Role of land-surface processes for seasonal prediction

Sonia I. Seneviratne

Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland
sonia.seneviratne@env.ethz.ch

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

Atmosphere

Oceans  Land
We are generally interested in climate over land!
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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.

Land vs. Oceans

ATMOSPHERE

energy, water, CO₂

energy, water, CO₂

Land

Oceans

energy, water, CO₂

energy, water, CO₂
Global water cycle

Oceanic Precipitation (350%)

Terrestrial Precipitation (100%)

Atmospheric transport (40%)

Terrestrial Evapotranspiration (60%)

Oceanic Evaporation (390%)

Streamflow (40%)

(Flux estimates: Oki and Kanae, Science 2006)
Land water, energy and carbon balances

- **Water**
  - $E = 60\%P$

- **Energy**
  - $\lambda E = 50-60\%Rn$

- **Carbon**
  - A is a sink for 30\% of C emissions
Evaporative fraction

\[ EF = \lambda E / R_n \]

\( EF_{\text{max}} \)

\( \theta_{\text{WILT}} \) \quad \theta_{\text{CRIT}} \quad \text{Soil moisture content}

(Dry, Transient, Wet)

Soil moisture limited, Energy limited

(see also Budyko 1956)

(Seneviratne et al. 2010, Earth-Science Reviews)
Soil moisture-temperature feedbacks

Evaporative fraction $EF = \frac{\lambda E}{R_n}$

Dry climate regime

Transitional climate regime

Wet climate regime

Dry soil

Transitional regime

Wet soil

Wilting point

“Critical” point

$\theta_{WILT}$

$\theta_{CRIT}$

Soil moisture content

$EF_{\text{max}}$
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)
Correlation NHD E-Int and preceding 3mn SPI CRU

NHD: # hot days
SPI: Standardized Precipitation Index

(Mueller and Seneviratne 2012, PNAS)
Link of hot spots of coupling to ET regimes

\[ \rho(E, Rg) \]
- blue: high
- red: small

\[ \rho(E, P) \]
- blue: high \( \rho(E, Rg) \), small \( \rho(E, P) \)
- red: small \( \rho(E, Rg) \), high \( \rho(E, P) \)

\[ \rho(E, T) \]
- blue: positive \( \rho(E, T) \)
- red: negative \( \rho(E, T) \)

(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
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

90th percentile regression slope

10th percentile regression slope

NHD: # hot days
SPI: Standardized Precipitation Index

(Mueller and Seneviratne 2012, PNAS)
Link to forecasting: conditional probability

Above avg. NHD after SPI < -0.8

Above avg. NHD after SPI > 0.8

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
• Basic relevant land-climate feedbacks and observational evidence

• Diagnosing prediction potential from land surface initialization
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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)
Series 1

- Initialize land states with “observations”, using GSWP approach
- Initialize atmosphere with “observations”, via reanalysis
- Prescribed, observed SSTs or the use of a coupled ocean model
- Perform ensembles of retrospective seasonal forecasts
- Evaluate P, T forecasts against observations
Series 2

“Randomize” land initialization!

Initialize atmosphere with “observations”, via reanalysis

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

Perform ensembles of retrospective seasonal forecasts

Evaluate P, T forecasts against observations
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

Correlation NHD E-Int and preceding 3mn SPI CRU

(Pueller and Seneviratne 2012, PNAS)

(Koster et al. 2011, JHM)
Global analysis: Actual skill

(Koster et al. 2011, JHM)
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)

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)

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

(Koster et al. 2010, GRL)
• 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
• 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)

(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.)
Analytical decomposition: 4 main terms controlling memory \((Koster \text{ and } Suarez \ 2001, \ Seneviratne \text{ and } Koster \ 2012)\)

- **Spread of initial anomalies** \((\sigma_{w_n})\)
- **Spread of forcing** \((\sigma_{\Phi_n})\)
- **Damping factors** (sensitivity of ET and runoff to soil moisture)
- **Enhancing factors** (correlation with subsequent forcing)

<table>
<thead>
<tr>
<th></th>
<th>Large (\sigma_{\Phi_n})</th>
<th>Small (\sigma_{\Phi_n})</th>
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<tbody>
<tr>
<td><strong>Small (\sigma_{w_n})</strong></td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
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<tr>
<td></td>
<td><strong>No memory</strong></td>
<td><strong>Some memory</strong></td>
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<tr>
<td><strong>Large (\sigma_{w_n})</strong></td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td><strong>Some memory</strong></td>
<td><strong>High memory</strong></td>
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\((Seneviratne \text{ and } Koster \ 2012, \ JHM)\)
• 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.
• Basic relevant land-climate feedbacks and observational evidence

• Diagnosing prediction potential from land surface initialization
  • GLACE-2: Forecasting of atmospheric variables
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• 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
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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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)*
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
Soil moisture initialization: Land data assimilation

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

(Liu et al. 2011, JHM)

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

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

(IPCC 2012; Summary for Policymakers & Chapter 3)
Hot spots of soil moisture-climate coupling are expected to shift with changing climate (and changing soil moisture regimes)

RCM simulations: Up to 60% of *summer temperature variability* is induced by soil moisture feedbacks:
- In the Mediterranean area in late 20\textsuperscript{th} century climate
- In Central and Eastern Europe in late 21\textsuperscript{st} century climate

(Seneviratne et al. 2006, Nature)

**ΔLH, JJA [W/m²]**

**ΔTmean, JJA [K]**

**ΔTmax₉₅, JJA [K]**

(Seneviratne et al. 2012, submitted)
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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)

(Seneviratne et al. 2012, submitted)
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<thead>
<tr>
<th>Group/Model</th>
<th># models</th>
<th>Points of Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. NASA/GSFC (USA): GMAO seasonal forecast system (old and new)</td>
<td>2</td>
<td>R. Koster, S. Mahanama</td>
</tr>
<tr>
<td>2. COLA (USA): COLA GCM, NCAR/CAM GCM</td>
<td>2</td>
<td>P. Dirmeyer, Z. Guo</td>
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<td>3. Princeton (USA): NCEP GCM</td>
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<td>E. Wood, L. Luo</td>
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<td>4. ETH Zurich (Switzerland): ECHAM GCM</td>
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<td>S. Seneviratne, T. Stanelle</td>
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<tr>
<td>5. KNMI (Netherlands): ECMWF</td>
<td>1</td>
<td>B. van den Hurk</td>
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<td>6. ECMWF</td>
<td>1</td>
<td>G. Balsamo, F. Doblas-Reyes</td>
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<td>7. GFDL (USA): GFDL system</td>
<td>1</td>
<td>T. Gordon</td>
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<td>9. CCSR/NIES/FRCGC (Japan): CCSR GCM</td>
<td>1</td>
<td>T. Yamada</td>
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<td>10. FSU/COAPS</td>
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<td>M. Boisserie</td>
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<td>11. CCCma</td>
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<td>B. Merryfield</td>
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<td>13 models</td>
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</table>
Land surface processes

Hydrology
- Precipitation
  - Intercepted by vegetation
  - Evaporation
- Transpiration
  - Throughfall stemflow
  - Sublimation
  - Melt
  - Snow
  - Infiltration
  - Surface runoff
  - Drainage
  - Soil water

Surface energy fluxes
- Direct solar radiation
- Reflected solar radiation
- Absorbed solar radiation
- Longwave radiation
- Latent heat flux
- Sensible heat flux
- Momentum flux
  - Wind speed
  - $u_a$

Carbon Cycle
- Photosynthesis
- Autotrophic respiration
- Fire
- Heterotrophic respiration
- Nutrient uptake
- Mineralization
- Foliage
- Stem
- Root
- Soil carbon

(Bonan, Science 2008)
Changes in hydrological cycle

a) Precipitation

b) Soil moisture

(c) Runoff

d) Evaporation

(IPCC 2007)
Observational evidence for soil-moisture impact on hot extremes in southeastern Europe

Martin Hirschi¹²*, Sonia I. Seneviratne¹*, Vesselin Alexandrov³, Fredrik Boberg⁴, Constanta Boroneant⁵, Ole B. Christensen⁴, Herbert Formayer⁶, Boris Orlowsky⁷ and Petr Stepanek⁷

Radiation-limited evapotranspiration regime

Soil moisture-limited evapotranspiration regime

(Hirschi et al. 2011, Nature Geoscience)
Possibly more skill for hot extremes after wet vs dry conditions (dry soil necessary but not sufficient condition)

(Hirschi et al. 2011, Nature Geoscience)
Distribution of summer Tmax block maxima
RCM simulation with COSMO/CCLM (France, 1959-2006)

(Jaeger and Seneviratne, Climate Dynamics, 2011)
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 $\Delta T_{\text{max, local, seas}}/\Delta T_{\text{max, global}}$ for 10% (left) and 90%ile (right)