Using ARM Observations to Evaluate CAM5.1/CLM4 Simulations of Land-Atmosphere Coupling on the Southern Great Plains

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Background

Here, we summarize work described in a recent paper (Phillips et al. 2017 *J. Geophys. Res-Atmos*.) that investigates the *terrestrial component* of land-atmosphere coupling (LAC) between several soil moisture (SM) and atmospheric variables such as the surface evaporative fraction EF and temperature T at the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains Central Facility (SGP-CF) near Lamont, Oklahoma, as well as in the broader region surrounding the SGP-CF site.

The investigation includes:

- Three independent ARM measurements of SM (by 'SWATS', 'CO2FLX', and 'EBBR' instruments) and two independent measurements of EF (by 'EBBR' and 'ECOR' instruments) and T (by 'SMOS' and 'CO2FLX' instruments) are used to estimate observational uncertainties in SM-EF and SM-T coupling strength at SGP-CF during May-June-July-August (MJJA) warm seasons for the period 2003-2011.
- Two independent ARM measurements of SM (by 'SWATS' and 'EBBR' instruments) and one measurement of EF (by 'EBBR' instrument) at six ARM extended facilities surrounding the SGP-CF site are used to estimate EF-SM observed coupling strength on a region-wide scale for MJJA seasons during 2003-2011.
- Calculation of comparable LAC strength estimates for CAM5.1/CLM4 coupled atmosphere/ land model simulations of 2003-2011 MJJA, both near the SGP-CF site and across the SGP region. Here, the model was run in two different configurations:

1) a *free-running* Atmospheric Model Intercomparison Project (AMIP) simulation with sea surface temperatures and sea ice extents (SSTs/ SIEs) prescribed from observations

2) a *constrained* Hindcast (HC) simulation in which the AMIP SSTs/SIEs were prescribed, but in which the atmospheric state was continuously updated by 6-hourly ERA-Interim reanalysis, and the land state was nudged by observed precipitation, net radiation, and winds (Ma et al. 2015 *J. Adv. Model. Earth Sys.*).

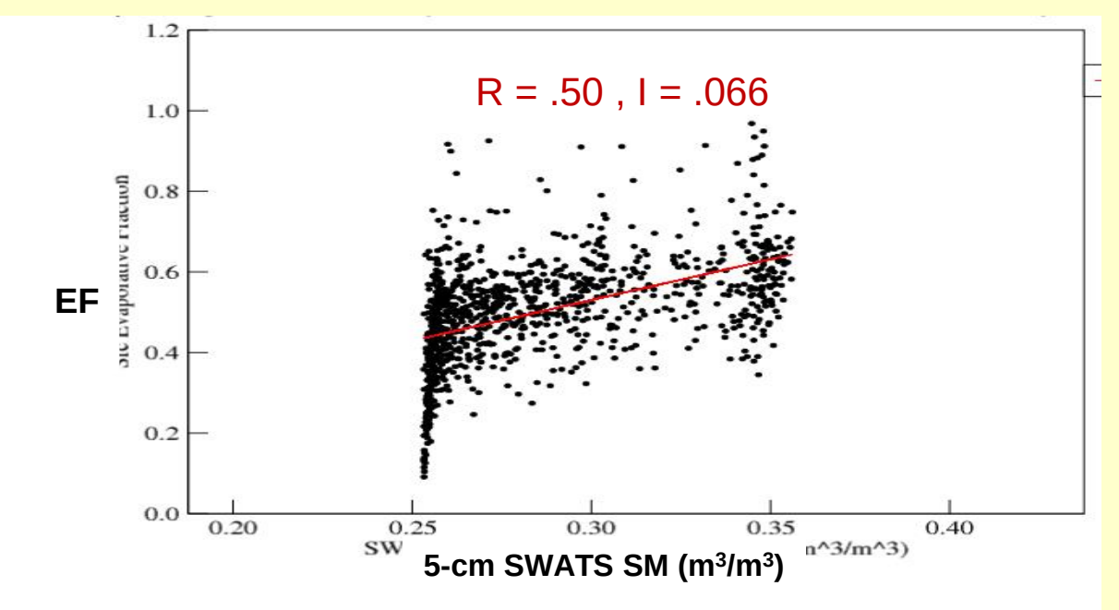
LAC is manifested in the covariations of soil moisture with atmospheric and surface fluxes or state variables, as illustrated, for example, by scatter plots. To investigate details of observed land-atmosphere interactions at the SGP site, we exploit the ARM Best Estimate (ARMBE) observations and supplementary ARM data that are available at hourly sampling rates for the 9 years from 2003 to 2011.

Climate models--when operating realistically--should exhibit similar covariance relationships and coupling strengths in their land-atmosphere interactions. Here, we evaluate whether the AMIP and HC simulations of the CAM5.1/CLM4 model do so, within the observational LAC uncertainty envelope. Failure to simulate the observed land-atmosphere covariance relationships and associated LAC strengths can impact the simulation of continental climate adversely, and implies a need to make appropriate parameterization changes in the CAM5 land and/or atmospheric models.

Methodology

Following the approach of Alan Betts (Betts, 2004 *BAMS*), we examine scatter plots of *daily averages* of soil moisture SM with, e.g. evaporative fraction EF, defined as

EF = LH/ (LH + SH), where LH = Surface Latent Heat Flux, and SH = Surface Sensible Heat Flux



Metrics to quantify each paired covariation (i.e. coupling strength) of land and atmospheric variables x (in this case, soil moisture) and y (an atmospheric variable) include:

Correlation Coefficient $\mathbf{R} = x'\cdot y'/(\sigma_x\cdot\sigma_y)$

where the numerator is the product of multi-year deviations x' and y' from the long-term means of x and y, and the denominator is the product of the corresponding standard deviations.

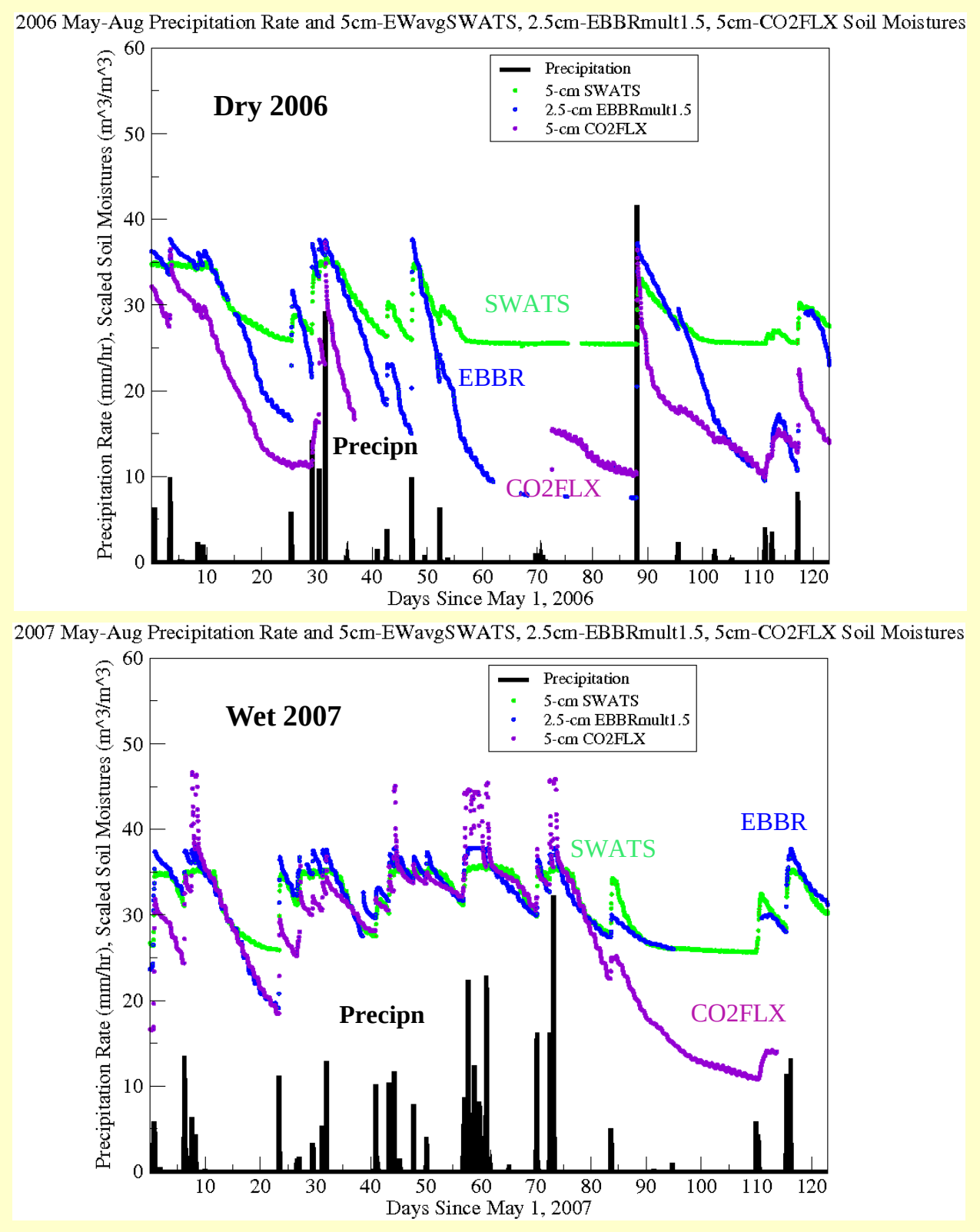
Because **R** may be sensitive to mismatches in the ranges of variables x and y, a "sensitivity index" **I** (Dirmeyer, 2011 *GRL*) is also calculated:

Sensitivity Index $\mathbf{I} = \sigma_x * \beta$

where σ_x is the x variable's standard deviation, and β is the slope of the linear regression of y versus x. I thus measures how much a change in variable y occurs for a standard-deviation change in variable x (in this example, how much EF changes for a standard-deviation change in SM). Note that **R** is a dimensionless metric, while **I** takes on the same units as y.

MJJA 2003-2011 Observations at the SGP-CF Site

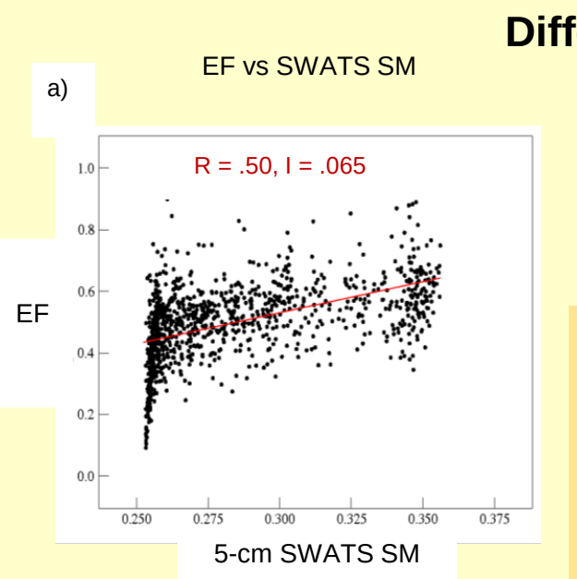
MJJA Time Series of 'SWATS', 'CO2FLX', and 'EBBR' Soil Moisture Measurements, shown with Precipitation Events in Dry Year 2006 versus Wet Year 2007 at the SGP-CF Site



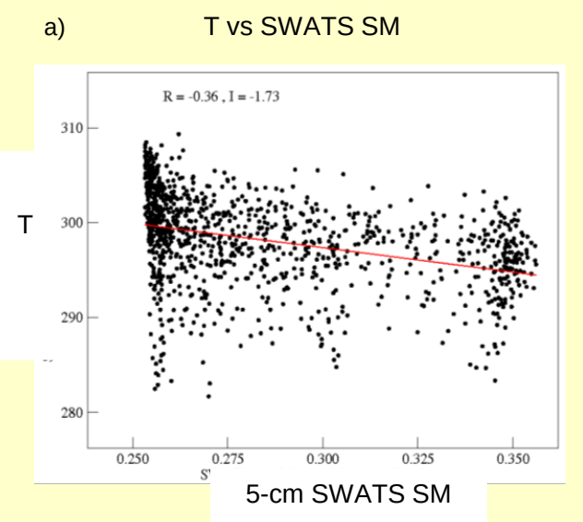
Note the reduced range of the SWATS soil moisture compared with the CO2FLX and EBBR measurements, especially in the dry year o2006.

Covariation of Observed Surface EF and T with Three Measurements of Shallow-Depth Soil Moisture

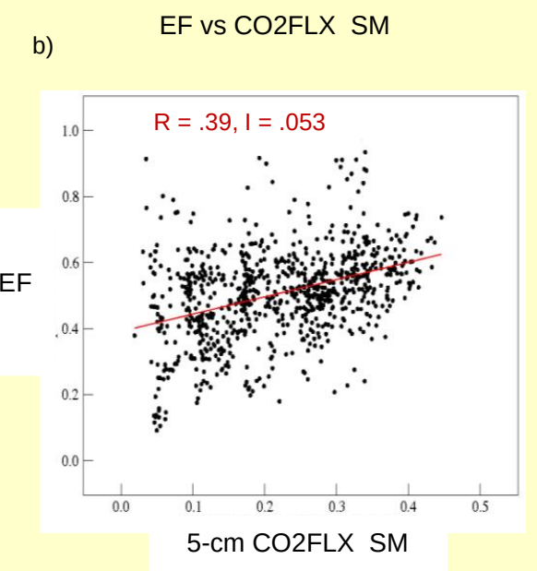
Comparing OBS Estimates of LAC from Different ARM Instrument Systems

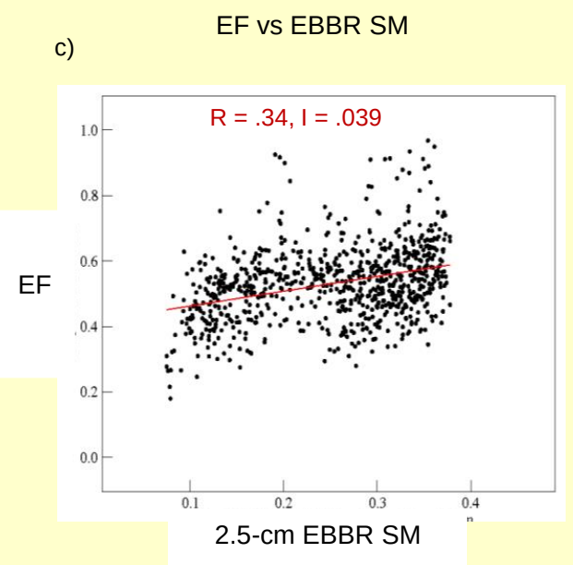


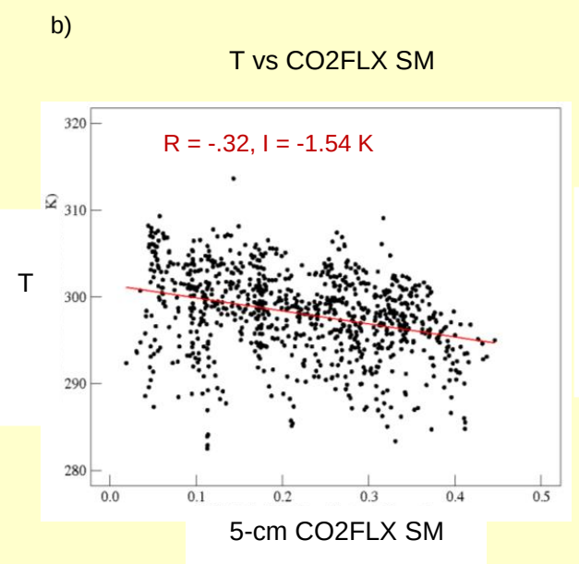
There is substantial difference in observationally estimated EF-SM coupling strength, depending on the chosen SM data set.

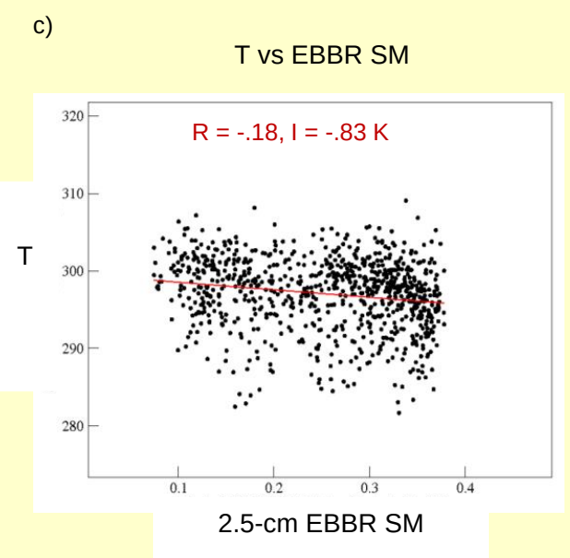


The surface temperature negatively correlated with SM, and the T-SM coupling is less strong than that of EF-SM.







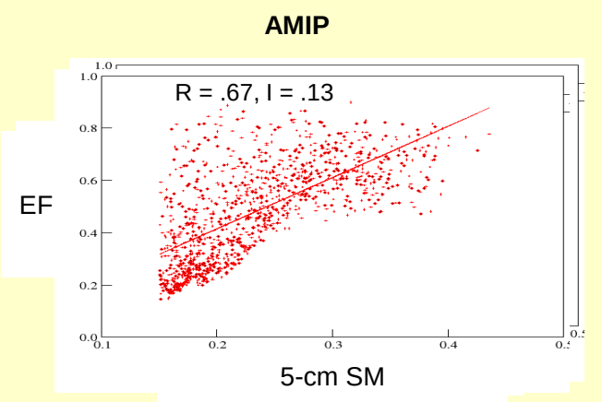


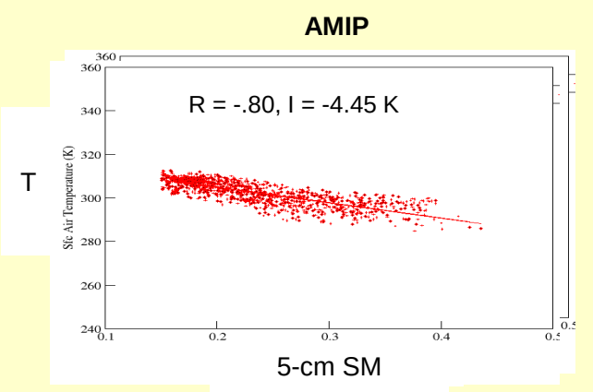
Table, right

LAC strength shows relatively low sensitivity to different observational estimates of EF or T (columns). Instead, the choice of SM data set (rows) has a much greater impact on the estimates of LAC.

Soil Moisture Data Sets	EF		T	
	EBBR	ECOR*	SMOS	CO2FLX
SWATS	R = 0.50 I = 0.066	R = 0.54 I = 0.083	R = -0.36 I = -1.70	R = -0.37 I = -1.80
CO2FLX	R = 0.39 I = 0.053	R = 0.40 I = 0.061	R = -0.32 I = -1.54	R = -0.30 I = -1.46
EBBR	R = 0.34 I = 0.039	R = 0.36 I = 0.048	R = -0.18 I = -0.83	R = -0.17 I = -0.83

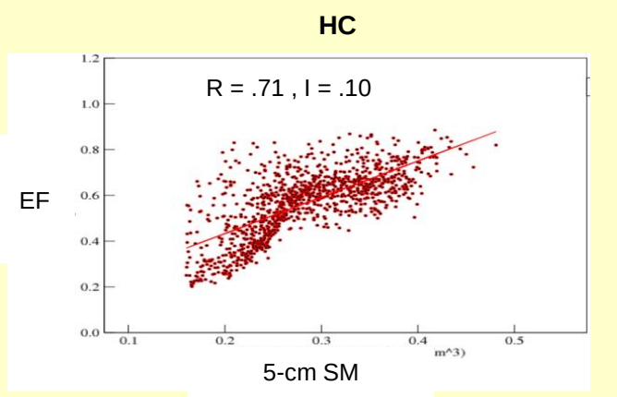
Coupling Strength of Model Surface EF and T with Model 5-cm depth Soil Moisture: AMIP versus HC simulations

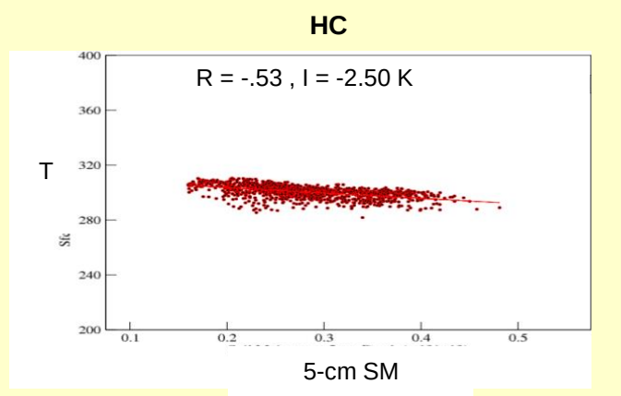




Compared with OBS estimates (see above), both free-running AMIP and constrained HC simulations show too strong LAC strength for SM interacting with EF, and especially with T—most notably for the AMIP run.

Near the SGP-CF site, both AMIP and HC simulations of EF-SM and T-SM lie well outside the range of the observational LAC estimates (compare red plots with black plots, above). However, the constrained HC simulation of T-SM coupling strength deviates less extremely than does the free-running AMIP simulation.



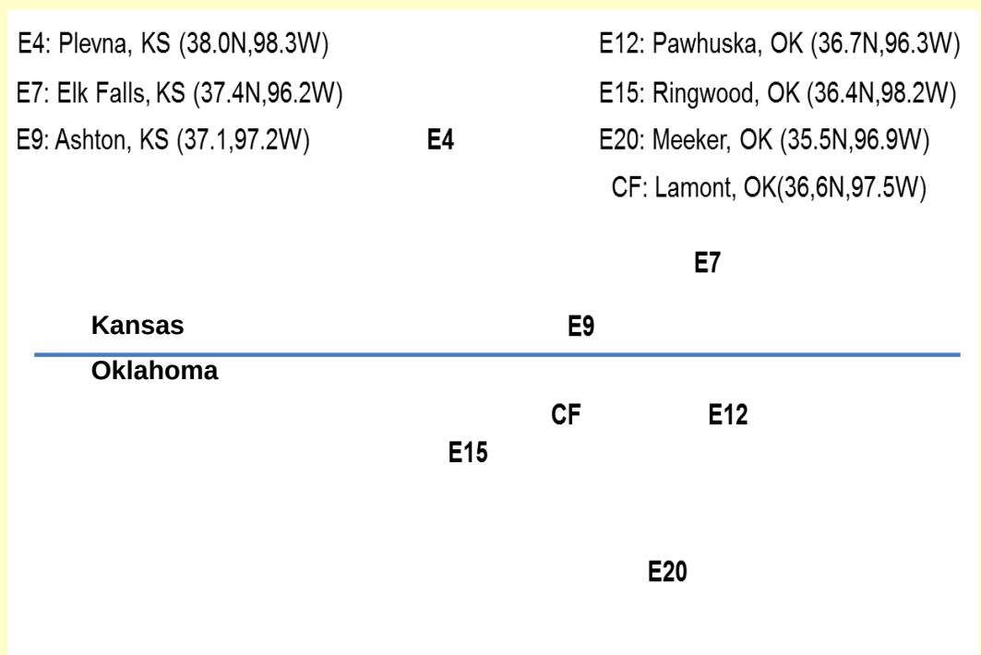


Despite similarly too-strong LAC strengths, errors in HC surface variables (gray bands) mostly are substantially less than in the corresponding AMIP variables (white bands):

Variable	Observed Mean	Model Mean	Mean Bias	RMSE	σ_m^2/σ_o^2
Precipitation Rate (mm day^{-1})	3.11	2.01	-1.04.	10.69	0.12
		2.77	-0.33	10.37	0.37
Surface Net Downward SW Flux (W m^{-2})	233.	222.	-11.	109.	0.67
		221.	-12.	88.	0.78
Surface Net Upward LW Flu (W m^{-2})	62.	77.	+15.	40.	1.83
		69.	+7.	20.	1.46
Surface Latent Heat Flux (W m^{-2})	101.	73.	-28.	70.	0.47
		96.	-5.	58.	0.52
Surface Sensible Heat Flux (W m^{-2})	47.	57.	+10.	60.	0.55
		41.	-6.	54.	0.36
Surface Evaporative Fraction	0.474	0.454	-.020	0.20	1.54
		0.536	+.062	0.16	1.20
Surface Relative Humidity (%)	65.5	52.3	-13.2	26.0	2.76
		61.1	-4.4	11.7	1.67
Surface Air Temperature (K)	297.3	301.5	+4.2	6.4	1.04
		299.5	+2.2	2.9	1.01

MJJA 2003-2011 Observational vs. Modeled LAC over the SGP Region

Schematic map of ARM Extended Facility locations E4, E7, etc. relative to the SGP-CF Central Facility



E4: Plevna, KS (38.0N,98.3W)
E7: Elk Falls, KS (37.4N,96.2W)
E9: Ashton, KS (37.1,97.2W)
E12: Pawhuska, OK (36.7N,96.3W)
E15: Ringwood, OK (36.4N,98.2W)
E20: Meeker, OK (35.5N,96.9W)
CF: Lamont, OK(36,6N,97.5W)

Observational Estimates of Regional LAC

Site	Location Soil, Vegetation Type	R, I SWATS SM	R, I EBBR SM
E4	Plevna, KS (38.0 N, 98.3 W) fine sandy loam, shrubs and grass	.55, .062	.50, .058
E7	Elk Falls, KS (37.4 N,96.2 W) silt loam, pasture	.38, .038	.22, .022
E9	Ashton, KS (37.1 N, 97.2 W) loam, pasture	.21, .022	.15, .017
E12	Pawhuska, OK (36.7 N,96.3 W) sandy loam, tallgrass prairie	.090,.008	.14, .012
E15	Ringwood, OK (36.4 N, 98.2 W) sandy loam, pasture	.33, .033	.28, .032
E20	Meeker, OK (35.5 N, 96.9 W) fine sandy loam, pasture	.52, .059	.57, .064
Regional-average values:		**R = .35, I = .037 for SWATS SM** **R = .31, I = .034 for EBBR SM**	

AMIP Estimates of Regional LAC

Grid-Point Coordinates	Model R, I for EF
(38.17 N, 98.75 W)	.67,.13
(38.17 N, 97.50 W)	.63,.11
(38.17 N, 96.25 W)	.60,.093
(37.23 N, 98.75 W)	.67,.13
(37.23 N, 97.50 W)	.65,.12
(37.23 N, 96.25 W)	.62,.10
(36.28 N, 98.75 W)	.68,.14
(36.28 N, 96.25 W)	.67,.14
(35.34 N, 98.75 W)	.69,.11
(35.34 N, 97.50 W)	.65,.084
(35.34 N, 96.25 W)	.63,.093
Regional-average values: R =.65, I = .11	

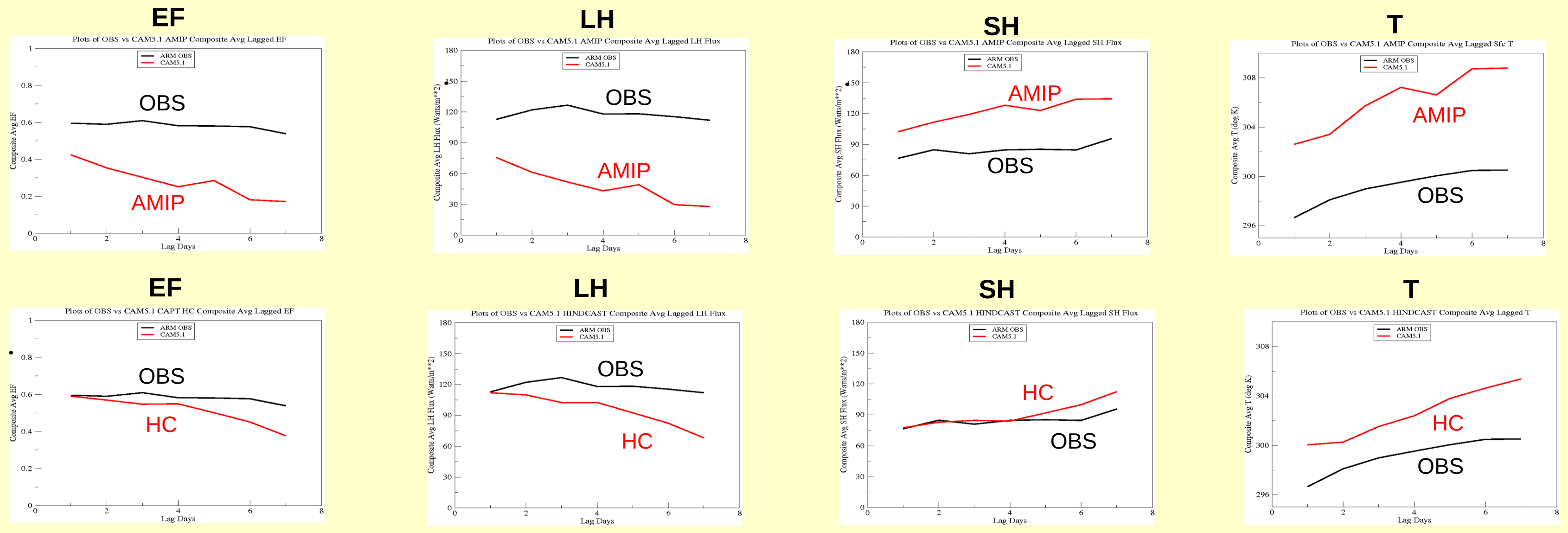
HC Estimates of Regional LAC

Grid-Point Coordinates	Model R, Ifor EF
(38.17 N, 98.75 W)	.69,.11
(38.17 N, 97.50 W)	.65,.084
(38.17 N, 96.25 W)	.49,.050
(37.23 N, 98.75 W)	.72,.13
(37.23 N, 97.50 W)	.67,.091
(37.23 N, 96.25 W)	.56,.059
(36.28 N, 98.75 W)	.73,.14
(36.28 N, 96.25 W)	.65,.076
(35.34 N, 98.75 W)	.74,.14
(35.34 N, 97.50 W)	.72,.10
(35.34 N, 96.25 W)	.63,.075
Regional-average values: R = .66, I = .10	

- To obtain a region-wide estimate of EF-SM coupling strength, a simple arithmetic average of observational station values (or model grid-point values) of LAC is calculated. (An alternative average obtained by weighting each station by its distance from the SGP-CF site yields very similar results to the simple arithmetic average.)
- For both the AMIP and HC configurations, the model's EF-SM regional-average coupling strength remains much too strong (compare values in AMIP and HC Tables to the left with the Observational Estimates above).
- The *spatial variability* of observationally estimated LAC over the SGP region is substantial (**R** ranging from .09 to .57, **I** from .008 to .062—see above Table). This is a result of both a pronounced east-west gradient in precipitation/soil moisture and qualitative differences in soil type and land cover across the region.
- The observed large spatial variability of LAC also is not well reproduced by the model, either in its AMIP or HC configuration (see Tables to the left).

MJJA 2003-2011 Composite Daily Averages of Lagged Dry-down Characteristics at SGP-CF: Observations vs. Model Configurations

- It is instructive to investigate the mean dry-down characteristics of observed surface variables (e.g. EF, LH, SH, and T) by averaging composites of these variables at different days lagging precipitation events. During the dry-down phase, observed EF and LH slowly decrease with lag day, while SH increases slowly, and T somewhat more rapidly.
- The model, when operated in the free-running AMIP configuration, shows more extreme dry-down behaviors, especially for the free-running AMIP configuration: EF and LH decrease more rapidly than observed, while SH and especially T increase more rapidly. The AMIP simulation biases are fairly large at the start of the dry-down phase, and increase with lag day.
- In the constrained HC configuration, model EF remains close to observations, but LH, SH, and T deviate increasingly from the corresponding observed dry-down characteristics. The mostly small initial model biases also increase with lag day.
- While the HC model configuration shows less extreme dry-down deviations from observations than in the AMIP configuration, there are qualitative similarities. This is another indication that the source of the too-strong LAC strengths in both AMIP and HC simulations are probably located in the CAM5.1/CLM4 land-atmosphere coupling parameterizations.



Summary Points

- The CAM5.1/CLM4 model--whether it is run in a free-running AMIP or in a constrained HC configuration—displays much too strong values of atmospheric coupling with soil moisture, both at the SGP-CF site, and in the wider region as well. However, the *spatial variability* of modeled EF-SM coupling strength is substantially less than the observational estimates.
- The model in the constrained HC configuration shows less extreme, but qualitatively similar dry-down characteristics as in the free-running AMIP configuration.
- Running the CAM5.1/CLM4 model in the constrained HC mode is not sufficient to avoid unrealistically strong LAC. This implies that the model's land and/or atmospheric parameterizations are the main source of the problem. Future work thus will involve closer investigation of the aspects of model physical parameterizations that are pertinent for land-atmosphere coupling.

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