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Non-stationarity in the terrestrial water cycle, anthropogenic influences and uncertainty

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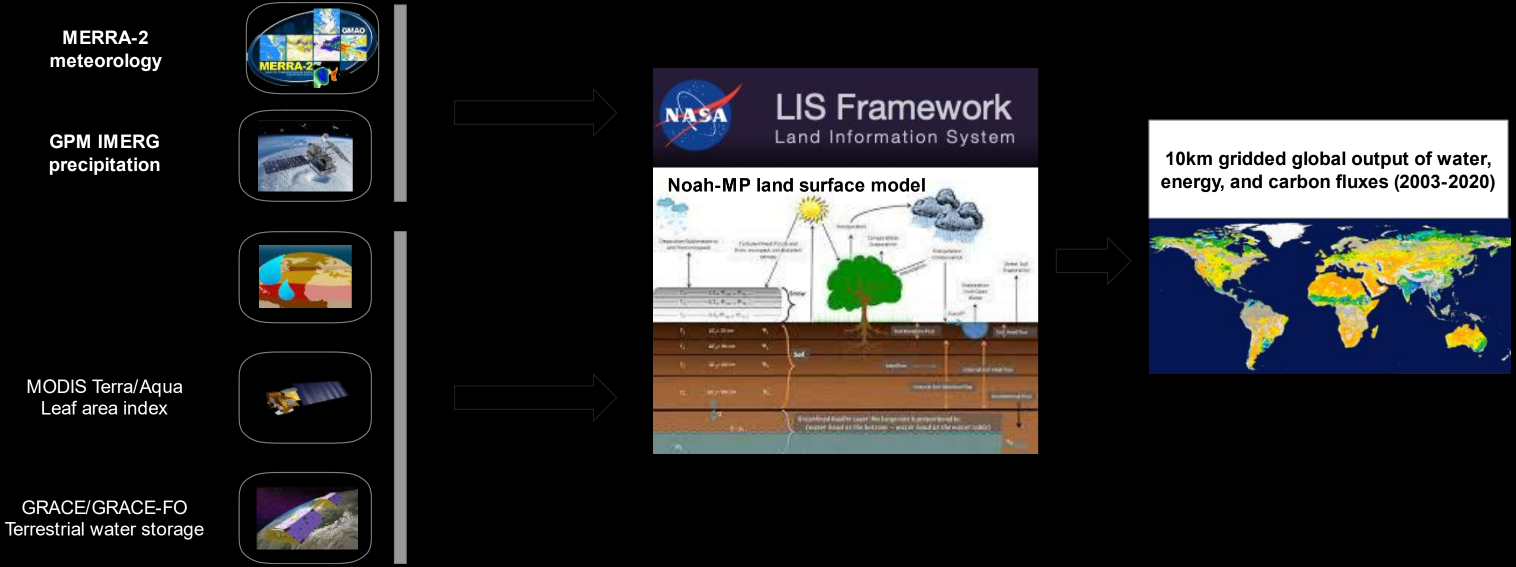
Global water cycle reanalysis informed by remote sensing observations of precipitation (GPM), soil moisture (SMAP), leaf area index (MODIS), and terrestrial water storage (GRACE and GRACE-FO), MODIS-based snow water equivalent, SWOT water level, …

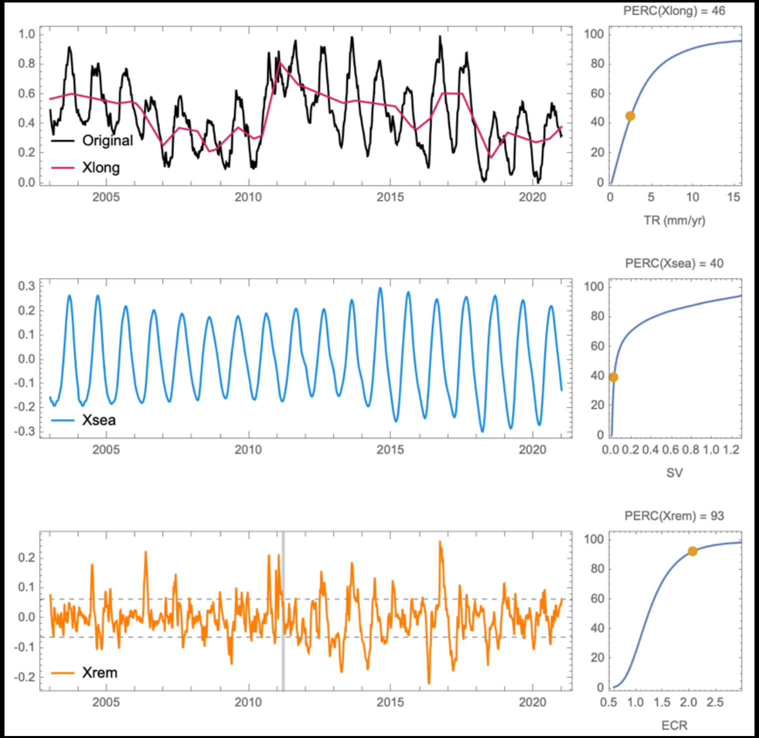


The RobustSTL (seasonal-trend decomposition loess algorithm) is used to decompose the time series (from the reanalysis) into trend, seasonality, and remainder (extremes) components

X_{long}

X_{sea}

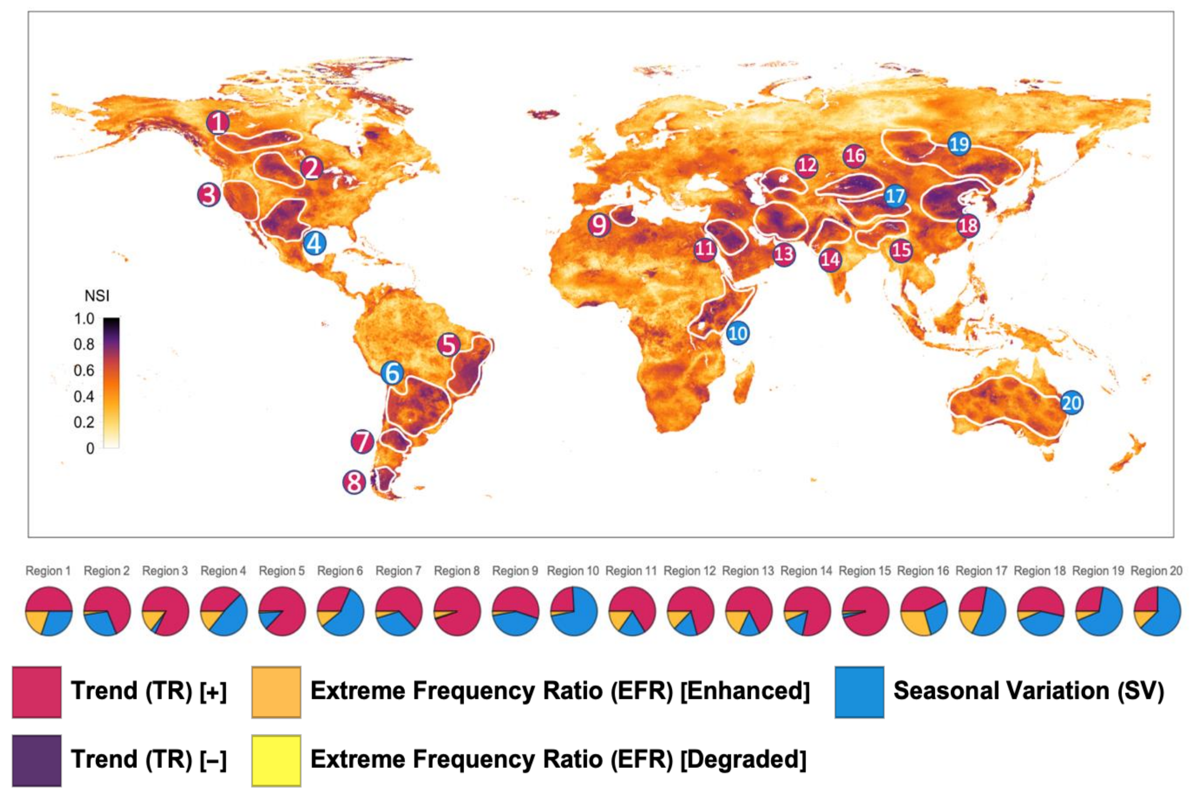
X_{rem}



$$X = X_{long} + X_{sea} + X_{rem}$$

The nonstationarity index is then calculated as a normalized measure of the percentile ranking of each of the three component terms

Nie et al. "Nonstationarity in the global terrestrial water cycle and its interlinkages in the Anthropocene", PNAS, 2025

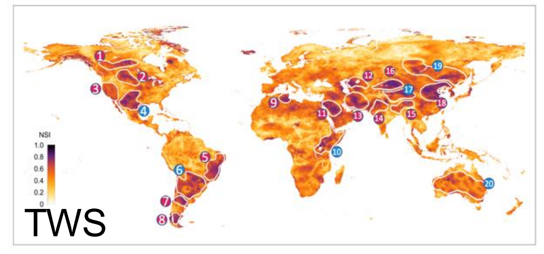


15 out of 20 regions have non-stationary water cycle changes dominated by trend component, with 14 of them showing a depletion.

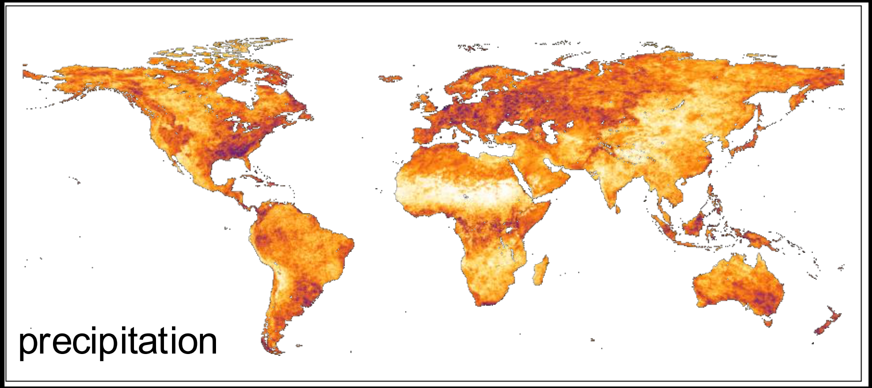
5 regions have non-stationarity dominated by seasonal shifting.

Half of the regions have more than 10% area dominated by extreme frequency ratio, indicating different level of extreme increases with significant abrupt changes.

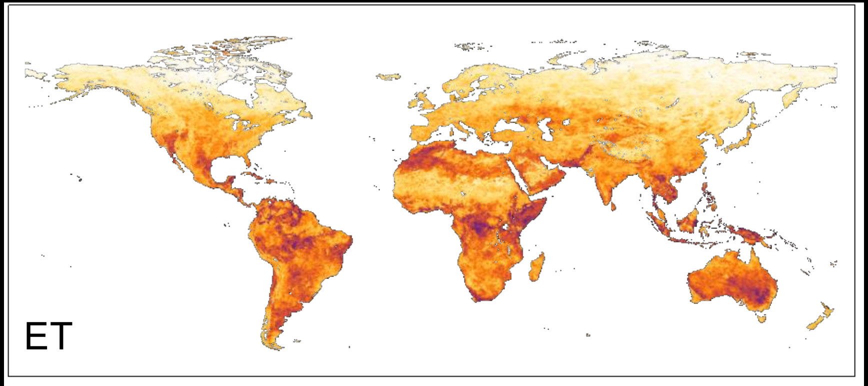
Nie et al. "Nonstationarity in the global terrestrial water cycle and its interlinkages in the Anthropocene", PNAS, 2024

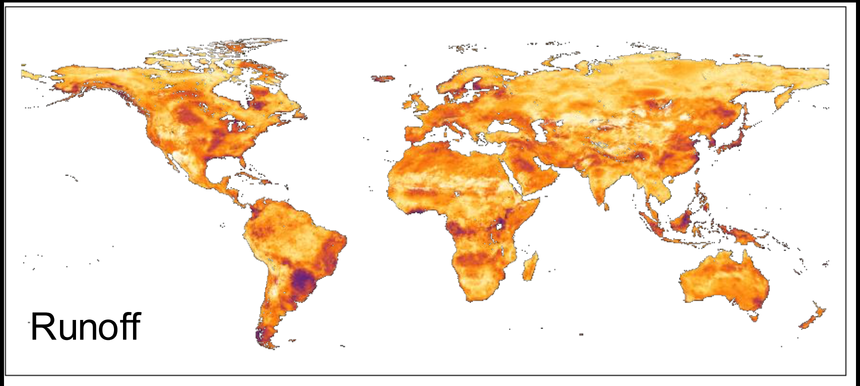


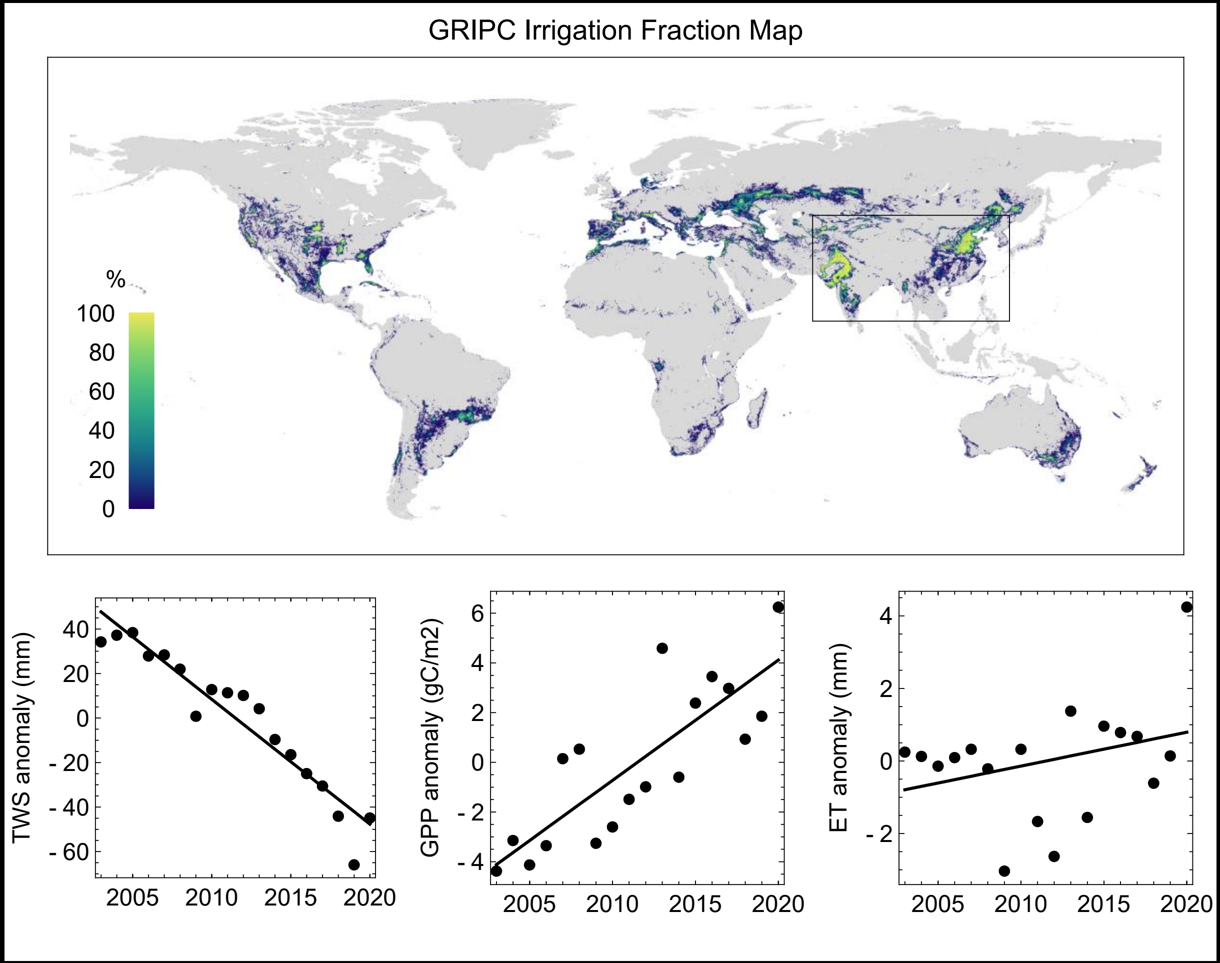
Nonstationarity in the driving meteorology is less strong



The nonstationarity impacts on ET and runoff are mixed

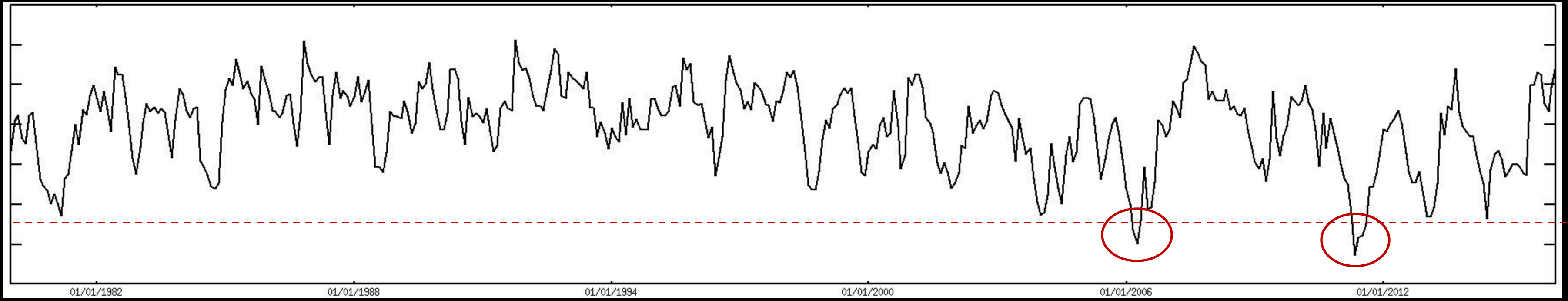






For irrigated south Asia, depletion of TWS due to GW pumping has supported crop growth. The reduced water availability and increased vegetation leads to mixed impacts in ET.

How do we usually compute measures of extremes (e.g. droughts)?



From the time series of a geophysical variable (e.g. soil moisture, groundwater), identify conditions that are below a specific threshold

Category	Description
D0	Abnormally Dry
D1	Moderate Drought
D2	Severe Drought
D3	Extreme Drought
D4	Exceptional Drought

Percentile < 30%

Percentile < 20%

Percentile < 10%

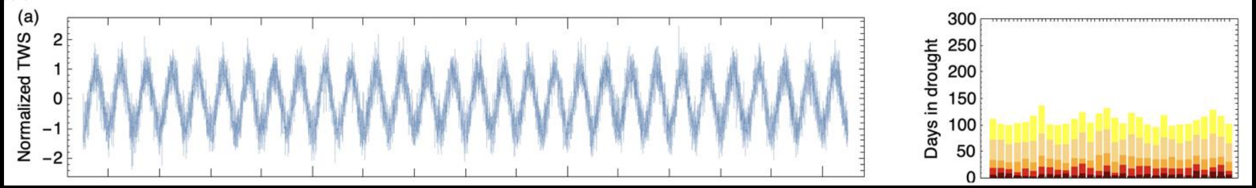
Percentile < 5%

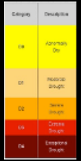
Percentile < 2%

<u>Implicit assumption</u>

The underlying distribution that defines the "norm"/climatology is time-invariant/stationary

What does this mean for quantification of extremes?



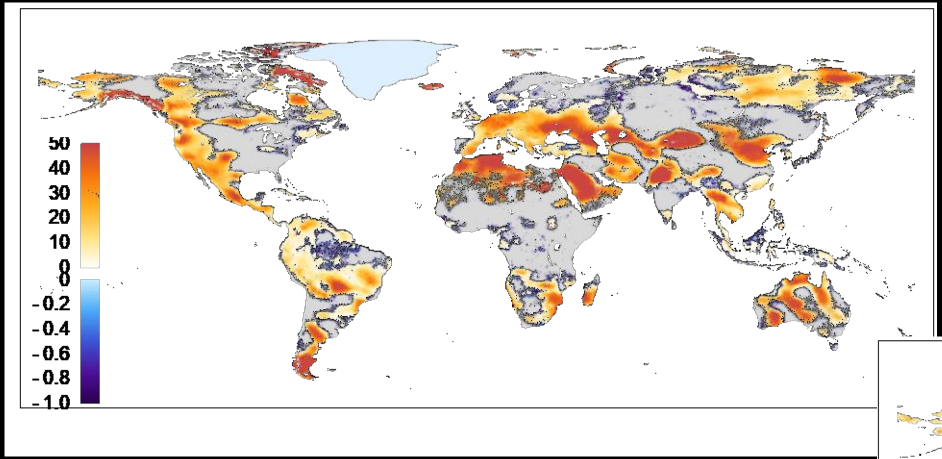


Percentile < 30%
Percentile < 20%
Percentile < 10%
Percentile < 5%
Percentile < 2%

Stationary

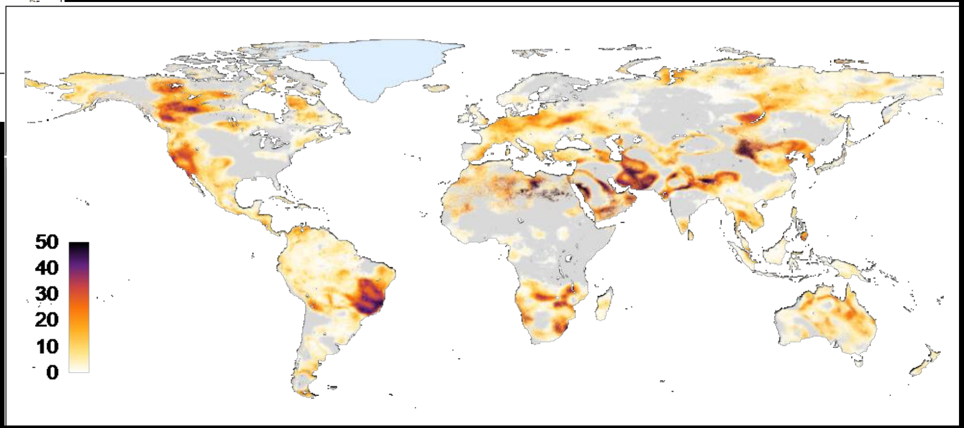
Nie et al. "Anthropogenic influences on the water cycle amplify uncertainty in drought assessments", One Earth (2025).

Large errors in drought estimation when nonstationarity is not acknowledged!



Median bias in drought estimation across the ensemble members relative
a stationary assumption

IQR in drought estimation across the ensemble members



Several (~100) scenarios for estimating drought were considered, using different periods for reference data and climatology

Summary

- Data sources: Nonstationarities in the terrestrial water cycle is dominated by management influences – therefore, remote sensing observations are key (the only way) to capture these impacts accurately.

- Metrics and indicators: Current metrics reliant on stationary assumptions can lead to large errors based on the period of record and sampling windows.

- Methodologies to address non-stationarity: Deviations (in drought metrics) from stationary assumptions can be used to quantify underlying uncertainties

North American Land Data Assimilation System Phase 3 (NLDAS-3)