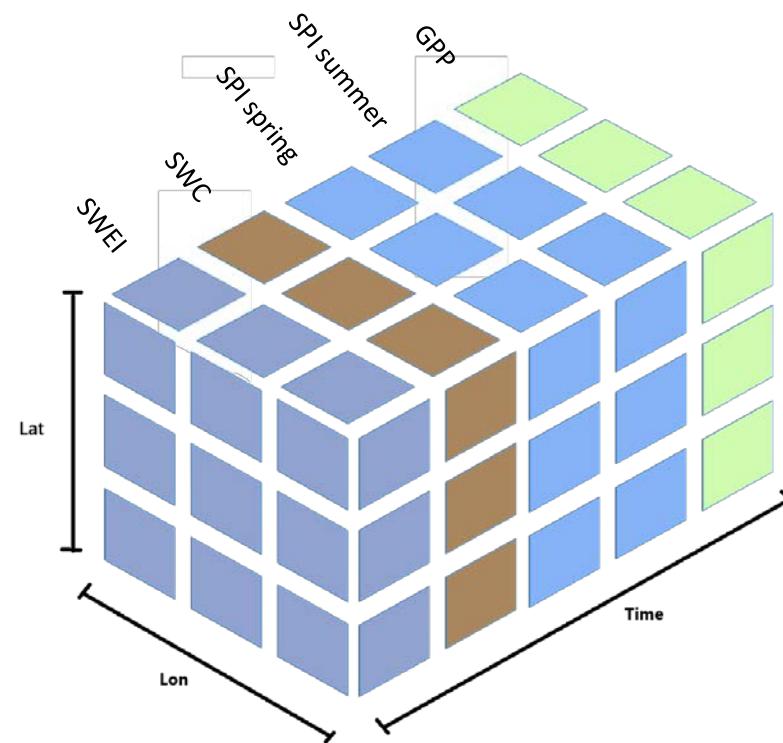
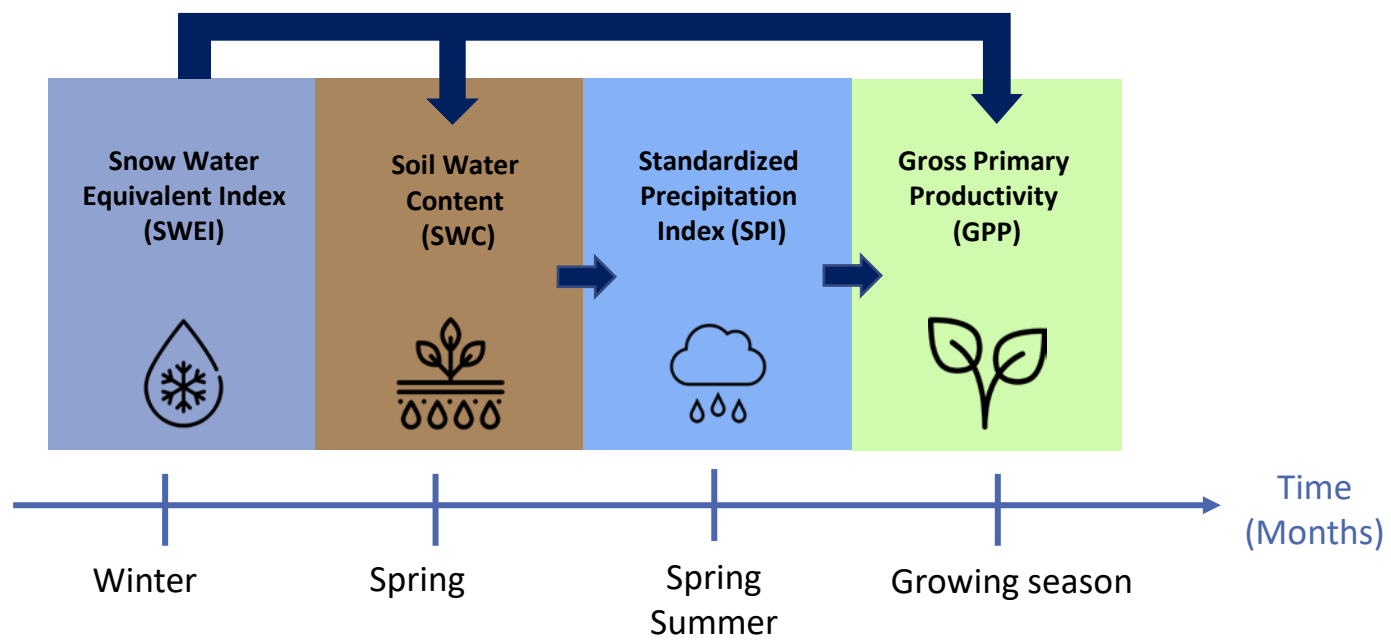


# Gross Primary Productivity (GPP)



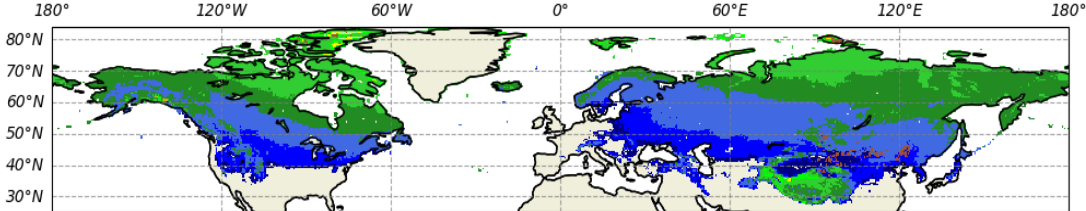
- Harmonize all data sets to units [gC/month]
- Detrend data and calculate anomalies
- Sum anomalies over the growing season

# Methods

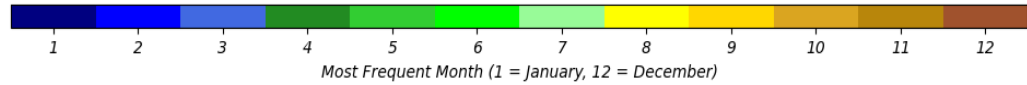
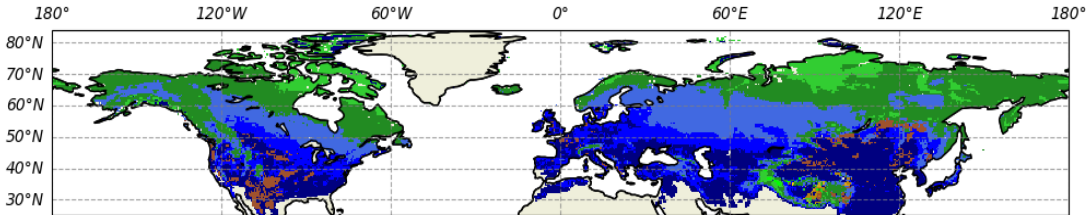


# Methods

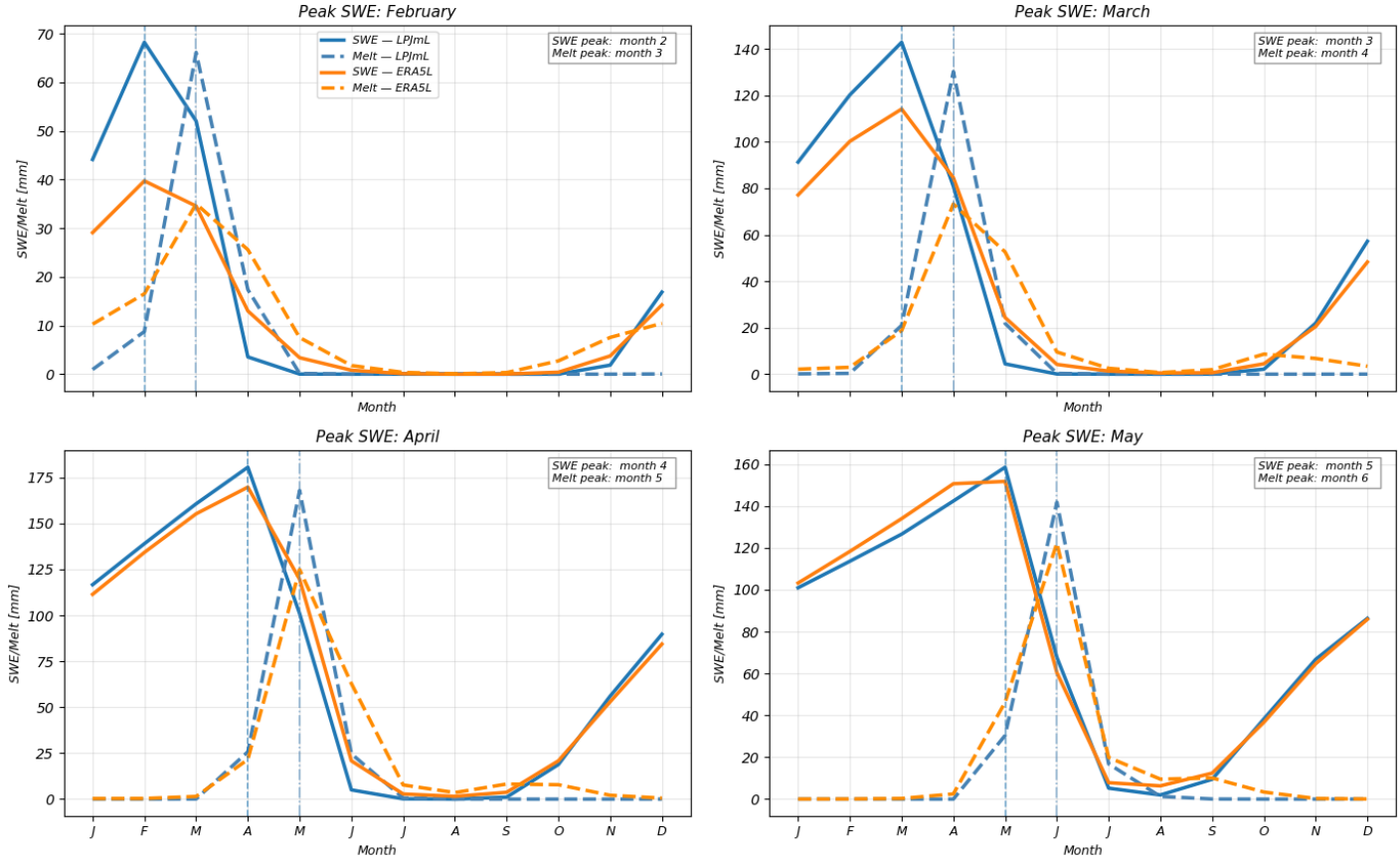
Mode of Peak SWE month  
LPJmL



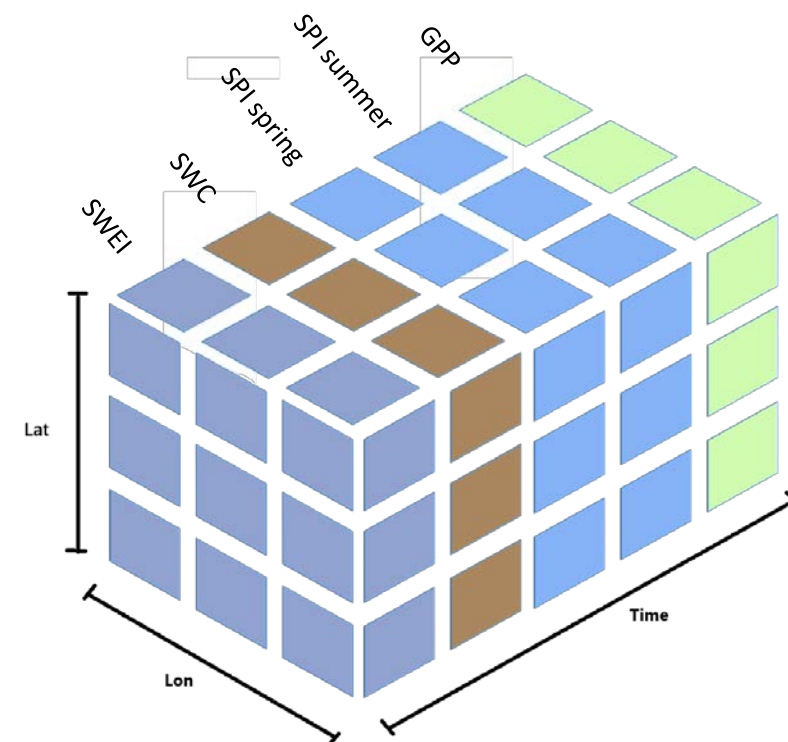
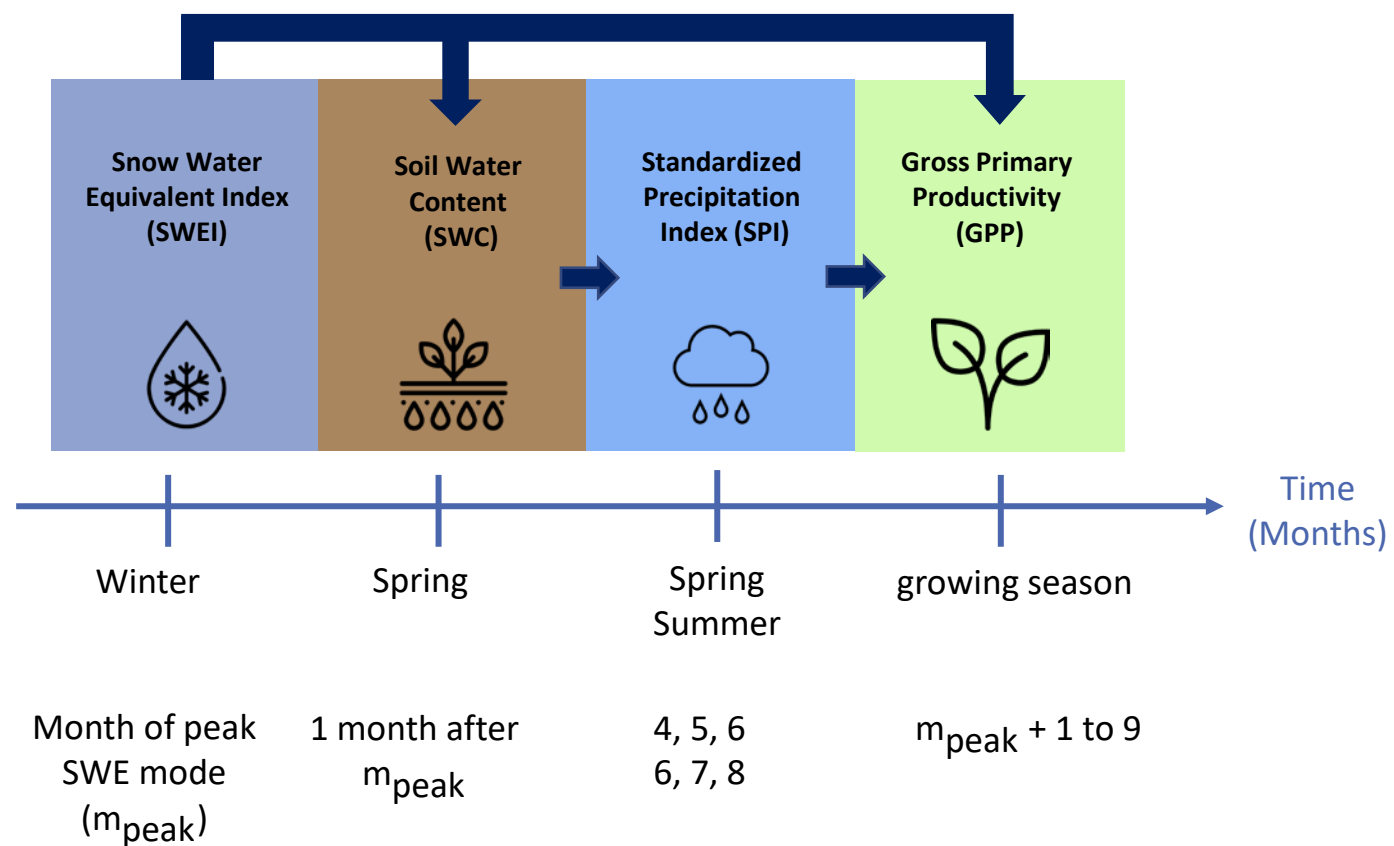
ERA5L



Long-term Average SWE and snowmelt



# Methods

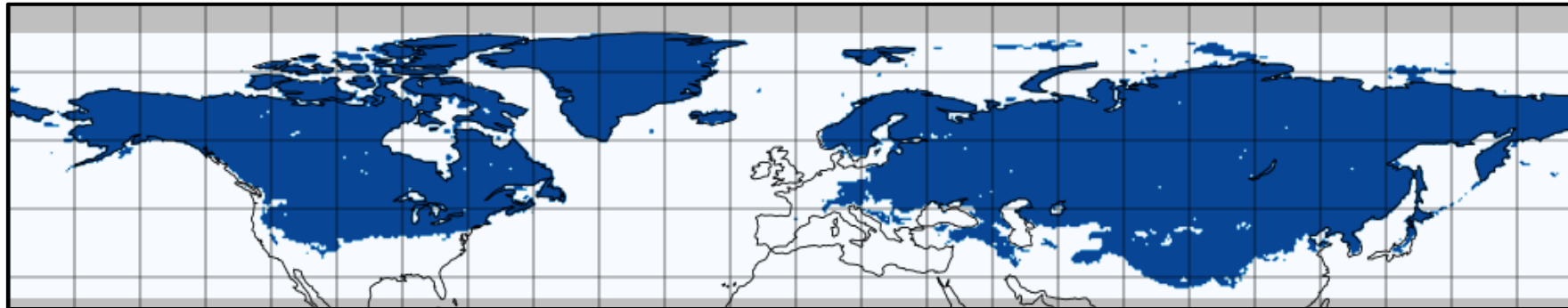


# Methods

## Threshold mask

- To select grid cells where snow occurs reliably across years
- Steps:
  - Mark year as valid if SWE over 3 months  $> 0$  at least once
  - Keep grid cell if snow occurs in at least 75% of years

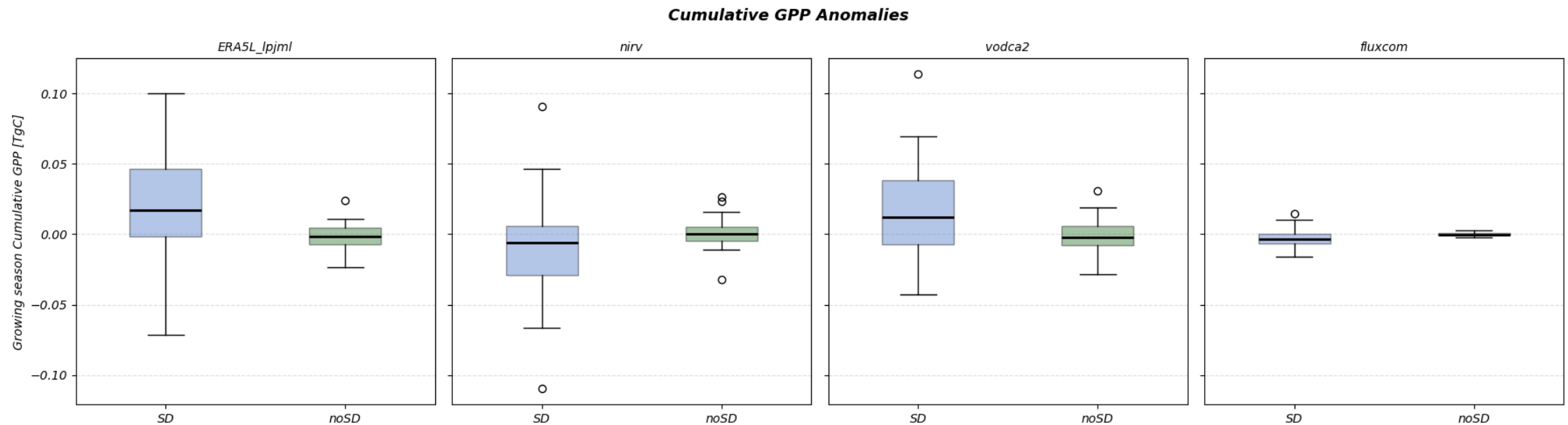
LPJmL SWE Threshold Mask



# Effect of Snow droughts on GPP



- Cumulative GPP anomalies over the growing season  
→ 1 value per year for **snow drought (SD)** and **no snow drought (noSD)**, averaged per number of events



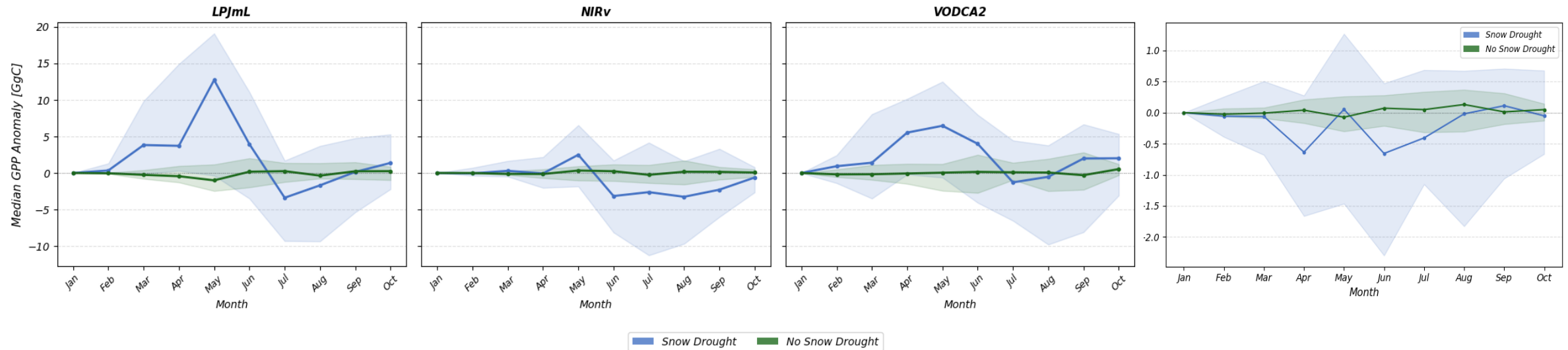
- LPJmL and Vodca2 show overall benefits on GPP anomalies from SD. Fluxcom and Nirv show the opposite
- Higher variability for SD due to statistics

# Seasonal effect of Snow droughts on GPP



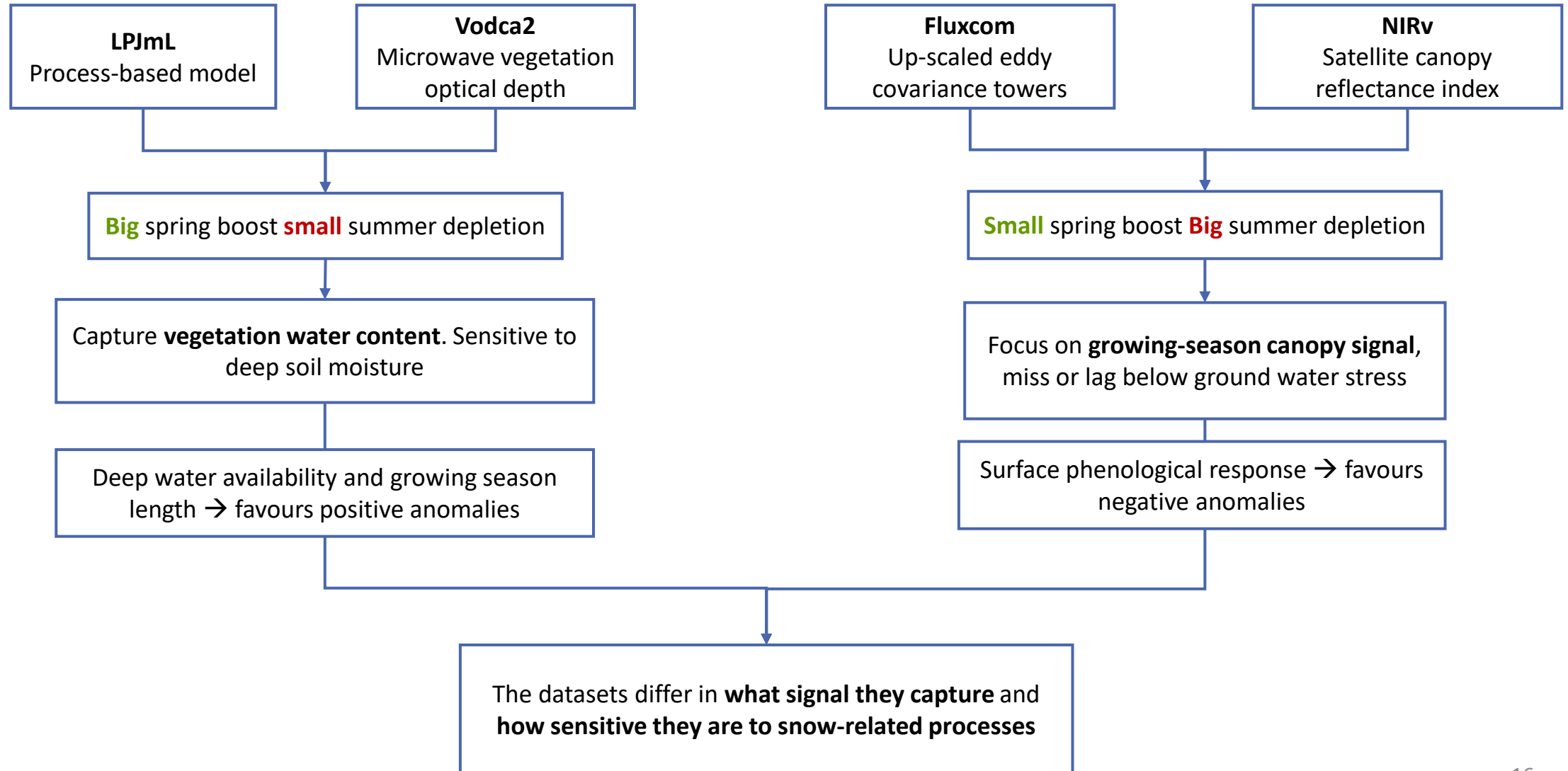
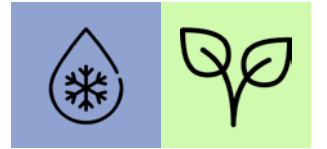
- We compare the cumulative GPP anomalies of **SD** vs. **noSD** conditions for each month over the studied period

Seasonal GPP Anomaly  
Snow Drought vs. No Snow Drought



- For SD conditions, productivity gets redistributed in time: **spring boost** and a **summer depletion**
  - Datasets agree on pattern but not on net outcome

# Why datasets show different responses?



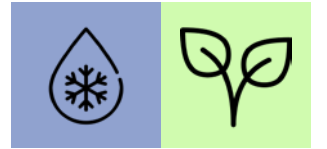
# Seasonal effect of Snow droughts on GPP



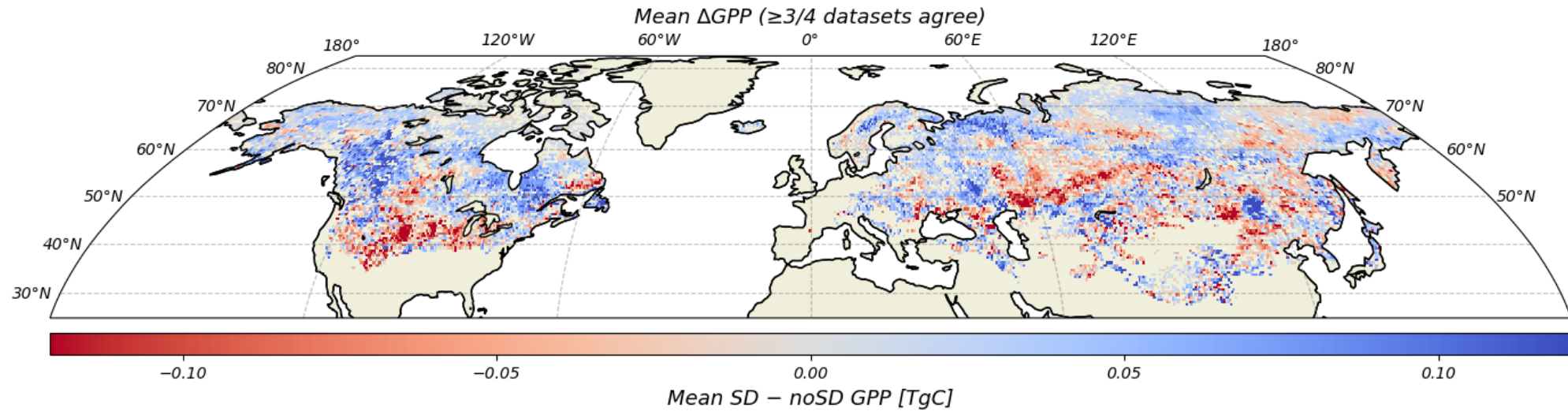
- Go into spatial variations to see:
  - If this pattern is true everywhere
  - Where SD have an overall negative/positive impact
- Look at the difference between snow drought and no snow drought anomalies per pixel

$$\Delta\text{GPP} = \text{GPP}_{\text{SD}} - \text{GPP}_{\text{noSD}} = \begin{cases} \Delta\text{GPP} < 0 : \text{SD impact} \\ \Delta\text{GPP} > 0 : \text{SD boost} \end{cases}$$

# Effect of Snow droughts on GPP



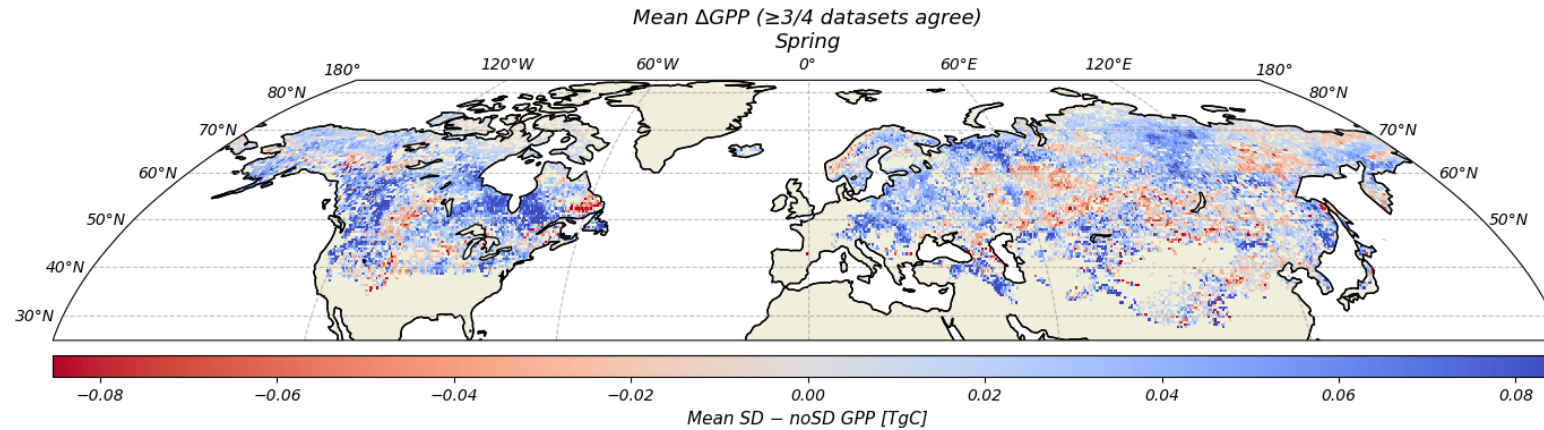
- Net response (Mean)



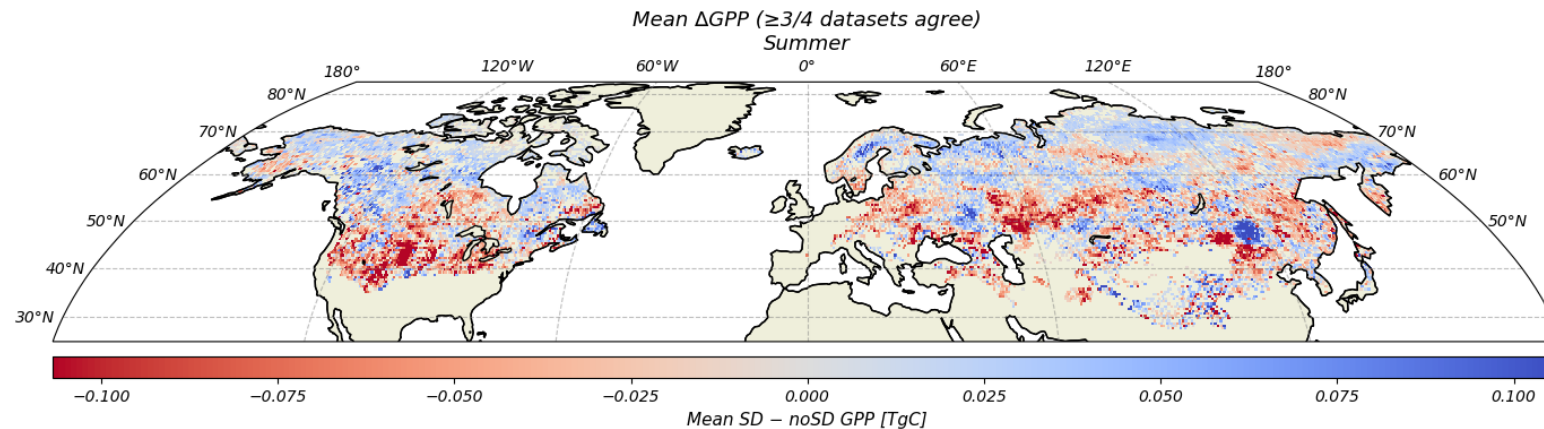
# Effect of Snow droughts on GPP



- **Spring** (from SWE<sub>max</sub> month + 1 to 2 months after)



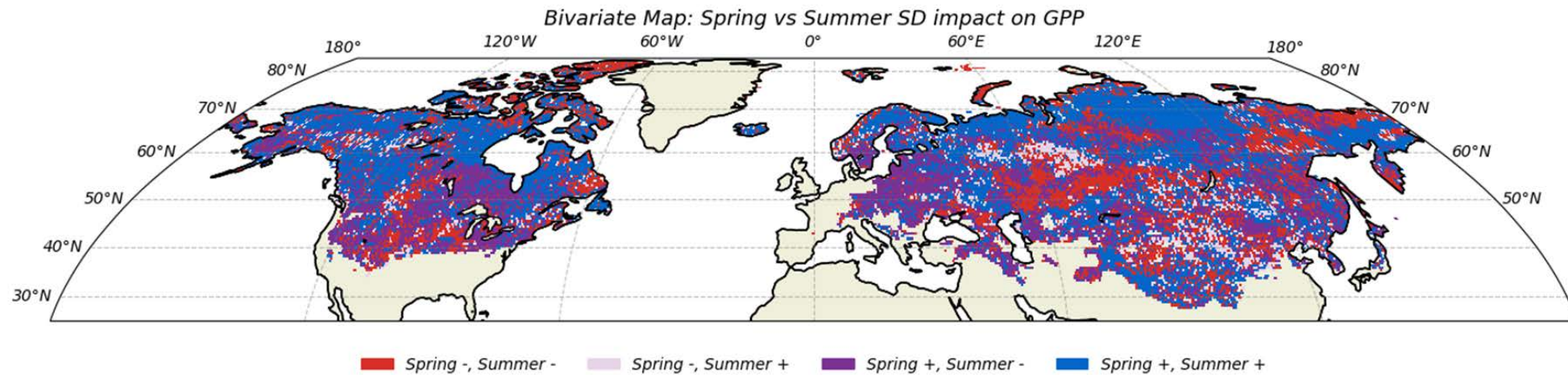
- **Summer** (from June to Sept)



# Effect of Snow droughts on GPP



- Is the spring boost- summer depletion pattern true everywhere?



# Effect of Snow droughts on GPP

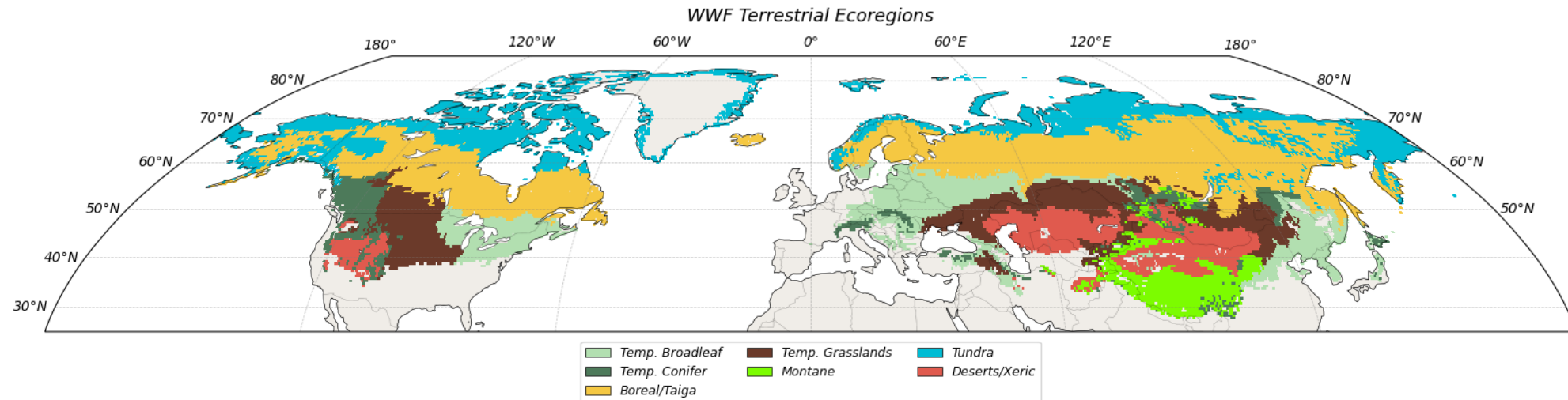


- To find hemispheric-scale patterns, subdivide results into:
  - Ecoregions
  - Global Aridity Index

# Effect of Snow droughts on GPP



- Ecoregions → different biomes have different sensitivities because they have different water use strategies, rooting depths and phenology

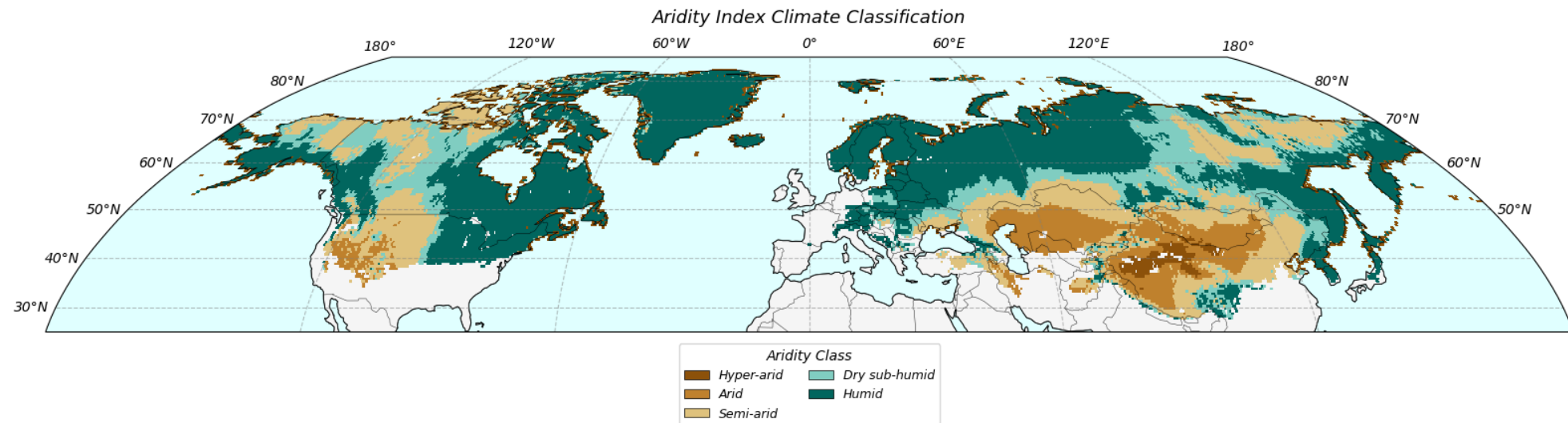


Data from D. M. Olson, E. Dinerstein, et al. (2001)

# Effect of Snow droughts on GPP



- Aridity index → water-limited or energy-limited

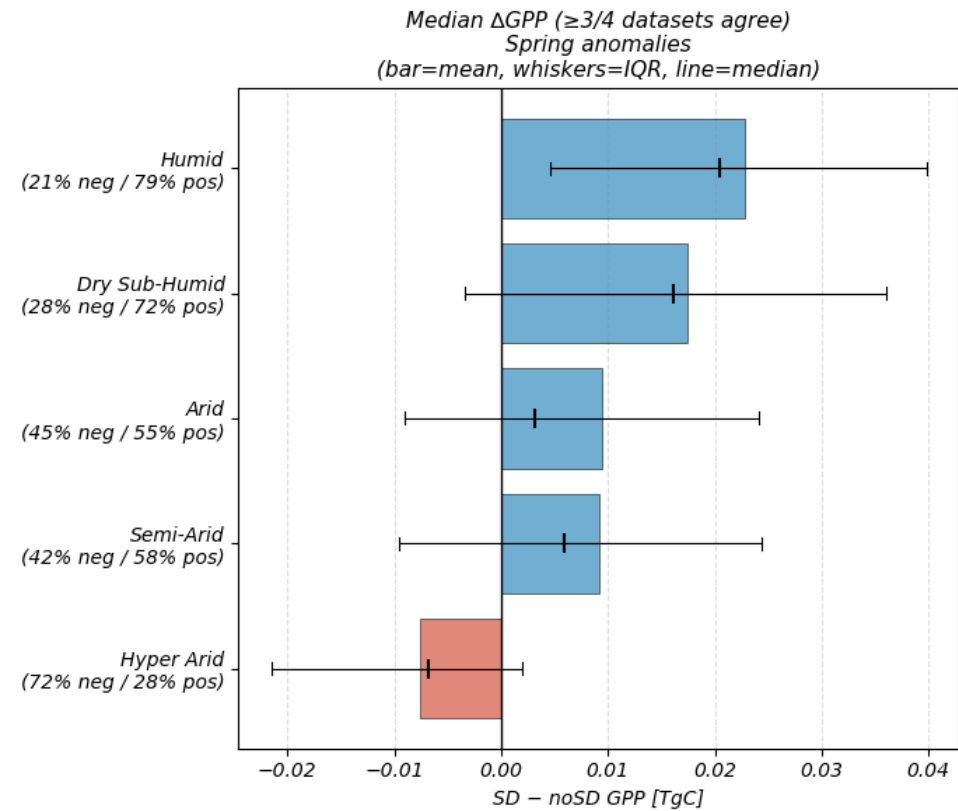
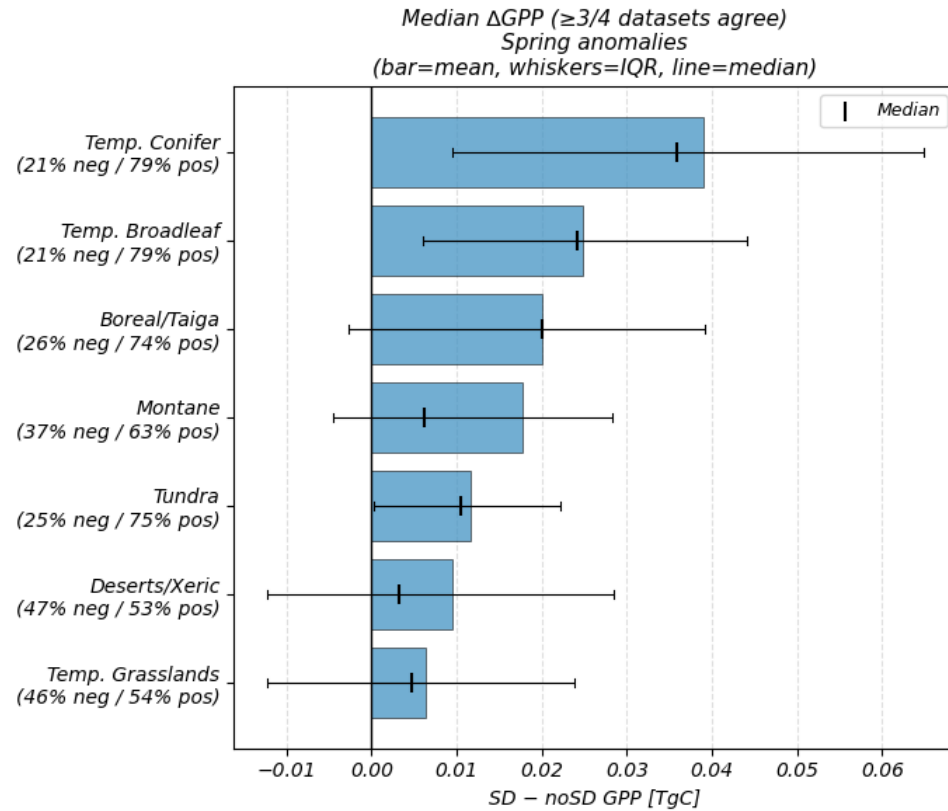


Data from Zomer, R.J.; Xu, J.; Trabucco, A. (2022)

# Effect of Snow droughts on GPP



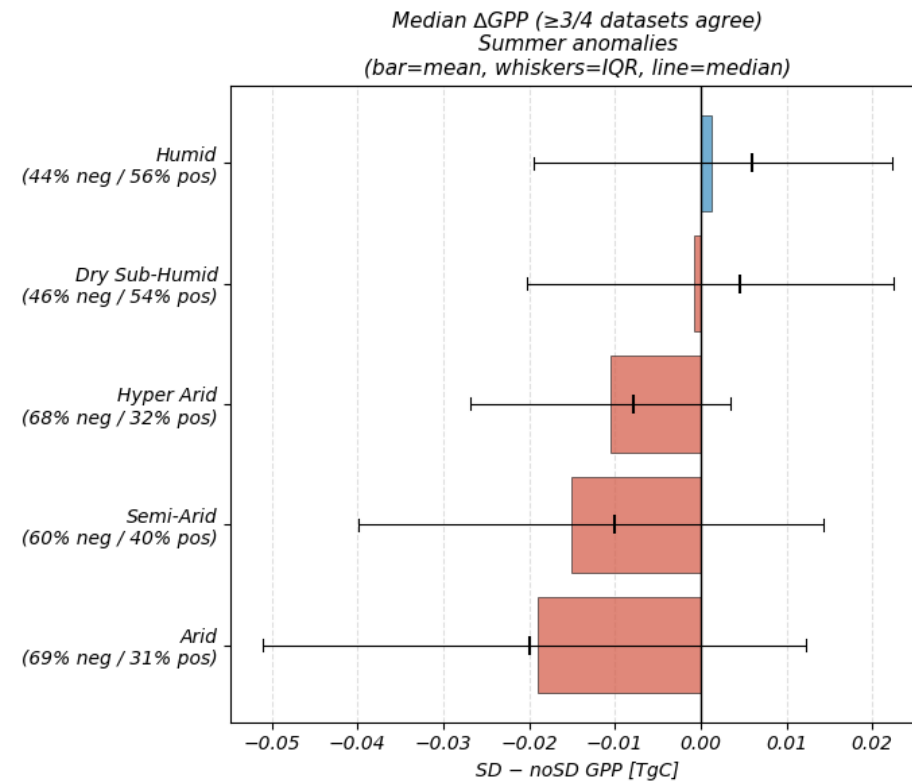
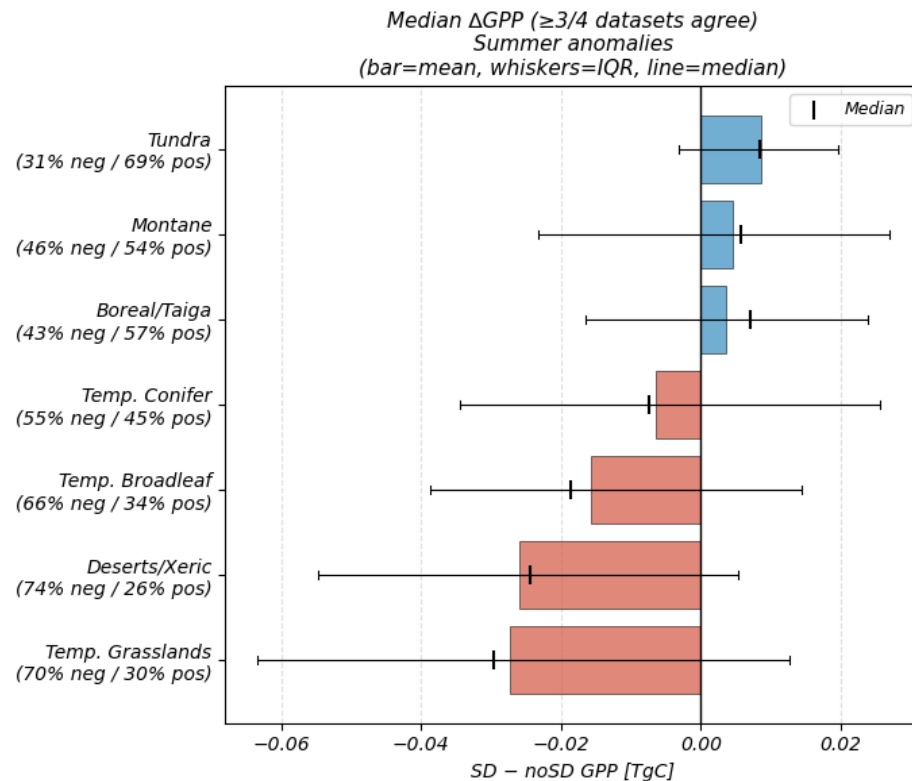
## Spring $\Delta$ GPP (SWE<sub>max</sub> month + 1 to 2 months after)



# Effect of Snow droughts on GPP



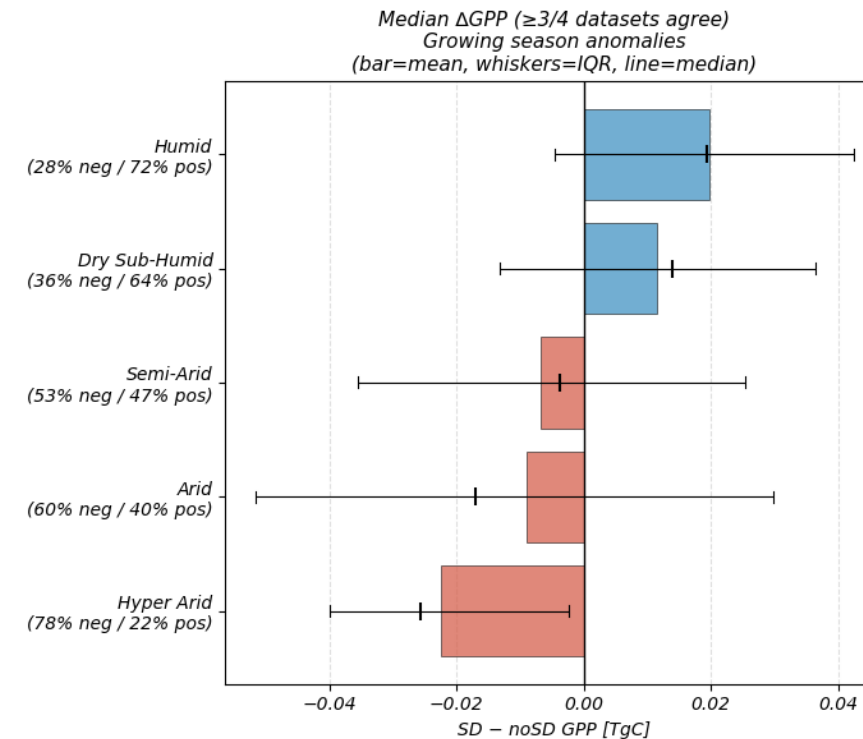
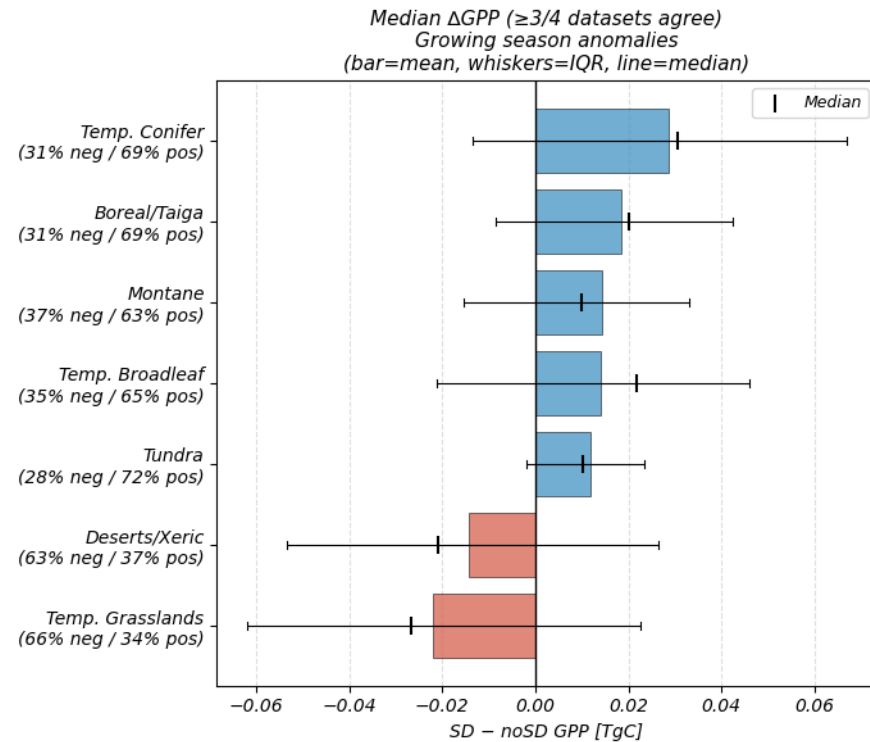
## Summer $\Delta$ GPP (Summer = June-Sept)



# Effect of Snow droughts on GPP



## Growing season $\Delta$ GPP (SWE<sub>max</sub> month + 1 to Sept)



- Water-limited systems tend to be negatively impacted by SD, energy-limited systems tend to be positively impacted by SD.
- High spatial variability within each category.
- Does the GPP response during snow drought years differ depending on spring/summer conditions?.

# Compensation Effects



## Can spring/summer conditions change the GPP response?

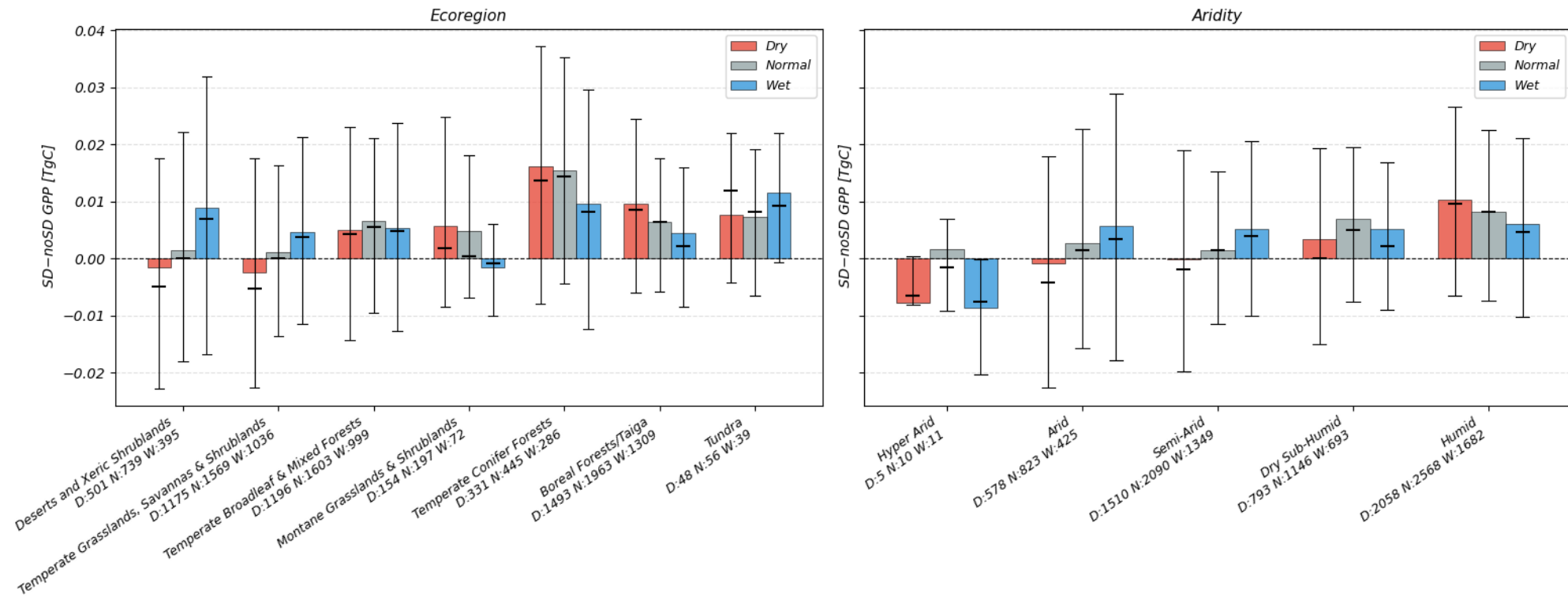
- SD and noSD events
  - Spring SWC
  - Spring SPI
  - Summer SPI
- Each variable split into: Dry / Normal / Wet conditions
- Credible window defined per variable:
  - Spring SWC (SWE peak + 1)
  - Spring Precip (Apr–Jun)
  - Summer Precip (Jun–Sept)

# Compensation Effects



## Spring SWC (SWE peak month + 1)

Mean  $\Delta$ GPP ( $\geq 3/4$  agree)  
by Spring SWC condition (months SWE peak + 1)  
(bar=mean, whiskers=IQR, line=median)

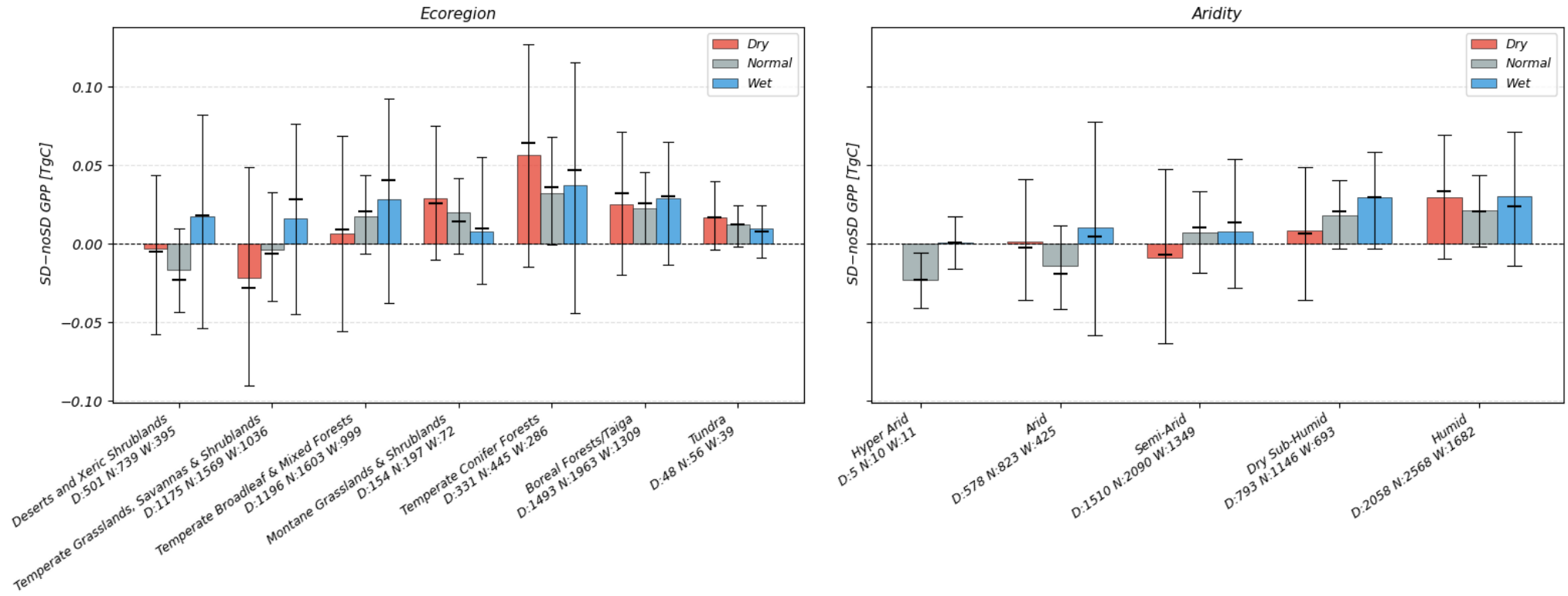


# Compensation Effects



## Spring precipitation (from April to June)

Mean  $\Delta GPP$  ( $\geq 3/4$  agree)  
by Spring Precip condition (months 4-6)  
(bar=mean, whiskers=IQR, line=median)

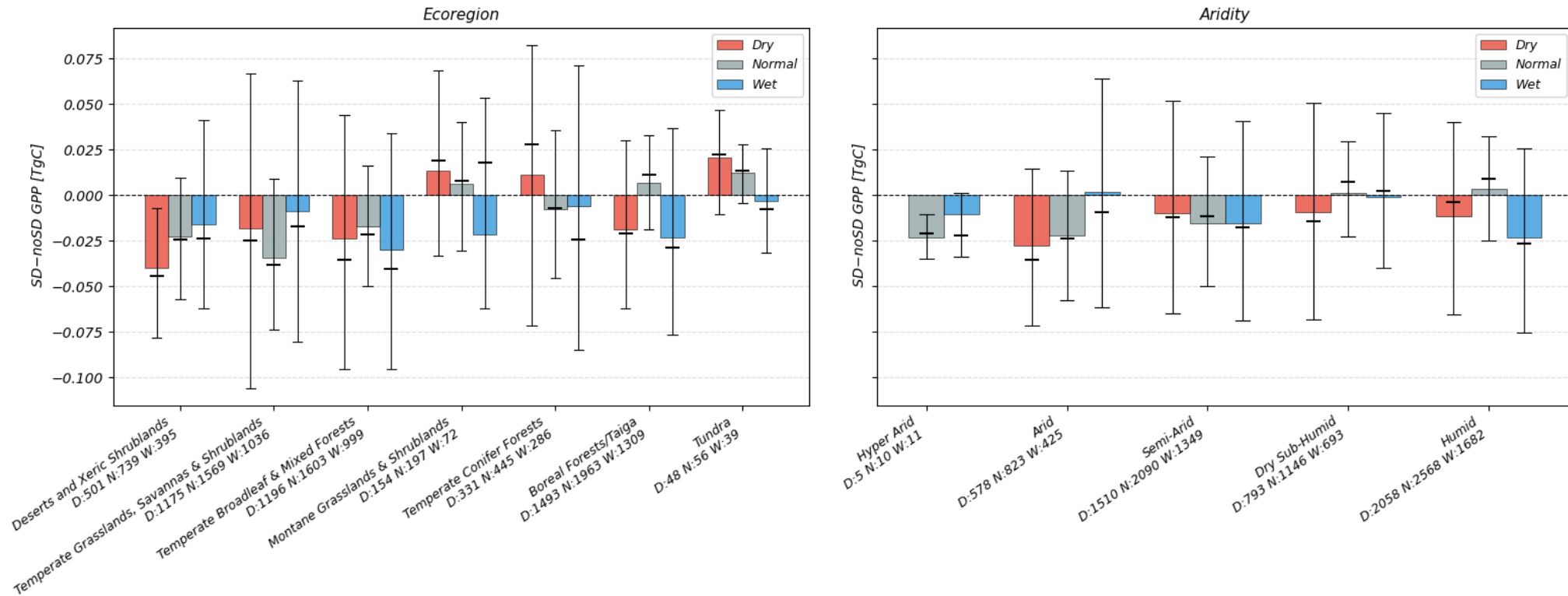


# Compensation Effects



## Summer precipitation (from June to September)

Mean  $\Delta$ GPP ( $\geq 3/4$  agree)  
by Summer Precip condition (months 6-9)  
(bar=mean, whiskers=IQR, line=median)



# Conclusions



- Snow droughts shift the seasonal timing of water availability, creating a spring productivity boost but increasing summer water stress
- The net effect is unclear
  - It depends on region/ecosystem and conditions during the season
- Overall, we observe
  - Water-limited systems are most vulnerable
  - Energy-limited regions show benefit
- In terms of compensation
  - Spring SWC depletion is only seen in water-limited systems
  - High spring precipitation helps compensate arid regions
  - Summer precipitation hardly compensates summer losses

# References

Pulliainen J. (2024). Snow loss pinned to human-induced emissions. *Nature*, 625(7994), 246–247.

A. Bondeau, P. C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, M. Reichstein, and B. Smith. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, 13:679–706, 2007.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., and Thépaut, J.-N. (2021). ERA5-Land: a state-of-the-art global reanalysis dataset for land applications, *Earth Syst. Sci. Data*, 13, 4349–4383.

Huning, L. S., & AghaKouchak, A. (2020). Global snow drought hot spots and characteristics. *Proceedings of the National Academy of Sciences of the United States of America*, 117(33), 19753–19759.

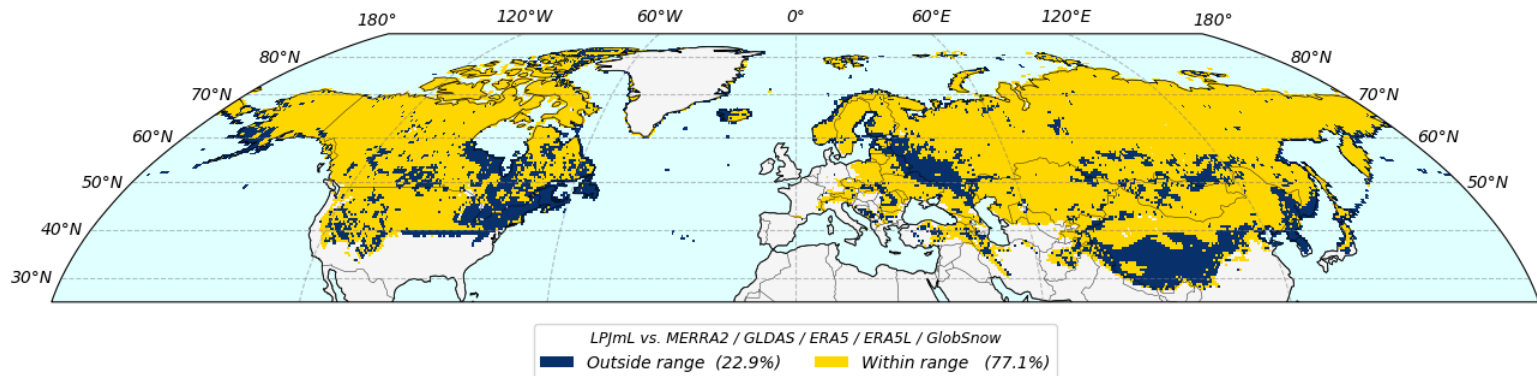
D. M. Olson, E. Dinerstein, et al. Terrestrial ecoregions of the world: A new map of life on earth. *BioScience*, 51(11):933–938, 2001.

Zomer, R.J.; Xu, J.; Trabucco, A. 2022. Version 3 of the Global Aridity Index and Potential Evapotranspiration Database. *Scientific Data* 9, 409

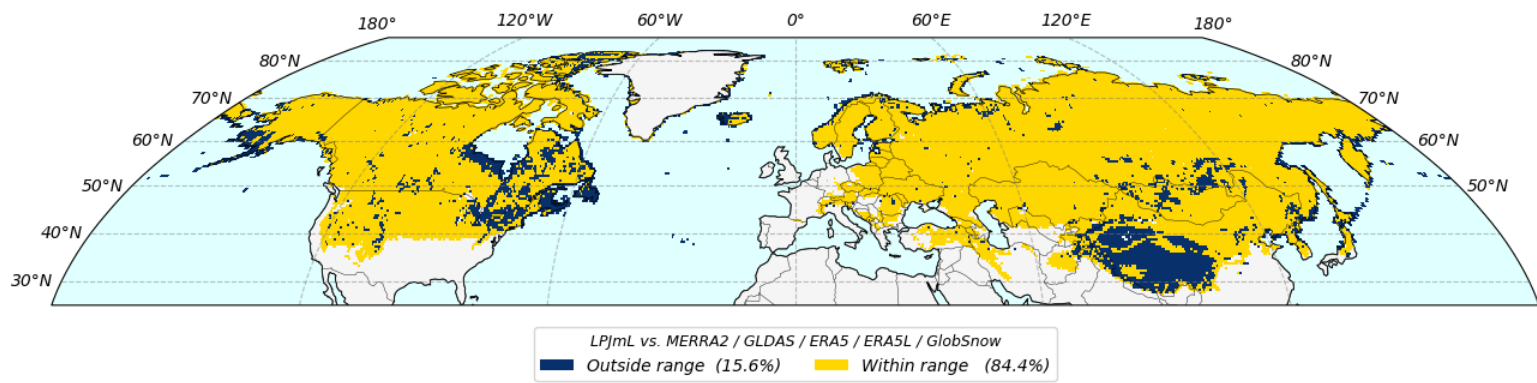
# APPENDIX

# Why LPJmL?

LPJmL SWE validation: Feb-May seasonal mean  
Agreement: 77.1% of pixels within multi-dataset range



LPJmL SWE validation: March-May seasonal mean  
Agreement: 84.4% of pixels within multi-dataset range

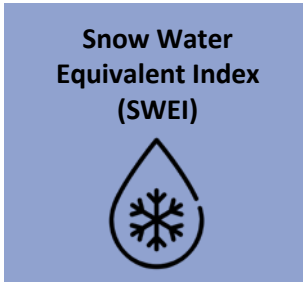


SWE datasets considered  
(period: 1950-2018):

- Globsnow
- GLDAS
- ERA5L
- Merra2
- ERA5



# Snow Water Equivalent Index (SWEI)



- A measure of how unusual the current snowpack is for a given location and time of year (Huning and AghaKouchak (2020)).
- Locally standardized, allowing fair comparison across regions.

## Step 1: 3-month accumulation

- Sums SWE over the past 3 months:  $A_m = SWE_{m-2} + SWE_{m-1} + SWE_m$

## Step 2: Ranking

- For each calendar month, all historical values are ranked smallest to largest

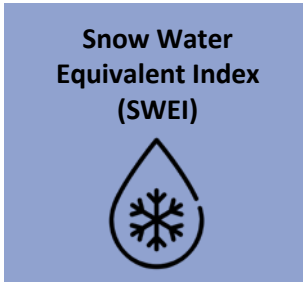
## Step 3: Gringorten formula → probability

- Converts rank into empirical probability  $P(A_{m,i}) = \frac{i - 0.44}{N + 0.12}$
- Non-parametric

## Step 4: Convert to Z-score

- Probability is transformed to a standard normal scale using the inverse normal distribution
- Allows direct comparison across space and time

# Snow Water Equivalent Index (SWEI)



$$\text{SWEI}(A_{m,i}) = \Phi^{-1}[P(A_{m,i})]$$

- Threshold:

Snow drought:  $\text{SWEI} \leq -1.3$

No snow drought:  $\text{SWEI} > -1.3$

**Table S1.** Drought and wet spell classifications.

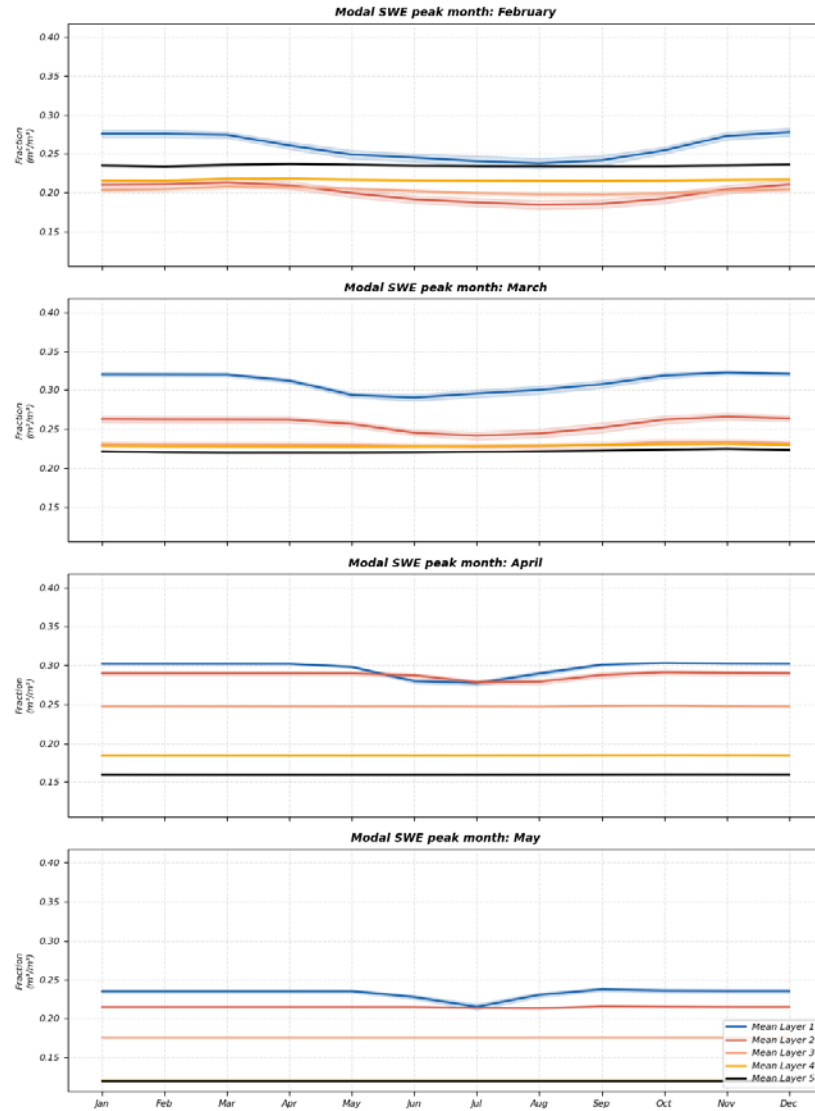
Classification	Description	SWEI Values
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D0	Abnormally Dry	$-0.8 < \text{SWEI} \leq -0.5$
NN	Near Normal*	$-0.5 < \text{SWEI} < +0.5$
W0	Abnormally Wet	$+0.5 \leq \text{SWEI} < +0.8$
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W3	Extreme Wet Spell	$+1.6 \leq \text{SWEI} < +2.0$
W4	Exceptional Wet Spell	$\text{SWEI} \geq +2.0$

From Huning and AghaKouchak (2020)

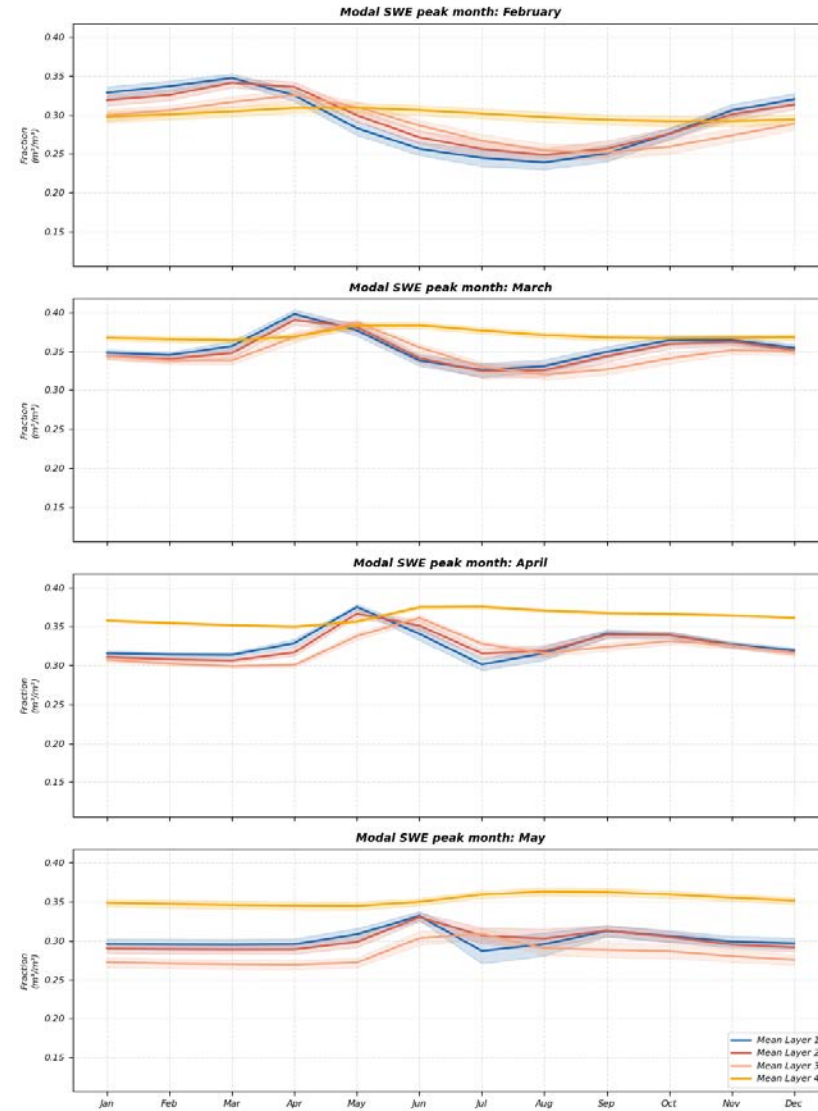
# Soil Water Content (SWC)



SWC Seasonal Cycle by Modal SWE Peak Month  
LPJmL (1988-2018)



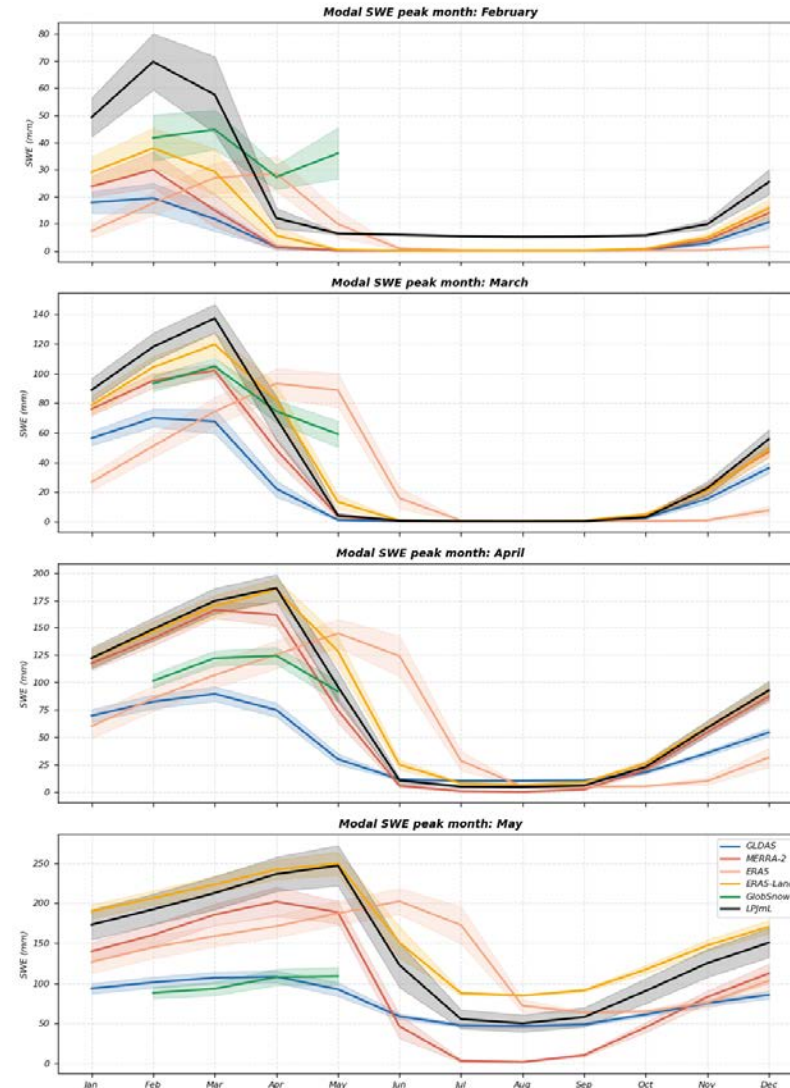
SWC Seasonal Cycle by Modal SWE Peak Month  
ERA5-Land (1988-2018)



# Snow Water Equivalent (SWE)



SWE Seasonal Cycle by Modal SWE Peak Month



# Standardized Precipitation Index (SPI)

Standardized  
Precipitation  
Index (SPI)

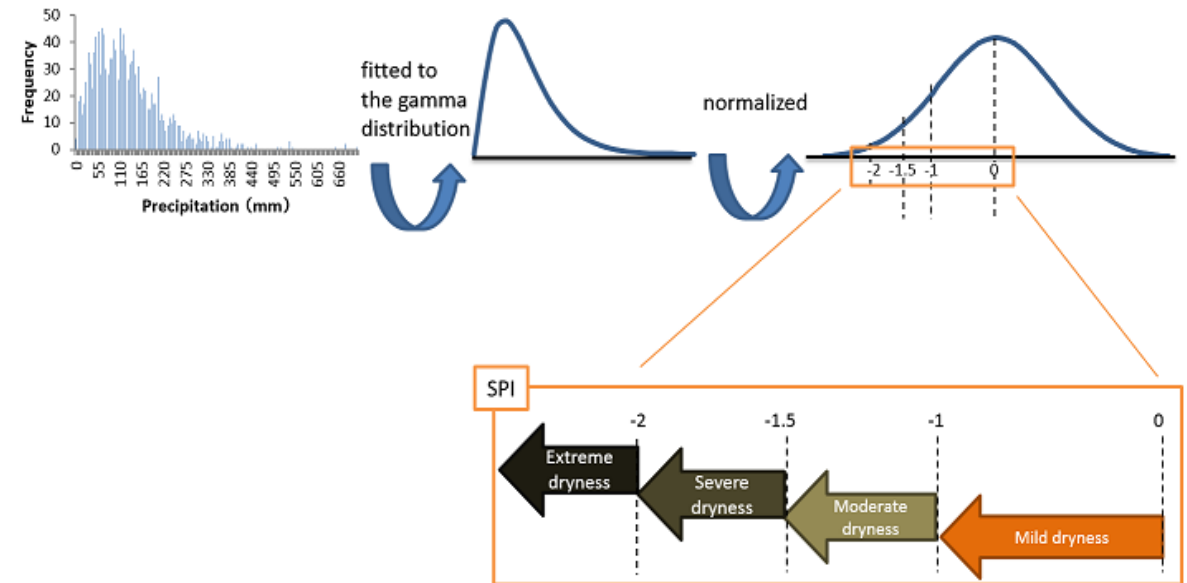


- Measures how unusual the current precipitation is for a given location and time of year
- Locally standardized
- 3-month accumulation window
- Fits a Gamma distribution to the historical precipitation data for each calendar month
- The fitted Gamma distribution converts each precipitation value into a cumulative probability
- Convert to Z-score
- Threshold:

Low:  $SPI \leq -1.3$

Normal:  $-1.3 < SPI < 1.3$

High:  $SPI \geq 1.3$

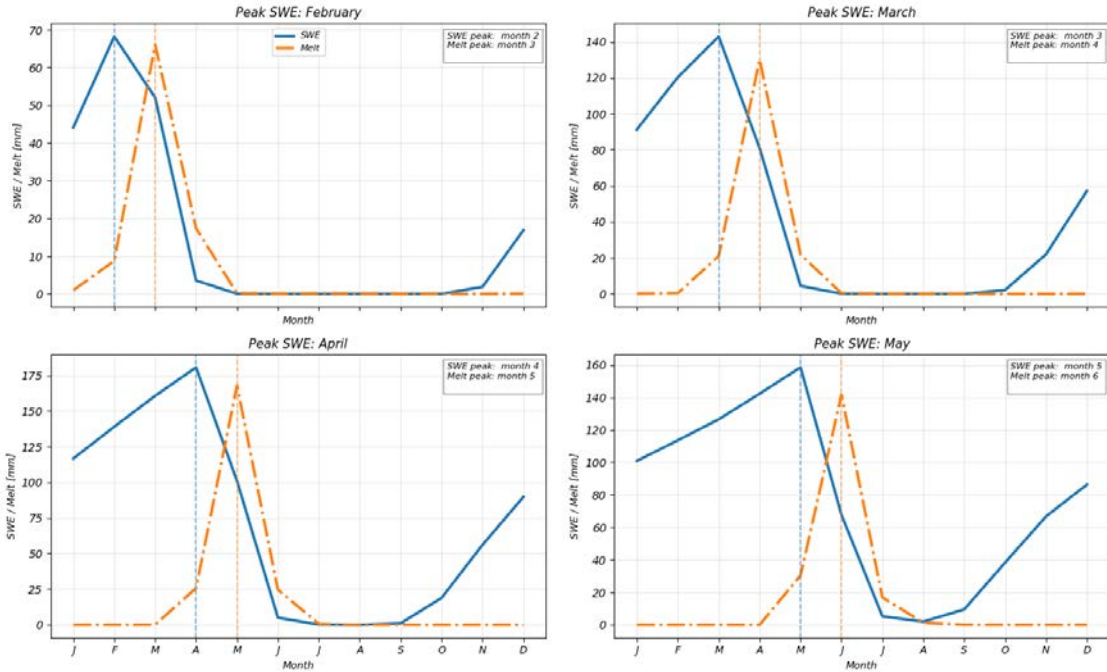


Schematic representation of SPI calculation (From Tokyo Climate Center, Climate Prediction Division. Copyright(C) 2002. Japan Meteorological Agency)

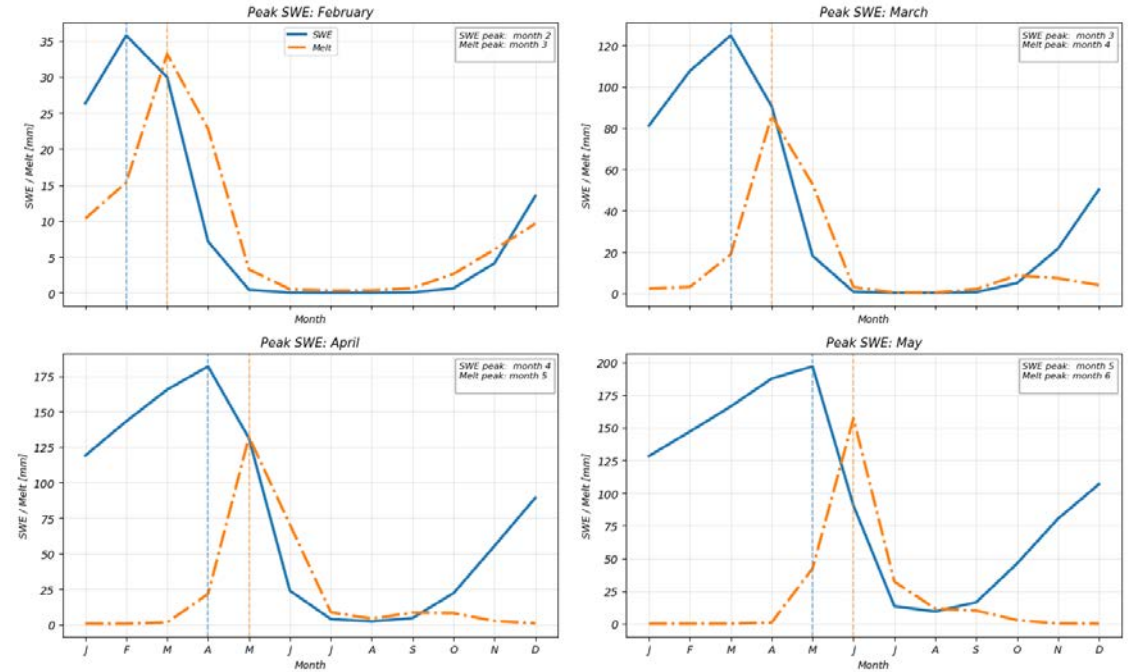
# Mean peak SWE and Snowmelt For LPJmL and ERA5L



Mean SWE and snowmelt  
ERA5L\_lpjml



Mean SWE and snowmelt  
ERA5L

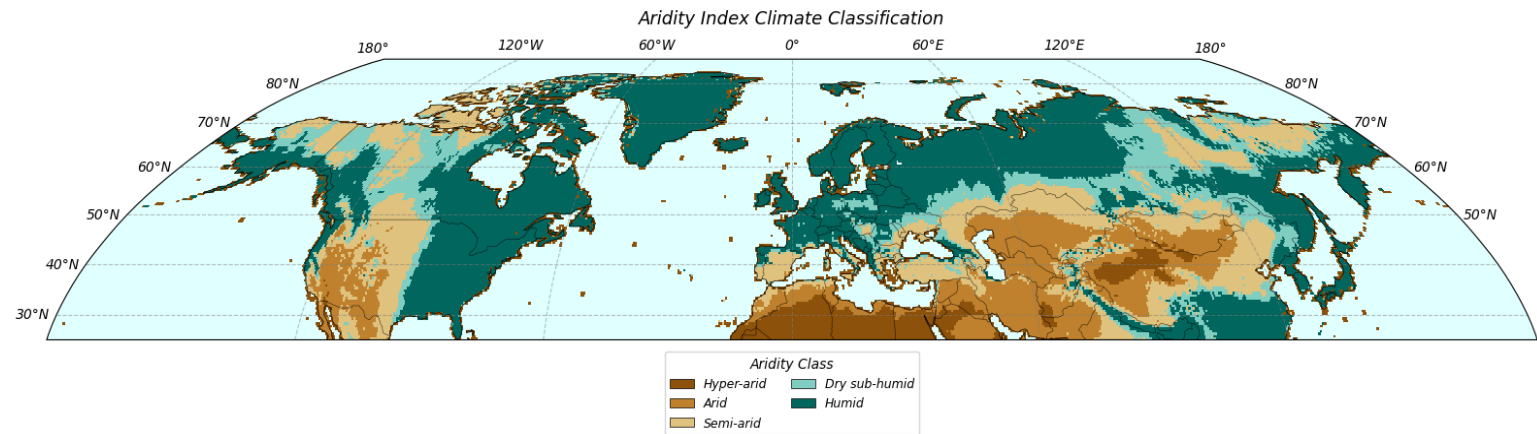


# Datasets description

Dataset	Approach	Advantages	Disadvantages
<b>Fluxcom</b>	<ul style="list-style-type: none"> <li>Takes in-situ eddy covariance measurements from FLUXNET tower sites and upscales it using ML, remote sensing and meteo data (ERA5)</li> </ul>	<ul style="list-style-type: none"> <li>Physically grounded (based on real flux measurements)</li> </ul>	<ul style="list-style-type: none"> <li>Biased toward tower locations (temperate forests and grasslands in Europe and North America). Sparse in snow-dominated regions, extrapolated with less confidence</li> <li>Snow drought effects on soil moisture or root zone water stress are not directly observed.</li> </ul>
<b>NIRV</b>	<ul style="list-style-type: none"> <li>NIRv is a spectral index derived from satellite reflectance</li> <li>Proxy for the fraction of absorbed photosynthetically active radiation (fAPAR) which correlates tightly with GPP across many biome types (Empirical relationship)</li> <li>(NIRv = NIR reflectance of veg. × NDVI-like signal)</li> <li>NDVI index detects and quantifies the presence of living green vegetation</li> </ul>	<ul style="list-style-type: none"> <li>Direct observation of canopy structure and greenness</li> <li>Captures phenological response well</li> </ul>	<ul style="list-style-type: none"> <li>Weak sensitivity to: cold-season processes, snow-covered vegetation</li> <li>Cannot detect subsurface water stress</li> <li>Snow cover interferes with the signal (phenology transitions in and out of snow can introduce artifacts)</li> </ul>
<b>VODCA2</b>	<ul style="list-style-type: none"> <li>Estimates GPP passive microwave vegetation optical depth</li> <li>Proxy for vegetation water content and biomass</li> <li>Empirical model using Vegetation Optical Depth (VOD) as a key predictor, trained on FLUXNET GPP data</li> </ul>	<ul style="list-style-type: none"> <li>VOD penetrates clouds</li> <li>Sensitive to deep-rooted vegetation water content</li> </ul>	<ul style="list-style-type: none"> <li>Less sensitive to rapid photosynthesis changes (Slower temporal response)</li> <li>limitations in cold or snow-covered regions because the microwave signal is contaminated by frozen ground and snow.</li> </ul>
<b>LPJmL</b>	<ul style="list-style-type: none"> <li>Process-based vegetation model</li> <li>Simulates coupled carbon and water cycle processes</li> </ul>	<ul style="list-style-type: none"> <li>Physically consistent with snow processes</li> <li>Can represent lag effects</li> <li>Mechanistic ecosystem response</li> </ul>	<ul style="list-style-type: none"> <li>Model assumptions</li> <li>Parameter uncertainty</li> </ul>

# Aridity Index Value and Climate Class

Aridity Index Value	Climate Class
< 0.03	Hyper Arid
0.03 – 0.2	Arid
0.2 – 0.5	Semi-Arid
0.5 – 0.65	Dry sub-humid
> 0.65	Humid



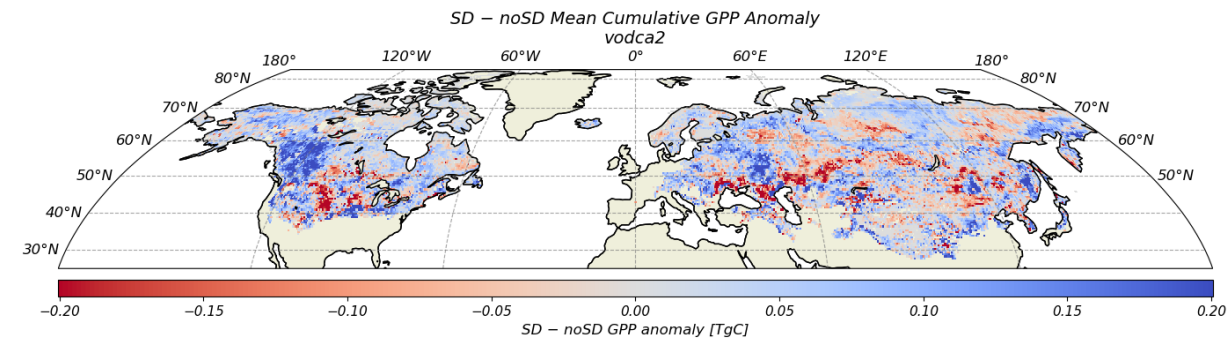
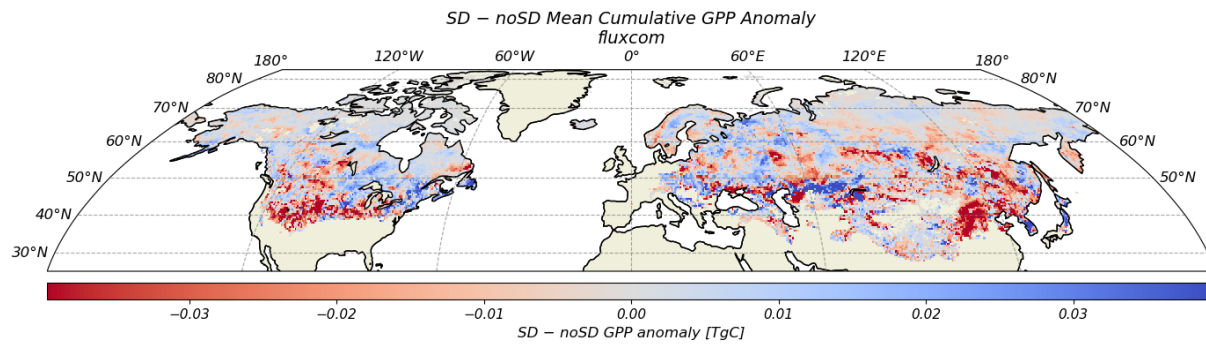
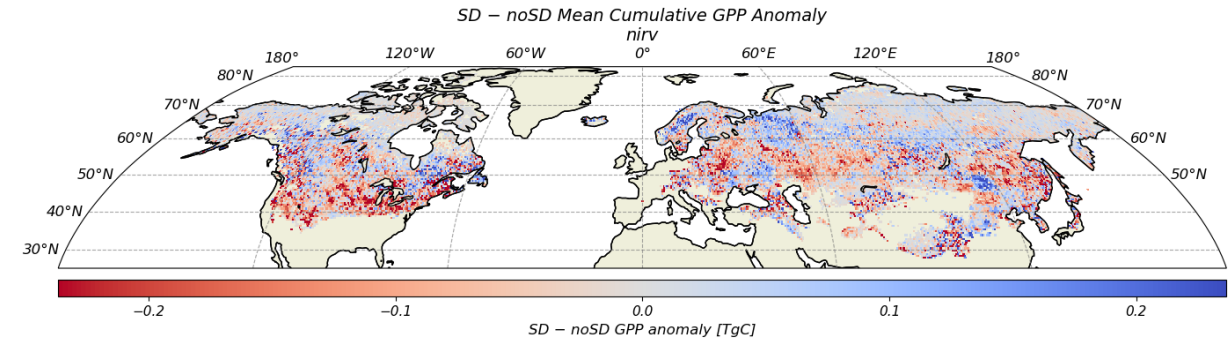
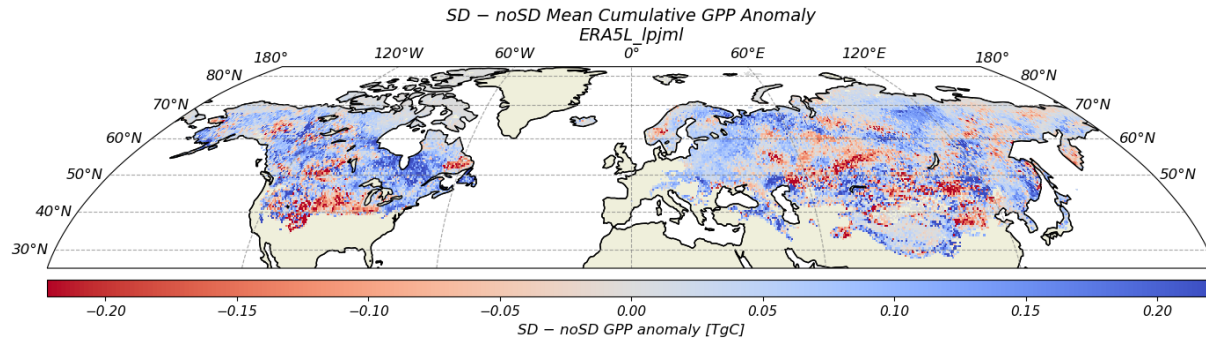
$$AI = \frac{P}{PET}$$

*P* = average annual precipitation

*PET* = potential evapotranspiration

From Zomer, R.J.; Xu, J.; Trabucco, A. (2022)

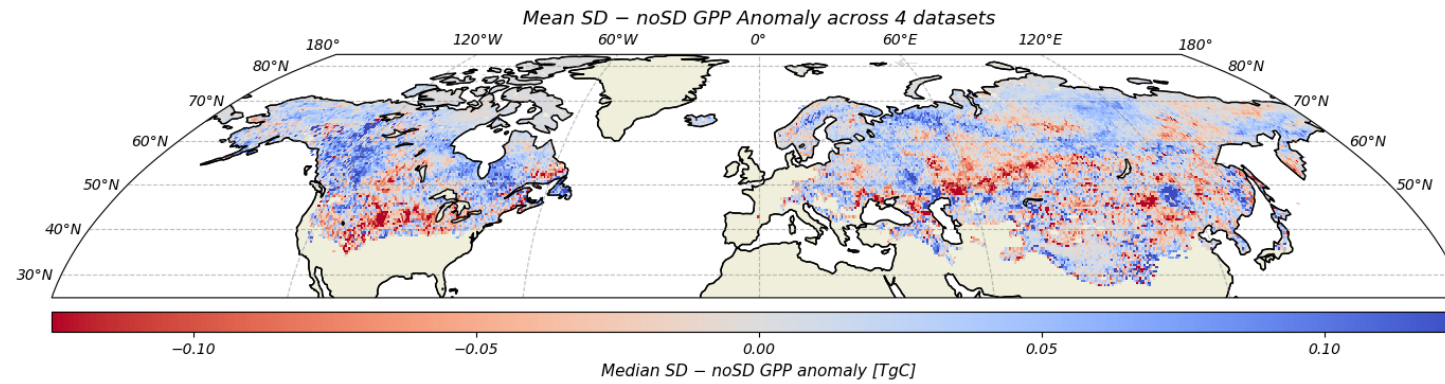
# Difference of total GPP anomalies (SD – noSD)



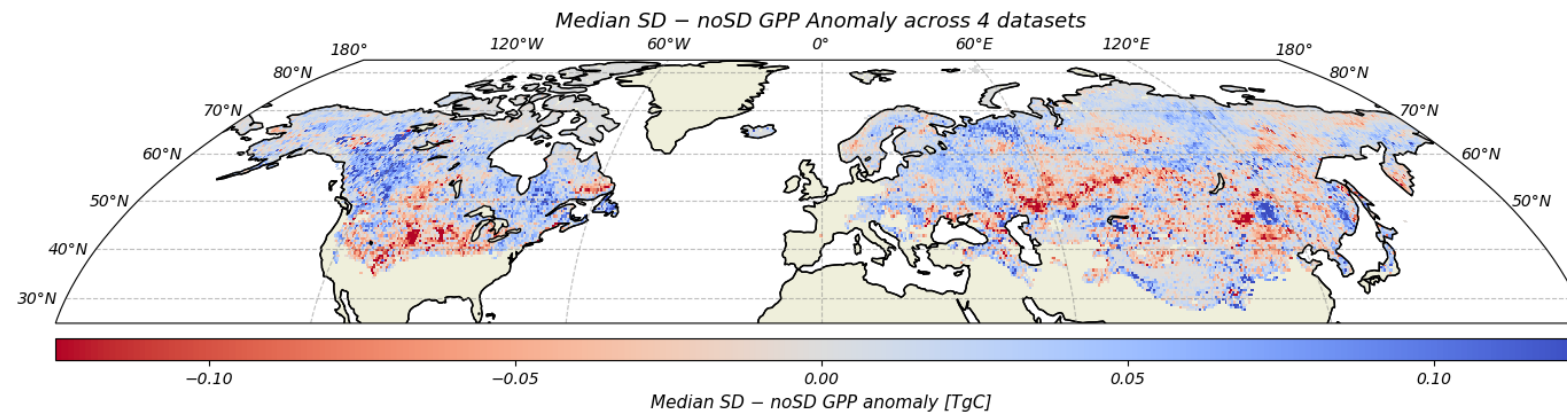
# Difference of total GPP anomalies (SD – noSD)



- Mean value across datasets



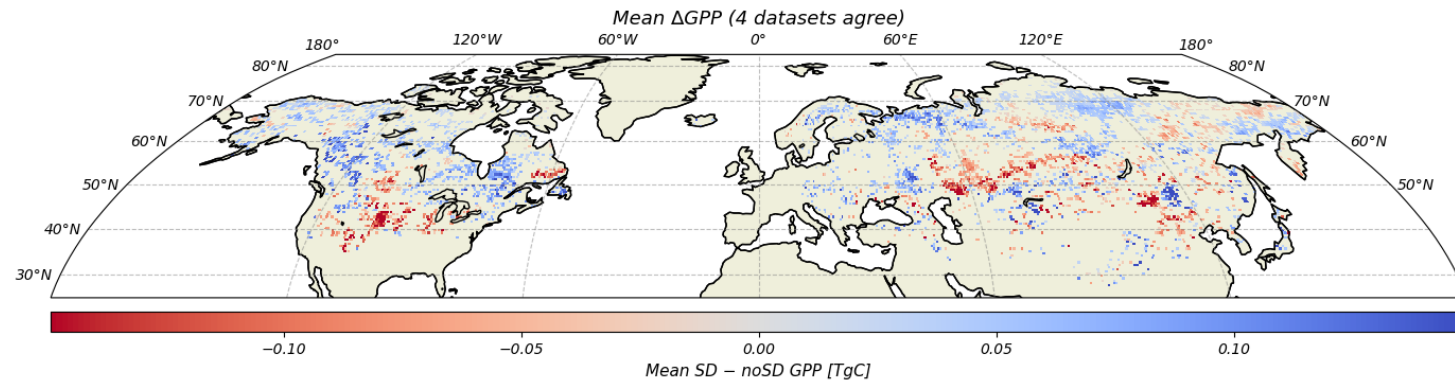
- Median value across datasets



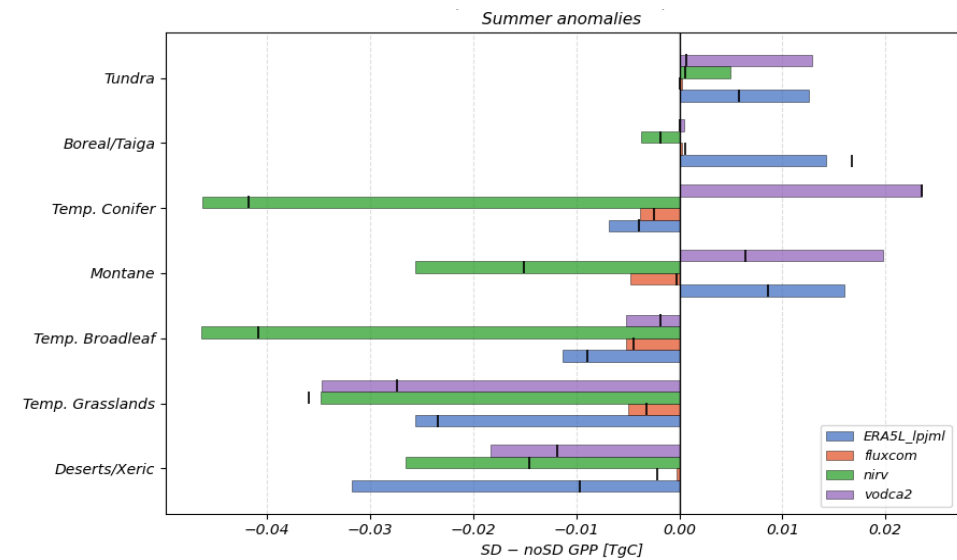
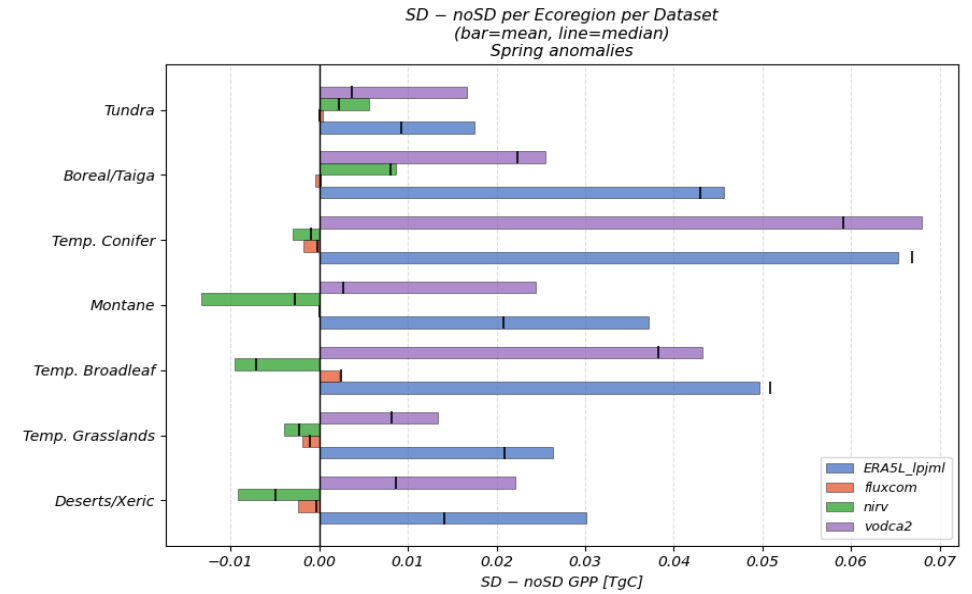
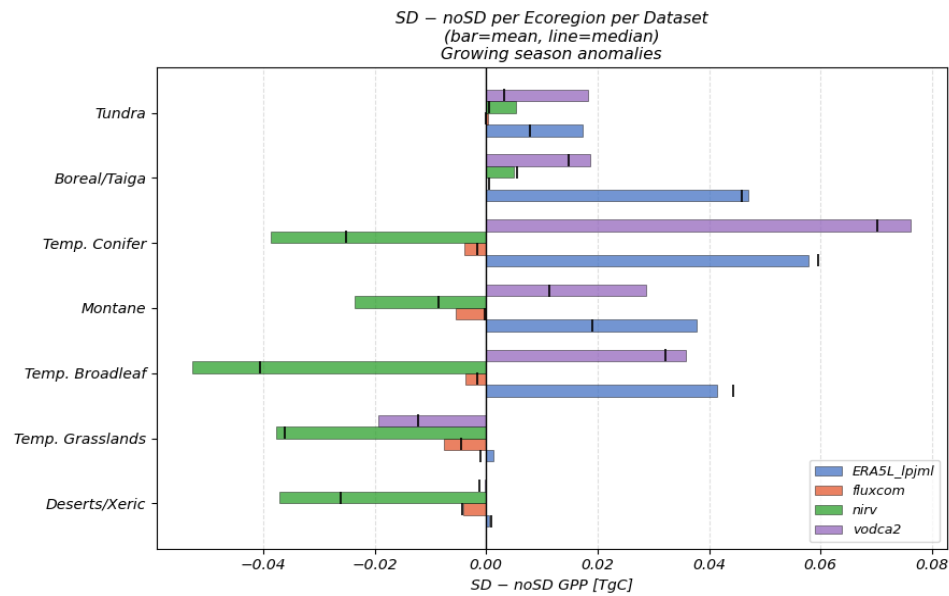
# Difference of total GPP anomalies (SD – noSD)



- 4/4 agreement dataset



# Effect of SD on GPP per dataset - Ecoregion



# Effect of SD on GPP per dataset - Aridity

