ETH

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Role of land-surface processes for seasonal prediction

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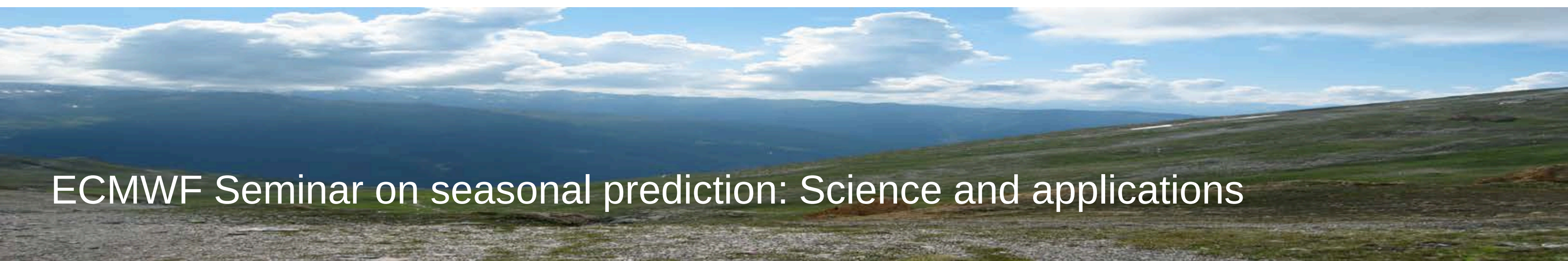
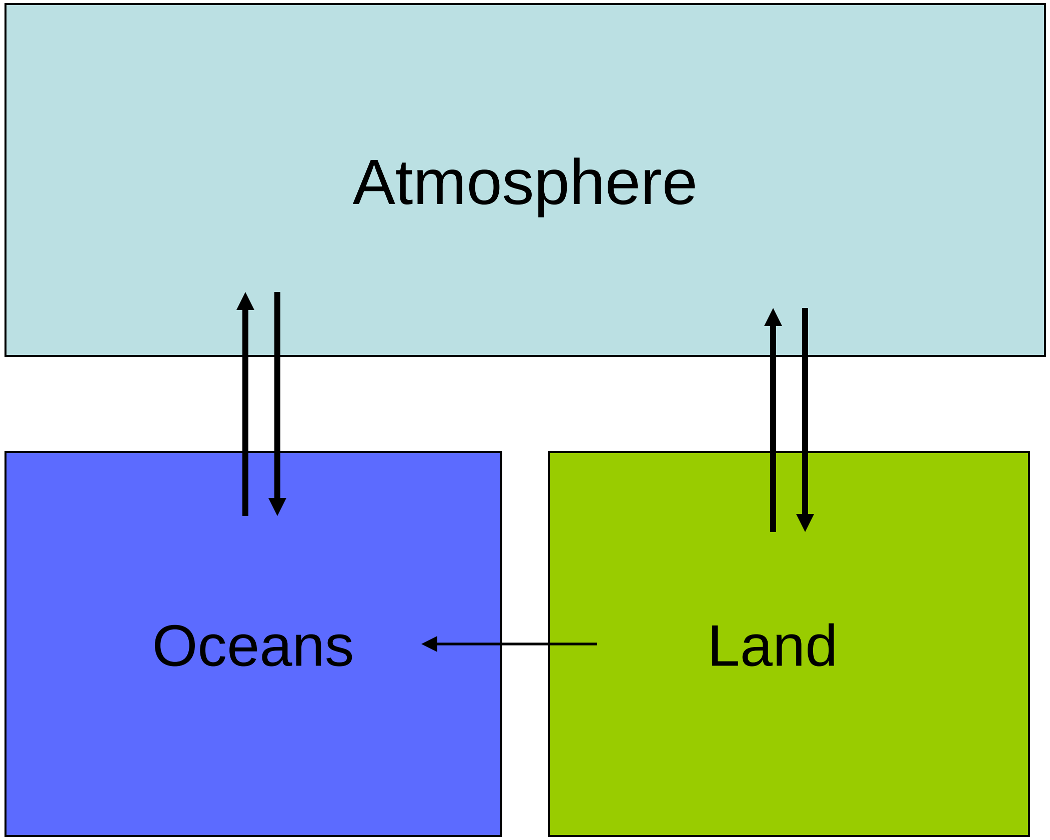
Thanks to: R. Koster, B. Mueller, R. Orth



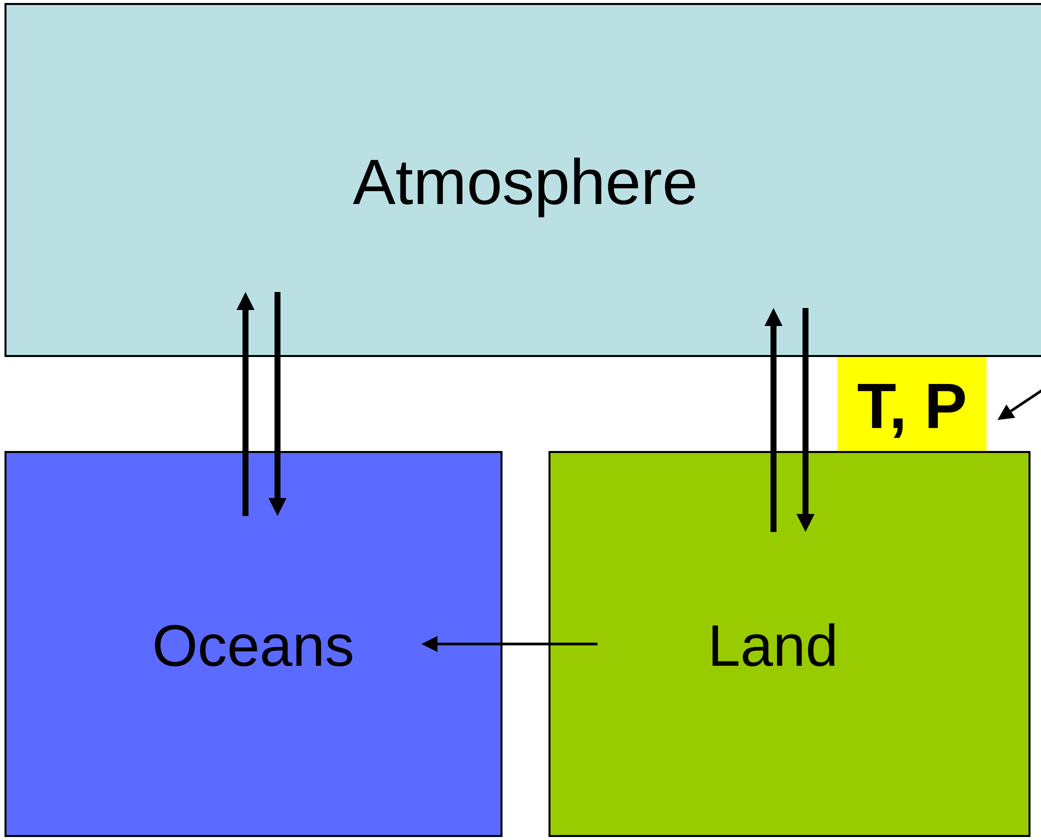
Outline

- Basic relevant land-climate feedbacks and observational evidence
- Diagnosing prediction potential from land surface initialization
  - GLACE-2: Forecasting of atmospheric variables
  - Drought forecasting
- Discussion
- Conclusions

Land in the climate system

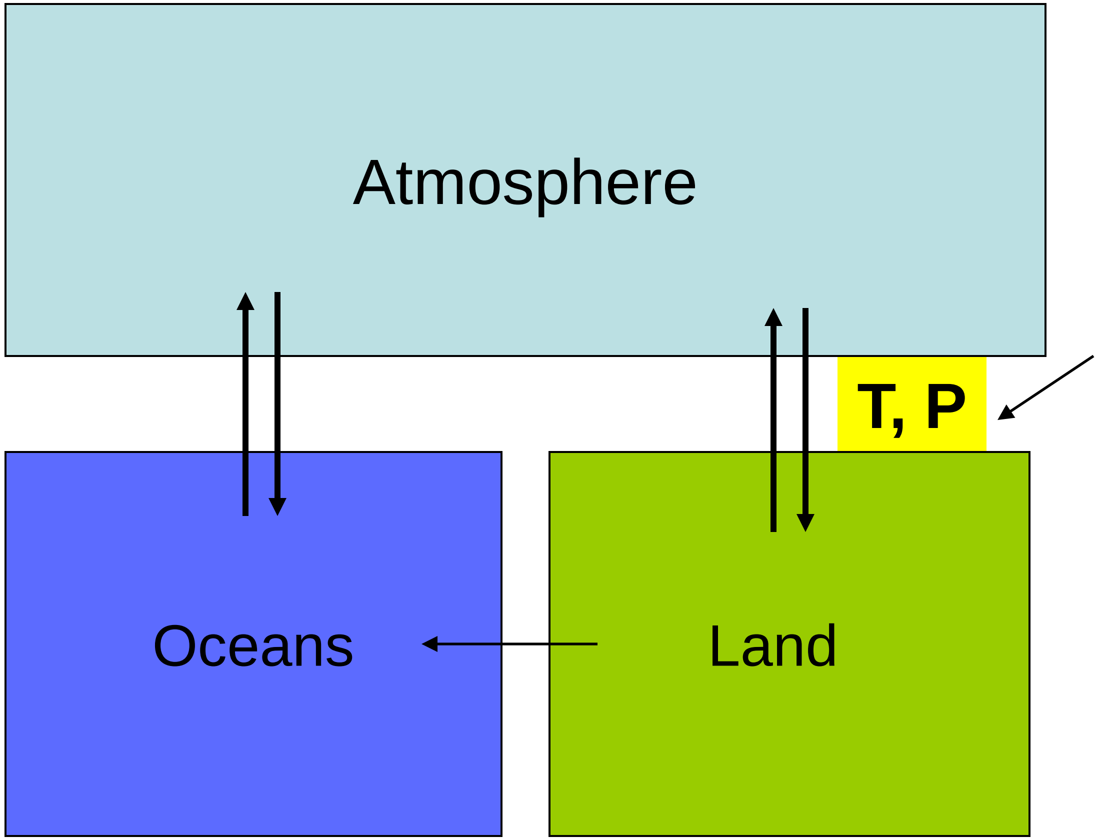


Land in the climate system



We are generally interested in climate over land!

Land in the climate system



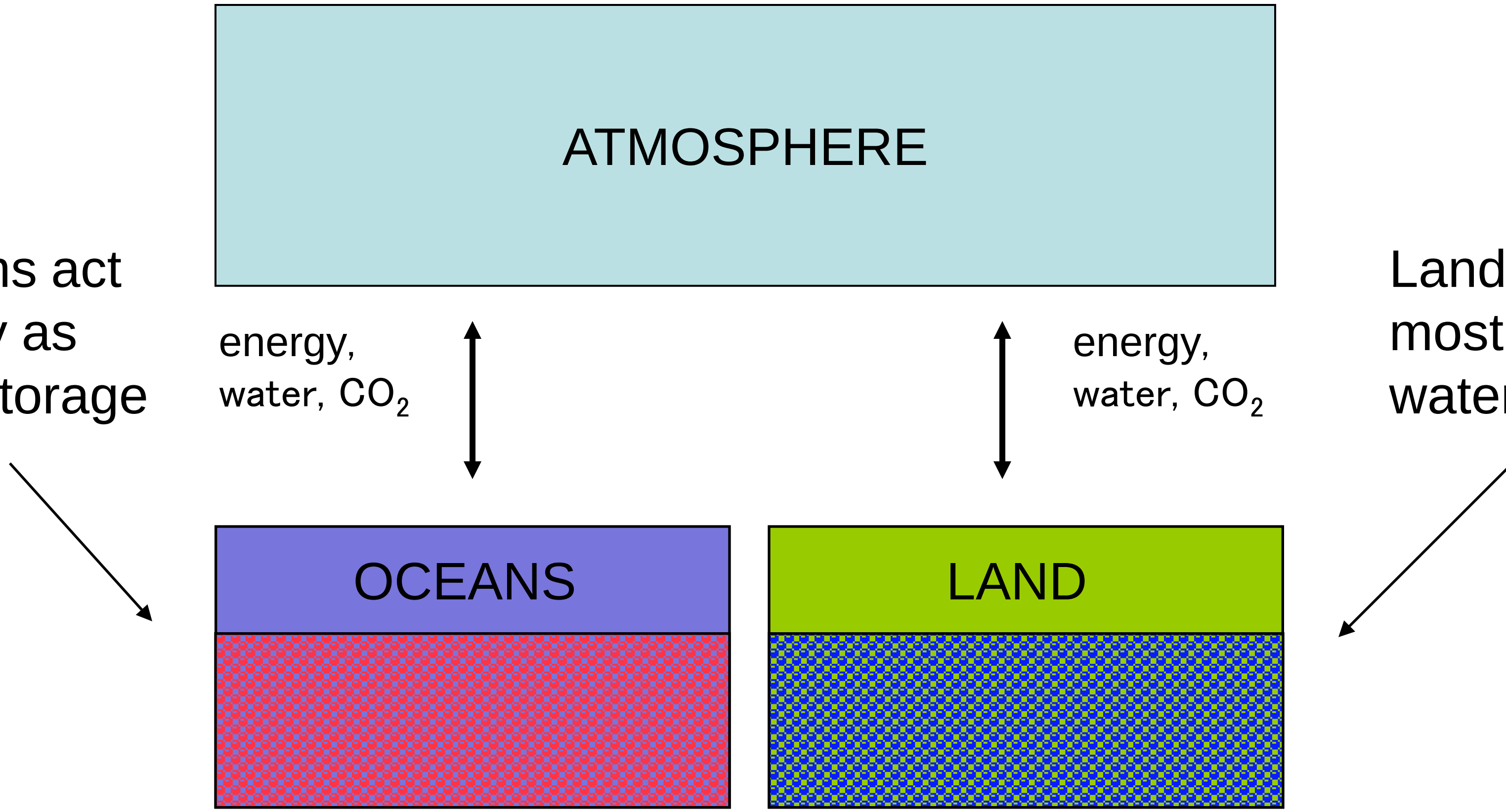
We are generally interested in climate over land!

Land climate is strongly affected by land processes in several regions

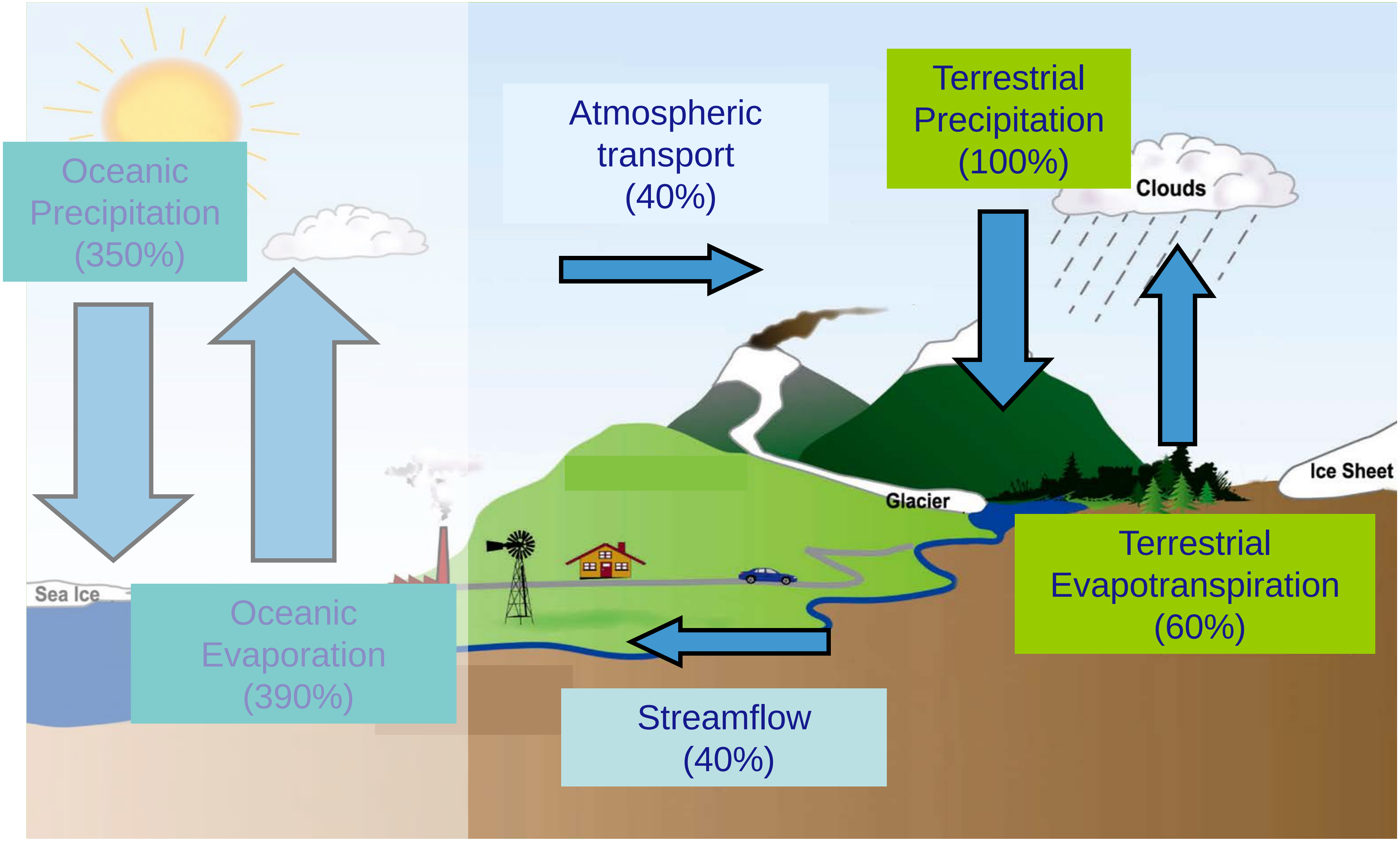
Land water storage vs oceans' heat storage:

Oceans act mostly as heat storage

Land areas act mostly as water storage



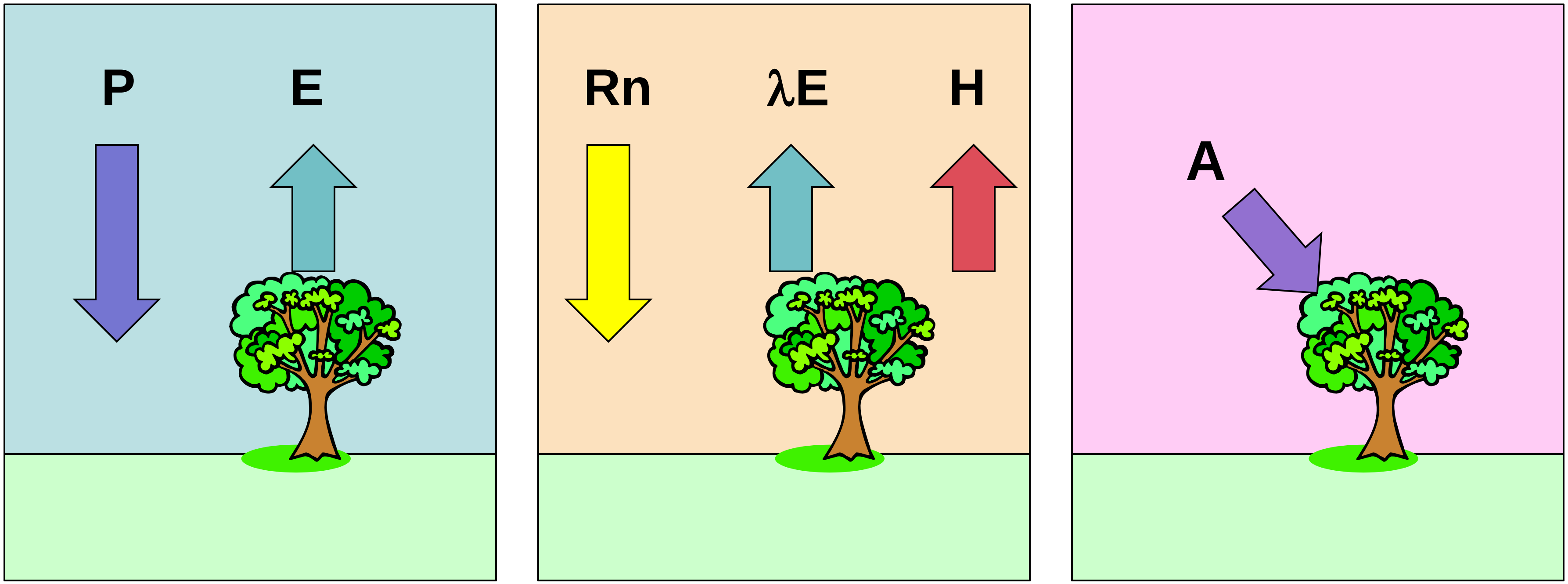
Global water cycle



(Flux estimates: Oki and Kanae, Science 2006)

Land water, energy and carbon balances

Water | **Energy** | **Carbon**



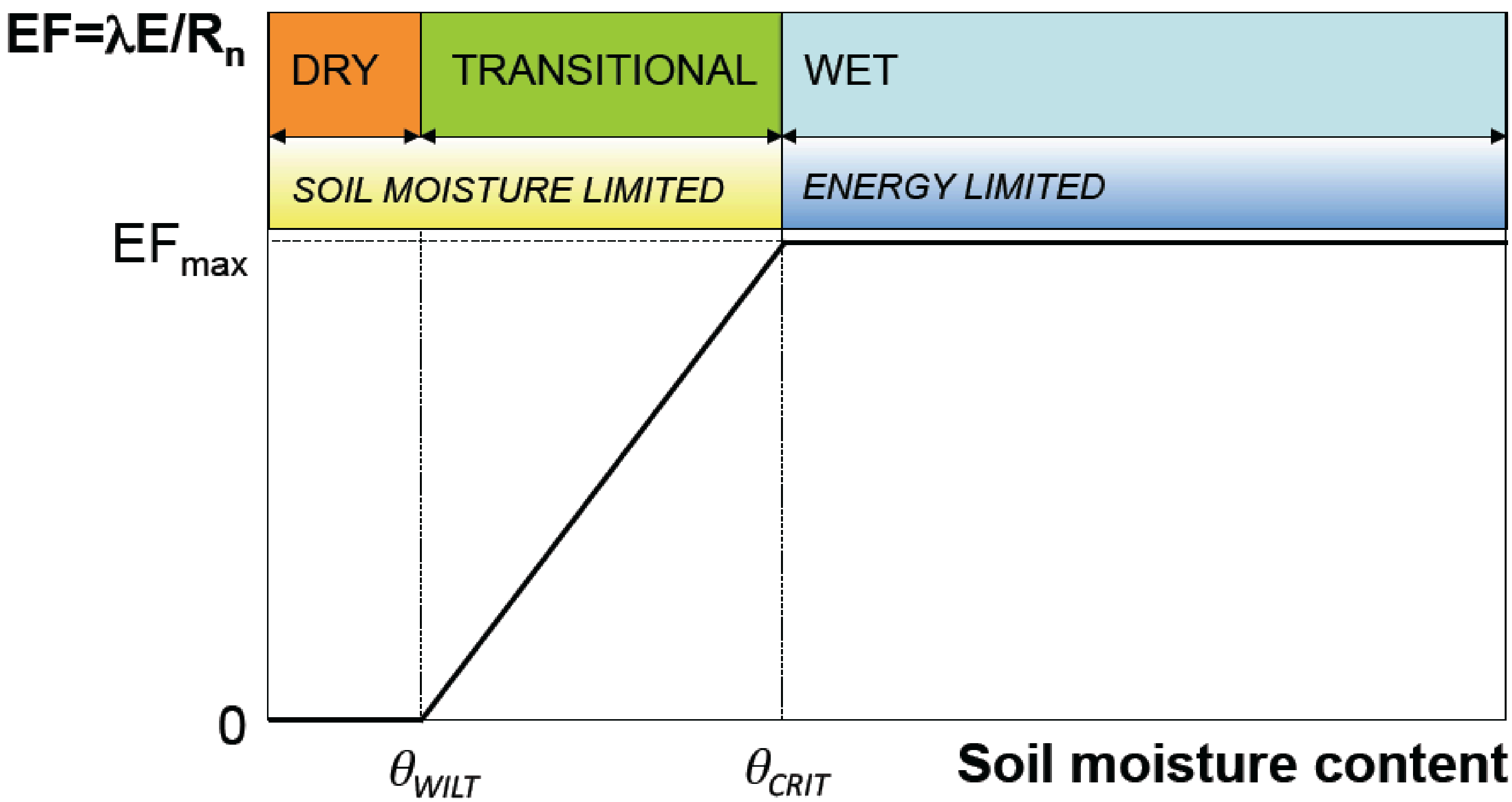
E=60%P

λE=50-60%Rn

A is a sink for 30% of C emissions

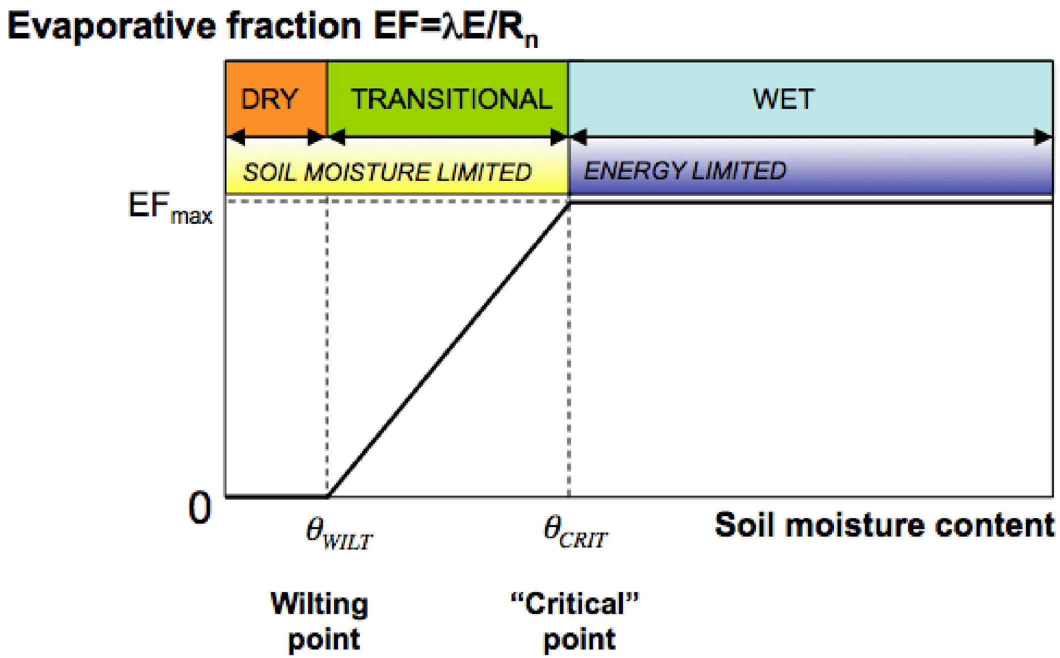
(see also Budyko 1956)

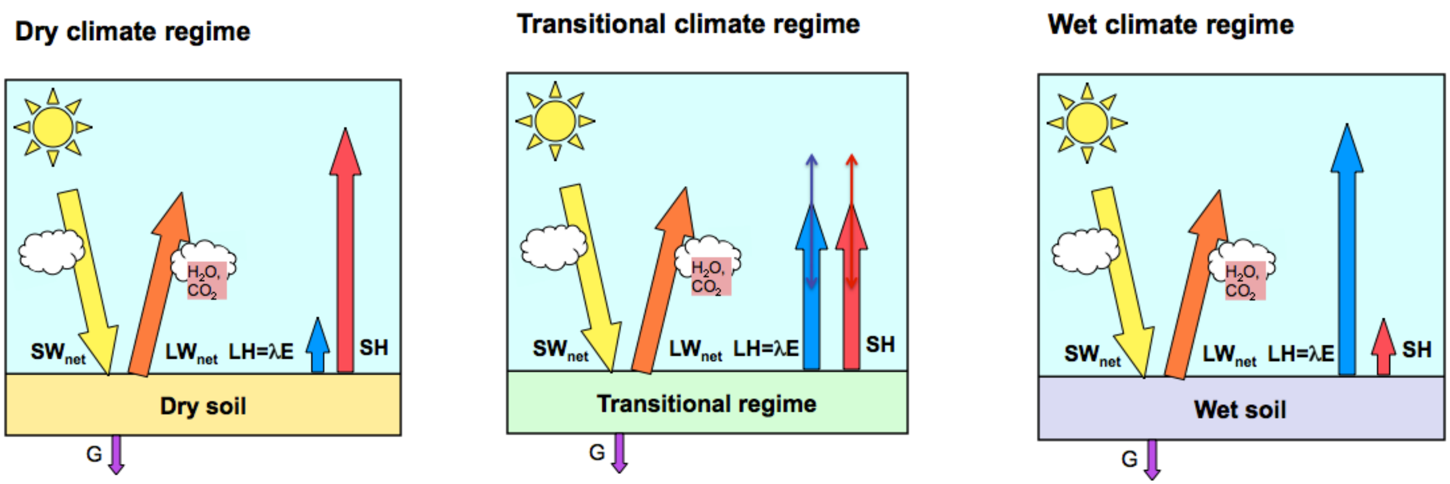
Evaporative fraction



(Seneviratne et al. 2010, Earth-Science Reviews)

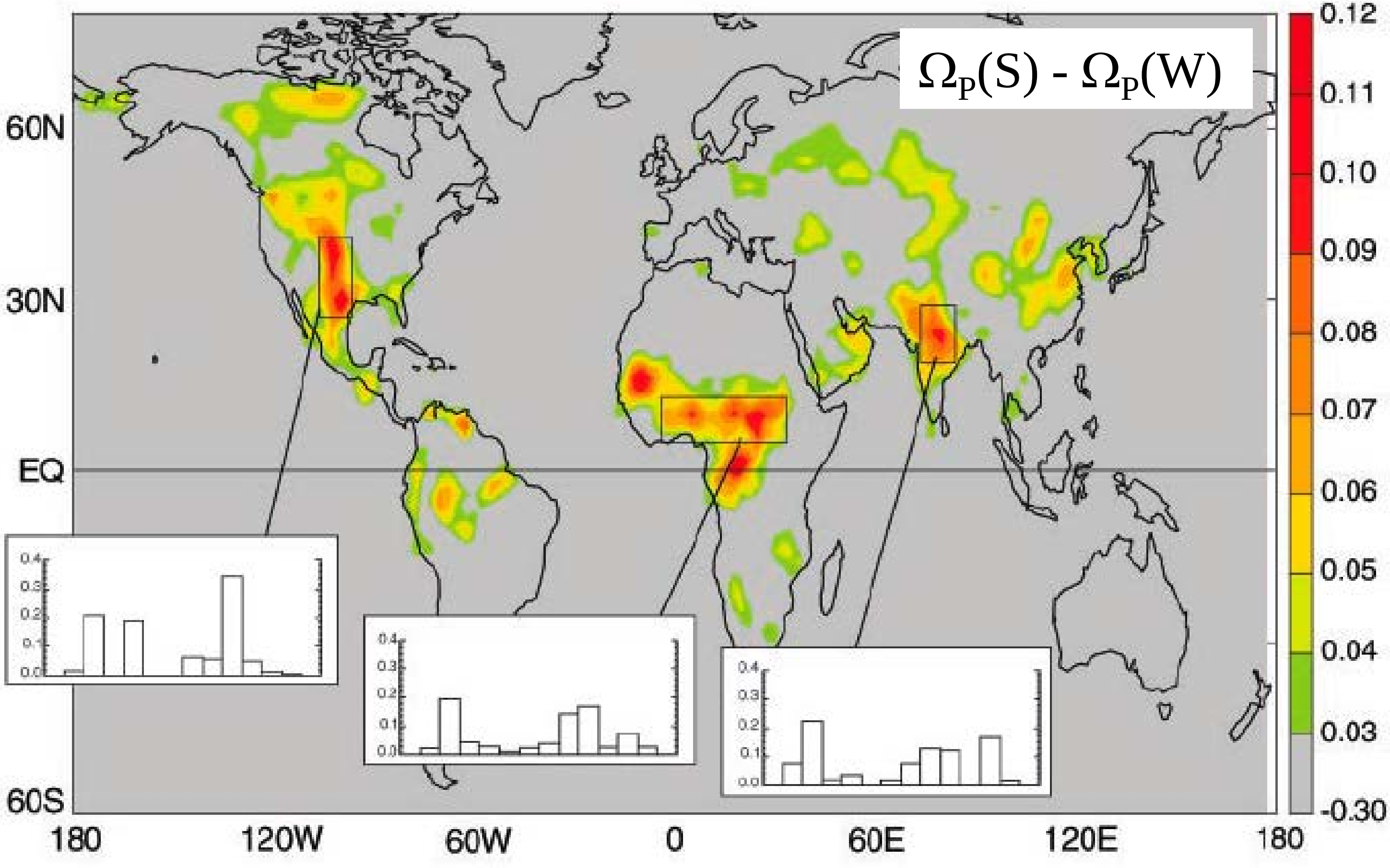
Soil moisture-temperature feedbacks





Global Land-Atmosphere Coupling Experiment (GLACE)

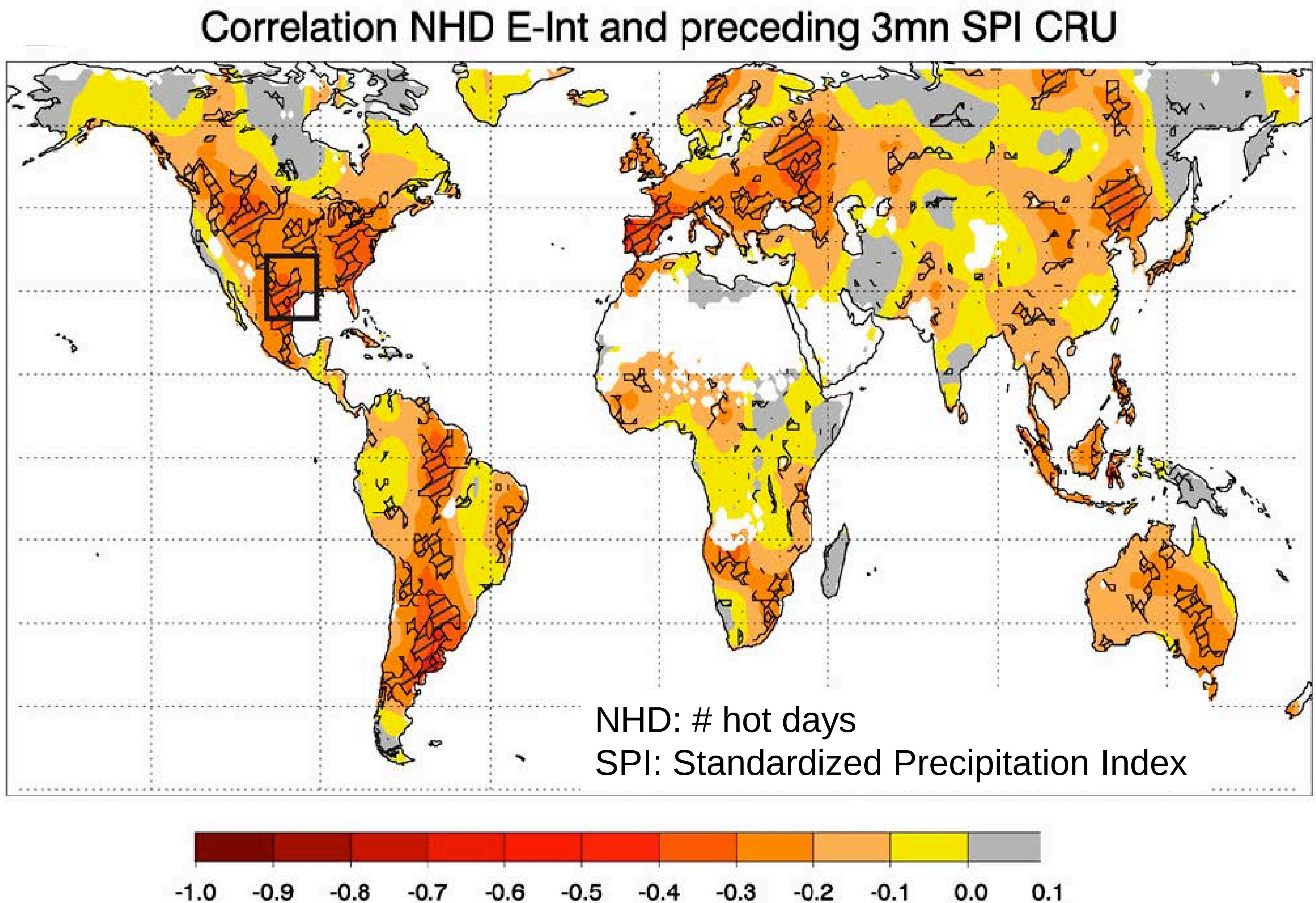
12 AGCMs, experiments for JJA 1994



Strong SM-P coupling in transitional zones between dry and wet climates

(Koster et al. 2004, Science)

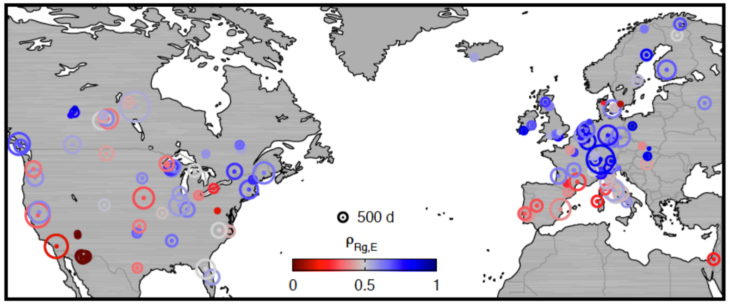
Why soil moisture matters…



(Mueller and Seneviratne 2012, PNAS)

Link of hot spots of coupling to ET regimes

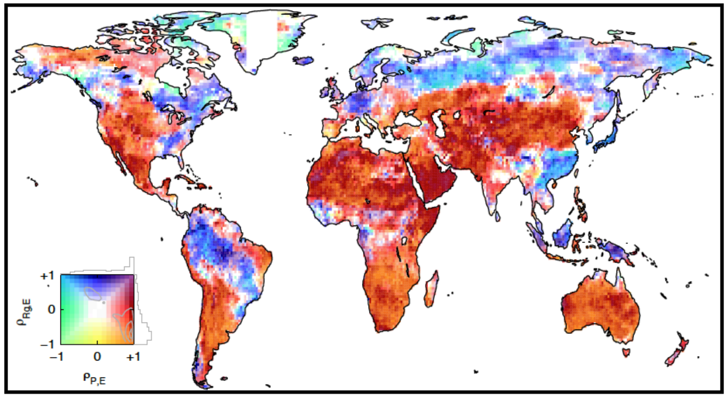
E drivers, FLUXNET dataset



ρ(E, Rg)
- blue: high
- red: small

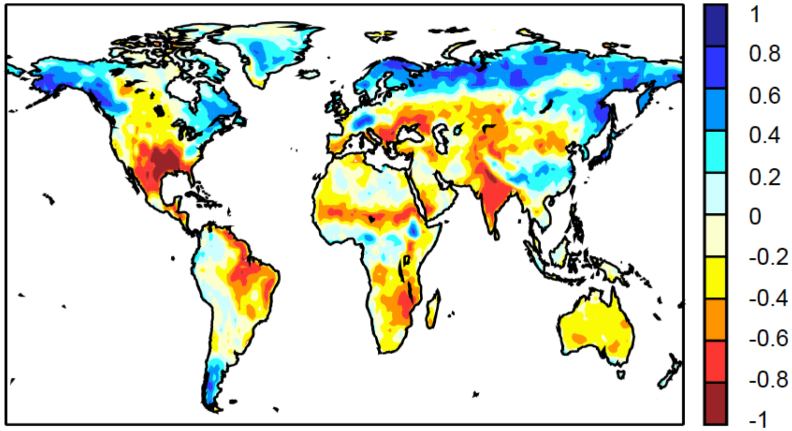
Estimates of ET regimes
Blue: Radiation limited
Red: Soil moisture limited

E drivers, GSWP dataset



ρ(E, Rg) & ρ(E, P)
- blue: high ρ(E,Rg), small ρ(E,P)
- red: small ρ(E,Rg), high ρ(E,P)

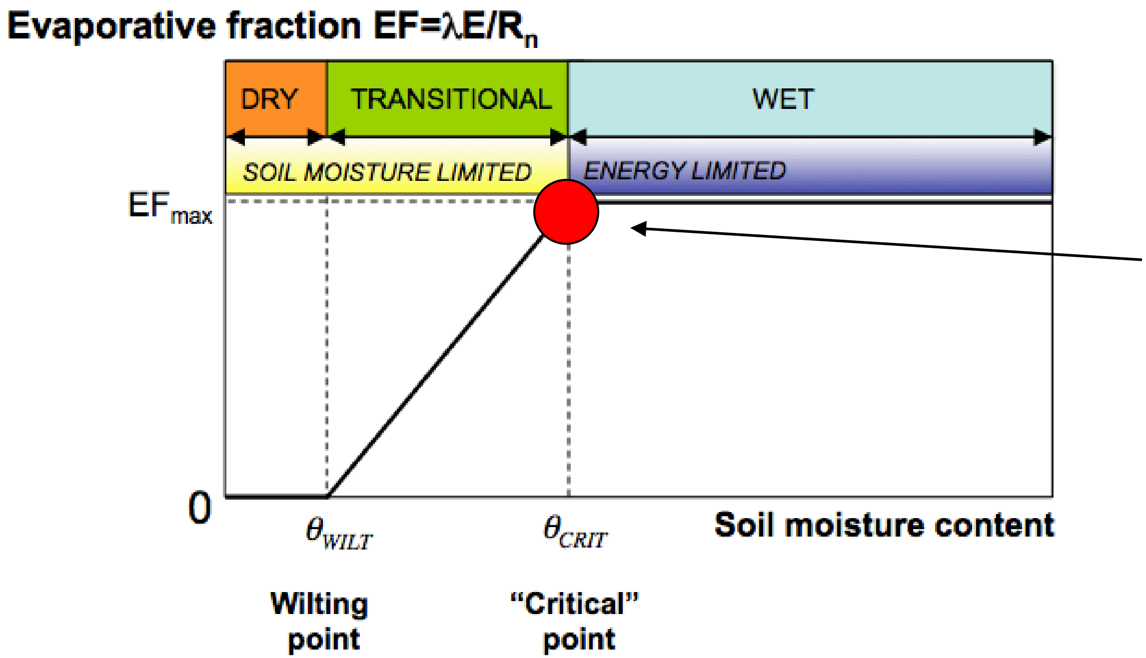
ρ(E,T), IPCC AR4, 1970-1989



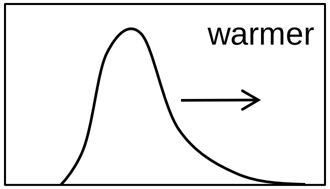
ρ(E, T)
- blue: positive ρ(E,T)
- red: negative ρ(E,T)

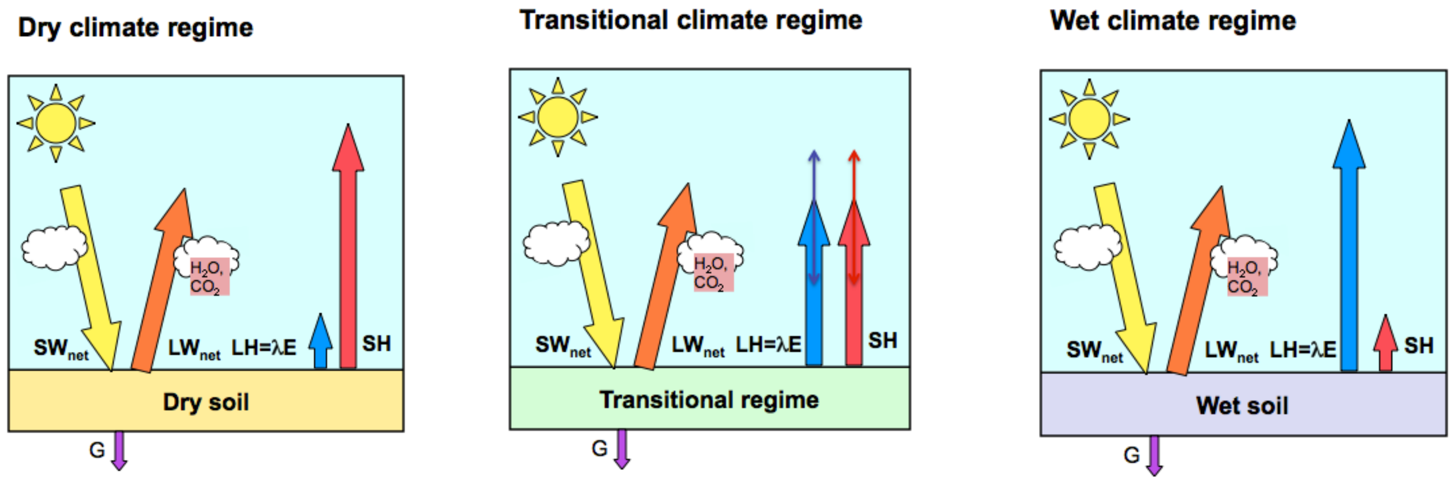
(Seneviratne et al. 2006, Nature; Teuling et al. 2009, GRL; Seneviratne et al. 2010, ESR)

Soil moisture-temperature feedbacks: Extreme events



Discrete threshold implies non-linear effect & relevance for extreme events

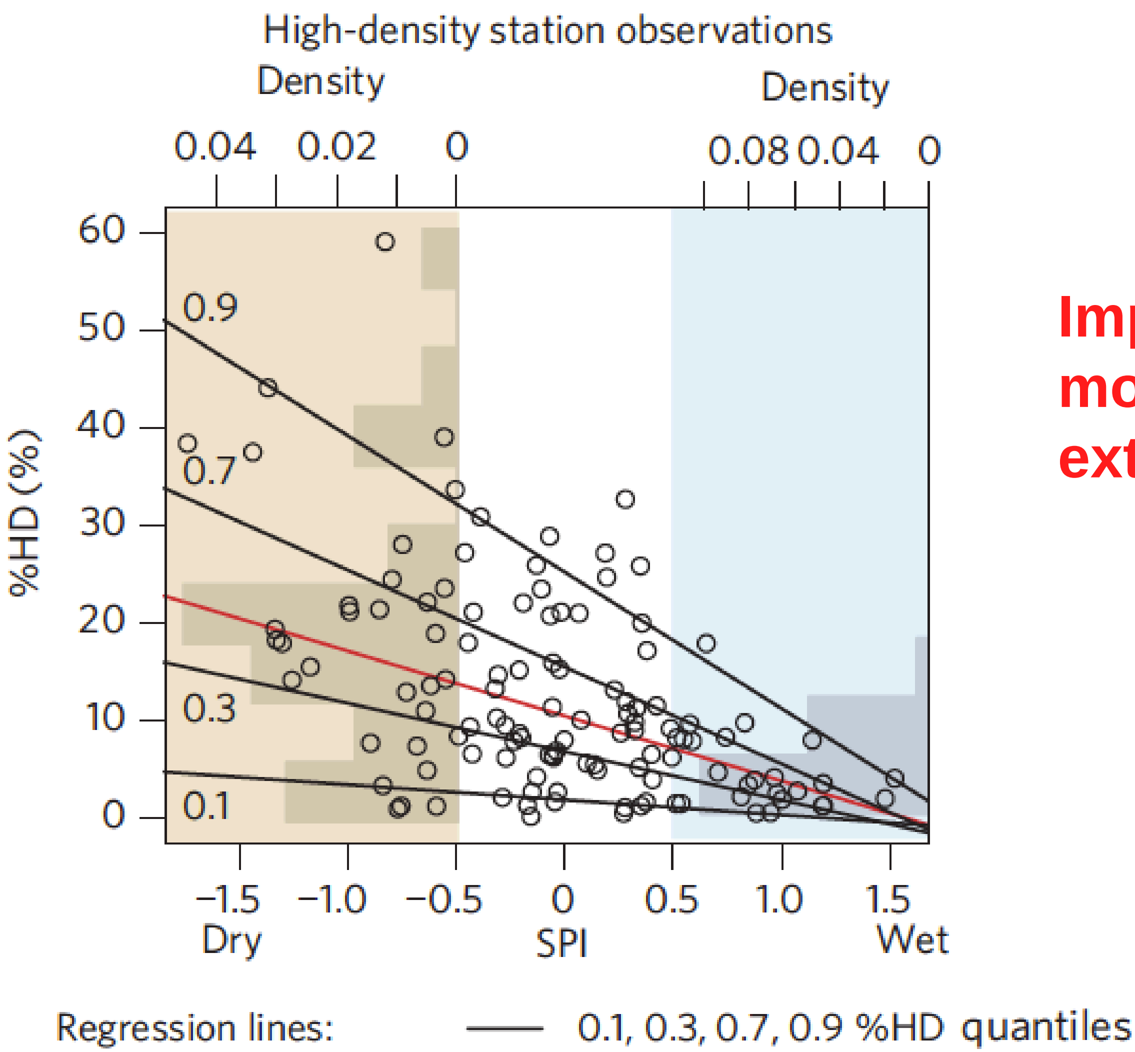




Soil moisture-temperature feedbacks: Extreme events

Analysis for Southeastern Europe

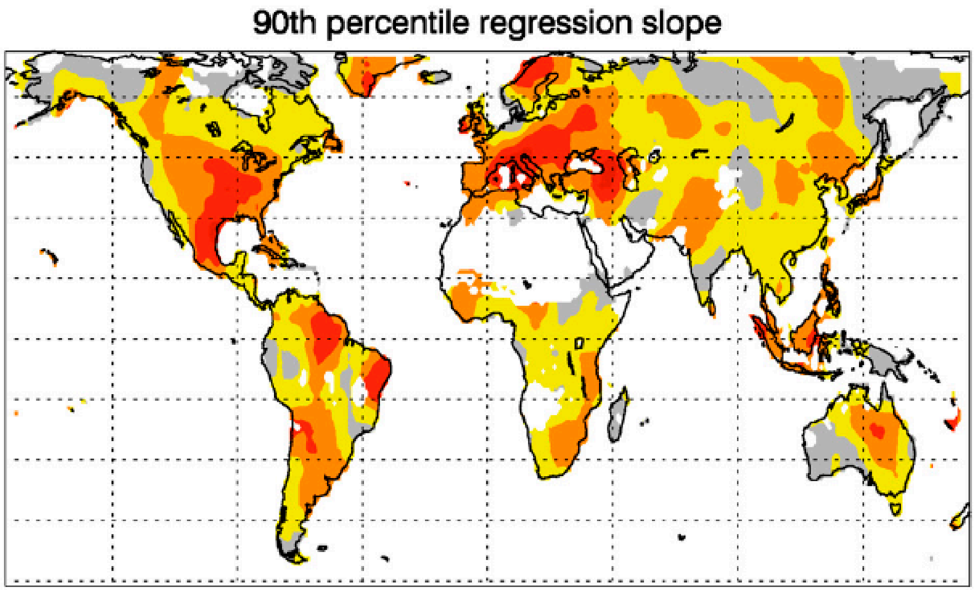
Quantile regression of %HD with 6-month SPI

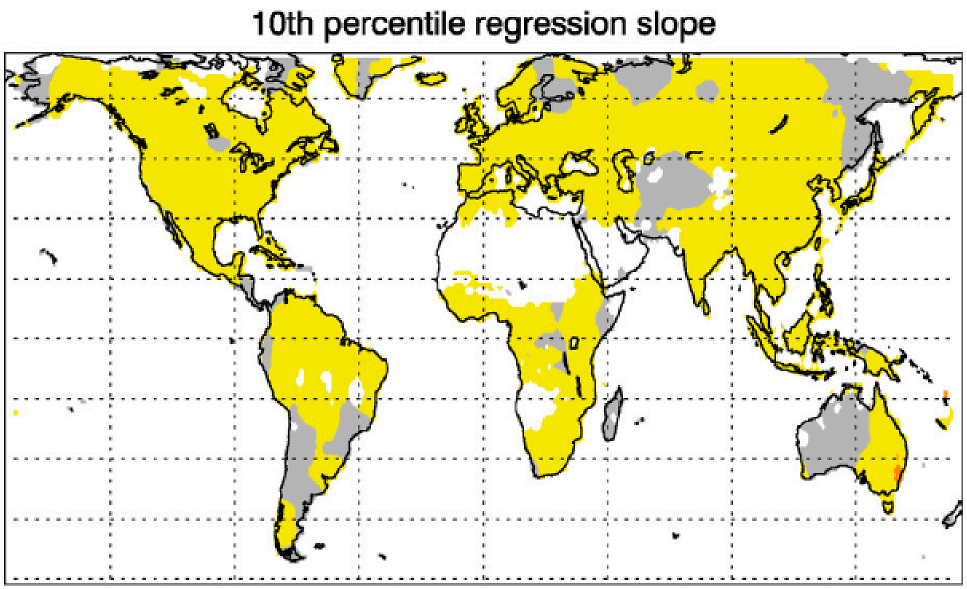


Impact of soil moisture on hot extremes

(Hirschi et al. 2011, Nature Geoscience)

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

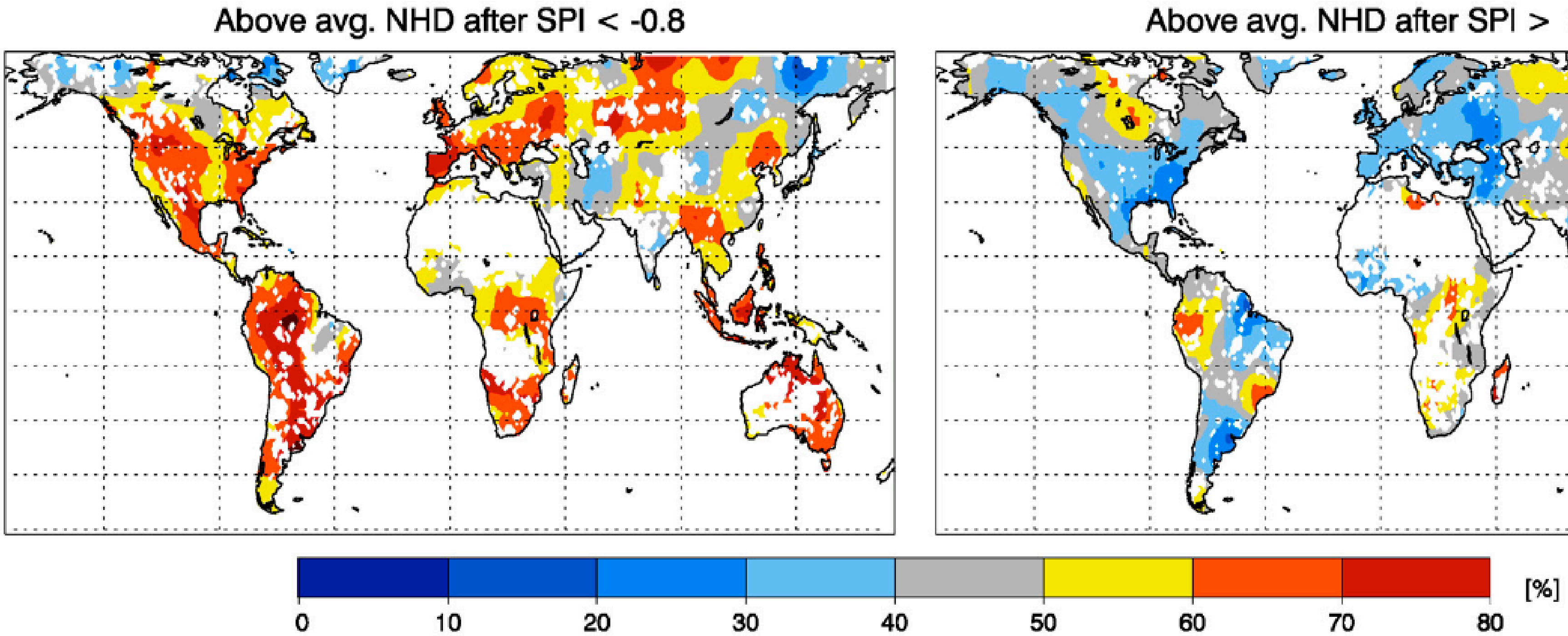




NHD: # hot days
SPI: Standardized Precipitation Index

(Mueller and Seneviratne 2012, PNAS)

Link to forecasting: conditional probability



NHD: # hot days
SPI: Standardized Precipitation Index

(Mueller and Seneviratne 2012, PNAS)

Observational evidence: Key points

- Soil moisture affects evapotranspiration in transitional climate regions, thereby leading to impacts on temperature and precipitation
- Temperature: Widespread impacts, in particular for extreme events
- Soil moisture is a storage: ➔ associated memory and forecasting potential

Outline

- Basic relevant land-climate feedbacks and observational evidence
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GLACE-2: An international project aimed at quantifying soil moisture impacts on prediction skill.

Overall goal of GLACE-2: Determine the degree to which realistic land surface (soil moisture) initialization contributes to forecast skill (rainfall, temperature) at 1-2 month leads, using a wide array of state-of-the-art forecast systems.

(Koster et al. 2010, GRL; Koster et al. 2011, JHM)

GLACE-2: Experiment overview

Series 1

Initialize land states with "observations", using GSWP approach

Initialize atmosphere with "observations", via reanalysis

Perform ensembles of retrospective seasonal forecasts

Prescribed, observed SSTs or the use of a coupled ocean model

Evaluate P, T forecasts against observations

GLACE-2: Experiment overview

Series 2

“Randomize” land initialization!

…s”, using … approach

…itialize atmosphere with “observations”, via reanalysis

Perform ensembles of retrospective seasonal forecasts

Evaluate P, T forecasts against observations

Prescribed, observed SSTs or the use of a coupled ocean model

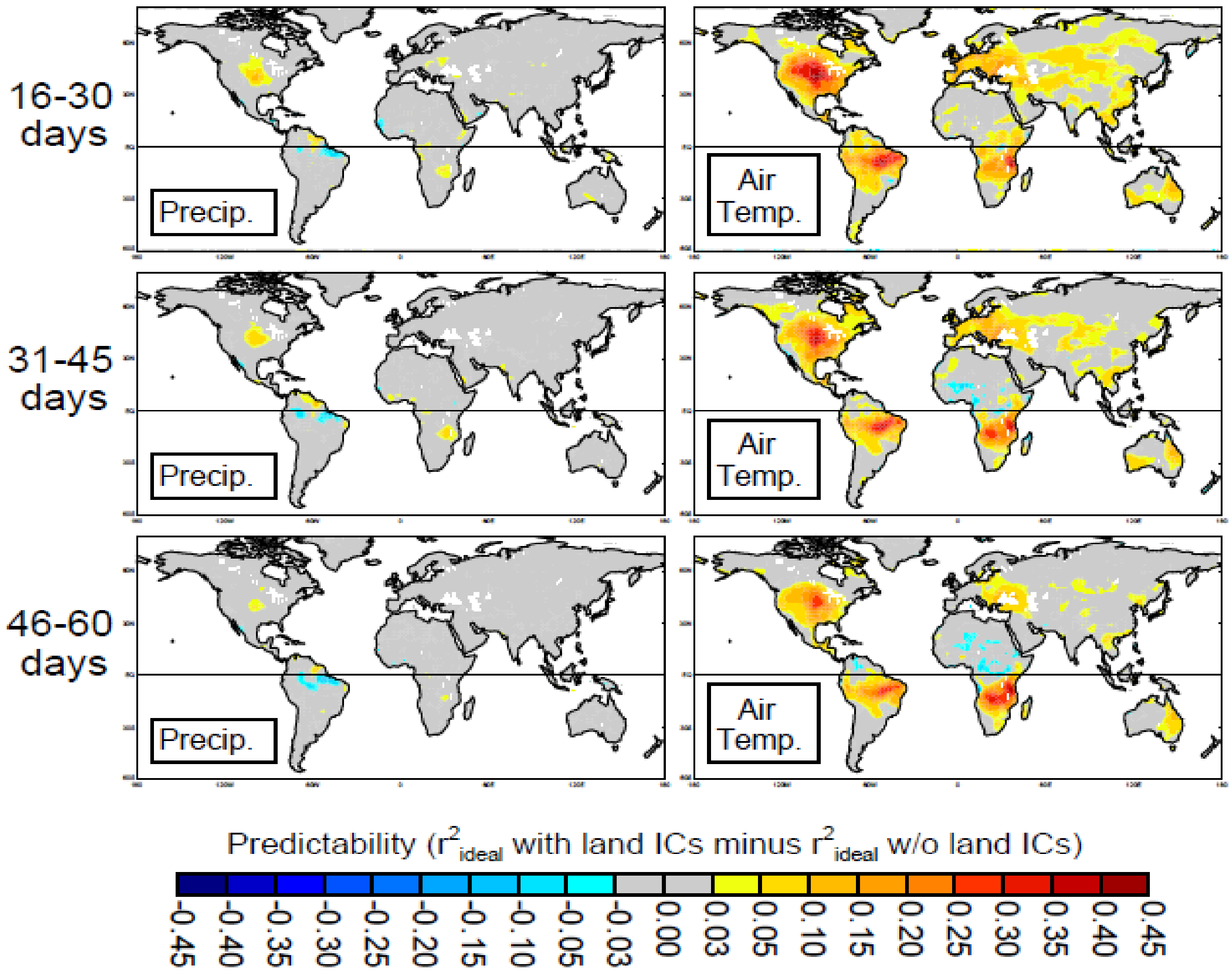
GLACE-2: Experiment overview

Step 3: Compare skill in two sets of forecasts; isolate contribution of realistic land initialization

Forecast skill, Series 1 − Forecast skill, Series 2 = Forecast skill due to land initialization

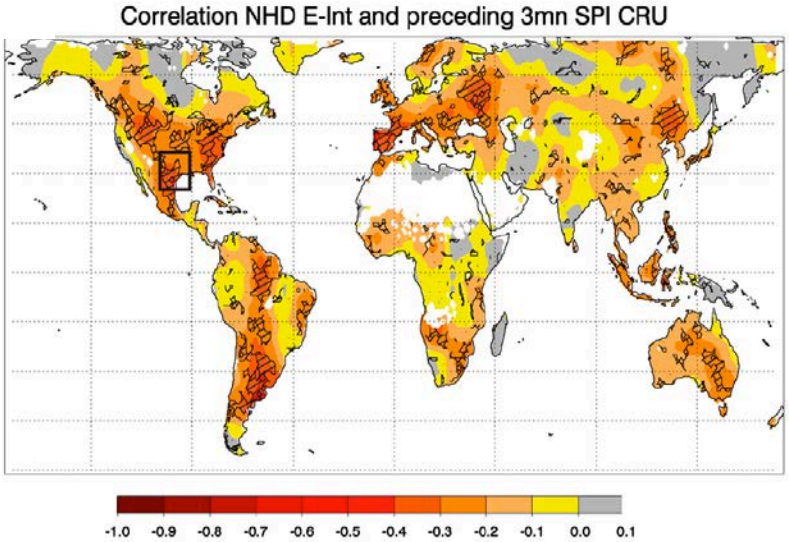
13 participating modeling systems

Global analysis: “Ideal” predictability

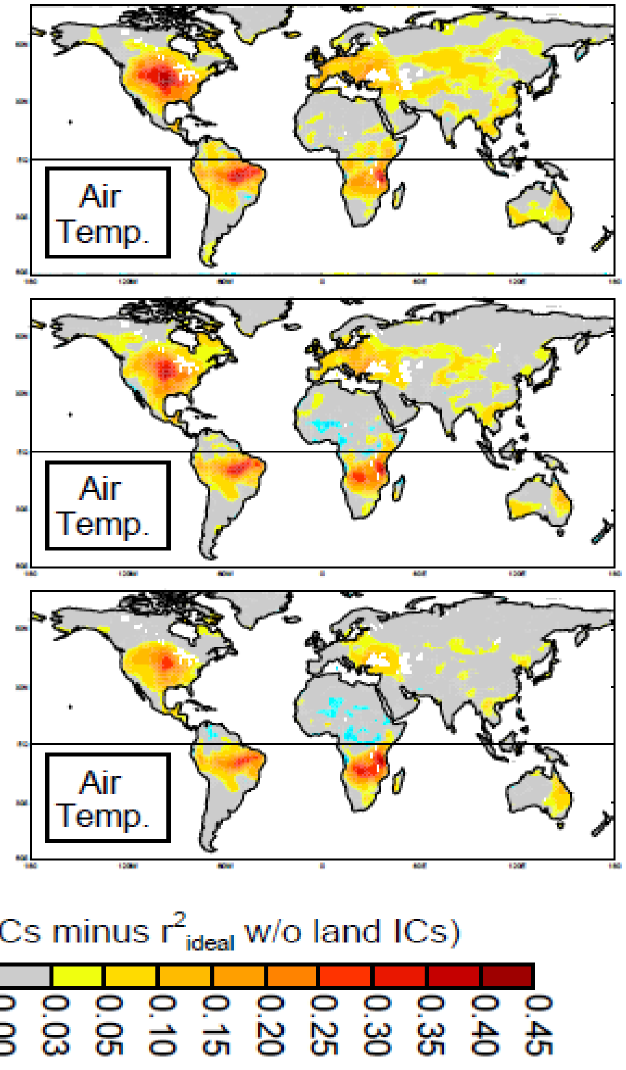


(Koster et al. 2011, JHM)

Global analysis: "Ideal" predictability

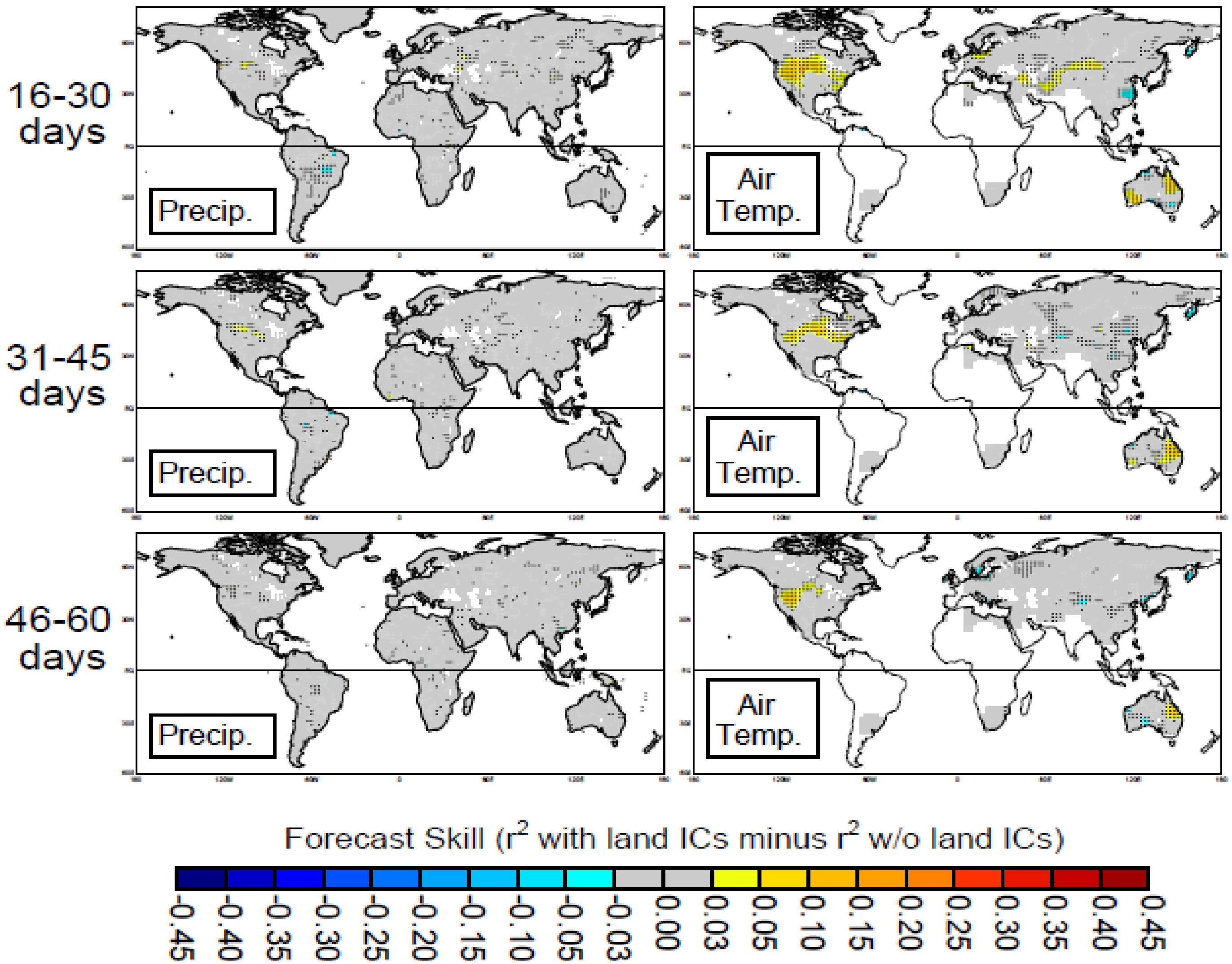


(Mueller and Seneviratne 2012, PNAS)



(Koster et al. 2011, JHM)

Global analysis: Actual skill



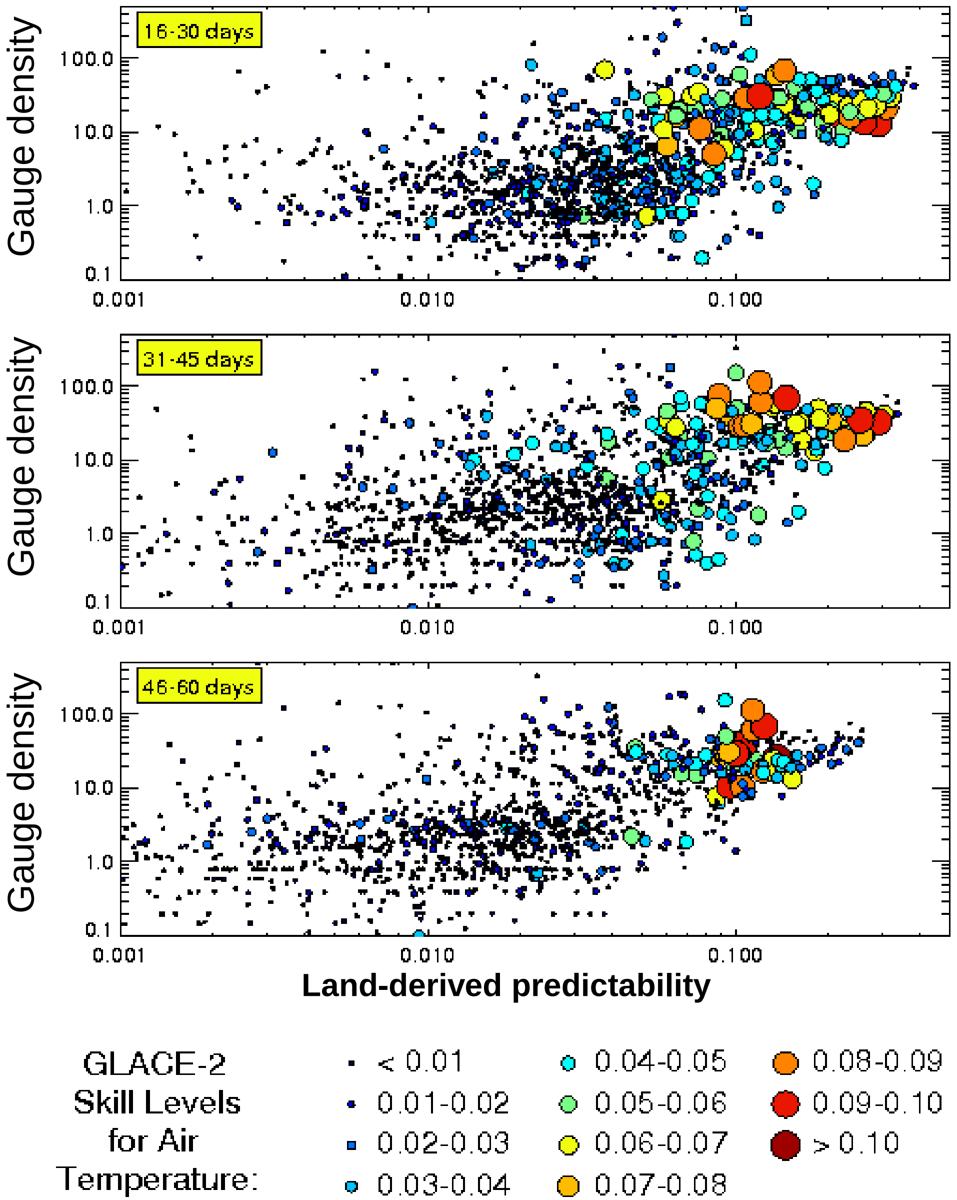
(Koster et al. 2011, JHM)

Global analysis

Forecast skill levels are highest in regions with both:

a) some inherent model “predictability”, and

b) an adequate observational network for accurate initialization



(Koster et al. 2011, JHM)

Temperature forecasts: Increase in skill (JJA)

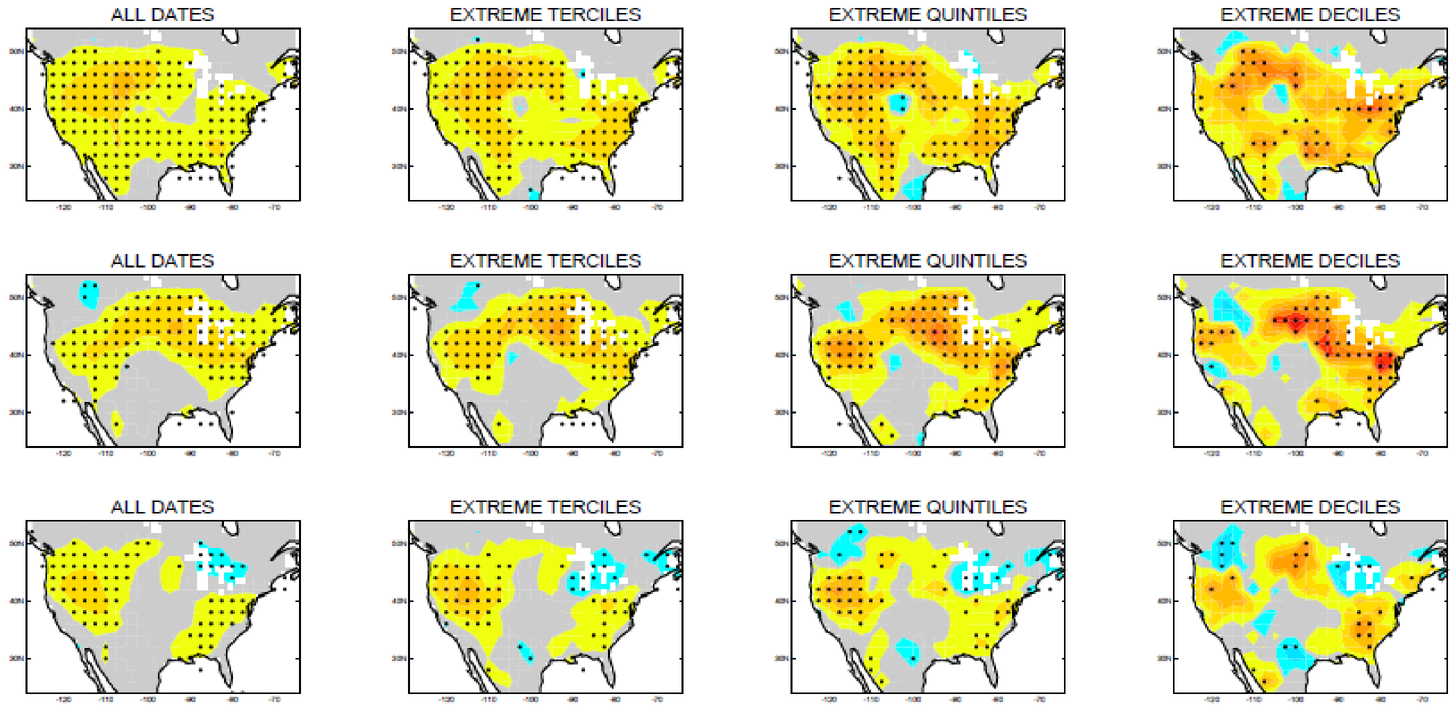
(conditioned on strength of local initial soil moisture anomaly)

all points | Extreme terciles | Extreme quintiles | Extreme deciles

16-30 days

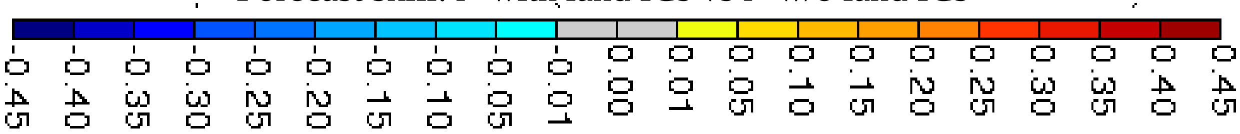
31-45 days

46-60 days



Dates for conditioning vary w/location

Forecast skill: r^2 with land ICs vs r^2 w/o land ICs



(Koster et al. 2010, GRL)

Precipitation forecasts: Increase in skill (JJA)

(conditioned on strength of local initial soil moisture anomaly)

	all points	Extreme terciles	Extreme quintiles	Extreme deciles
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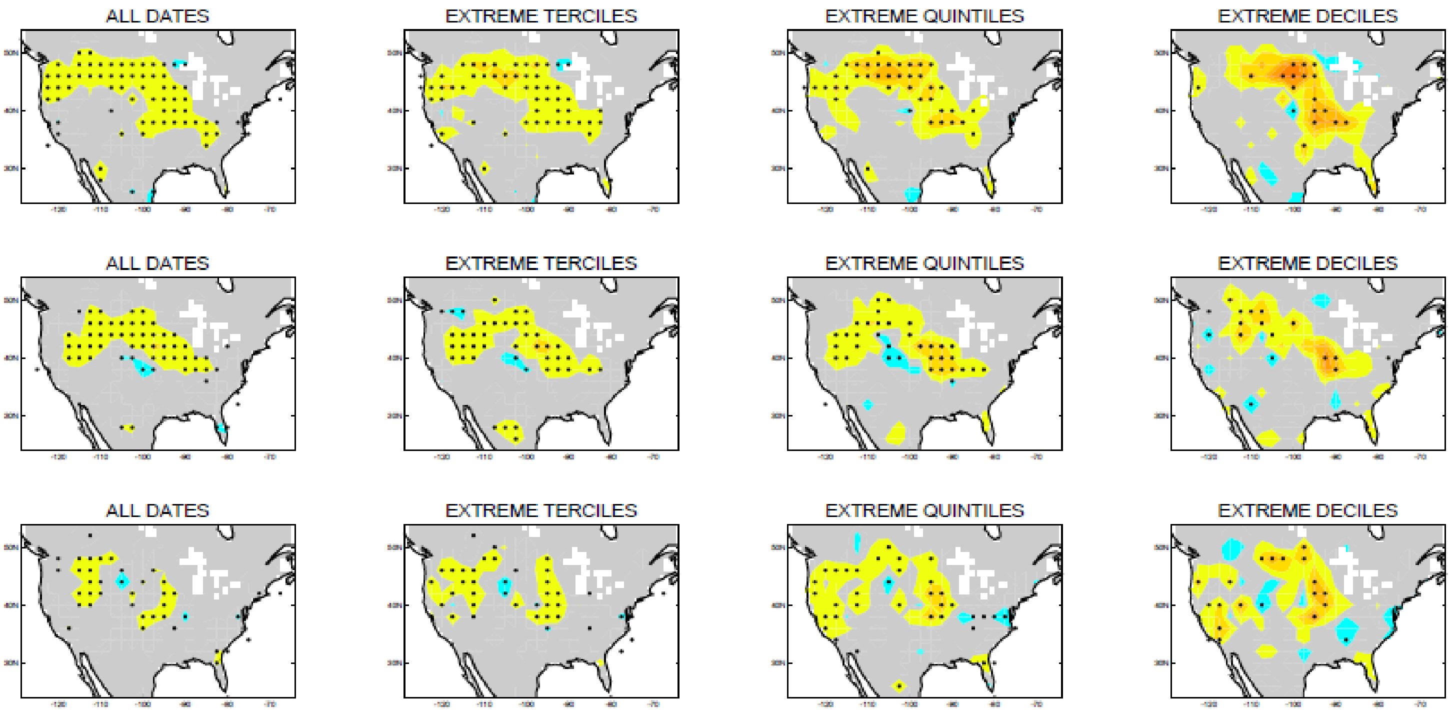
31-45 days				
46-60 days				



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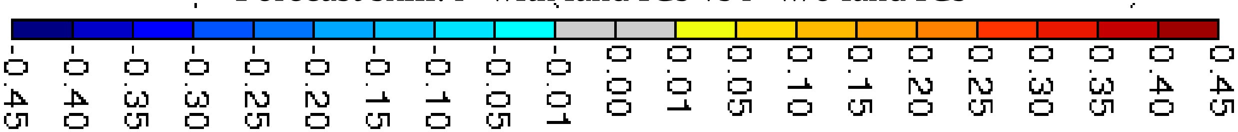


(Koster et al. 2010, GRL)

GLACE-2: Key messages

- Moderate skill for temperature and precipitation (in some regions) **up to 2 months** → source of skill in mid-latitude regions where ocean teleconnections play a rather minor role!

- Highest potential for **temperature** and for **extreme conditions**

- **Ideal skill much higher than actual skill:**
  - Issue with quality of initial data: poor coverage in most regions
  - Models overestimate skill?
  - Interestingly, observational data (for extremes) suggests similar map as ideal skill: Problem in translation of information?

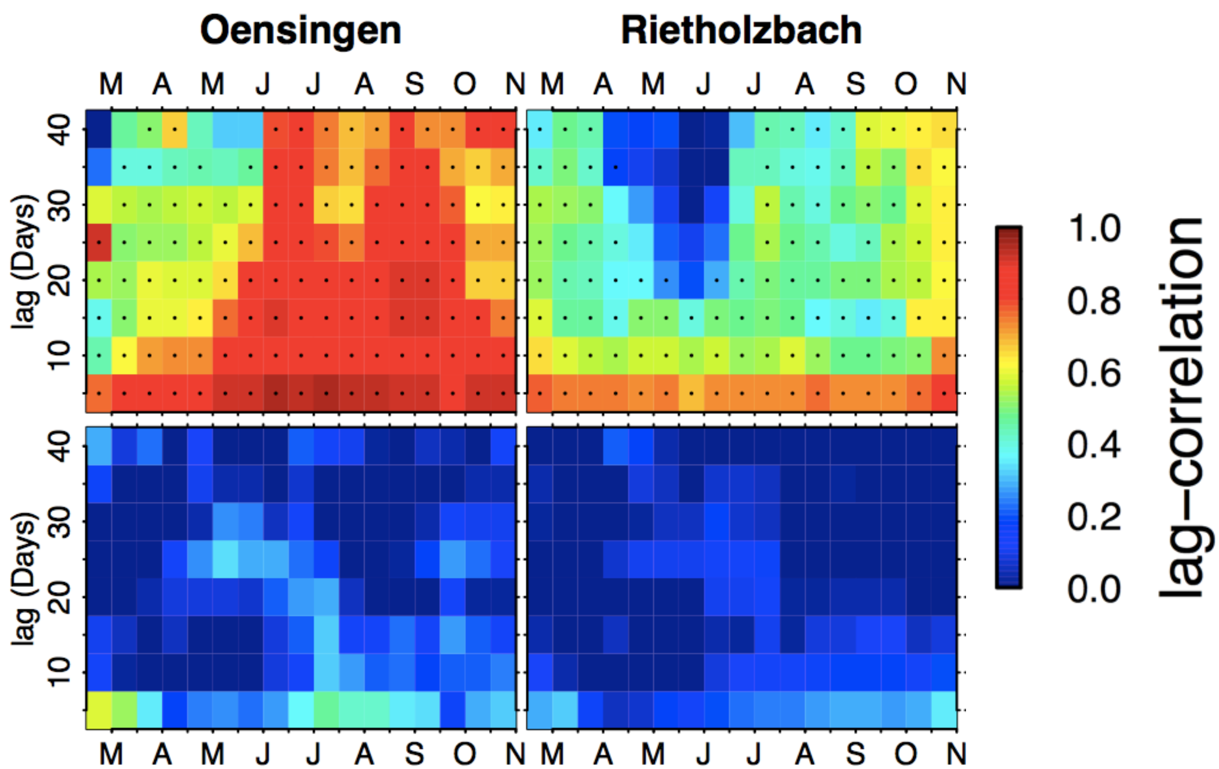
- Area of current research development: **Suggests substantial potential that could be tapped in operational applications**

Drought early warning and forecasting

- Soil moisture is characterized by long persistence
- This implies high potential for improved **early warning and subseasonal forecasting of drought based on land surface information alone** (from several weeks to several months)

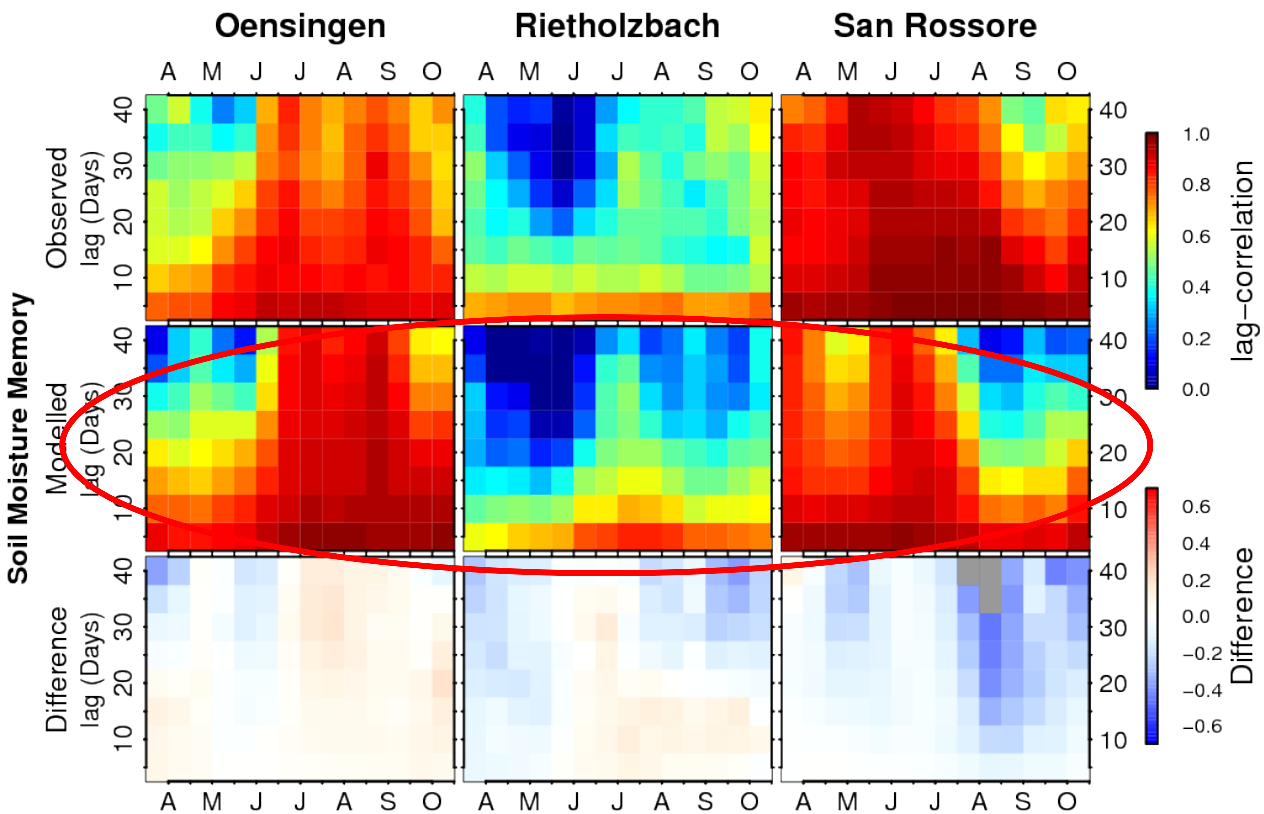
Soil moisture persistence (“memory”)

Temperature persistence



(Orth and Seneviratne 2012, JGR)

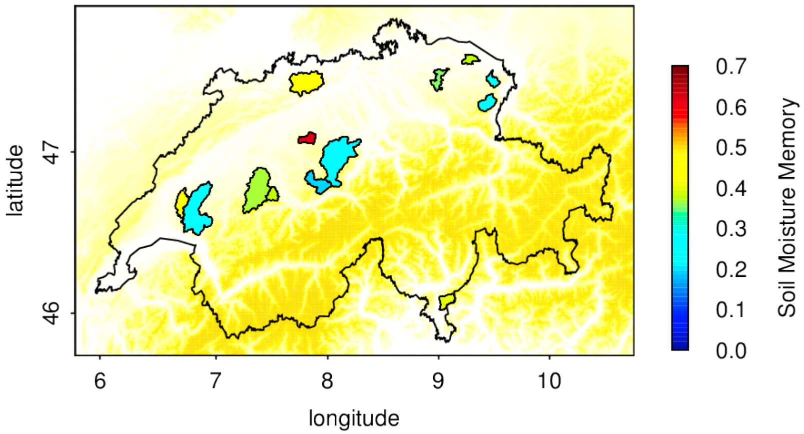
Drought early warning and forecasting

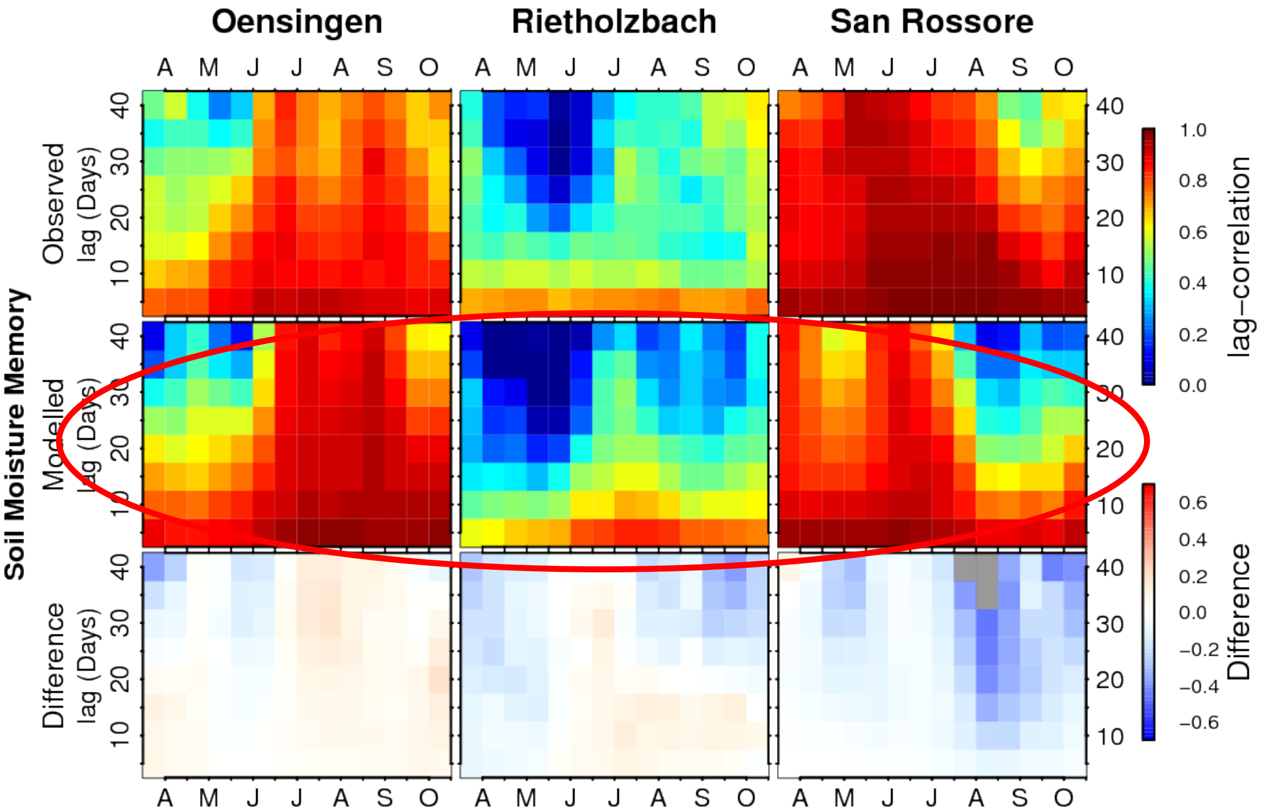


Good approximation of memory using simple water-balance model only calibrated with runoff observations (no soil moisture and ET information)

(Orth et al. submitted, JHM)

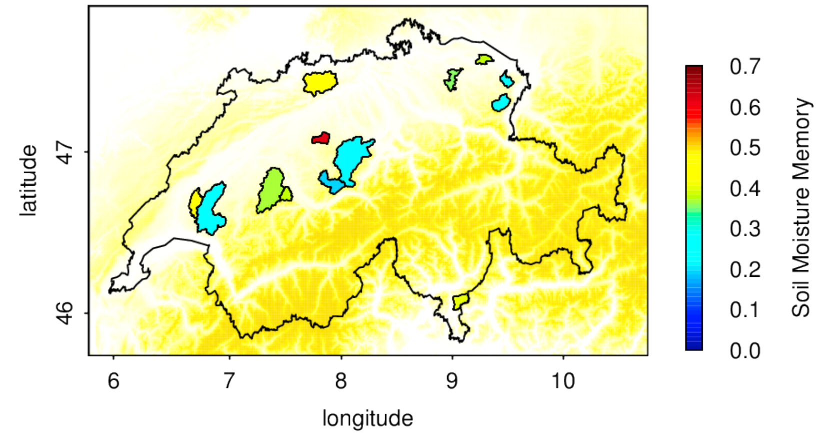
Drought early warning and forecasting

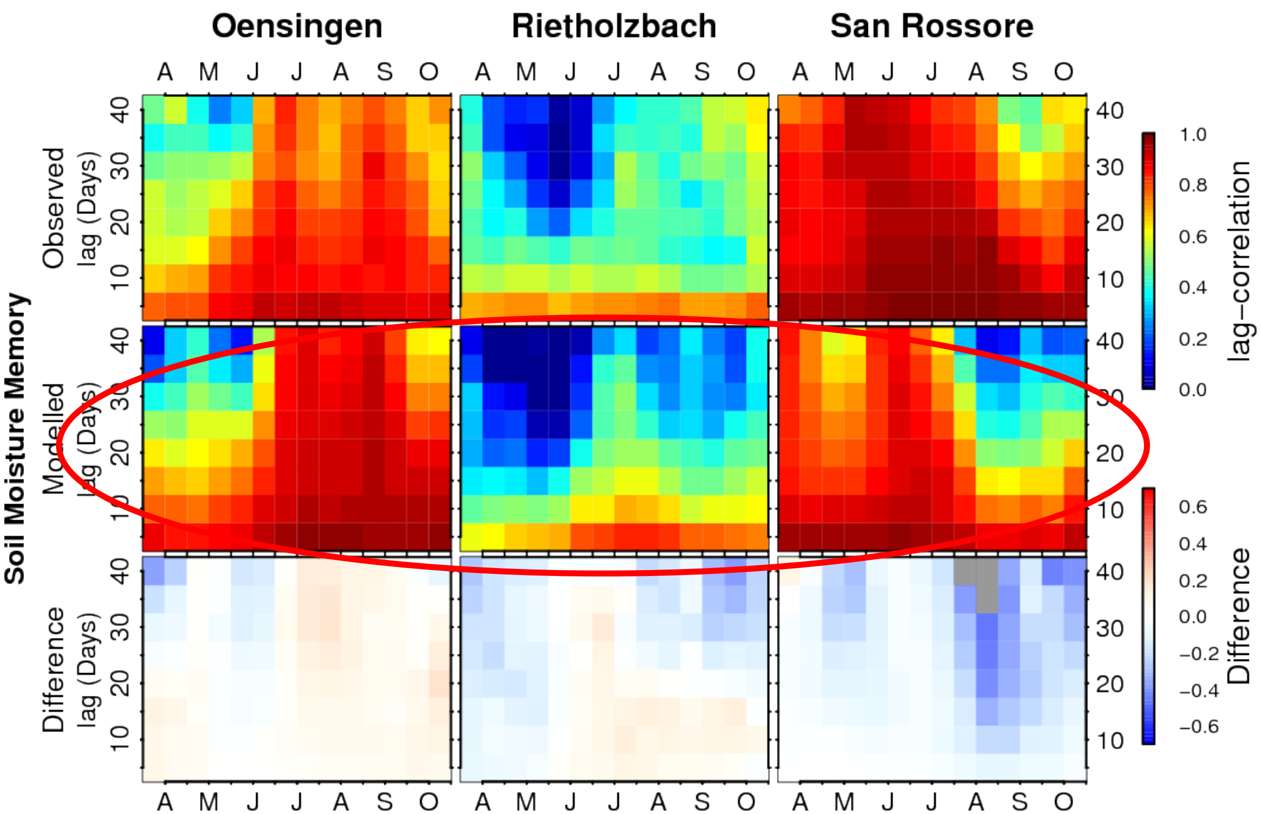


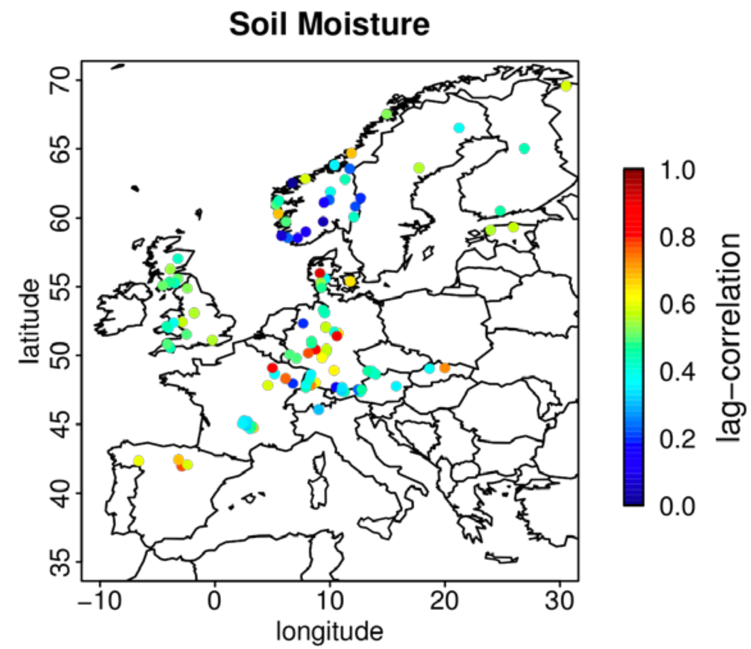


(Orth et al. submitted, JHM; Orth and Seneviratne, in prep.)

Drought early warning and forecasting





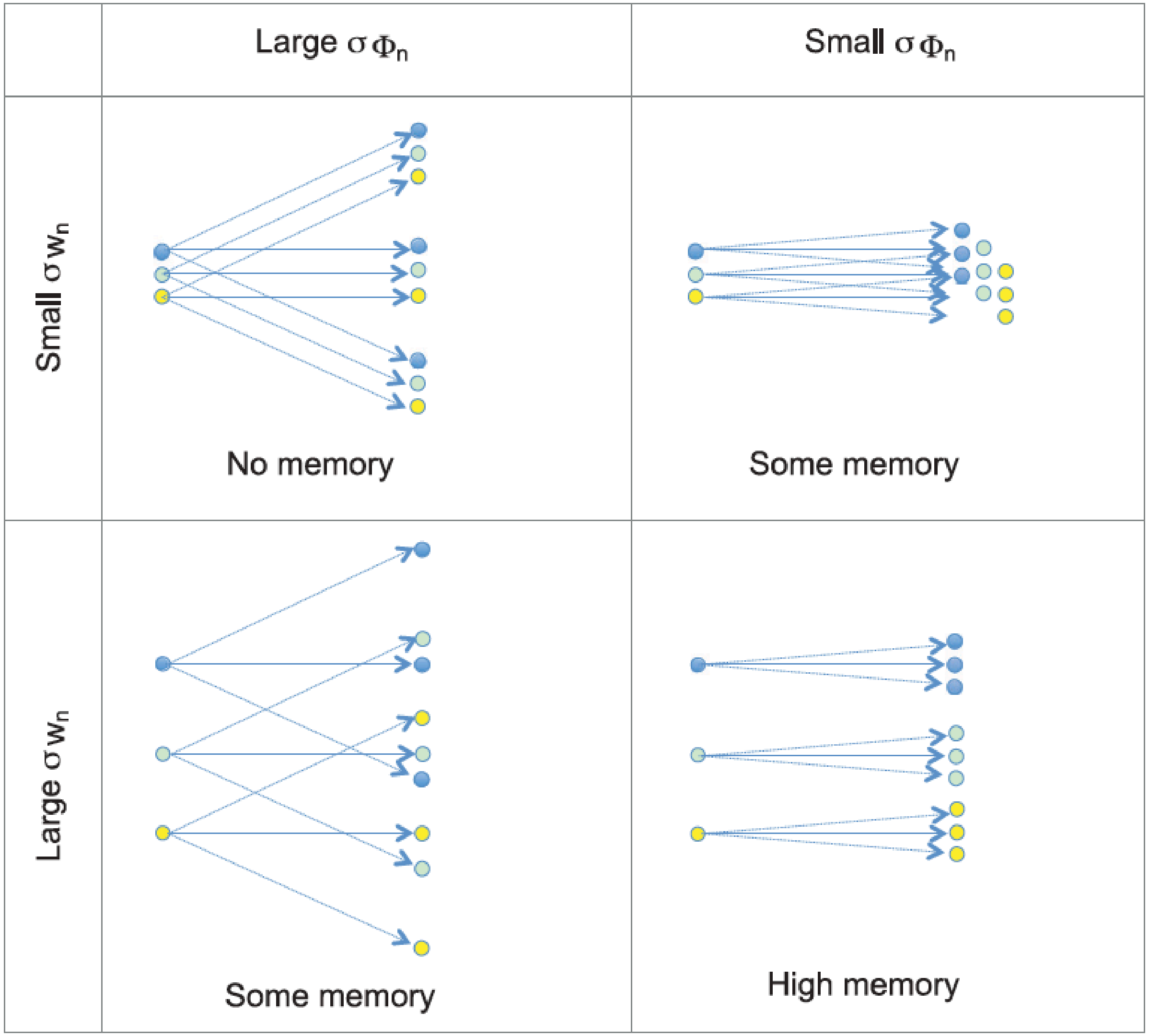


(Orth et al. submitted, JHM; Orth and Seneviratne, in prep.)

Soil moisture memory

Analytical decomposition: 4 main terms controlling memory *(Koster and Suarez 2001, Seneviratne and Koster 2012)*

- **Spread of initial anomalies (σw_n)**
- **Spread of forcing ($\sigma\Phi_n$)**
- Damping factors (sensitivity of ET and runoff to soil moisture)
- Enhancing factors (correlation with subsequent forcing)



(Seneviratne and Koster 2012, JHM)

Drought early warning: Key messages

- Independently of possible feedbacks to the atmosphere, the **soil moisture (and groundwater) persistence implies potential skill for land hydrology** (soil moisture, runoff): Could be used for drought early warning and forecasting

- Memory patterns can be approximated with a simple water balance model calibrated with runoff observations ➔ estimation of persistence characteristics for wide areas

Outline

- Basic relevant land-climate feedbacks and observational evidence
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  - GLACE-2: Forecasting of atmospheric variables
  - Drought forecasting
- Discussion
  - Combined effects of large-scale circulation forcing and soil moisture feedbacks
  - Soil moisture initialization
  - Land-climate feedbacks in the context of climate change
- Conclusions

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, published online)

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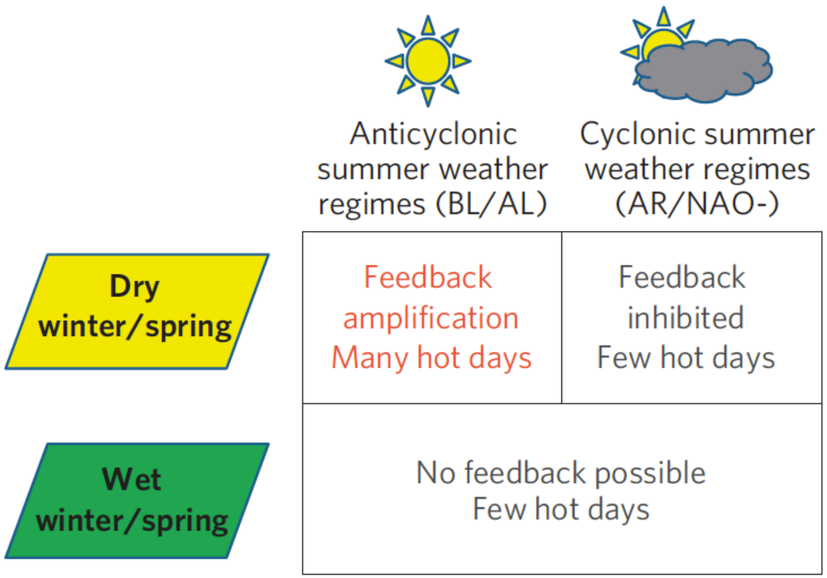

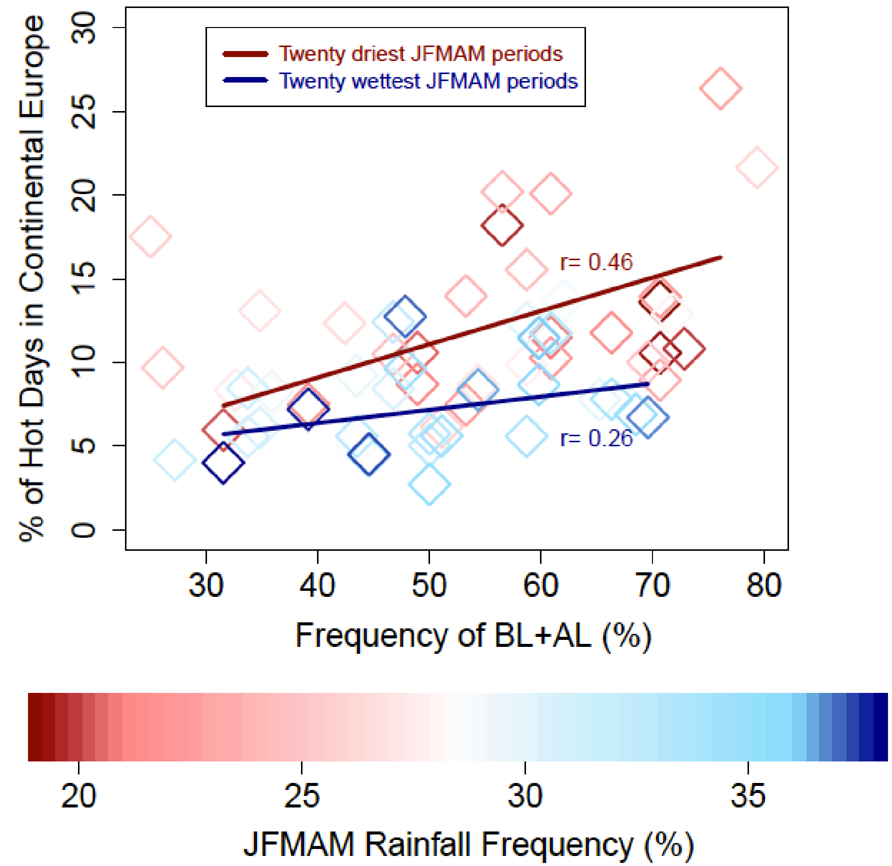

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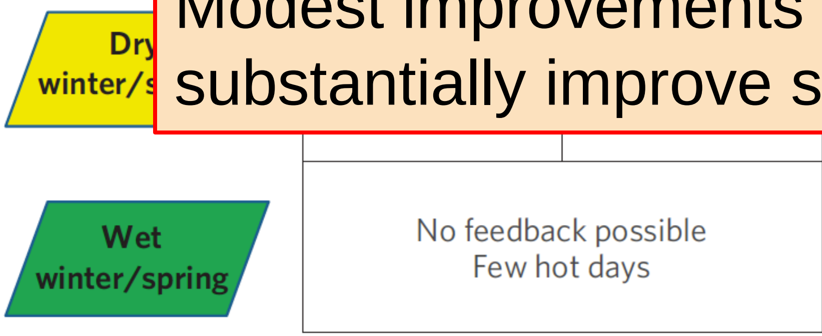
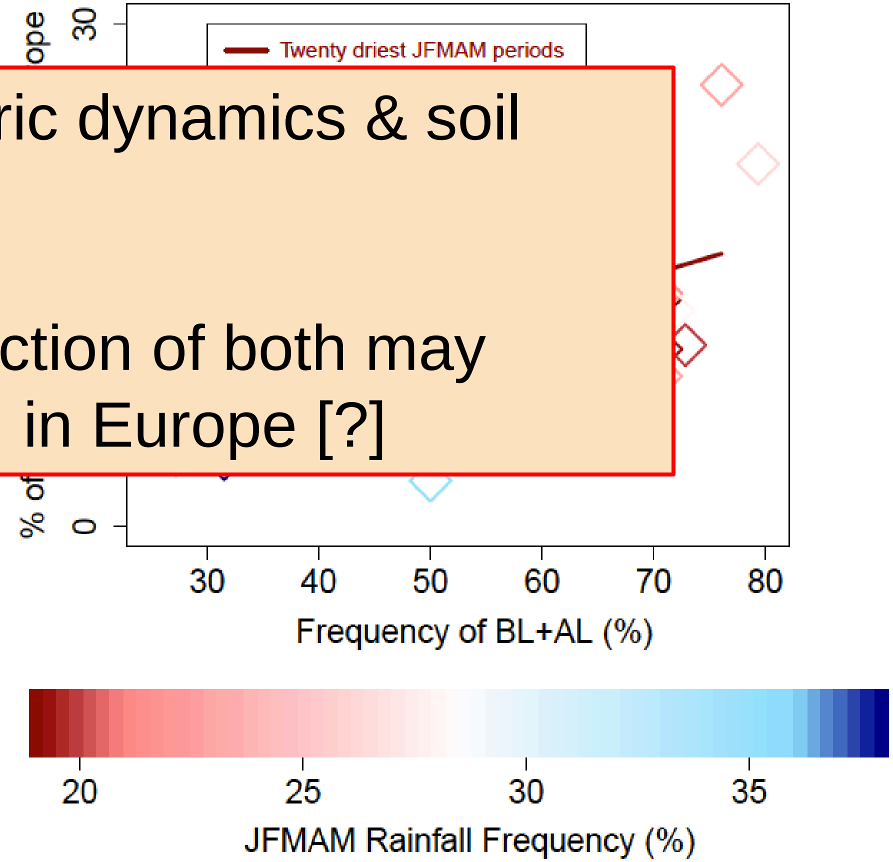
Combined roles of soil moisture & circulation

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

Information on both atmospheric dynamics & soil moisture state are critical

Modest improvements in prediction of both may substantially improve skill, e.g. in Europe [?]



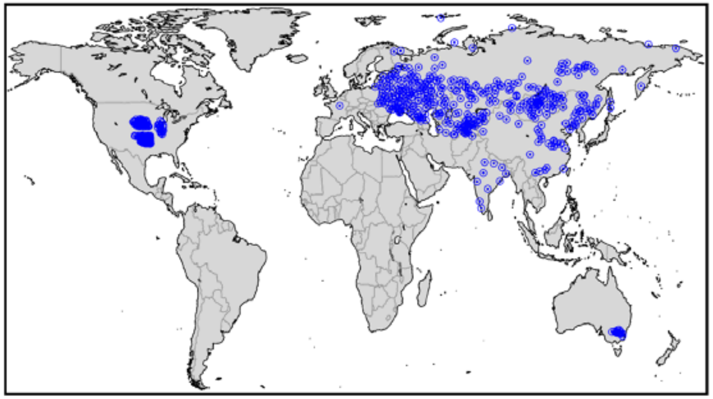


(Quesada et al. 2012, Nature Climate Change, published online)

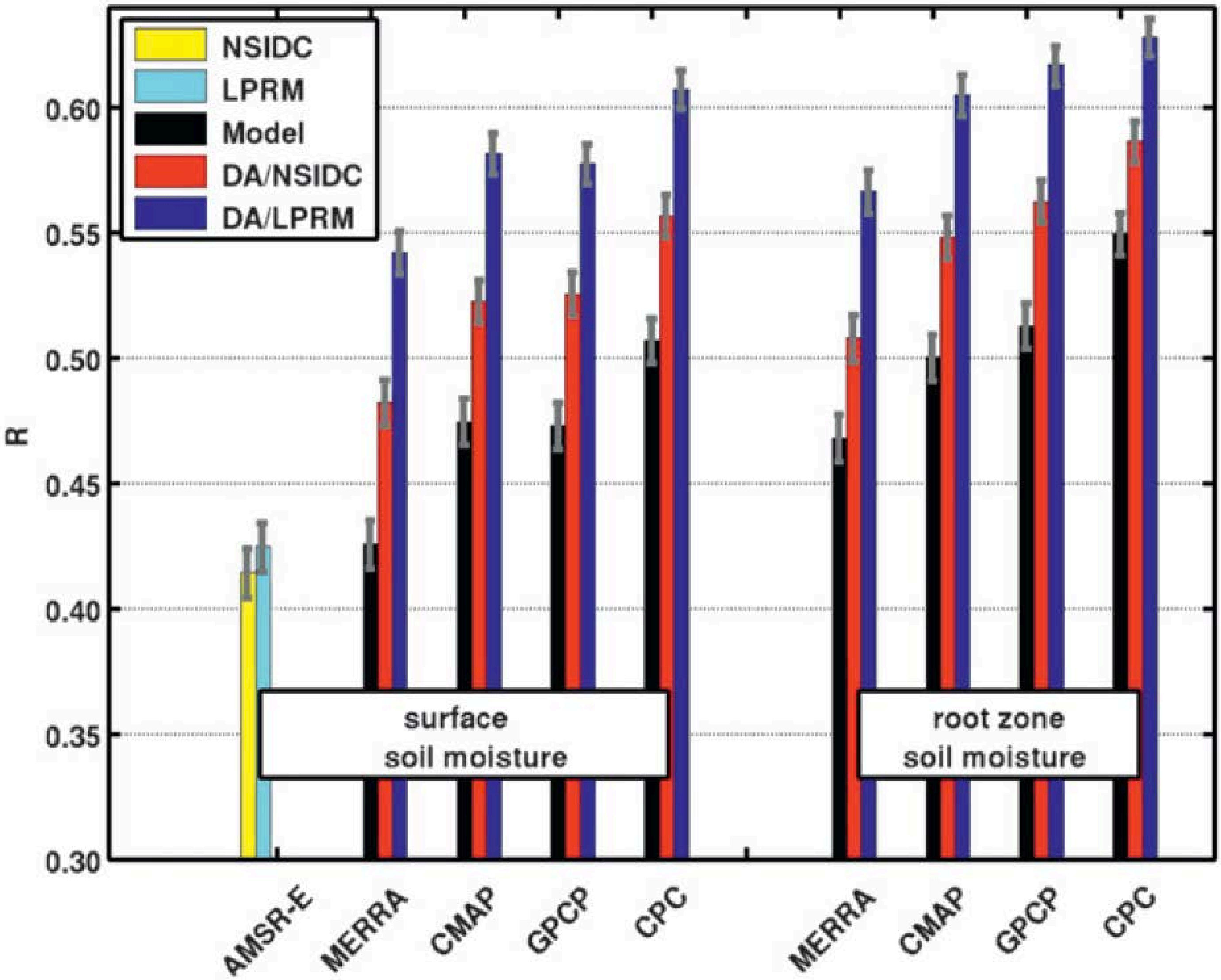
Soil moisture initialization

- A major issue for any forecast using land surface information is the derivation of suitable initial conditions:
    - Few ground soil moisture networks (but soil moisture is newly characterized as essential climate variable, GCOS 2010)
    - Standard approach is to derive land surface model estimates using observation-based forcing (nonetheless also in this case data availability is an issue)
    - In development: Also use of remote-sensing based surface soil moisture estimates (e.g. microwave) using data assimilation, e.g. at NASA and ECMWF

Global Soil Moisture Data Bank



Soil moisture initialization: Land data assimilation

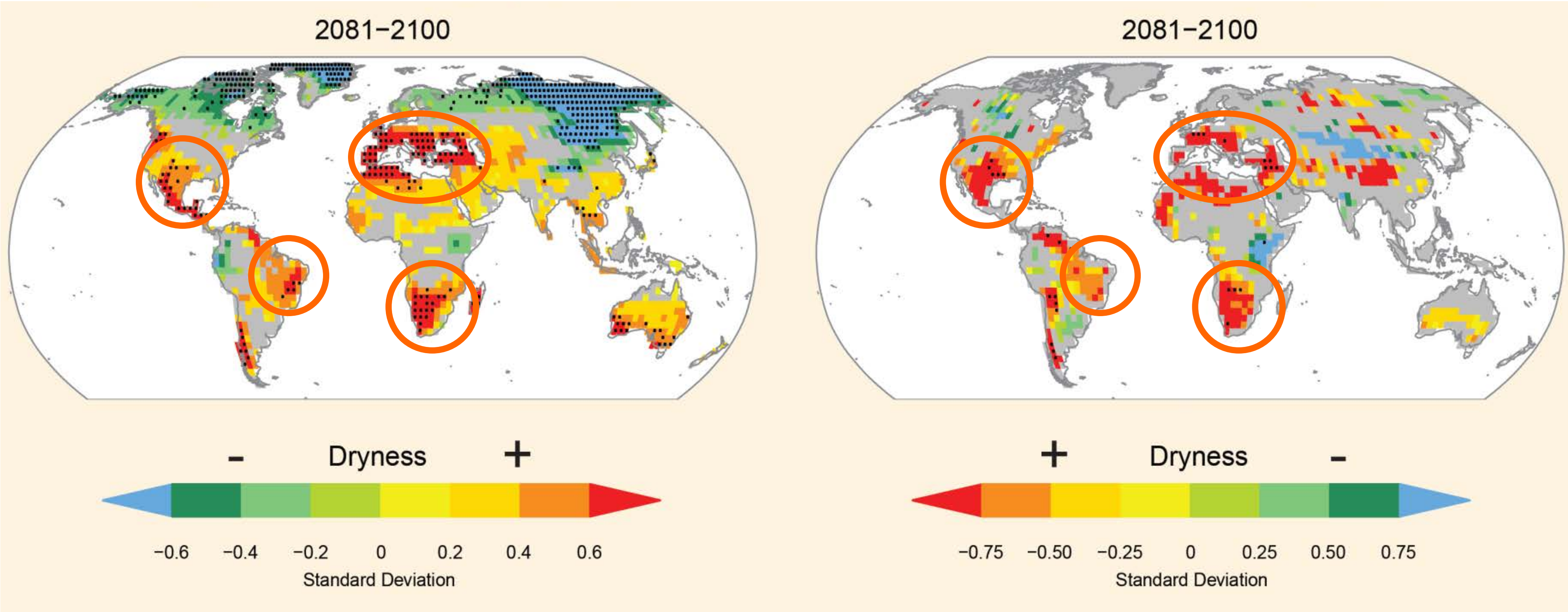


Correlation with surface soil moisture data (SCAN network, US)

(Liu et al. 2011, JHM)

Climate change: Projected changes in drought patterns

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



(IPCC 2012; Summary for Policymakers & Chapter 3)

Consistent projections of increased dryness in the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa

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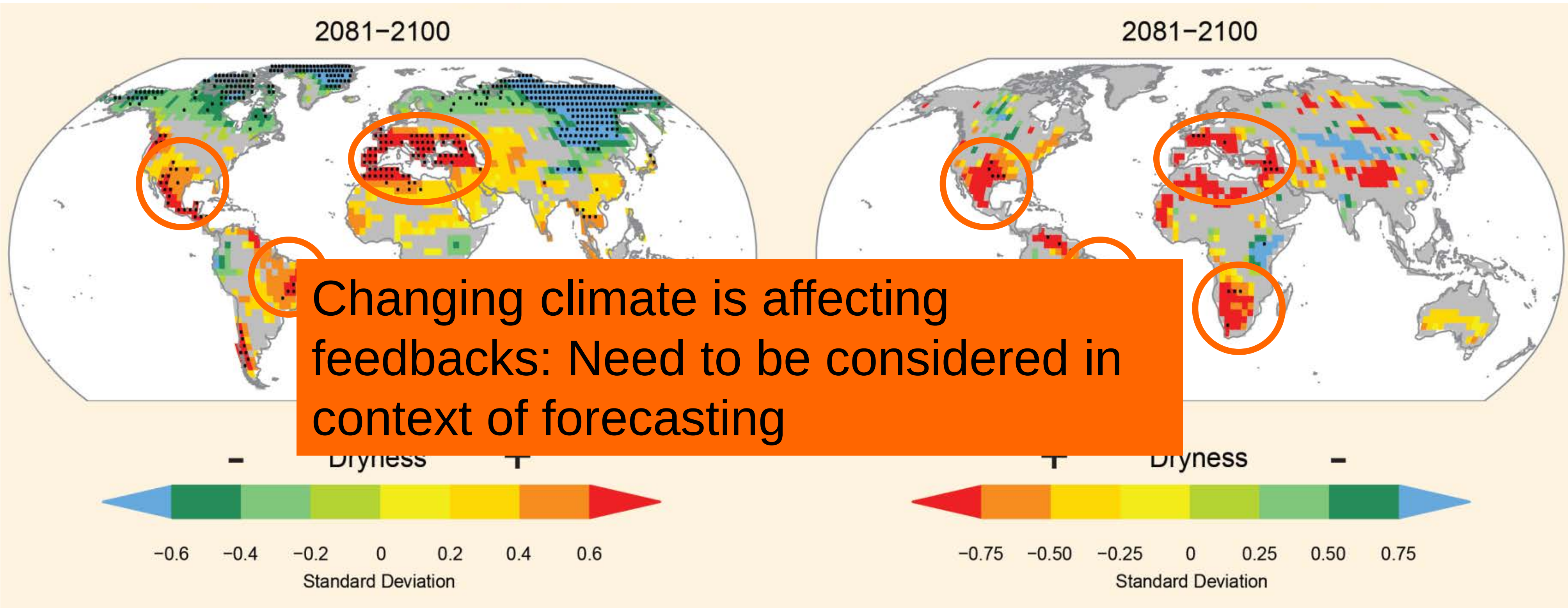

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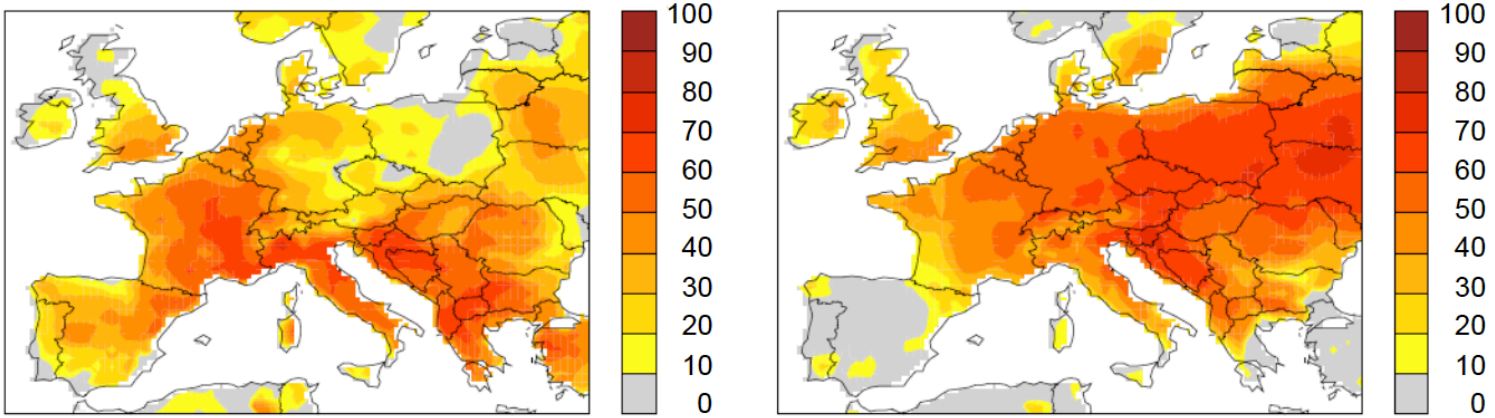
Consistent projections of increased dryness in the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa

Hot spots of soil moisture-climate coupling are expected to shift with changing climate (and changing soil moisture regimes)

1970-1989 **2080-2099**



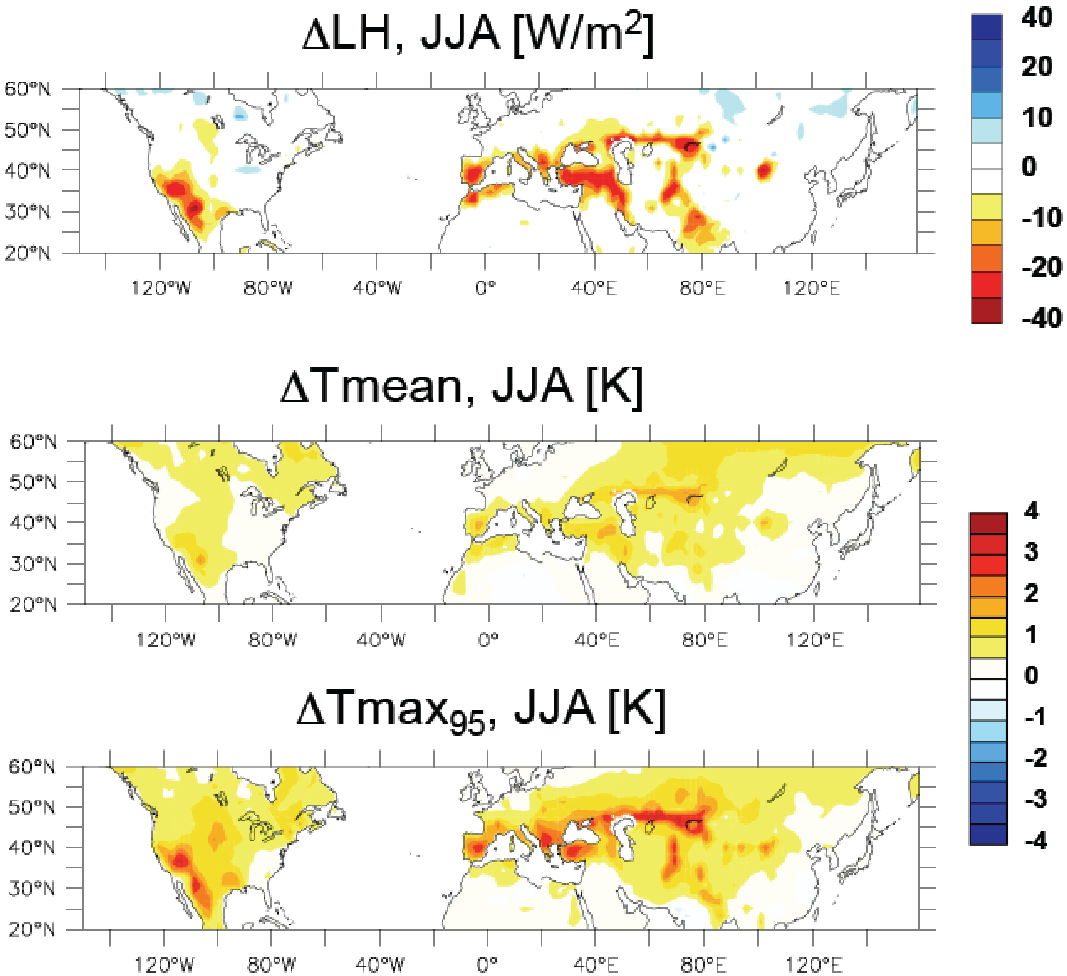
%age of summer temperature variability attributable to soil moisture variability (model estimate)

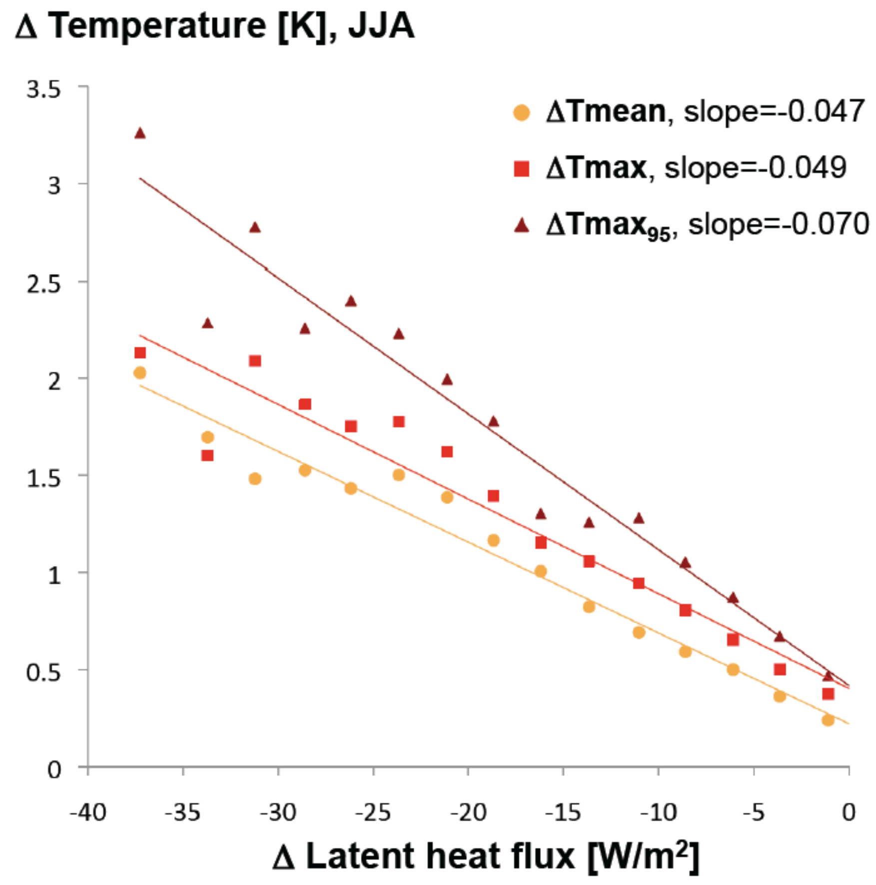
RCM simulations: Up to **60%** of *summer temperature variability* is induced by soil moisture feedbacks:

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

(Seneviratne et al. 2006, Nature)

GLACE-CMIP5: Impact of changes in soil moisture regimes for projected climate (2071-2100 vs 1971-2000)





(Seneviratne et al. 2012, submitted)

Outline

- Basic relevant land-climate feedbacks and observational evidence

- Diagnosing prediction potential from land surface initialization
  - GLACE-2: Forecasting of atmospheric variables
  - Drought forecasting

- Discussion
  - Combined effects of large-scale circulation forcing and soil moisture feedbacks
  - Soil moisture initialization
  - Land-climate feedbacks in the context of climate change

- Conclusions

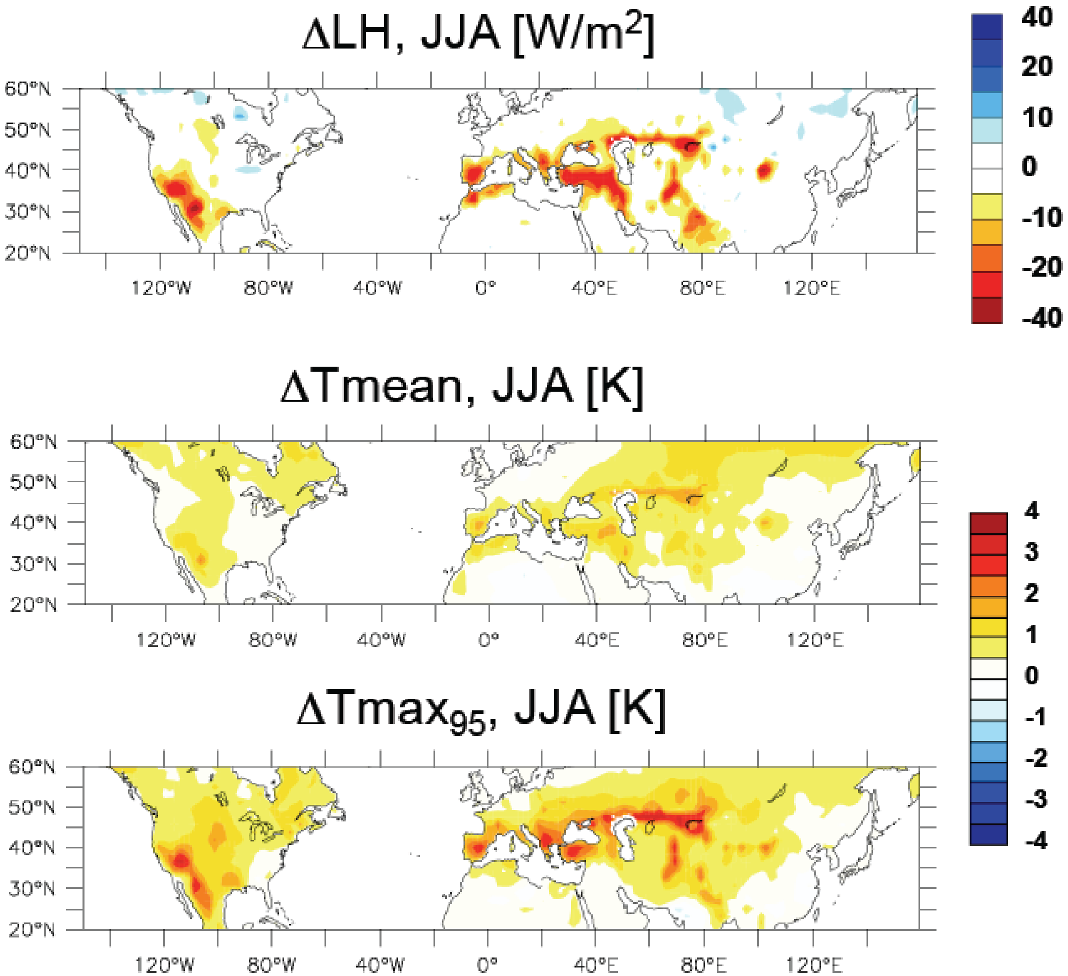
Conclusions

- High relevance of land-climate feedbacks for **climate variability over continents, in particular hot extremes**

- Soil moisture persistence implies **potential for improved monthly-subseasonal predictability** of temperature, precipitation, and agricultural and hydrological droughts: ➔ not used at present!

- Key areas of research:
  - Respective role of large-circulation anomalies and soil moisture feedbacks for climate variability
  - Improved observational estimates and quantification of feedbacks based on observations
  - Feedbacks in the context of climate change (also for attribution)

GLACE-CMIP5: Impact of changes in soil moisture regimes for projected climate (2071-2100 vs 1971-2000)

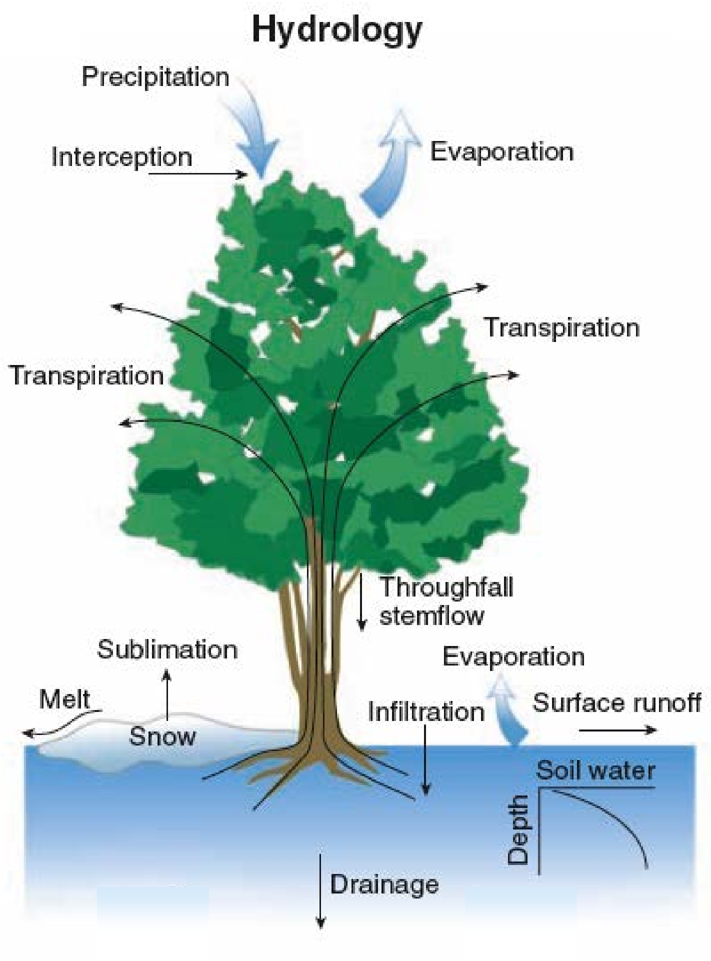


(Seneviratne et al. 2012, submitted)

GLACE-2: Participants' list

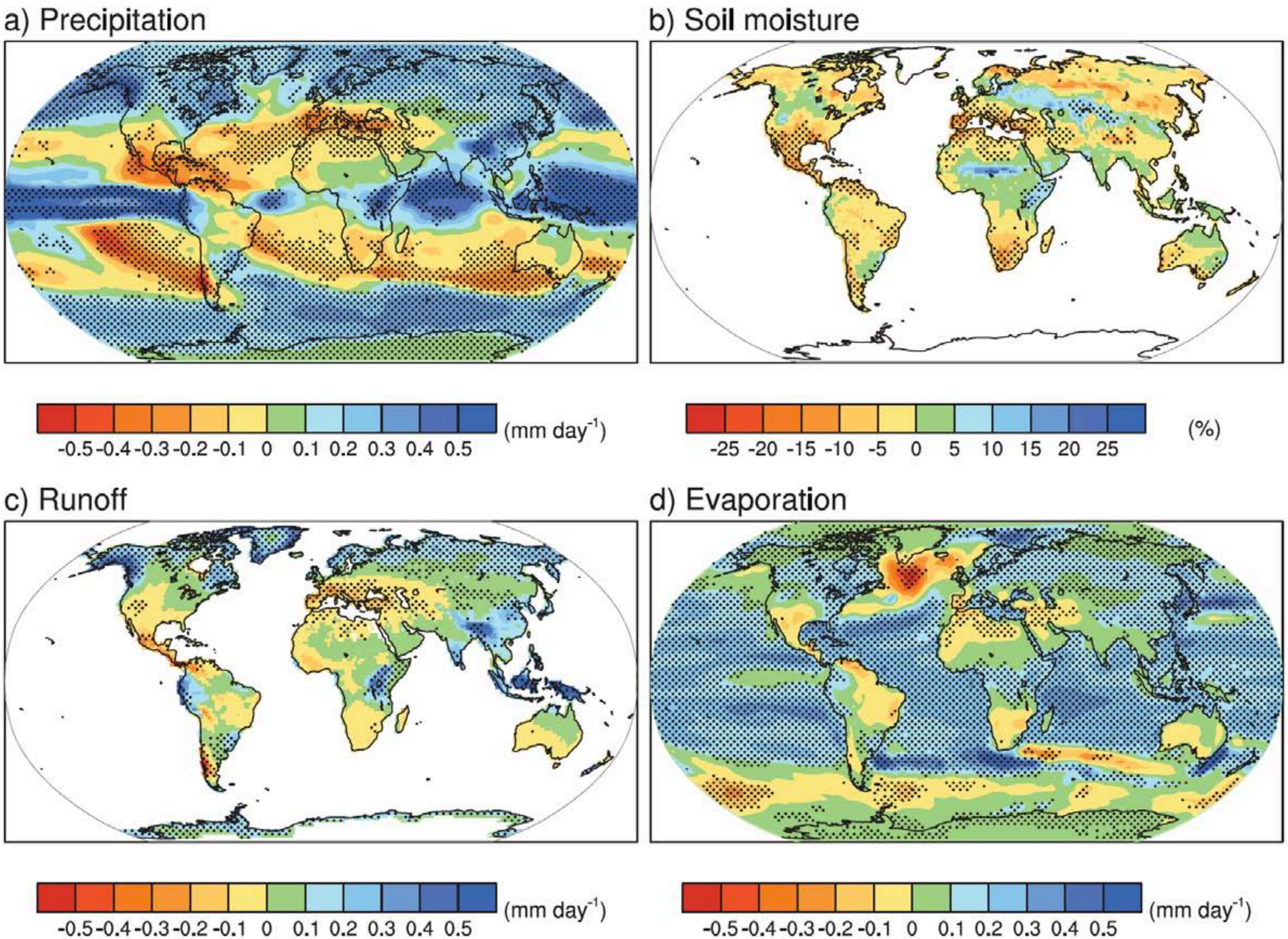
Group/Model	# models	Points of Contact
1. NASA/GSFC (USA): GMAO seasonal forecast system (old and new)	2	R. Koster, S. Mahanama
2. COLA (USA): COLA GCM, NCAR/CAM GCM	2	P. Dirmeyer, Z. Guo
3. Princeton (USA): NCEP GCM	1	E. Wood, L. Luo
4. ETH Zurich (Switzerland): ECHAM GCM	1	S. Seneviratne, T. Stanelle
5. KNMI (Netherlands): ECMWF	1	B. van den Hurk
6. ECMWF	1	G. Balsamo, F. Doblas-Reyes
7. GFDL (USA): GFDL system	1	T. Gordon
8. U. Gothenburg (Sweden): NCAR	1	J.-H. Jeong
9. CCSR/NIES/FRCGC (Japan): CCSR GCM	1	T. Yamada
10. FSU/COAPS	1	M. Boisserie
11. CCCma	1	B. Merryfield
	13 models	

Land surface processes



(Bonan, Science 2008)

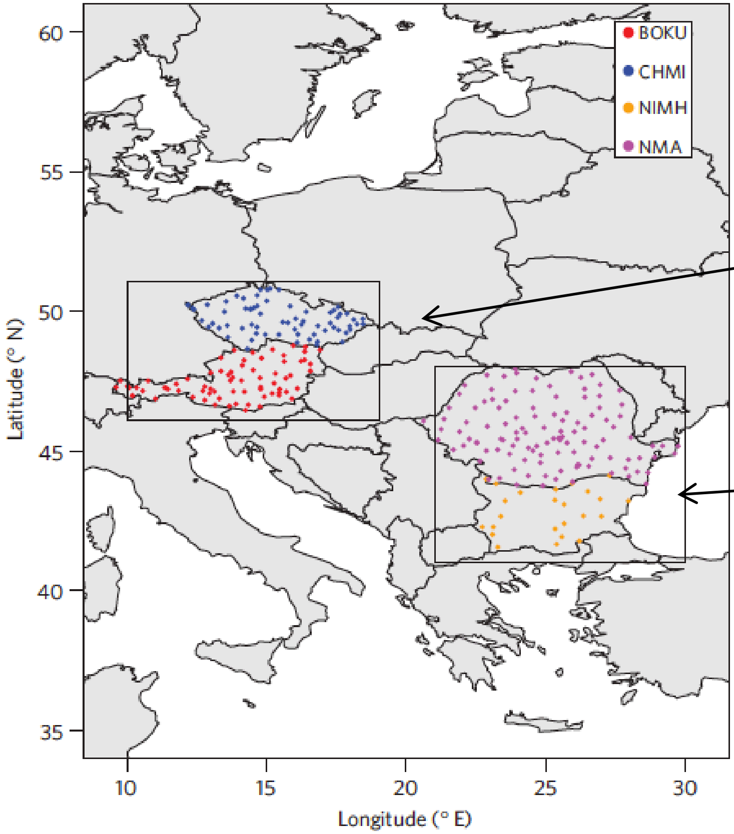
Changes in hydrological cycle



(IPCC 2007)

Observational evidence for soil-moisture impact on hot extremes in southeastern Europe

Martin Hirschi[1,2★], Sonia I. Seneviratne[1★], Vesselin Alexandrov[3], Fredrik Boberg[4], Constanta Boroneant[5], Ole B. Christensen[4], Herbert Formayer[6], Boris Orlowsky[1] and Petr Stepanek[7]



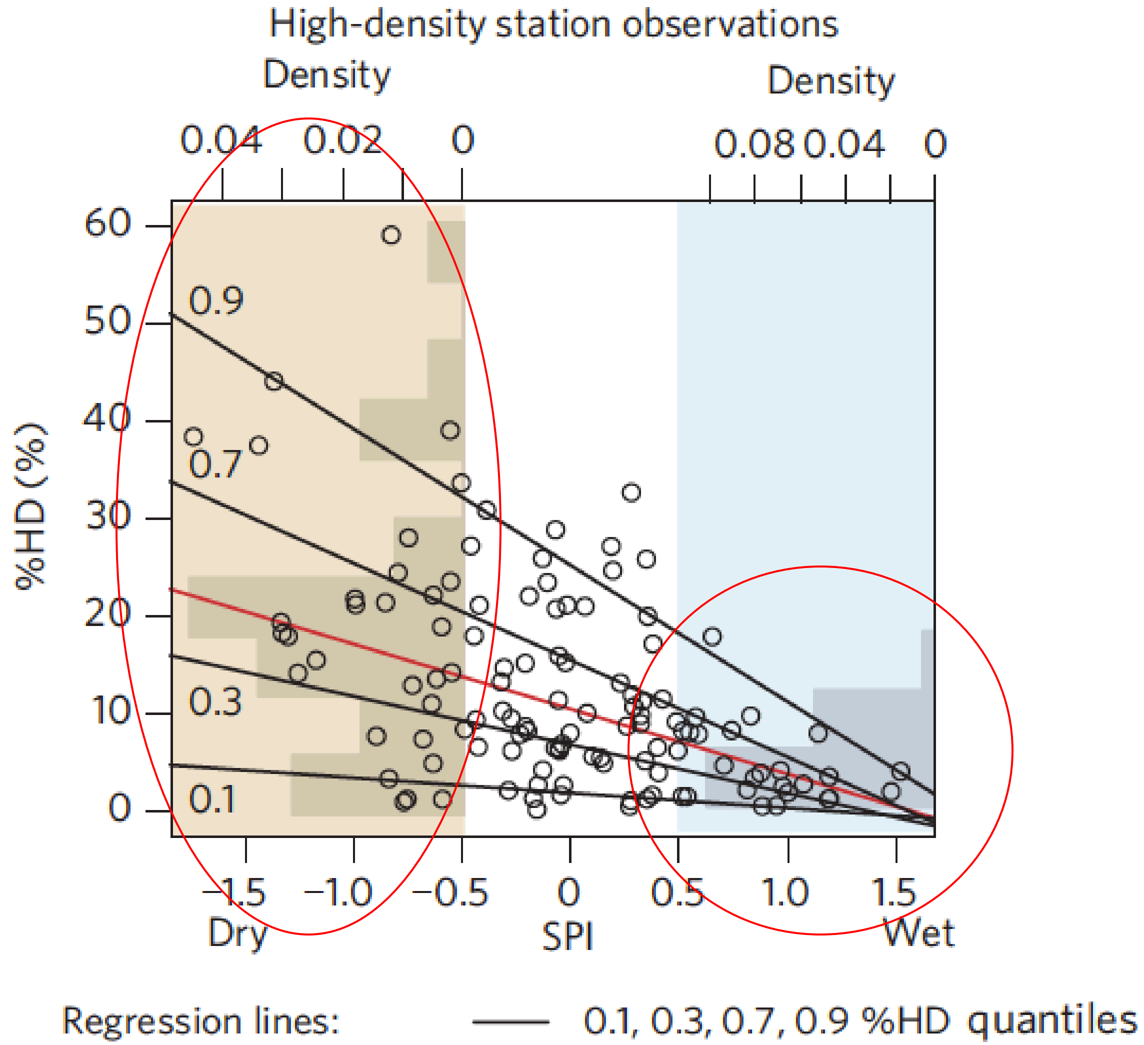
Radiation-limited evapotranspiration regime

Soil moisture-limited evapotranspiration regime

(Hirschi et al. 2011, Nature Geoscience)

Role of soil moisture on hot extremes: Observations

Possibly more skill for hot extremes after wet vs dry conditions (dry soil necessary but not sufficient condition)

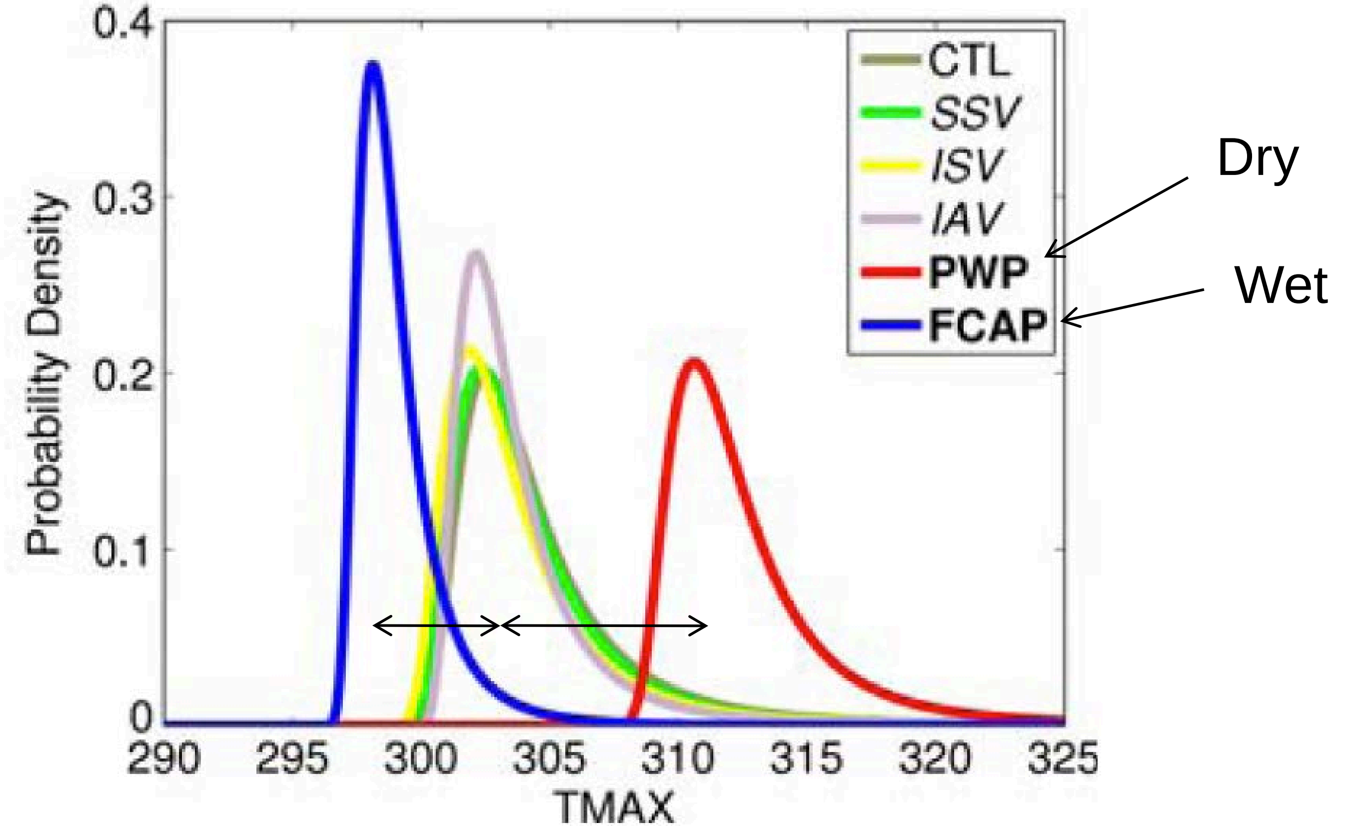


(Hirschi et al. 2011, Nature Geoscience)

Asymmetric effects of soil moisture on extremes

Distribution of summer Tmax block maxima

RCM simulation with COSMO/CCLM (France, 1959-2006)



(Jaeger and Seneviratne, Climate Dynamics, 2011)

GLACE-2: Conclusions

1. The individual models vary in their ability to extract forecast skill from land initialization (not shown). In general,
   -- Low skill for precipitation
   -- Moderate skill (in places) for temperature, even out to two months.

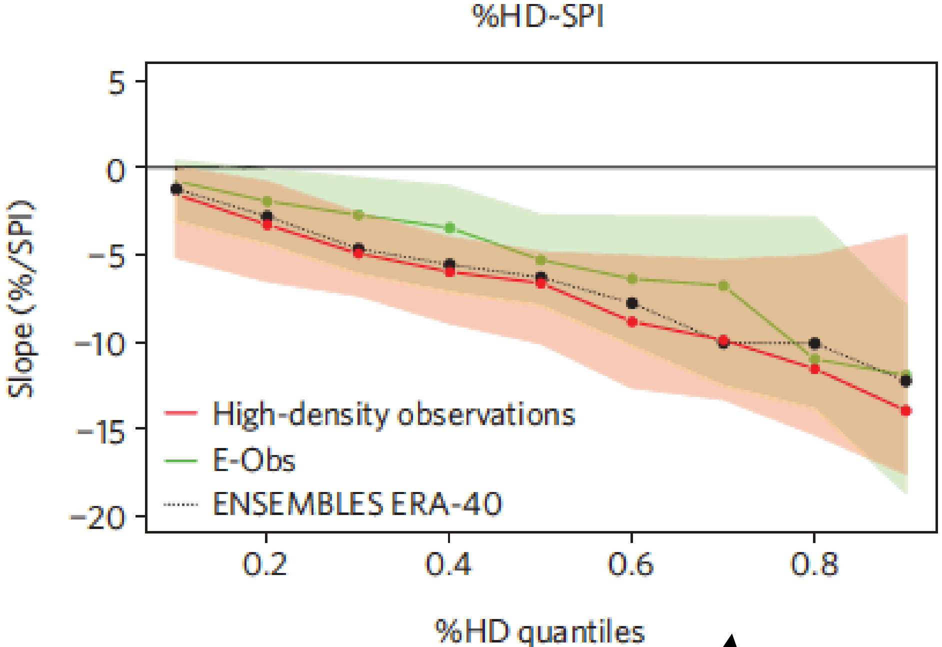
2. Land initialization impacts on skill increase dramatically when conditioned on the size of the initial local soil moisture anomaly.

→ If you know the local soil moisture anomaly at time 0 is large, you can expect (in places) that initializing the land correctly will improve your temperature forecast significantly, and your precipitation forecast slightly, even out to 2 months.

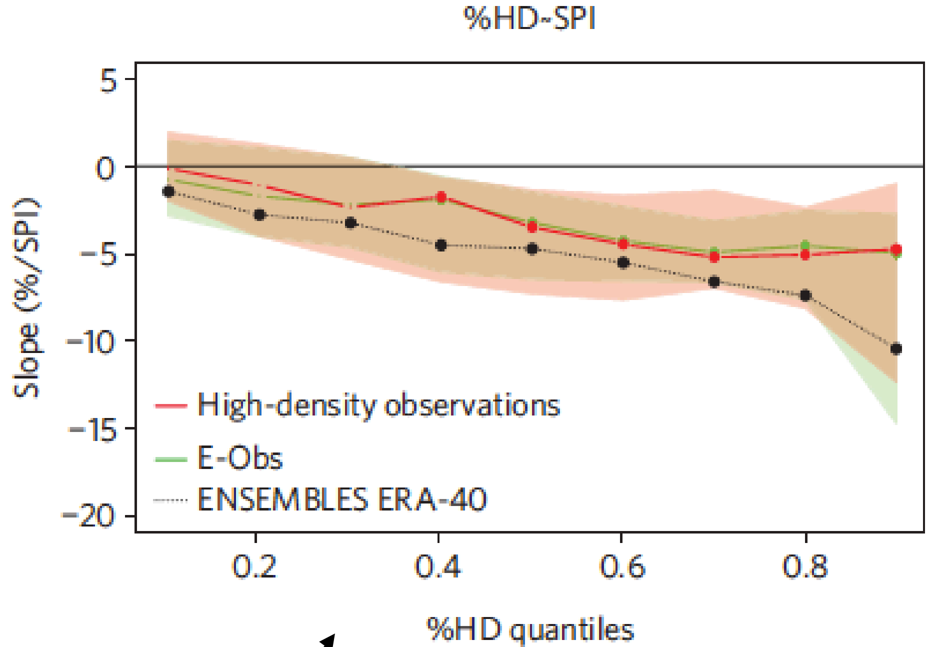
2. The results highlight the potential usefulness of improved observational networks for prediction.

Can we fully trust models regarding forecasting potential?

Southeastern Europe



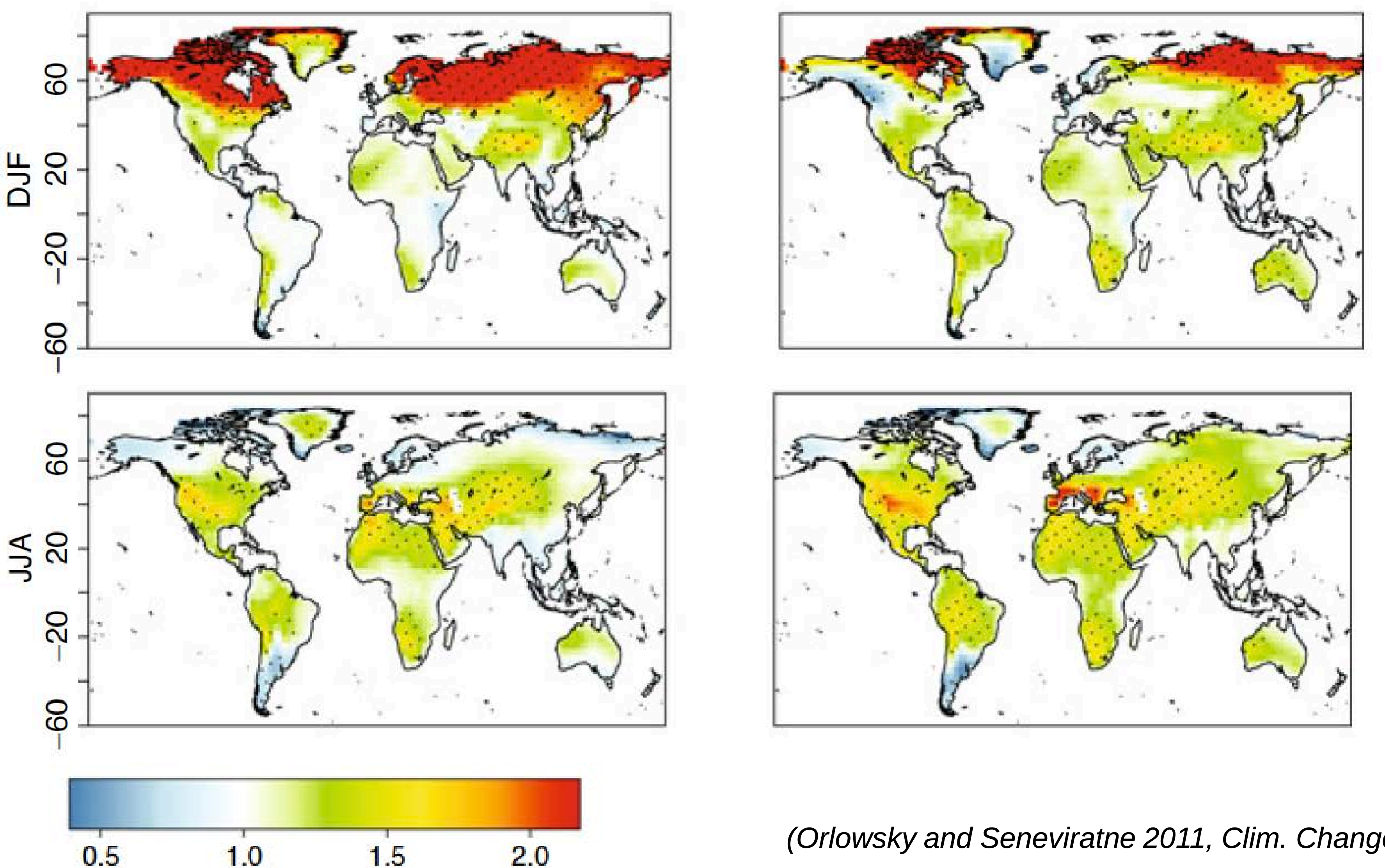
Central Europe



Quantile regressions: RCMs from ENSEMBLES perform fairly well but display an overestimation of feedback strength in C. Europe

(Hirschi et al. 2011, Nature Geoscience)

Scaling $\Delta Tmax_{local,seas}/\Delta Tmax_{global}$ for 10% (left) and 90%ile (right)



(Orlowsky and Seneviratne 2011, Clim. Change, publ. online)