The Cusp of Progress in Climate Prediction from Land-Atmosphere Interactions

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WHAT IS THE KEY TO BETTER FORECASTS?
MAKE THE RIGHT MODEL CHANGES.

HOW DO YOU KNOW YOU MADE THE RIGHT ONES?
YOU KNOW BECAUSE THE FORECAST IS BETTER.

SO THE KEY TO SUCCESS IS CIRCULAR REASONING?
YES, BECAUSE CIRCULAR REASONING IS THE KEY.
Predictability and Prediction

- Land states (namely soil moisture*) can provide predictability in the window beyond deterministic (weather) into climate (O-A) time scales.

*Snow and vegetation too!
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Modern Land-Atmosphere Paradigm

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  – When and where is there an active feedback from land surface states to the atmosphere?
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“Shake vigorously for 45 seconds”
Hotspots of Land-Atmosphere Coupling

- The Global Land-Atmosphere Coupling Experiment (GLACE): 12 weather and climate models differ in their land-atmosphere coupling strengths, yet “hot spots” emerged in transitions zones between arid and humid climates.

“Famous” figure from Science paper which became used (and over-used) to justify the role of the land surface in climate. This includes sensitivity and variability but not memory!

Koster et al. (2004; Science)
Hotspots of Land-Atmosphere Coupling

- The Global Land-Atmosphere Coupling Experiment (GLACE): 12 weather and climate models differ in their land-atmosphere coupling strengths, yet “hot spots” emerged in transitions zones between arid and humid climates.
- These largely correspond to major agricultural areas!
- Thus, places of intense land management are also where atmosphere is most sensitive to the land state!

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Koster et al. (2004; Science)
Coupled Feedback Loop

Precipitation → Evap → Soil Moisture → Precipitation

Arid

Humid
Arid regime:
ET (mostly surface evaporation) is very sensitive to soil wetness variations, but the dry atmosphere is unresponsive to small inputs of water vapor.
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**Humid regime:**
Small variations in evaporation affect the conditionally unstable atmosphere (easy to trigger clouds), but deep-rooted vegetation (transpiration) is not responsive to typical soil wetness variations.
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Humid regime:
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In between, soil wetness sensitivity and atmospheric “pre-conditioning” both have some effect.
Feedback Via Two Legs

- GLACE coupling strength for summer soil moisture to rainfall (the “hot spot”) corresponds to regions where there are both of these factors:

\[ \Delta P \rightarrow \Delta SM \rightarrow \Delta E \rightarrow \Delta P \]

Feedback path: Terrestrial leg \[ \rightarrow \]
Atmospheric leg
Feedback Via Two Legs

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- High correlation between daily soil moisture and evapotranspiration during summer [from the GSWP multi-model analysis, units are significance thresholds], and

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- High correlation between daily soil moisture and evapotranspiration during summer [from the GSWP multi-model analysis, units are significance thresholds], and
- High CAPE [from the North American Regional Reanalysis, J/kg]

$$\Delta P \rightarrow \Delta SM \rightarrow \Delta E \rightarrow \Delta P$$

Feedback path: Terrestrial leg \hspace{1cm} Atmospheric leg
GLACE-2: A 12-Model Prediction Experiment

**Series 1:**
- Realistic initial land surface states
- Perform ensembles of retrospective seasonal forecasts
- Prescribed, observed SSTs
- Evaluate forecasts against observations

**Series 2:**
- "Randomize" land initialization!
- Realistic initial atmospheric states
- Perform ensembles of retrospective seasonal forecasts
- Prescribed, observed SSTs
- Evaluate forecasts against observations

Translating Process Understanding to Improve Climate Models 15 October 2015 P. A. Dirmeyer
Land Initialization

• Garbage in – garbage out.
  – Need good meteorological forcing data as input to these “offline” land surface models, especially rainfall.

Koster et al. (2011: JHM)

2m Temperature Forecast Skill Improvement

Red: Large Improvement
Black: No Improvement

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  – So-called “land data assimilation” still not assimilating any data – working on it...

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Finally Data!

- In situ fluxes (FluxNET, ARM/CART, field campaigns, etc.), soil moisture networks of networks (NASMDB, ISMN)
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- Remote sensing (orbital, radar, lidar, cosmic ray, GPS, etc.)
- Long time series, co-location, QC are essential – we need land & PBL measurements together!!
Remote Sensing

- Satellites hold much promise for monitoring soil moisture globally.

Ratio of Random to Real StdDev

Courtesy: Sujay Kumar (NASA/GSFC)
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- We can estimate random measurement error of red-spectrum data like soil moisture from the statistical behavior of lagged autocorrelations.

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- Preliminary results – more to do....

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US Hotspot Weak on Memory?

- GLACE-2 found increased forecast skill from soil moisture initialization in subseasonal forecasts, but not centered over the “hotspot”.

Source: Guo, & Dirmeyer, (2015; GRL)
US Hotspot Weak on Memory?

- GLACE-2 found increased forecast skill from soil moisture initialization in subseasonal forecasts, but not centered over the “hotspot”.
- Reason may be a lack of persistence of anomalies there, compared to regions further west.
GLACE-2 Predictability Rebound

- Box over US Great Plains.

Guo et al. (2013: J. Hydromet)
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Land Surface Impacts on Atmospheric Predictability
(solid lines for LA/O case, dotted lines for A/O case)

Model: COLA AGCM Years: 1982–2006

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GLACE-2 Predictability Rebound

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- Late spring and summer, all pieces are in place.
GLACE-2 Predictability Rebound

- Box over US Great Plains.
- Soil moisture memory is high during spring and summer.
- In early spring soil moisture does not control ET.
- Late spring and summer, all pieces are in place. The impact of soil moisture on temperature and precip maximizes, predictability “rebounds”
Coupled Errors

- GLACE models suffered from a tendency to simulate excessively warm temperatures and unrealistically low daytime relative humidity over the Southern Great Plains.
- Figure: categorical frequency of occurrence of indicated variables over the ARM region for observations (bars), and the mean of 12 GCMs (markers). Vertical lines span the range of models for each bin.

Dirmeyer et al. (2006: J. Hydromet)
Coupled Errors

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Excessive downward radiation (systematic cloud errors) at surface in all models lead to a drying (LSMs first allocate extra energy to evapotranspiration) and then warming (as soil moisture is depleted, energy goes to sensible and ground heat flux instead). Positive feedbacks exacerbate errors.
LCL vs. Soil Wetness

Observed ARM relationship agrees with Betts’ theory of soil wetness controls on SHF, PBL depth. The models are all over the place.

Dirmeyer et al. (2006: J. Hydromet)
The Quick Fix

- To correct warm biases in CFSR, roots for Noah crop vegetation type were extended to all 4 soil layers; it transpires freely.

Green: Total and partial cropland
Sensible heat fluxes

- Essentially zero over much of Midwest in CFS over crop vegetation type.
- This seems to cause problems for boundary layer simulation (essentially there is none)... perpetual fog.
- But hey, the temperature error was reduced! Right result for wrong reason.
Sensible heat fluxes

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• Global Energy and Water Exchanges (GEWEX) program, Global Land/Atmosphere System Study (GLASS) project: Accurately understand, model, and predict the role of Local Land-Atmosphere Coupling “LoCo” in water and energy cycles in weather and climate models.

Courtesy: Michael Ek (NOAA/NCEP/EMC)
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• All land-atmosphere coupling is local... ...at least initially...
Benchmarking and Metrics

- Benchmarking LSM performance against regression models and flux tower data: PLUMBER (PALS Land sUrface Model Benchmarking Evaluation pRoject) [Best et al. (2015; J. Hydromet.)]
  - where PALS = Protocol for the Analysis of Land Surface models (PALS; pals.unsw.edu.au) [Abramowitz (2012; GMD)]
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- GLASS scientists are compiling a suite of metrics to diagnose coupled land-atmosphere processes in observations and validate them in models (cf. www.ahmedbtawfik.com/comet/).
Coupled processes matter!

- Uncoupled LSM – global removal of vegetation leads to an increase in ET over many areas.
- When LSM is coupled to AGCM so that feedbacks occur, ET decreases over most areas.

Courtesy: Liang Chen (GMU/COLA)
Coupled processes matter!

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• When LSM is coupled to AGCM so that feedbacks occur, ET decreases over most areas.
• Model development is also a coupled problem!
Conclusions

- Land-atmosphere interactions based on soil moisture anomalies provide predictability on sub-seasonal to seasonal time scales.
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• Process-based coupled land-atmosphere metrics have been developed to understand nature, “confront” models.
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- Process-based coupled land-atmosphere metrics have been developed to understand nature, “confront” models.
- The observational data to validate models is reaching a useful mass in many regards.
Extra Slides...
Soil Moisture Controls on Evaporation

- Over many parts of the world, there is a range of SM over which evaporation rates increase as soil moisture increases (soil moisture is a limiting factor – moisture controlled).
- Above some amount of moisture in the soil, evaporation levels off.
- In that wet range, moisture is plentiful, and is no longer controlling the partitioning of fluxes (it’s energy controlled).
This Affects Predictability in GLACE-2

- Soil moisture anomalies that push the local L-A system toward the regime of greatest sensitivity generate biggest improvements.
- When a **desert area becomes moist** (A), it gains predictability, and thus skill.
- When a **humid area becomes dry** (B), it gains predictability, and thus skill.
Memory: model vs obs

ECMWF Models - $\tau_{0-7cm}$

- Offline HTERSEL has too much memory – because no feedback??
- When coupled to IFS, HTERSEL has too little memory – problem with IFS rainfall spectrum?
- Data assimilation helps a little.
- Spatial patterns consistent – strongly determined by LSM parameter maps.

Shading = model $\tau$, dots are errors relative to each station (ISMN networks shown here)
Variability (Std. Dev.)

ECMWF Models - $\sigma_{0-7cm}$
- Offline HTESSEL seems to have too much day-to-day variability of volumetric SM in most locations
- Free-running IFS has small overall bias, still has regional errors
- ERA-Interim has **way too little** variability (*Mahfoufery?*)
- This only intra-seasonal variability of daily SM – interannual $\sigma$ removed!

Shading = model $\sigma$, dots are errors relative to each station (ISMN and NASMDB networks combined)
“...improve accuracy, lead time and utilization of weather prediction.”

“Determine the predictability of climate and effect of human activities on climate.”

“Weather, Water, Climate”
PLUMBER

- PALS Land sUrface Model Benchmarking Evaluation pRoject (PLUMBER)
  - where PALS = Protocol for the Analysis of Land Surface models (PALS; Abramowitz 2012; pals.unsw.edu.au)
- Compare today’s LSMs to some very basic statistical regressions (against $SW_{DOWN}$ ($+T_2$ (NL+$q_2$))) for estimating surface fluxes – who validates better?
- This is a “no-brainer”, right? It must be the physically-based, complex land surface models. Right?
- Wrong – especially for daily sensible heat flux regressions win!

Best et al. (2015; J. Hydromet.)
Missing Processes

- One example: hydrology with “low connectivity”
  - Many locations have fractured soils, permeable subsurface (karst)
  - Isotope studies suggest much infiltration bypasses root zone, drains straight to water table.
  - Modeling studies show errors larger over karst, sfc. flux differences affect convection, circulation.

Good et al. (2015; Science)