ETH
Eidgenössische Technische Hochschule Zürich
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Physical mechanisms (Land-climate feedbacks & forcings; Local vs large-scale drivers)

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Outline

Introduction

Soil moisture-temperature feedbacks

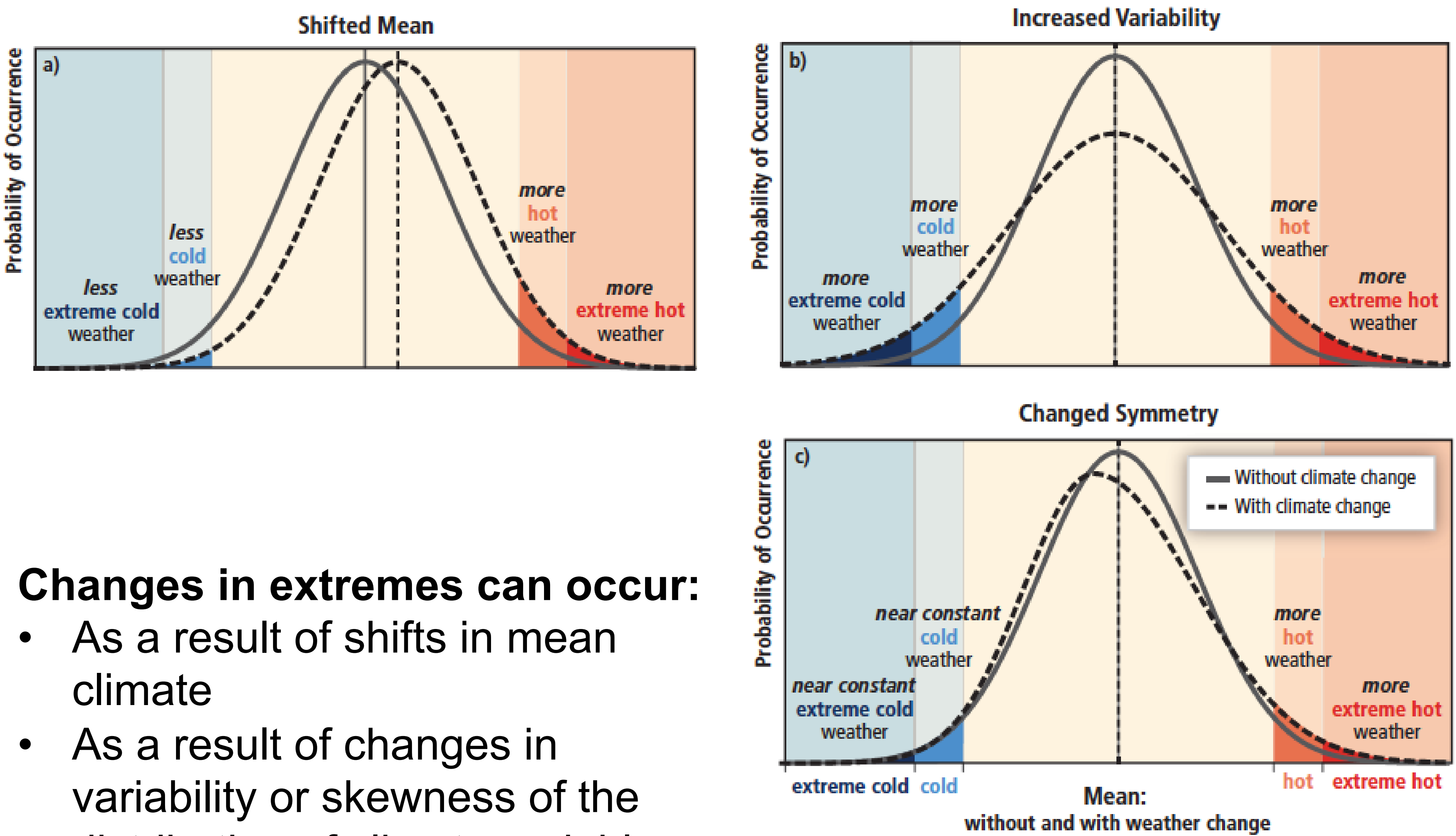
Surface albedo-temperature interactions

Physical drivers of droughts

Precipitation extremes

Conclusions

Changes in extremes vs changes in mean



Changes in extremes can occur:

- As a result of shifts in mean climate
- As a result of changes in variability or skewness of the distribution of climate variables

(IPCC SREX, 2012: http://ipcc-wg2.gov/SREX/)

Physical processes

Physical processes can affect both changes in mean climate as well as changes in variability and changes in skewness

What are physical processes that specifically affect extremes?

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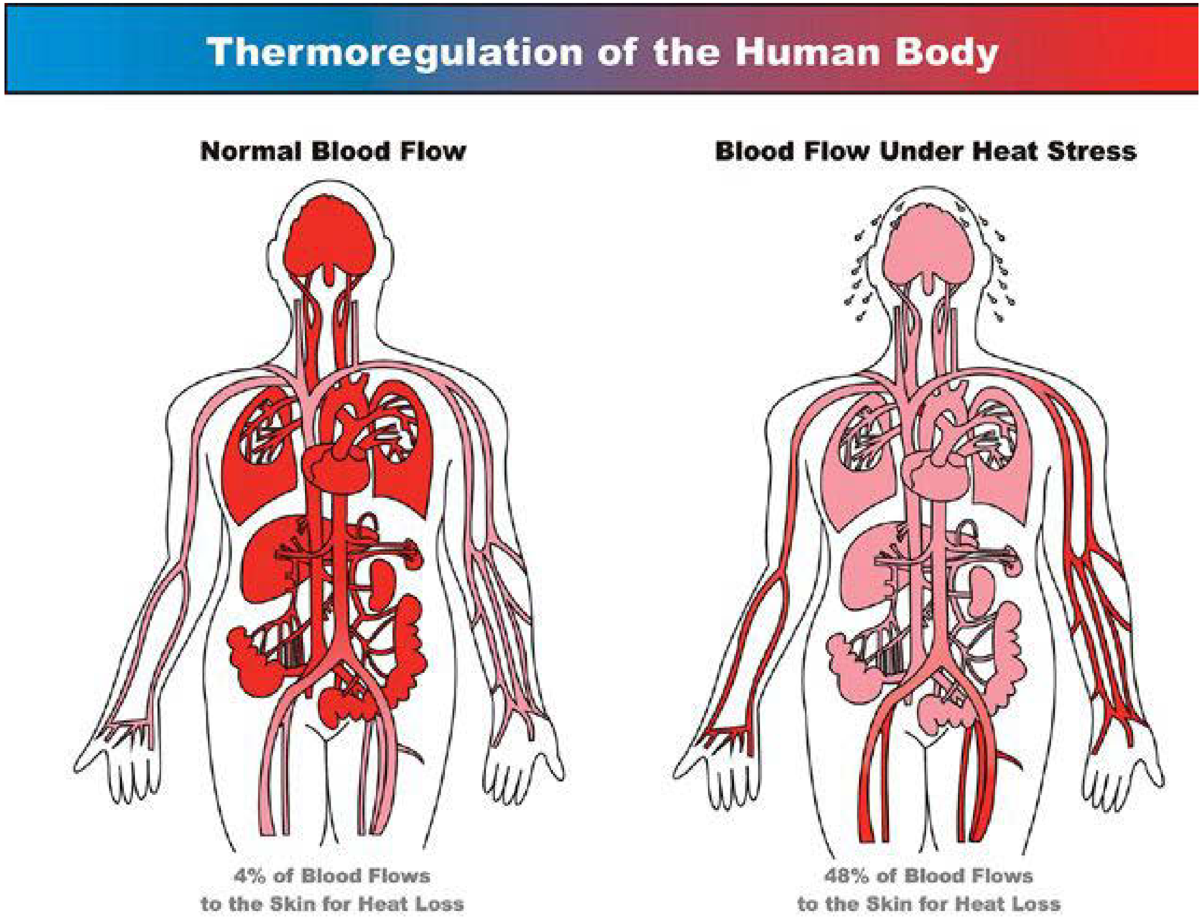
Evaporation & temperature



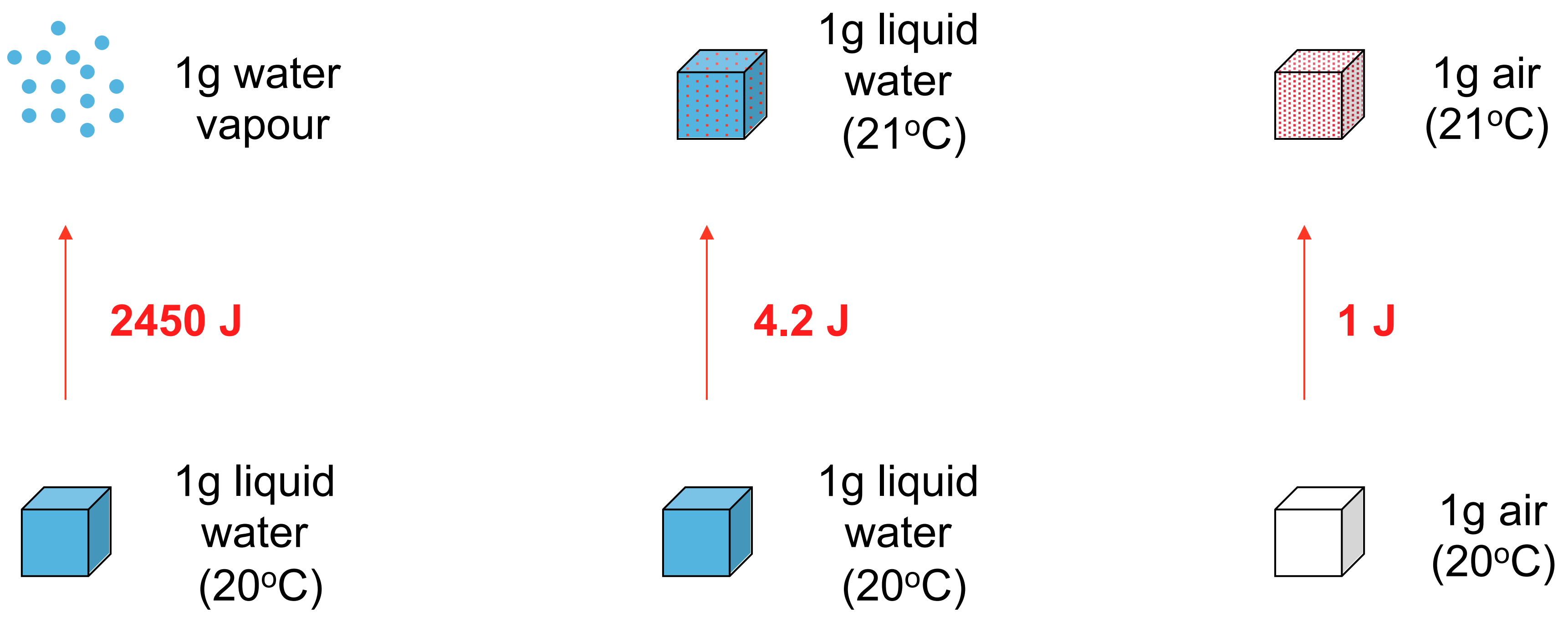
Our body uses evaporation for cooling

Evaporation & temperature

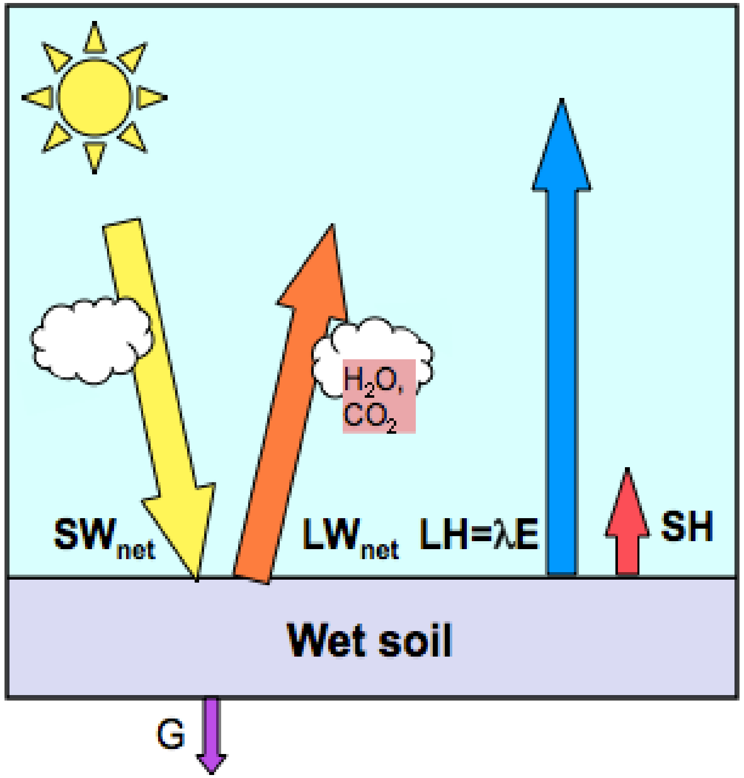
Our body uses evaporation for cooling

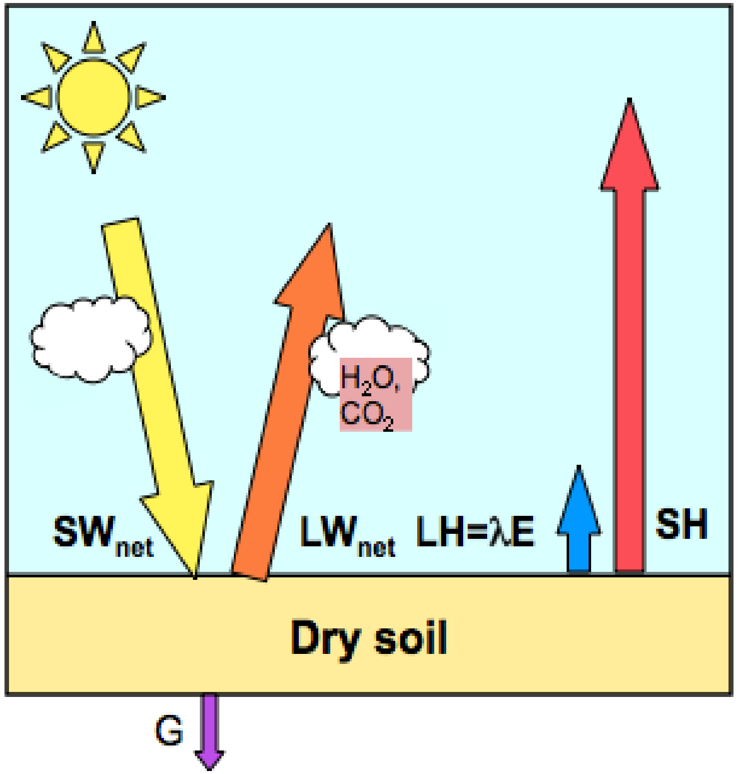
➔ Similar mechanism maintains cool temperatures on land surfaces!

Evapotranspiration uses large amounts of energy!

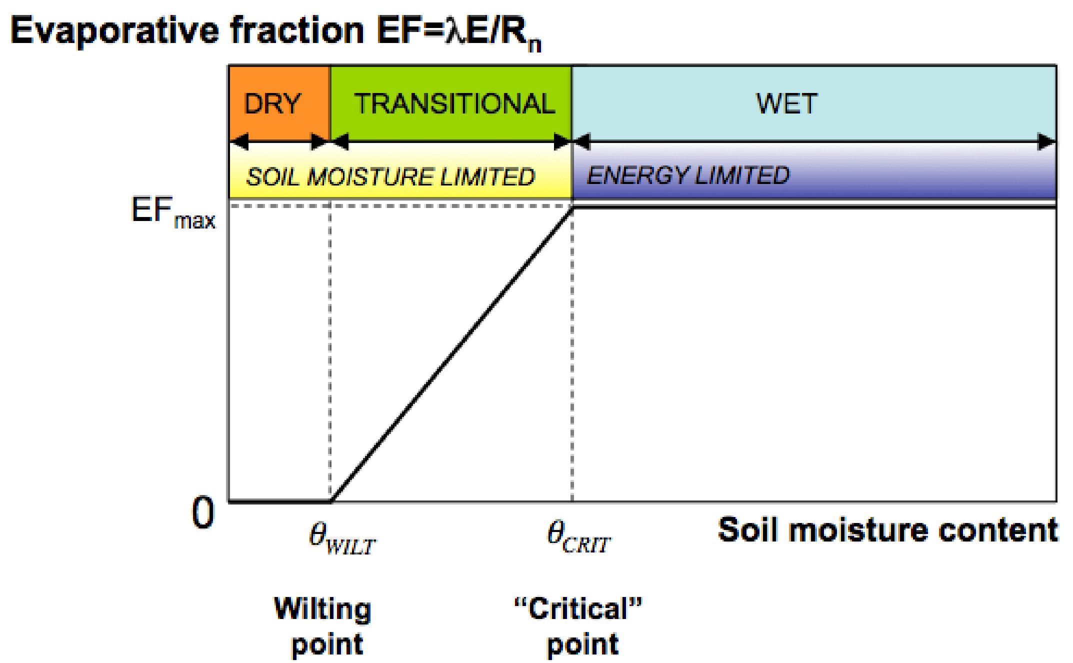


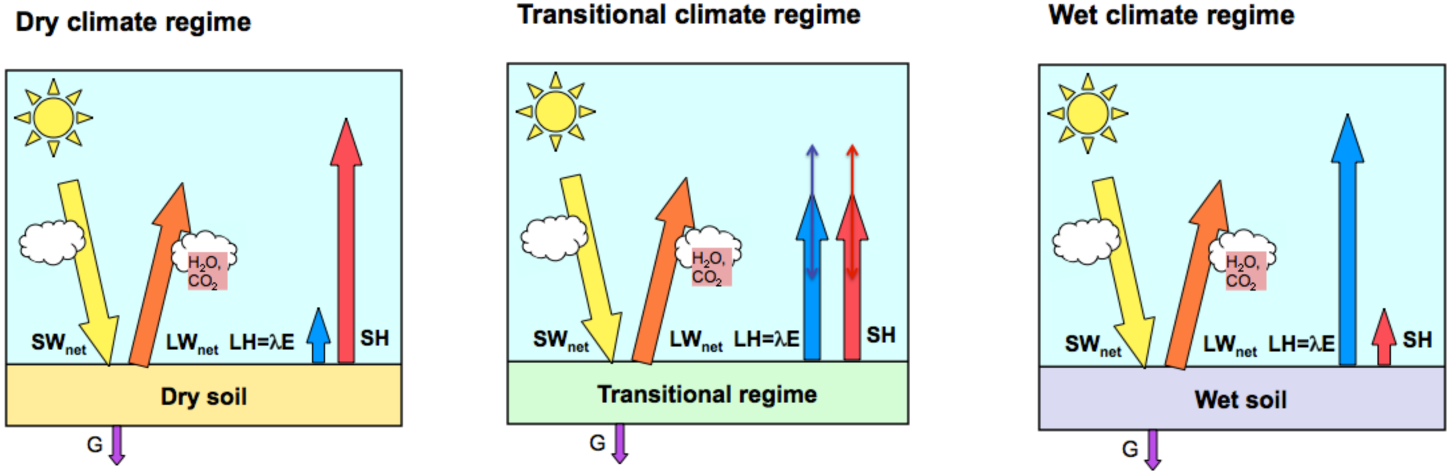
Soil moisture – temperature feedbacks





Soil moisture – temperature feedbacks

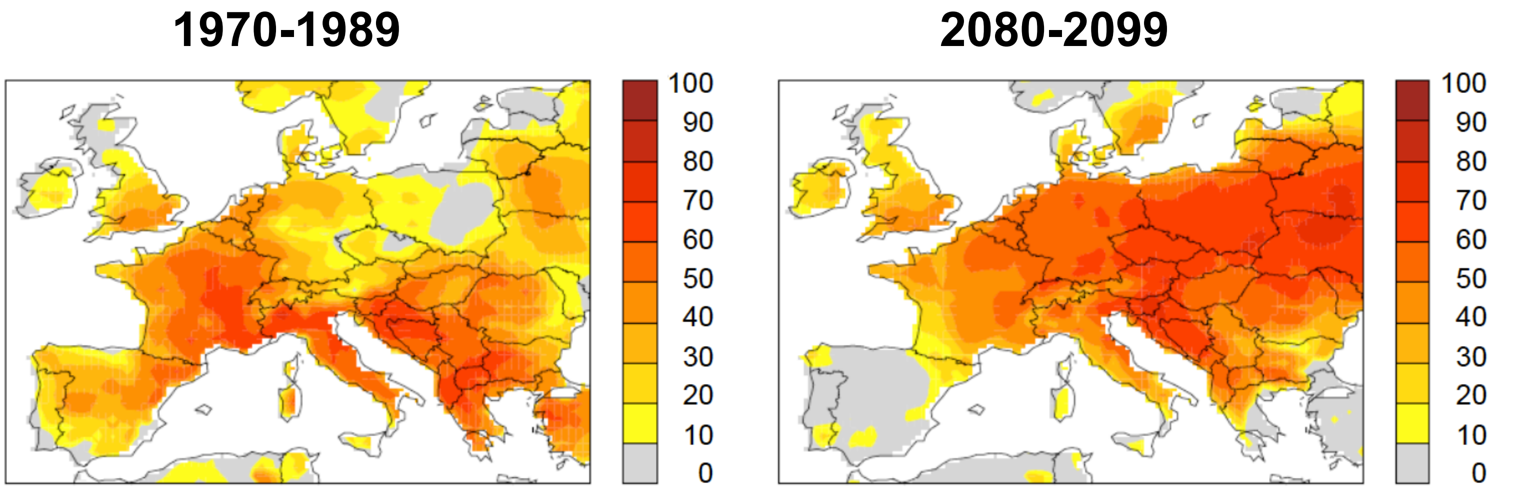




(Seneviratne et al. 2010, Earth Science Reviews)

Soil moisture – temperature feedbacks

Soil moisture variability found to be a main driver for temperature variability in Europe in model simulations for both present and future



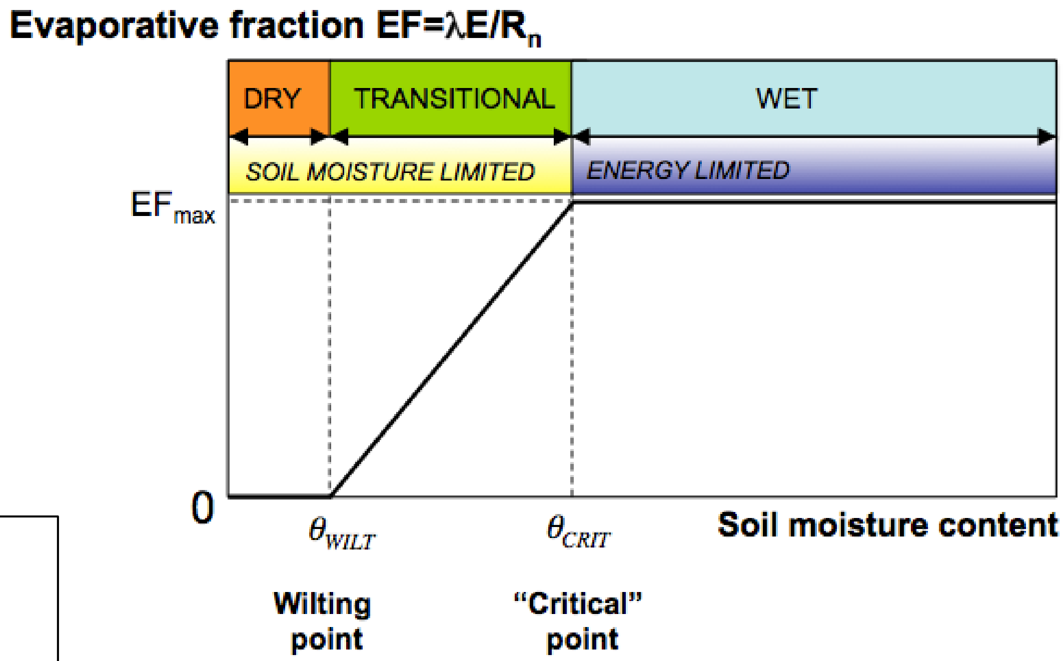
%age of summer temperature variability attributable to soil moisture variability (model estimate)

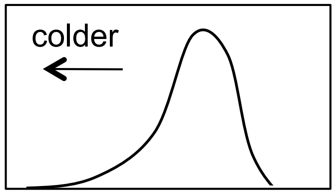
Up to **60%** of *summer temperature variability* is induced by soil moisture feedbacks:

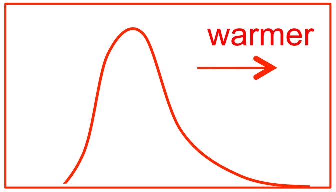
- In the Mediterranean area in late 20th century climate
- In Central and Eastern Europe in late 21st century climate

(Seneviratne et al. 2006, Nature)

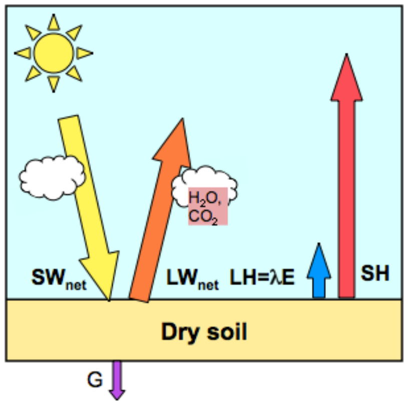
Soil moisture – temperature feedbacks



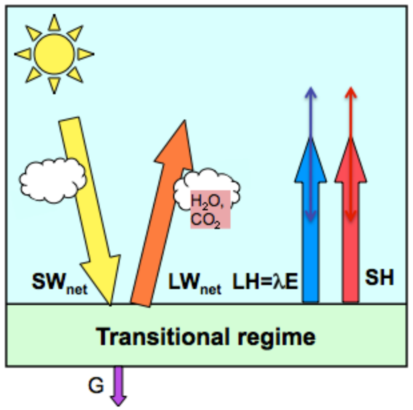




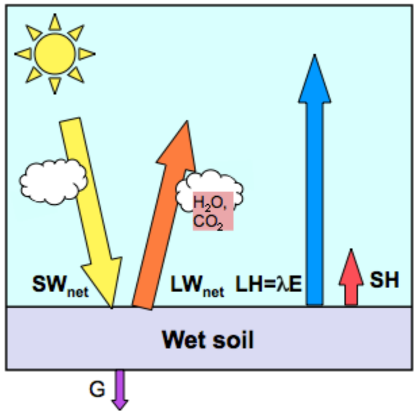
Dry climate regime



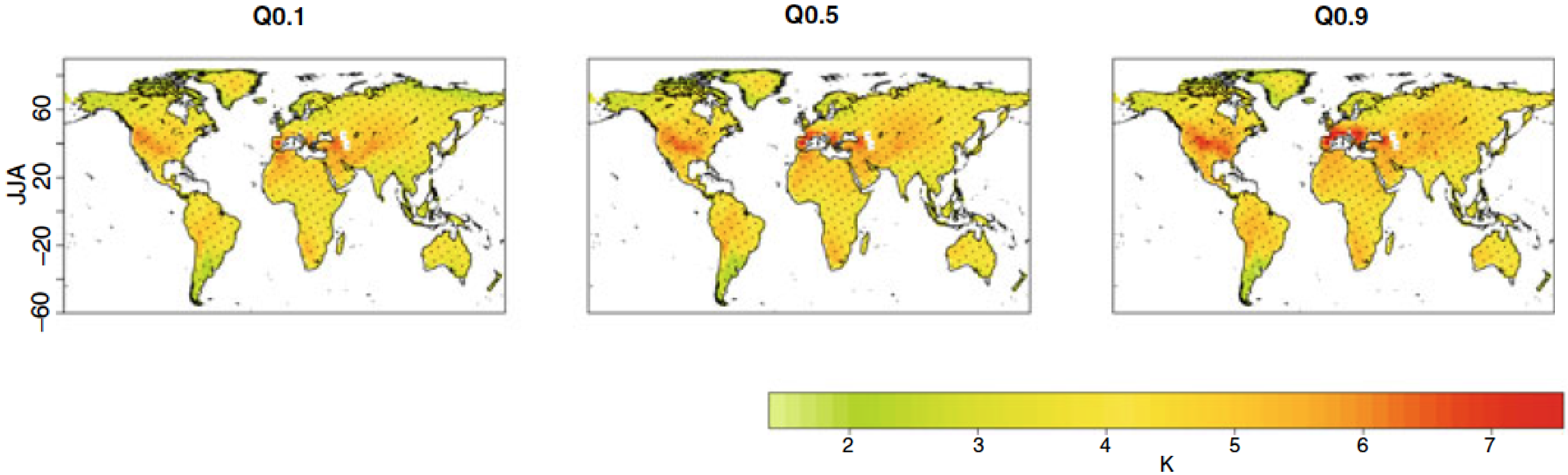
Transitional climate regime



Wet climate regime



ΔTmax [(2081-2100)-(1980-1999)] for 10th (left), 50th (middle), and 90th percentile (right), JJA



Stronger warming of hot extremes in mid-latitude regions: Soil moisture feedback

(Orlowsky and Seneviratne 2012, Climatic Change)

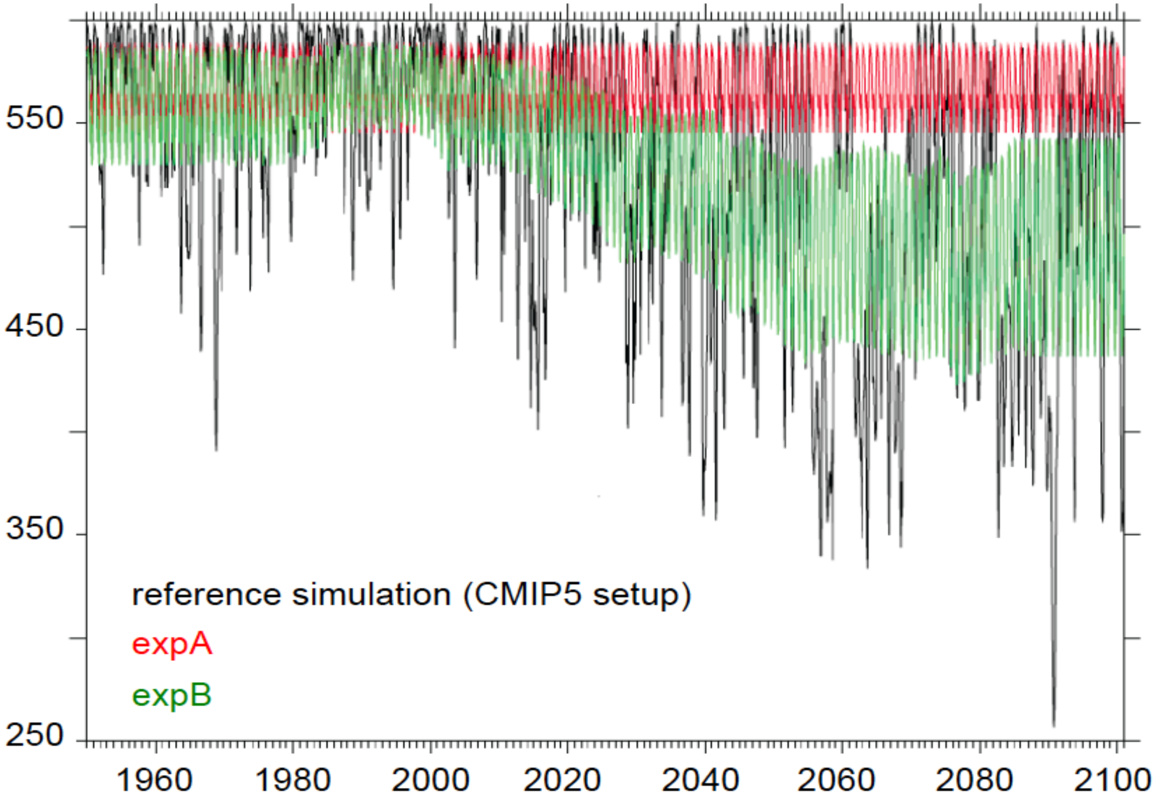
GLACE-CMIP5: Soil moisture feedbacks in projections

Experimental set-up

Impact of soil moisture-climate feedbacks on CMIP5 projections: First results from the GLACE-CMIP5 experiment

Sonia I. Seneviratne,[1] Micah Wilhelm,[1] Tanja Stanelle,[1] Bart van den Hurk,[2] Stefan Hagemann,[3] Alexis Berg,[4,5] Frederique Cheruy,[6] Matthew E. Higgins,[7] Arndt Meier,[8] Victor Brovkin,[3] Martin Claussen,[3] Agnès Ducharne,[9] Jean-Louis Dufresne,[6] Kirsten L. Findell,[4] Joséfine Ghattas,[9] David M. Lawrence,[7] Sergey Malyshev,[10] Markku Rummukainen,[8] and Benjamin Smith[11]

Soil moisture (point in Central Europe)

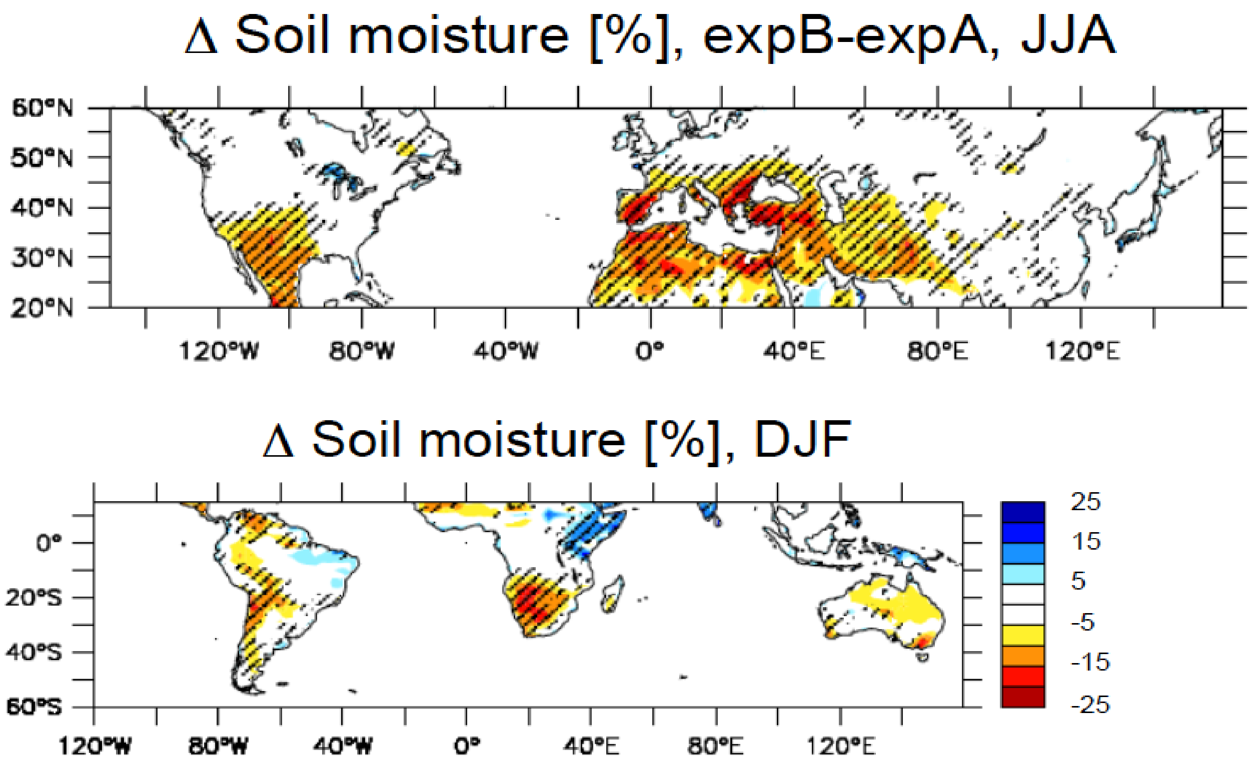


GLACE-CMIP5 investigates the impact of **decadal changes in soil moisture** on climate

First stage: 5 CMIP5 models (CESM, EC-EARTH, GFDL, IPSL, MPI-ESM)

(Seneviratne et al. 2013, GRL)

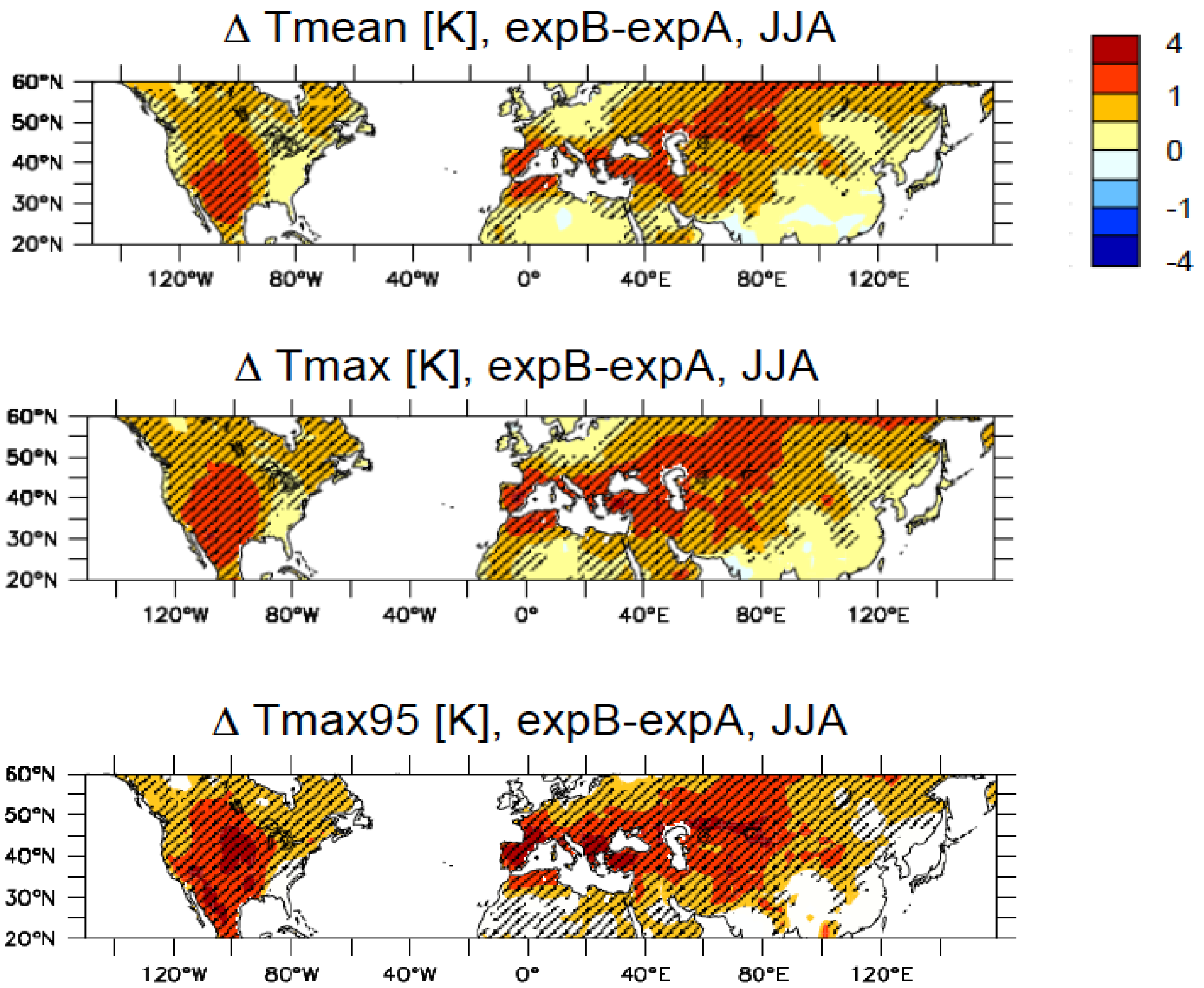
GLACE-CMIP5: Imposed soil moisture anomalies



Consistent sign in 4 out of 5 models

Large imposed anomalies: Consistent with regions projected to be affected by more droughts in CMIP3 and CMIP5

GLACE-CMIP5: Impacts on temperature projections



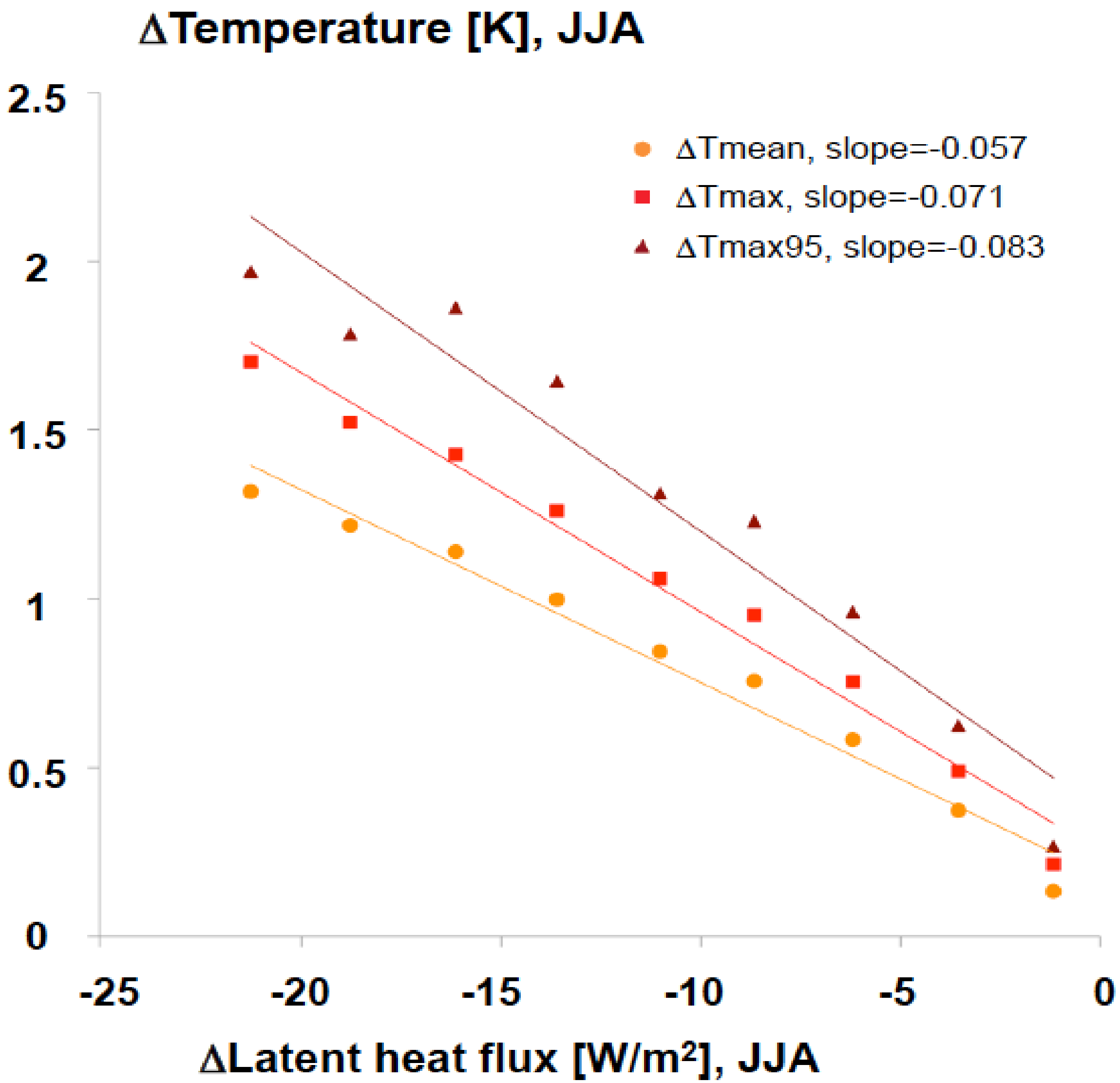
Stronger impacts on Tmax than on daily mean temperature

Stronger impacts on temperature extremes (Tmax95)

Presence of non local effects (generally downwind)

(Seneviratne et al. 2013, GRL)

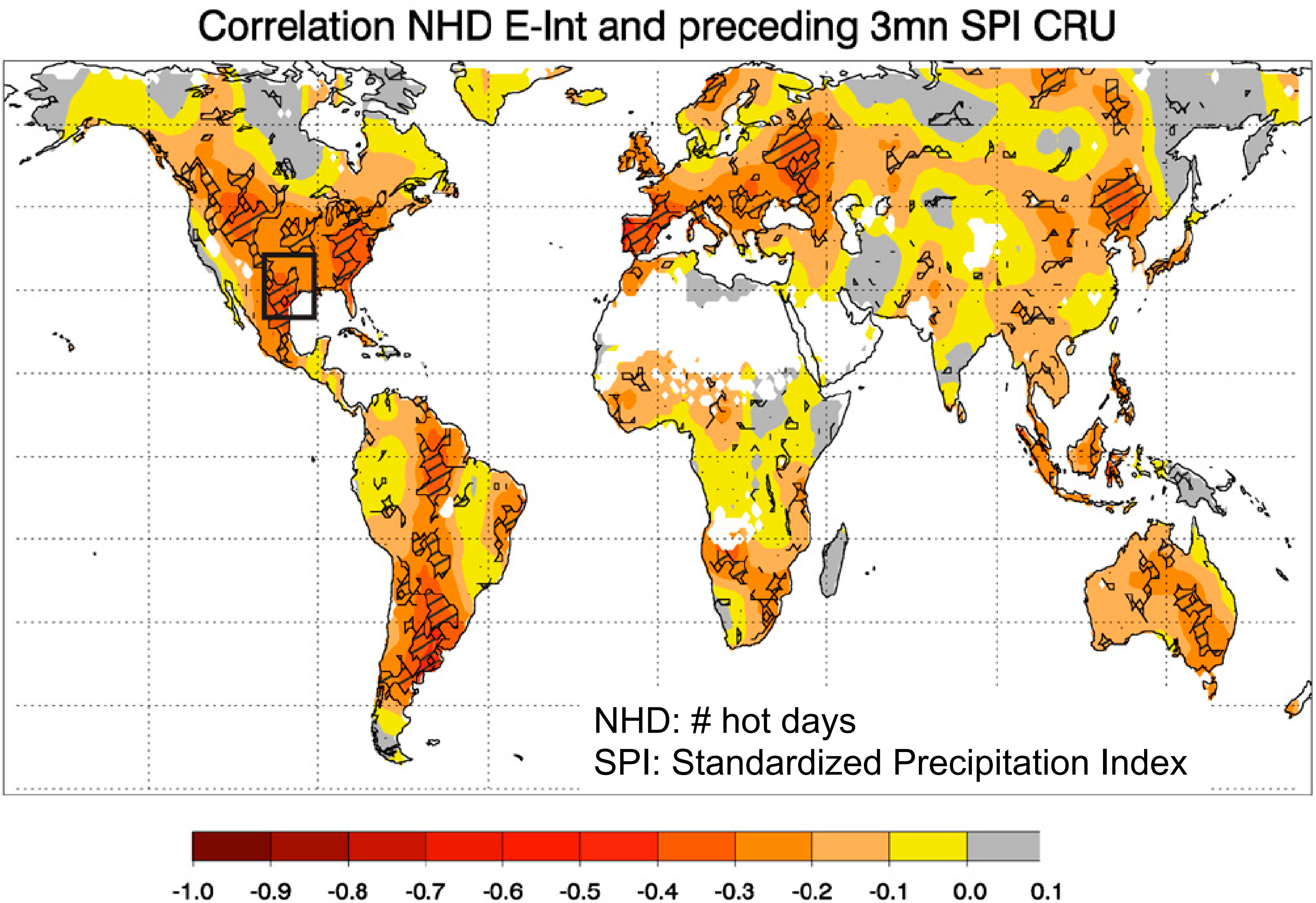
GLACE-CMIP5: Impacts on temperature projections



Clear scaling between ΔLH and ΔT (with different sensitivities for Tmean, Tmax, and Tmax95)

(Seneviratne et al. 2013, GRL)

Soil moisture – temperature feedbacks



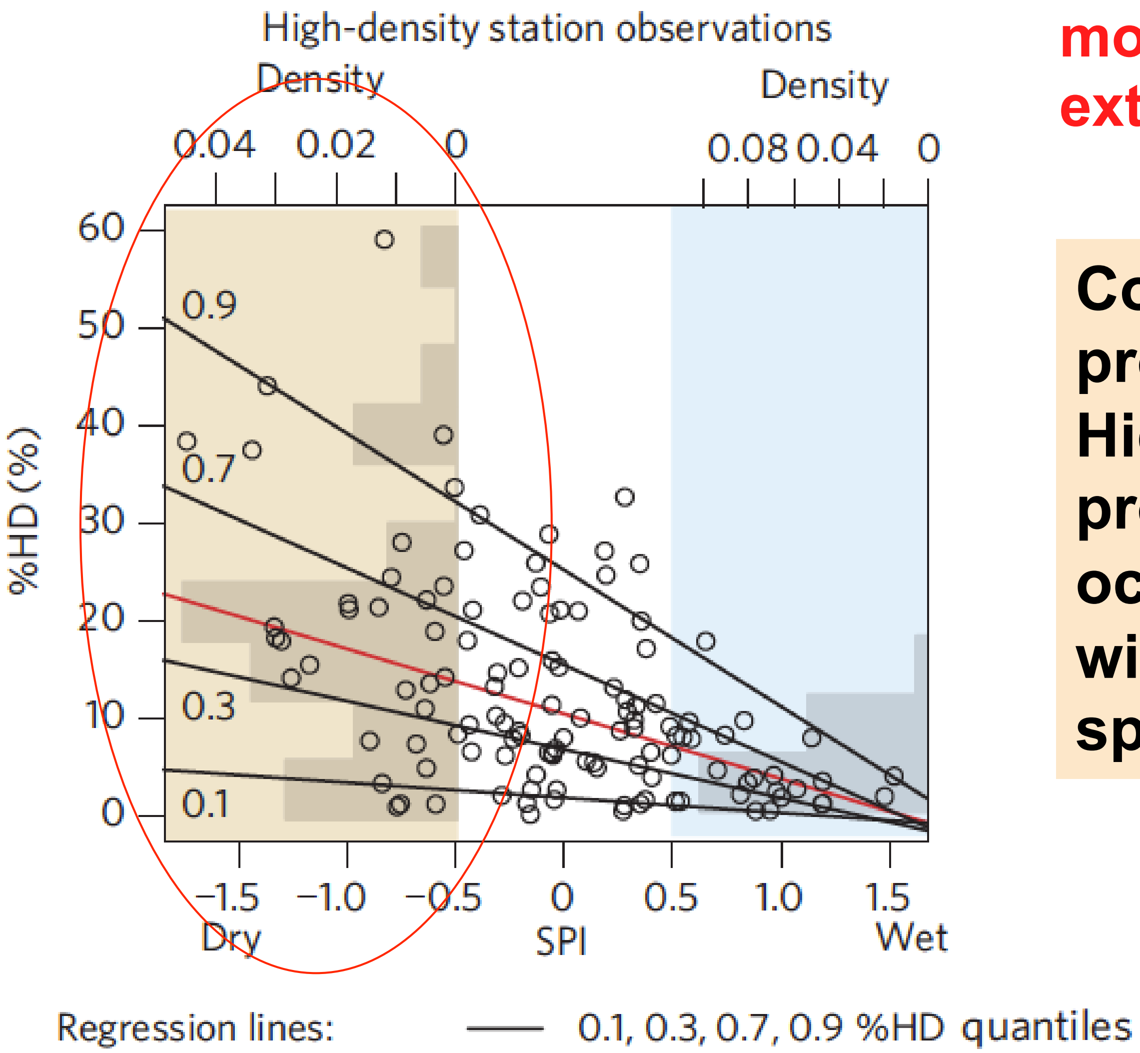
(Mueller and Seneviratne 2012, PNAS)

Soil moisture – temperature feedbacks: Extremes

Impact of soil moisture on hot extremes

Analysis for Southeastern Europe

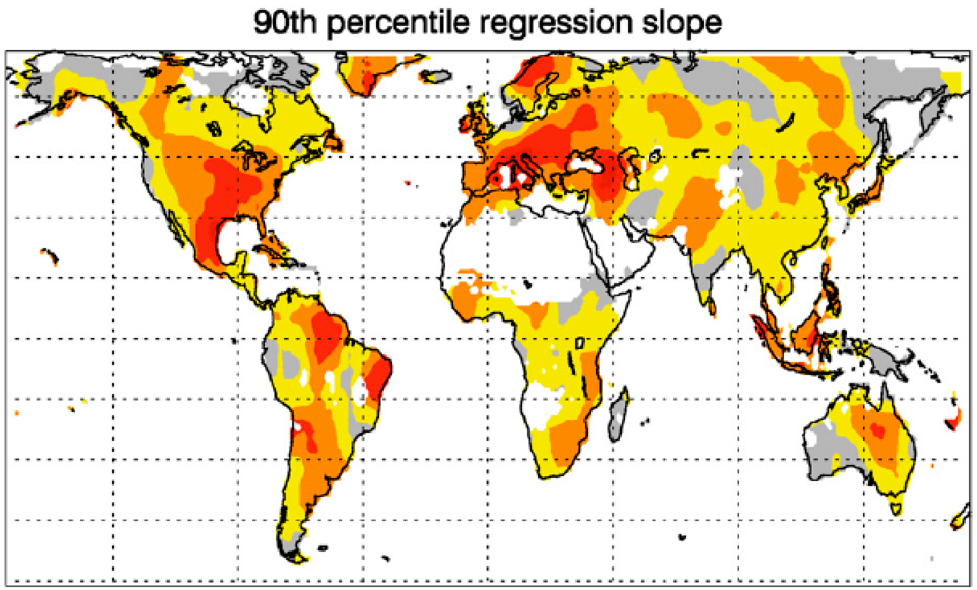
Quantile regression of %HD with 6-month SPI

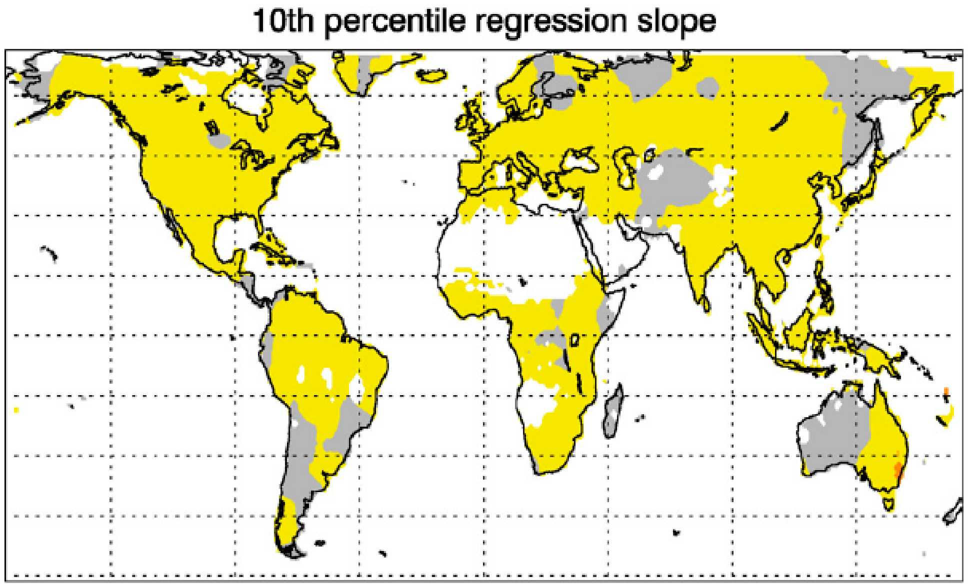


Conditional probability: Higher probability of occurrence with drier springs

(Hirschi et al. 2011, Nature Geoscience)

Quantile regression of NHD E-Int and preceding 3mn SPI CRU



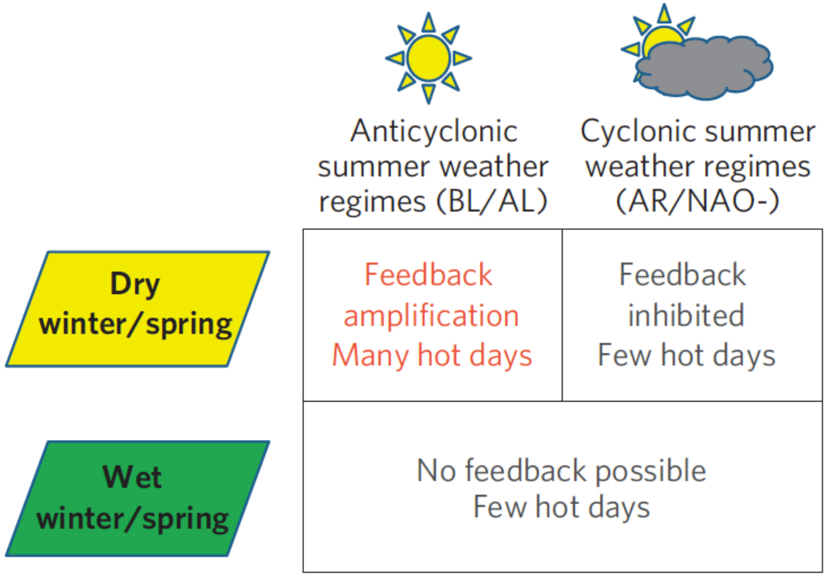


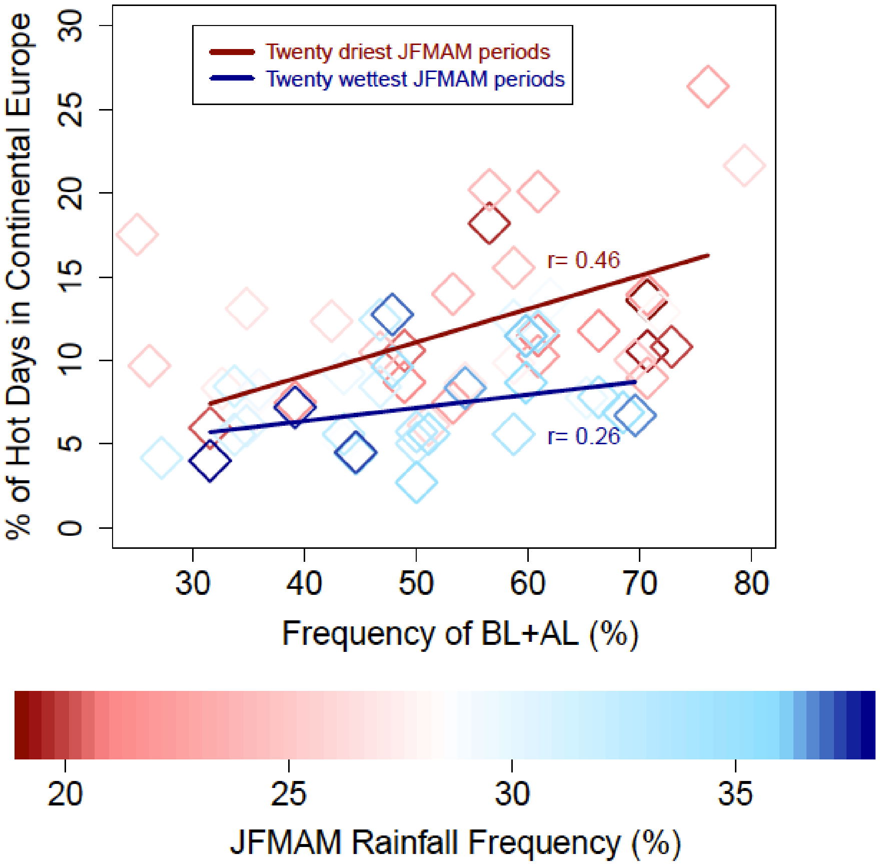
NHD: # hot days
SPI: Standardized Precipitation Index

(Mueller and Seneviratne 2012, PNAS)

Combined roles of soil moisture & circulation

European analysis: High percentage of hot days found for combination of 1) dry springs and 2) anticyclonic summer weather regimes



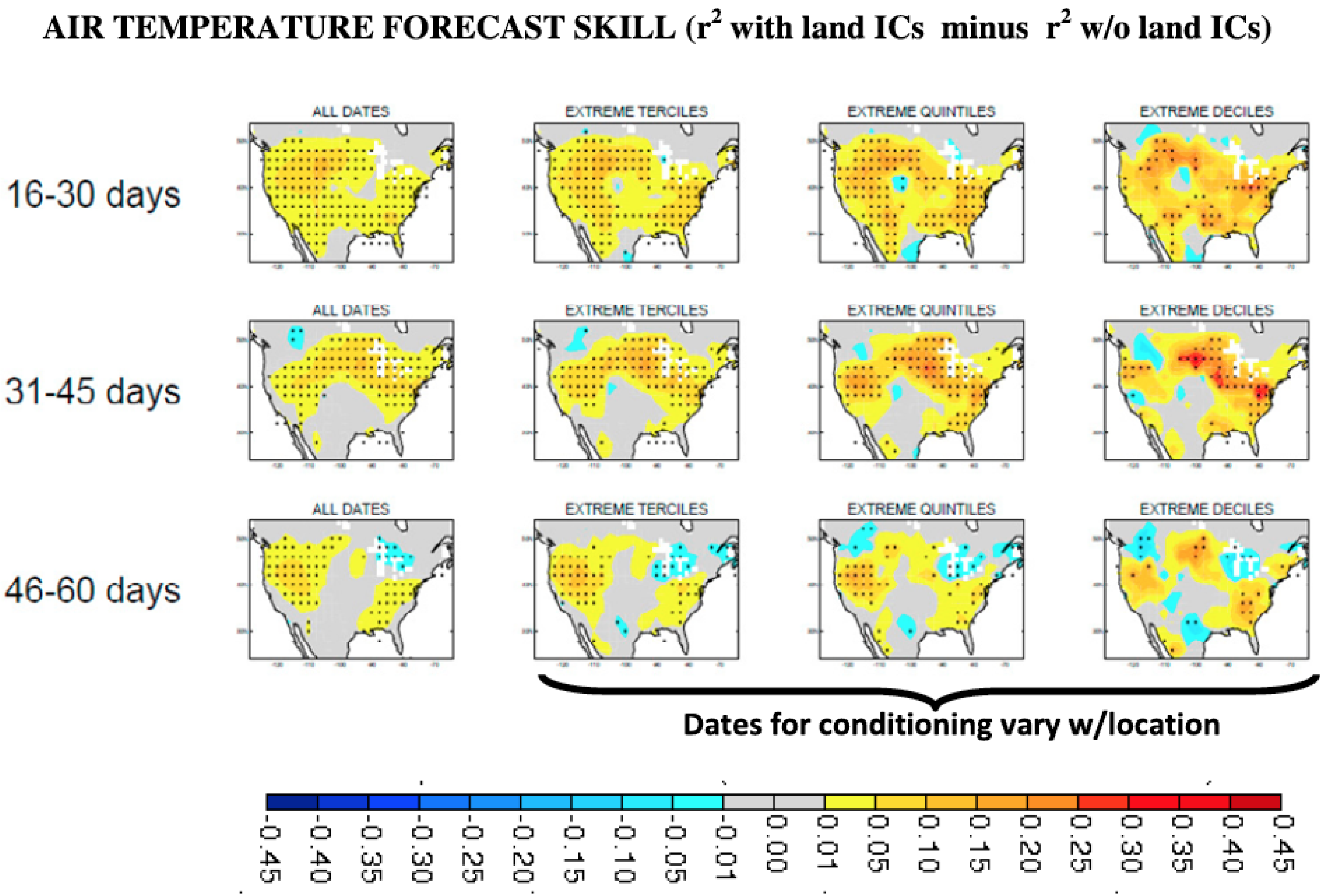


(Quesada et al. 2012, Nature Climate Change)

Combined roles of soil moisture & circulation

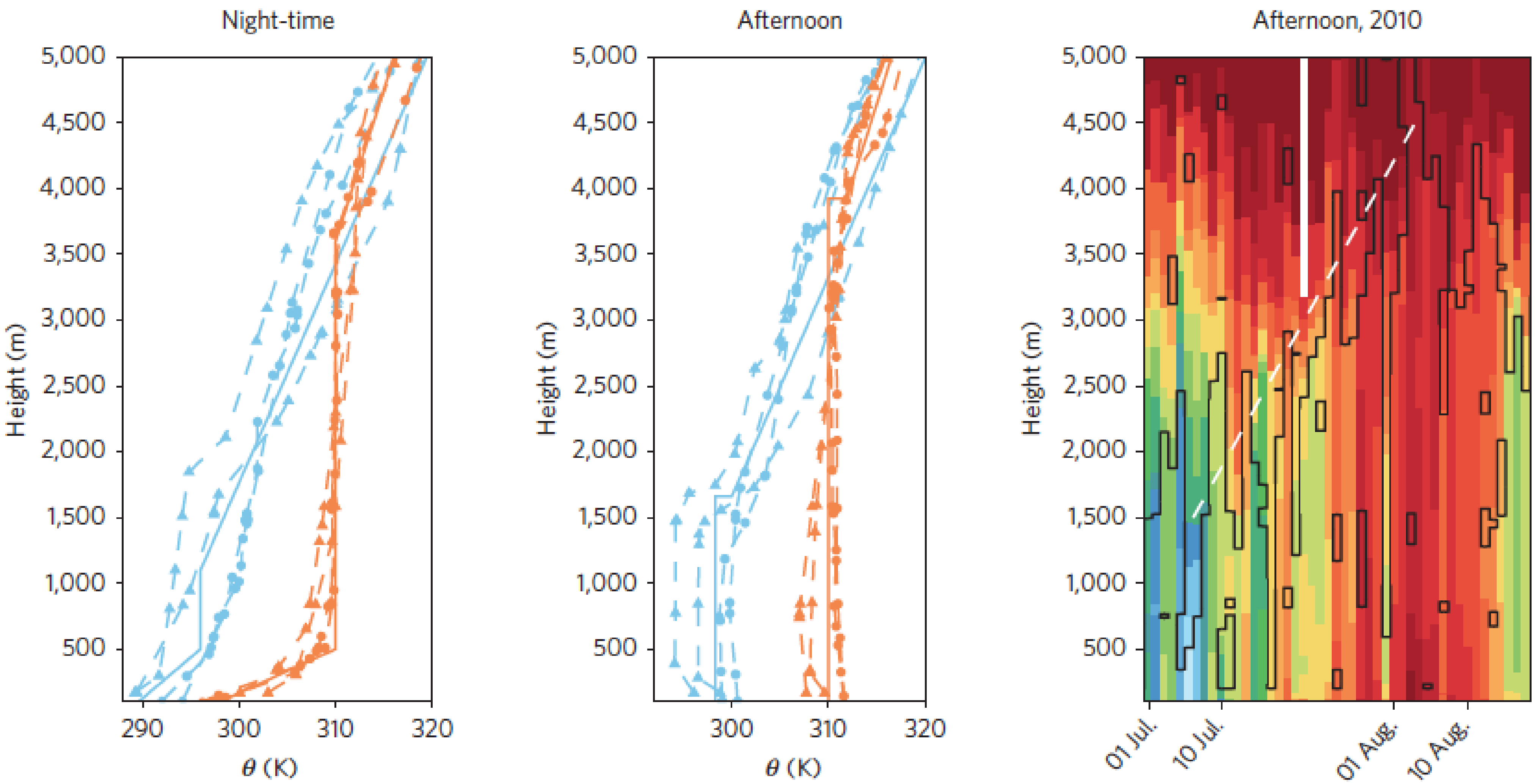
Both dry springs and anticyclonic summer weather regimes are necessary but not sufficient conditions for the occurrence of hot extremes

Soil moisture – temperature feedbacks: Forecasting



(GLACE-2 Experiment; Koster et al. 2010, GRL)

Role of boundary-layer development



(Miralles et al. 2014, Nature Geoscience)

Soil moisture - temperature feedbacks: Summary

- Drying of soil moisture prior to heat waves or during heat waves is a important factor contributing to hot temperature extremes
- Soil moisture regime explains projected asymmetric increase of temperature extremes in mid-latitude regions compared to that of mean global temperature
- Both anticyclonic circulation patterns and antecedent dry conditions are necessary conditions for the occurrence of hot days in Europe; also feedbacks with boundary layer are relevant

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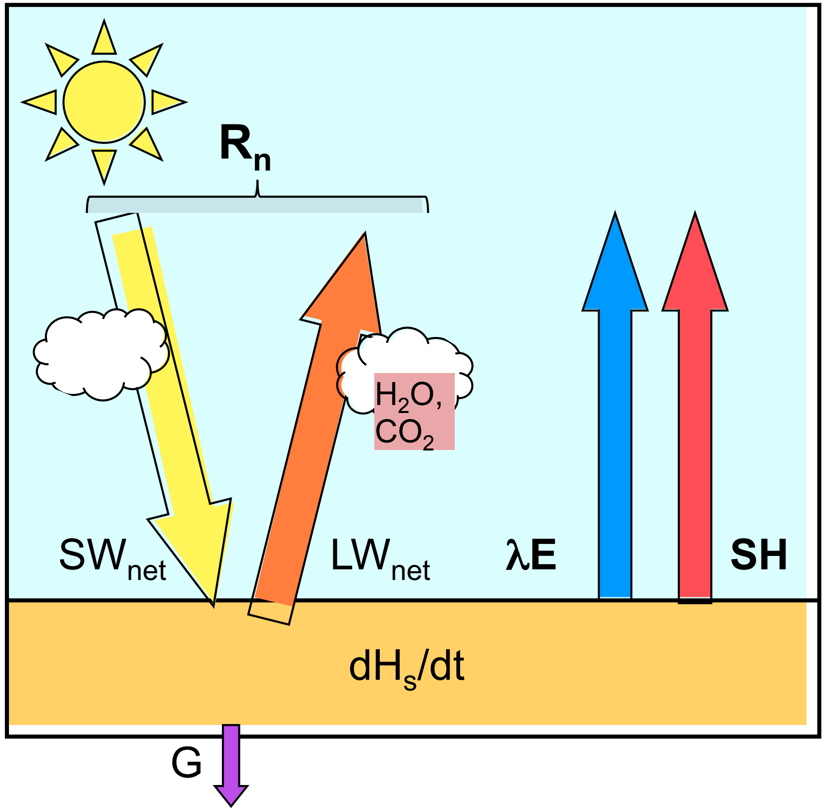
The sensible heat flux can be affected either by changes in latent heat flux, or by changes in net radiation

Land energy balance



$$R_n \cong \lambda E + SH$$

H: Heat storage (within considered layer)
R_n: Net radiation
λE: Latent heat flux (= latent heat of vaporization * E)
SH: Sensible heat flux
G: Ground heat flux

Radiation balance

"Global" radiation

"Atmospheric" radiation

albedo

Infrared emission from the earth's surface: Boltzmann law

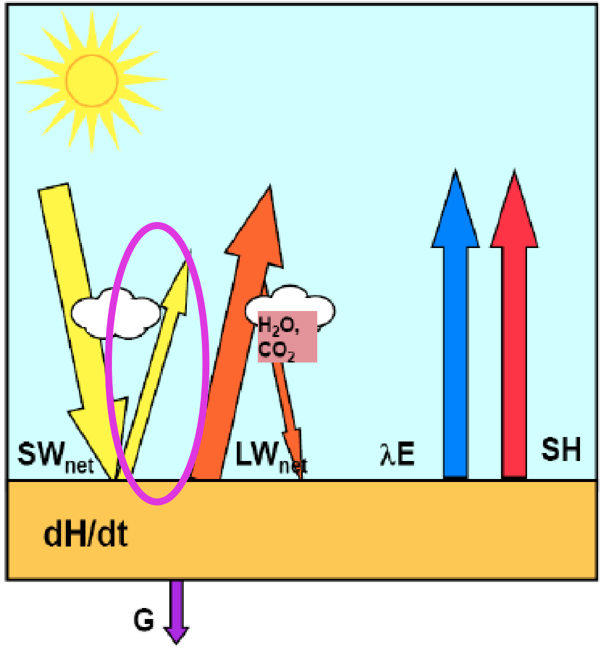
$$R_n = R_g - \alpha R_g + R_a - \sigma T_s^4$$

$$= (1 - \alpha) R_g + R_a - \sigma T_s^4$$

SW_{in} SW_{out} LW_{in} LW_{out}

SW_{in}: incoming shortwave radiation
SW_{out}: outgoing shortwave radiation
} SW_{net}

LW_{in}: incoming longwave radiation
LW_{out}: outgoing longwave radiation
} LW_{net}



Albedo: Typical values

Surface	Conditions	α
Clouds	not so thick/quite thick	0.4/0.7
Open water	zenith angle 30/60/85°	0.05/0.1/0.6
Grass land *		0.2-0.3
Forest *		0.1-0.2
Ice	quite dirty/not so dirty	0.25-0.35
Snow	**old/fresh**	**0.45/0.85**
Global	with clouds	0.3
	surface	0.15

Source: Dingmann 1993; IPCC 2007; Corti & Peter 2009

* See more precise estimates on next slide

Albedo: Typical values

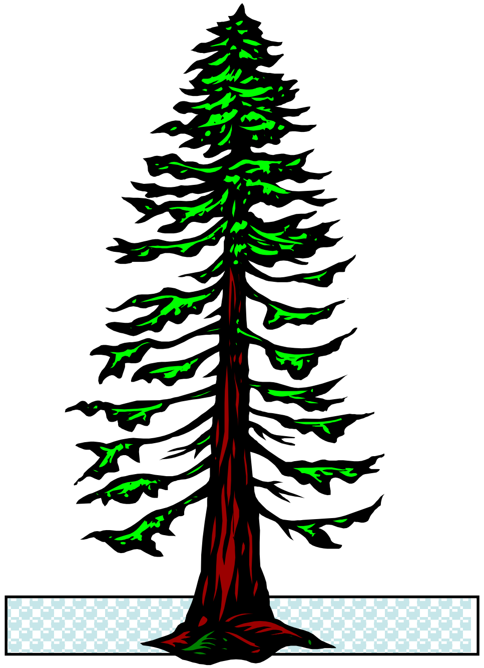
Land cover group	DJF (SC)	DJF (SF)	JJA (SF)
Crops	0.59 ± 0.07	0.15 ± 0.03	0.15 ± 0.02
Grasses	0.61 ± 0.07	0.19 ± 0.03	0.16 ± 0.02
Evergreen trees	0.22 ± 0.05	0.10 ± 0.02	0.09 ± 0.01
Deciduous trees	0.29 ± 0.04	0.12 ± 0.02	0.12 ± 0.02
Bare soil	0.59 ± 0.08	0.26 ± 0.07	0.26 ± 0.07

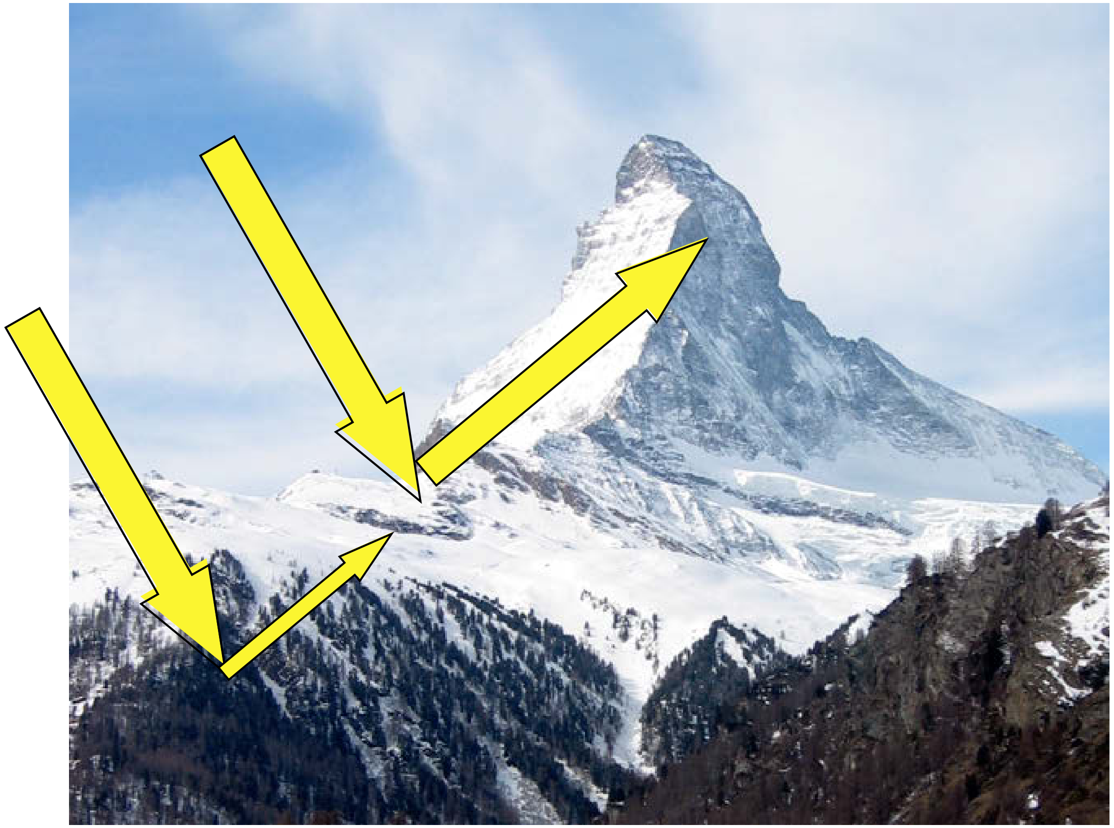
Table 2: MODIS seasonal mean shortwave broadband (0.3 – 5 μm) directional hemispherical reflectance (black-sky albedo) in the northern temperate regions (30-60°N) for the five land cover groups

DJF: December-January-February; **JJA:** June-July-August
SC: Snow covered
SF: Snow free

(Boisier et al. 2013, Biogeosciences)

Strength of snow-albedo feedback depends on the background vegetation (forests can also warm the climate!)





Albedo – temperature effects

Surface albedo can either be modified externally (forcing):

- Land cover changes (deforestation)
- Land use changes, changes in land management (e.g. agricultural practices: see later)
- White roofs, etc.

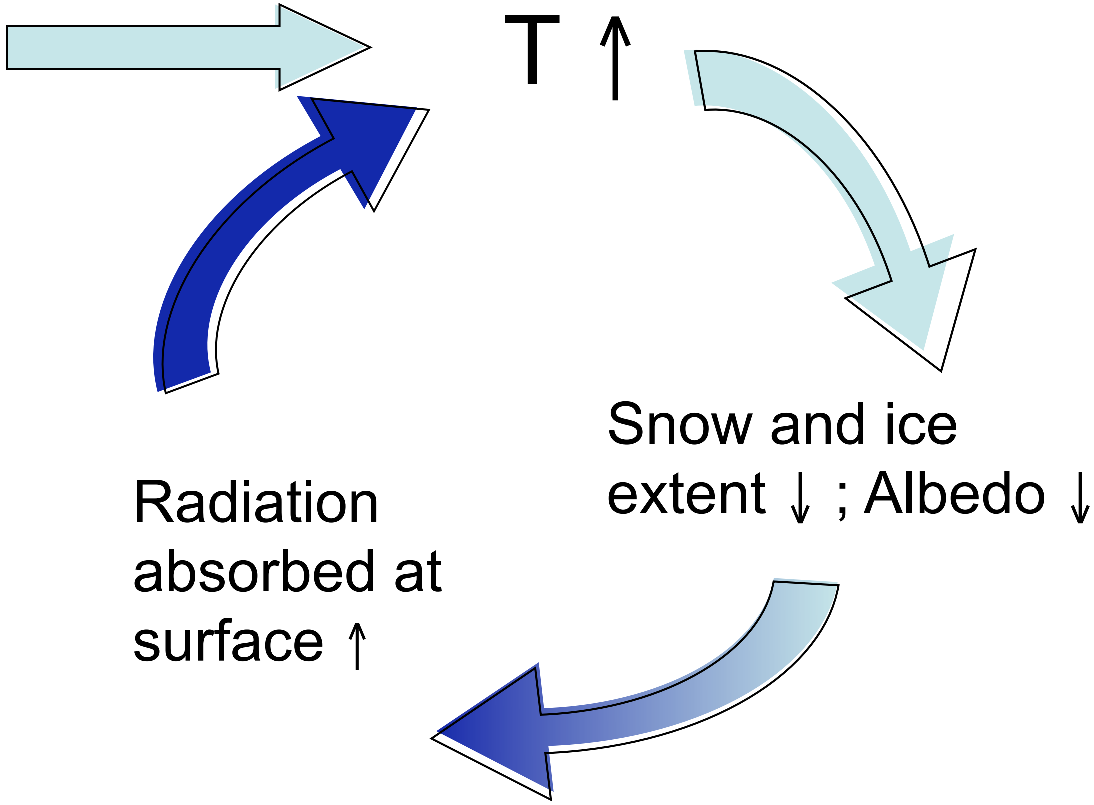
or through feedbacks:

- Changes in snow cover
- Changes in soil moisture (affect soil albedo, vegetation albedo)
- Plant phenology
- Vegetation dynamics

or through combination of both!

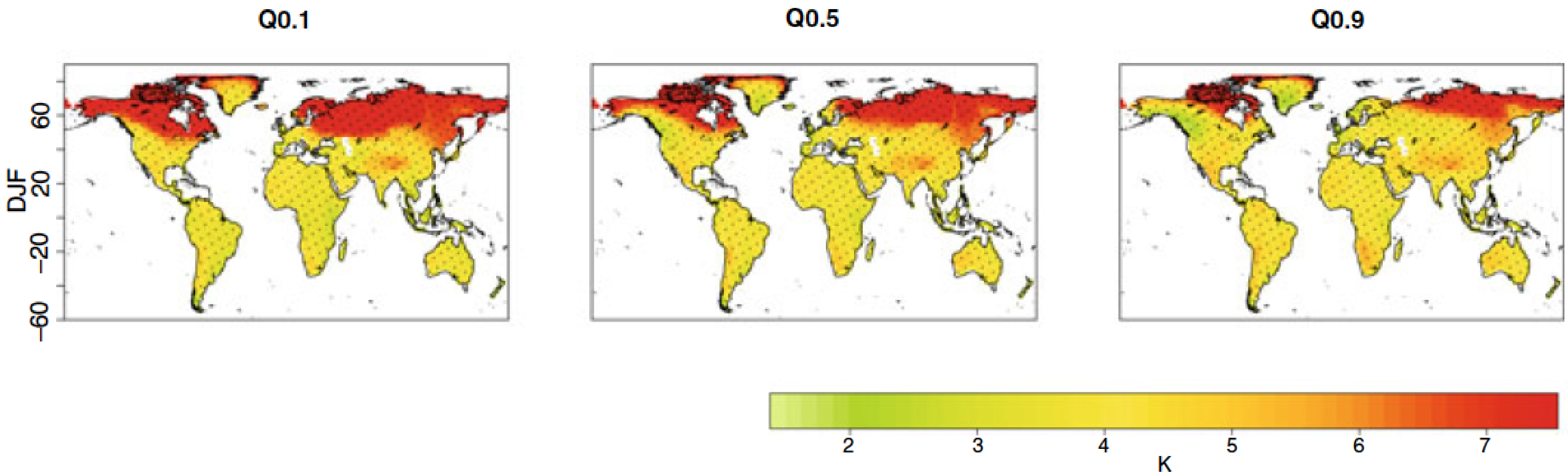
Snow/ice – albedo feedbacks

Strongest effect at limit of snow/ice cover



Asymmetric warming of extremes

ΔTmax [(2081-2100)-(1980-1999)] for 10th (left), 50th (middle), and 90th percentile (right), DJF

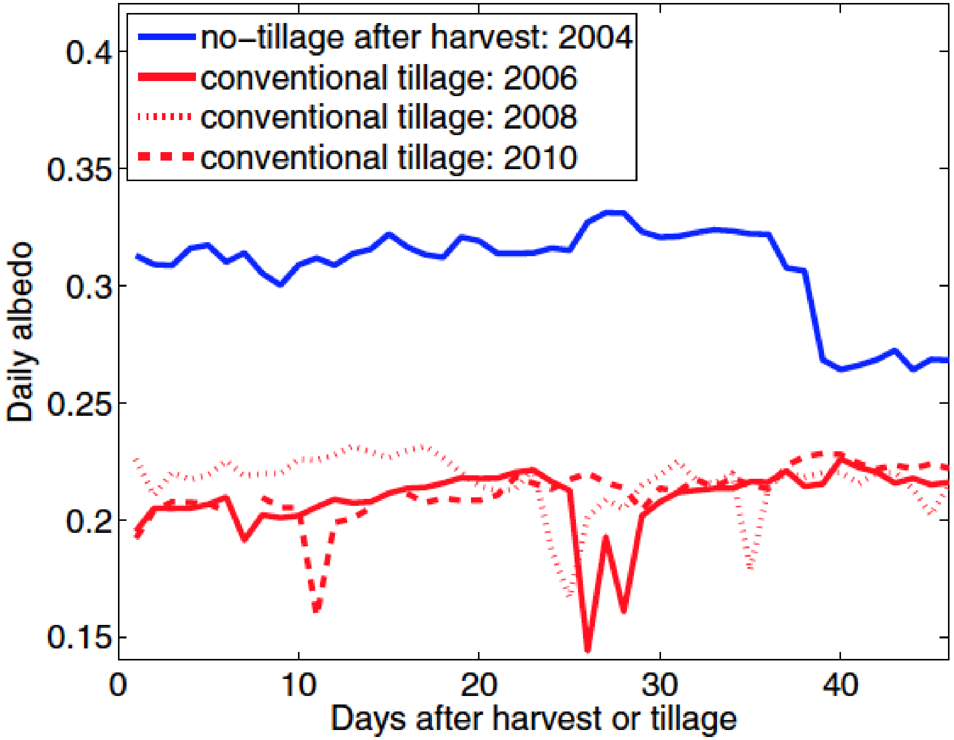


Stronger warming of cold extremes in high-latitude regions: Snow feedback

(Orlowsky and Seneviratne 2012, Climatic Change)

Changes in albedo induced by agricultural management

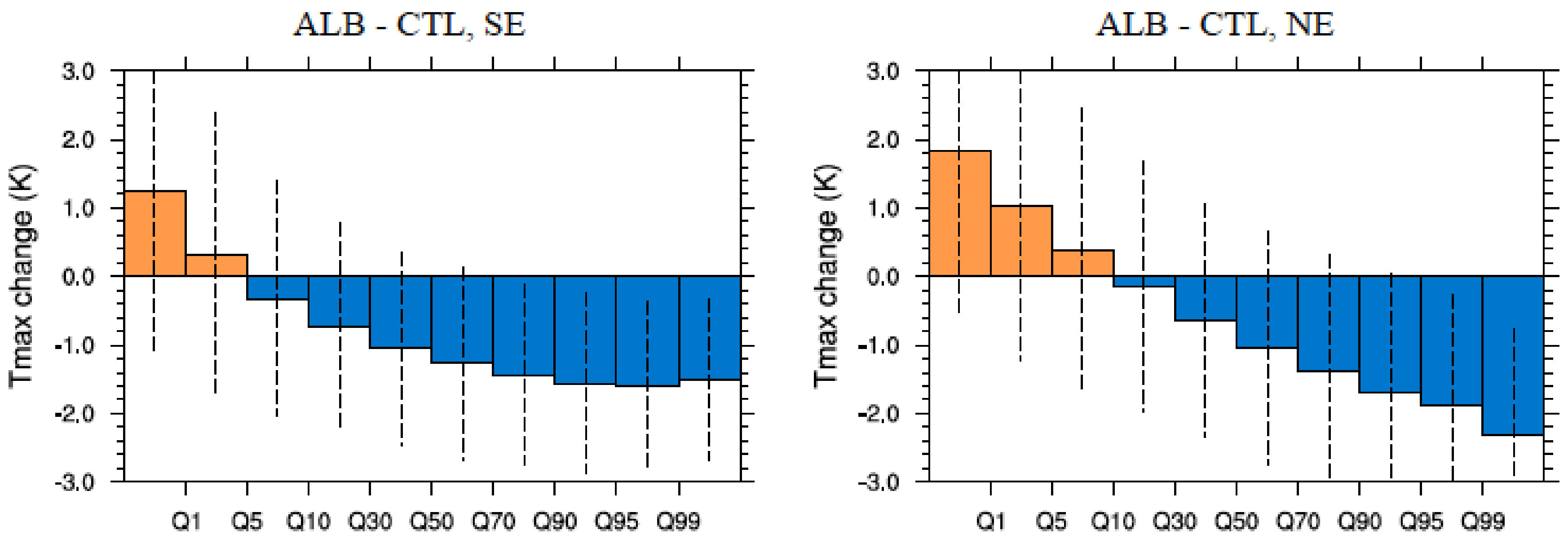
Differences in surface albedo from no-till farming



(Davin et al. 2014, PNAS)

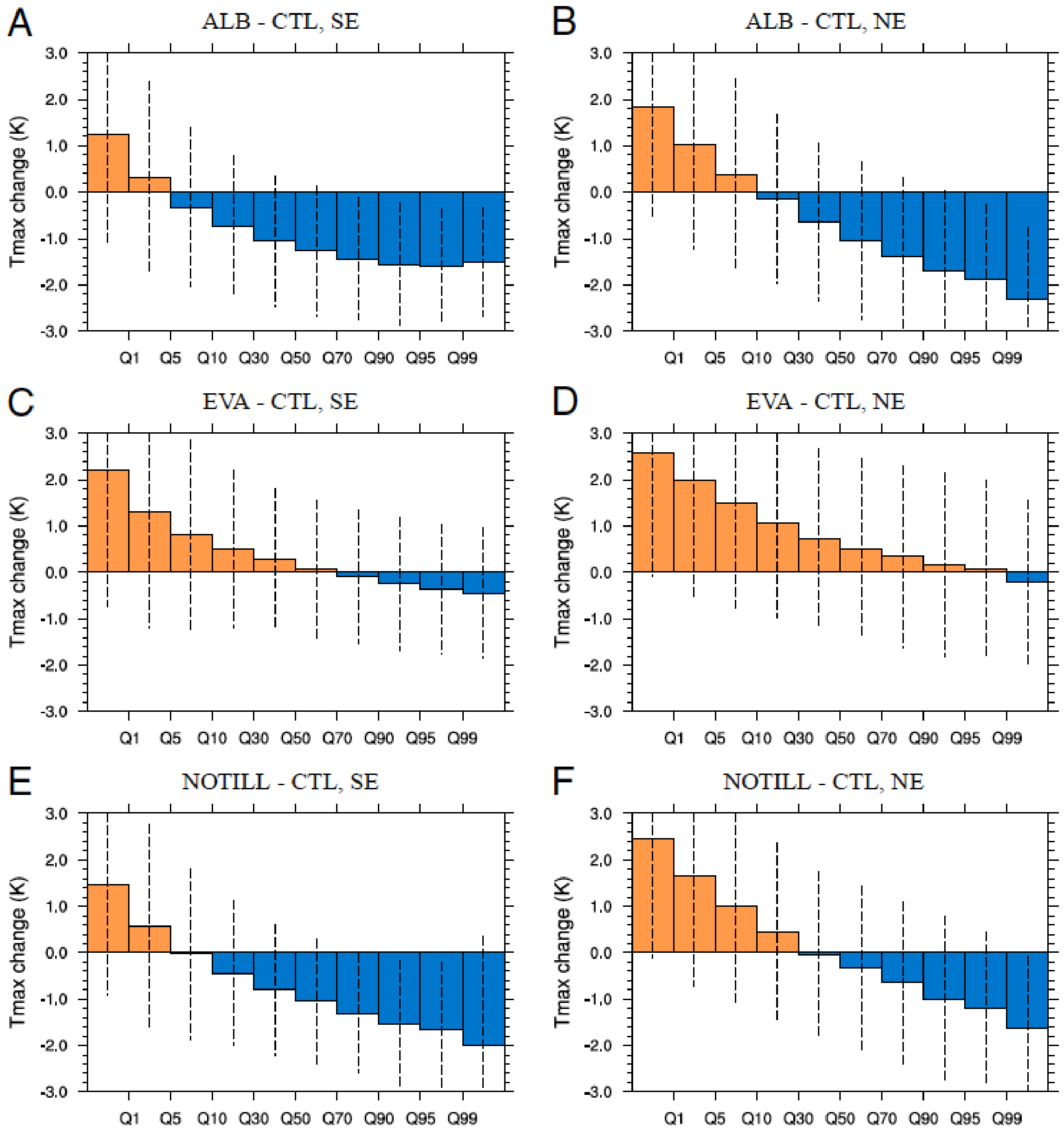
Changes in albedo induced by agricultural management

Preferential cooling of warmer extremes from surface albedo forcing



(Davin et al. 2014, PNAS)

Changes in albedo induced by agricultural management



Overall effect of no-till farming (also including evaporation impacts):

Strong preferential cooling of hot extremes!

(Davin et al. 2014, PNAS)

Surface albedo – temperature interactions: Summary

- Changes in albedo (either as feedback or forcing) strongly impact temperature and also include non-linear effects
- Stronger warming of cold extremes in winter in many high latitude regions
- Stronger cooling of hot temperatures in mid-latitude summer when surface albedo is increased (possibly relevant for climate adaptation?)

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Drought drivers

Impacted both by *large-scale* and *local* drivers + feedbacks

Precipitation deficit
(meteorological drought)

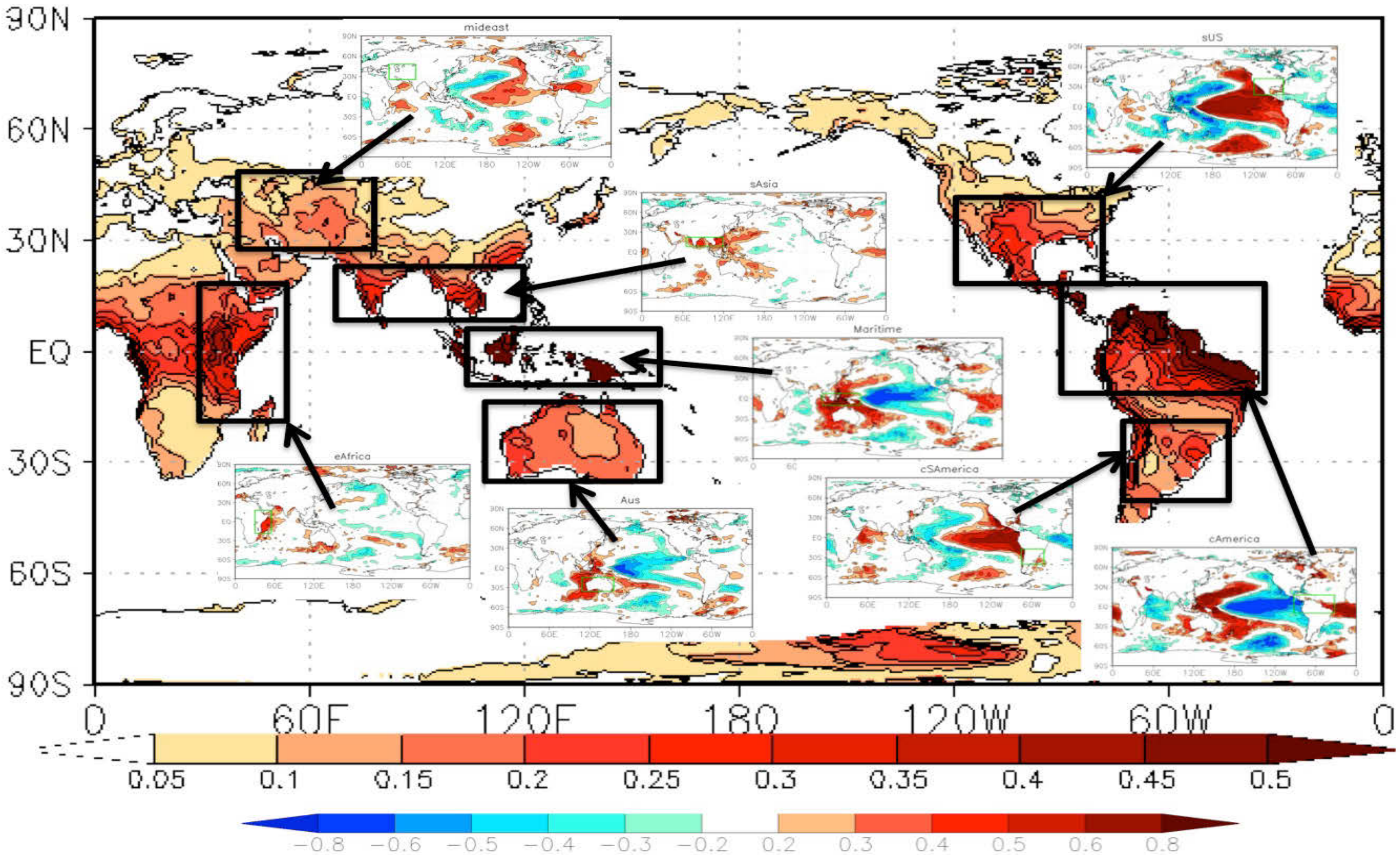
Critical soil moisture deficit
(soil moisture drought)

Critical streamflow and groundwater deficit
(hydrological drought)

Evapotranspiration

Pre-event soil moisture and groundwater storage

Fraction of interannual precipitation variance forced by SSTs



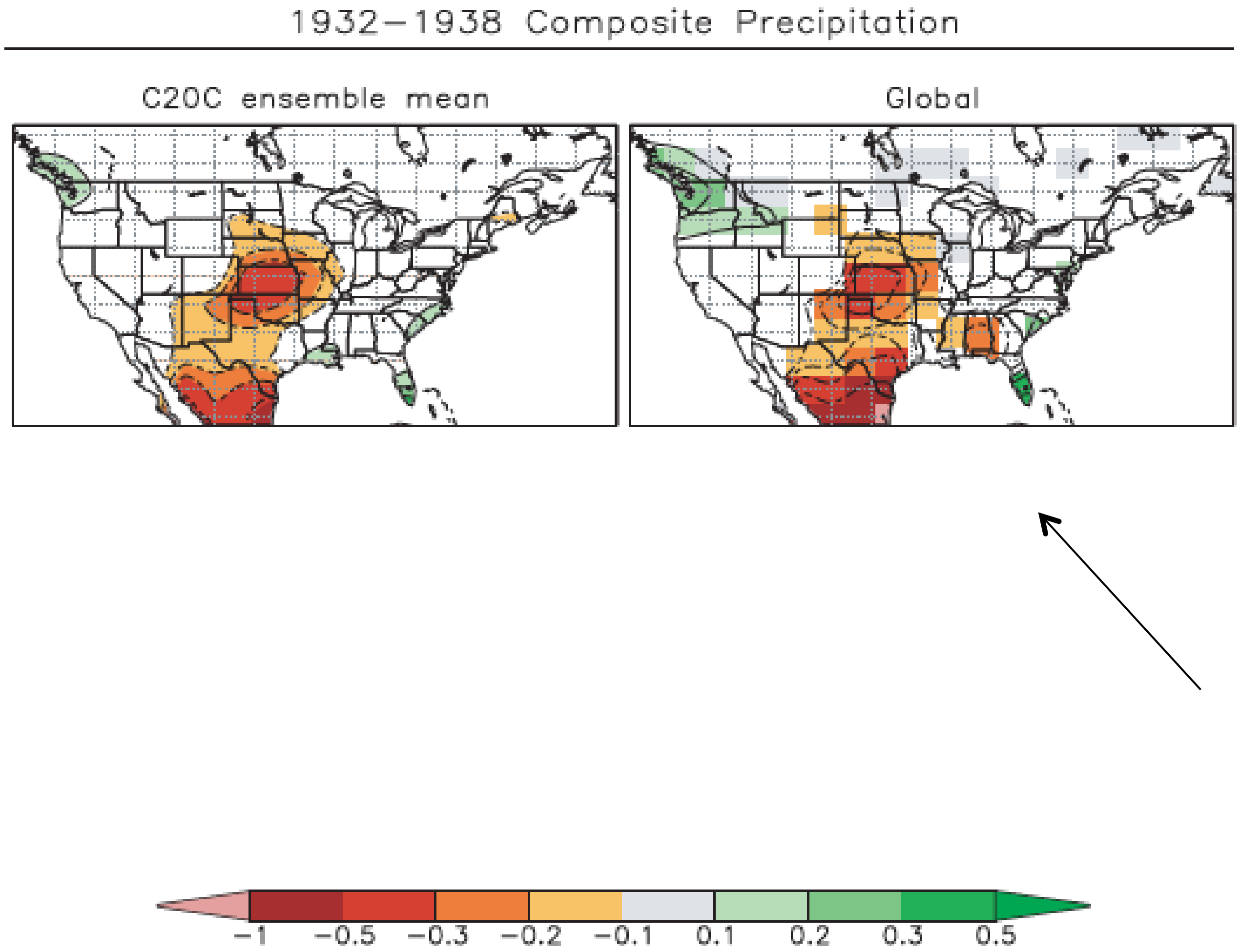
(Schubert et al., in prep.)

Role of sea surface temperatures

SST explains a large amount of the interannual precipitation variability in many regions, but:

- Some of the resulting effects may be due to the amplification of land-atmosphere feedbacks
- In many regions, SSTs do not provide any (or only little) forcing
- Some local/regional effects (not resolved by GCMs) are strongly affected by local/regional characteristics

Drought drivers: Precipitation

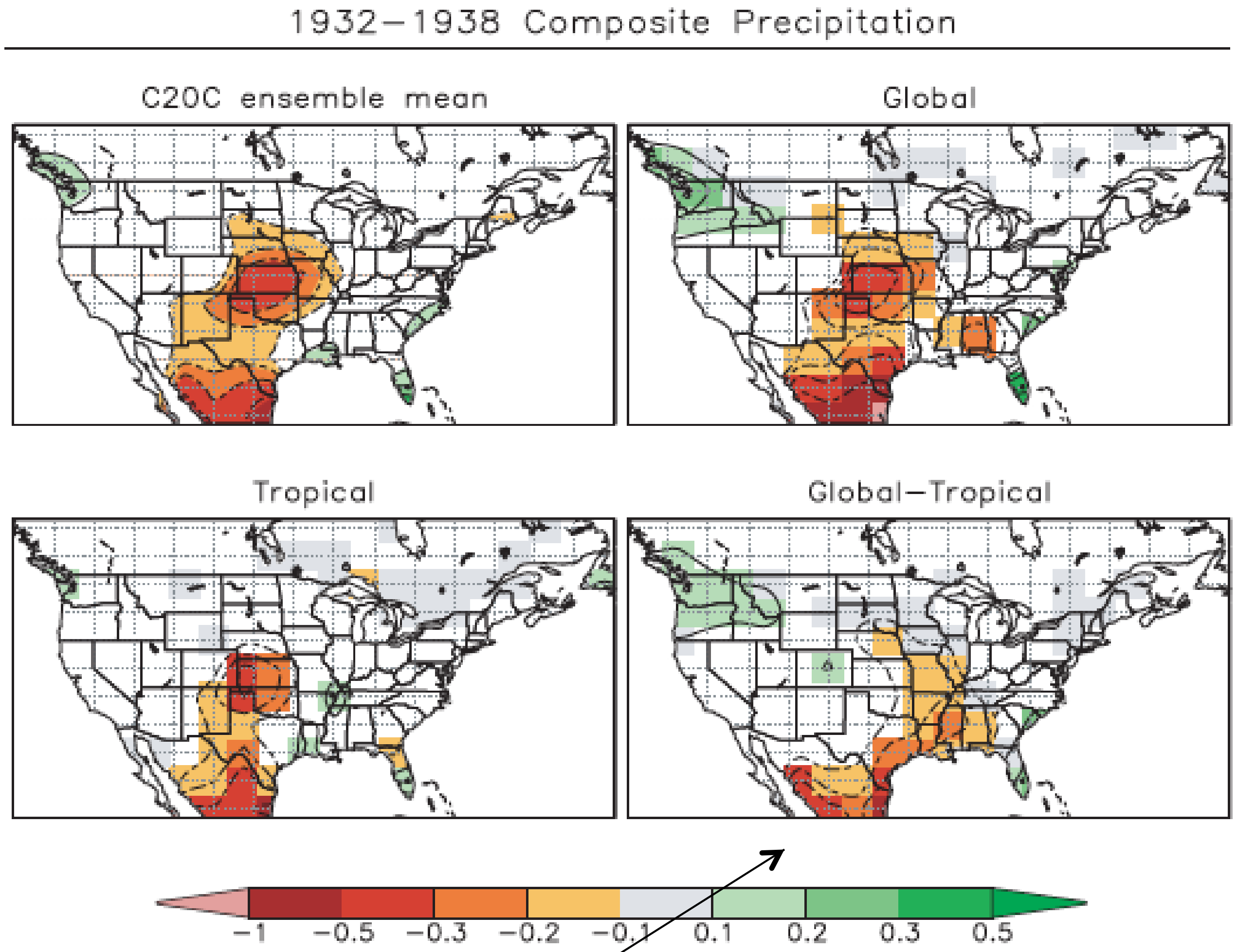


US dust bowl: SST vs land-atmosphere effects on droughts

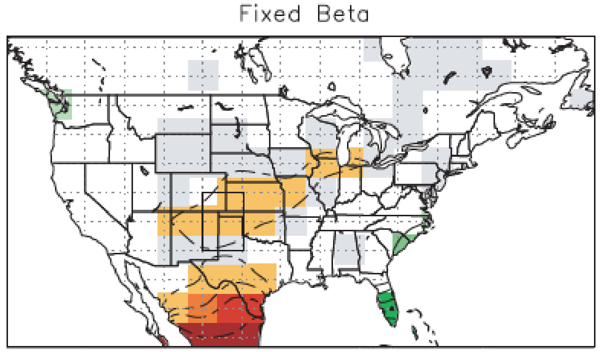
Model representation prescribing global SST

(Schubert et al. 2004, Science)

Drought drivers: Precipitation



US dust bowl: SST vs land-atmosphere effects on droughts



Tropical SSTs responsible for large part of signal

But also soil moisture-precipitation feedbacks!

(Schubert et al. 2004, Science)

Drought drivers

Large number of drivers for *potential* and *actual* evapotranspiration:
Requires detailed land hydrological representation

Precipitation deficit
(meteorological drought)

Critical soil moisture deficit
(soil moisture drought)

Evapotranspiration

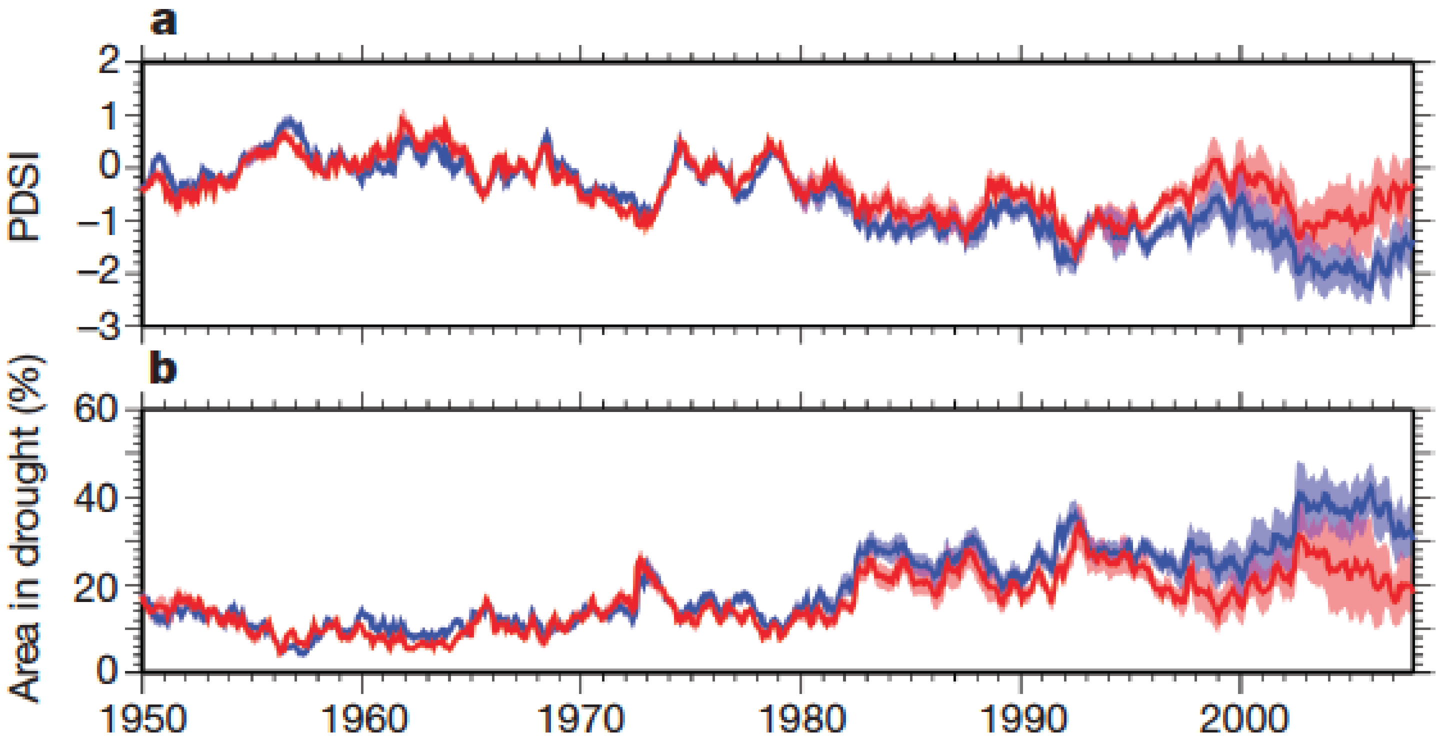
Pre-event soil moisture and groundwater storage

Critical streamflow and groundwater deficit
(hydrological drought)

Drivers of drought: Potential evapotranspiration

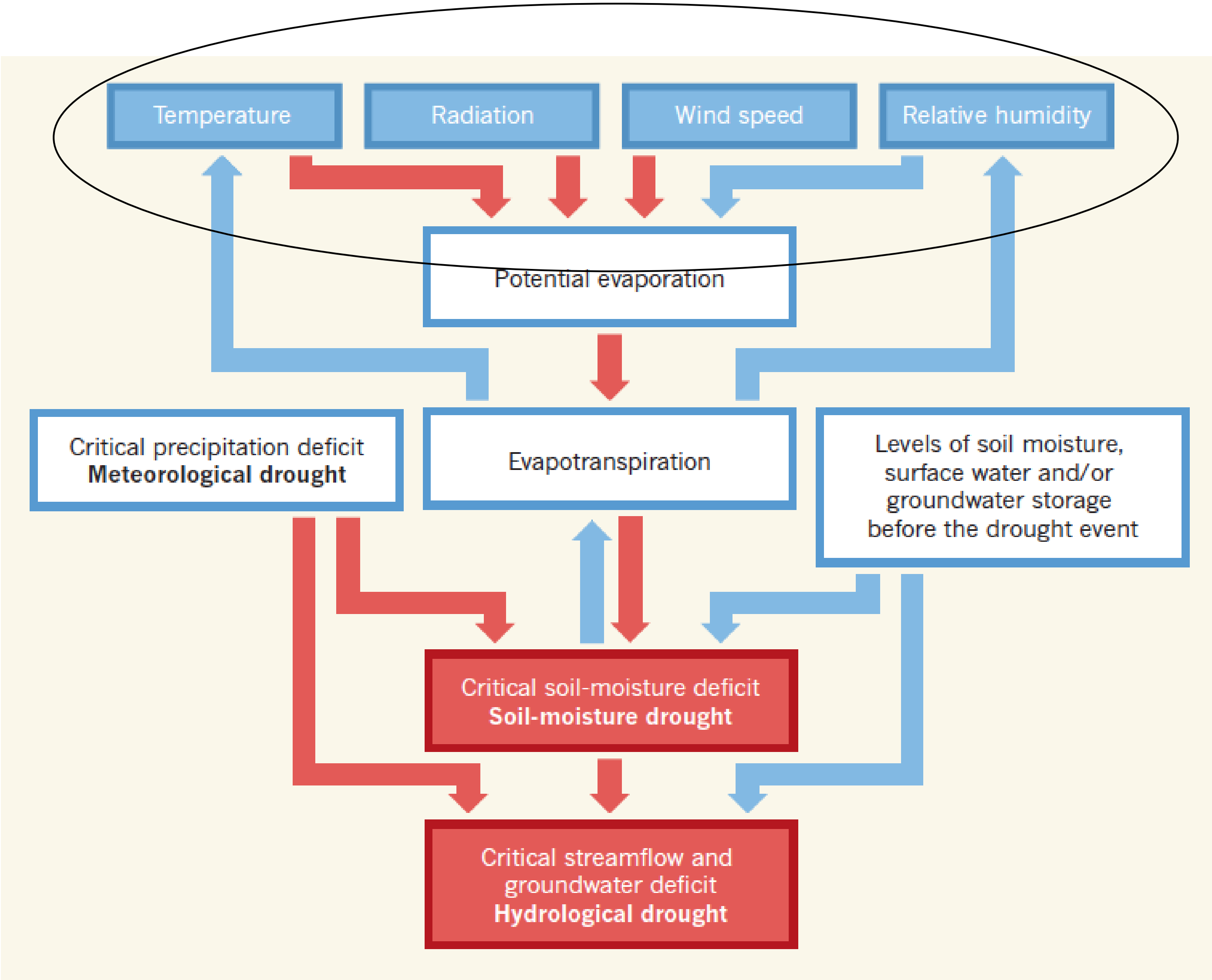
Impact of parameterization of potential evapotranspiration for trends in global droughts

- Red: Penman-Monteith (temperature, radiation, wind speed, relative humidity)
- Blue: Thornthwaite (temperature only)



(Sheffield et al. 2012, Nature)

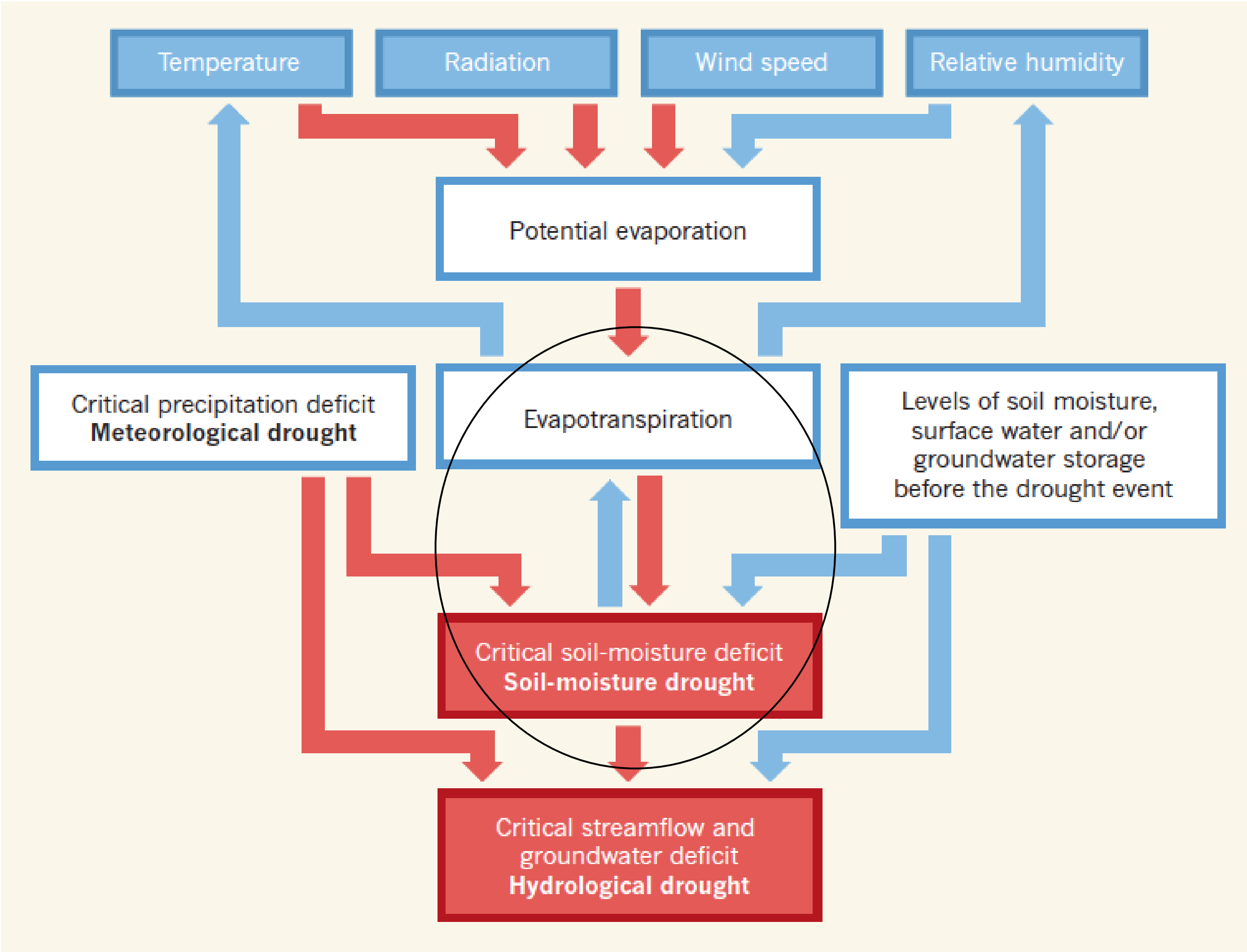
Drivers of drought: Potential evapotranspiration



The drivers of potential evapotranspiration are themselves affected by feedbacks from the land surface!

(Seneviratne 2014, Nature News and Views)

Drivers of drought: Actual evapotranspiration



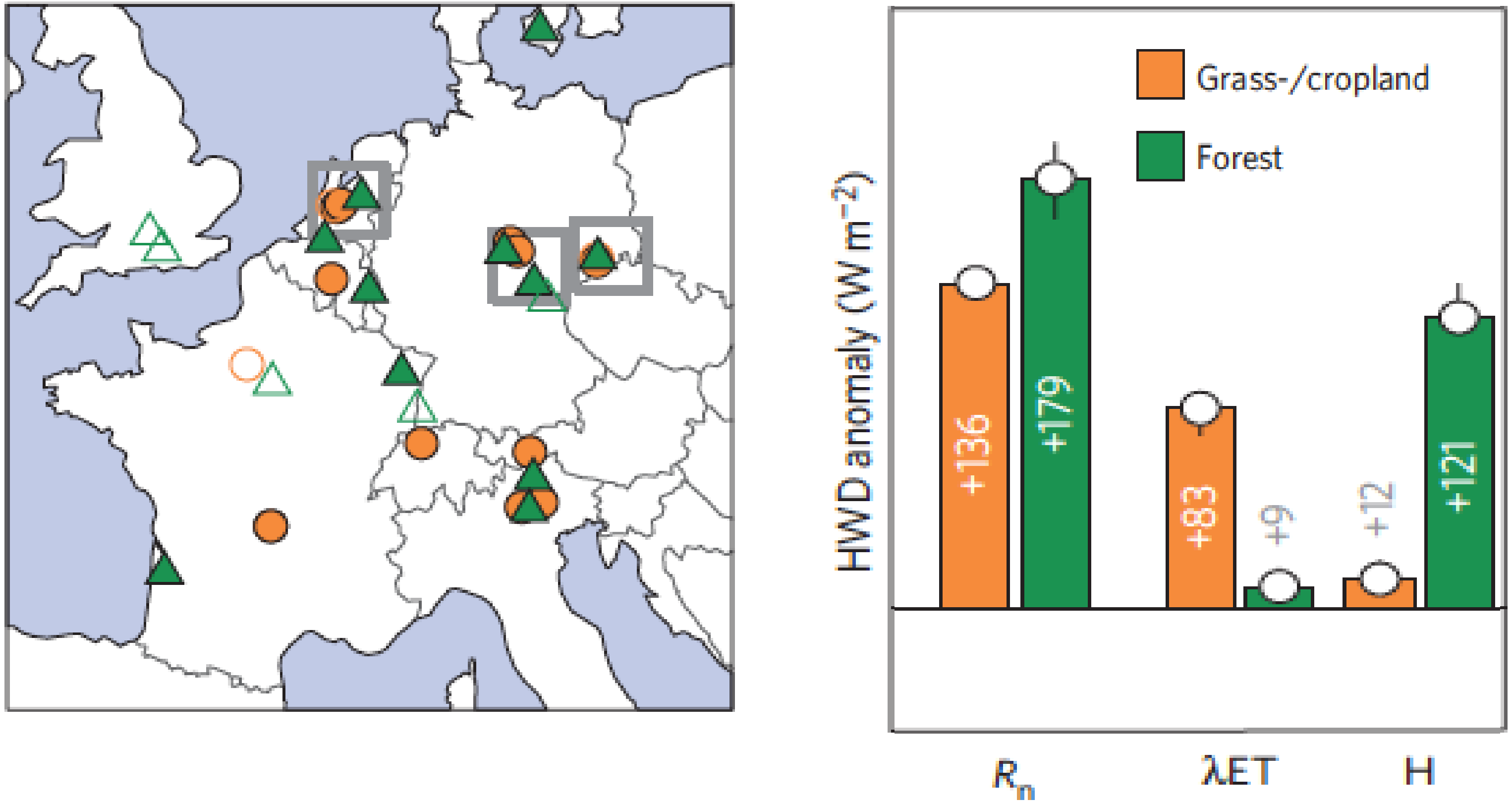
The interactions between soil moisture drought and evapotranspiration depend on various factors, e.g. **land cover, land use, plant photosynthesis**

(Seneviratne 2014, Nature News and Views)

Land cover impacts on evapotranspiration

During heatwave days in Central Europe (data mostly available after 2003), forests are found to evaporate less than grassland!

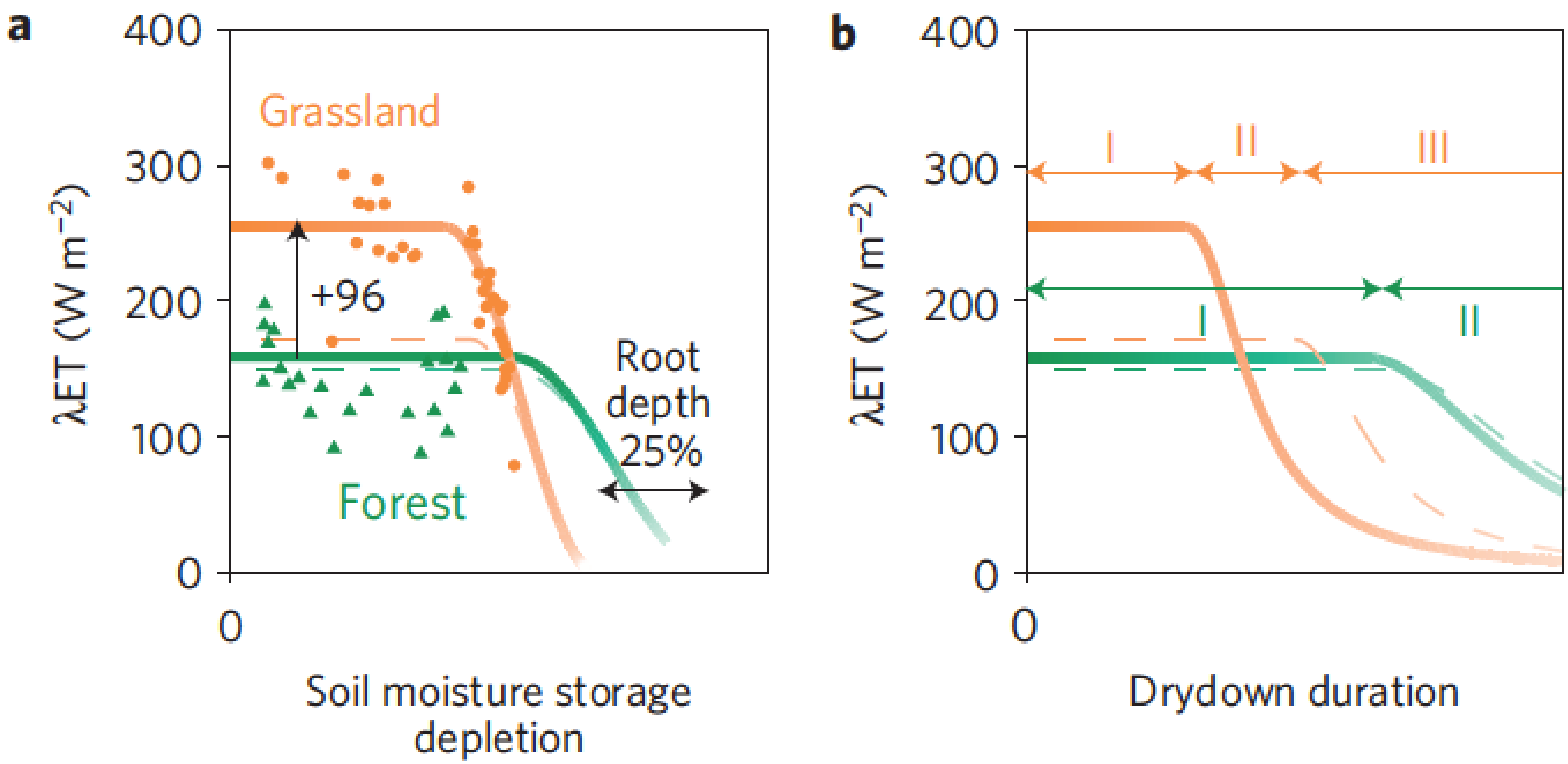
Behaviour under long-term drought may reverse



(Teuling et al. 2010, Nature Geoscience)

Land cover impacts on evapotranspiration

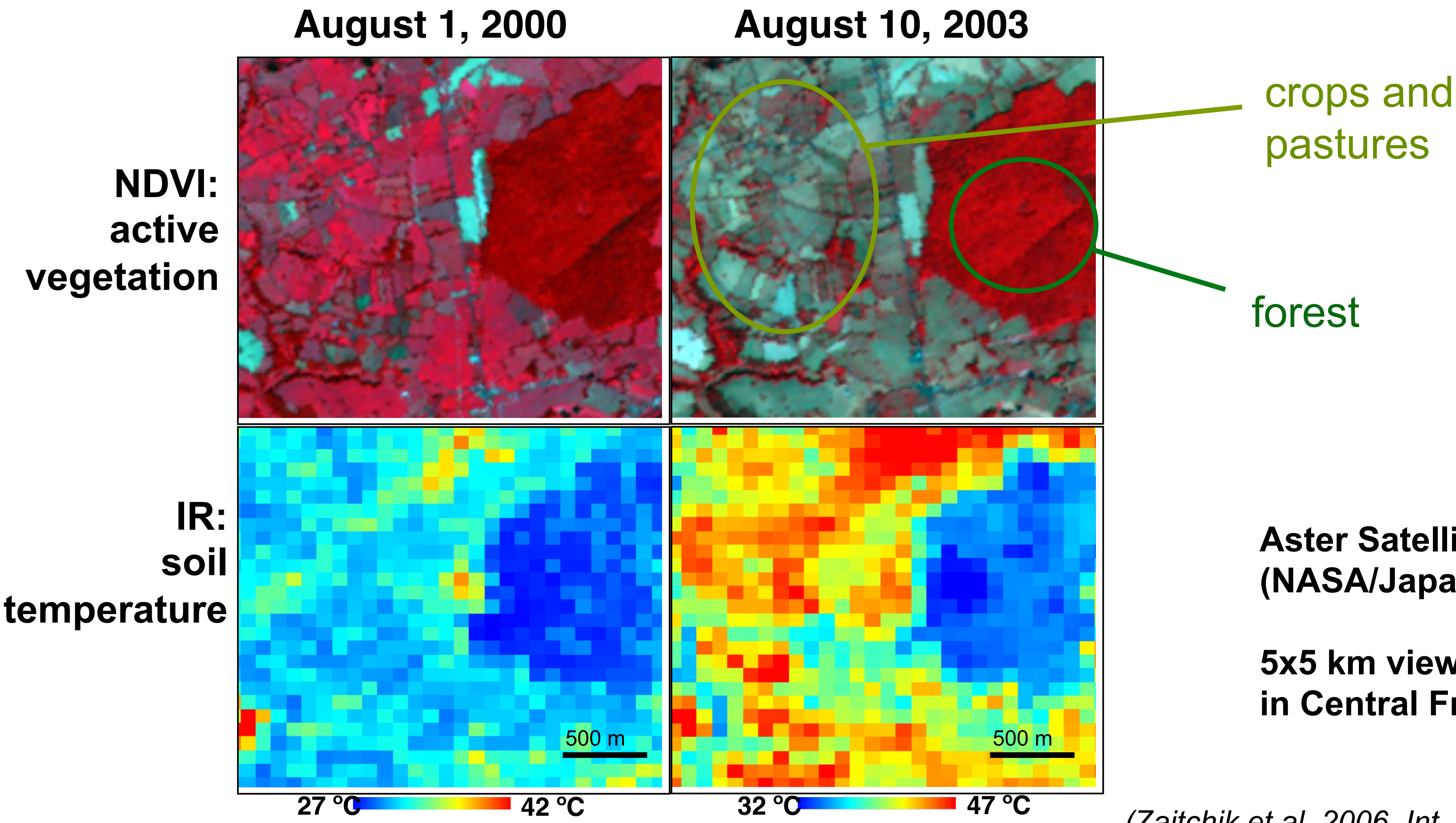
Conceptual model: Although grassland evaporates more in the short term, this can lead to a quicker drying! ➔ reversal of relationship after critical threshold



(Teuling et al. 2010, Nature Geoscience)

Land cover impacts on evapotranspiration

Impact of vegetation cover in 2003 heatwave: region with particularly strong temperature increase in France

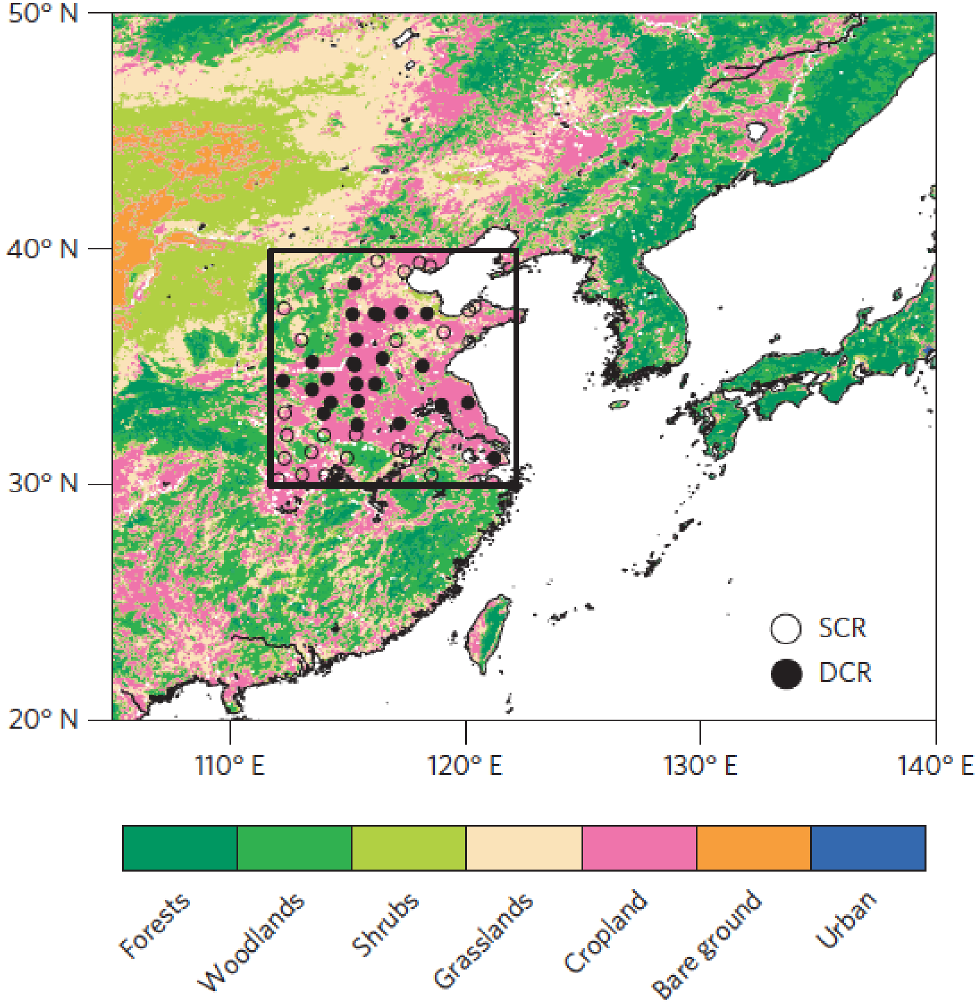


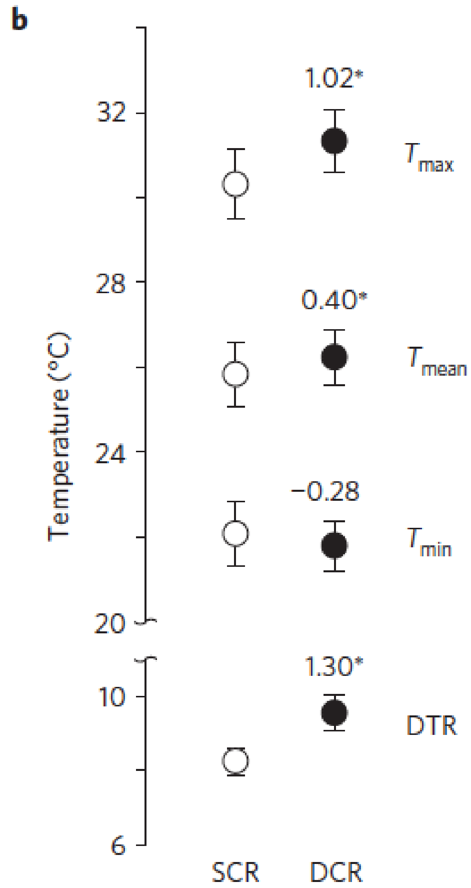
Aster Satellite (NASA/Japan)

5x5 km view in Central France

(Zaitchik et al. 2006, Int. J. Clim.)

Double cropping leads to drying in intercropping season: Effect seen in temperature

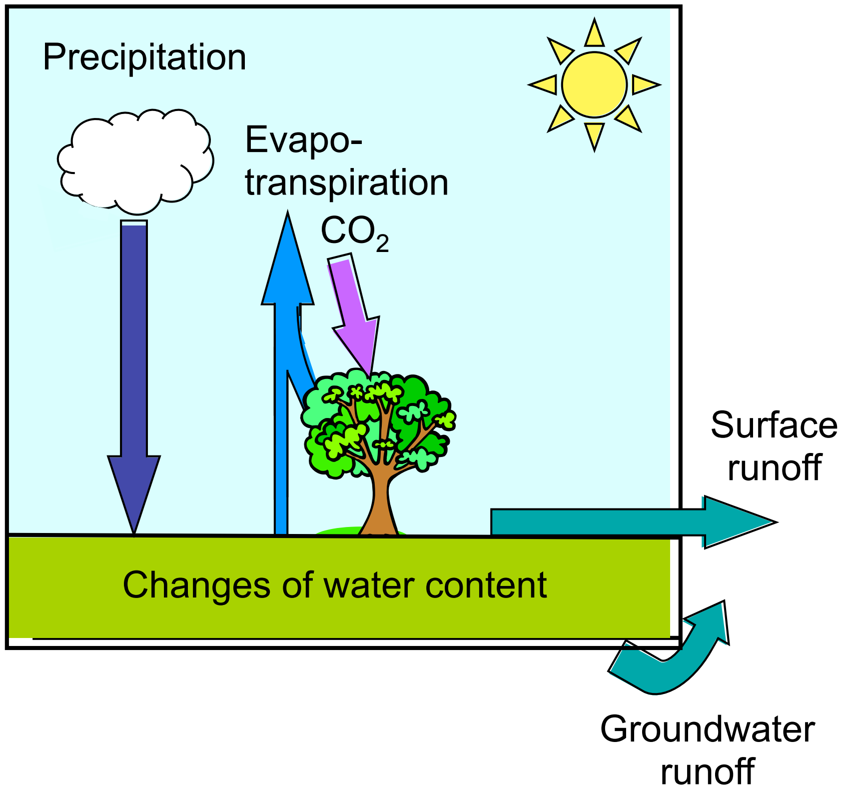


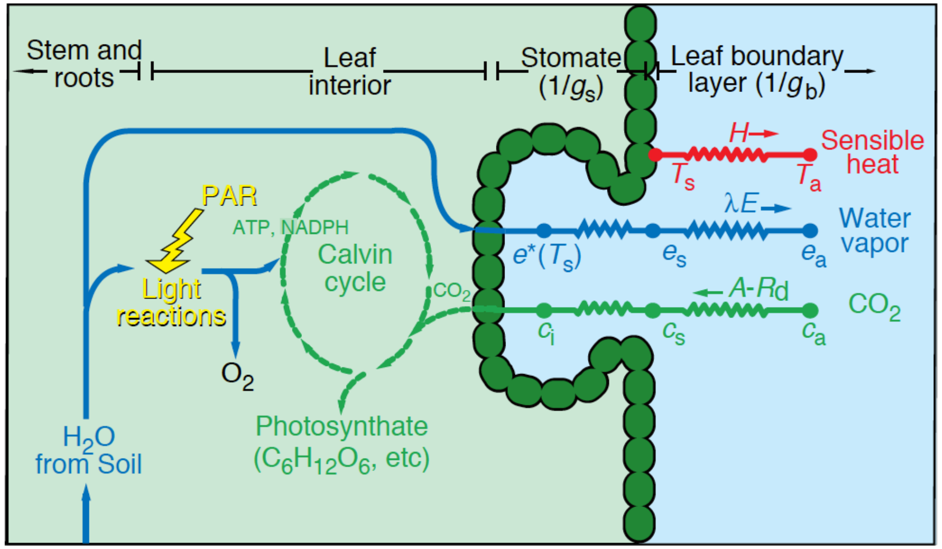


(Jeong et al. 2014, Nature Clim. Ch.)

Through vegetation, the water and carbon cycles are interlinked

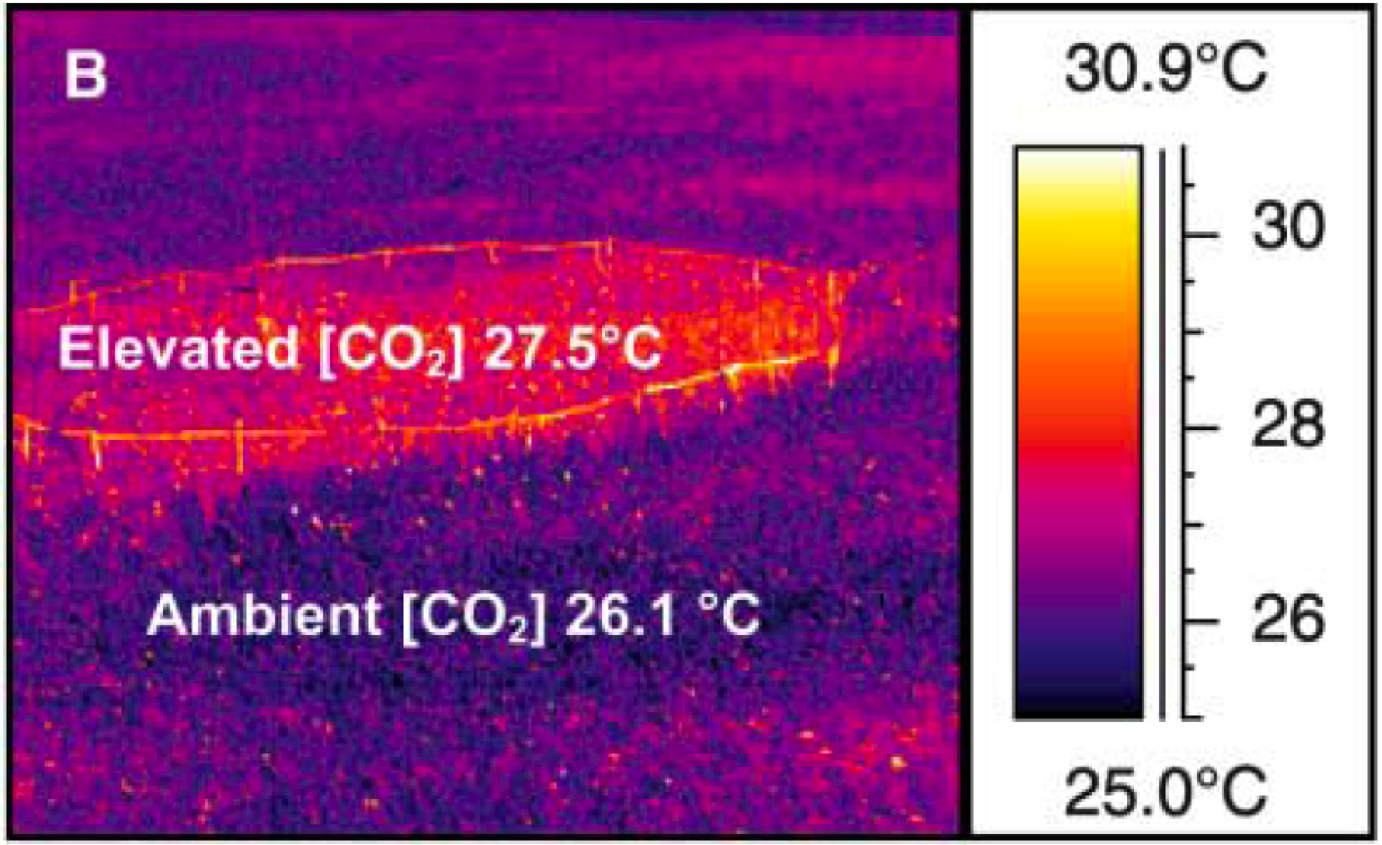
➔ Leads to large number of feedbacks and interactions





(Sellers et al. 1997, Science)

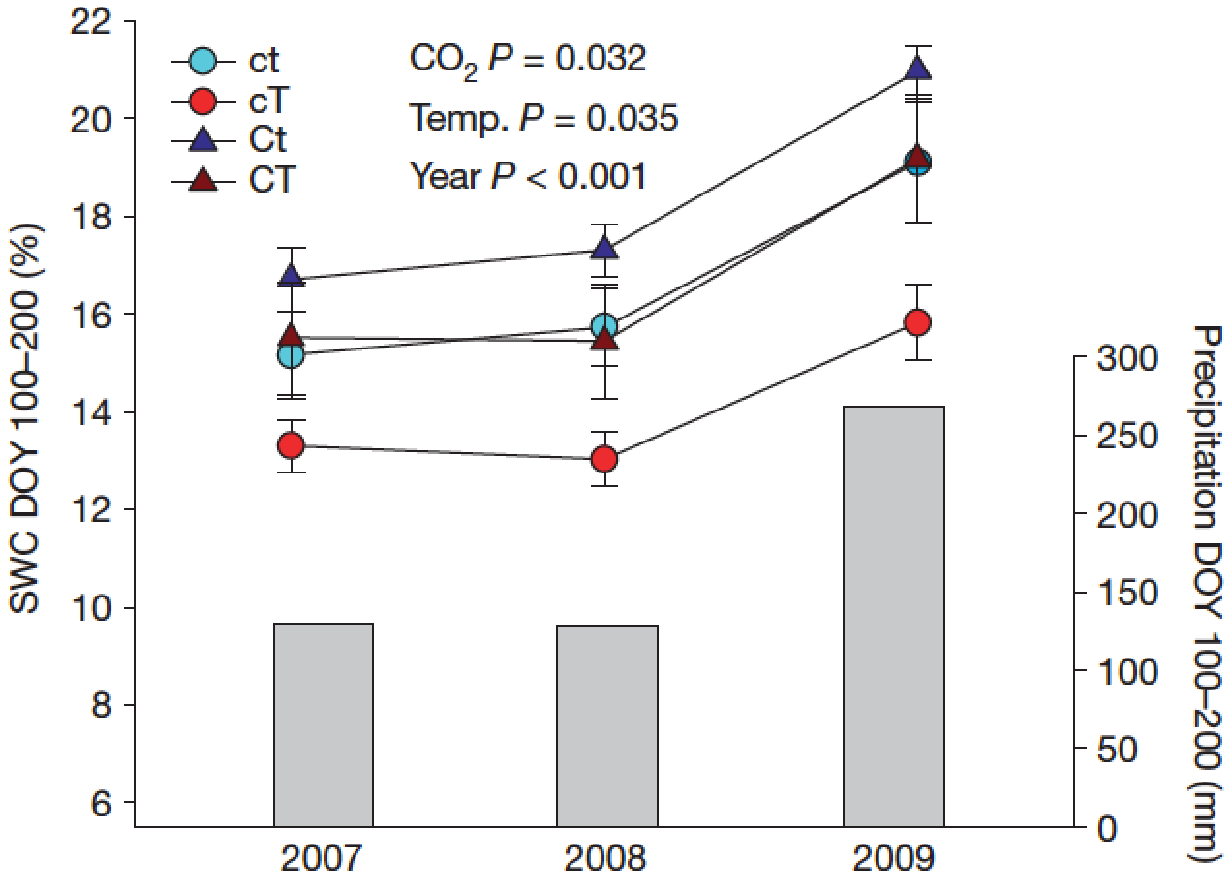
Effects of enhanced CO_2: Enhanced water-use efficiency



Decreased ET (L*ET), i.e. enhanced sensible heat flux, leads to enhanced air temperature inside the elevated CO_2 plot (SoyFACE, Illinois)

(Long et al. 2006, Science)

Effects of enhanced CO_2: Enhanced water-use efficiency



Competing effects of temperature and CO_2 on grassland evapotranspiration (plot experiment)

(Morgan et al. 2011, Nature)

Plants-CO_2 effects: Impact on hydrological droughts

x: proportion of land under 'drought' at the same time
F(x): cumulative density functions.

For JULES (including plant-CO_2 effect) the maximum land over under drought is 20% (0.2) and is reached under historical climate; for H08 maximum drought extent is ~ 55%

When JULES is run without CO_2 effect, the maximum land area under drought is 40%.

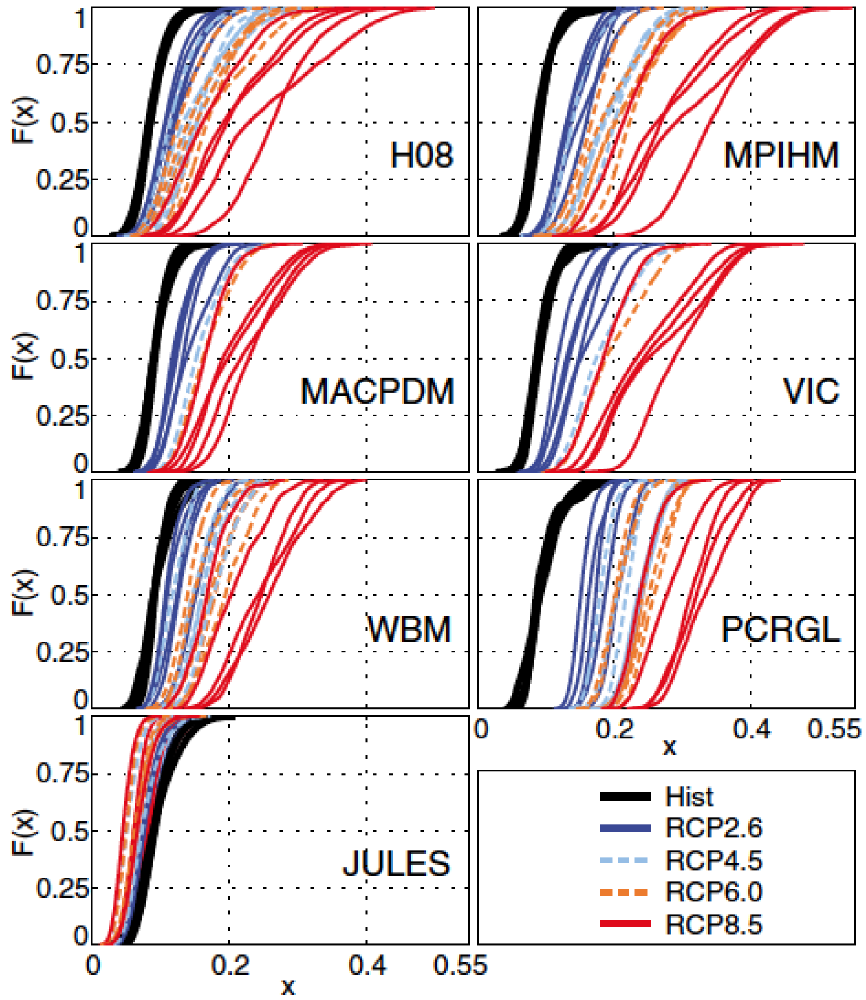
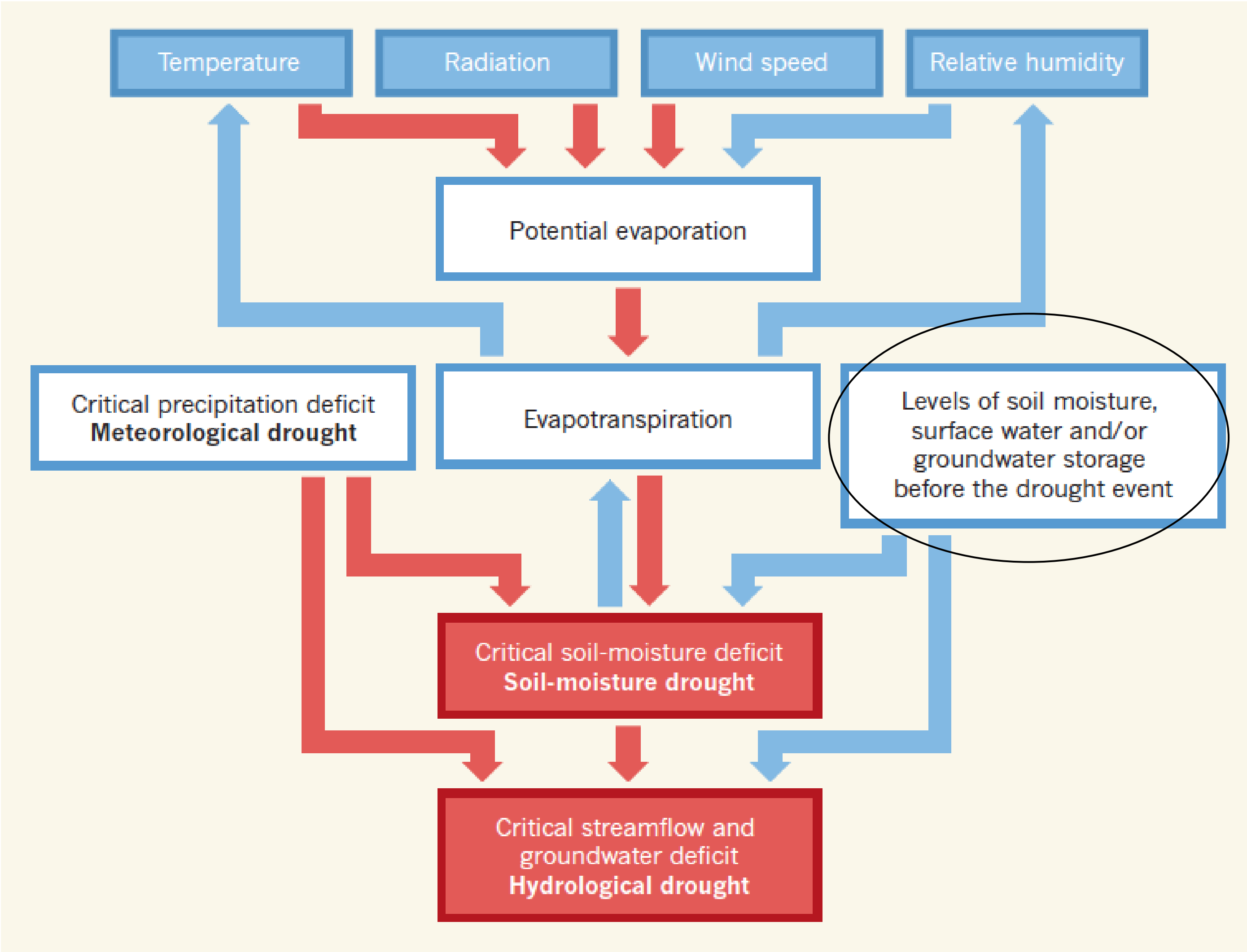


Fig. 3. Cumulative density functions (CDFs) of daily global deficit index (GDI) calculated over 30-y periods (1976-2005 for historical forcing and 2070–2099 for RCP forcings) for each multimodel ensemble member.

(Prudhomme et al. 2014, PNAS)

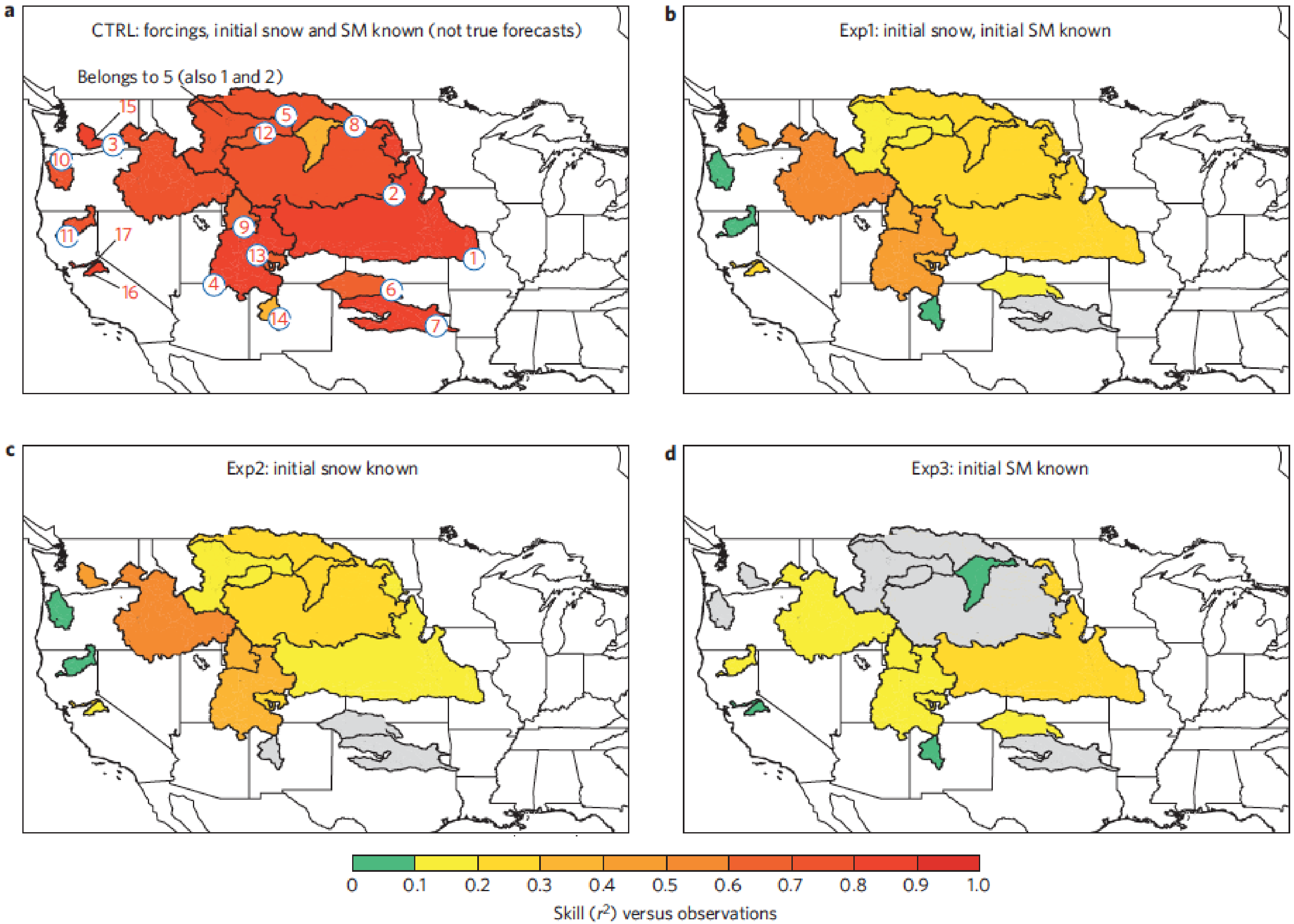
Drivers of drought: Preconditioning



Preconditioning is important for many drought events

(Seneviratne 2014, Nature News and Views)

Preconditioning: Soil moisture and Snow

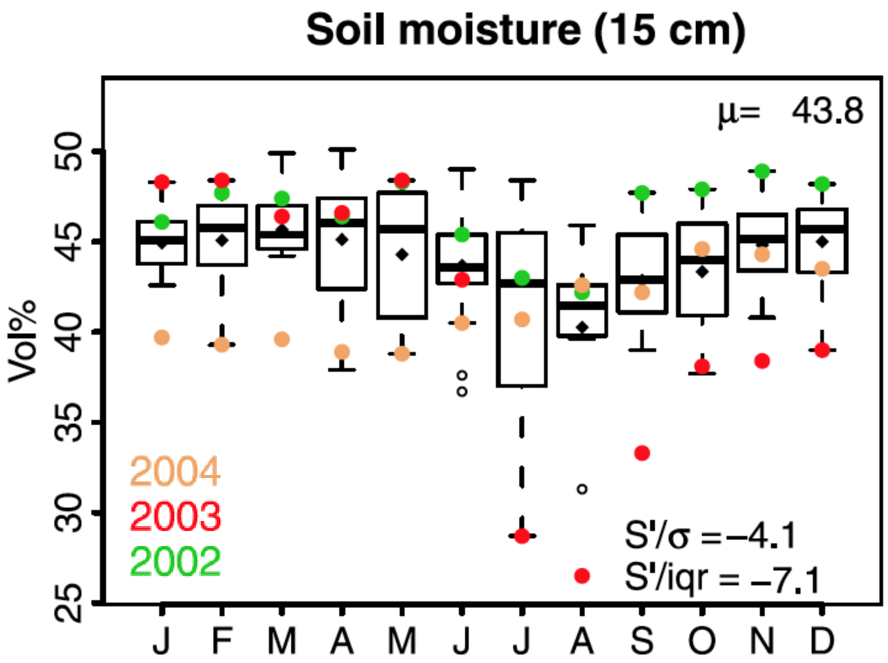


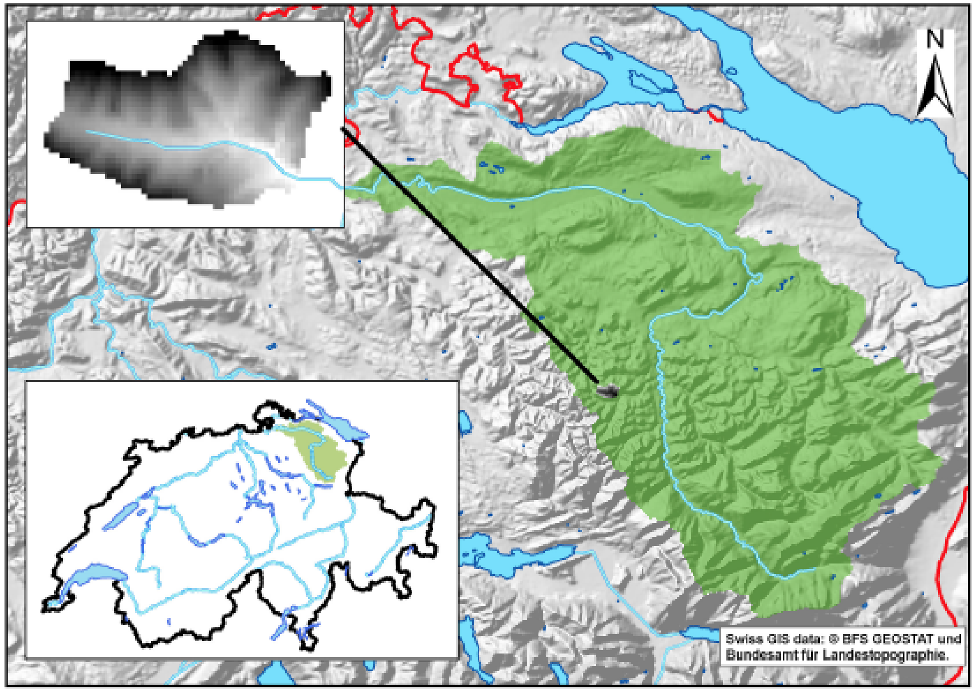
Forecasts for streamflow in MAMJJ

(Koster et al. 2010, Nature Geoscience)

Soil moisture "memory"

Soil moisture anomaly at Rietholzbach catchment

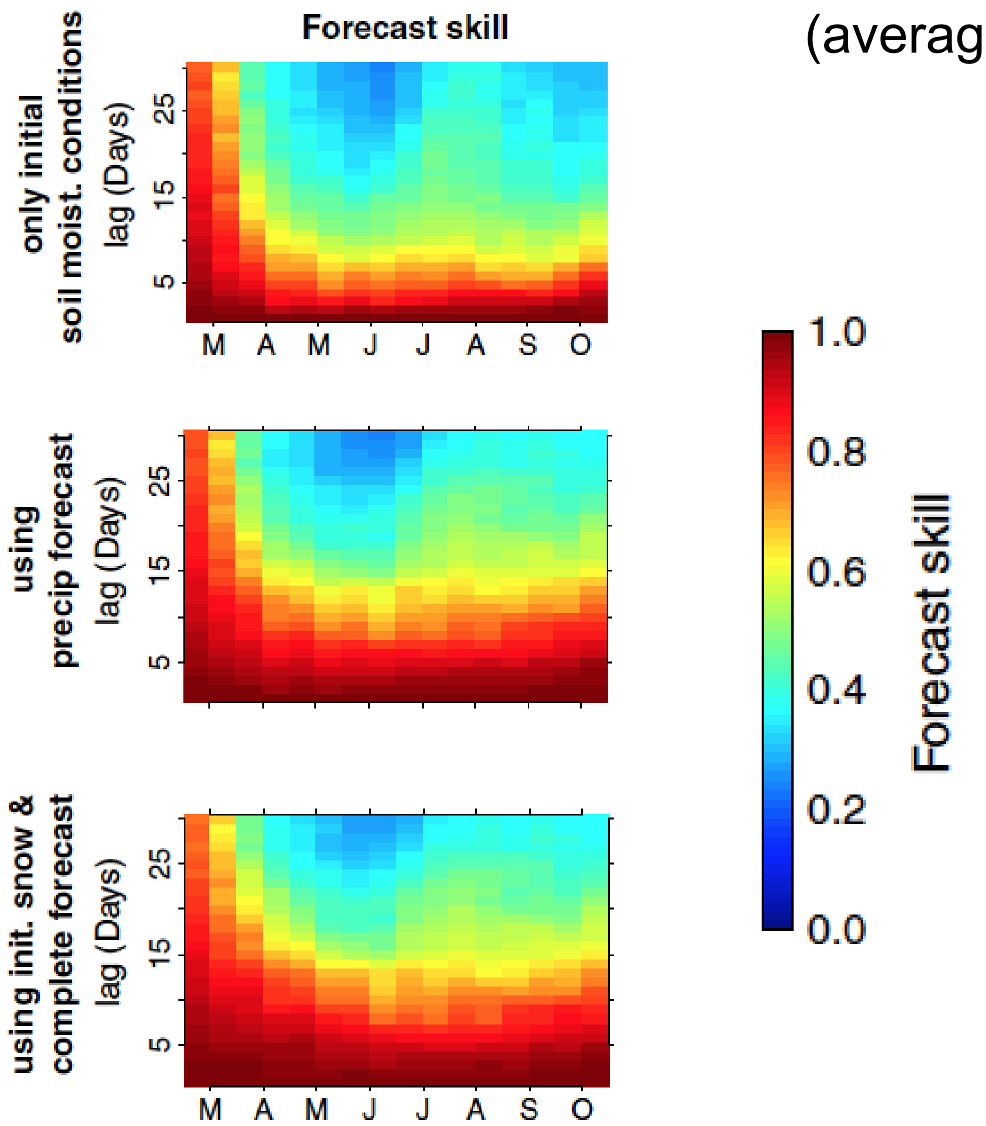




(Seneviratne et al. 2012, WRR)

Soil moisture "memory"

Idealized soil moisture forecasts in Switzerland (average performance over 22 catchments)



Substantial skill from soil moisture alone

Using precipitation forecasts (ECMWF) and snow initialization further increases skill

(Orth and Seneviratne 2013, JGR)

Droughts: Summary

Although large-scale drivers are important for droughts, local and regional effects play an essential part as well:

- Precipitation anomalies are affected by soil moisture feedbacks
- Evapotranspiration is controlled by several feedbacks with the land surface and by local and regional processes and forcings (plant physiology, land cover, land management, …)
- Preconditioning (soil moisture, snow or groundwater anomalies) can strongly affect soil moisture and hydrological drought events

Outline

Introduction

Soil moisture-temperature feedbacks

Surface albedo-temperature interactions

Physical drivers of droughts

Precipitation extremes

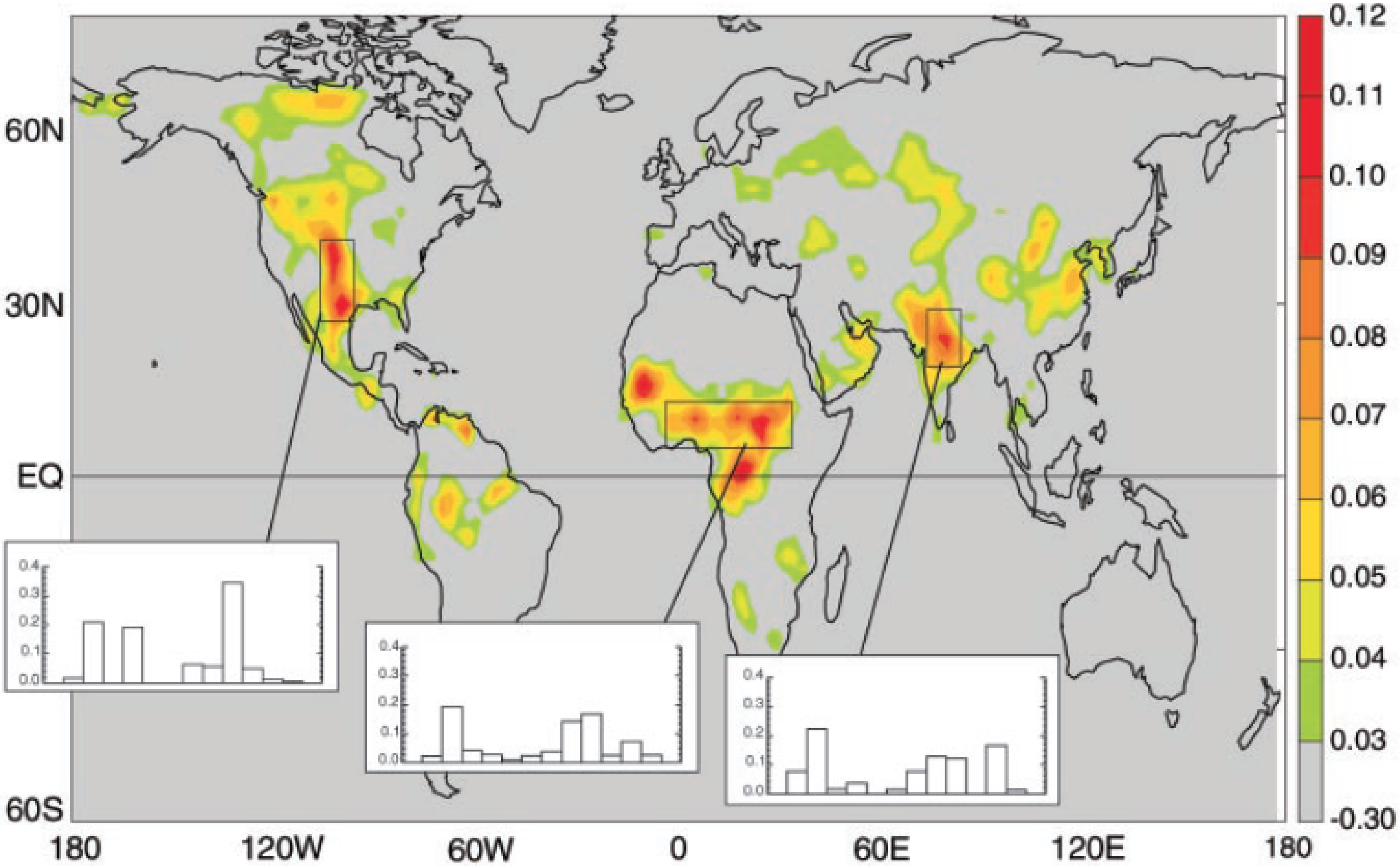
Conclusions

Soil moisture-precipitation feedbacks

- Several studies suggest that soil moisture-precipitation feedbacks play an important role *(e.g. Koster et al. 2004, Science)*
- Studies document both positive and negative feedbacks *(e.g. Findell et al. 2011, Nature Geoscience; Taylor et al. 2012, Nature)*. Effects include moisture recycling, changes in boundary layer stability and mesoscale circulation pattterns.
- Possible confounding effects from precipitation persistence *(e.g. Guillod et al., in press)* and model dependency of results *(Hohenegger et al. 2009, J. Climate)* cause problems for analyses
- Despite (or because of) uncertainties: Need to be better investigated, in particular for extremes

Soil moisture-precipitation feedbacks

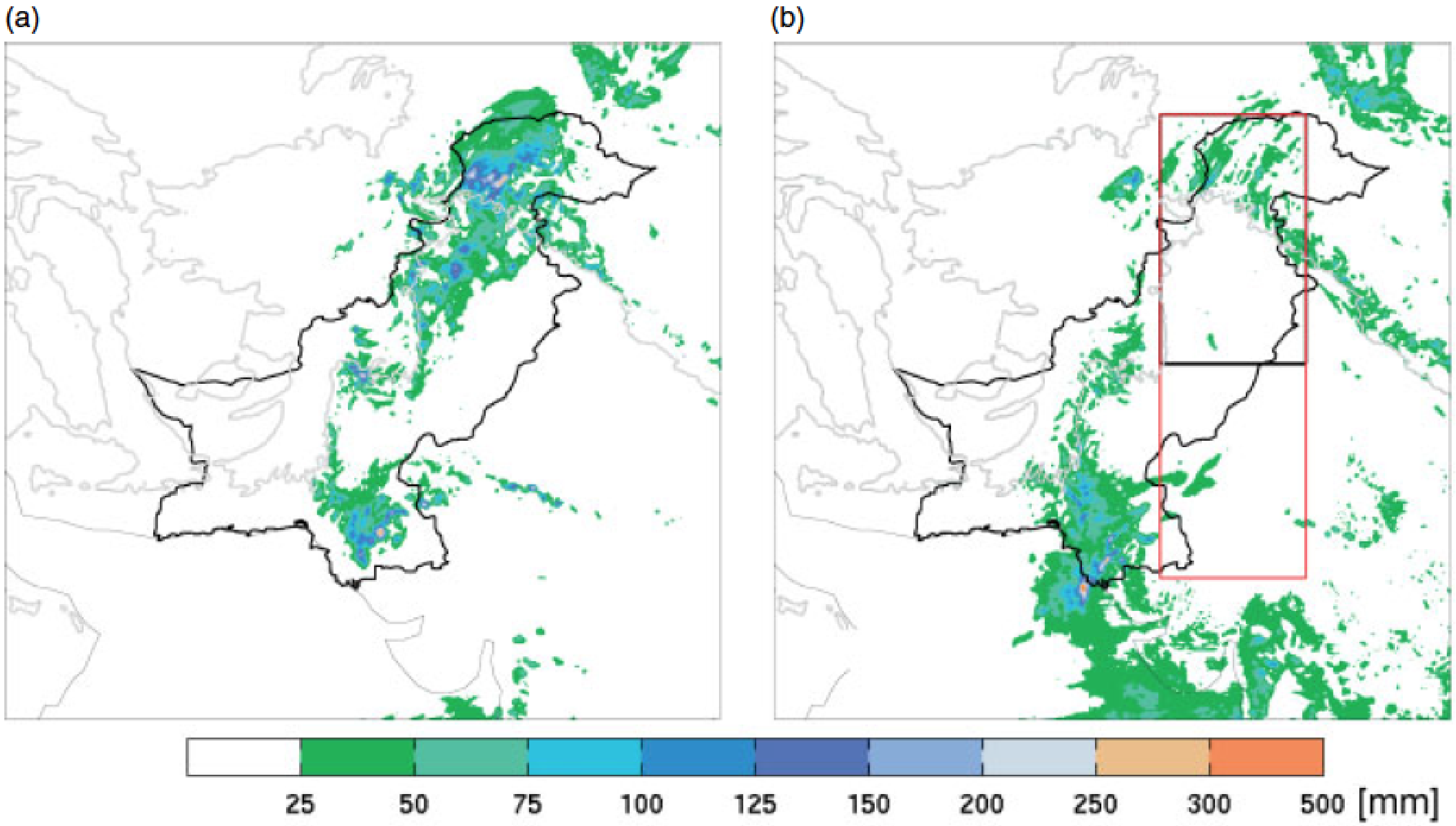
Soil moisture - precipitation coupling strength (JJA) averaged across AGCMs



(Koster et al. 2004, Science)

Soil moisture-precipitation feedbacks

Model simulations of Pakistan 2010 floods with (left) and without (right) evapotranspiration from land surface

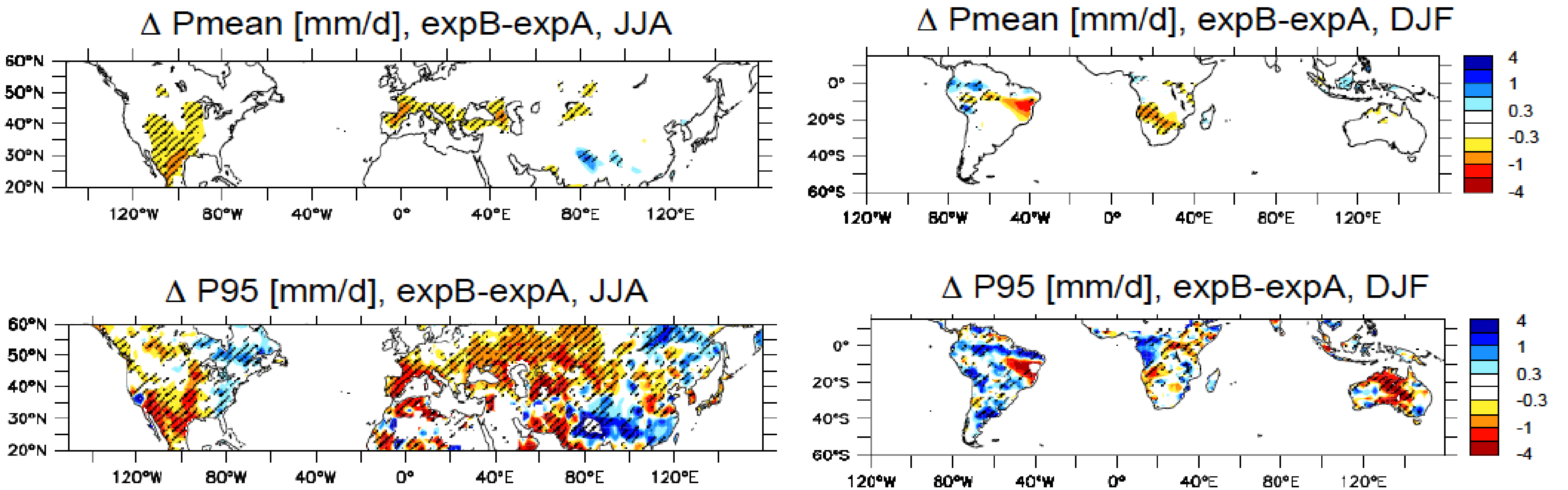


Air masses spent 72 hours over land before raining out: Model suggests that 90% and 60% of rainfall over Pakistan was originating from land (reevaporation)

(Martius et al. 2013, Quart. J. Roy. Met. Soc)

Impacts of changes in soil moisture under future climate

GLACE-CMIP5 experiment

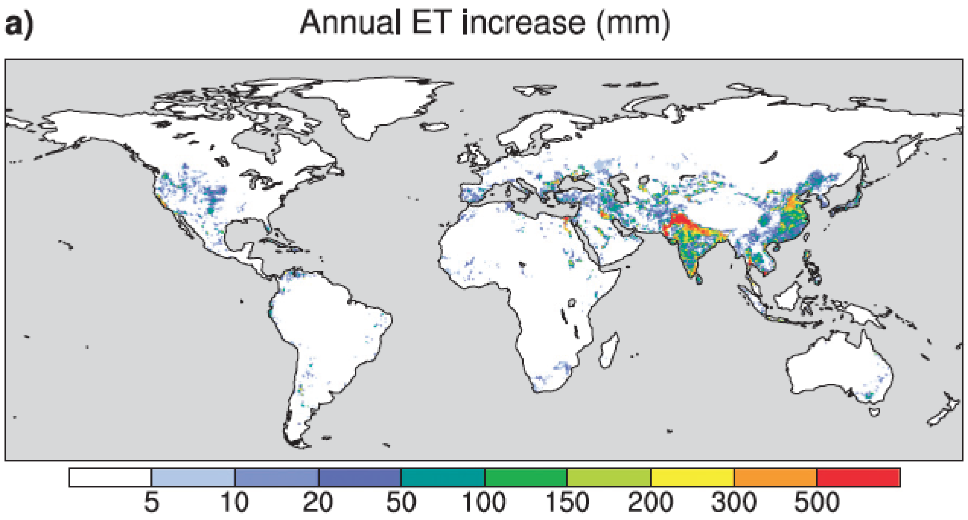


Part of projected mean precipitation drying in mid-latitudes in future scenarios is due to soil moisture-precipitation feedbacks

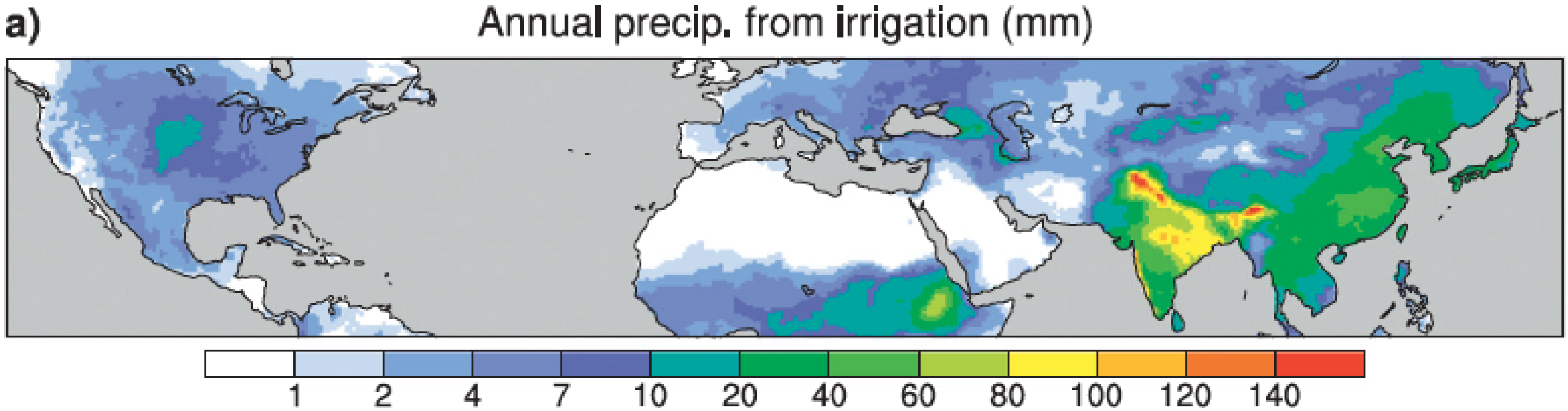
Extreme precipitation: Leads overall to a decrease (counteracts Clausius-Clapeyron effect)

(Seneviratne et al. 2013, GRL)

Land management, irrigation, and precipitation



Impact of irrigation on precipitation



(Wei et al. 2013, JHM; based on ET data from Wisser et al. 2010, HESS)

Precipitation extremes: Summary

Large uncertainties, model dependency of results, but high relevance:

- Evaporation from land possibly major source of moisture for Pakistan floods
- Substantial impacts in future climate (due to land drying: counteracting Clausius-Clapeyron effect)
- Land management effects (e.g. irrigation) are relevant

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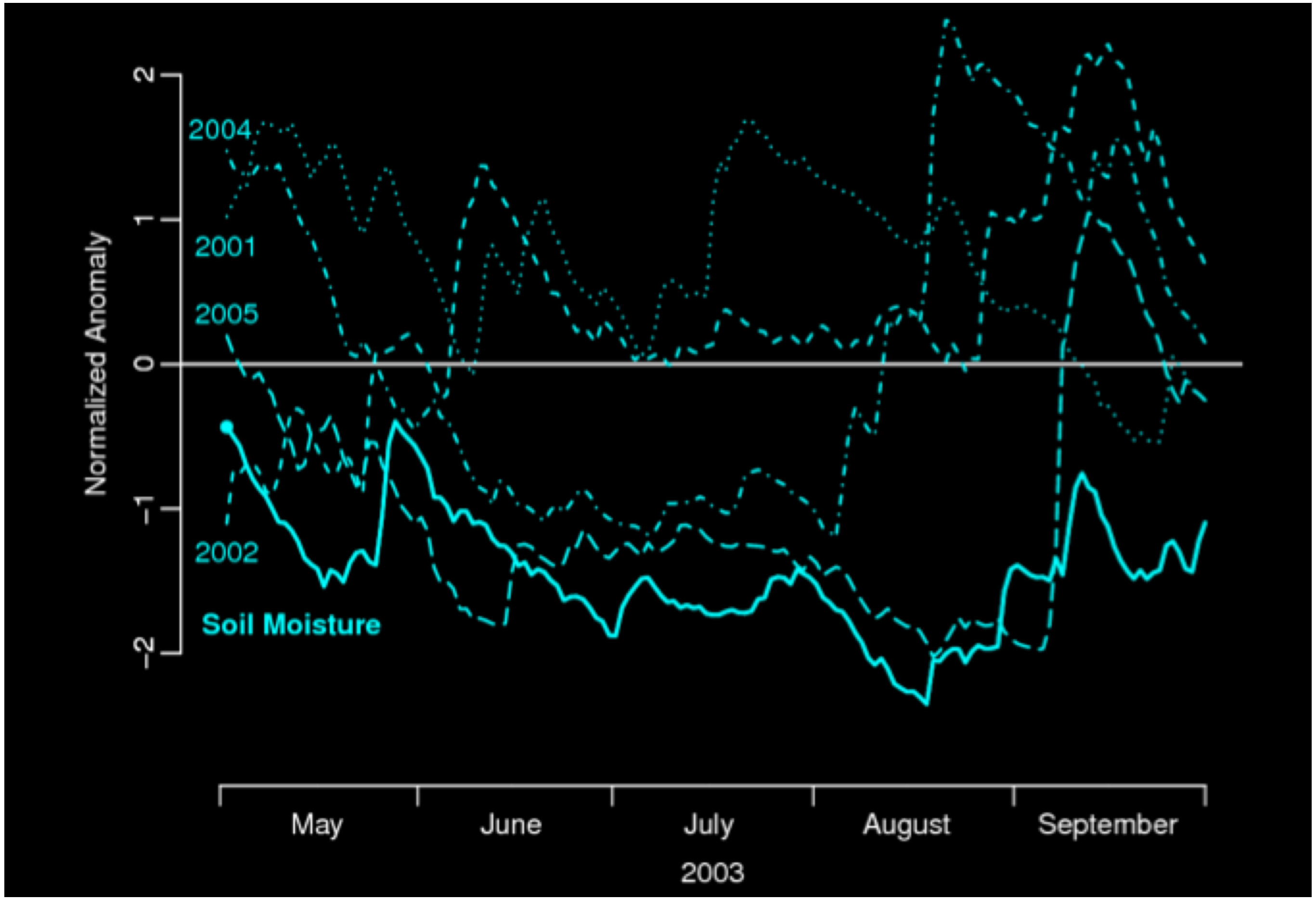
- Land-climate interactions play an important role in controlling extremes (hot extremes, droughts, heavy precipitation)
- Local/regional feedbacks include a range of poorly constrained processes (vegetation physiology, land cover and land use changes)
- The respective contributions of large-scale drivers and regional land feedbacks and forcings need to be considered jointly

Preconditioning: Soil moisture (2003 summer in Europe)

Persistence of soil moisture



(R. Orth, ETH Zurich)