Influence of land surface variability over Europe

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FCT support through project AMIC

ECMWF Seminar 2010: Predictability in the European and Atlantic regions from days to years. 6 to 9 September 2010

First "S": Semantics

- Seminar on Predictability in the European and Atlantic regions from days to years
- Session 1: Dynamical understanding ...
- Session 2: Predictability and actual predictive skill ...
- This Session: Influence of ocean/land-surface/stratospheric conditions on Europe
  - This talk: Influence of land surface variability over Europe
  - 2nd talk: Impact of ENSO over Europe
  - 3rd talk: Impact of sea surface temperatures on African climate
  - 4th talk: Prediction of the Madden-Julian Oscillation and its impact on the European weather in the ECMWF monthly forecasts
  - 5th talk: Predictability of the coupled troposphere-stratosphere system
  - 6th talk: Variability of Arctic sea-ice and its influence

Second “S”: Statistics

- **Circa 80 references were consulted, selected in a rather unsystematic way and covering 2002-2010**
- **Crude classification (not mutually exclusive):**
  - **Summer 2003: 12**
  - **European Heat Waves: 19**
  - **Surface-Atmosphere feedbacks: 27**
  - **Land-Surface Observations: 7**
  - **European drought: 2**
  - **Predictability: 5**
  - **Reviews: 3**
    - **Seneviratne, S.I., T. Corti, E.L. Davin, M. Hirschi, E.B. Jaeger, I. Lehner, B. Orlowsky, and A.J. Teuling, 2010: Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99, 125-161.**
    - **Seneviratne, S.I., and R. Stöckli, 2008: The role of land-atmosphere interactions for climate variability in Europe. In: Climate Variability and Extremes during the Past 100 years, Brönnimann et al. (eds.), *Adv. Global Change Research*, 33, Springer Verlag.**
    - **Garcia-Herrera, R., J. Diaz, R.M. Trigo, J. Luterbacher, E.M. Fischer, 2010: A review of the European summer heat wave of 2003. *Critical Reviews in Environmental Science and Technology*, 40, 267-306.**

Layout

- General physical considerations
- Soil moisture (SM) and atmosphere coupling: Conceptual aspects
- SM and atmosphere coupling: Model estimates and “hot spots”
- SM-Temperature and SM-Precipitation coupling
- Increased persistence: Surface “memory”
- Impacts of initial soil moisture anomalies
- Conclusions (questions for future research)

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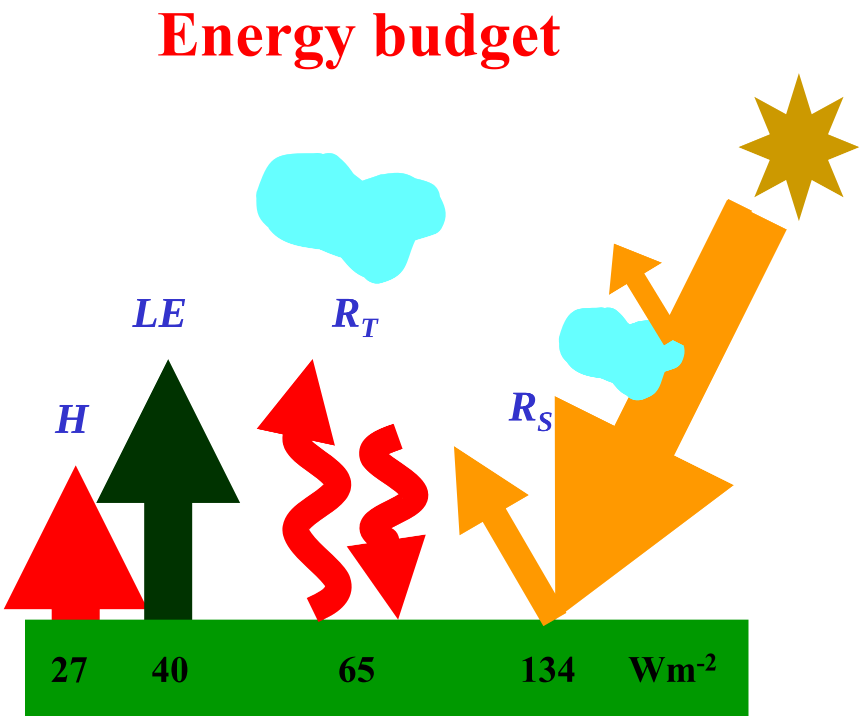
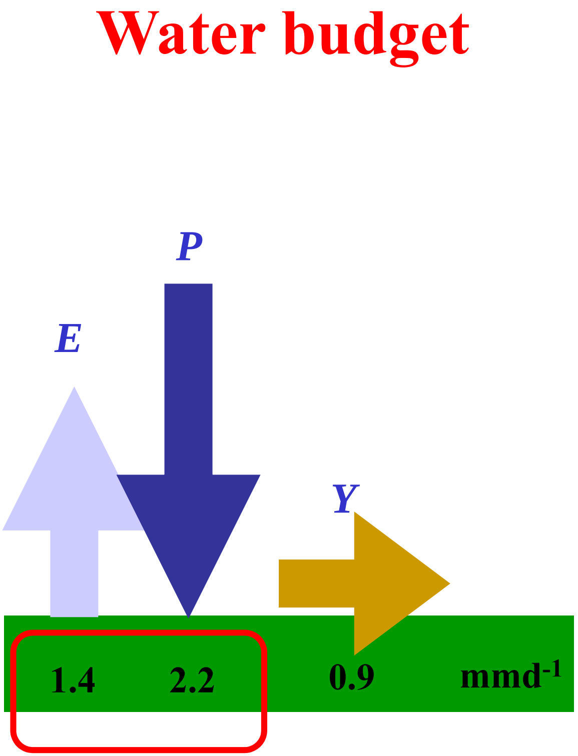
Continental surface energy and water budgets



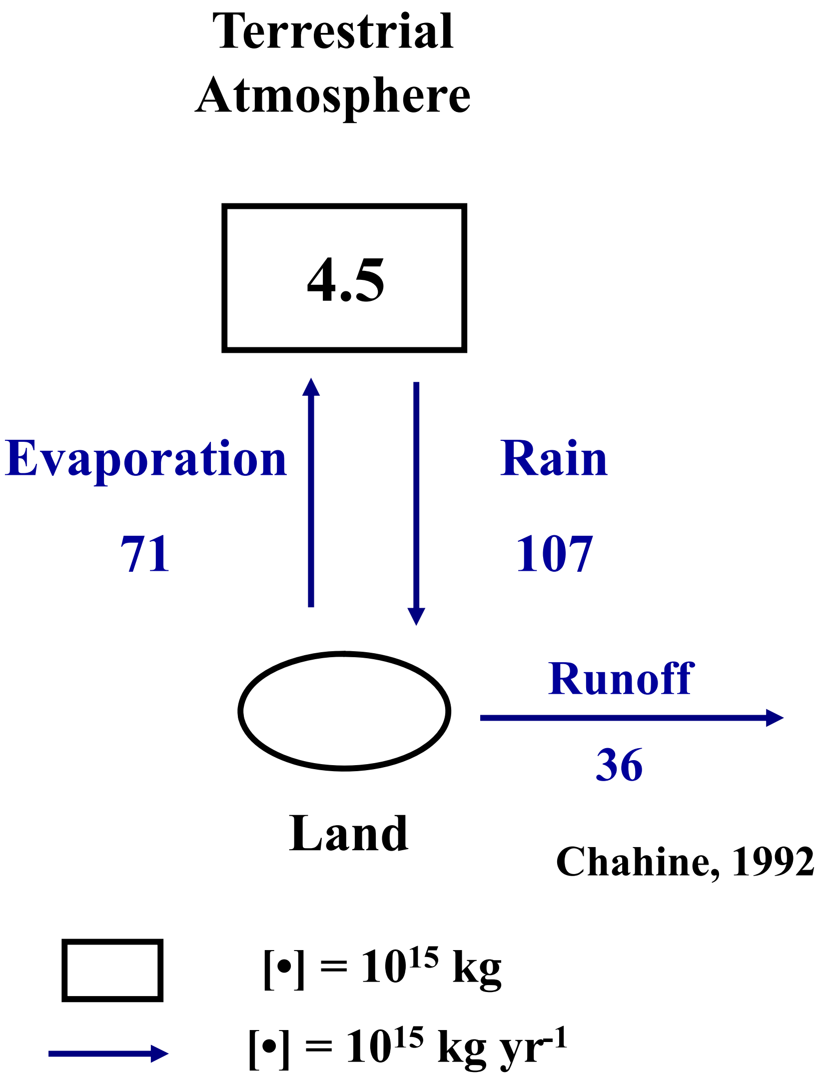


ERA40 land-averaged values 1958-2001

Land averaged evaporation is ~63% of precipitation

Evaporative fraction (EF) $EF=LE/R_{net}=58\%$

Terrestrial atmosphere time scales (memory)



Terrestrial Atmosphere

4.5

Evaporation

71

Rain

107

Runoff

36

Land

Chahine, 1992

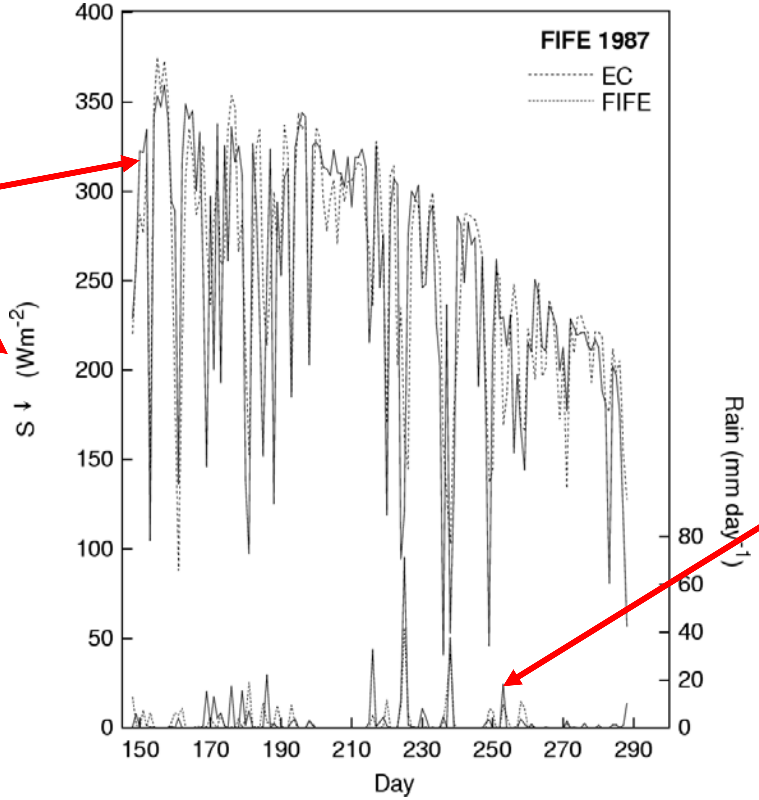
□ [•] = 10^{15} kg

→ [•] = 10^{15} kg yr^{-1}

- Atmosphere recycling time scales associated with land reservoir
  - Precipitation 4.5/107 = 15 days
  - Evaporation 4.5/71 = 23 days

Surface time scales: Forcing time scales

- **Diurnal time scale**
  - Time scale determined by the quasi-sinusoidal radiation modulated by clouds
- **Diurnal/weekly time scale**
  - Time scale determined by the "quasi-random" precipitation (synoptic/mesoscale)



Downward solar radiation

Precipitation

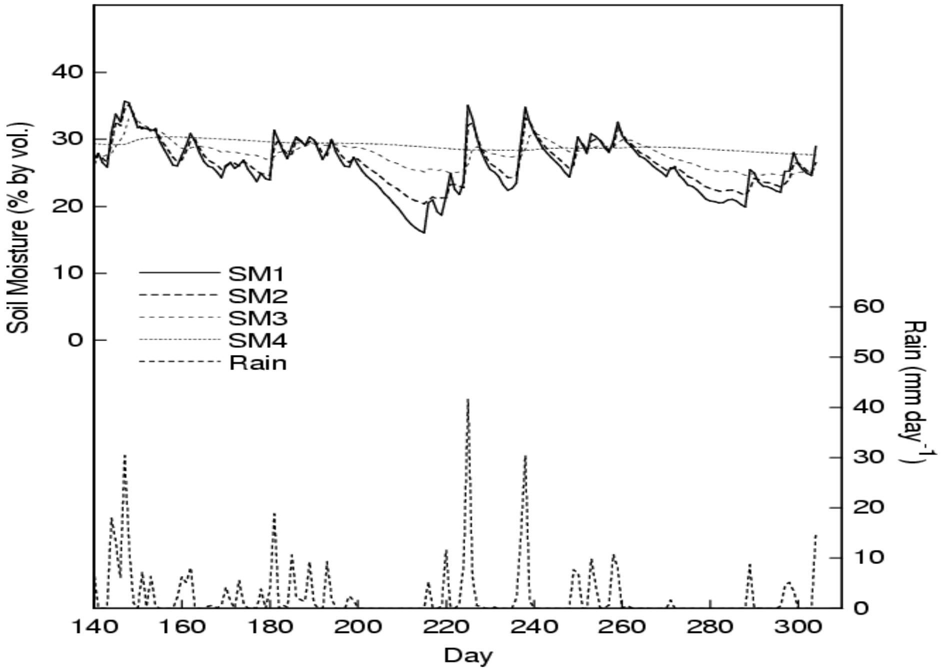
1 May **1 July** **1 Sep**

Betts et al 1998

FIFE (Kansas, US) 1987

Surface time scales (memory)

- **Weekly/monthly time scale**
  - **Internal time scale determined by the physics of soil water exchanges/transfer**



Betts et al 1998

- **Weekly/monthly time scale**
  - **Evaporation time scale determined by the ratio (net radiative forcing)/(available soil water)**

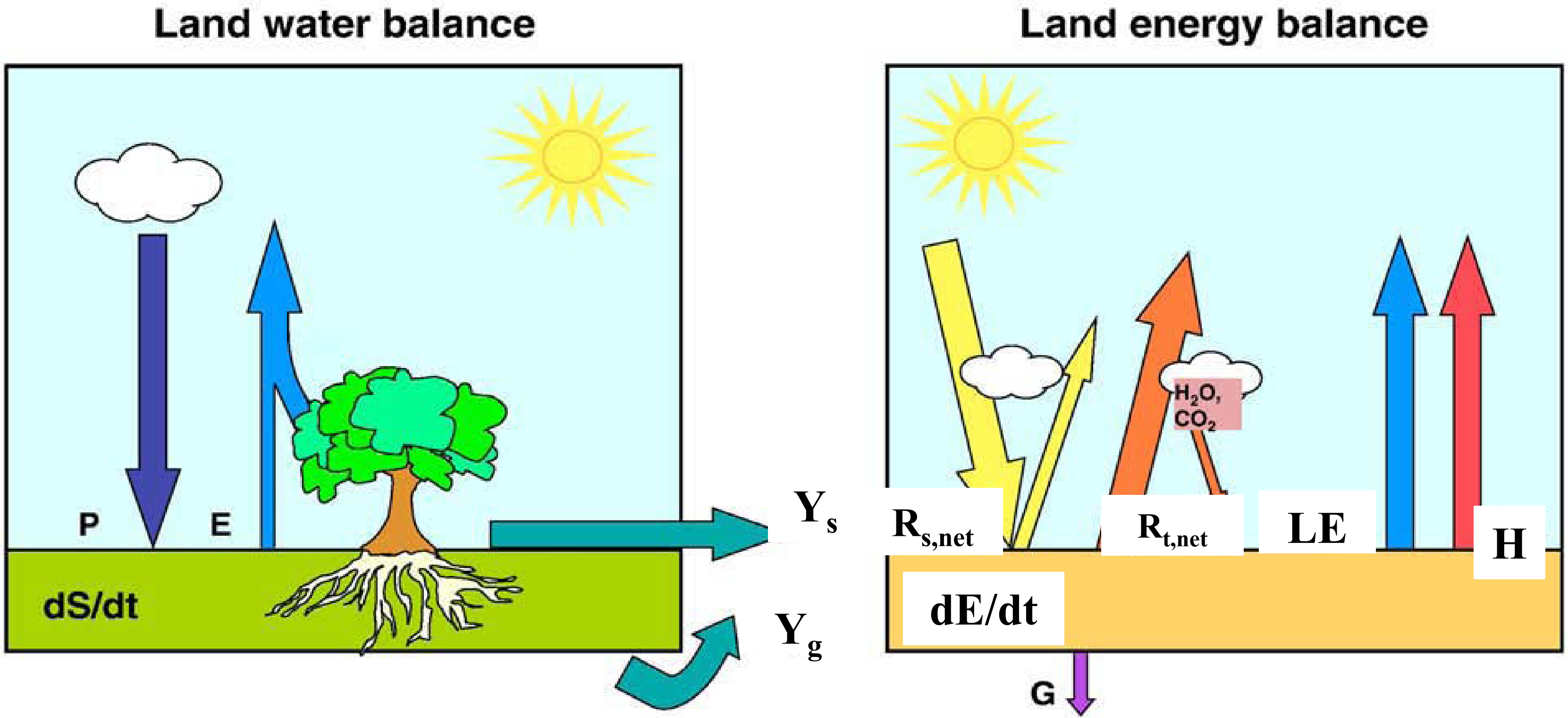
R_n=150 Wm^{-2} ~ (5 mmd^{-1})

Soil water=150 mm

(5 mmd^{-1})/(150 mm) = 30 days

FIFE (Kansas, US) 1987

Budget of a slab of surface



Seneviratne et al, 2010

$$\frac{dS}{dt} = P - E - Y_s - Y_g$$

$$\frac{d\mathrm{E}}{dt} = R_{net} - H - LE - G$$

Budget of a slab of surface

$$\frac{dS}{dt} = P - E - Y_s - Y_g$$

$$\frac{d\mathrm{E}}{dt} = R_{net} - H - LE - G$$

- **Soil moisture plays a role on the surface energy and water budget**
- **Energy and water budget are linked through evaporation**
- **Soil moisture is also linked to biogeochemical cycles (via photosynthesis):**
  - **Carbon cycle**
  - **Nitrogen cycle**
- **Influence and effects only important when soil moisture is the main controlling factor for evapotranspiration**

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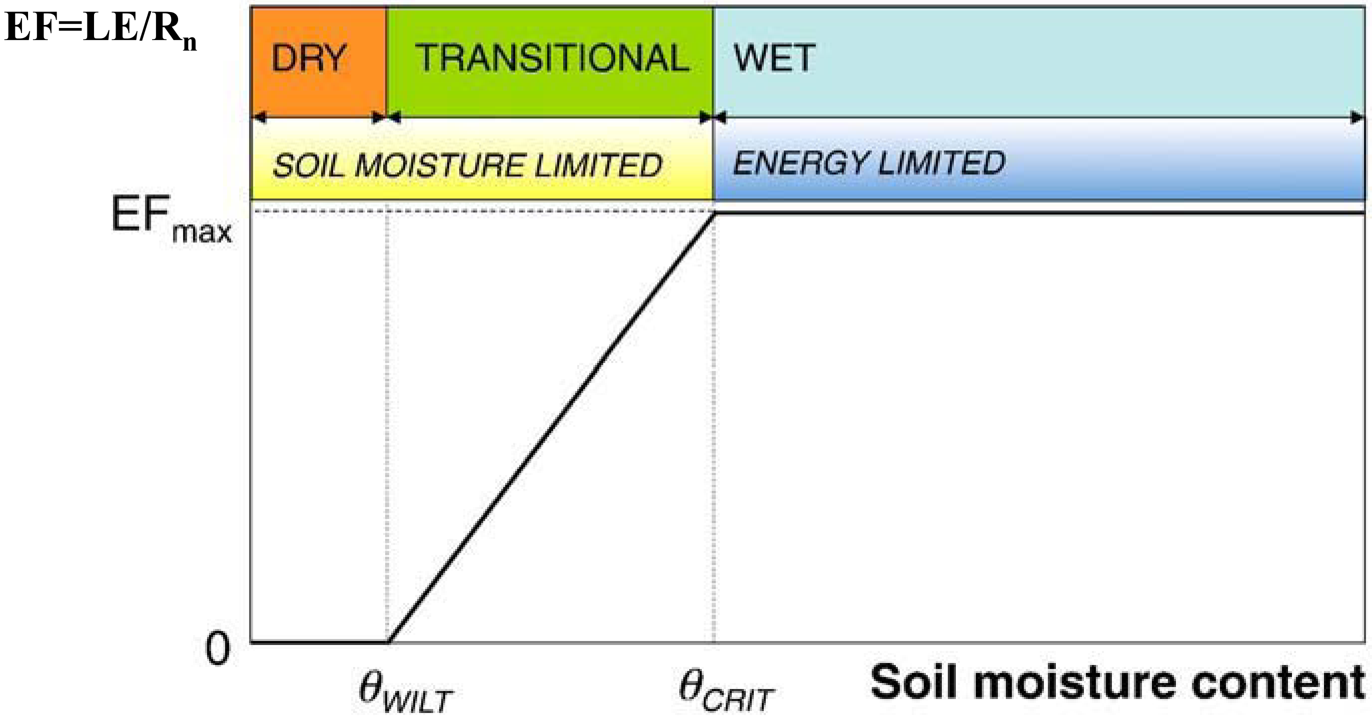
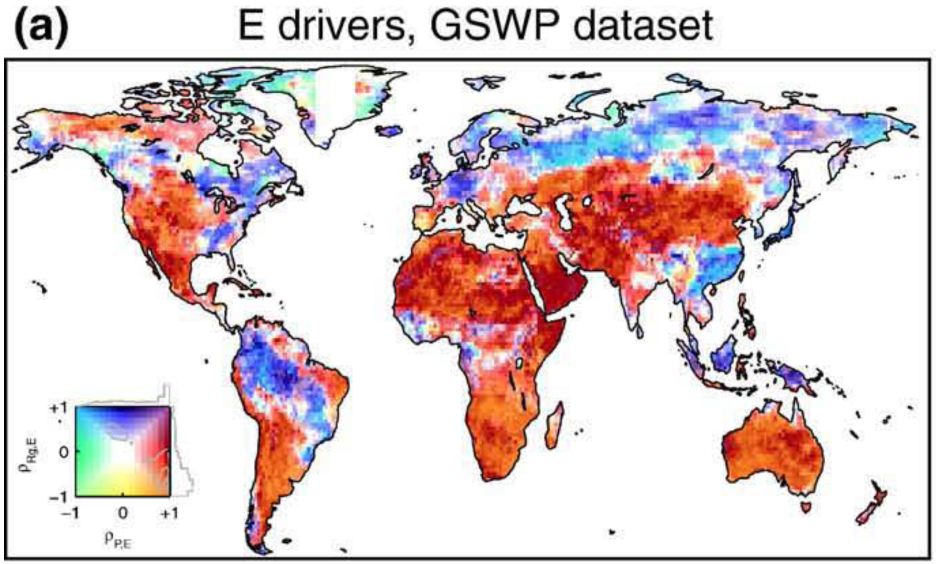
Soil moisture regimes: Water and energy limited

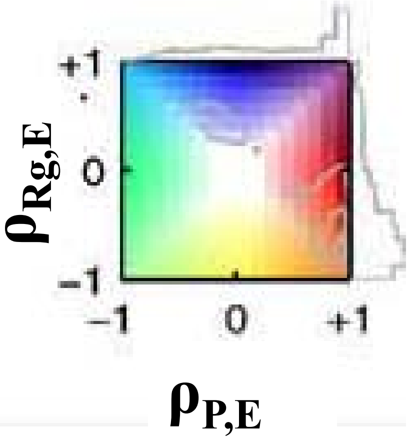


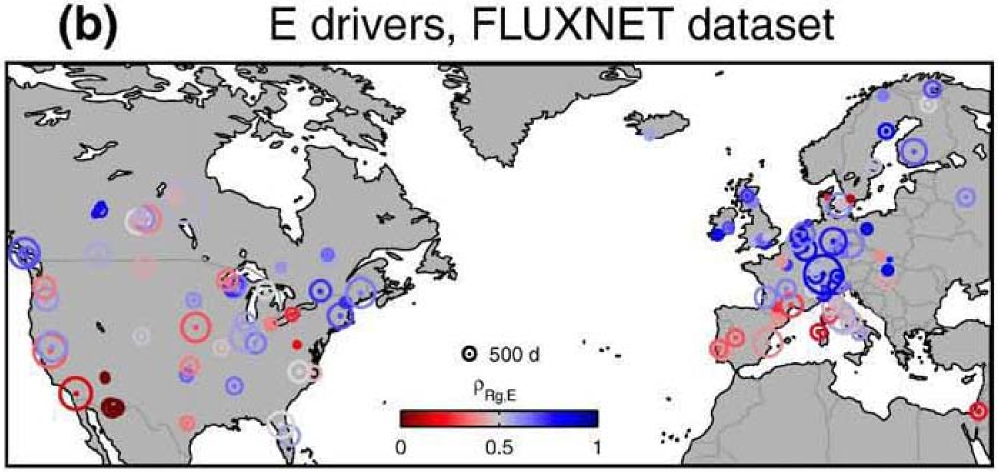
Seneviratne et al, 2010

- •High latitudes: Abundance of soil water, a short growing season and low solar radiation; evaporation is energy limited
- •Subtropics and mid-latitudes: High solar radiation and long dry periods; evaporation is soil water limited (note linearity)

Model estimates of drivers of evaporation, using observations







$\rho_{Rg,E}$

Seneviratne et al, 2010

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Land-Atmosphere coupling: The problem

- **Accurate monthly to seasonal forecasts depends on simulating the atmospheric response to slowly varying states of the ocean and land surface components of the Earth system that can be predicted weeks to months in advance.**
- **What is the response of the atmosphere to such variations in the lower boundary?**
- **Soil moisture**
  - **Can influence weather through its on evaporation**
  - **Anomalies can persist for weeks to months**
  - **Modelling studies suggest (see later), for specific years and areas, that soil moisture impacts on precipitation are commensurate with impacts from the ocean (SST)**

Scientific question: Are there specific locations on the Earth surface for which soil moisture anomalies have a substantial impact on precipitation?

Land-Atmosphere coupling: GLACE

- **GLACE: Global Land-Atmosphere Coupling Experiment**
- **The main question**
  - **Identification of land surface "hot spots", locations for which soil moisture anomalies have a substantial impact on precipitation?**
- **Subsidiary questions**
  - **Identify the contribution of the land surface to explain the variance of precipitation**
- **Importance**
  - **Design of seasonal prediction systems**
  - **Development of ground-based and satellite based strategies for monitoring soil moisture**
  - **In a broader sense, further the understanding of the Earth's climate system and the limits of predictability**

Koster, R.D. et al., 2004. *Science*, 305, 1138-1140.

GLACE: Methods

- **Three 16-member ensembles of AGCM integrations (SST prescribed to observations) for summer (JJA) 1994**
  - **W (“write” ensemble): Free AGCM integrations, with a prescribed method of perturbed initial conditions to generate the ensemble**
    - **Write-up of all land surface fields prognostic fields during the integration for one member, randomly chosen, labelled “W1”**
  - **R (“read” ensemble): As for W, but all members replace the land surface fields, every time step, by the land surface field from the file created in W1**
  - **S (“subsurface” ensemble): As for S, but only for soil moisture below the top surface level**
- **12 participating models**

Ω diagnostic: Explained variance

P_i Precipitation of member i of the ensemble

$$\widehat{P}(t) = \frac{1}{16}\sum_i P_i(t)$$

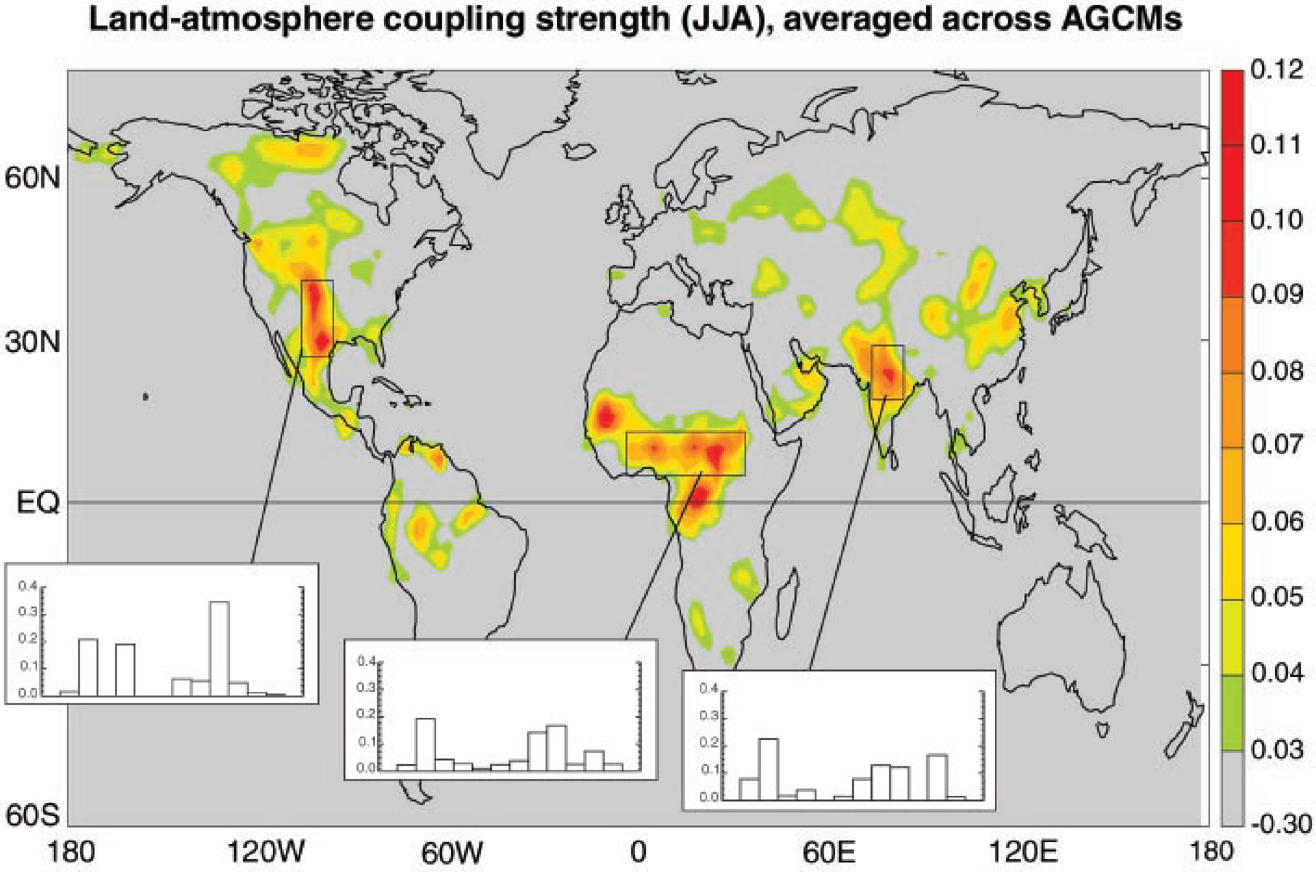
$$\Omega_P = \frac{\sigma_{\widehat{P}}^2 - \sigma_P^2}{15\sigma_{\widehat{P}}^2}$$

$0 < \Omega_P < 1$ Degree to which the 16 precipitation time series in the ensemble are similar

Ratio of explained precipitation variance to total variance

Experiment	Description	Key diagnostic
W	Free integrations	**Ω_P(W)**: Fraction of variance “explained” (forced) by all boundary and initial conditions
R	All land surface variables constrained	**Ω_P(R)-Ω_P(W)**: Fraction of variance “explained” by all land surface variables
S	Only subsurface constrained	**Ω_P(S)-Ω_P(W):** Fraction of variance “explained” by subsurface variables

Land-atmosphere coupling strength (P)



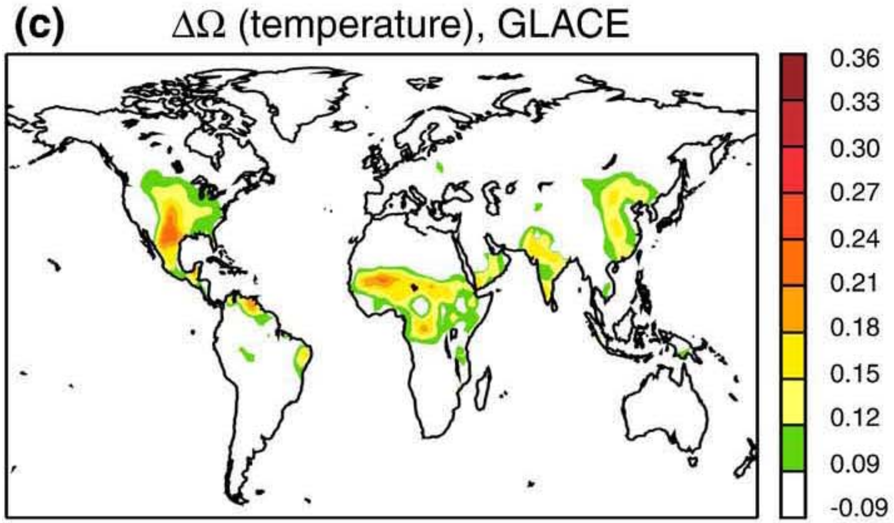
Land-atmosphere coupling strength (JJA), averaged across AGCMs

Koster, R.D. et al., 2004. *Science*, 305, 1138-1140.

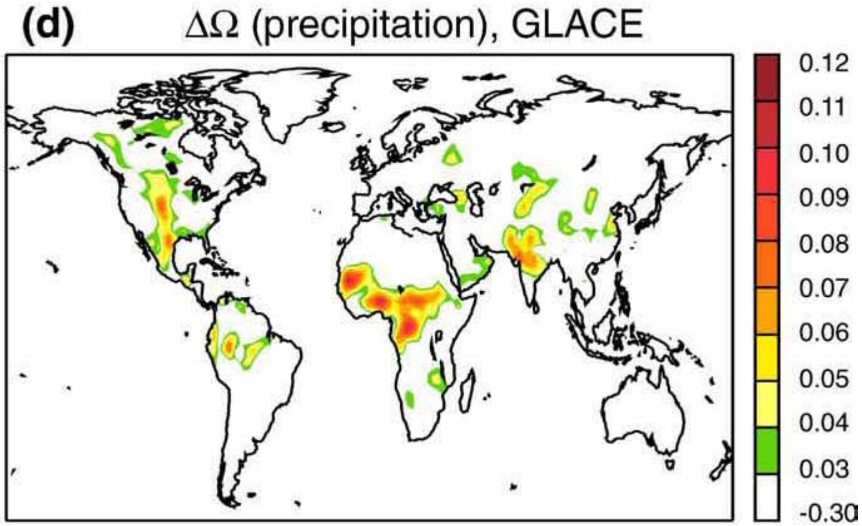
- The hot spots (regions of maximum coupling strength) are in monsoon and semi-arid areas.
- Note large inter-model variability
- No signal for Europe! Caveat: 1994 only

Coupling strength: Temperature VS. Precipitation

Temperature



Precipitation

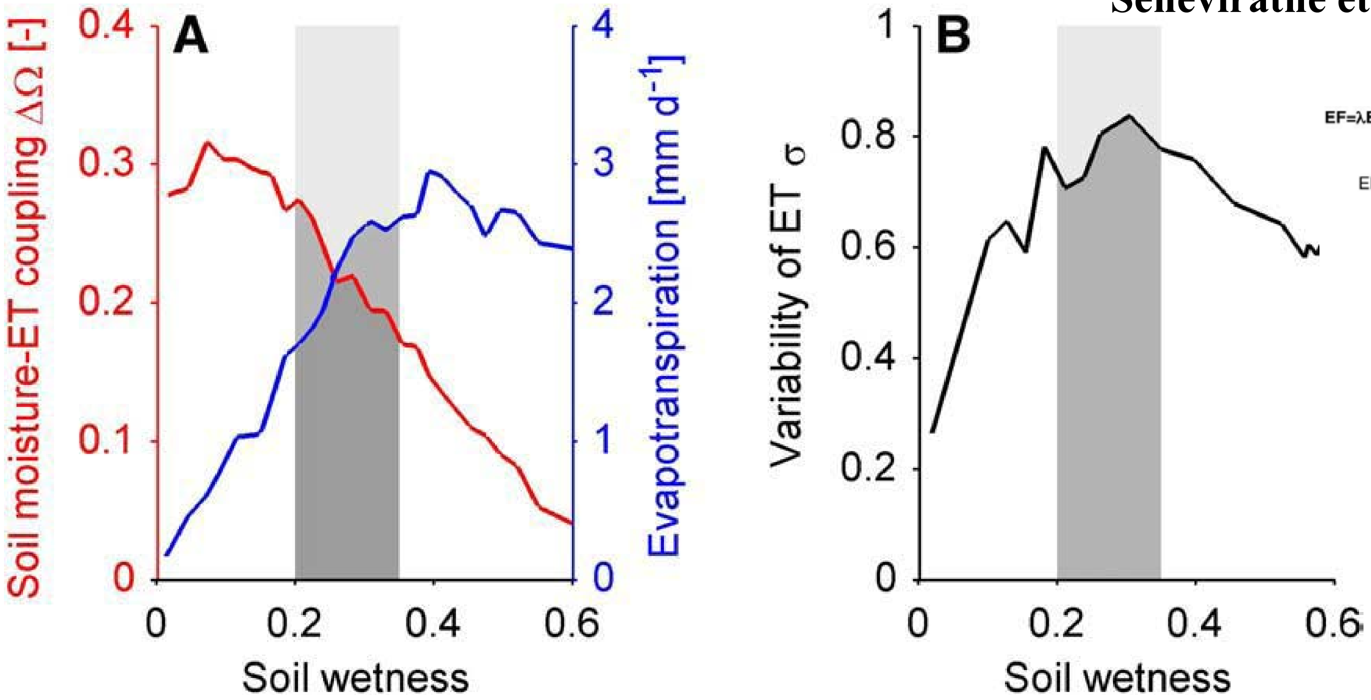


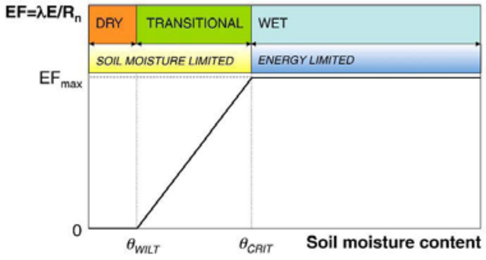
Still no signal for Europe

Koster et al., 2006. J. Hydromet.

Coupling strength and soil water regime

Seneviratne et al., 2010. Earth-Sci Rev.

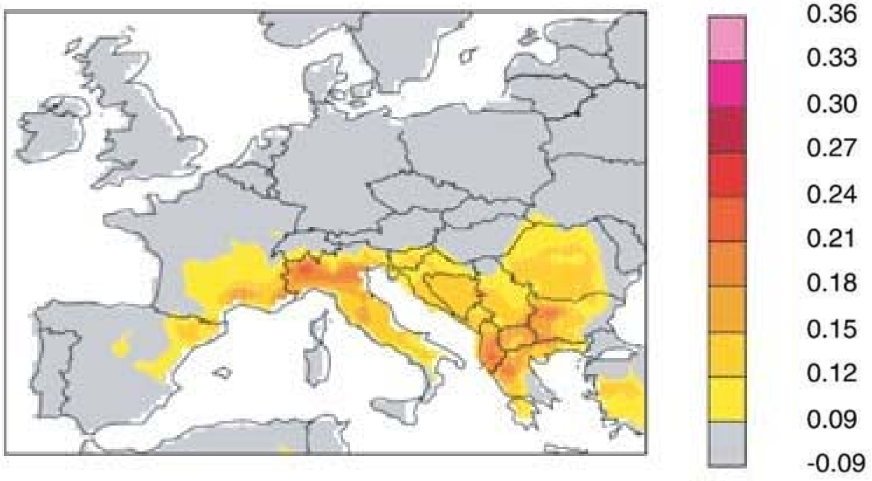


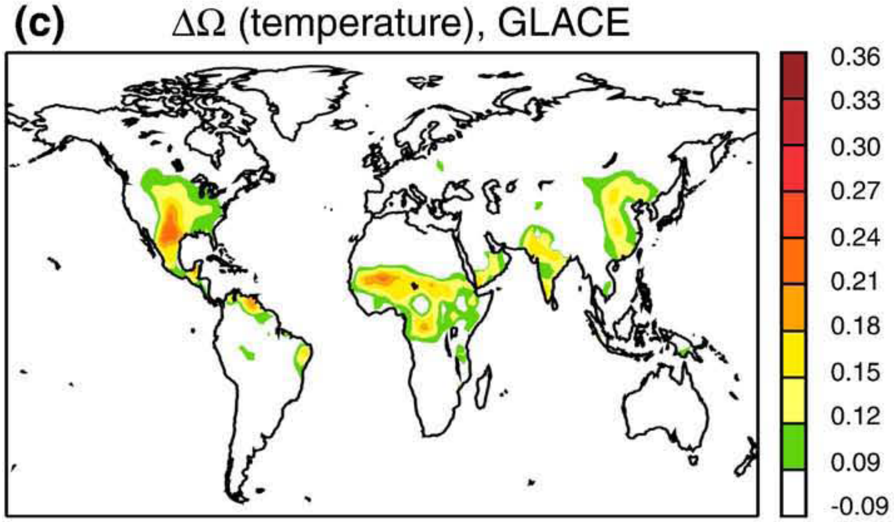


- The importance of transition regions between dry and wet climates
  - In dry regions, ET is strongly controlled by soil moisture, but absolute value and variability is low, so it will not impact on the atmosphere
  - In wet regions, ET is high, but not controlled by soil moisture
  - Transition regions: Strong dependency of ET on soil moisture and large ET mean and variability
- Note quasi-linearity

A note of optimism for Europe: RCM model

ΔΩ (temperature) for ETH RCM, 30 year run





Seneviratne et al., 2006. Nature.

- A signal in Southern Europe (transition regions), in contrast to global GLACE experiments.
- But ETH simulation has the following differences
  - 30-year simulations (interannual SST simulations) vs. 1994 16-member
  - One model only
  - RCM vs. GCM (RCM might have smaller internal variability)
  - Higher horizontal resolution

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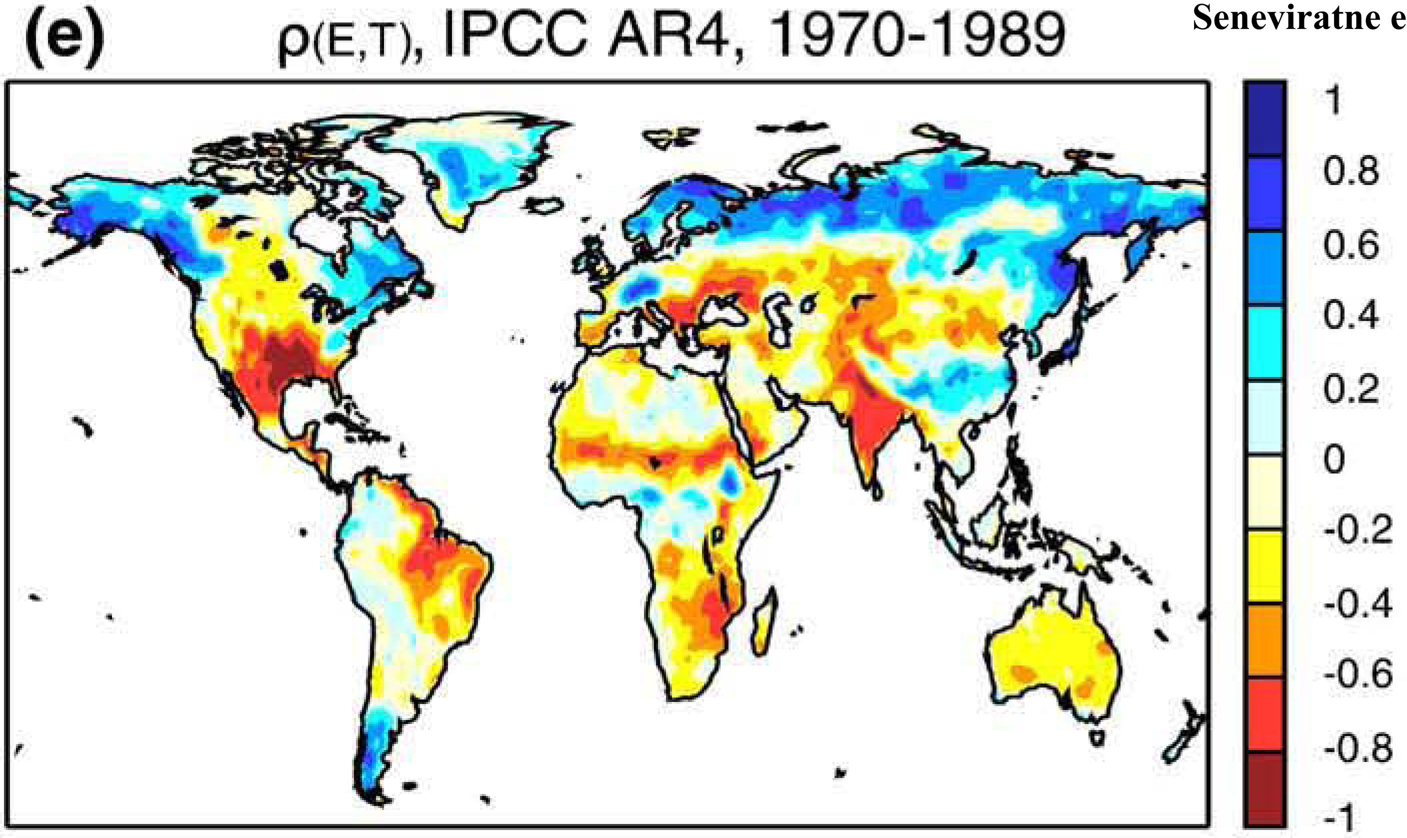
JJA Soil moisture-Temperature coupling



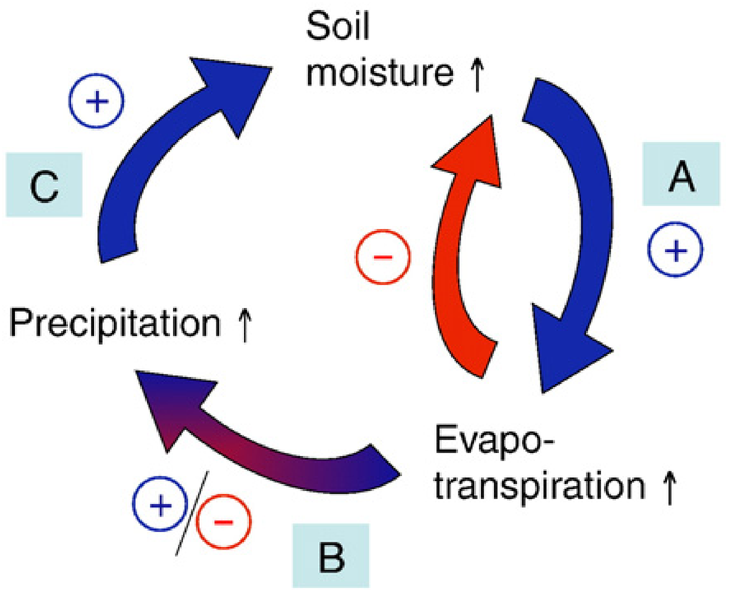
Seneviratne et al, 2010

- **Negative correlations in semi-arid and transition areas (soil water limited evaporation). Note Southern Europe !!!**
- **Positive correlations in energy limited areas**

SM-P coupling: Mechanisms

- **Early results (papers until mid-90s) focus on moisture recycling, a local effect: Higher soil moisture results on higher evaporation leading to higher precipitation**
- **Recent studies (cluster of papers on Mississippi 1993 floods, several papers over Europe, AMMA results over West Africa) emphasize indirect effects. Changes in SM can lead to**
  - **Changes in boundary layer stability**
  - **Changes in cloud cover or cloud base**
  - **Changes in precipitation formation mechanisms (e.g. Nicholson 2000)**
  - **Non-local changes such as advection of moisture (e.g. Beljaars et al. 2006)**
  - **Land surface heterogeneity (Avissar and collaborators, Taylor and collaborators, AMMA results)**

Feedback mechanisms



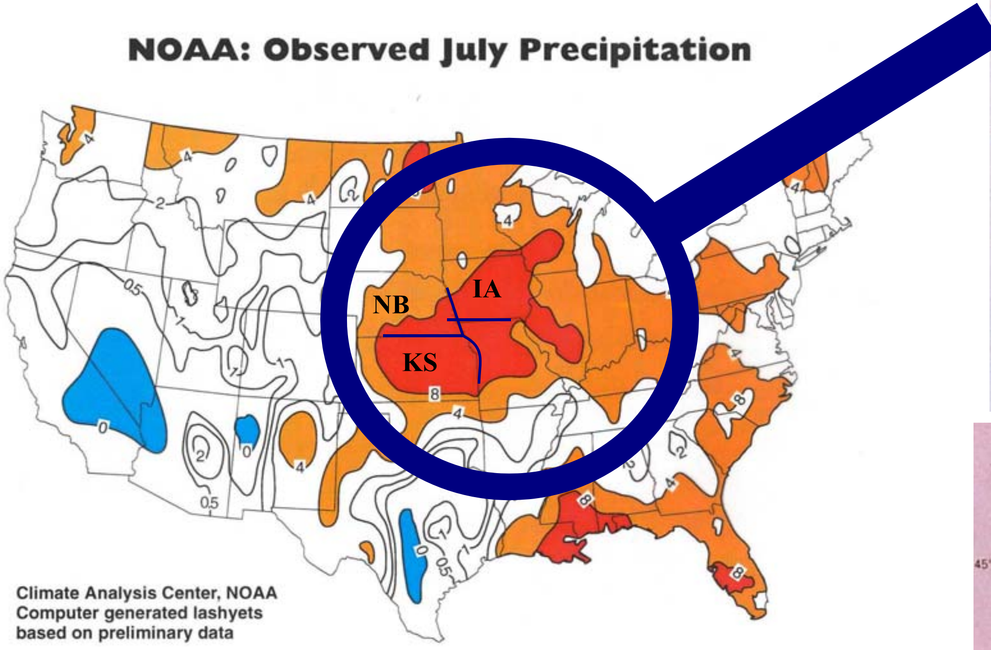
Seneviratne et al, 2010

Blue arrows:
Positive feedbacks

Red arrow:
Negative feedback

- **C – Higher precipitation leads to increase in soil water**
- **A – Higher soil moisture leads to higher evaporation (blue)**
  - **But higher evaporation depletes soil moisture, reducing the evaporation**
  - **Increase in precipitation in C has to compensate for the possible negative feedback in A**
- **B – The majority of studies suggest that ET leads to higher P**
  - **A few studies suggest negative feedback: (i) dry soils can enhance convective instability and favour precipitation, or (ii) non-local and heterogeneity effects**
- **There is a large uncertainty on the strength of the SM-P coupling (GLACE)**

Summer: US July 1993 (1)


NOAA: Observed July Precipitation

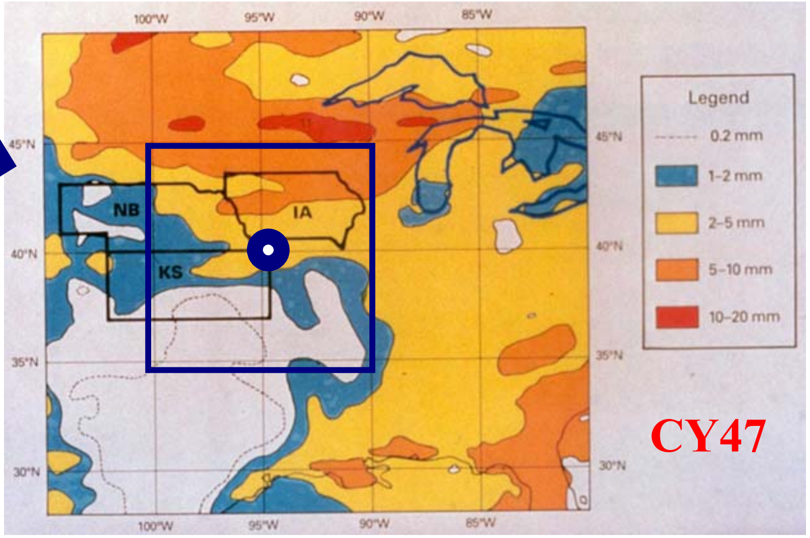
Climate Analysis Center, NOAA
Computer generated Iashyets
based on preliminary data

🟥 > 7 mm/day

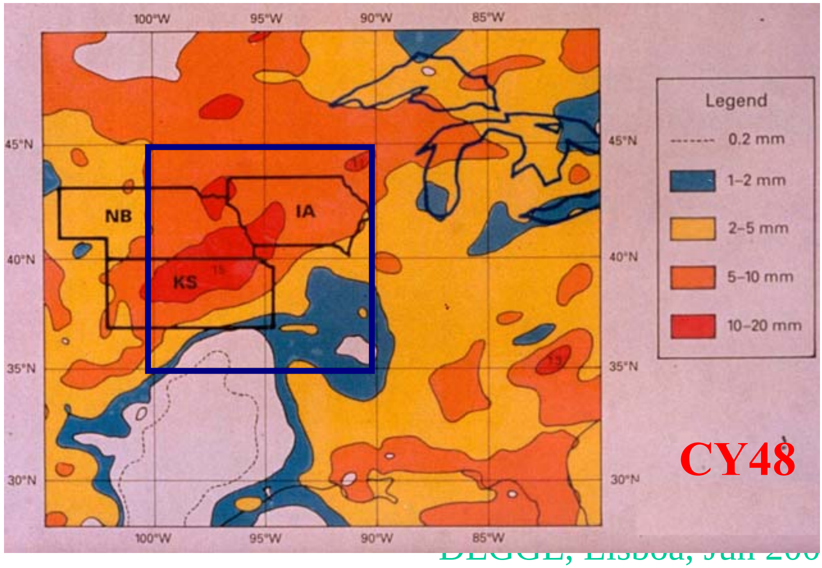
🟧 3.5 < < 7

Beljaars, Viterbo, Miller and Betts, 1996:
Mon. Wea. Rev., 124, 362-383.

Model day 3 precipitation 9-25/7



CY47



CY48

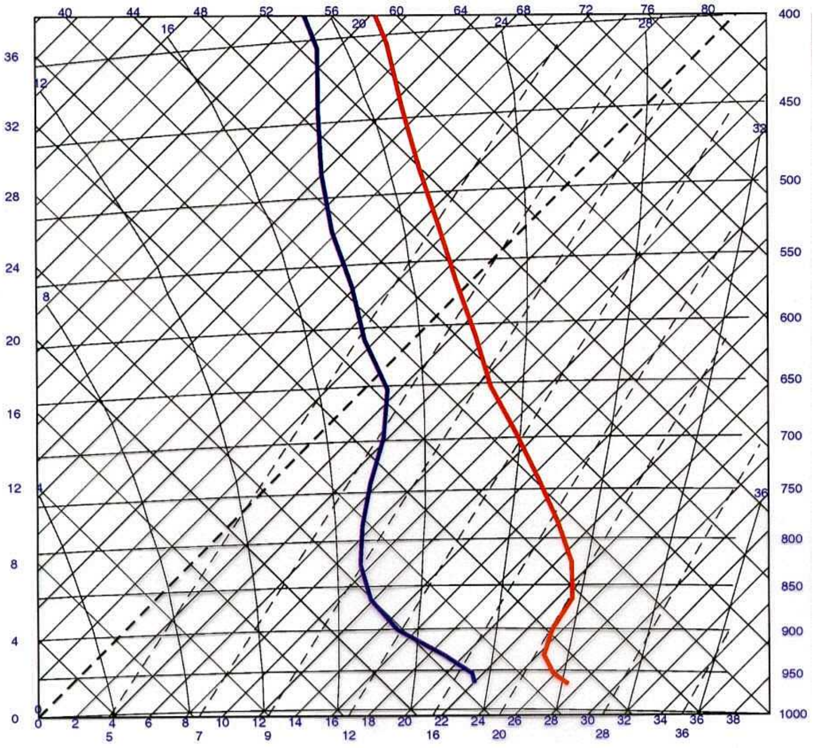
Summer: US July 1993 (3)

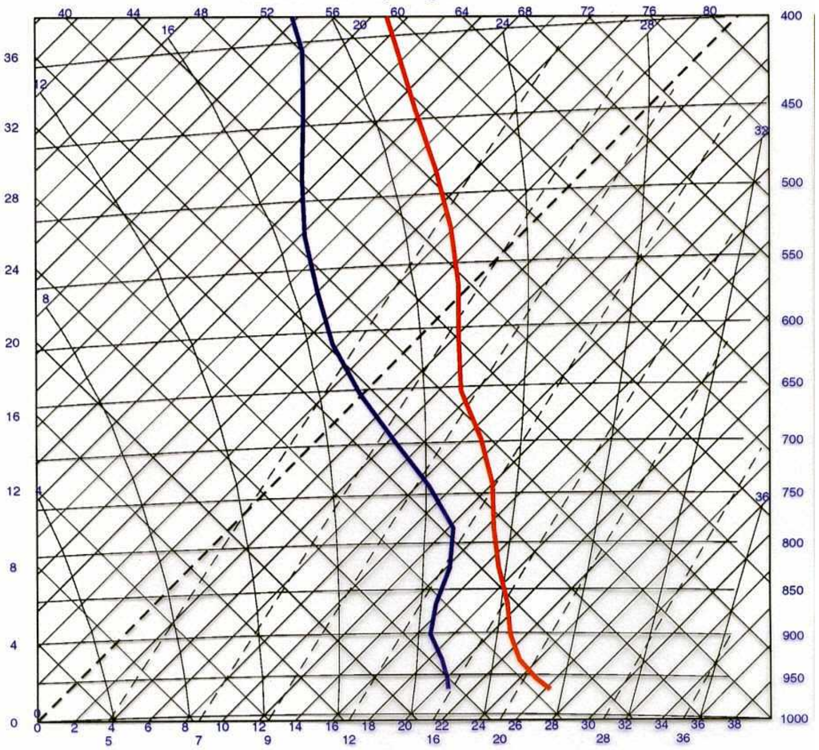
INSTITUTO DE METEOROLOGIA
PORTUGAL

Averaged values on 10x10 degree box

	Forecast	Precipitation	Evaporation
CY47	Day 1	6.4	4.4
	Day 3	2.6	4.6

	Forecast	Precipitation	Evaporation
CY48	Day 1	6.6	4.4
	Day 3	5.6	4.5


Profile 40 N 95 W CY47


Profile 40 N 95 W CY48

All results time averaged 9-25 July

DEGGE, Lisboa, Jun 2008

Summer: US July 1993 (3)

Mean back-trajectories ending at 40 N 95 W

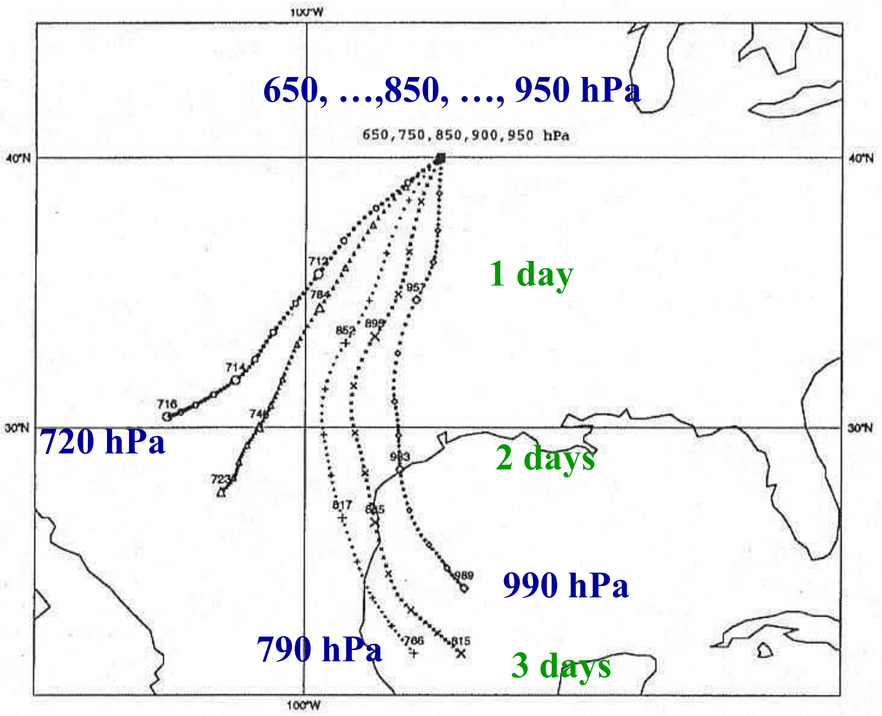


FIG. 5. Three-day backward trajectories from location 40°N, 95°W at the levels 950, 900, 850, 750, and 650 hPa. The fields at successive forecast ranges 72, 66, 60, . . ., 12, 6, 0 h, averaged between verifying dates 9 to 25 July, have been used for the computation of these trajectories. The printed numbers along the trajectories indicate the pressure height at one-day intervals.

- **Two distinct treatments of the land surface (CY47 and CY48) give a substantially different forecast of precipitation at short-range, yet very similar local evaporation**

- **The difference can be explained by a distinct evaporation upstream of the area of maximum precipitation; In CY47, warmer/drier air is advected from the S/SW (Mexican plateau) resulting in a larger capping inversion**

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Earlier studies

- **Soil moisture evolution depends on the time integrated precipitation**
- **Soil moisture has a long persistence time-scale, 1-2 months**
- **The potential of soil moisture initial conditions as an important ingredient of monthly and seasonal forecasts depends on the co-existence, over a given region of**
  - **Strength of soil moisture–climate coupling**
  - **Soil moisture memory**
- **Early mechanistic experiments, e.g., Shukla and Mintz 1982**
  - **Comparison of “parking lot” Earth with vegetated Earth: Impacts everywhere**
- **Non-European impacts**
  - **Many studies over the USA**
  - **Some studies over West Africa and India (e.g. Douville 2002)**
  - **Indirect climate effect over West Africa (Nicholson 2000): Drought leading to increase of dust, changing the radiation balance and circulation patterns**

Impacts for Europe

- **Rowntree and Bolton 1983, 1976 European drought**
  - Two 60-day integrations initialized with dry and wet anomalous soil moisture in Central Europe (mimicking the area affected by the 1976 European drought)
  - Impact (on fluxes and precpitation) can be seen over the perturbed area until day-3 and over Scandinavia (downstream of the pertubed area) at day-6
  - Impact of initial conditions lasts until day 50
  - A repeat experiment in the presence of slightly stronger westerlies leads to impact until day 20
- **Vautard et al. 2007, obs study on extreme heat waves (EHW)**
  - Winter drought in S. Europe is a necessary condition for the development of summertime EHW; advection of dry air from S. Europe propagates the heat wave to N. Europe.
  - There are no changes in circulation patterns, but a modification of the air humidity that gets advected by the large-scale circulation

SM interaction with biogeochemical cycles

- Ciais et al. 2005
  - Summer 2003 drought dramatically reduced plant productivity and European continent acted as a source of CO2
  - Jones and Cox (2005) suggested that the signal was so large as to be visible in the Mauna Loa observations record
- Summer 2003: Species/ecosystem dependency on tolerance to drought anomalies might induce local/regional signatures of warming (which might be important for medium.range forecasts) (Granier et al. 2007)
- 2003 earlier spring led to earlier onset of evaporation in some species, inducing SM depletion with possible impacts during summer (Fischer et al. 2007)

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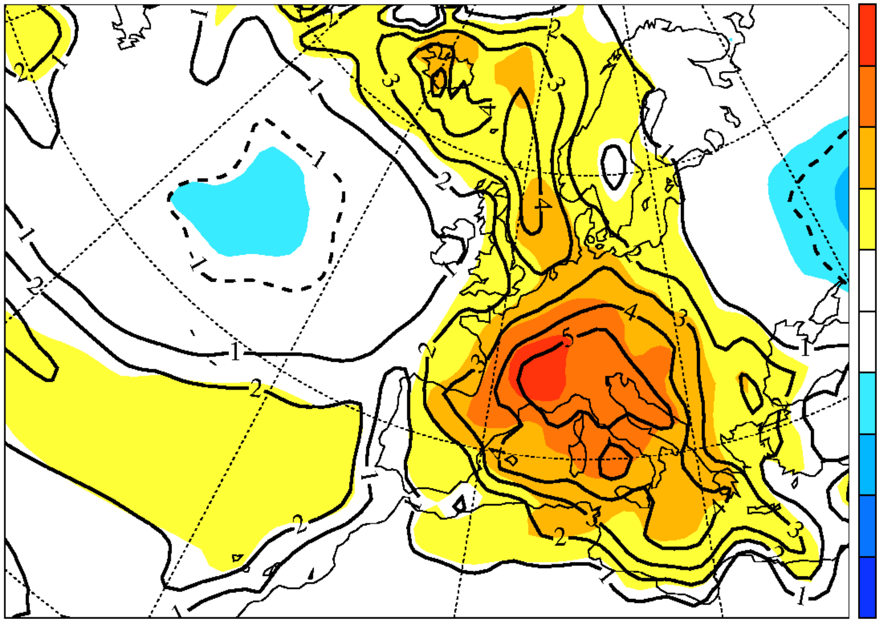
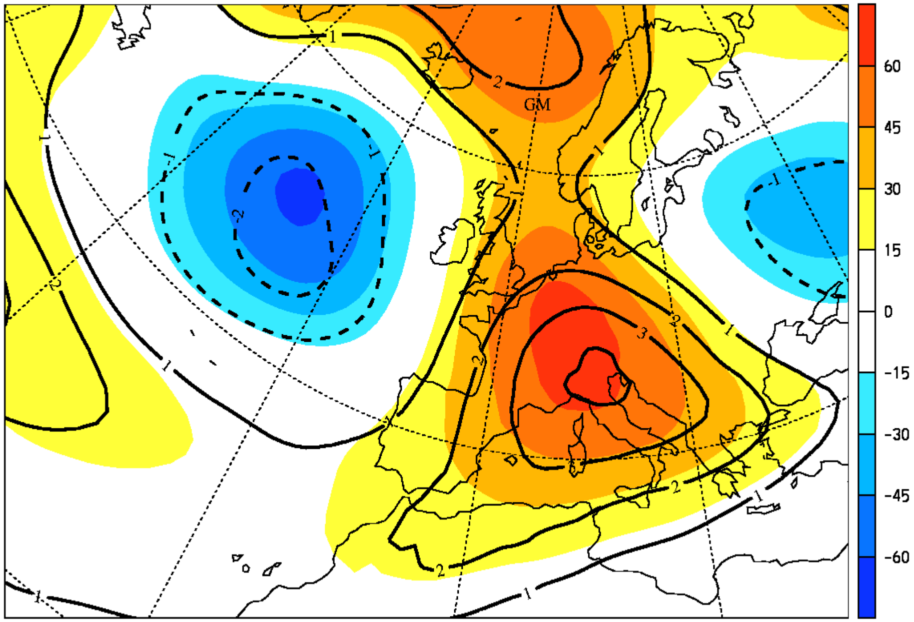
Summer 2003: 850 hPa T and 500 hPa z anomalies

850 hPa T anomaly JJA 2003



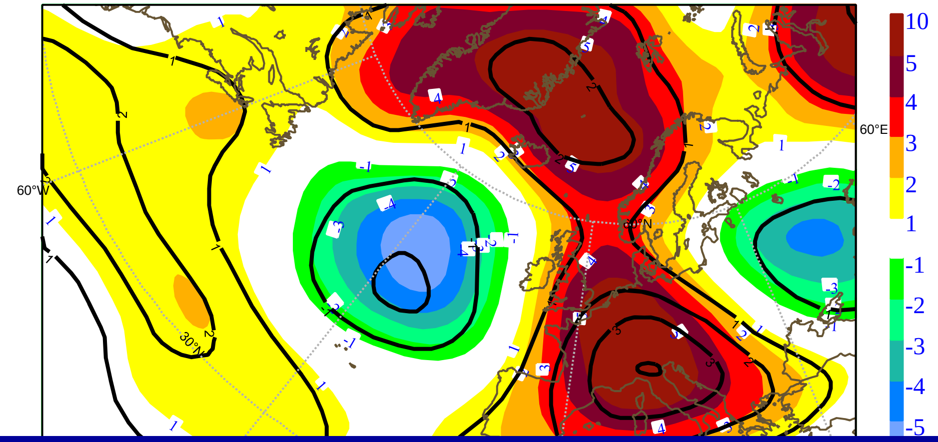
Z 500 hPa anomaly JJA 2003



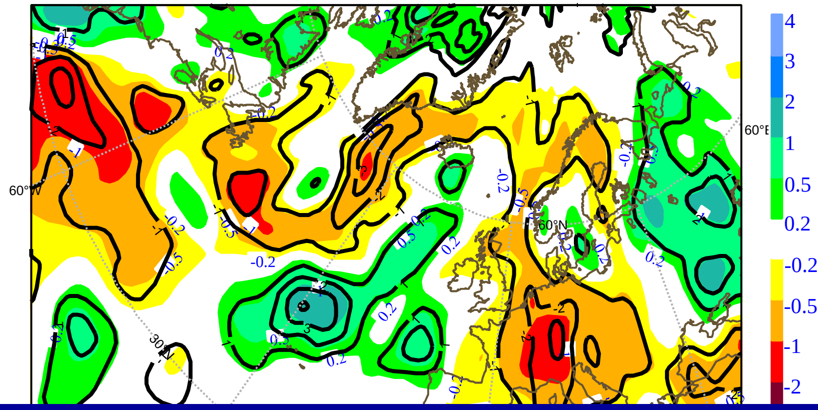
(Schär et al. 2004, *Nature*, **427**, 332-336)

Anomaly: Spring and summer

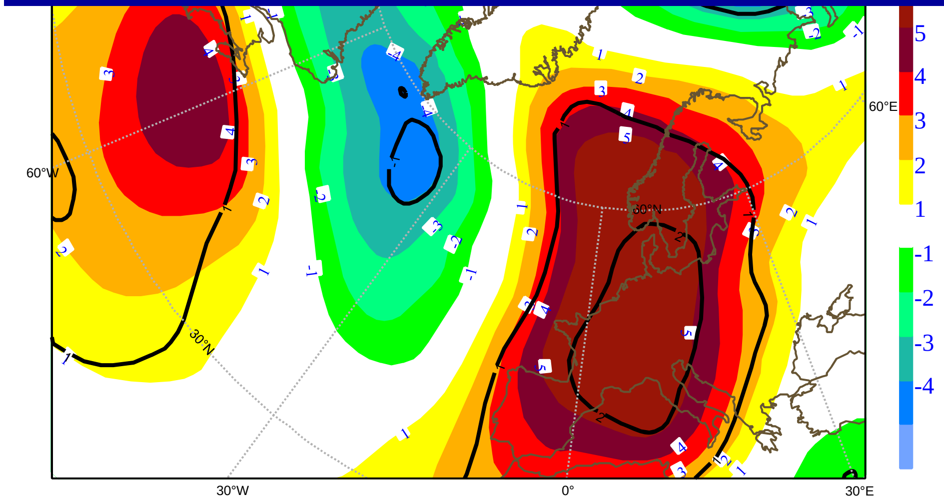
Summer: z500

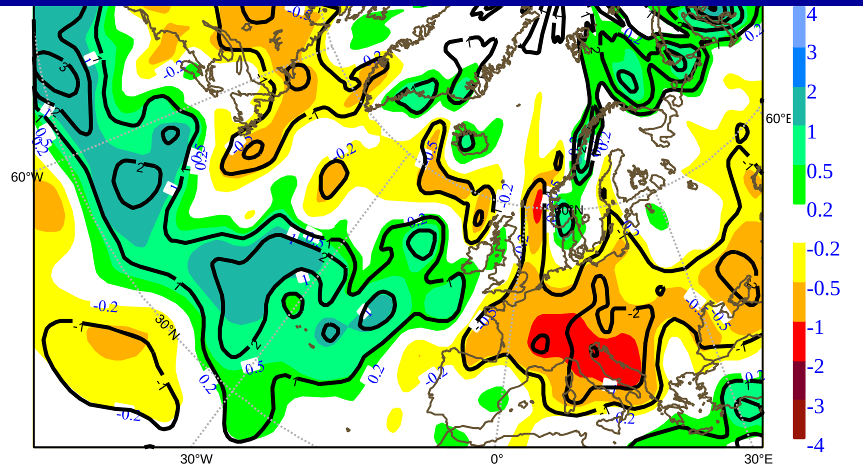


Summer: precip



The anomalous circulation in summer was preceded by a European-wide anomaly, with a dry spring and a 500 hPa ridge

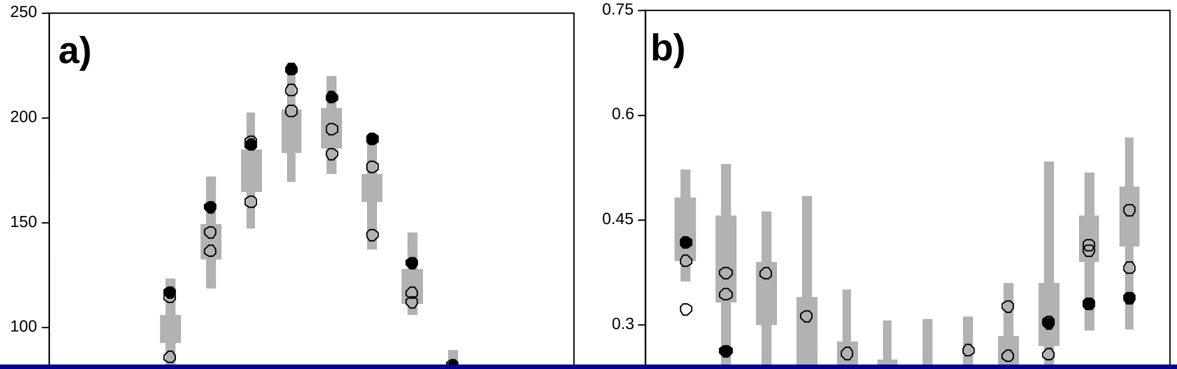




Surface energy budget (41º-50ºN 2ºW-16ºE)

ERA-40: Boxes and whiskers; 2001 e 2002 ¤; 2003 •

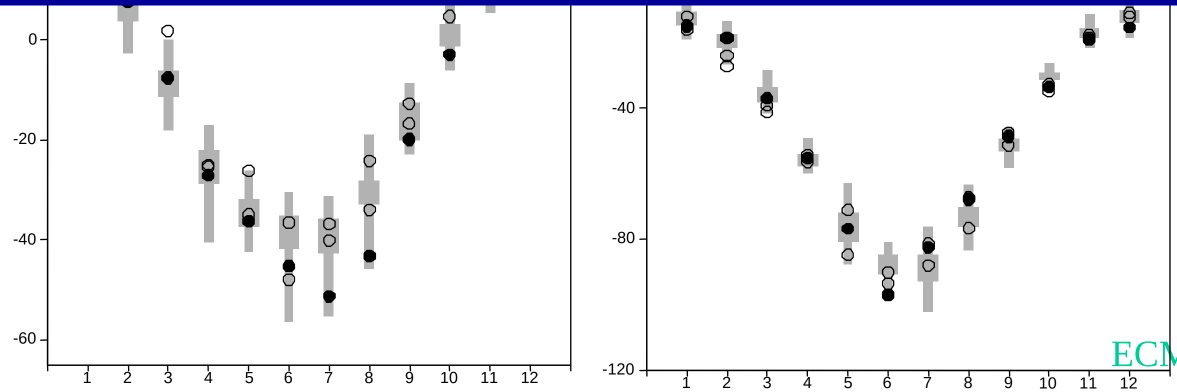
Sw_{net} (Wm^{-2})



cloudiness

- Since March, positive anomalies on surface solar radiation, associated to a deficit in low clouds
- The land surface starts to respond in June, with an increase in sensible heat flux, and a decrease in evaporation since July

H (Wm^{-2})

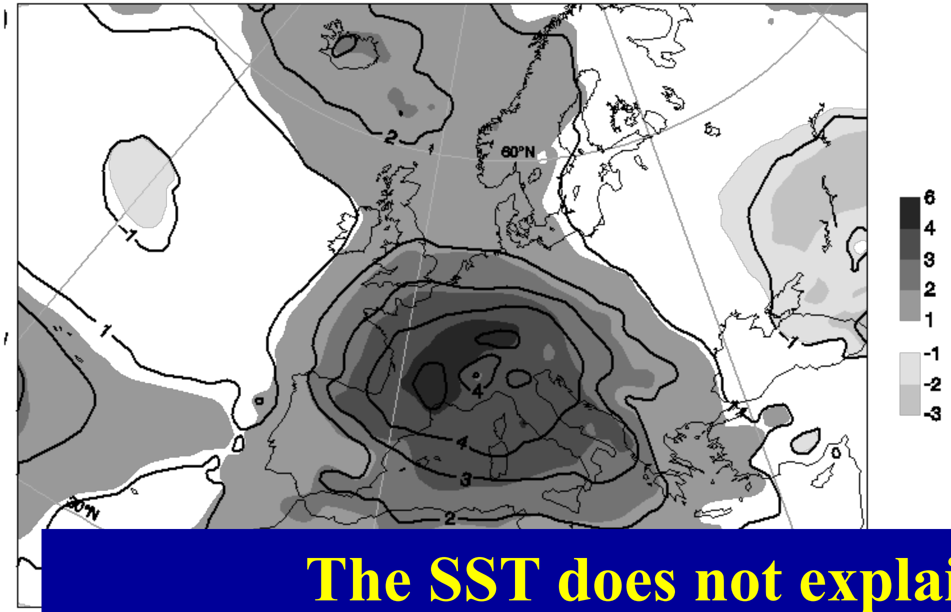


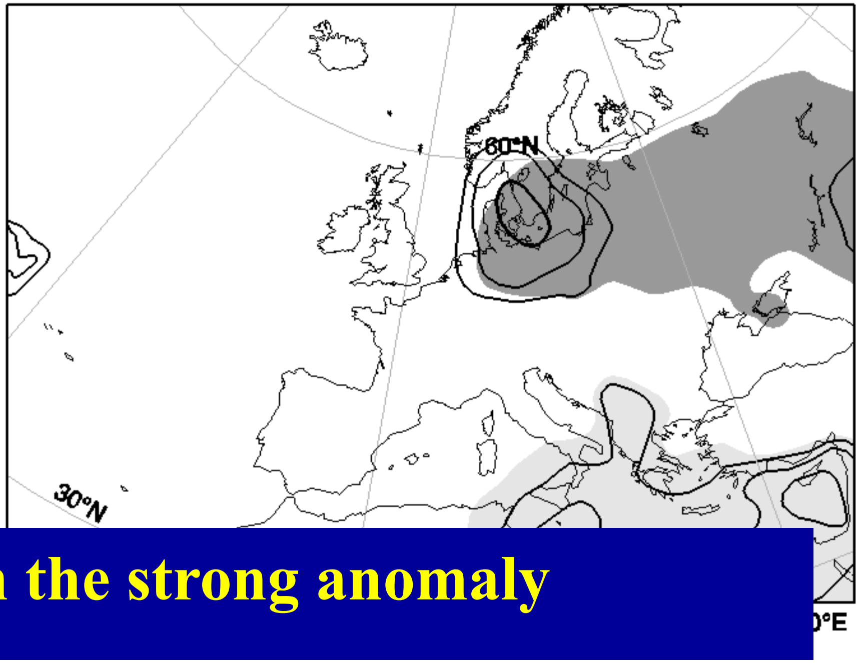
LE (Wm^{-2})

Impact of SST on 850 hPa temperature, JJA

Observed anomaly, T850

T850 difference: (ObsSST-climSST) experiments





The SST does not explain the strong anomaly

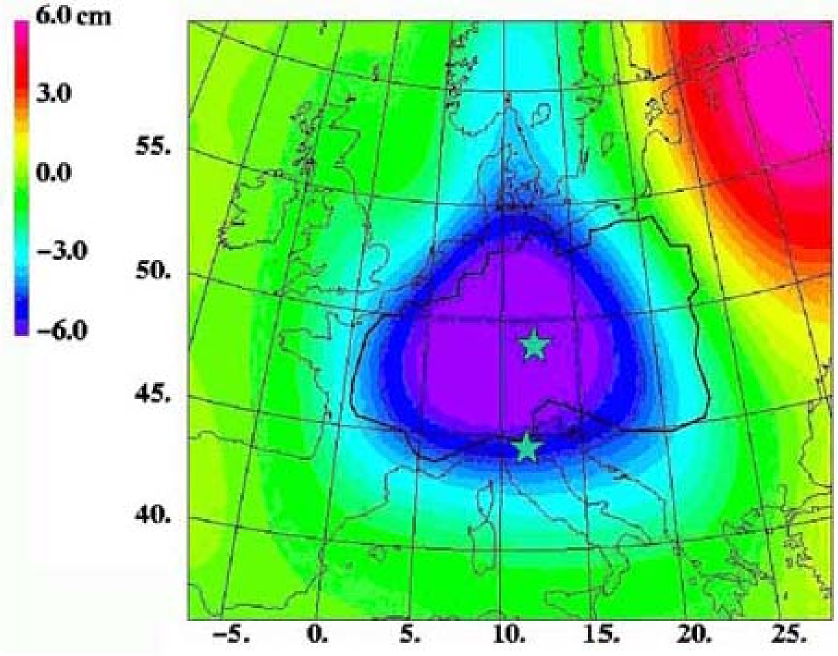
Greys: temperature

Isolines: t-significance 90, 95, 99%

Ferranti and Viterbo, 2006

Anomaly in soil water: GRACE Total Water Storage (TWS)

Fitted TWS 2002-2003 linear trend



April to August depletion of Total Water Storage (TWS) in 2002, 2003 and difference (excess TWS drying)		
2002	**2003**	**Difference**
3.5 cm	**9.2 cm**	**5.7 cm**

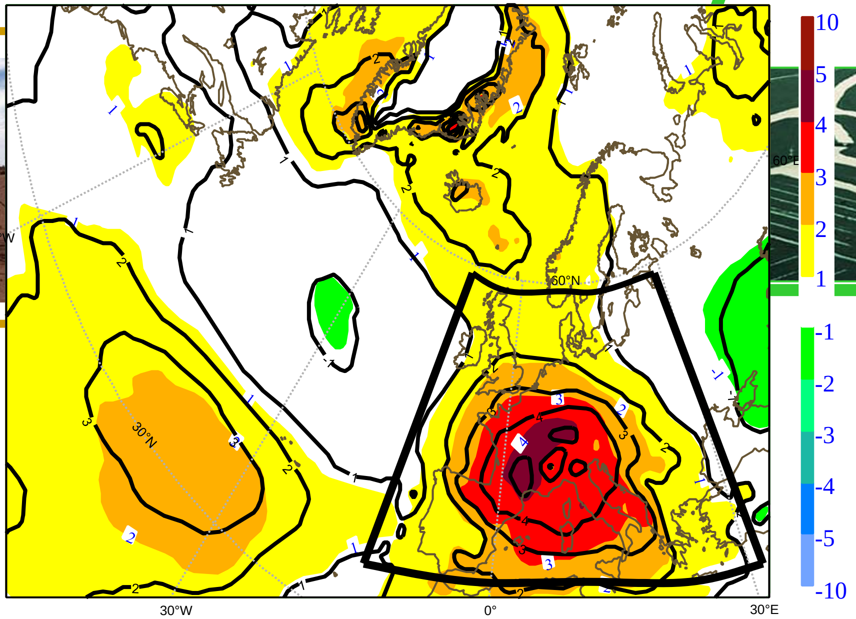
Description of experimentation

- Integrations of atmospheric model (imposed SST) June-to-September
- ECMWF (global) model, 210 km horizontal resolution and 40 levels
- 9 members-ensembles
  - Initial conditions 28,29,30,31 May 1,2,3,4,5 June 2003

- Control (INIWO) ("Perfect ocean")
  - Initial soil water conditions
  - Observed SST imposed daily
- Sensitivity to soil water (RxxxO or TxxxO)
  - Soil water initialized in Europe to an uniform value
  - Observed SST imposed daily
- Climate (INIWC) ("Ocean model without prediction capability: climatology")
  - Initial soil water conditions
  - Climatological SST imposed daily

Ensembles: Prescribed initial conditions for the soil water for [37-60 N 10W-30E]

	Initial soil water					
SST	**0** **DRY**	**0.25** **25% cap**	**0.5** **50%cap**	**0.75** **75% cap**	**1** **WET (Field capacity)**	**1 June**
Observed	**R000O** **T000O**	**R025O** **T025O**	**R050O** **T050O**	**R075O** **T075O**	**R100O** **T100O**	**INIWO**
Climate						**INIWC**



Total water impact

Area: 37º-52ºN 10ºW-20ºE

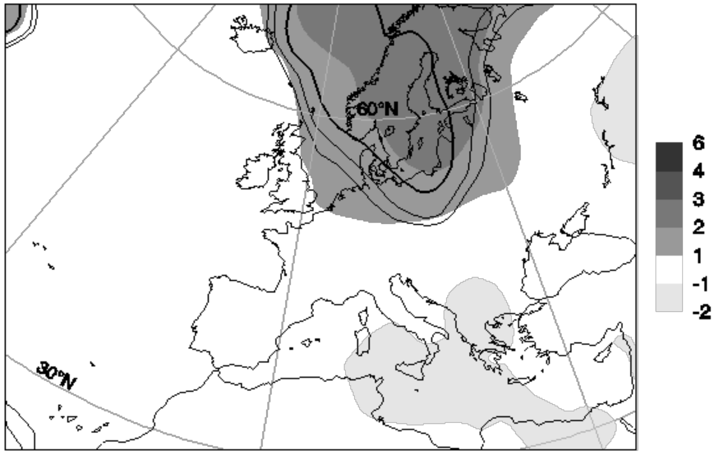
Initial SMI range	Impact month 1	Impact month 2	Impact month 3	Field
0-1	**20.2 +4.3 -18.5**	**+3.4 -19.1**	**+2.7 -11.2**	z500 (m) T850 (K) z1000 (m)
0-0.75	**25.9 +4.3 -15.4**	**+2.8 -27.6**	**1.7 -14.5**	z500 (m) T850 (K) z1000 (m)
0.25-1	**+2.7**	**+2.9 -11.8**	**+2.4 -11.3**	z500 (m) T850 (K) z1000 (m)
[illegible]	[illegible]	[illegible]	[illegible]	z500 (m)
0.5-1	**1.3**	**1.5**		T850 (K) z1000 (m)
0-0.25	**+1.6 -10.8**			z500 (m) T850 (K) z1000 (m)
0.5-0.75	**1.3**	**-14.7**		z500 (m) T850 (K) z1000 (m)

- **An initial soil water anomaly in the total depth has a larger, longer-lasting impact (memory)**
- **The impact extends trough the troposphere**

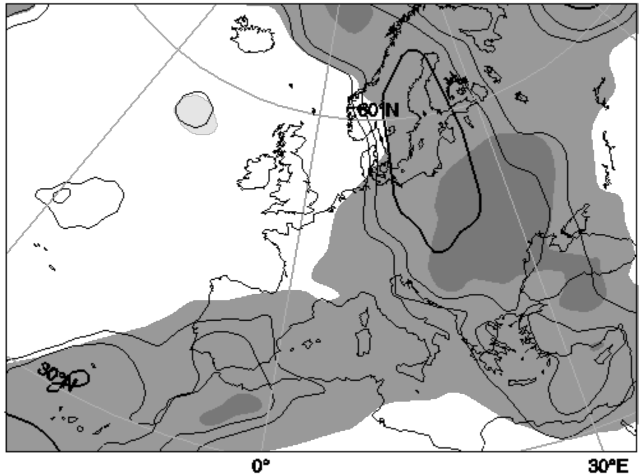
850 hPa temperature: SST vs. Soil water, month 3 (August)

Ferranti and Viterbo, 2006

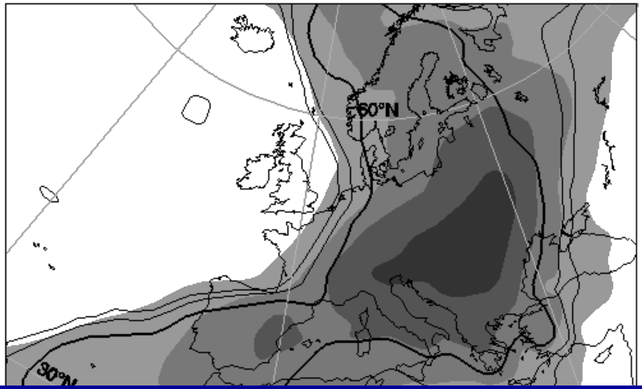
SST impact



Impact of root zone soil water



Impact of the total soil water



SSt impact (INIWO-INIWC) is much smaller than the combined impact of a dry pertubation on the soil water initial conditions, imposed in the root zone or total soil water

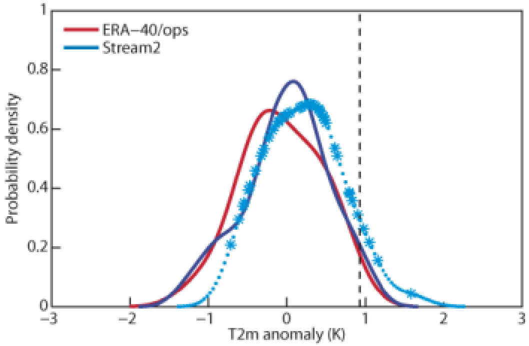
850 hPa temperature, JJA

	Impact of:	T850 (K)
INIWO-INIWC	Ocean anomalies	0.1
R025O-INIWO	**Root zone soil water anomalies**	**1.4**
T025O-INIWO	**Total soil water anomalies**	**2.5**
Observed anomaly		2.6 (3.1 σ)

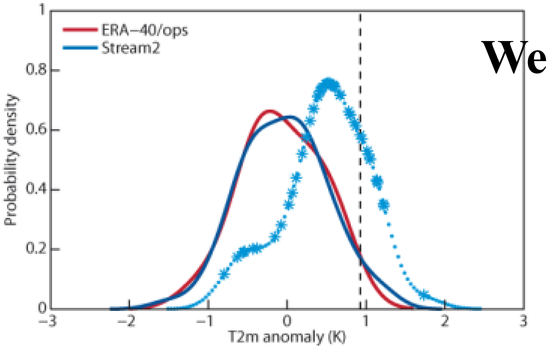
Summer 2003: Sensitivity to physical processes

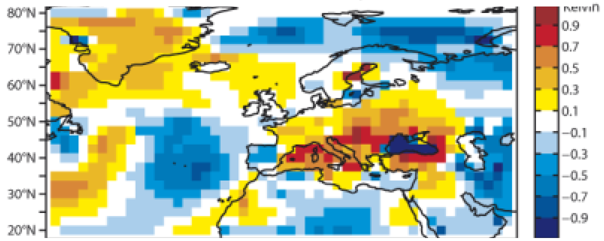
Weisheimer, 2009

System 3

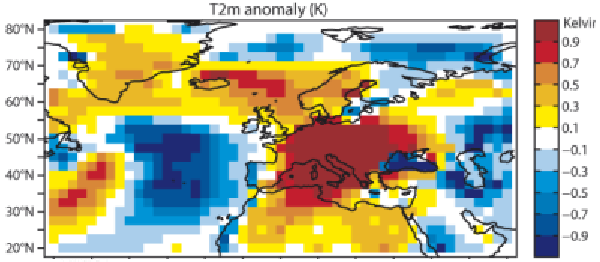


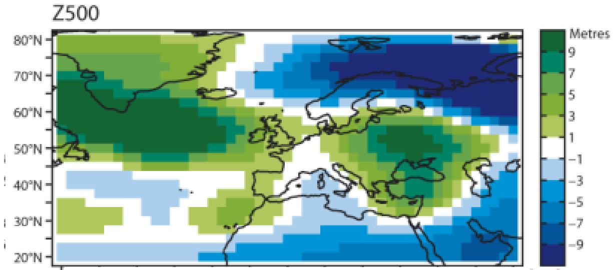
2T



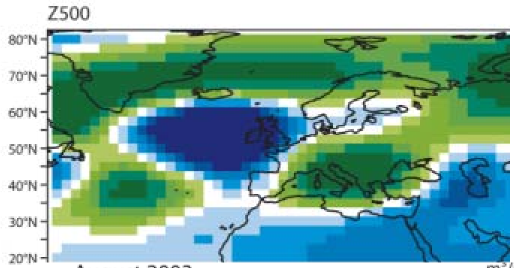


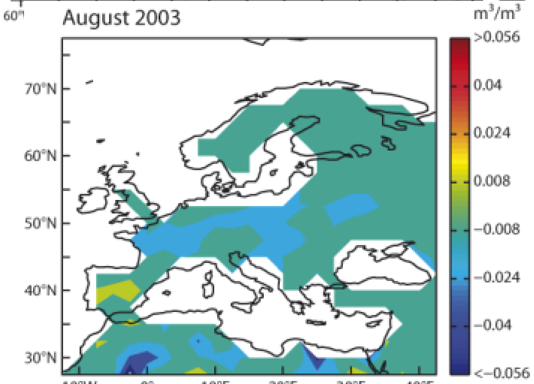
2T



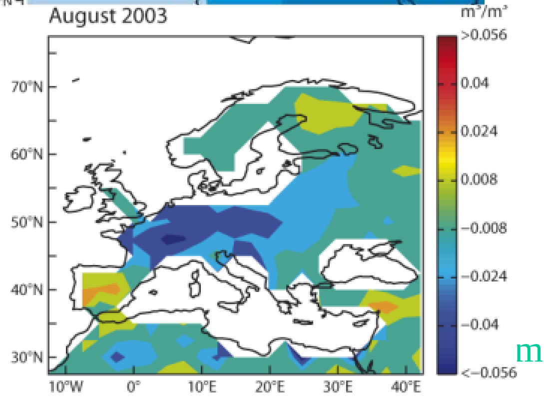


z500





Soil moisture



System 3 + new physics

Sensitivity to land initial conditions: GLACE-2

- **The main scientific question**
  - **Does realistic soil moisture initialisation improve subseasonal forecasts?**
- **Methods**
  - **2 sets of one hundred 2-monthAGCM integrations (SST prescribed to observations) , with initial conditions every half-month 1 April and 15 August, for years 1996 to 2005**
    - **1st set: Realistic soil moisture initialisation**
      - obtained, for each model, by an offline land-surface model run forced by “observations” (GSWP datasets)
    - **2nd set: Randomly chosen soil moisture initialisation**

Koster et al., 2010. *GRL*.

GLACE-2: Measures of skill

- Variables: Mean daily 2m temperature and precipitation
- Observations
  - USA
    - Hadley Centre Tmin and Tmax dataset mean daily 2T dataset
    - Higgins (2000) precipitation dataset (gauge-based) for the USA
  - Europe
    - Haylock et al. (2008) for both 2T and precipitation
- Model data
  - Results averaged for 3 15-day forecast periods: 16-30, 31-45, 46-60
  - Initial conditions between 1 June and 15 August
- Metrics
  - Standardized X variables for both forecasts and observations $\frac{X - \hat{X}}{\sigma_X}$
  - r^2 of model and observations
  - Skill measured as r^2 difference between the sets of correct initialisation minus random initialisation experiments

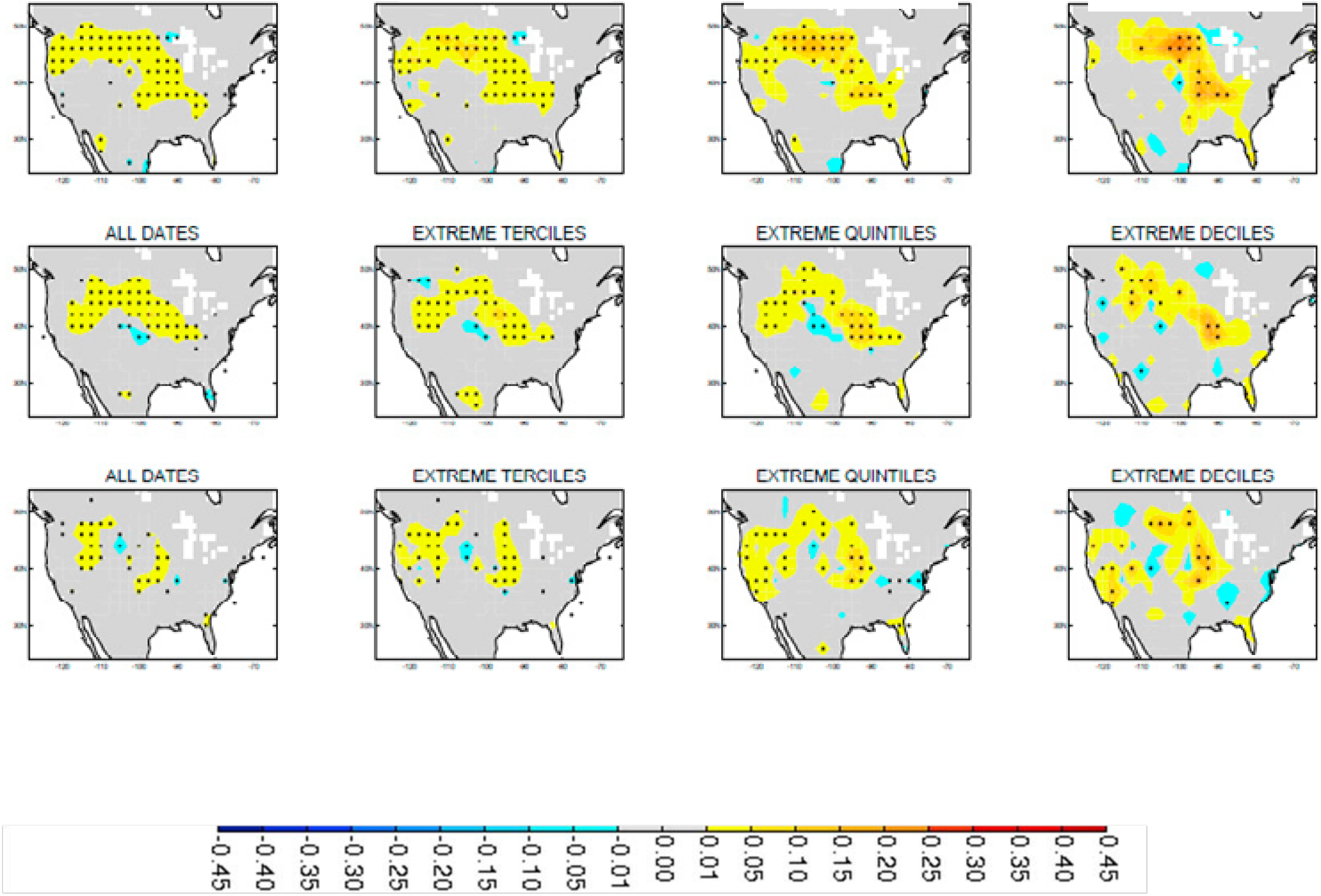
Impact of initial soil moisture on precipitation: USA

All values | **Extreme terciles** | **Extreme quintiles** | **Extreme deciles**

16-30 days

31-45 days

46-60 days



Koster et al., 2010. *GRL*.

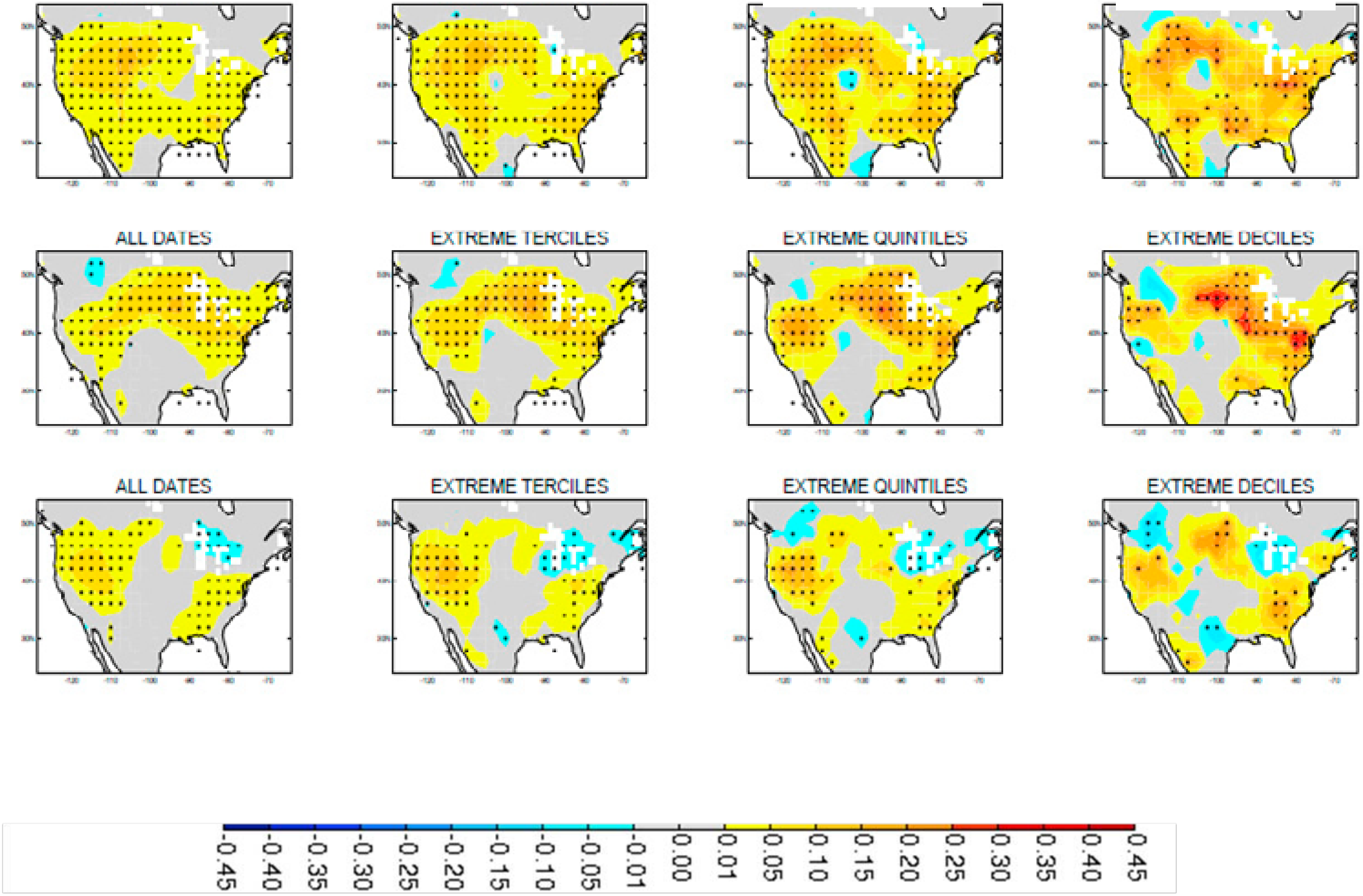
Impact of initial soil moisture on 2m temperature: USA

All values | Extreme terciles | Extreme quintiles | Extreme deciles

16-30 days

31-45 days

46-60 days



Koster et al., 2010. *GRL.*

2T and Precipitation: USA and Europe

All values

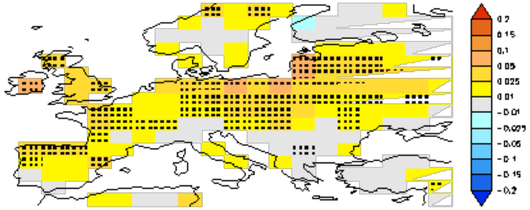
Van den Hurk et al., 2010, submitted

2m temperature

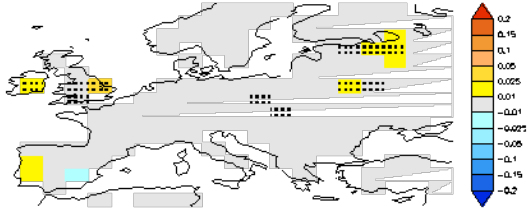
Precipitation

16-30 days

JJA t2m R2 16−30days conf.level 0.98



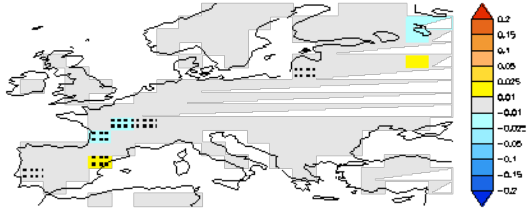
prec R2 16−30days



31-45 days

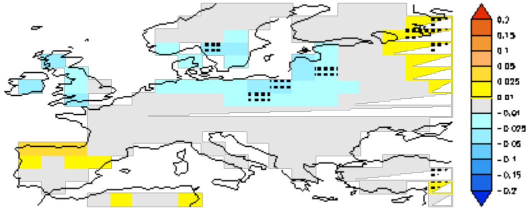
t2m R2 31−45days

prec R2 31−45days

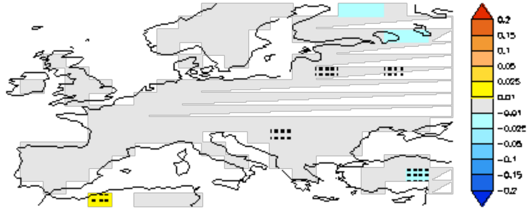


46-60 days

t2m R2 46−60days

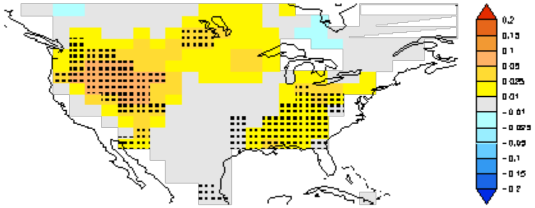


prec R2 46−60days

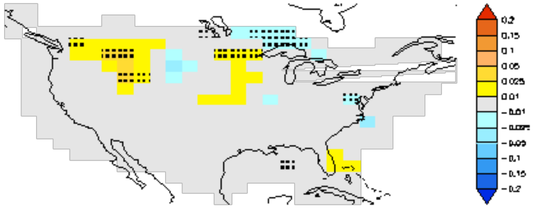


46-60 days

t2m R2 46−60days



prec R2 46−60days



2m temperature: USA and Europe

2m temperature **Van den Hurk et al., 2010, submitted**

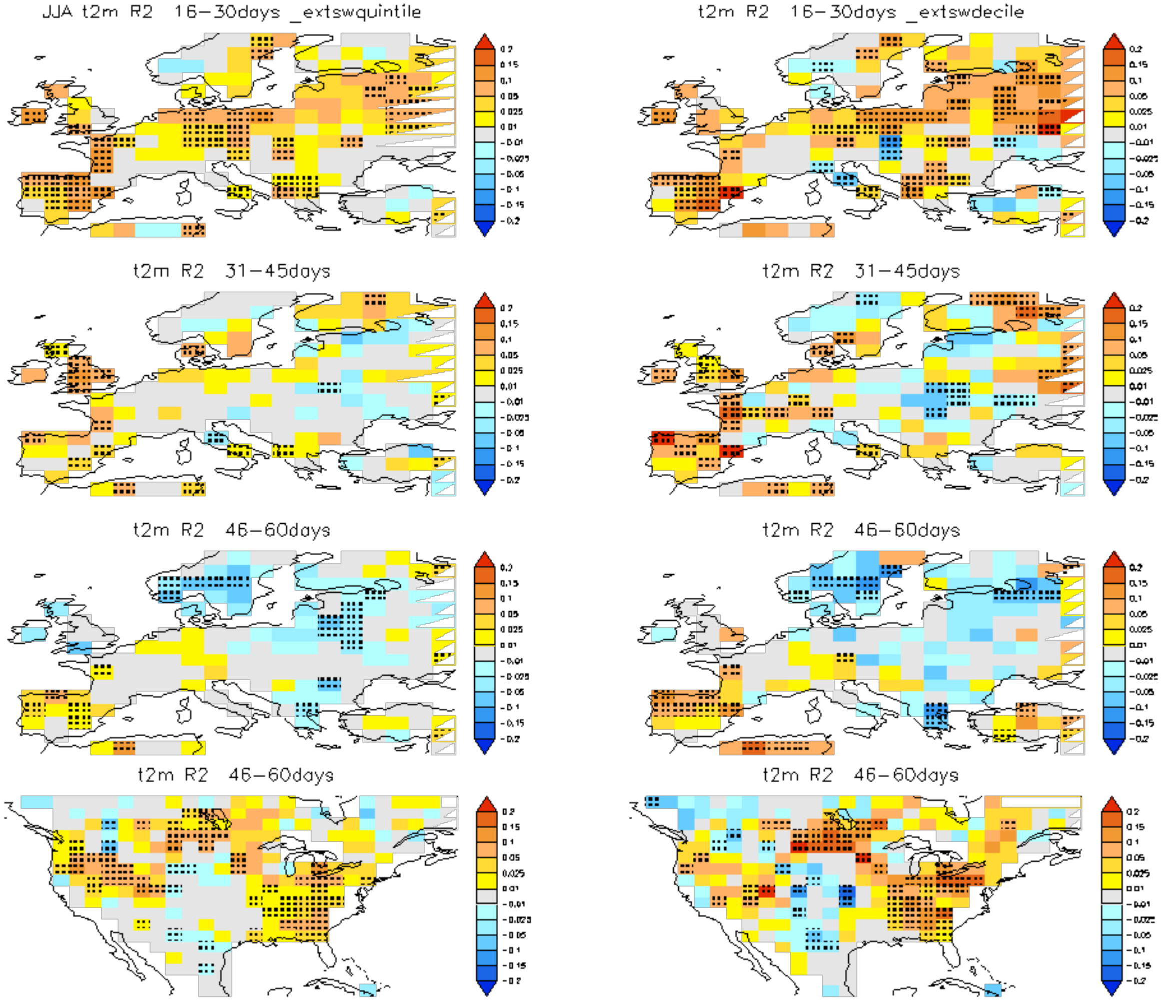
Extreme quintile **Extreme decile**

16-30 days

31-45 days

46-60 days

46-60 days



Layout

- General physical considerations
- Soil moisture (SM) and atmosphere coupling: Conceptual aspects
- SM and atmosphere coupling: Model estimates and “hot spots”
- SM-Temperature and SM-Precipitation coupling
- Increased persistence: Surface “memory”
- Impacts of initial soil moisture anomalies
- **Conclusions**

Conclusions

- Regions of coupling between soil moisture and atmosphere were robustly identified, together with some relevant mechanisms
  - Dry to wet transition zones and monsoon areas
  - Model dependent
- Regions of impact were robustly identified
  - Broadly speaking similar to the regions of coupling
  - Impacts are larger for extreme initial anomalies, e.g. drought precursors
    - European extreme heat waves seem to be predictable
  - The impact is model physics dependent (Weishmeier results)
- Focus on monthly to seasonal
  - Snow and other cold season processes were not addressed here
- The curse of Europe
  - Degree of coupling and impact of IC is much smaller than the USA
- Future
  - Importance of community efforts
  - Model dependency of GLACE and GLACE-2 suggest that it is worth to look into model physics
  - GLACE and GLACE-2 needed for snow
  - Observations problem to define intial conditions for soil moisture and snow
  - Specific applications on drought forecasting seem to be promising