Observational Evaluation of Land-Atmosphere Coupling in CAM5 Hindcasts at the ARM Southern Great Plains Site

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Background

In a recently published study (Phillips and Klein, *JGR* 2014), we investigated selected features of land-atmosphere coupling observed at the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains Central Facility (SGP CF) site near Lamont, Oklahoma USA. Following the perspective of boundary-layer specialist Alan Betts (e.g. Betts, 2009 *JAMES*), land-atmosphere coupling is manifested in the covariations of daily averaged atmospheric surface/boundary-layer variables with land variables such as soil moisture, as expressed graphically by scatter plots. To investigate details of such land-atmosphere interactions at the SGP site, we exploited the ARM Best Estimate (ARMBE) and supplementary field observations of soil moisture (such as the "SWATS" data set) that were available for the years 1997-2008.

Climate models--when operating realistically--should exhibit similar covariance relationships in their land-atmosphere interactions. To determine whether this is the case, we have begun to analyze hindcasts of May-August of 2008-2009 made with version 5 of the Community Atmospheric Model (CAM5) coupled to version 4 of the Community Land Model (CLM4). For these extended two-year hindcasts, the CAM5's global atmospheric state variables were initialized daily from the corresponding ECMWF Year of Tropical Convection (YOTC) Reanalysis variables, while the CLM4's soil moisture and other land variables were spun up, beginning several months prior to the start of the 2008 hindcasts, via application of the CAM5's radiative and precipitation forcings. Downscaling the hindcast variables to the SGP site then allows a detailed comparison with ARM 2008-2009 May-August observations to be made. The extent to which CAM5 fails to adequately simulate the observed land-atmosphere covariance relationships implies a need to make corrections in the atmospheric model's forcings of the land, as well as in the land or ABL parameterizations. We will investigate such issues further by employing planned decade-long CAM5 hindcasts, to be run under an improved land spin-up protocol.

Methodology

In elaborating his perspective on land-atmosphere coupling, Betts makes use of several derived dimensionless quantities:

Surface Evaporative Fraction

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

Soil Moisture Index

SMI = $(W - W_{min})/(W_{max} - W_{min})$, where **W** is the soil moisture at 10 cm depth and W_{min} and W_{max} are the minimum and maximum soil moisture values, e.g. as obtained from the **"SWATS"** data set.

Coupling Metrics

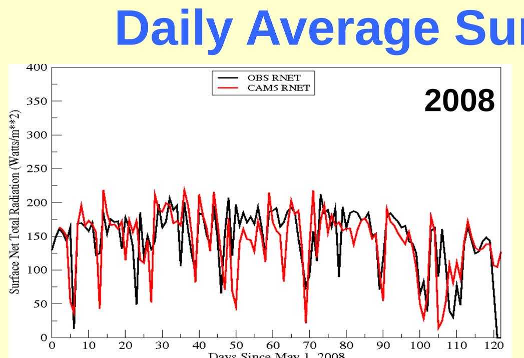
In applying Betts' approach, we used the following metrics to quantify the covariations of land and atmospheric variables **x** and **y**:

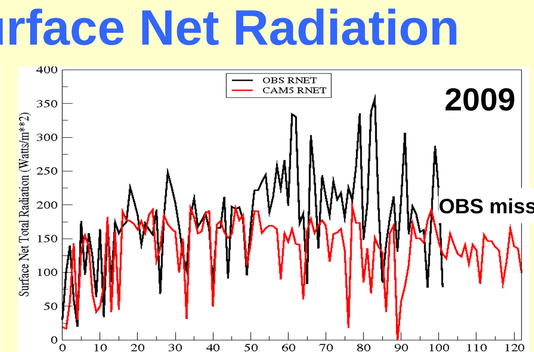
Correlation Coefficient $R = x'{\cdot}y'/(\sigma_x{\cdot}\sigma_y)$, where the numerator is the product of multi-year deviations **x'** and **y'** from the long-term means of **x** and **y**, and the denominator is the product of the corresponding standard deviations. Because **R** may be sensitive to mismatches in the ranges of variables **x** and **y**, a "sensitivity index" **I** (after Dirmeyer, *GRL* 2011) is also calculated:

Sensitivity Index $I = \sigma_x{\cdot}\beta$, 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**. *(Note: **R** is a dimensionless metric, while **I** takes on the same units as variable **y**.)*

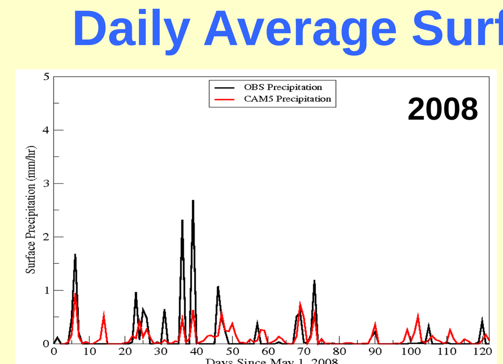
OBS versus CAM5: Comparison of Radiative and Precipitation Forcings May-August of 2008 & 2009:

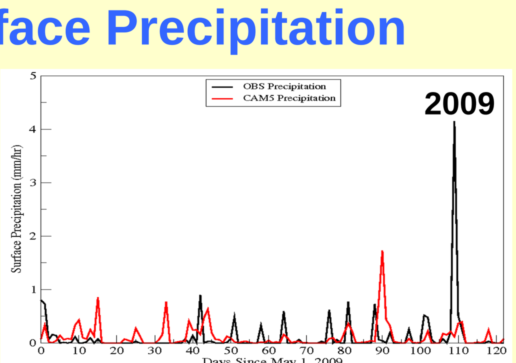
Daily Average Surface Net Radiation





Daily Average Surface Precipitation

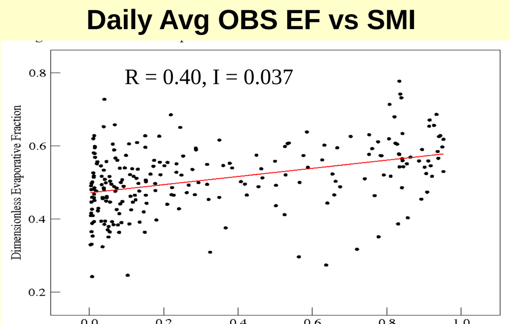




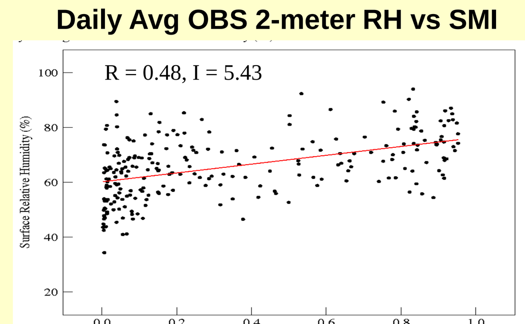
CAM5 surface RNET compares fairly well with **OBS** in 2008, but falls too low in July of 2009, mainly due to reduced downwelling shortwave radiation related to overly extensive model cloud cover, and to excessive longwave cooling from an overly warm surface (not shown). **CAM5** precipitation also better tracks the *timing* of OBS events in 2008, but with amounts that are generally too scant in both years.

OBS versus CAM5: Comparison of Land-Atmosphere Coupling May-August 2008 & 2009:

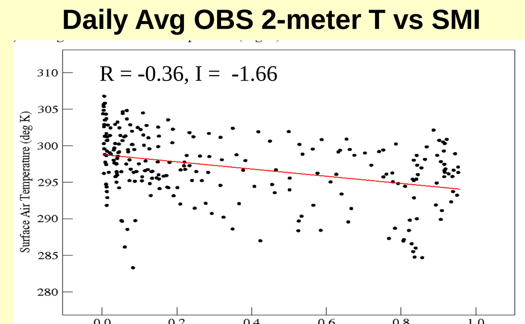
Daily Avg OBS EF vs SMI



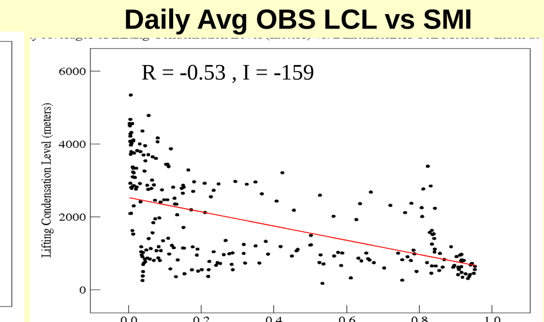
Daily Avg OBS 2-meter RH vs SMI



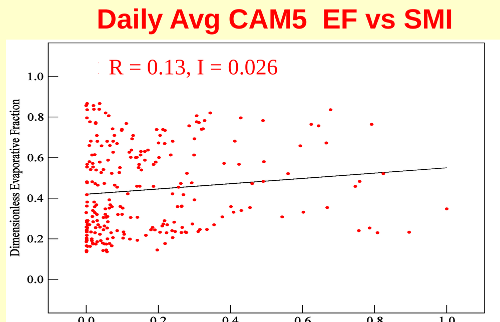
Daily Avg OBS 2-meter T vs SMI



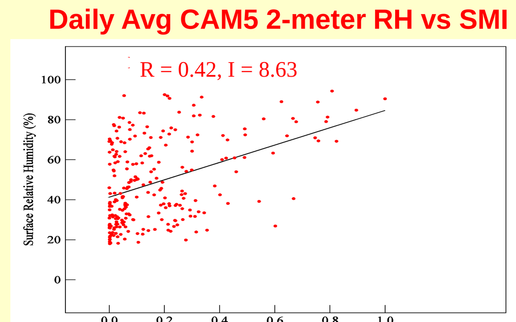
Daily Avg OBS LCL vs SMI



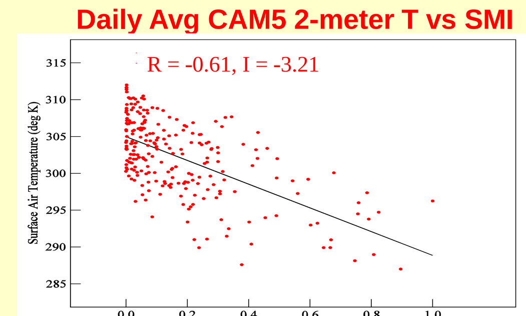
Daily Avg CAM5 EF vs SMI



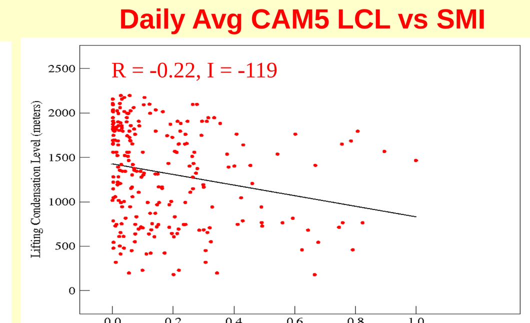
Daily Avg CAM5 2-meter RH vs SMI



Daily Avg CAM5 2-meter T vs SMI



Daily Avg CAM5 LCL vs SMI



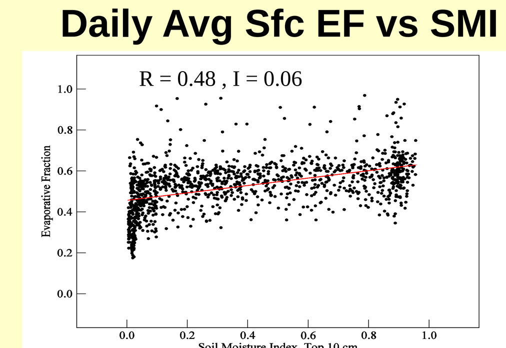
In these two warm seasons, **CAM5** surface and boundary-layer variables mostly co-vary less coherently (showing lower correlations **R**) with the **SWATS** soil moisture than do the corresponding observed variables; but some of the CAM5 variables display more "sensitivity" (higher **I** values) than is observed. The discrepancy in radiative and hydrological forcings in CAM5 versus the observations makes it difficult to interpret these model behaviors unambiguously.

Selected Observational Results

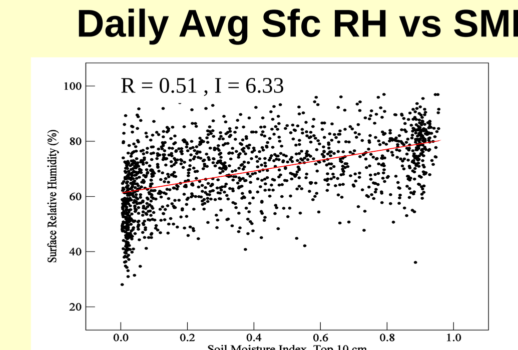
For 12 years of warm-season observations at the SGP Central Facility site, scatter plots illustrate the covariation of paired *daily averaged* land and atmospheric variables. Values of the correlation **R** and sensitivity index **I** also are shown for each pairing. For daily-average samples of **x** and **y** over 12 warm seasons, a correlation **R** > ~0.2 is statistically significant at the 99% confidence level, assuming every 5th sample is statistically independent.

Observed (OBS) Sfc Evaporative Fraction, Relative Humidity, Temperature; and Derived Lifting Condensation Level versus Soil Moisture Index May-August 1997-2008

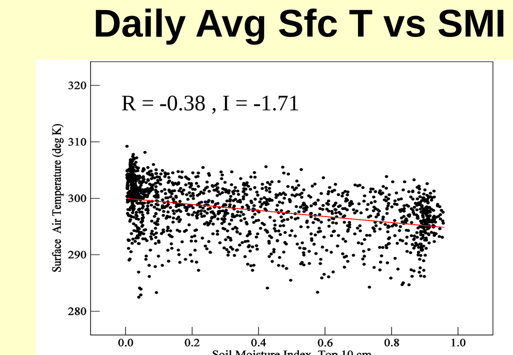
Daily Avg Sfc EF vs SMI



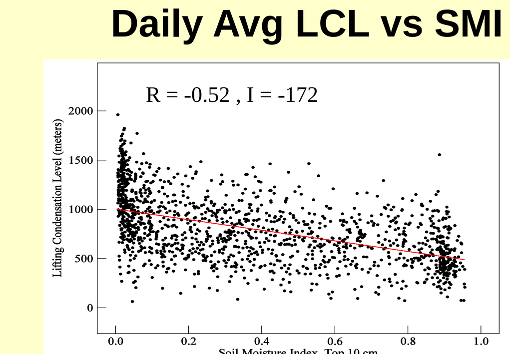
Daily Avg Sfc RH vs SMI



Daily Avg Sfc T vs SMI



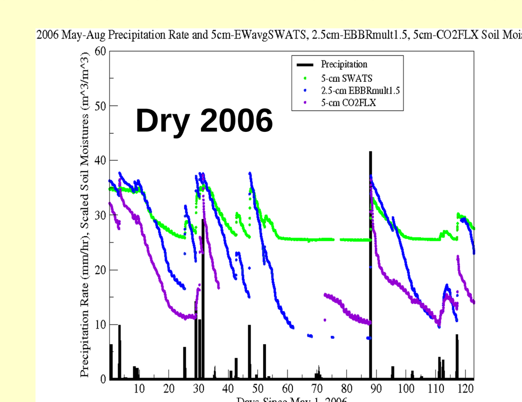
Daily Avg LCL vs SMI

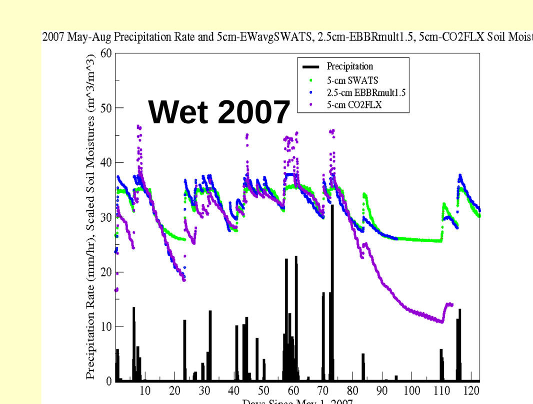


The observed surface evaporative fraction **EF** correlates positively with the 10-cm **SMI** , and the amount of surface evaporation thus is limited mainly by soil moisture amount, rather than by net radiation R_{net} (i.e. moisture-stressed conditions tend to prevail at this SGP site). The surface relative humidity **RH** also correlates positively with **SMI,** while the 2-meter surface air temperature **T** correlates negatively (**T** increases as the soil dries out). Because the derived **LCL** falls as **T** decreases and **RH** increases, the **LCL** varies inversely with **SMI**. (See Phillips and Klein, *JGR 2014* for further details.)

Sensitivity of Land-Atmosphere Coupling to Different Soil Moisture Measurements

Warm-Season Time Series of Three Different Soil Moisture Measurements at the SGP Site: Dry 2006 vs Wet 2007

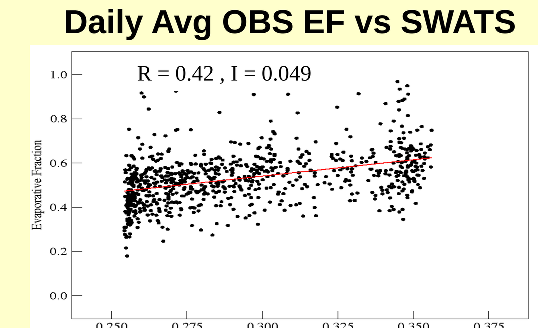




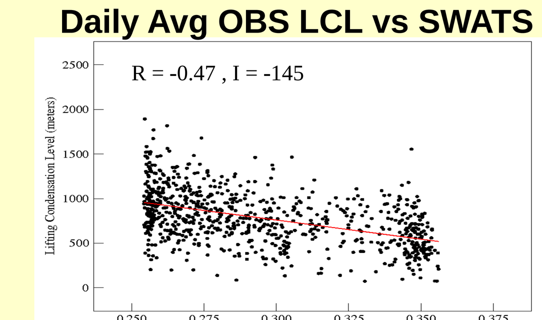
At the SGP Central Facility, we can choose among 3 soil moisture measurements: The **"SWATS"**, **"EBBR"**, and **"CO2FLX"** data sets, which overlap for the years 2003-2011. The plots at the left illustrate the *hourly* response of each soil moisture measurement (in units of m^3 soil water to m^3 of soil) to precipitation events (in units of mm/hour) occurring in the relatively dry 2006 and in the relatively wet 2007. Note the greater number of missing samples in the **EBBR** and **CO2FLX** data sets.

LAC Examples: 2003-2011 Scatter of EF and LCL versus SWATS, EBBR, and CO2FLX Soil Moisture Data Sets

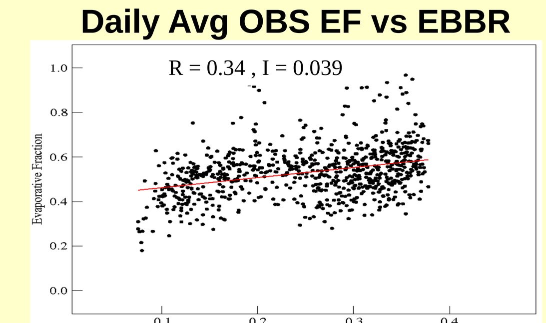
Daily Avg OBS EF vs SWATS



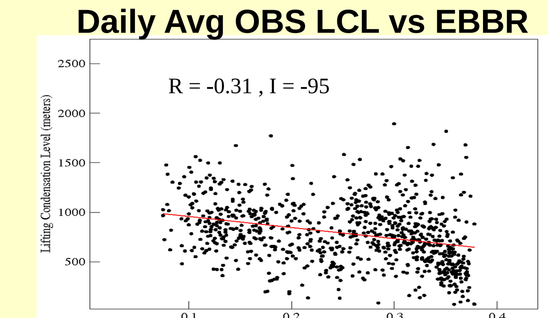
Daily Avg OBS LCL vs SWATS



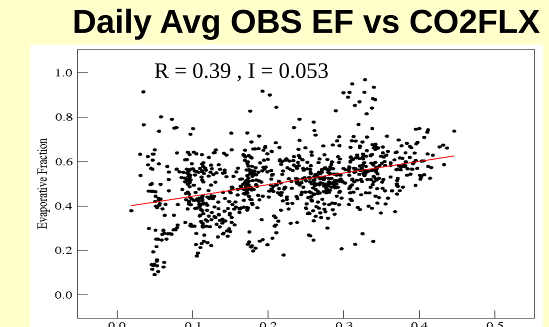
Daily Avg OBS EF vs EBBR



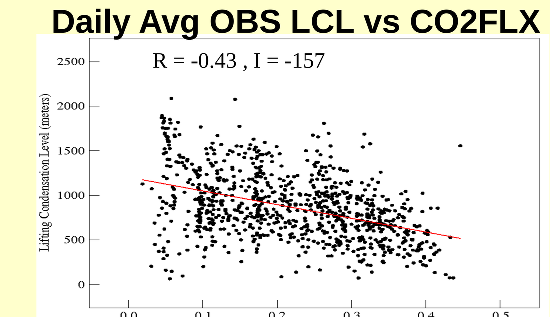
Daily Avg OBS LCL vs EBBR



Daily Avg OBS EF vs CO2FLX



Daily Avg OBS LCL vs CO2FLX



The plots to the left illustrate the scatter of daily averages of the observation-based evaporative fraction **EF** and the lifting condensation level **LCL** with respect to daily averages of the 3 soil moisture measurements **SWATS**, **EBBR**, and **CO2FLX**. (For more consistent comparison, here the hourly **SWATS** data used to form its daily averages were reduced to match the **EBBR** data, which had the smallest sample size of the 3 data sets.)

Note that for **EF** and **LCL**, the strength of their coupling with soil moisture (inferred from correlation coefficient **R** and sensitivity index **I**) tends to vary considerably, depending on the choice of soil moisture data set. This implies that there probably is substantial uncertainty in observationally based estimates of land-atmosphere coupling. This result therefore complicates the evaluation of land-atmosphere coupling strength in climate models such as the CAM5.

Summary

Comparing covariations of **CAM5** atmospheric surface or boundary-layer variables versus 10-cm soil moisture index **SMI** with the corresponding **OBS** pairings indicates that **CAM5** variables mostly co-vary less coherently (with lower correlations **R**) than the **OBS**, but with some model variables (e.g. **RH** and **T**) displaying more "sensitivity" (higher **I** values) to changes in soil moisture. **CAM5** soil moisture also tends to frequent relatively drier states than observed. These model behaviors are consistent with the too-scant model precipitation, but possibly also are related to excessive surface evaporation and/or drainage of soil water in the **CLM4** land model. Identifying the cause(s) of the apparent model deficiencies will be the focus of future investigations involving planned decade-long hind-casts, to be run under a more realistic land spin-up protocol that will employ *observed* radiative and precipitation forcings of the **CLM4** land model. Further complicating the evaluation of land-atmosphere coupling in climate models, however, is the apparent sensitivity of the coupling strength (as inferred from the R and **I** metrics) to different observational measurements of soil moisture at the same location.

ASR Atmospheric System Research

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