Summer school on the use of AI for the analysis of extreme events

An Introduction to Droughts and Compound Events

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CMCC Foundation – Euro-Mediterranean Center
on Climate Change

23 June 2026

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Session Overview

PART 1 — Droughts

1. Definitions & drought taxonomy
2. Flash drought vs. conventional
3. Types, indices & monitoring
4. Droughts in a changing climate

PART 2 — Compound Events

1. Definitions & why they matter
2. Typology of compound events
3. Concurrent extremes
4. Impacts & projections

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PART 1 — Droughts

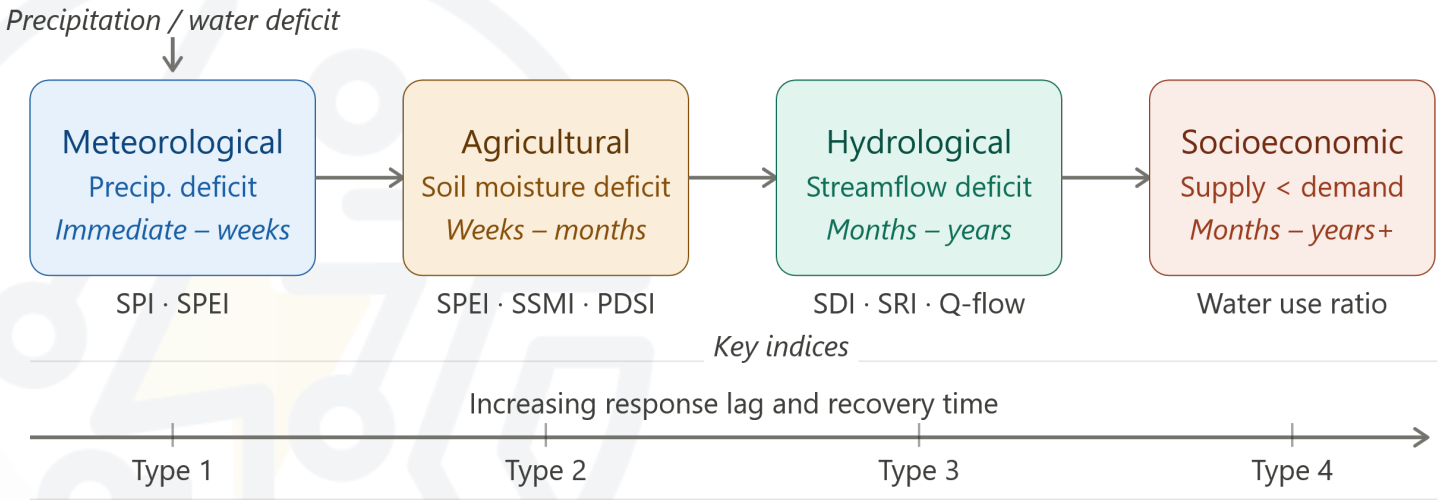
Definitions · Taxonomy · Flash Drought · Indices · Climate Change

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What is Drought?

> *"A deficiency of precipitation over an extended period of time (usually a season or more), resulting in a water shortage."*
>
> *American Meteorological Society (AMS)*



Source: Wilhite & Glantz (1985); Hao et al. (2022) Earth-Sci. Reviews, Fig. 1; IPCC AR6 (2021)

Lag times are typical ranges — actual values depend on region, severity, and antecedent conditions

Why is drought difficult to define?

150+ Published definitions of drought exist (Wilhite & Glantz 1985)

Multi Impacts span water, agriculture, energy and society simultaneously

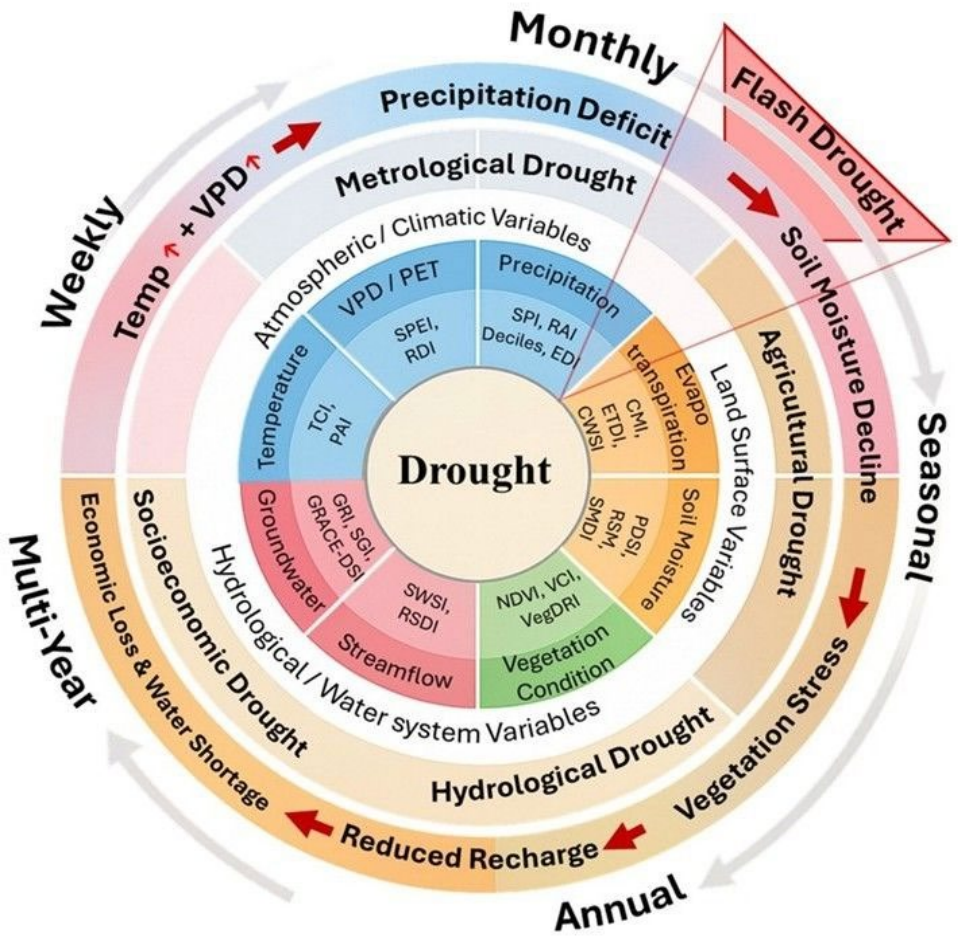
Slow Slow & insidious onset — it "creeps" in over weeks to months

New Flash drought: rapid-onset sub-type, develops within days-weeks

Source: AMS (1997); Wilhite & Glantz (1985); Sabut et al. (2026) J. Hydrology

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Drought Taxonomy



Source: Sabut et al. (2026) Journal of Hydrology, Fig. 1 | Wilhite & Glantz (1985)

Core → outer rings

Inner: drought types & input variables. Middle: indices. Outer: impacts & temporal scale.

Timescales

Weekly (flash drought) → monthly (meteorological) → seasonal (agricultural) → annual-multi-year (hydrological / socioeconomic).

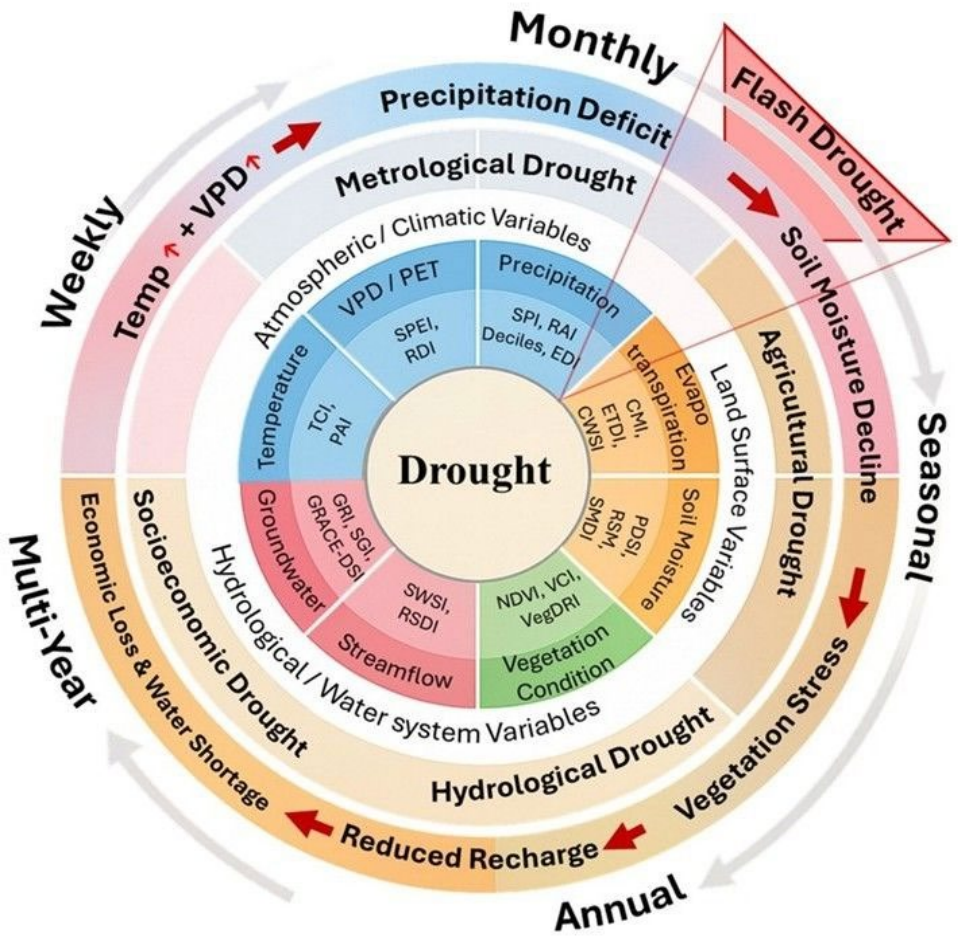
Flash drought

Rapid-onset pathway (upper right): triggered by Temp↑ + VPD↑. Develops in days–weeks, before conventional indicators register.

Drought characteristics

Any drought type is characterised by: onset timing, intensification rate, severity, duration/persistence, and spatial extent.

Drought Taxonomy



Meteorological Drought

Precipitation deficit |onset: immediate to weeks | SPI, SPEI; Flash drought sub-type: 2–8 weeks | SESR, EDDI

Agricultural Drought

Soil moisture deficit |onset: weeks to months | SPEI, SSMI

Hydrological Drought

Surface/groundwater | onset: months to years | SDI, SRI

Socioeconomic Drought

Supply vs. demand deficit | onset: ongoing, multi-year

Ecological Drought

Water stress on ecosystems | tree mortality, fire risk

Source: Sabut et al. (2026) Journal of Hydrology, Fig. 1 | Wilhite & Glantz (1985)

SCEWERO

Flash Drought

Definition

Rapid soil moisture depletion developing within 2–8 weeks, driven by precipitation deficit AND/OR elevated evaporative demand (high T, VPD, wind).

Why it matters

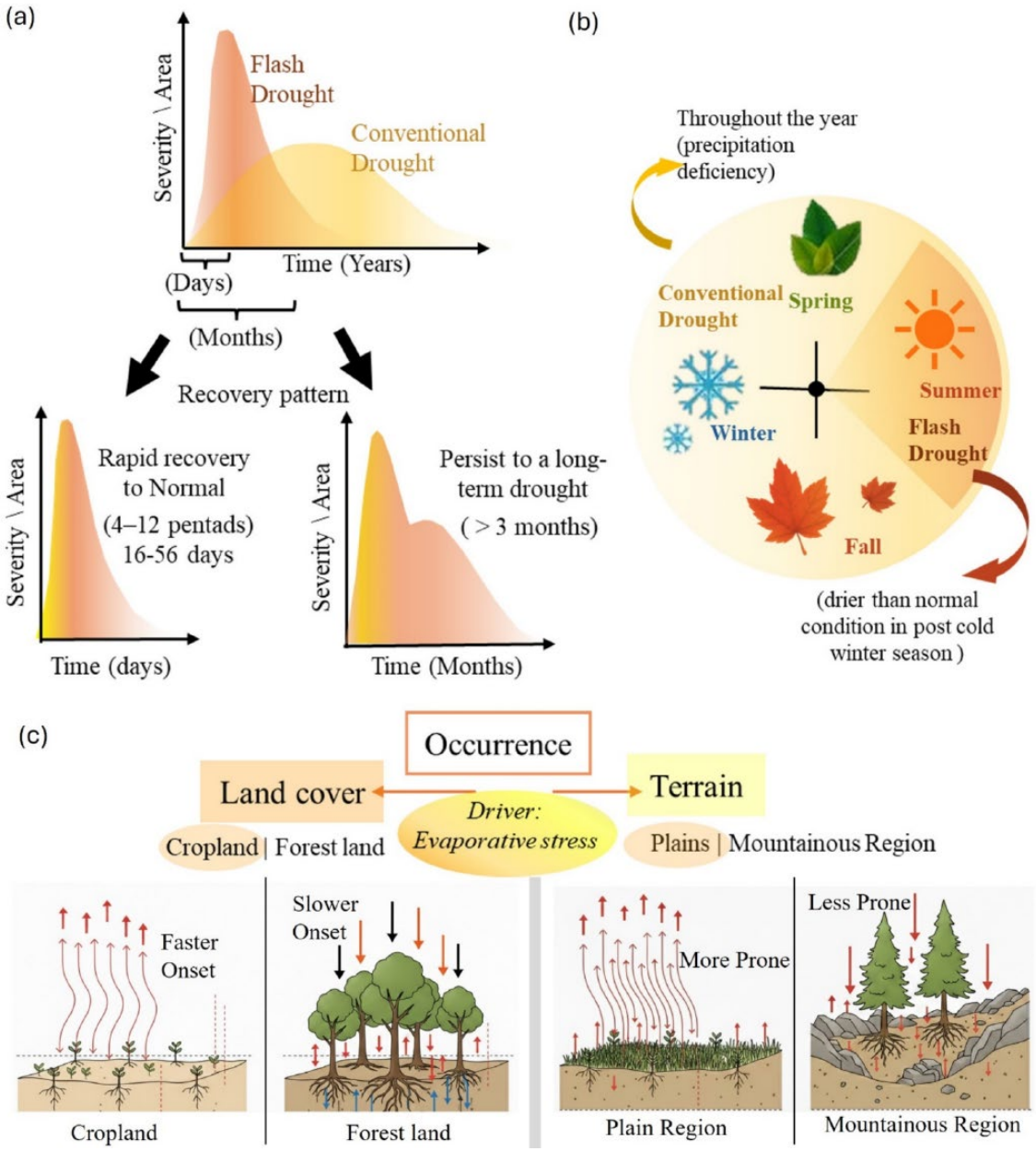
Flash drought is an 'extreme of extremes' — its compressed onset leaves little time for preparedness. Agriculture, water, ecosystems and energy are impacted before conventional drought monitors register.

Key distinction from conventional drought

Conventional droughts develop over months to years. Flash droughts are the fastest 10% of onsets (~15 days vs ~30 days; Goswami & Gallant 2025), more frequent in summer/autumn.

Two main types

(i) Temperature-driven / heatwave FD: elevated T + VPD deplete soil moisture even without precipitation deficit. (ii) Precipitation-deficit FD: abrupt rainfall shortfall + subsequent ET anomalies.



Source: Sabut et al. (2026) J. Hydrology, Fig. 4 | Goswami & Gallant (2025) | Otkin et al. (2018)

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Summary: Four Classical Drought Types

Drought Type	Key Variable	Lag Time	Example & Index
Meteorological	Precipitation deficit	Immediate → weeks	Below-normal rainfall for a season; SPI-based
Agricultural	Soil moisture deficit	Weeks–months	Crop failure, poor harvest; SPEI, SSMI
Hydrological	Surface/groundwater	Months–years	River low-flow, reservoir depletion; SDI, SRI
Socioeconomic	Supply vs. demand	Ongoing / multi-year	Water rationing, food price spike

A fifth type — ecological / environmental drought, and flash drought as rapid-onset sub-type, are increasingly recognised.

Source: Wilhite & Glantz (1985); NWS; Sabut et al. (2026); Hao et al. (2022)

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Measuring Drought: Key Indices

SPI

Precipitation only

Standardised Precipitation Index
Number of std. deviations that observed precipitation deviates from climatological average. Computed at 1–24 month timescales. Positive = wet; negative = dry.

McKee et al. (1993)

SPEI

Precipitation + Potential ET

Standardised Precipitation Evapotranspiration Index
Like SPI but uses P–PET balance. Captures the role of warming on drought via increased evaporative demand. Preferred under climate change.

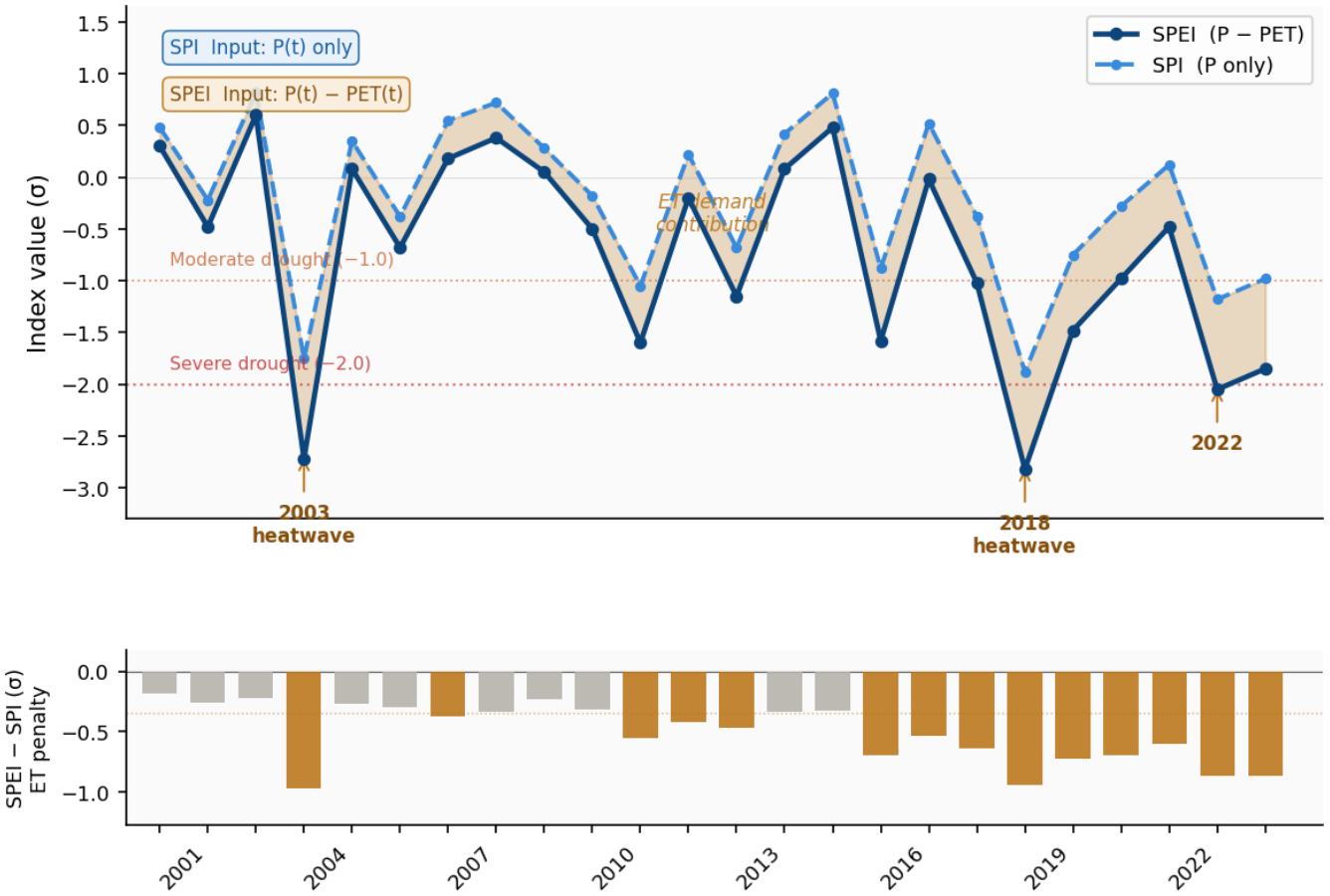
Vicente-Serrano et al. (2010)

PDSI

P, T, soil water capacity

Palmer Drought Severity Index
Physically-based index using a simplified water balance. Widely used for long-term drought monitoring. Fixed timescale (~9 months); local calibration needed.

Palmer (1965)



Source: McKee et al. (1993); Vicente-Serrano et al. (2010); CLINT MS11 (2022)

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Measuring Drought: Further Indices

CDI — *SPI, SMA, FAPAR*

Combined Drought Index
Identification of different classes of drought and their extent with a particular focus on vegetated areas

https://drought.emergency.copernicus.eu/

SRI — *Streamflow / runoff*

Standardised Runoff Index
Like SPI, addressing deviations from the average of a standardized distribution but replacing the precipitation data with the surface runoff ones.

Shukla and Wood (2008); Vicente-Serrano et al. (2012)

SSMI — *Soil moisture*

Standardized Soil moisture Index
Like SPI, addressing deviations from the average of a standardized distribution but replacing the precipitation data with the soil moisture ones.

Hao and Aghakouchak (2013)

SDI — *Streamflow volume*

Streamflow Drought Index
Like SPI, addressing deviations from the average of a standardized distribution but replacing the precipitation data with the streamflow volume ones.

Nalbantis and Tsakiris (2009)

EDDI — *PET / atmospheric demand*

Evaporative Demand Drought Index
Anomalies in atmospheric evaporative demand prior to soil moisture response; early-warning value but high false-alarm rate

Hobbins et al. (2016); McEvoy et al. (2016)

SESR — *Ratio actual ET vs. PET*

Standardized Evaporative Stress Ratio
Addresses water-stressed vegetation; *response*; stress presence

Christian et al. (2019)

>50 indices

Visit the Integrated Drought Management Programme (IDMP)
https://www.droughtmanagement.info/indices/

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Drought Monitoring: Key Systems

European Drought Observatory (EDO / GDO)

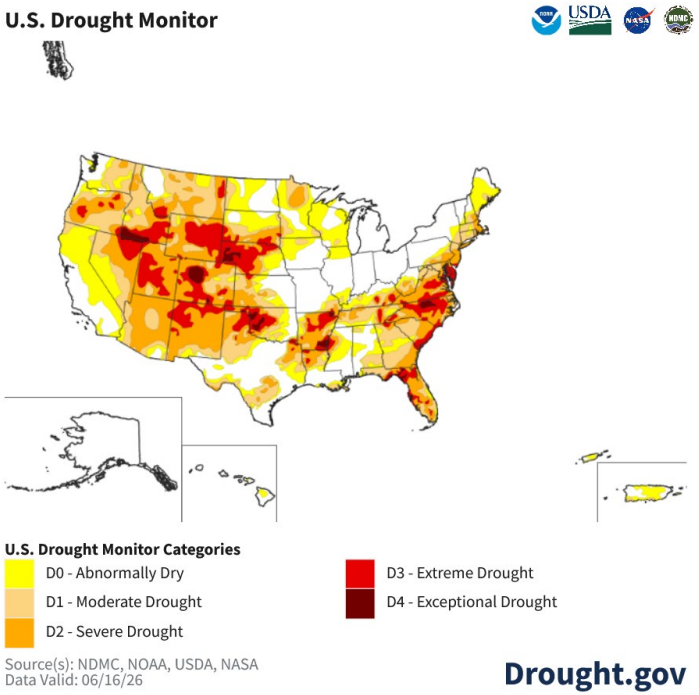
JRC near-real-time monitoring using SPI, soil moisture anomalies, FAPAR. Updated every 10 days. Extended globally by GDO.

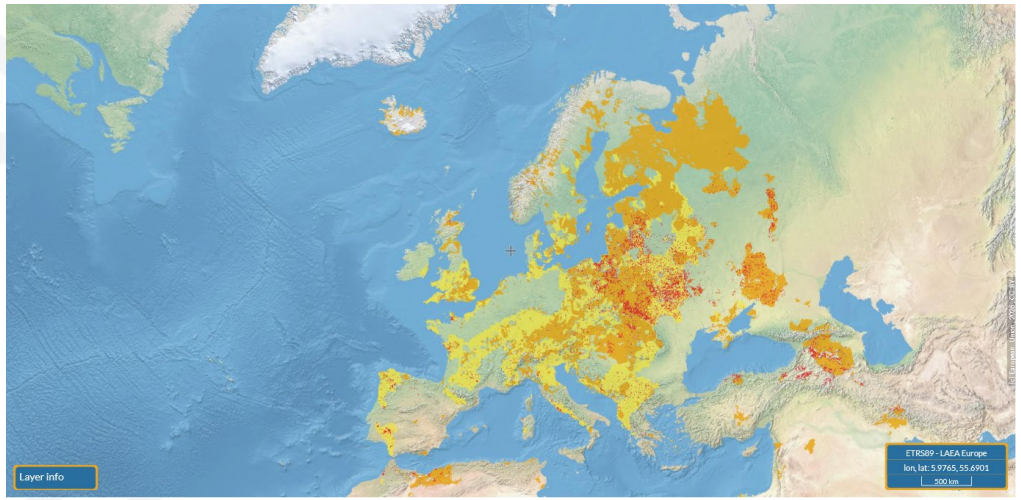
Copernicus Emergency Management Service

EU Earth observation providing SPI, SPEI, soil moisture anomalies for European policy decision-making.

US Drought Monitor (USDM)

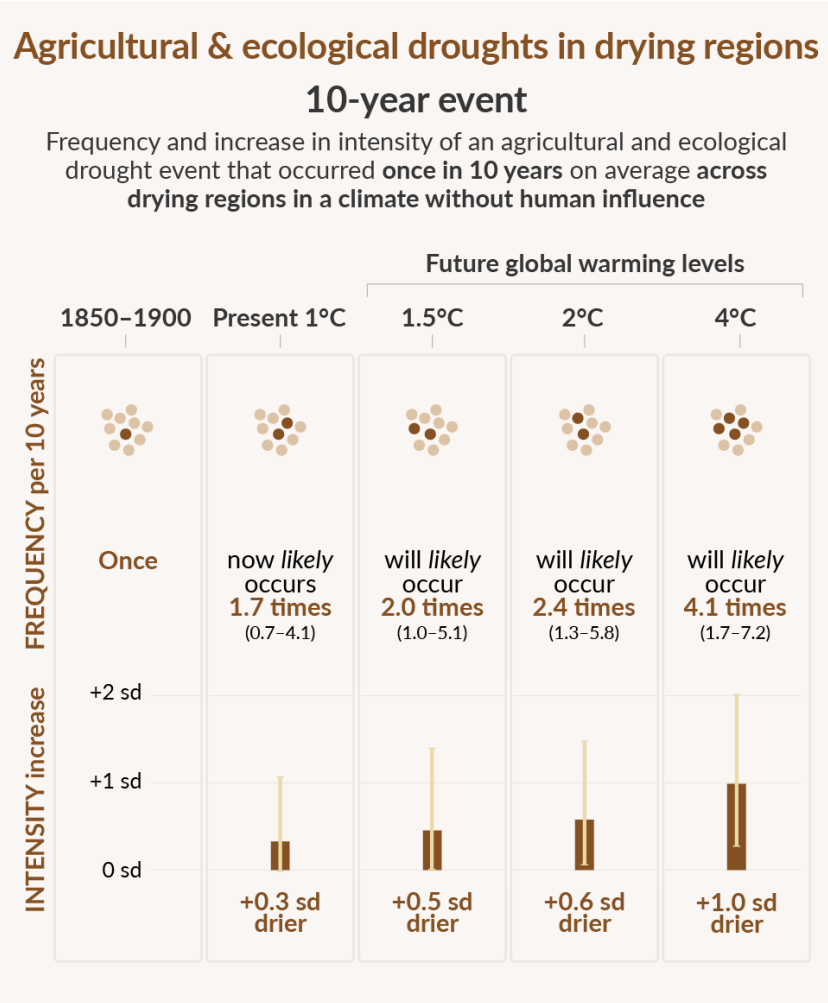
Weekly D0–D4 map combining multiple indices + expert interpretation. Key reference for drought communication worldwide.





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Drought Frequency: IPCC AR6



Source: IPCC AR6 WGI (2021), SPM Figure 6 | Includes Western/Central Europe, Mediterranean, Southern Africa, Eastern & Southern Australia

1.7× more frequent droughts already today (1°C warming)

2.4× more frequent at 2°C warming (Paris Agreement target)

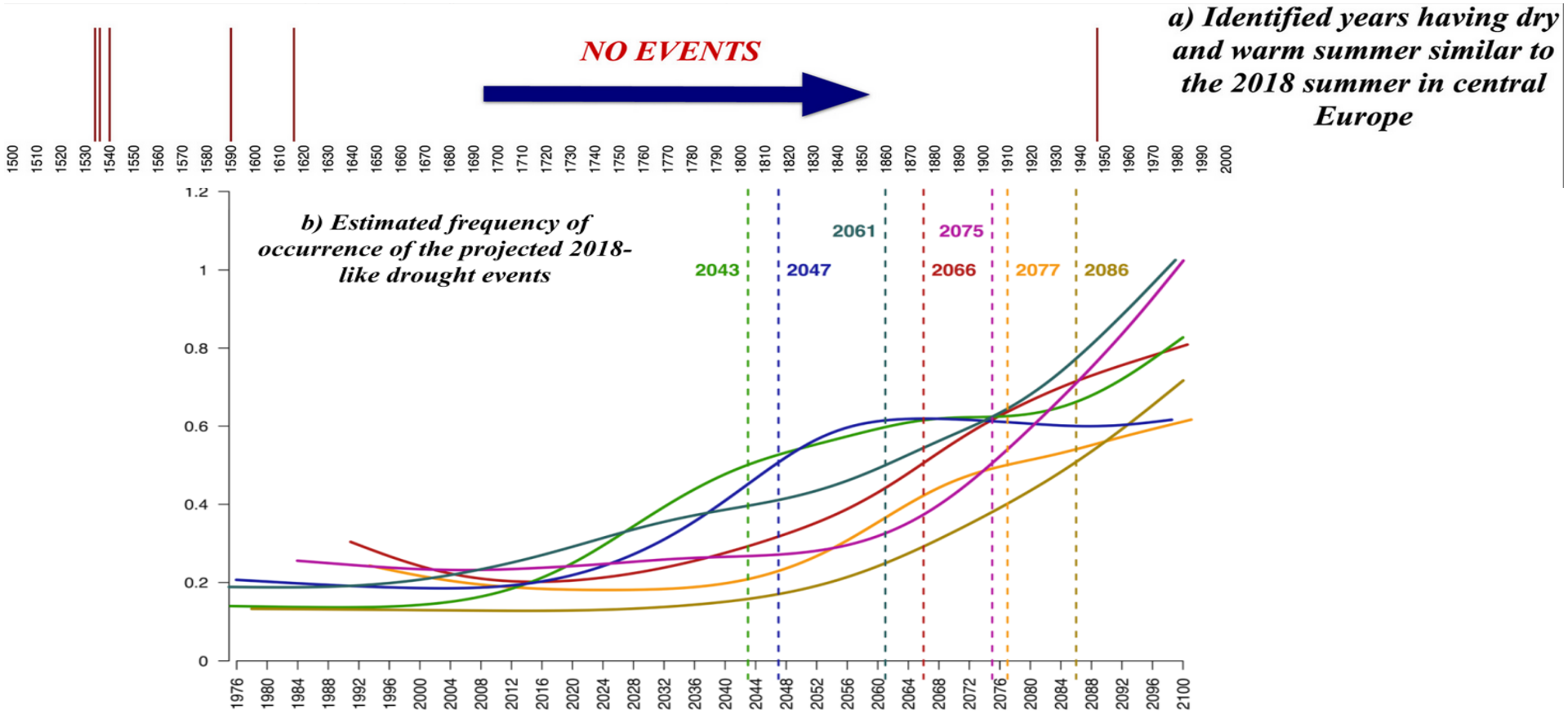
4.1× more frequent at 4°C — the high-emissions pathway

+1.0 sd drier intensity at 4°C (soil moisture standard deviation)

Drying regions only; CMIP6 multi-model median

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European Drought Trends



Source: Toreti et al. 2019a

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PART 2 — Compound Events

Definitions · Typology · Concurrent Extremes · Impacts · Projections

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What are Compound Events?

> ***"Combination of multiple drivers and/or hazards that contribute to societal / environmental risk."***
>
> *Zscheischler et al. (2018)*

Key Properties

Multivariate — Involve two or more hazard drivers — not just a single extreme event

Non-linear impacts — Combined impacts amplify non-linearly; more destructive than the sum of parts

Non-extreme events — Individual components may NOT be extreme — context and combination determine severity

Underestimated risk — Assuming independence of components significantly underestimates return periods and risk

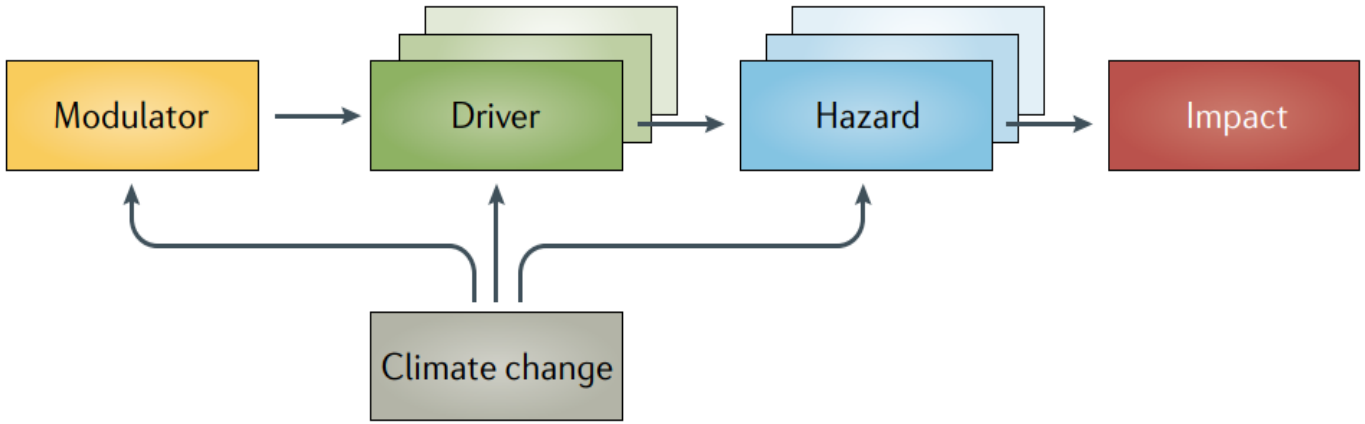
Source: Zscheischler et al. (2018); Zscheischler et al. (2020)

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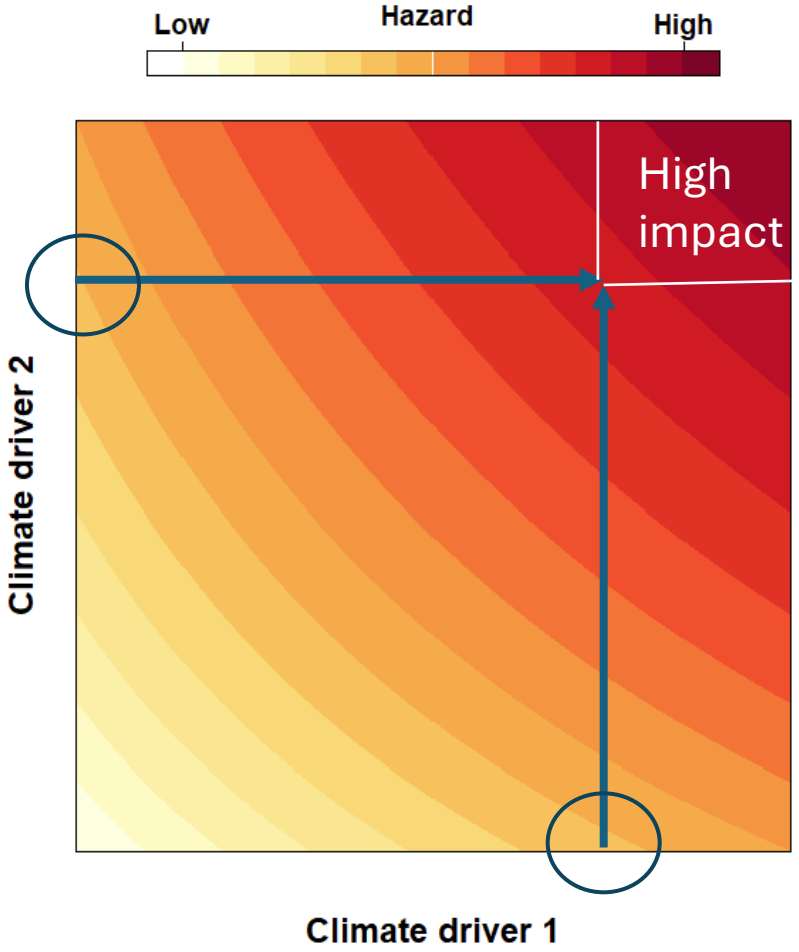
What are Compound Events?

Compound events occur when multiple weather and climate drivers converge — simultaneously or in sequence — overwhelming the coping capacity of affected systems. Their impacts unfold across three dimensions: space, time, and interacting impact chains. Crucially, the severity of compound events does not derive from the extremity of any individual driver, but from the unique synergistic combination of multiple stressors acting together.

Zscheischler et al. (2018, 2020); van der Wiel et al. (2020)



Source: Zscheischler et al. (2018); Zscheischler et al. (2020)

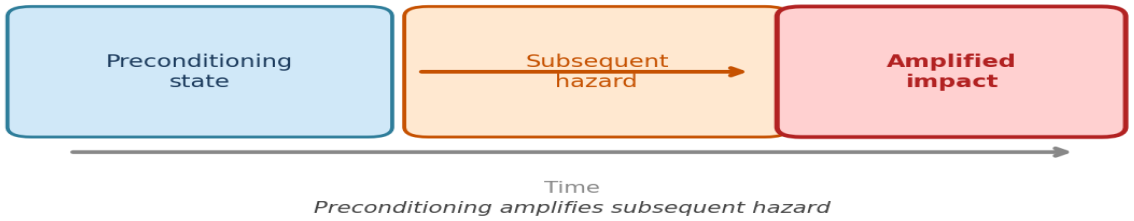


Replotted after Zscheichler et al. 2018

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Typology of Compound Events

Type 1: Preconditioned

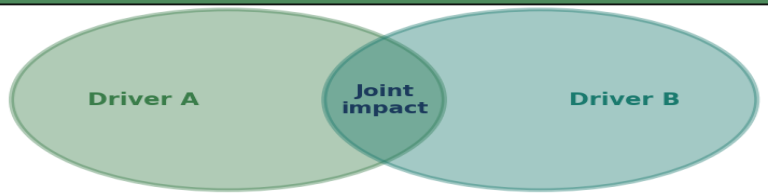


Preconditioning amplifies subsequent hazard

Prior state → subsequent hazard

Example: Dry winter (depleted soil moisture) → amplifies summer heatwave severity

Type 2: Multivariate

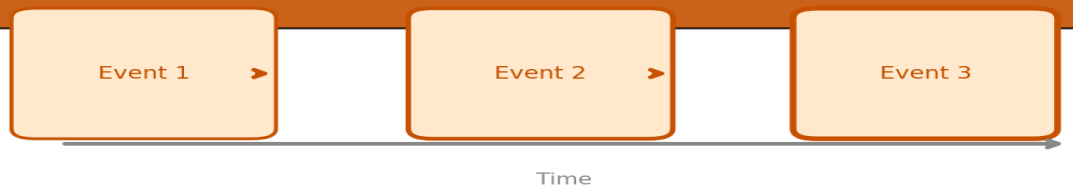


Joint probability of co-occurrence determines risk (> sum of individual risks)

Simultaneous co-located drivers → amplified impacts

Example: Simultaneous drought + heatwave during crop growing season

Type 3: Temporally Compounding

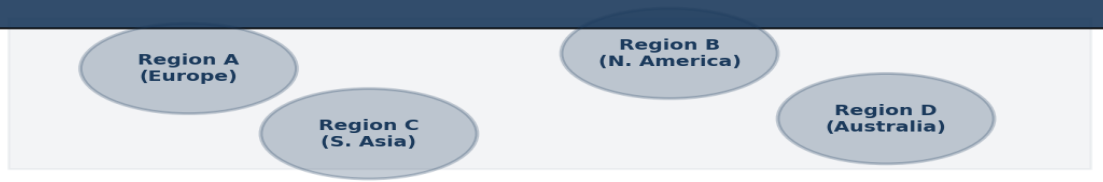


Sequential events before system recovery → cascading, non-linear impacts

Sequential hazards

Example: Sequence of dry spells before system has recovered

Type 4: Spatially Compounding



Simultaneous hazards in different regions → systemic risk to global supply chains

Events in different locations

Example: Concurrent crop failures in multiple breadbasket regions

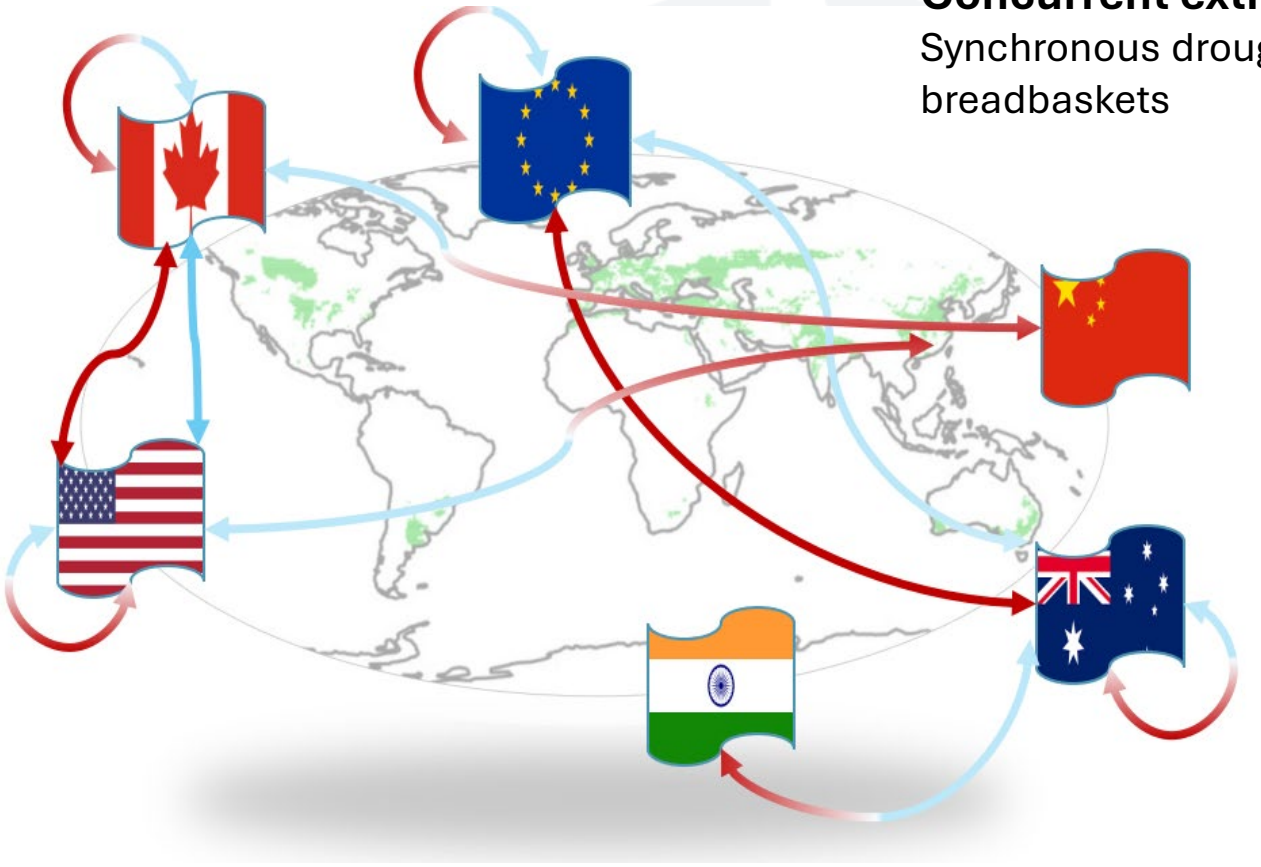
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Concurrent extremes

Concurrent extremes: different types, temporal lag

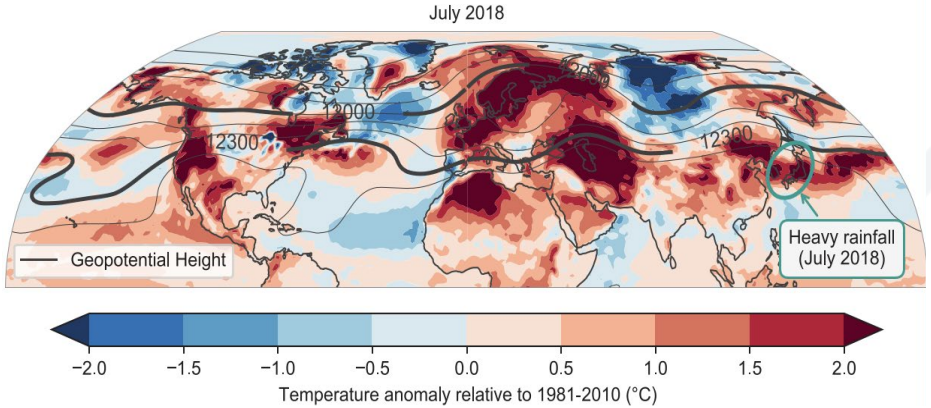
Synchronous droughts + heatwaves across global breadbaskets

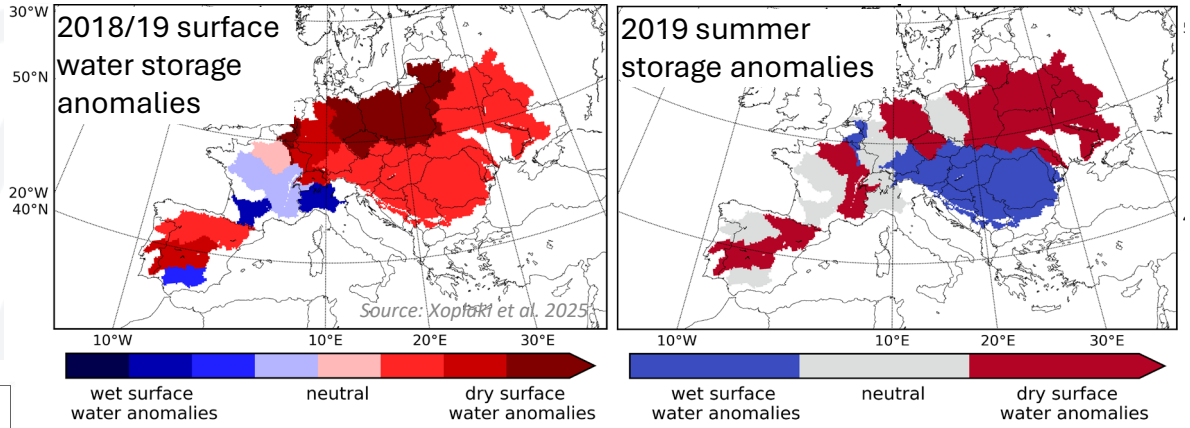


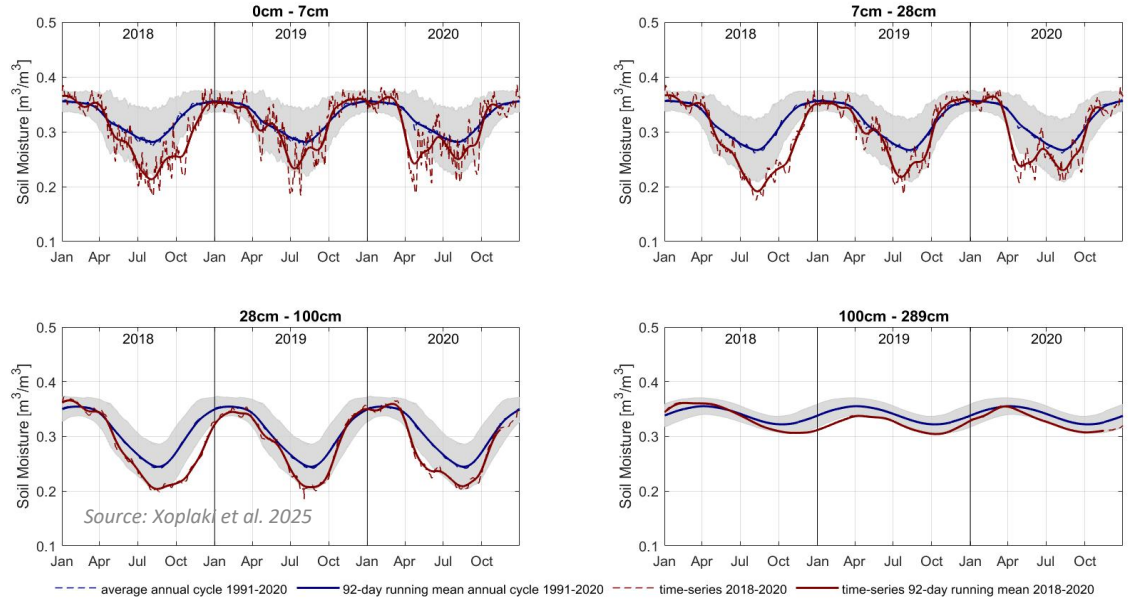
Source: Toreti et al. 2019b

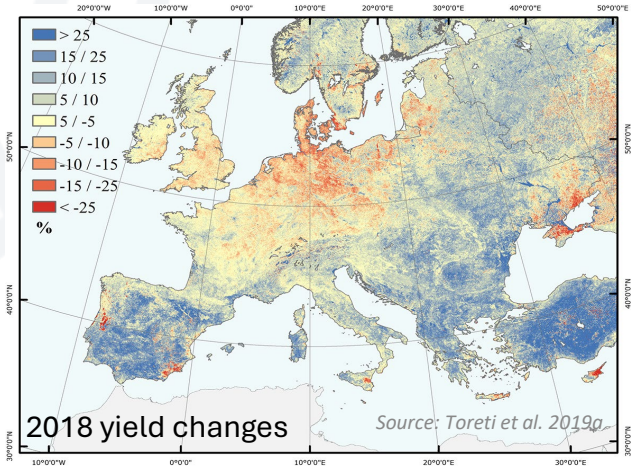
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The 2018 European Summer: Case Study



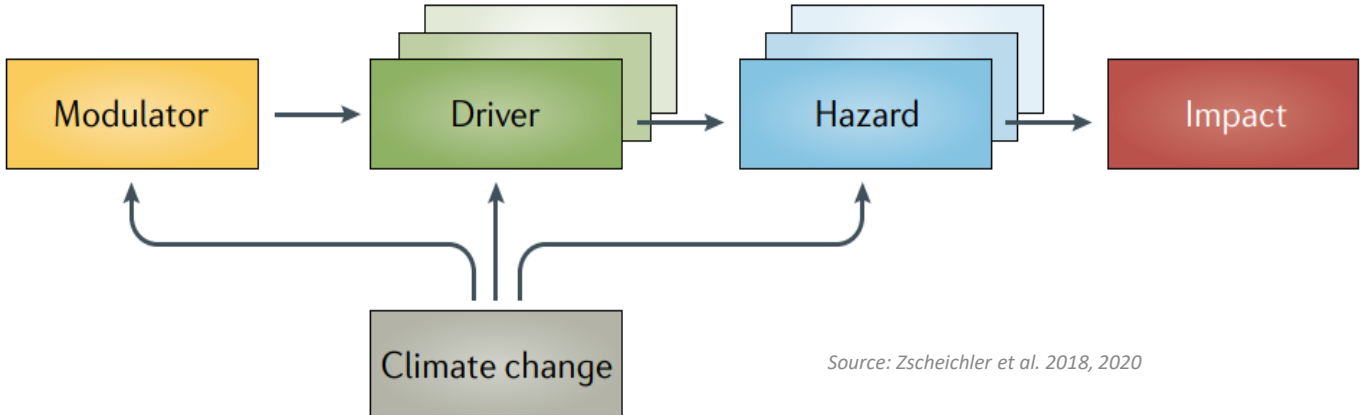




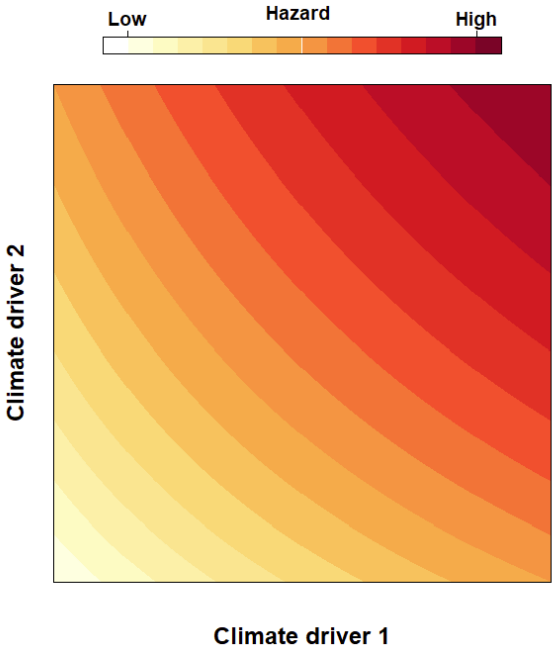


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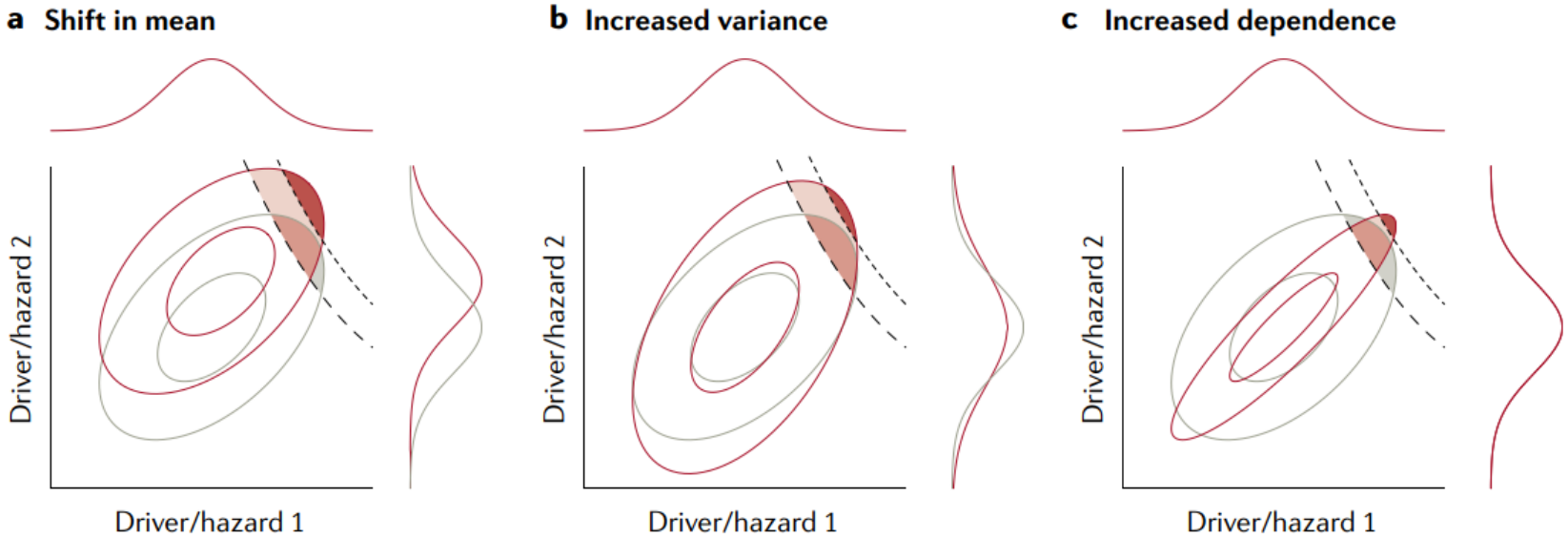
Compound Events in a Warming World



Source: Zscheichler et al. 2018, 2020



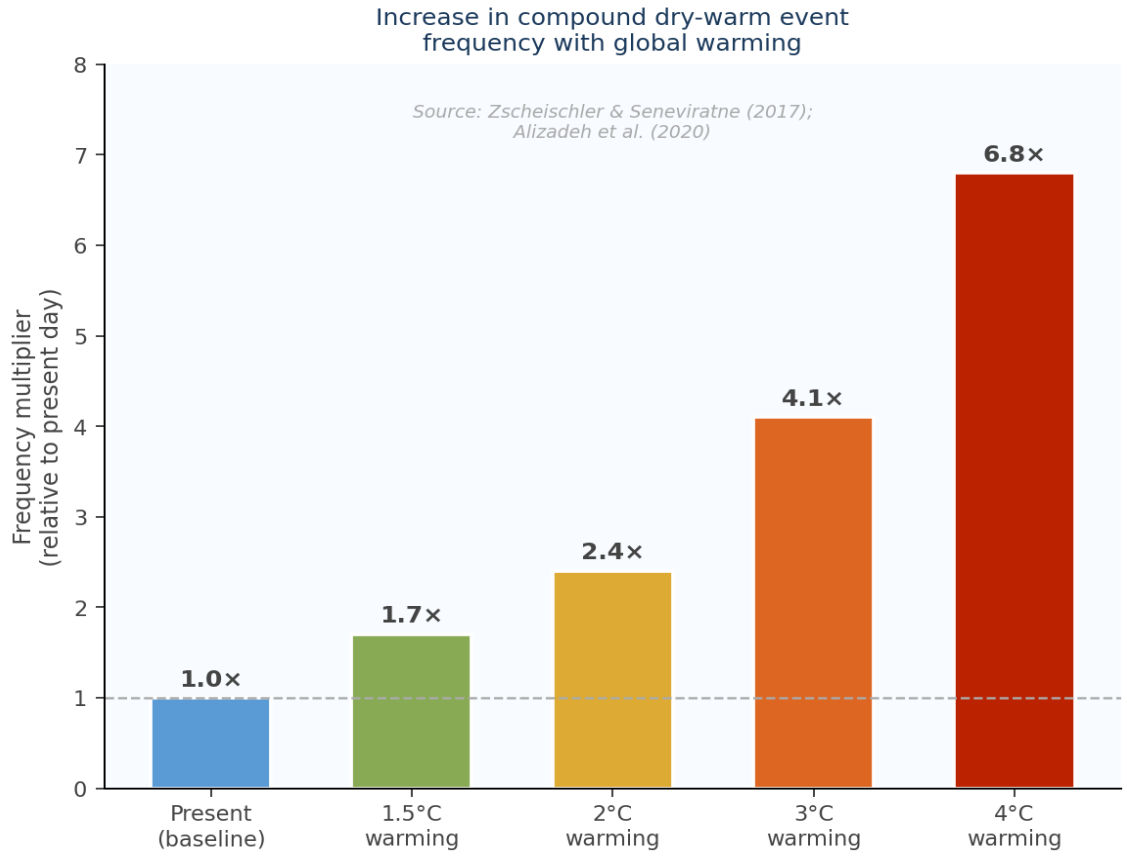
Replotted after Zscheichler et al. 2018

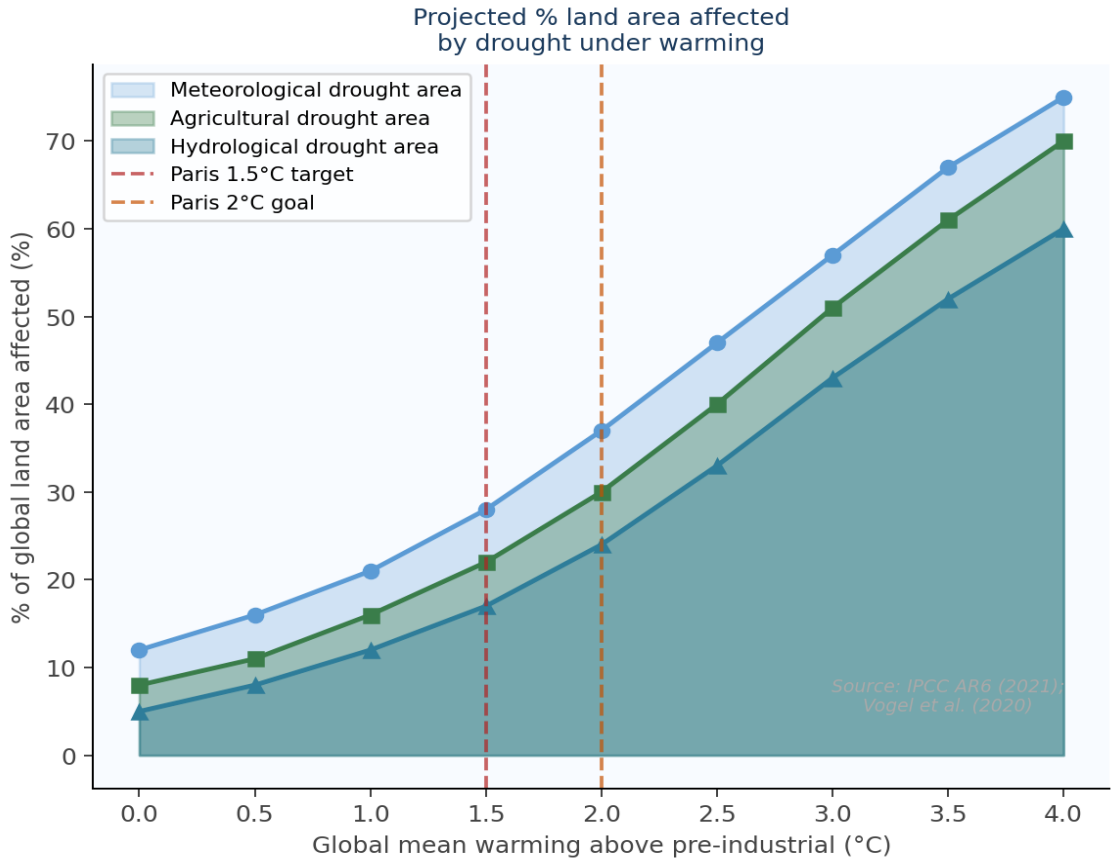


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Compound Events in a Warming World

Future Projections: Increasing Compound Drought-Heat Events Under Warming





Source: IPCC AR6 (2021); Zscheischler et al. (2018); Meng et al. (2022); Alizadeh et al. (2020); Vogel et al. (2020)

Key Takeaways

1. **Drought is not a single phenomenon but a cascade across Earth systems.**
   The four classical types, meteorological, agricultural, hydrological and socioeconomic, form a propagation chain from precipitation deficit to societal impact, each with increasing lag time and recovery time.
2. **Index choice is a scientific decision with real consequences.**
   SPI captures only the precipitation supply side; SPEI adds evaporative demand and is more physically appropriate under warming. In heatwave years, SPEI registers significantly more severe drought than SPI for the same precipitation record.
3. **Climate change is already amplifying drought frequency and intensity.**
   A once-per-decade drought now occurs 1.7 times more frequently at today's 1 °C of warming, 2.4 times at 2 °C, and 4.1 times at 4 °C. Europe's 2018 summer is projected to become an ordinary summer before 2086.
4. **Compound events are fundamentally different from single-hazard thinking.**
   A compound event combines multiple drivers whose interaction produces non-linear, disproportionate impacts and more destructive than the sum of parts. Individual components may not themselves be extreme; severity is emergent from their combination.

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Key Takeaways

5. **Assuming independence between drivers systematically underestimates risk.**
   Temperature and precipitation are strongly negatively correlated during the warm season over most land regions. A compound hot-and-dry event treated as independent becomes up to six times more likely once that correlation is properly accounted for.
6. **Climate change amplifies not just individual drivers but their dependence structure.**
   Under greenhouse-gas forcing, the negative T–P correlation intensifies in many regions on top of mean warming. Systems that adapt only to mean-state change will still be struck by compound extremes more frequently than projected.
7. **Compound dry-warm events are already increasing and will accelerate sharply.**
   Relative to the present baseline, compound dry-warm event frequency is projected at 2.4 times at 2 °C and 6.8 times at 4 °C. The difference between 1.5 °C and 2 °C alone represents a near-doubling of compound event frequency.
8. **Risk assessment must shift from univariate to multivariate thinking.**
   Monitoring systems, insurance frameworks and infrastructure standards designed around single-driver statistics are not conservative but insufficient. Joint probabilities of co-occurring hazards are both larger than independence implies and growing under warming.

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Funded by the European Union
Grant Agreement 101159497