Investigation of land-atmosphere interaction in UFS and its influence on model mean bias

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Unified Forecast System (UFS)

ufs-weather-model https://github.com/ufs-community/ufs-weather-model

Atmosphere
- FV3 dynamical core
- GFS Physics with GFDL microphysics
- CCPP physics driver
- C384 (~25km), 127 levels
- Noah LSM (P6) → Noah-MP LSM (P7)

Ocean
- MOM6 Modular Ocean Model
- ¼ degree tripolar grid, 75 hybrid levels
- OM4 Set up [Adcroft, 2019]

Waves
- WAVEWATCH III
- ½ degree regular lat/lon grid
- ST4 Physics [Ardhuin, 2010]

Ice
- CICE6 Los Alamos Sea Ice Model
- ¼ degree tripolar grid (same as ocean)
- 5 thickness categories
- No Mushy thermodynamics

Driver/Mediator
- NEMS driver
- CMEPS mediator

Unified Forecast System (UFS) - Prototype

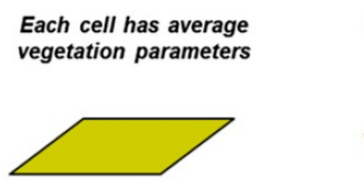
Prototype 5	Prototype 6 (CCPP physics update)	Prototype 7a (Noah-MP LSM)
• **Period**: 2011.07.01~2018.01.15 • **Initial condition**: **FV3 GFS** – CFSR (38km resolution) MOM6 – CPC 3DVar CICE – CPC ice analysis WW3 – Generated with CFS forcings • **Vertical resolution**: 64 levels in atm • **CMEPS Mediator**	• **Period**: 2011.07.01~2018.01.15 • **Initial condition**: **FV3 GFS** – CFSR Fractional grid • **Vertical resolution**: 127 levels in atm • **Physics update (GFSv16 CCPP version)** **PBL/turbulence** - K-EDMF replaced with sa-TKE-EDMF, Background diffusivity revised as a stability-dependent function **Gravity wave drag** - Parameterization for subgrid scale nonstationary gravity wave drag added **Radiation** - Solar radiation absorption by water clouds updated, Cloud overlap assumptions updated **Microphysics** - GFDL microphysics scheme for computing ice cloud effective radius updated **Noah LSM** - Ground heat flux calculation over snow covered surface updated, Vegetation impact on surface energy budget over urban area introduced	• **Period**: 2012.07.01~2013.07.01 • **Initial condition**: **FV3 GFS** – GEFSv12 Reanalysis (25km resolution) **Noah-MP** –land initial conditions from an offline land model spin-up experiment **VIIRS** based vegetation type climatology **Orography** updated • **Model update** **LSM - Noah-MP LSM** **Coupling** - Update z_bot calculation Switch to MOM mesh to have **consistent ice fraction** between MOM6 and CICE6 Include the open-water normalization for the **ATM→OCN fluxes** which are sent from ATM as ocean-only values Threading slowness issue resolved by using the ESMF811

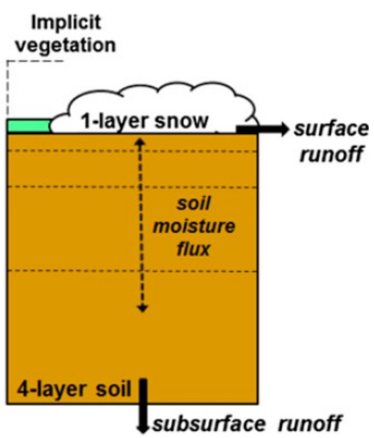
Prototype 7 now running – no results yet.

Background

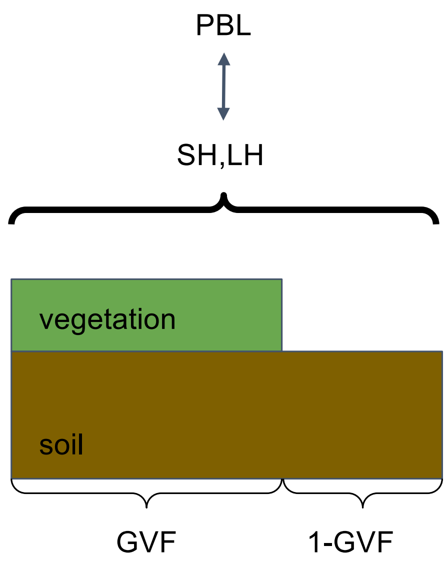
- Noah versus Noah-MP LSM

Noah vs. Noah-MP land surface model





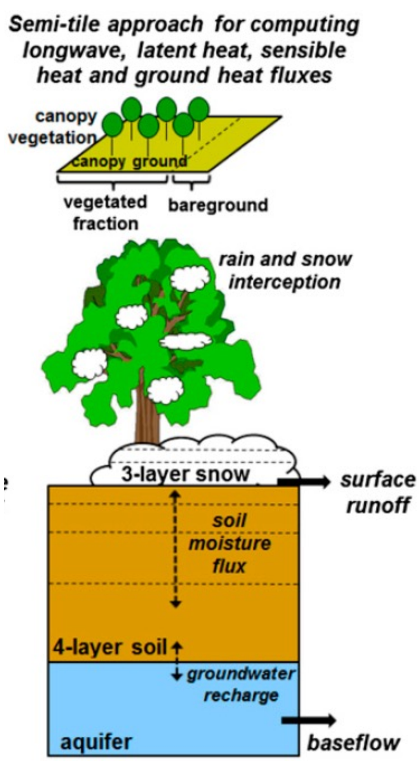
Noah-LSM



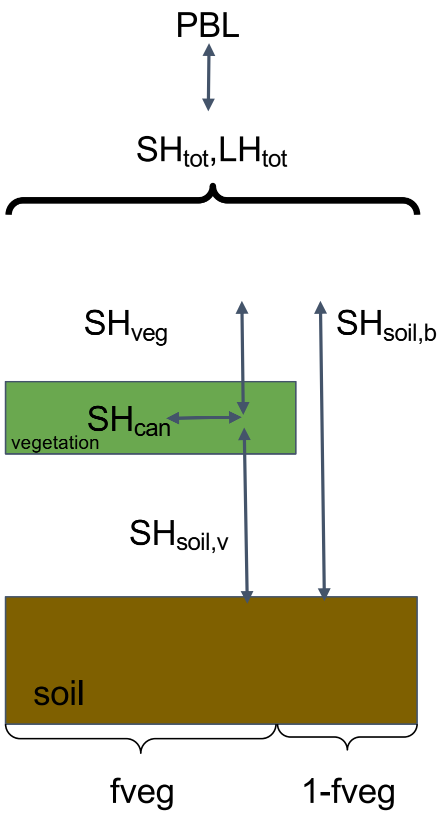
How does this work for Noah?

- Noah treats each grid cell as a "bulk" surface containing an active vegetation fraction (GVF) and active bare soil fraction (1-GVF)
- Soil under the vegetation does not "see" the atmosphere
- Each grid cell has one roughness length (and one albedo)
- One grid cell average flux (SH,LH) is sent to the PBL
- Only one bulk surface temperature, a skin temperature, is used for all calculations: sensible, latent, longwave
- Single-layer snowpack
- There is no groundwater recharge at bottom layer from aquifer (i.e., without groundwater interaction)

Noah vs. Noah-MP land surface model



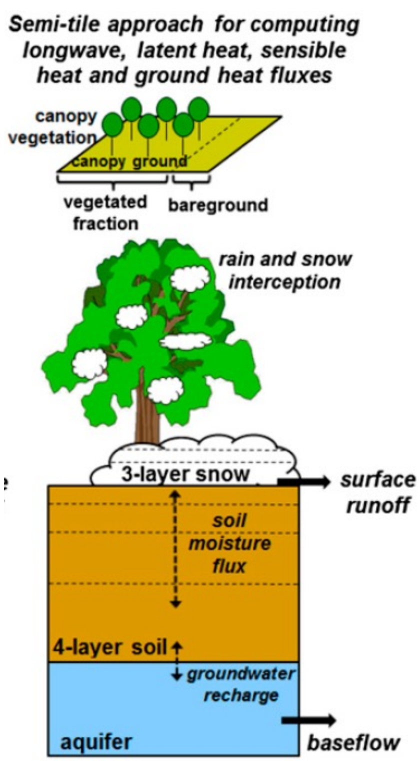
Noah-MP



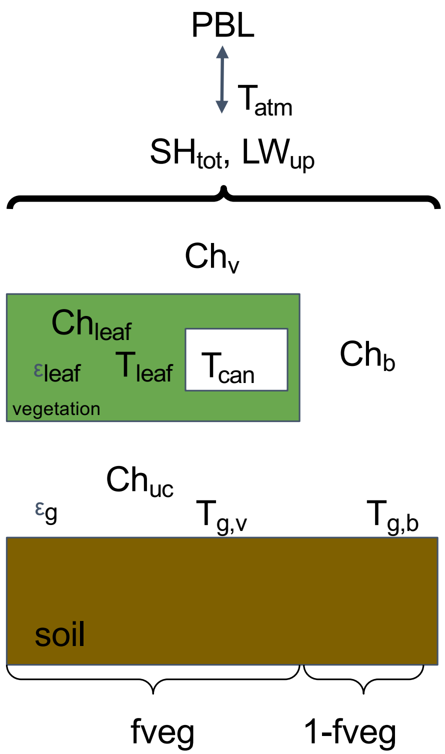
What is different for Noah-MP?

- Noah-MP treats each grid cell as two tiles containing a vegetation fraction (fveg) and bare soil fraction (1-fveg)
- As vegetation is separated from soil vertically, soil under the vegetation does “see” the atmosphere
- Each tile has at least one roughness length (and albedo and ε)
- Different exchange coefficients (Ch) are calculated for each flux, namely: Ch_{veg}, Ch_{can}, $Ch_{soil,v}$, $Ch_{soil,b}$
- Iteration until $SH_{veg} = SH_{can} + SH_{soil,v}$ and Ch recalculated each iteration
- $SH_{tot} = fveg * SH_{veg} + (1-fveg) * SH_{soil,b}$
- In PBL schemes that only require fluxes, no problem!
- Issues: non-linear processes for averaging Ch, etc.
- No single surface, e.g., temperatures in Noah-MP: leaf, canopy air, soil surface below canopy, soil surface with no canopy
- 3-layer snowpack
- There can be groundwater recharge at bottom layer from an aquifer (i.e., with groundwater interaction)

Noah vs. Noah-MP land surface model



Noah-MP



Need for two surface temperatures in UFS?

In Noah: $(1-\alpha)SW_{dn} + \varepsilon(LW_{dn} - \sigma T_s^4) =$

$$SH(T_s) + LH(T_s) + GH(T_s)$$

where T_s is the “skin” temperature and ε/α are the grid-avg emissivity/albedo.

In Noah-MP: $(1-\alpha)SW_{dn} + \varepsilon_{net}(LW_{dn} - \sigma T_{rad}^4) =$

$$SH_{tot} + LH_{tot} + GH_{tot}$$

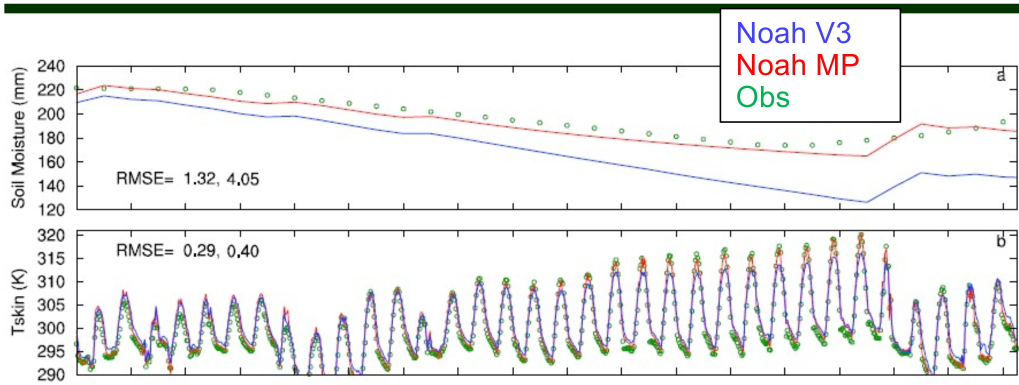
where

$$SH_{tot} = f_{veg}\rho c_p Ch_v(T_{can} - T_{atm}) + (1-f_{veg})\rho c_p Ch_b(T_{g,b} - T_{atm})$$

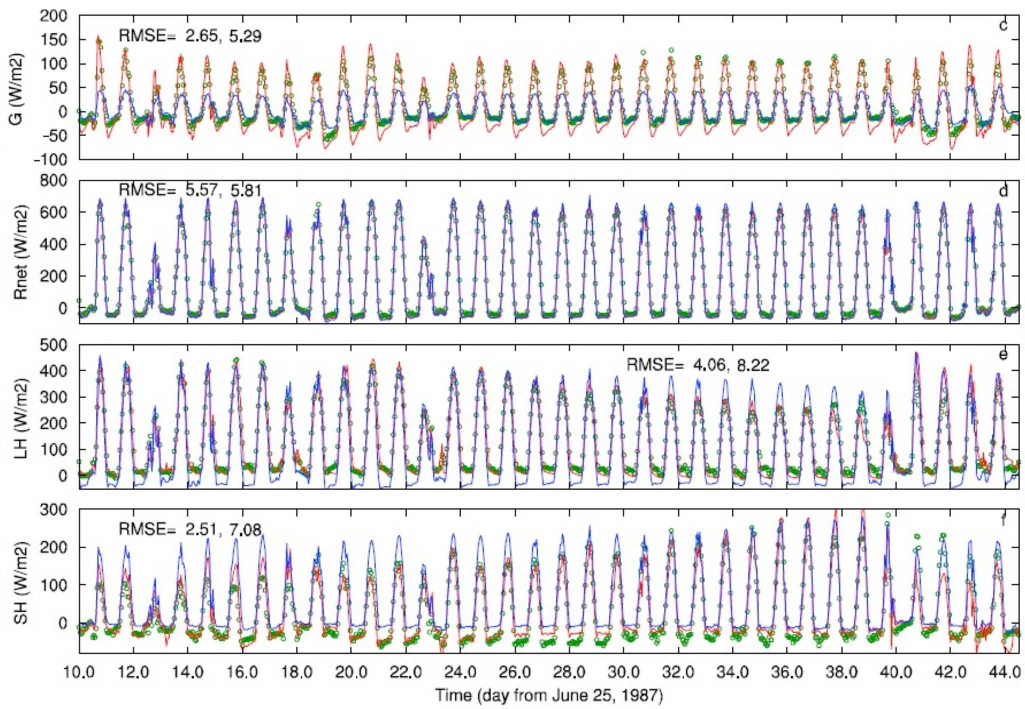
$$LW_{up} = LW_v(T_{leaf}, T_{g,v}, \varepsilon_{leaf}, \varepsilon_g) + \varepsilon_g \sigma T_{g,b}^4$$

So, in Noah-MP, unlike Noah, there are different “source temperatures” for SH and LW and the source temperatures, exchange coefficients (Ch) and emissivities (ε) must be averaged in different ways.

Noah vs. Noah-MP land surface model



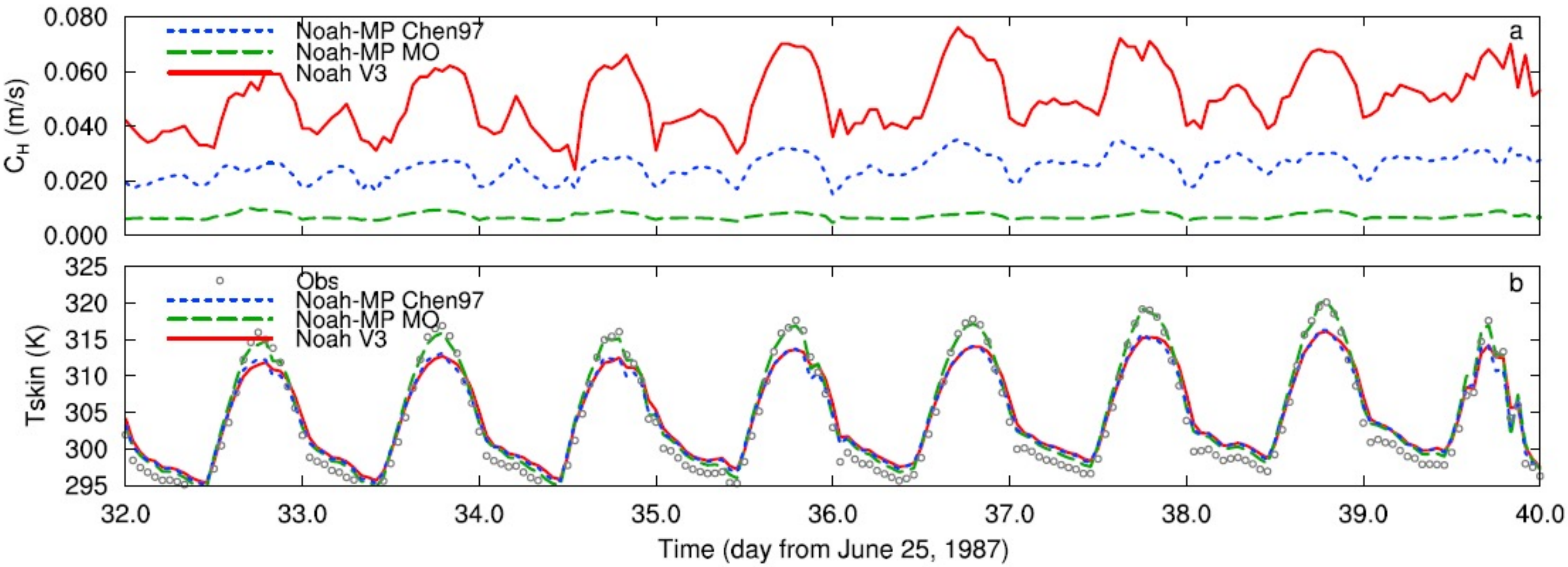
Niu et al. (2011)



- Model simulated Noah, Noah-MP versus the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) which is conducted on a 15 km×15 km site centered at 39.058N, 96.538W near Manhattan, Kansas (the site is predominately grassland of moderate topography).
- The RMSE of water and radiation variables is reduced in Noah-MP.

Noah vs. Noah-MP land surface model

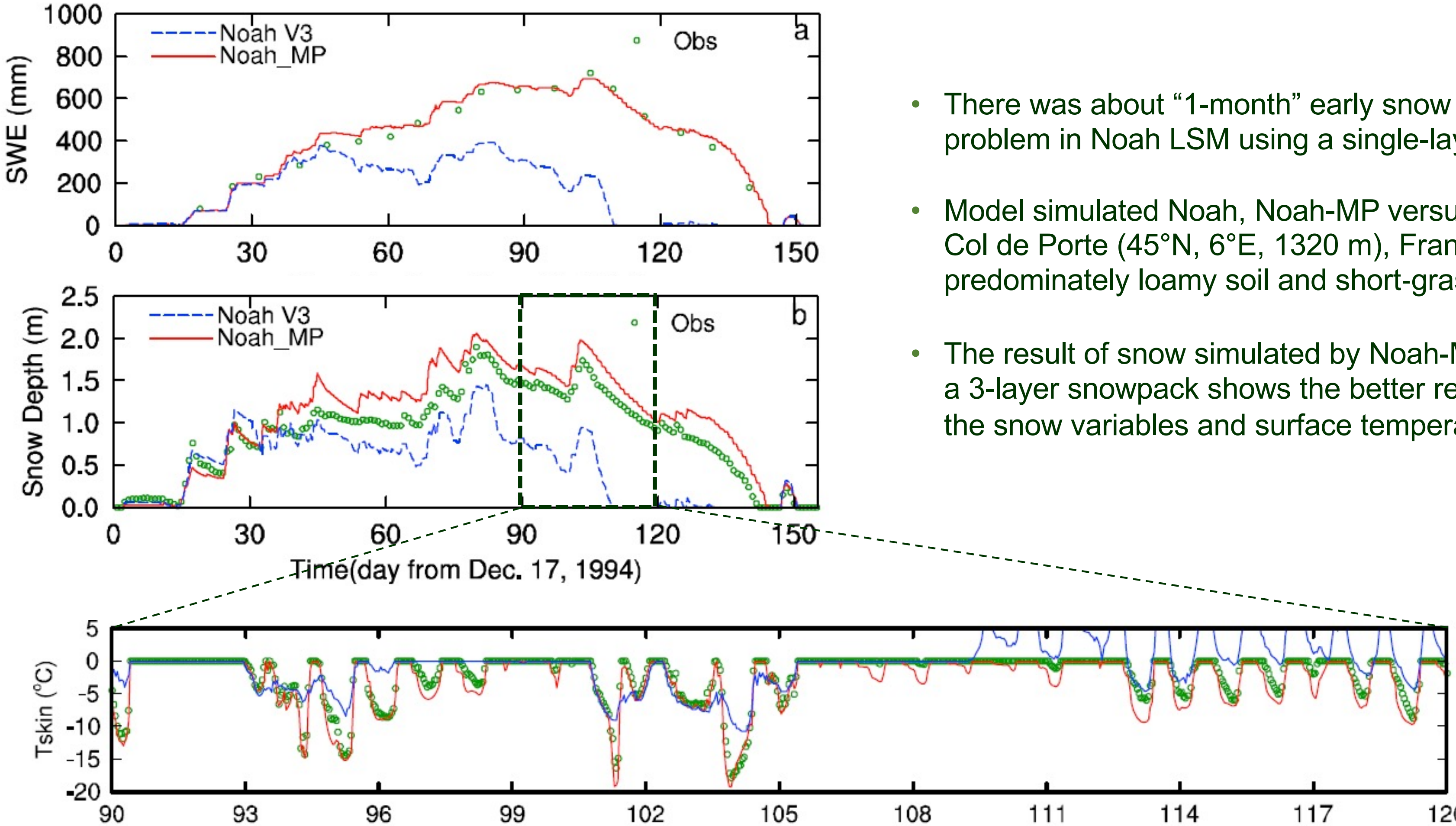
Niu et al. (2011)



- Exchange coefficient scheme uses "Chen97" and "M-O" scheme in Noah and Noah-MP LSM, respectively, in which "M-O" scheme represents the low exchange coefficient (C_h).

$$SH \propto \rho C_p C_h U_{atm}(T_{land} - T_{atm})$$

Noah vs. Noah-MP land surface model



- There was about "1-month" early snow melting problem in Noah LSM using a single-layer snowpack.
- Model simulated Noah, Noah-MP versus observed at Col de Porte (45°N, 6°E, 1320 m), France (the site is predominately loamy soil and short-grass vegetation).
- The result of snow simulated by Noah-MP LSM using a 3-layer snowpack shows the better representation in the snow variables and surface temperature.

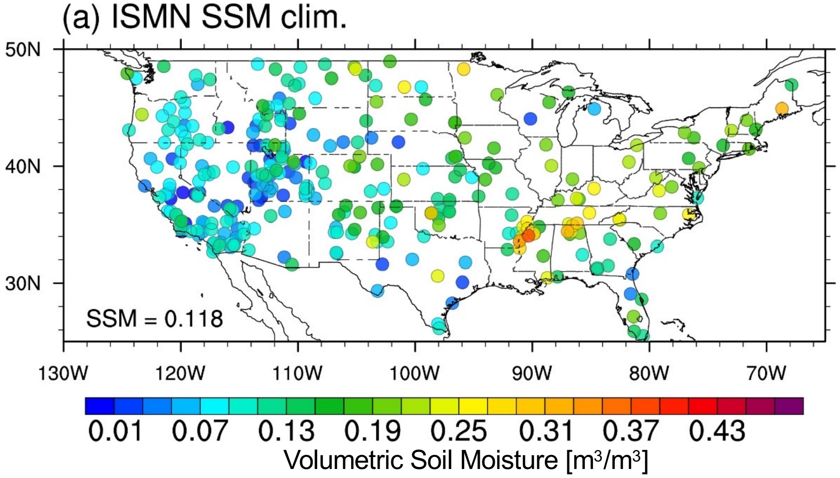
Niu et al. (2011)

UFS results

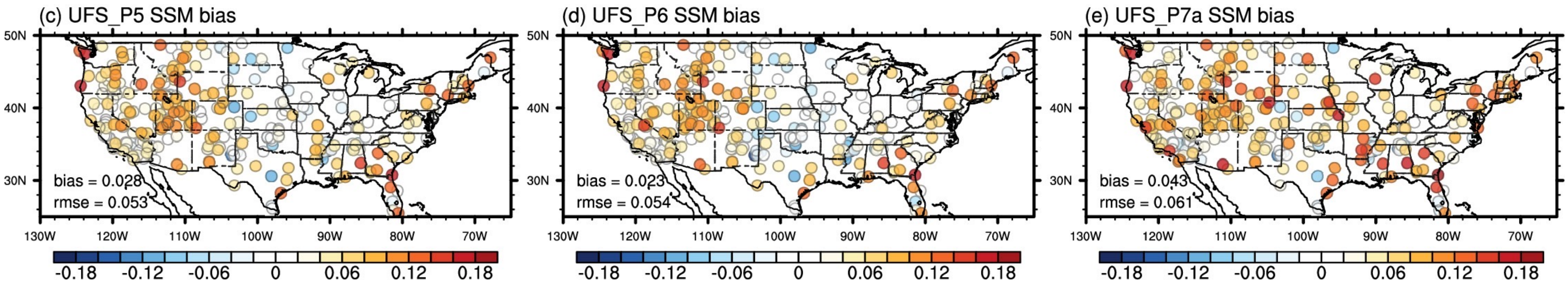
- For comparison to the P7a sub-prototype, we are limited to **July simulations from 2012 and 2013 only**. *(evaluation of 31-day model forecast for only 2-year summer)*

Soil moisture mean climatology (bias & rmse)

July (2012-2013)



- Surface soil moisture July mean climatology of UFS sub-prototype experiments is validated from ground-based observation dataset (ISMN except for COSMOS and SNOTEL networks).
- Although the spatial pattern of soil moisture climatology is well captured in the model, there is relatively large overestimation over the western US.
- The model error in prototypes P5 and P6 (using Noah LSM) is smaller than that in prototype P7a (using Noah-MP LSM). Noah-MP represents a slightly wetter soil moisture in the forecast model.
- Great Plains dry bias is removed in P7a.

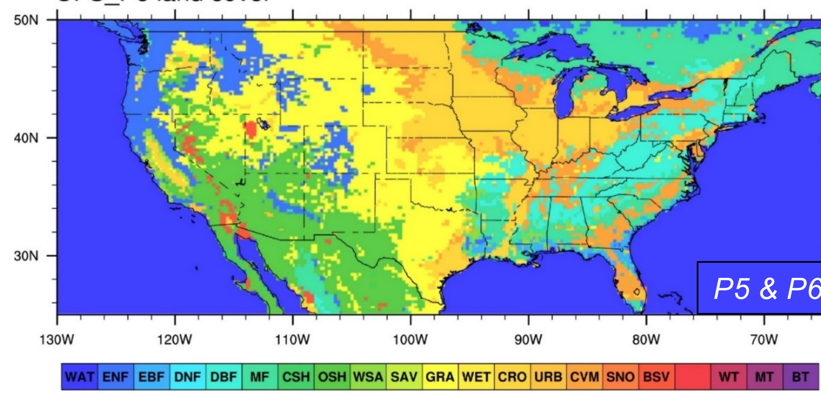


** Obs: ISMN (International Soil Moisture Network)*

Vegetation land cover

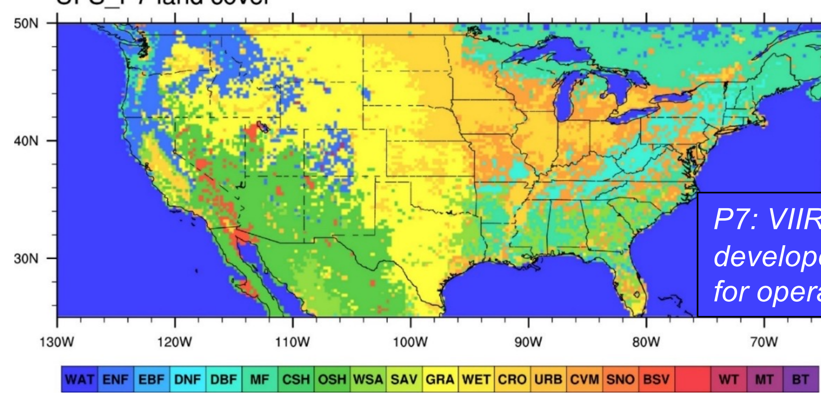
1	Evergreen Needleleaf Forest	ENF
2	Evergreen Broadleaf Forest	EBF
3	Deciduous Needleleaf Forest	DNF
4	Deciduous Broadleaf Forest	DBF
5	Mixed Forests	MF
6	Closed Shrublands	CSH
7	Open Shrublands	OSH
8	Woody Savannas	WSA
9	Savannas	SAV
10	Grasslands	GRA
11	Permanent wetlands	WET
12	Croplands	CRO
13	Urban and Built-Up	URB
14	Cropland/natural vegetation mosaic	CVM
15	Snow and Ice	SNO
16	Barren or Sparsely Vegetated	BSV
17	Water	WAT
18	Wooded Tundra	WT
19	Mixed Tundra	MT
20	Bare Ground Tundra	BT

UFS_P6 land cover



P5 & P6: MODIS

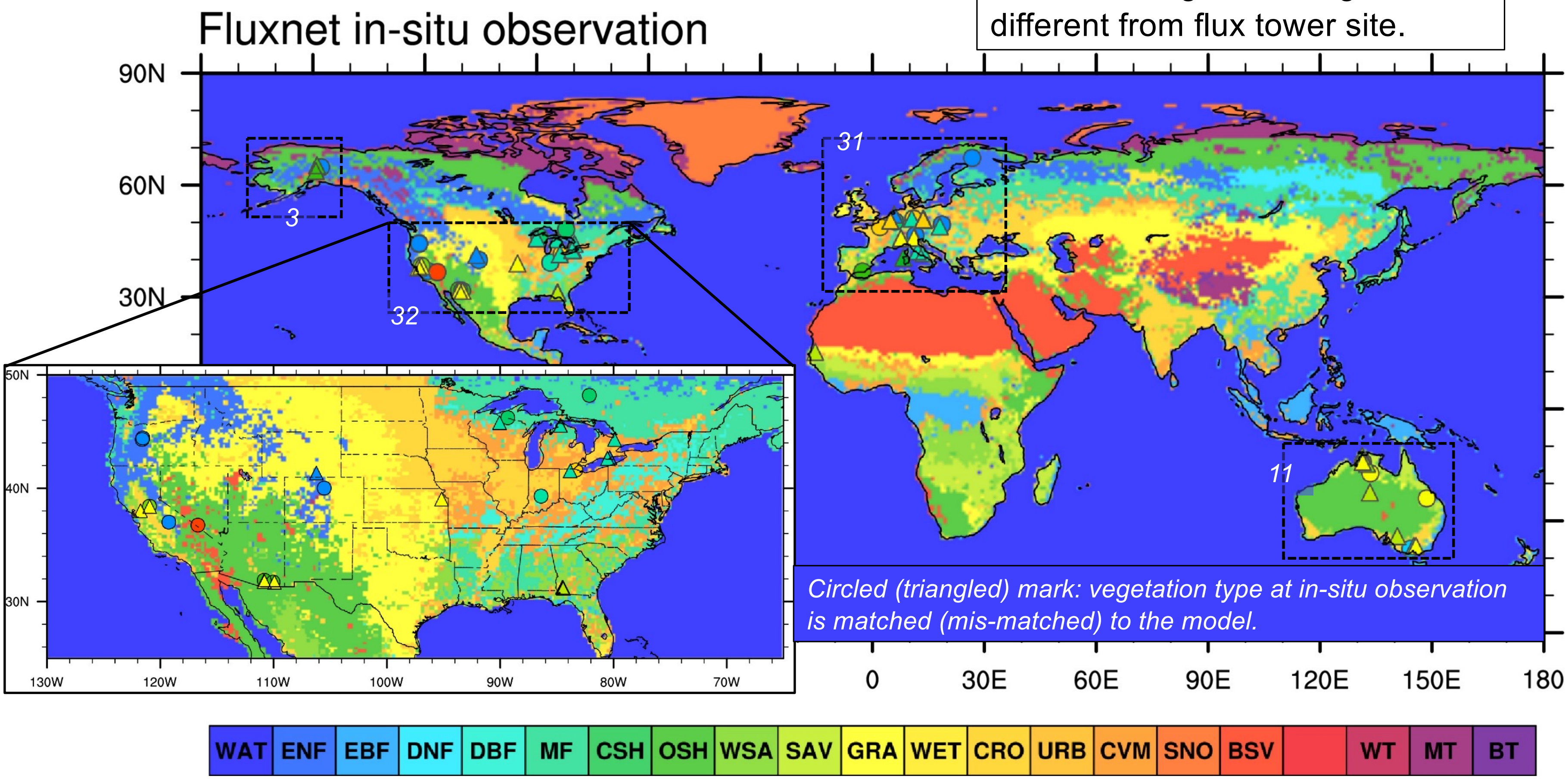
UFS_P7 land cover



P7: VIIRS – new dataset developed by NESDIS for operational use

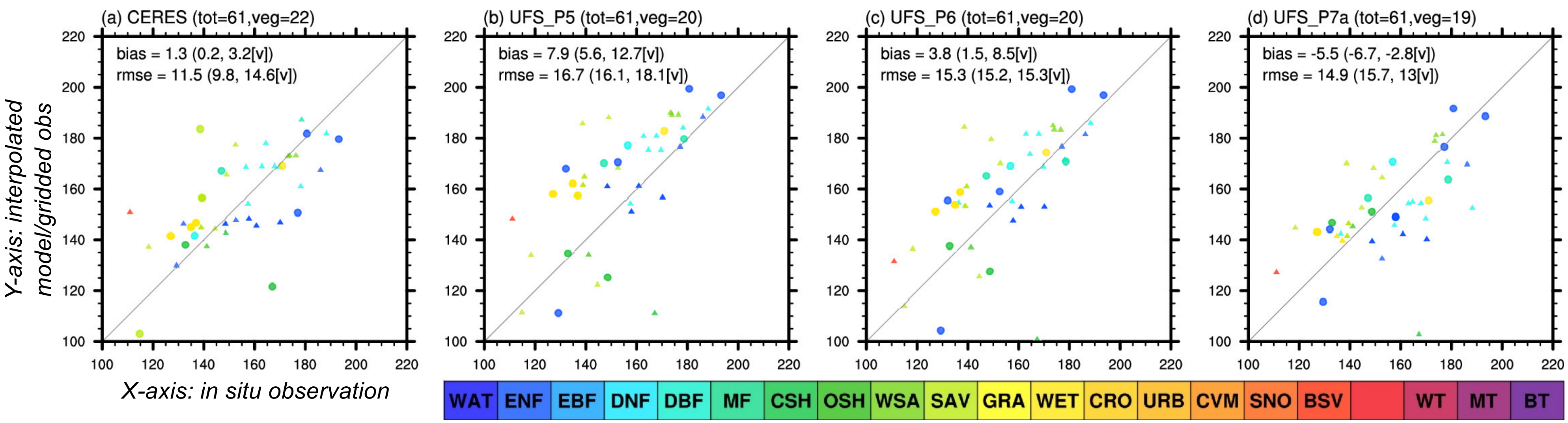
In-situ observations

Often model grid cell vegetation is different from flux tower site.



Incoming net radiation climatology (bias & rmse)

July (2012-2013)



** veg: vegetation type at in-situ site matches the model: ●, not match: ▲.* * bias/rmse = all stations (▲, ●)

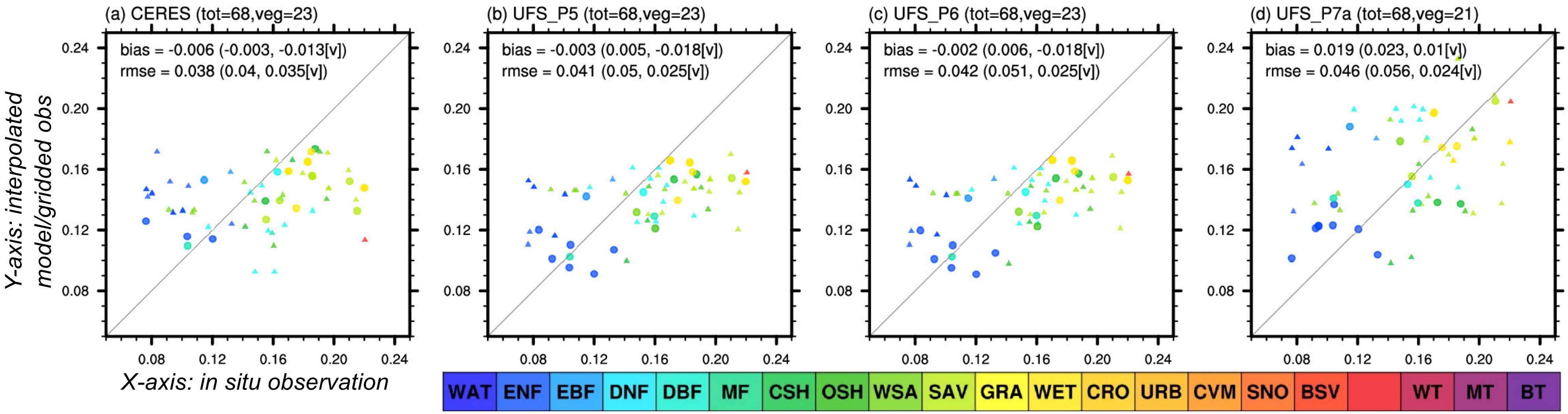
	CERES	UFS_P5	UFS_P6	UFS_P7a
All (61)	1.3 (11.5)	7.9 (16.7)	3.8 (15.3)	**-5.5 (14.9)**
Forest (28)	-4 (10.2)	5.7 (11.1)	**1 (10.3)**	-10.1 (13.9)
Shrub (3)	-15.2 (18.7)	-25.6 (26.9)	-27.2 (30.5)	**-15.7 (26.8)**
Savanna (8)	-1.3 (6.2)	7.2 (14.8)	5.6 (13.2)	**-3.8 (10)**
Grass (13)	9.5 (14.2)	13.7 (19.8)	11.6 (17.3)	**2 (16.7)**
Crop (7)	9.7 (10.2)	24.3 (24.3)	19.2 (19.2)	**5.4 (9.7)**

* Bias(RMSE)

- In-situ observation (FLUXNET and BSRN) is used to evaluate incoming net radiation in satellite-based and modeled datasets.
- UFS_P7a shows the relatively low bias and RMSE in the net radiation against the station observation except over the forest.

Albedo climatology (bias & rmse)

July (2012-2013)



** veg: vegetation type at in-situ site matches the model: ●, not match: ▲.*

* bias/rmse = all stations (▲, ●)

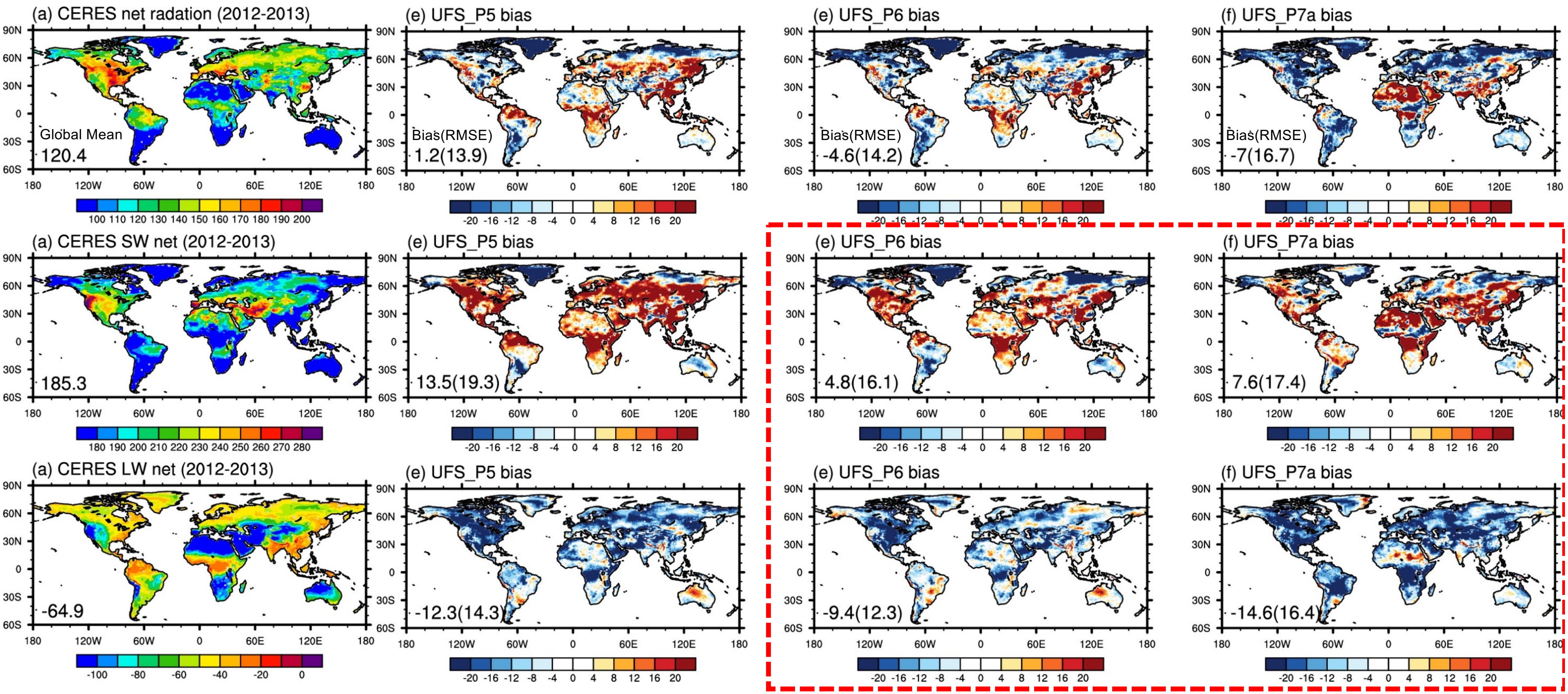
	CERES	UFS_P6	UFS_P7a
All (68)	-0.006 (0.038)	**-0.002 (0.042)**	0.019 (0.046)
Forest (30)	0.016 (0.038)	**0.013 (0.031)**	0.041 (0.048)
Shrub (4)	-0.013 (0.013)	**-0.03 (0.03)**	-0.045 (0.045)
Savanna (11)	-0.01 (0.032)	**-0.012 (0.036)**	-0.003 (0.04)
Grass (13)	-0.039 (0.04)	-0.043 (0.043)	**-0.012 (0.029)**
Crop (8)	-0.032 (0.032)	-0.029 (0.029)	**-0.009 (0.022)**

* Bias(RMSE)

- In-situ observation (FLUXNET and BSRN) is used to evaluate surface albedo.
- CERES and Noah LSM show the underestimated surface albedo over most land cover except for forest, but Noah-MP generally increases the surface albedo over the entire land type. Thus, Noah-MP shows realistic surface albedo over grassland and cropland even though it is somewhat overestimated in the forest.

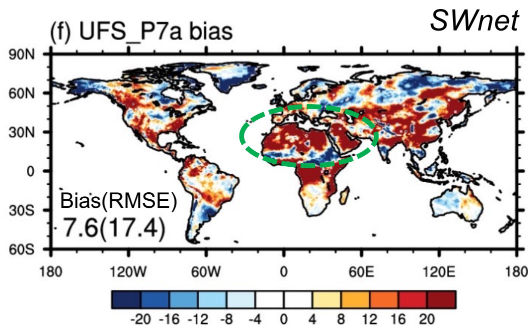
Incoming net radiation climatology (bias & rmse)

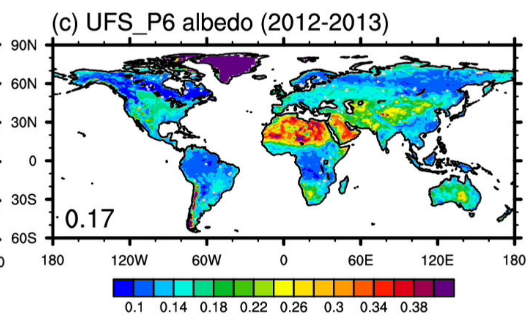
July (2012-2013)

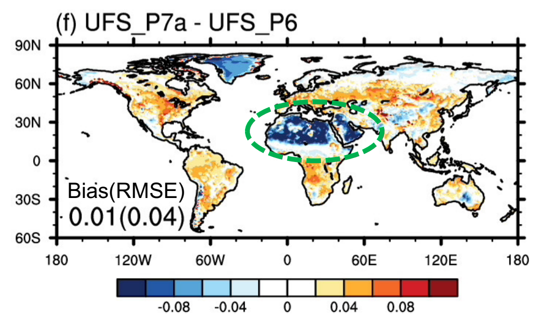


Surface radiation issues (bias & rmse)

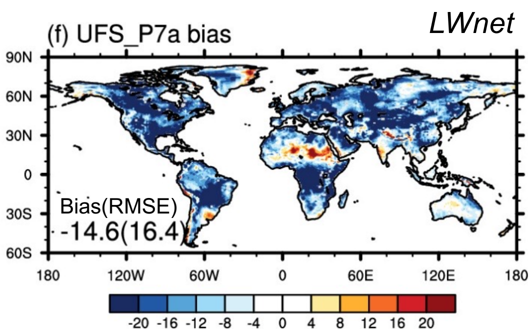
July (2012-2013)

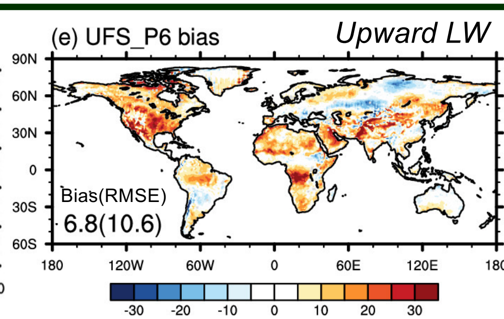


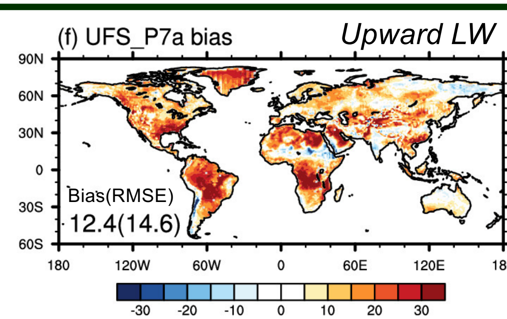


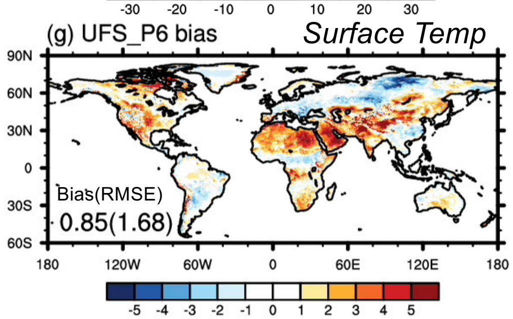


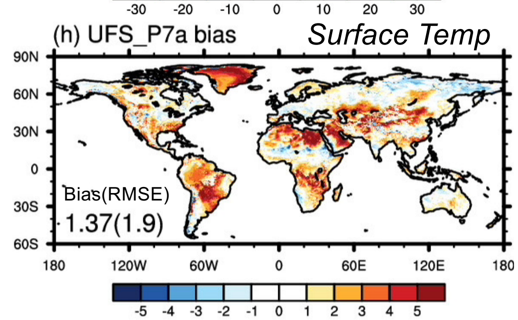
- Increased SW net radiation in UFS_P7a over the Sahara desert is attributed to the decreased surface albedo in Noah-MP.









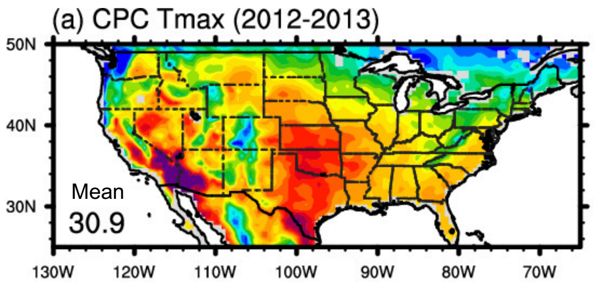


- Decreased LW net radiation in UFS_P7a is related to the upward LW which is due to increasing surface temperature in Noah-MP (especially over the southeast US, South America, central Africa, and Sahara desert).

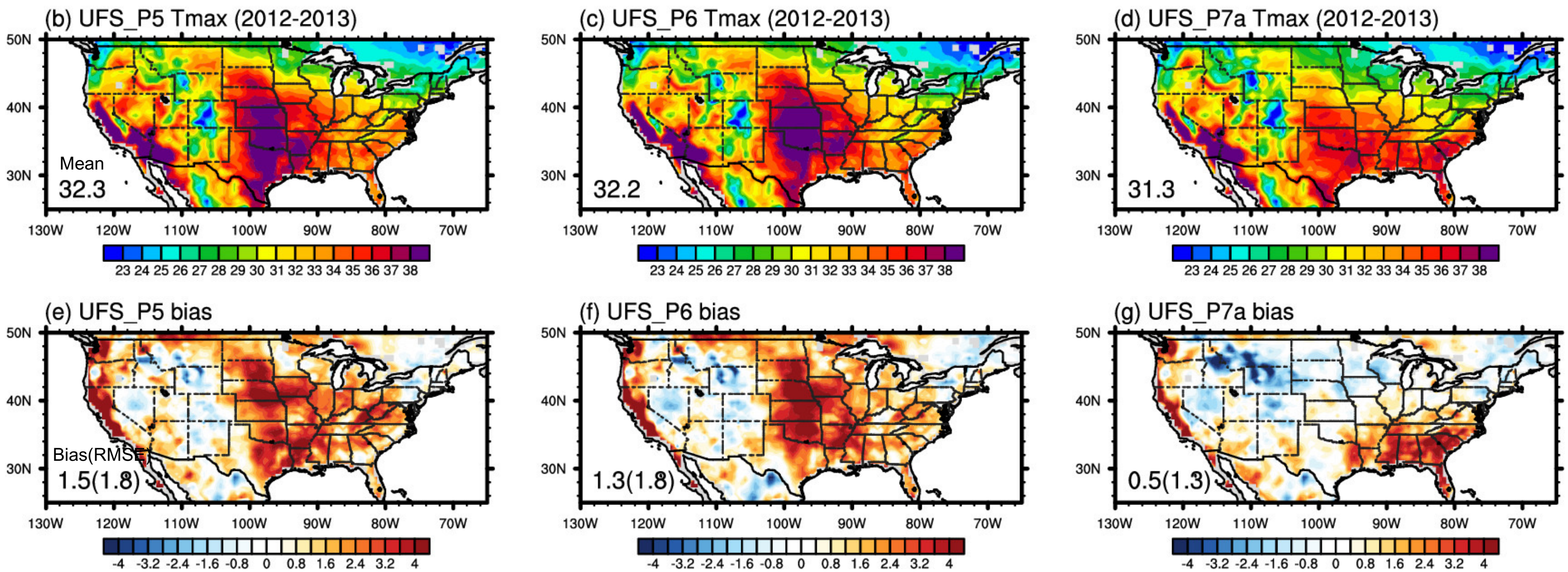
** reference data*
CERES satellite: SWnet, LWnet, LWup
ERA5 reanlysis: Tsfc

T_{max} mean climatology (bias & rmse)

July (2012-2013)

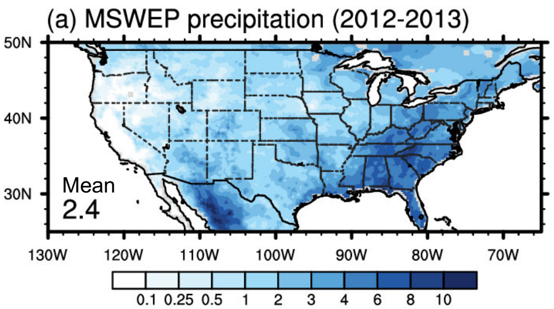


- UFS P5 and P6 simulations represent large warm bias from central to eastern US, but it is mostly corrected in the P7a runs even though the model develops a warm bias over the southeastern US.

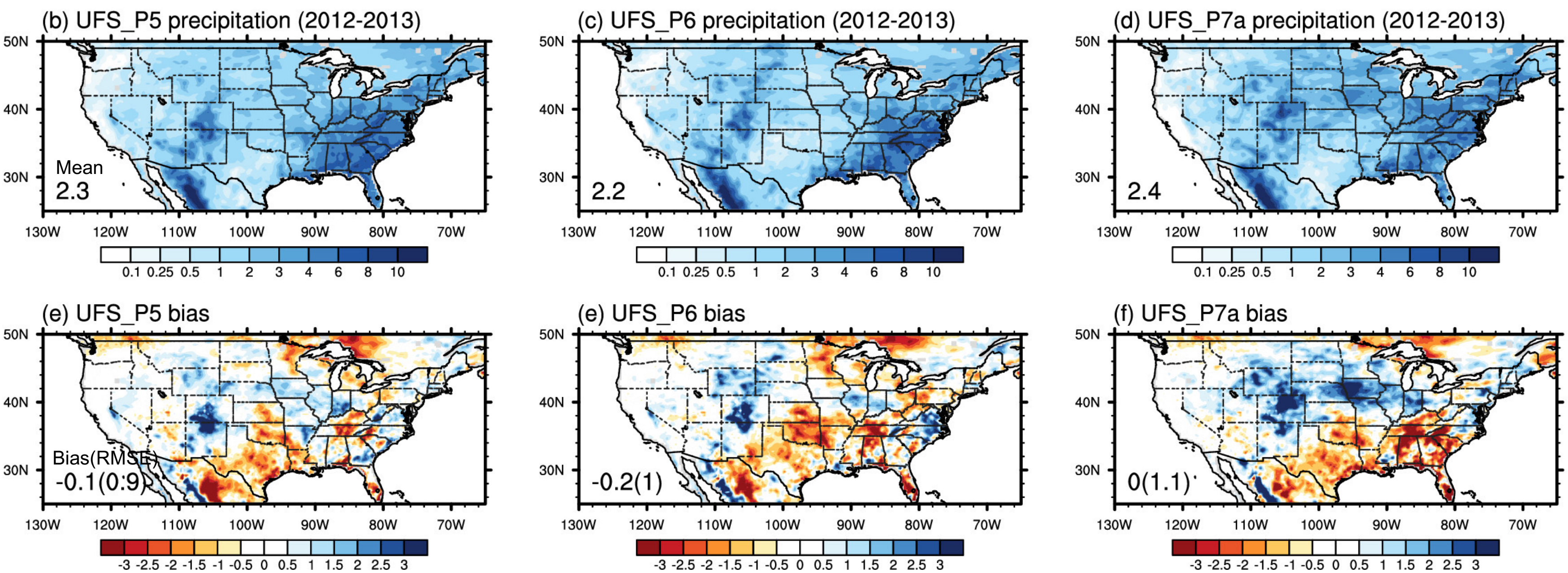


Precipitation mean climatology (bias & rmse)

July (2012-2013)



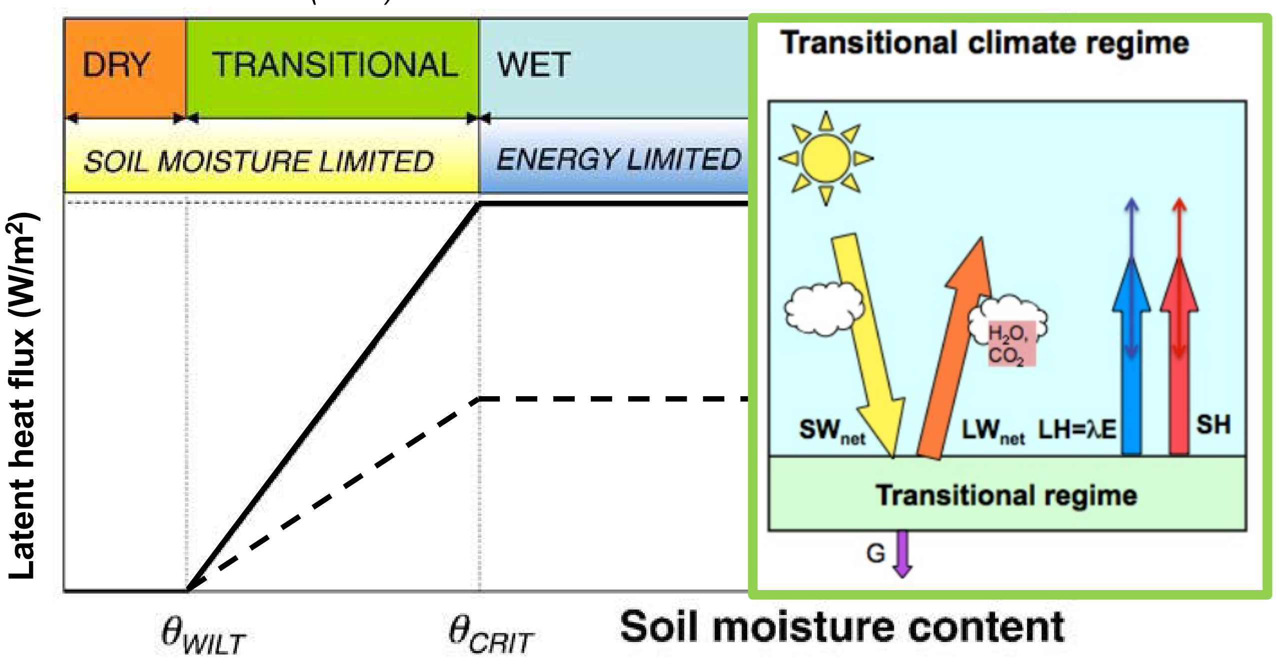
- All UFS prototype simulations represent positive precipitation biases over the Front Range of the Rockies. Compared to the previous runs, P7a has the highest RMSE due to the strong biases over the Midwest and Southeast US.



Land-atmosphere interaction (TCI)

$Terrestrial\ Coupling\ Index = \boldsymbol{Corr}(\boldsymbol{SM},\boldsymbol{LH}) \times \boldsymbol{STD}(\boldsymbol{LH})$ *Dirmeyer et al. (2013)*

Seneviratne et al. (2010)



- Terrestrial coupling index (TCI) quantifies surface flux (e.g., latent heat flux) sensitivity to representative soil moisture variability.

- In situ observation: FLUXNET
- Gridded observational dataset:
  SM – ESA CCI
  LH – GLEAM, FLUXCOM

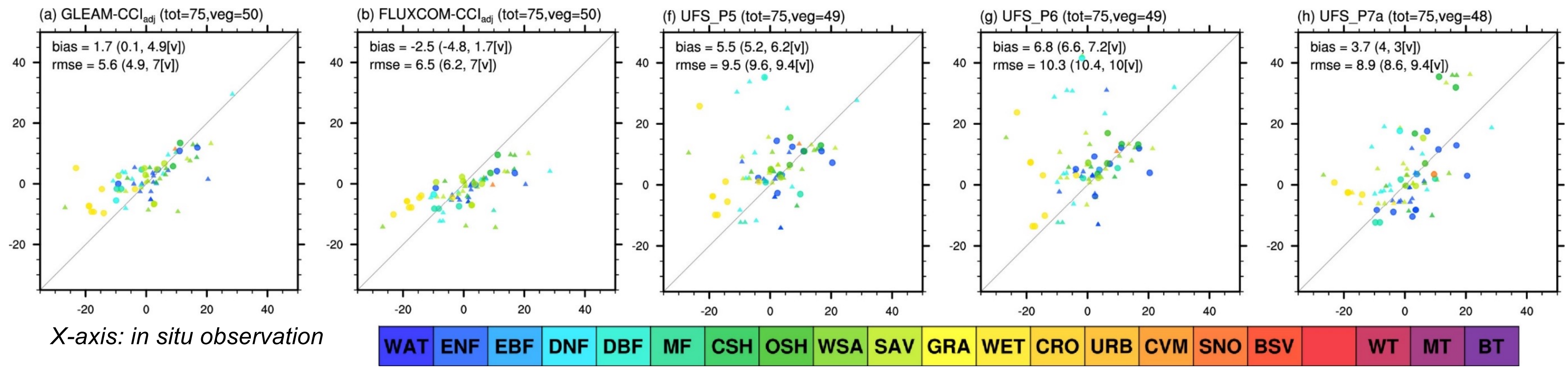
$\boldsymbol{Corr}(\boldsymbol{SM},\boldsymbol{LH})$: how SM & LH are strongly coupled (dashed: weak, solid: strong)
$\boldsymbol{STD}(\boldsymbol{LH})$: under this relationship, how sensitive LH is to SM (slop)

Land-atmosphere interaction (TCI)

July (2012-2013)

$$Terrestrial\ Coupling\ Index = \boldsymbol{Corr(SM, LH)} \times \boldsymbol{STD(LH)}$$ *Dirmeyer et al. (2013)*

Y-axis: interpolated model/gridded obs



X-axis: in situ observation

** veg: vegetation type at in-situ site matches the model: ●, not match: ▲.* * bias/rmse = all stations (▲, ●)

	GLEAM	FLUXCOM	UFS_P5	UFS_P6	UFS_P7a
All (75)	**1.7 (5.6)**	-2.5 (6.5)	5.5 (9.5)	6.8 (10.3)	**3.7 (8.9)**
Forest (35)	**1.6 (4.7)**	-4.3 (5.7)	3.9 (9.8)	6.2 (10.6)	**0.1 (7.2)**
Shrub (5)	**-1.3 (4)**	-5 (5)	-3 (4.6)	**-0.2 (3.4)**	5.1 (16.3)
Savanna (12)	**-1.4 (6.6)**	-4.7 (8.2)	**5.1 (8)**	6 (8.6)	4.9 (9)
Grass (14)	**0.4 (4.8)**	-2.2 (5.3)	7.3 (8.7)	5.9 (10)	**6.1 (7.8)**
Crop (8)	11 (11)	**9.8 (10)**	15.6 (15.6)	17.1 (17.1)	**13.2 (13.7)**

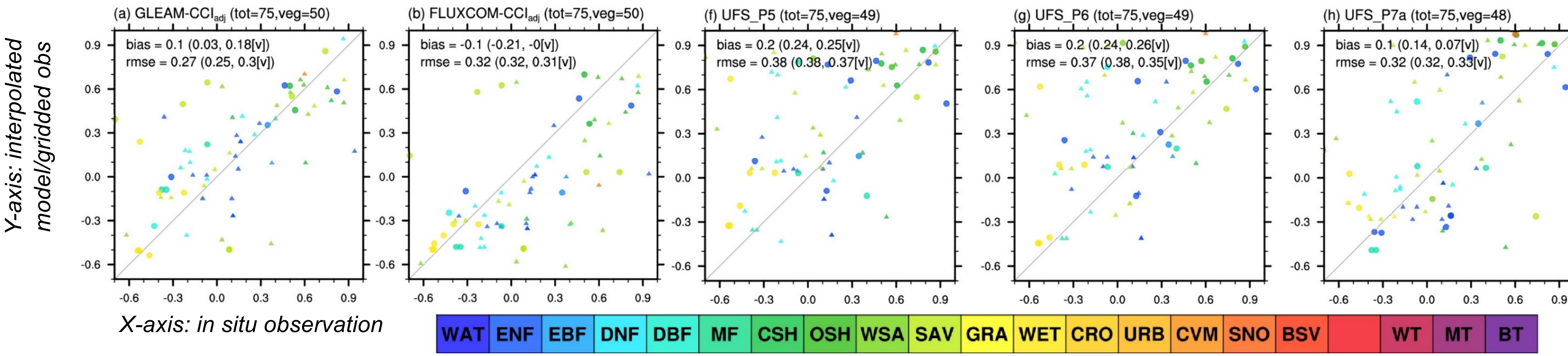
* Bias(RMSE)

- UFS_P7a shows reduced RMSE in the TCI (mainly in forest, grassland, and cropland) compared to the previous UFS runs even though there is still some overestimation, especially over the shrubland.

Land-atmosphere interaction (TCI)

July (2012-2013)

$Terrestrial\ Coupling\ Index = \mathbf{Corr(SM, LH)} \times STD(LH)$ *Dirmeyer et al. (2013)*



** veg: vegetation type at in-situ site matches the model: ●, not match: ▲.* * bias/rmse = all stations (▲, ●)

	GLEAM	FLUXCOM	UFS_P5	UFS_P6	UFS_P7a
All (75)	**0.08 (0.27)**	-0.14 (0.32)	0.24 (0.38)	0.25 (0.37)	**0.12 (0.32)**
Forest (35)	**0.06 (0.22)**	-0.21 (0.25)	0.12 (0.33)	0.15 (0.31)	**0.02 (0.26)**
Shrub (5)	**-0.08 (0.25)**	-0.23 (0.31)	-0.06 (0.25)	**0.03 (0.2)**	-0.1 (0.48)
Savanna (12)	**0.04 (0.37)**	-0.14 (0.54)	0.36 (0.44)	0.36 (0.43)	**0.2 (0.34)**
Grass (14)	**0.13 (0.35)**	-0.05 (0.4)	0.4 (0.44)	0.31 (0.49)	**0.2 (0.39)**
Crop (8)	0.21 (0.23)	**0.09 (0.12)**	0.48 (0.48)	0.51 (0.51)	**0.36 (0.37)**

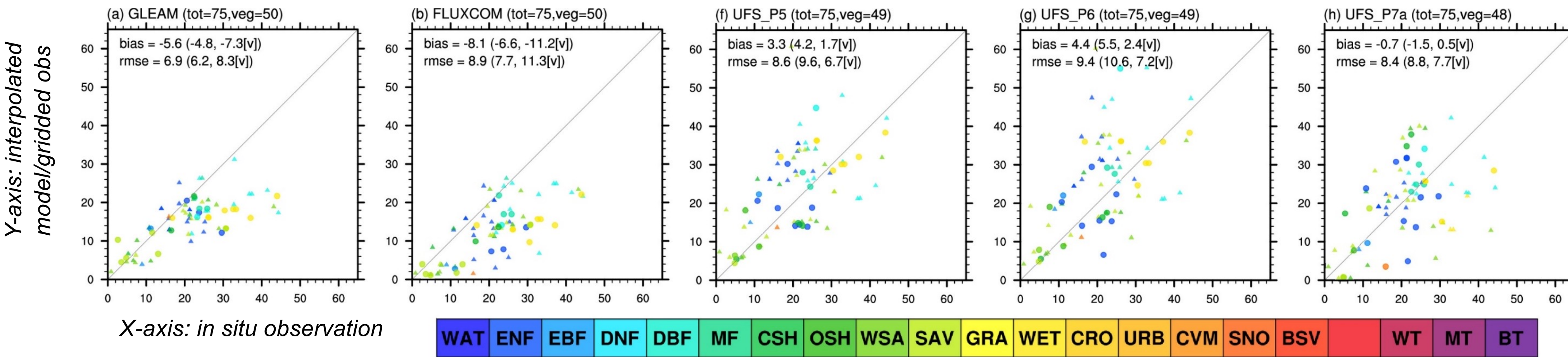
* Bias(RMSE)

- The results of TCI are mostly related to the correlation between surface soil moisture and latent heat flux.
- UFS_P7a generally shows the realistic relationship between both variables except for shrubland, even though there is a slight over-coupling.

Land-atmosphere interaction (TCI)

July (2012-2013)

$Terrestrial\ Coupling\ Index = Corr(SM, LH) \times \mathbf{STD(LH)}$ *Dirmeyer et al. (2013)*



* *veg: vegetation type at in-situ site matches the model: ●, not match: ▲.* * bias/rmse = all stations (▲, ●)

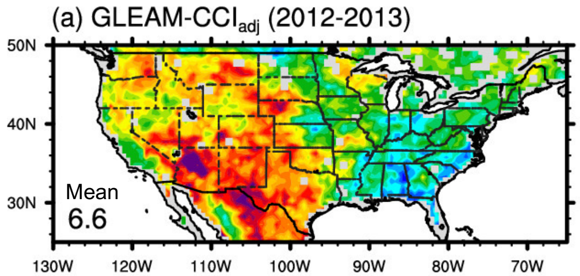
	GLEAM	FLUXCOM	UFS_P5	UFS_P6	UFS_P7a
All (75)	-5.6 (6.9)	-8.1 (8.9)	3.3 (8.6)	4.4 (9.4)	**-0.7 (8.4)**
Forest (35)	-5.5 (7)	-7.6 (8.5)	4.9 (9.6)	6.5 (11.4)	**0 (6.5)**
Shrub (5)	-0.8 (2.7)	-3.8 (6.3)	2 (7.8)	**2.3 (6.2)**	11.6 (11.6)
Savanna (12)	-5.1 (5.8)	-6.4 (7.1)	-1.2 (6.7)	**0.1 (6.6)**	-4.6 (10.4)
Grass (14)	-4.4 (5.9)	-7.5 (7.6)	4.6 (9.2)	5.3 (9.6)	**2.5 (8.2)**
Crop (8)	-13.2 (13.2)	-16.1 (16.1)	**2.2 (6.7)**	2.8 (7.1)	-10 (11.3)

- When the land cover prescribed in the model matches the in situ observation sites, the RMSE of latent heat flux variability decreases.
- Overall, UFS_P7a shows less RMSE in land heat flux variability, but its overestimation over the shrubland leads to the positive TCI biases there.

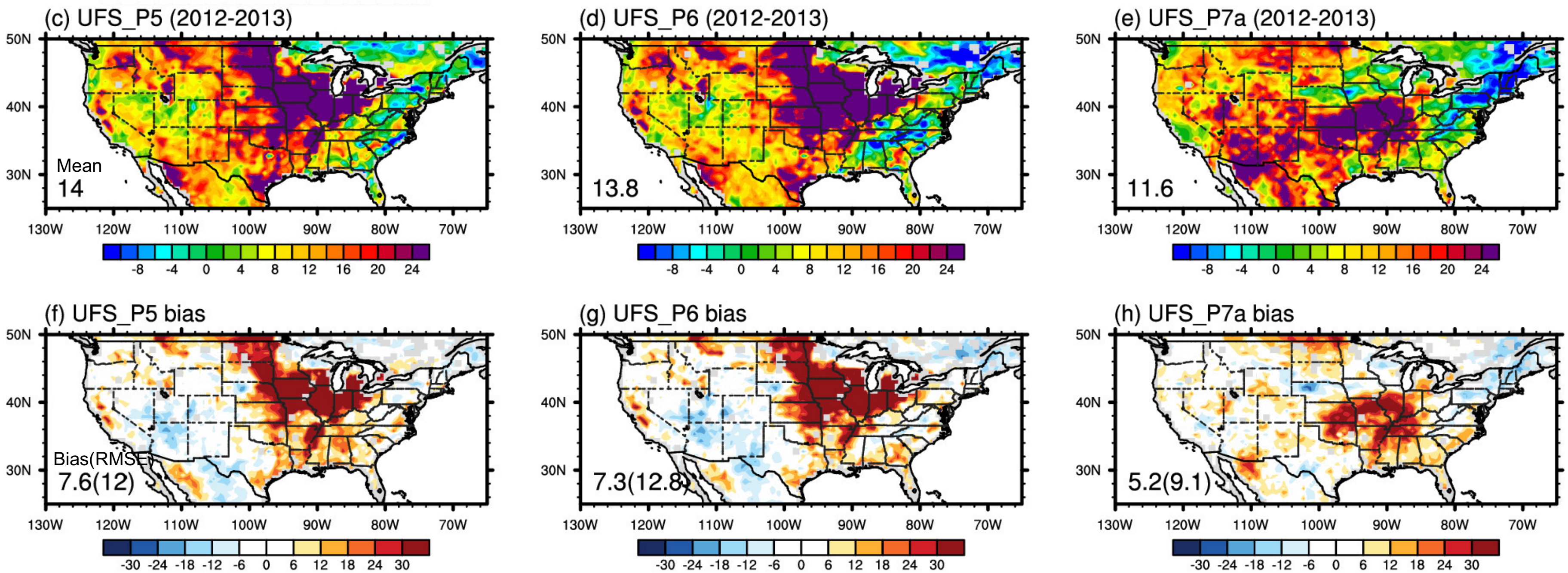
* Bias(RMSE)

Land-atmosphere interaction (TCI)

July (2012-2013)

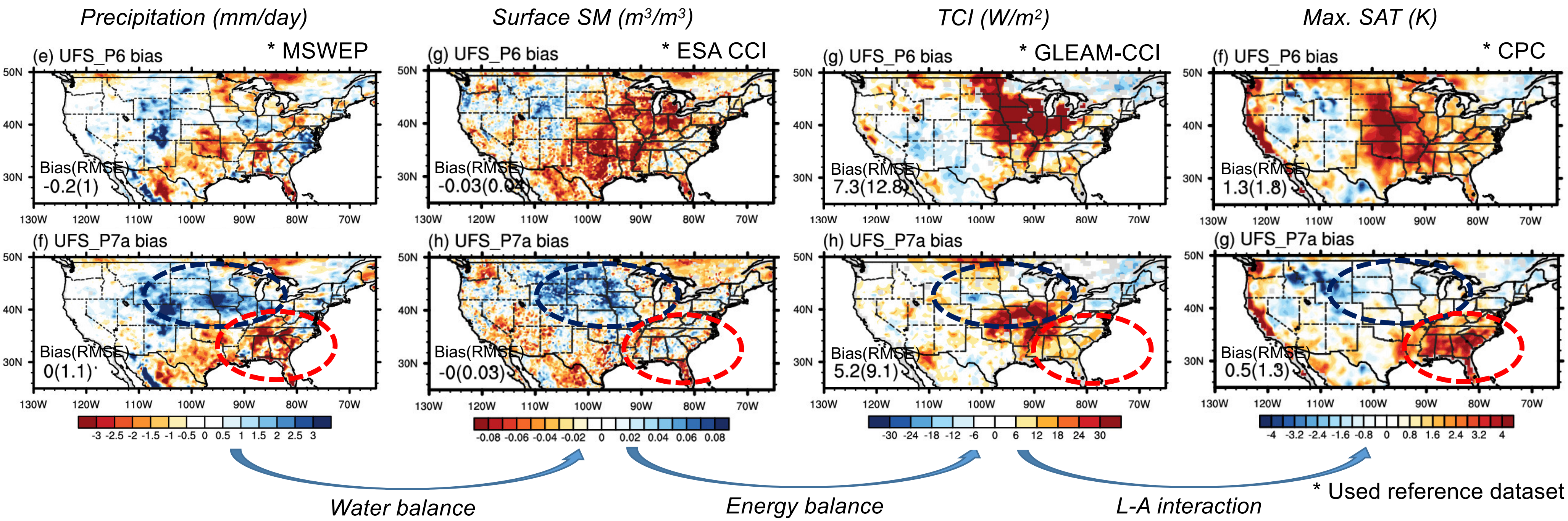


- UFS P5 and P6 simulations represent similar TCI spatial patterns in which there is a large positive TCI bias over the Midwest US (mostly in the cropland).
- However, UFS prototype P7a shows reduced bias, but there is still a positive bias of TCI over the Lower Mississippi Valley.



Mean climatology (bias & rmse)

July (2012-2013)



- Midwest US: In P7a, the positive bias of precipitation leads to wet soil moisture biases, which lead to reduced terrestrial coupling. It also reduces the warm bias. (water limited region)
- Southeast US: The negative bias in precipitation increases incoming SW radiation, emphasizing the warm bias. However, the soil moisture change is opposite by the water balance, so the area is influenced by 'only' energy balance (energy limited region). **Thus, the temperature bias is strongly influenced by atmospheric states in the model rather than the land surface**.

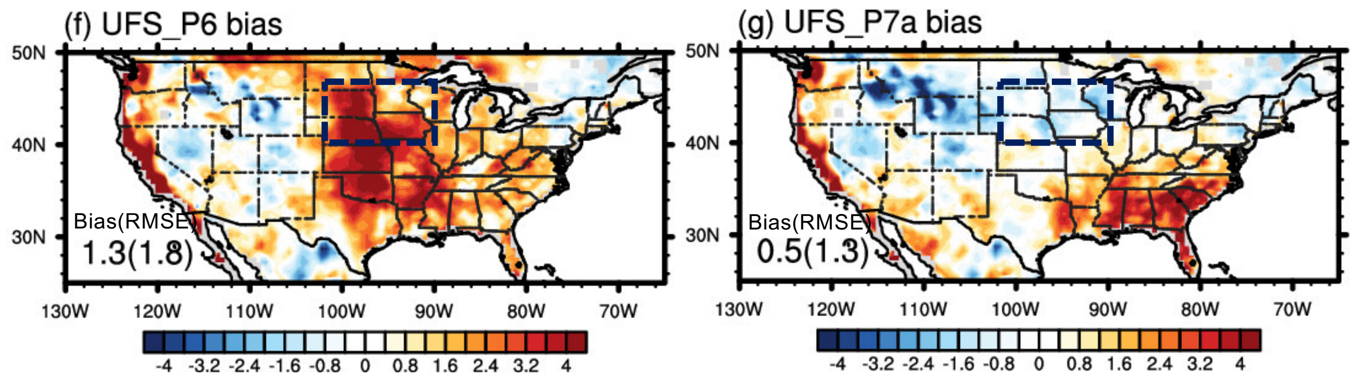
Mean climatology (bias & rmse)

July (2012-2013)

Water balance $\frac{dS}{dt} = P - E - R$

$$\frac{dH}{dt} = R_n - \lambda \mathbf{E} - SH - G$$

Energy balance



Water balance	Pr (mm/day)	SSM (m3/m3)	λE (W/m2)
Obs	1.42	0.19	93.7
UFS_P6	1.35 (-0.07)	0.15 (-0.04)	103.4 (9.7)
UFS_P7a	**2.95** (1.53)	**0.22** (0.03)	**123.3** (29.6)

* actual value (bias)

Transitional (mostly agricultural) region
Increased precipitation → more soil moisture → increased (decreased) latent (sensible) heat flux **+** *weak L-A coupling → cooling surface air temperature*

Energy balance	netRad	LH	SH	1-EF
Obs	183.1	93.7	89.7	0.36
UFS_P6	169.9 (-13.2)	103.4 (9.7)	66.5 (-23.2)	0.44 (0.08)
UFS_P7a	157.1 (-26)	**123.3** (29.6)	**33.8** (-55.9)	**0.21** (-0.15)

LA coupling	TCI (W/m2)	Tmax (degC)
Obs	4.5	30.8
UFS_P6	35.7 (31.2)	33.7 (2.9)
UFS_P7a	**7.9** (3.4)	**30.1** (-0.7)

* EF(evaporative fraction) = LH/netRad

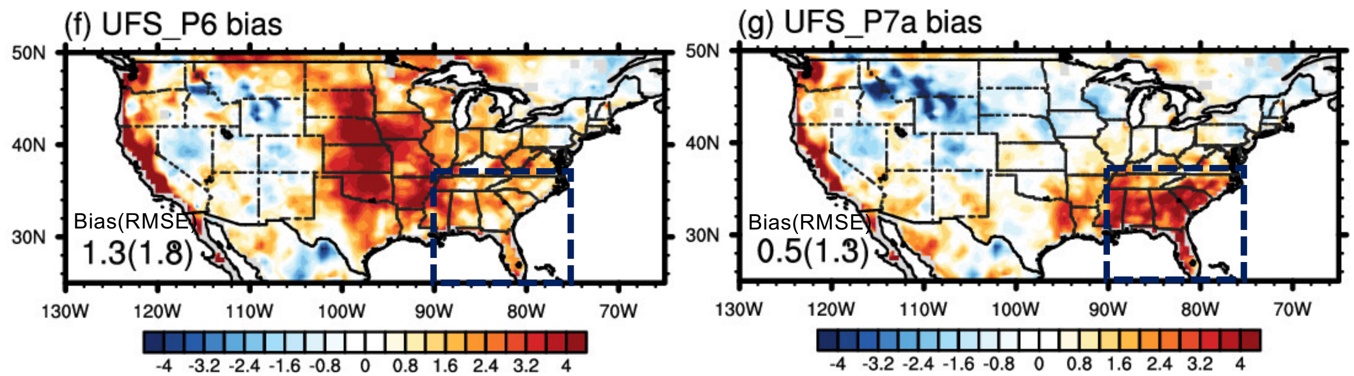
Mean climatology (bias & rmse)

July (2012-2013)

Water balance $\frac{dS}{dt} = P - E - R$

$$\frac{dH}{dt} = R_n - \lambda \mathbf{E} - SH - G$$

Energy balance



Water balance	Pr (mm/day)	SSM (m3/m3)	λE (W/m2)
Obs	5.97	0.25	112.3
UFS_P6	5.37 (-0.4)	0.22 (-0.03)	132.5 (20.2)
UFS_P7a	**4.14** (-1.83)	0.23 (-0.02)	**99** (-13.3)

* actual value (bias)

Humid (mostly forested) region

Decreased precipitation (not much change in SM) → decreased LH & increased SH (not much change in net radiation) **+** *strong L-A coupling → warming surface air temperature*

Energy balance	netRad	LH	SH	1-EF
Obs	178.2	112.3	65.9	0.22
UFS_P6	181.1 (2.9)	132.5 (20.2)	48.6 (-17.3)	0.25 (0.03)
UFS_P7a	174.1 (-4.1)	**99** (-13.3)	**75.1** (9.2)	**0.4** (0.18)

LA coupling	TCI (W/m2)	Tmax (degC)
Obs	-4.1	32
UFS_P6	4.1 (8.2)	33.8 (1.8)
UFS_P7a	**8.4** (12.5)	**34.9** (2.9)

* EF(evaporative fraction) = LH/netRad

Summary (1)

- This study investigates land-atmosphere interaction in UFS prototypes P5, P6, and P7a simulations and its influence on mean state bias.
- The main difference of P7a in the land surface process is the replacement of the model from Noah to Noah-MP LSM.

LSM	Land tiles	Snowpack layer	Aquifer
Noah	"bulk" surface containing an active vegetation fraction (GVF) and active bare soil fraction (1-GVF) → Only one bulk surface temperature, a skin temperature, is used for all calculations: sensible, latent, shortwave, longwave	Single-layer (early snow melting problem)	"No" aquifer → groundwater recharge at bottom layer from aquifer
Noah-MP	Two tiles containing a vegetation fraction (fveg) and bare soil fraction (1-fveg) → There are different "source temperatures" for SH and LW and the source temperatures, exchange coefficients (Ch) and emissivities (ε) can be averaged in different ways.	Three-layer (It acts as a reservoir of incoming energy from the atmosphere transferred to the ground)	"Yes" aquifer → groundwater recharge at bottom layer from aquifer (with groundwater interaction)

** surface albedo, water and radiation variables are clearly improved in Noah-MP.*

** early snow melting problem in Noah is corrected in Noah-MP.*

Summary (2)

- The modeled states related to the land-atmosphere interaction are evaluated by in situ observation as well as satellite-based product in terms of vegetated land cover.

Net radiation	Sfc Albedo	Sfc SM	Precip	SAT	TCI (LA-interaction)
P7a – best performance in general land cover, but there is an underestimation over the Forest	It highly depends on which LSM is used. **Noah** – small difference between land cover types **Noah-MP** – generally increased albedo	Both LSMs – wet bias over west US **Noah** – dry bias over Midwest & south US **Noah-MP** – wet bias over north Great Plains & Midwest US	**UFS_P5&6** – wet bias (Colorado), dry bias (south US) **UFS_P7** – wet bias (north Great Plains and Midwest US), dry bias (southeast US)	**UFS_P5&6** – warm bias (central to east US) **UFS_P7** – cold bias (northwest US), warm bias (southeast US)	**P7a – best performance** in general land cover except for shrubland and savannas. TCI overestimation over central US. **UFS_P5&6** – large overestimation of TCI over Midwest US

- The warm bias correction in P7a over the Midwest US can be explained by water limited process.

  wet soil moisture → increased (decreased) latent (sensible) heat flux **+** *weak L-A coupling → cooling surface air temperature*

- The warm bias in P7a over the southeast US can be explained by energy limited process.

  decreased precipitation (not much change in SM)→ decreased LH & increased SH **+** *strong L-A coupling → warming surface air temperature*

Thank you for your attention