Comparison and Assessment of Three Advanced Land Surface Models in Simulating Terrestrial Water Storage Components over the United States

(*J. Hydrometeor.*, 2016, in revision)

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Objective of Evaluation and Comparison

- **To help next phase NLDAS development (CLSM-F2.5, Noah-MP3.6, CLM4.0)**

- **To fill a gap for LIS-based NLDAS evaluation: NASA group evaluated Open Loop run and data assimilation run without considering current operational NLDAS run and LIS-based Open Loop run**

- **To check what gain we can obtain from model physical processes' upgrades including model versions and addition of extra subcomponents (e.g. ground water, multi-snow layer, vegetation dynamics, etc.)**

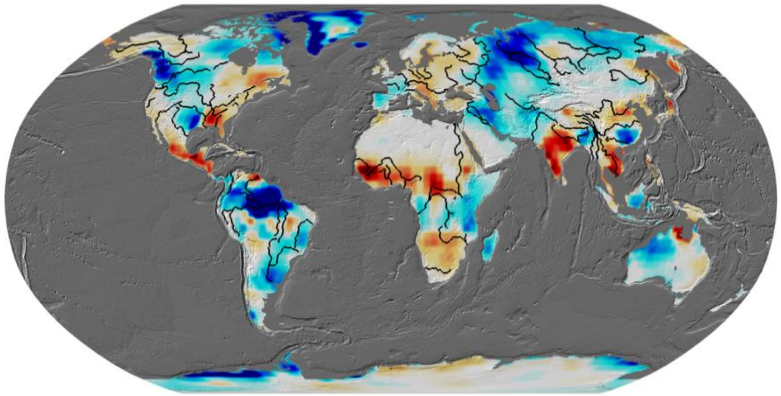
Data Source

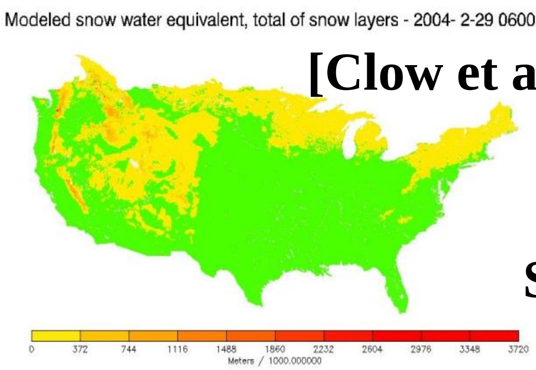
Model: CLM4.0, Noah-MP, CLSM-F2.5, monthly SWE, SMC, and GWS

Observation: GRACE TWSA, SNODAS SWE, USGS wells, and soil moisture (AL, IL, OK, WTX)

Time Scales: monthly

GRACE
[*Swenson and Wahr, 2006*, GRL]

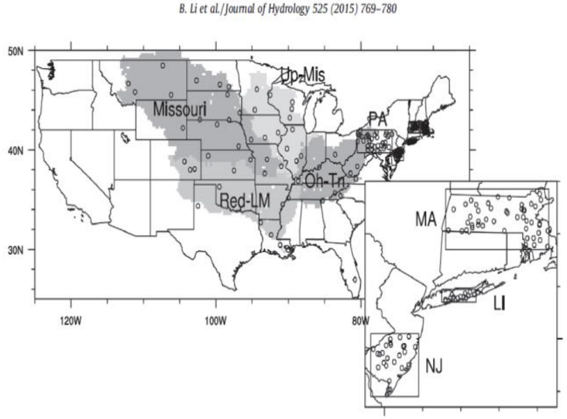




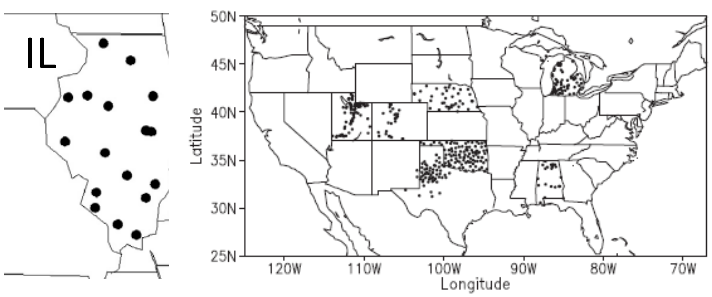
[Clow et al., *2014*, HYP]

SNODAS

USGS wells [*Li et al., 2015*, JH]



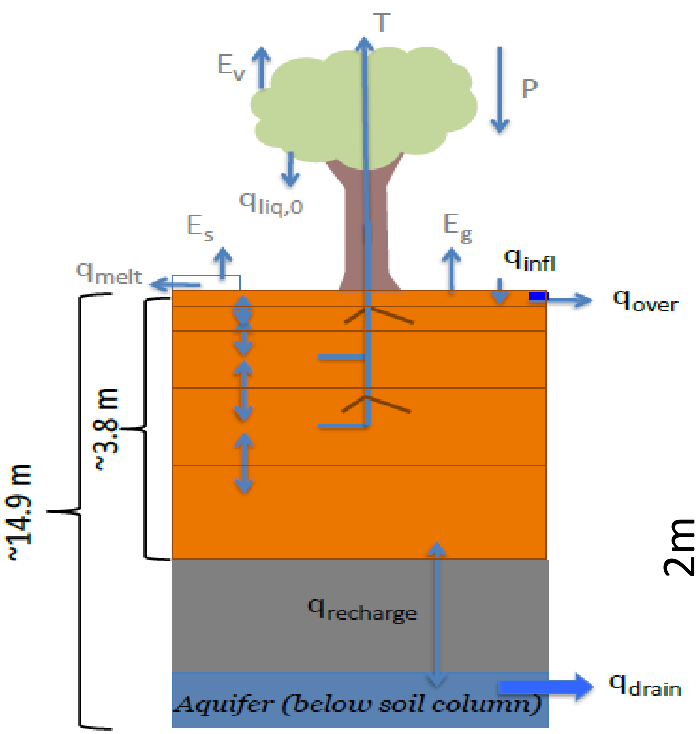
Soil Moisture Data
AL, IL, OK, WTX
[*Xia et al., 2014*, JH; *2015*, JHM]

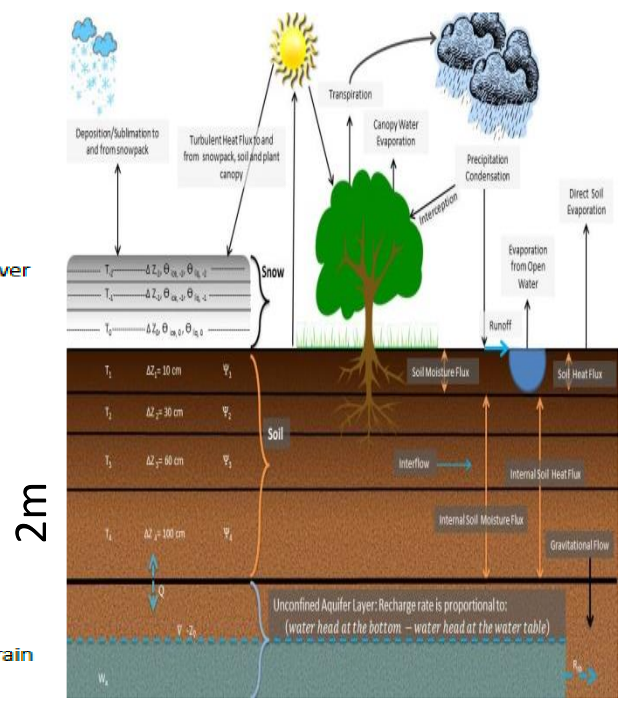


3.1. Total Water Storage Anomaly (TWSA)

Soil depth

CLM4.0	Noah-MP	CLSM-F2.5
3.8m	2.0m	1.0m





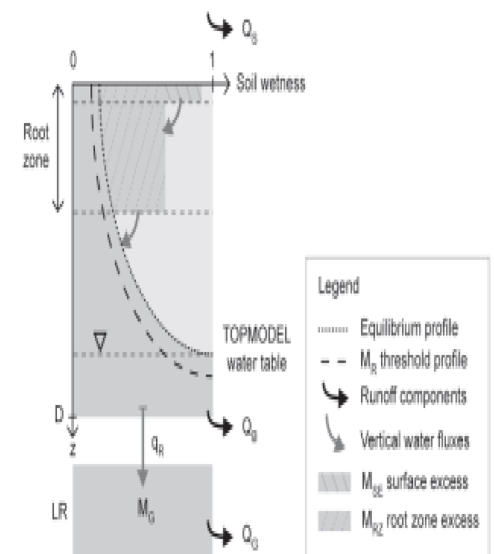


Figure 1

Total Water Storage Anomaly (TWSA)

$$\mathbf{TWSA = SMCA + SWEA + GWSA + CWSA} \qquad (1)$$

where SMCA is total column soil moisture content anomaly, SWEA is snow water equivalent anomaly, GWSA is ground water storage anomaly, and CWSA is canopy water storage anomaly.

As CWSA is much smaller than the other three terms, the Eq. (1) is modified as

$$\mathrm{TWSA = SMCA + SWEA + GWSA} \qquad (2)$$

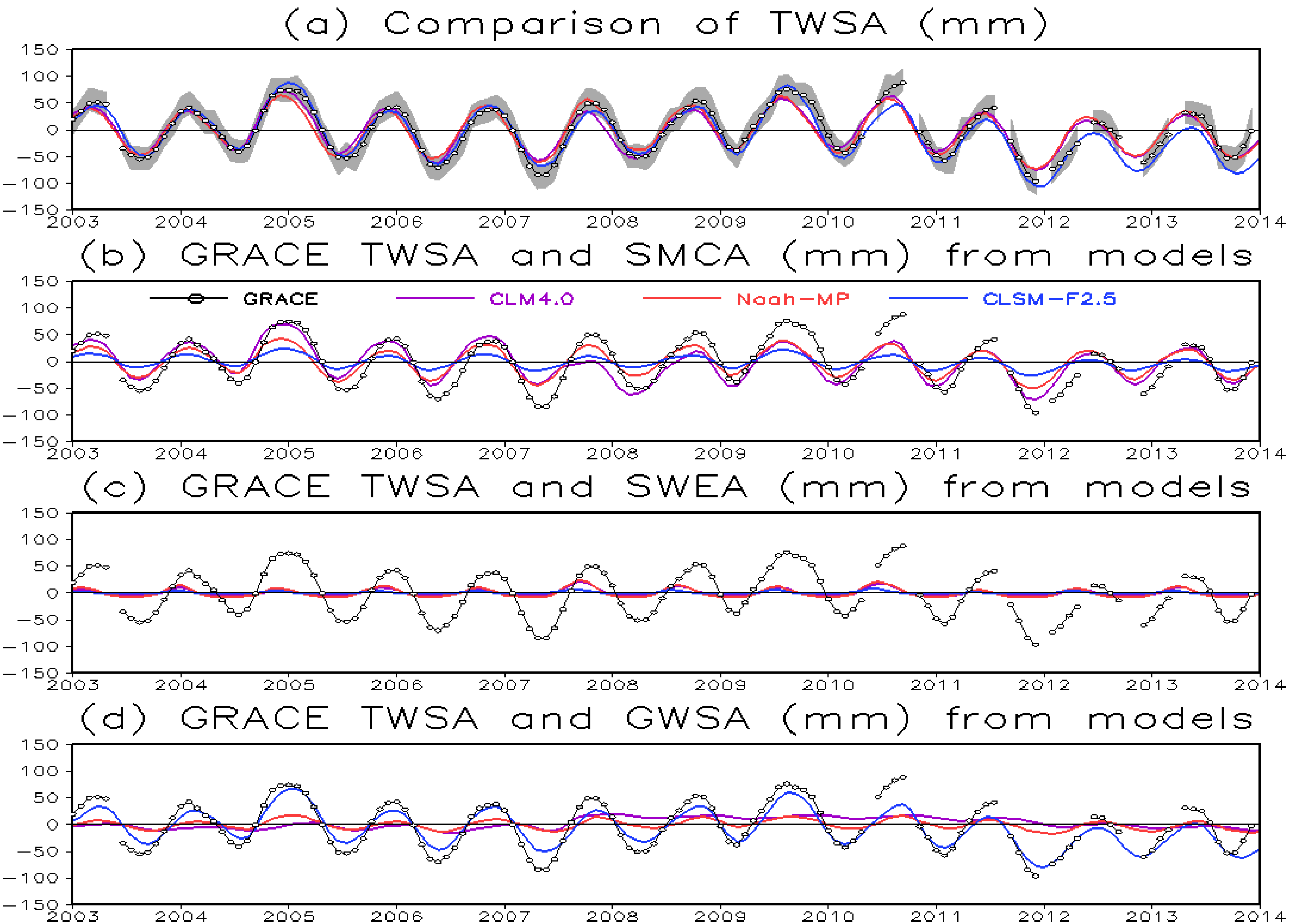
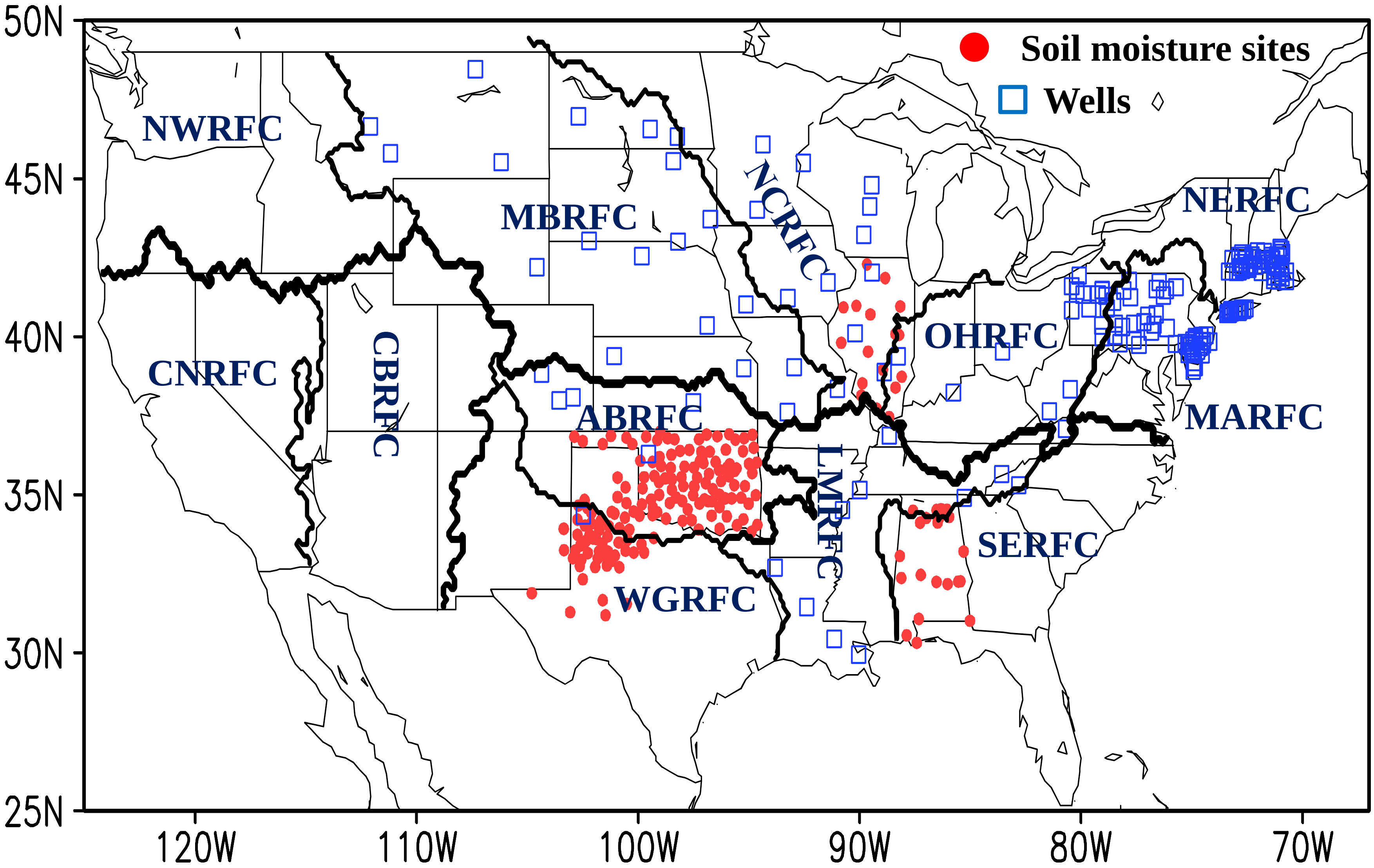


Figure 2: Nationwide total water storage anomaly comparison (mm)

Figure 3: Names and boundaries of the domains of 12 National Weather Service River Forecast Centers, locations of 181 USGS wells and 195 in situ soil moisture measurement sites.



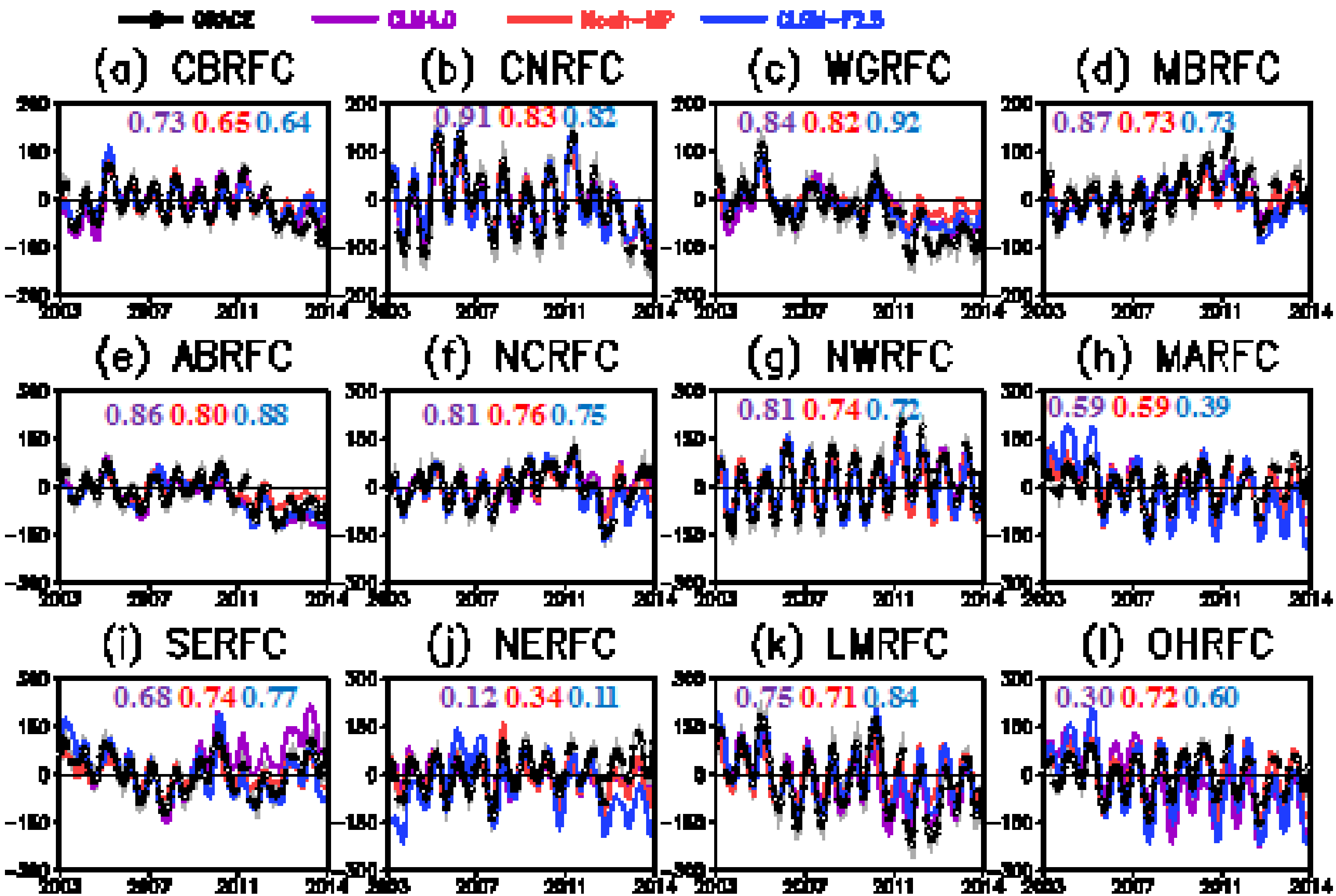


Figure 4: Comparison of the 12-year (2003-2014) time series of monthly total water storage anomaly (TWSA, unit: mm) from the GRACE-derived data set.

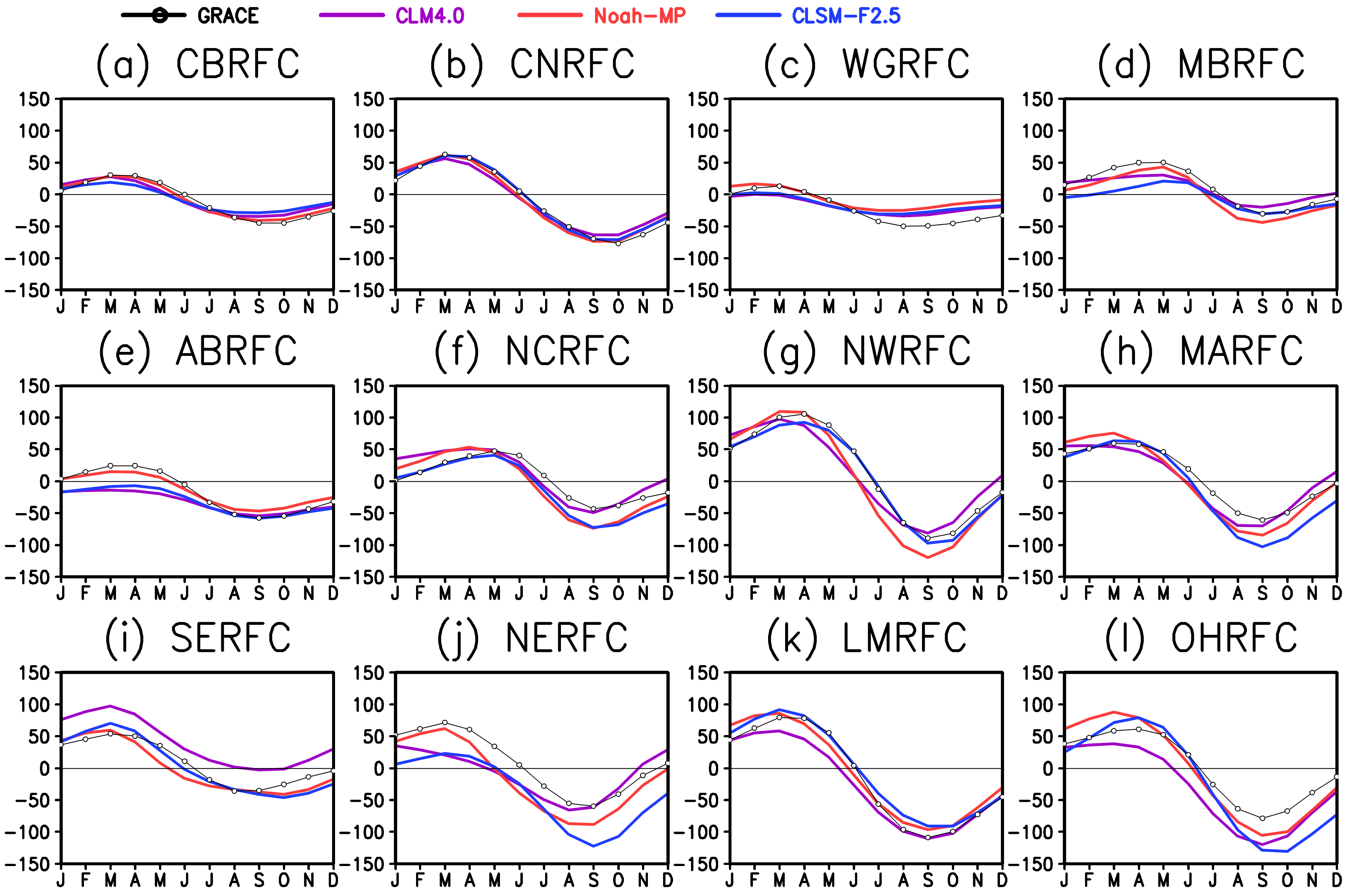


Figure 5: Mean seasonal cycle of TWSA for 12 RFCs)

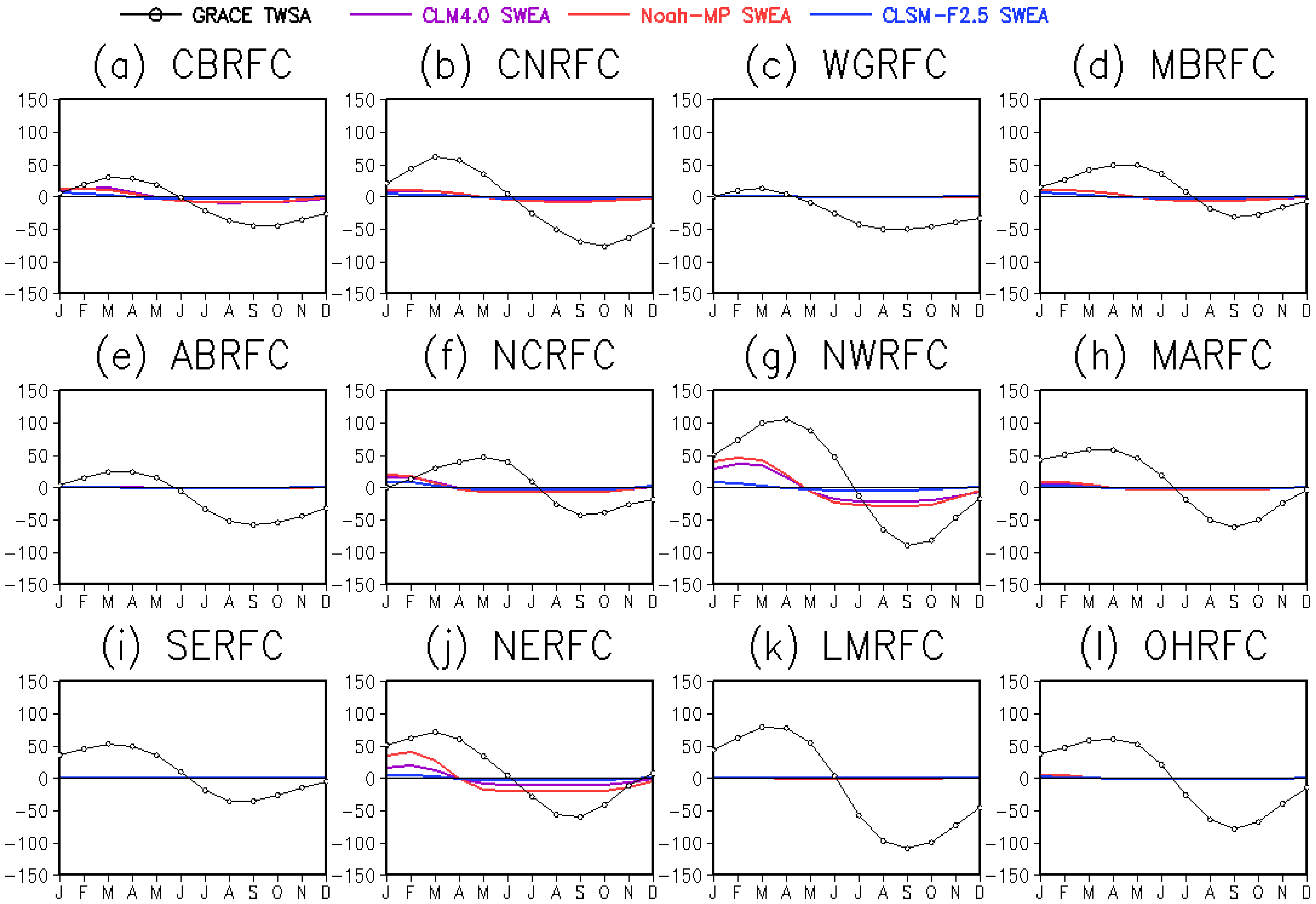


Figure 6: Effect of snow water equivalent anomaly (SWEA) when GRACE TWSA is referred.

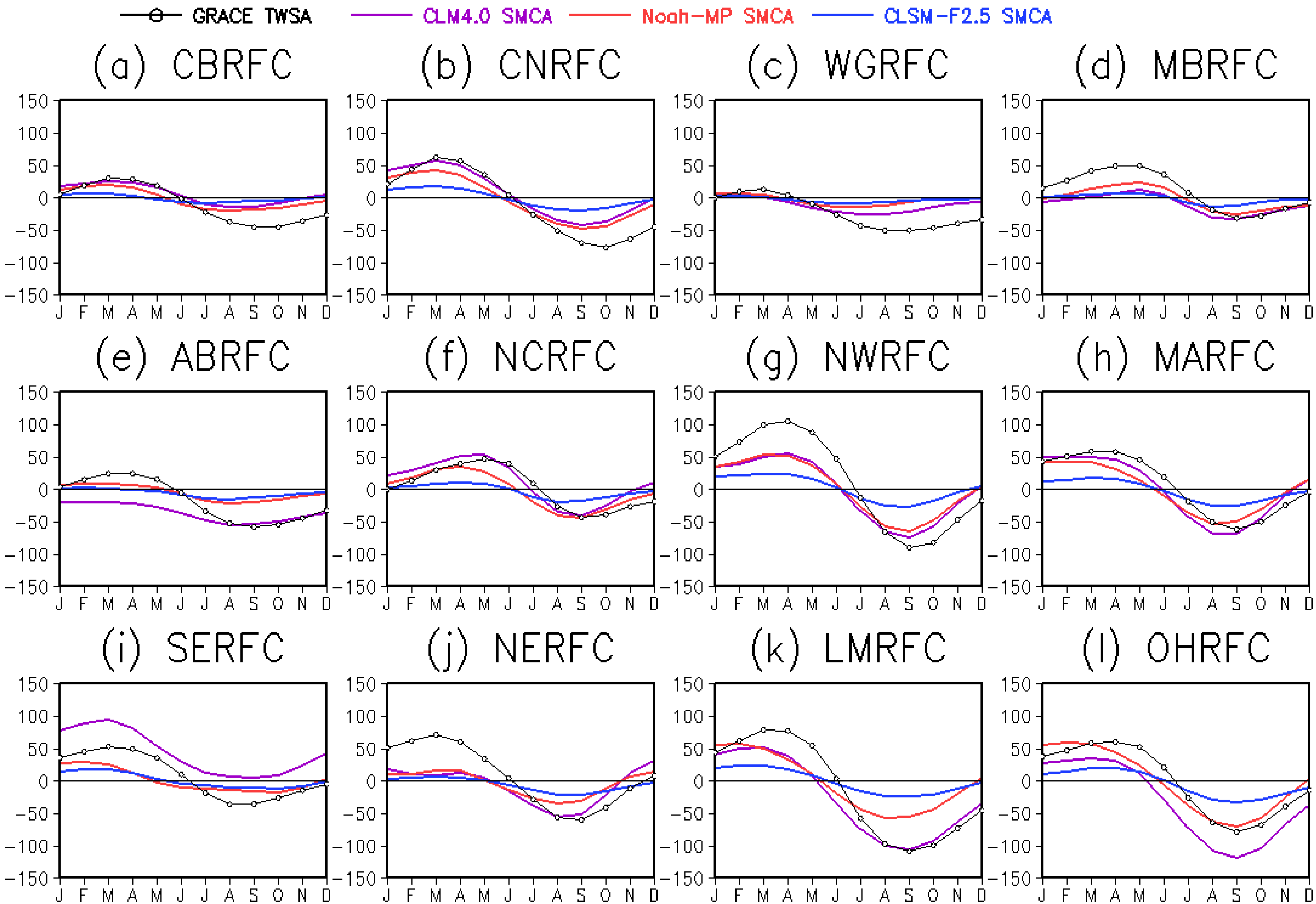


Figure 7: Same as **Fig.6** but for soil moisture content anomaly (mm).

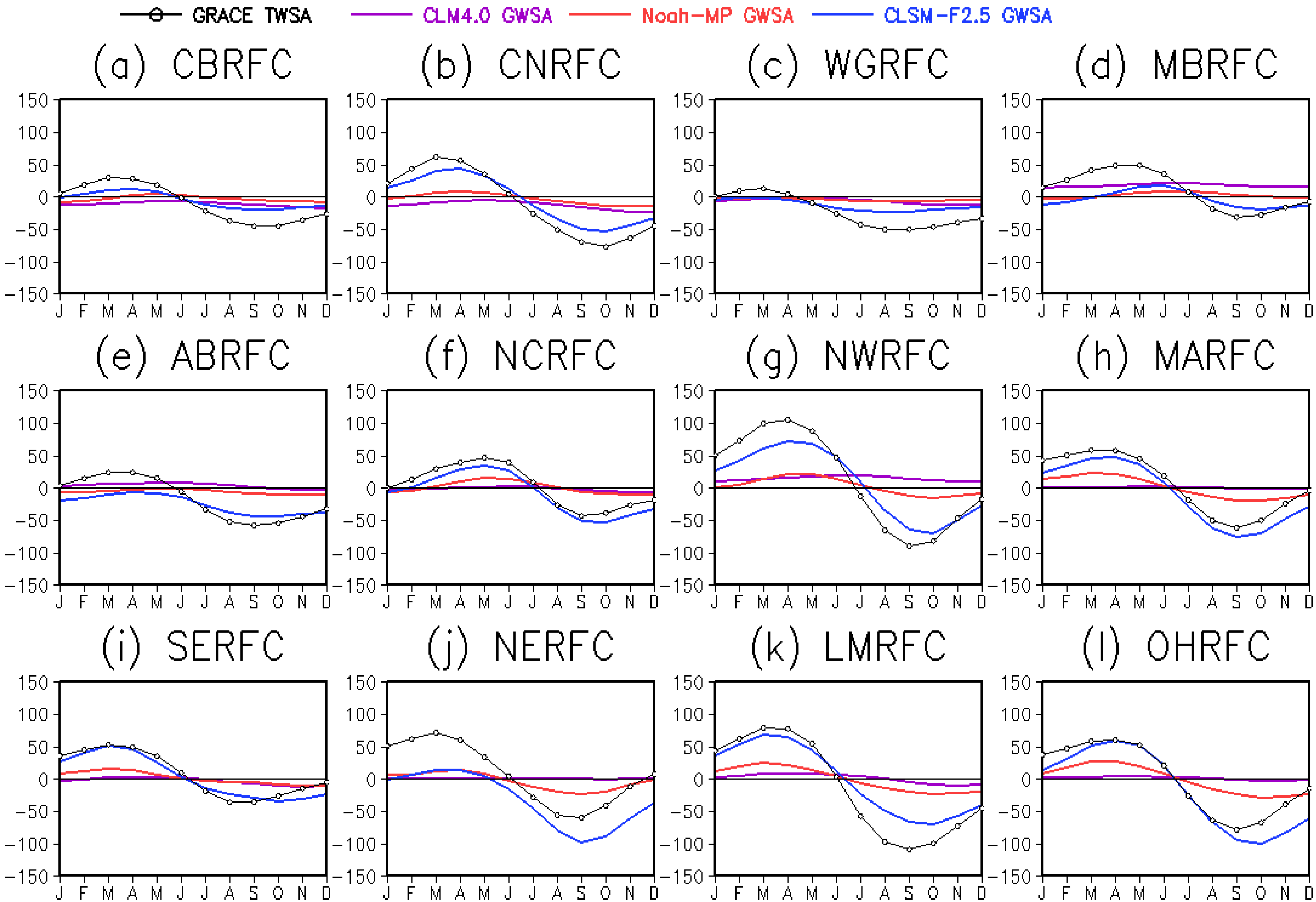


Figure 8: Same as **Fig.6** but for ground water storage anomaly (mm)

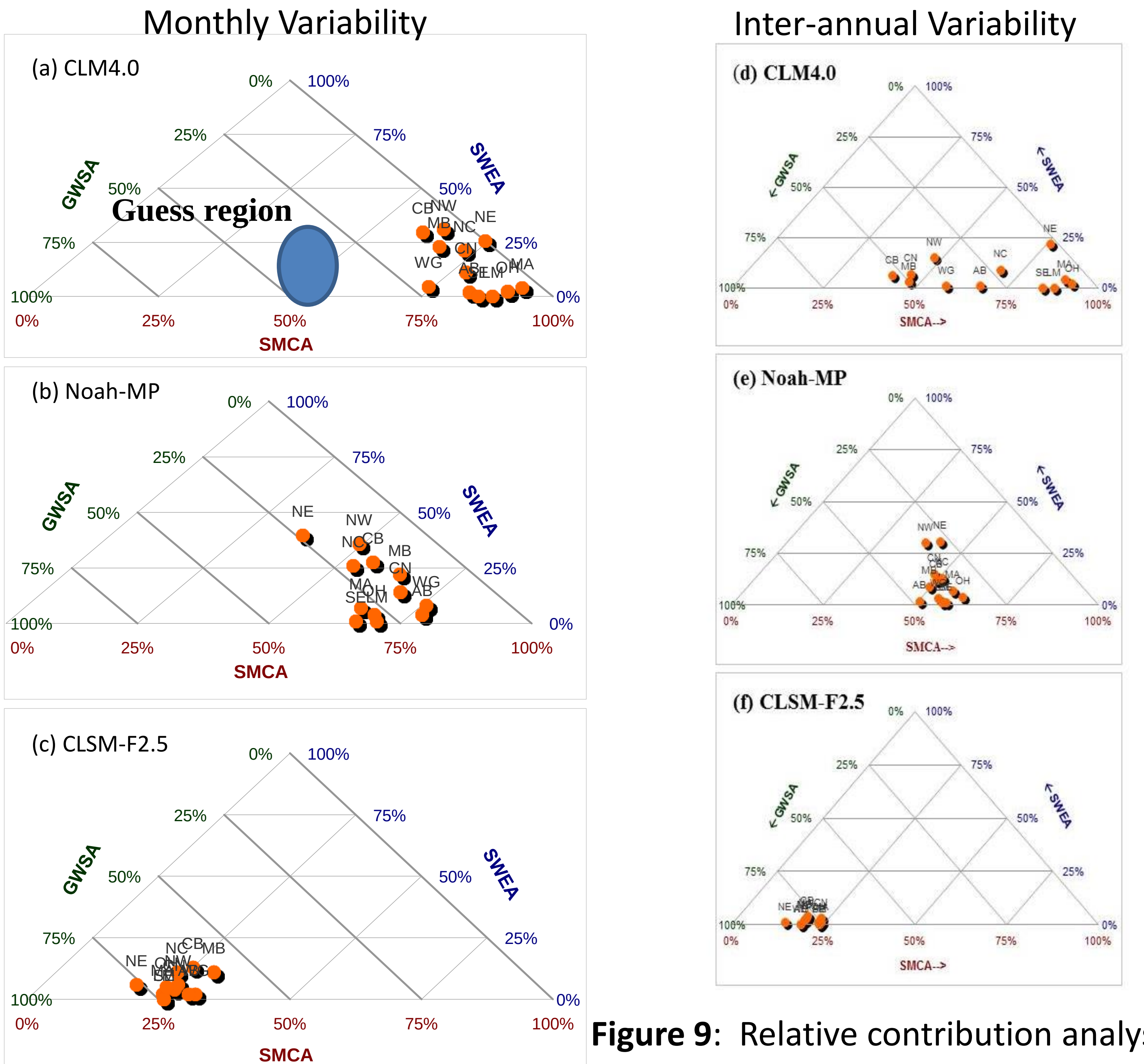


Figure 9: Relative contribution analysis of SMCA, SWEA, and GWSA to TWSA for 12 RFCs and three models.

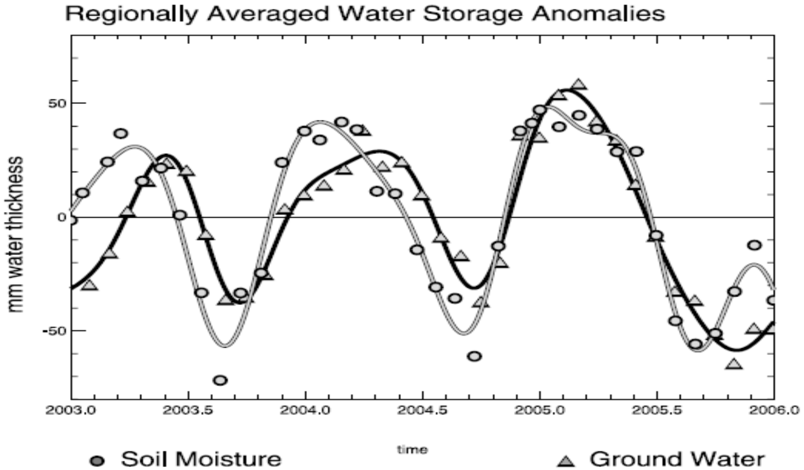


Figure 3. In situ soil moisture and groundwater storage anomalies. Circles are monthly anomalies of soil moisture to 1 meter depth, triangles are groundwater anomalies below 1 meter depth; gray/black lines are smoothed soil moisture/groundwater seasonal time series respectively. X-axis is time in years, and Y-axis is storage change in mm.

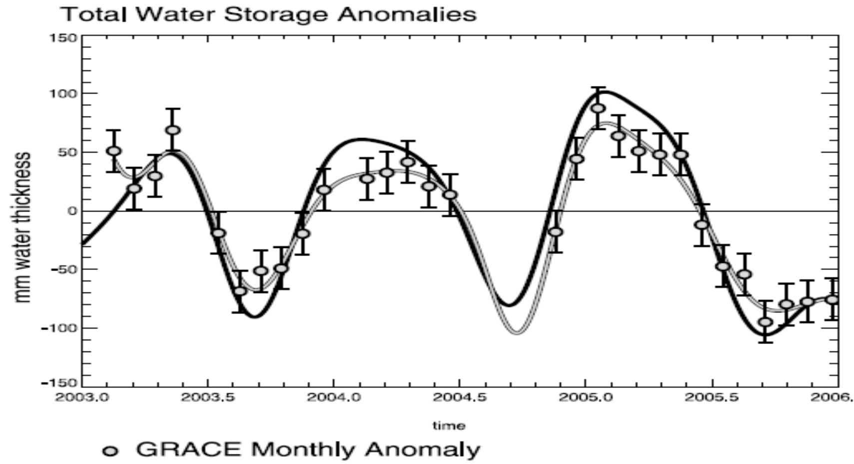


Figure 4. Total water storage anomalies derived from GRACE (circles are monthly anomalies, gray line is seasonal time series), and combined in situ soil moisture and groundwater measurements (black line is seasonal time series). X-axis is time in years, and Y-axis is storage change in mm.

Illinois Case

Swenson et al., 2006, GRL

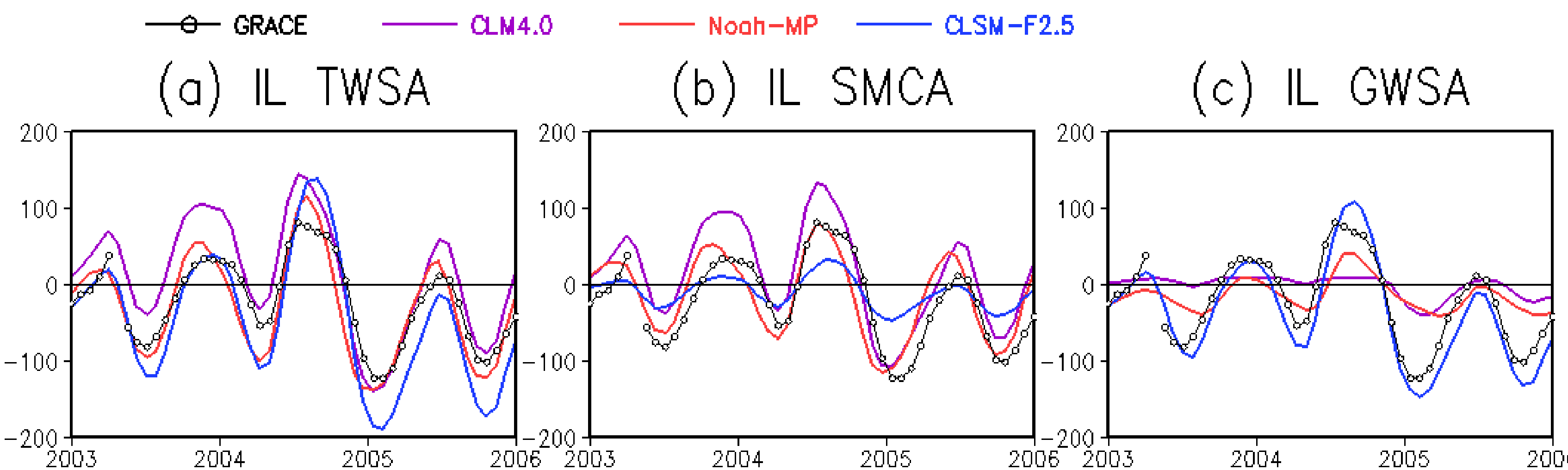


Figure 10: A visual comparison for Illinois.

W01413 SWENSON ET AL.: GRACE ESTIMATES OF GROUNDWATER VARIABILITY IN OKLAHOMA W01413

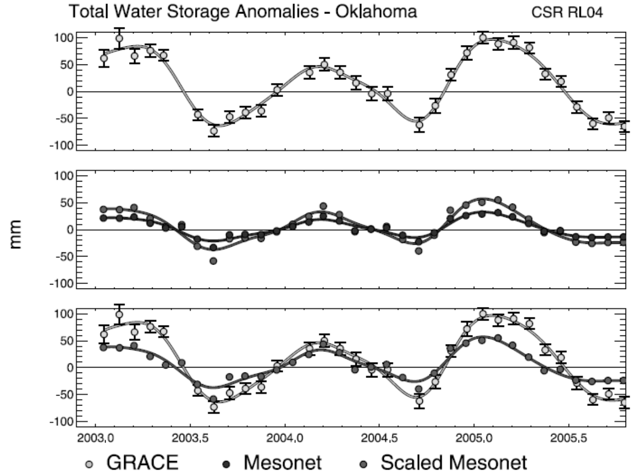


Figure 9. Top panel: GRACE regional average time series of total water storage anomalies. Circles represent monthly values, line represents seasonally varying values. Middle panel: monthly OM unsaturated zone soil moisture anomalies. Black circles represent 0–75 cm values, gray circles represent scaled 0–4 m values. Bottom panel: comparison of GRACE and scaled OM time series. *X* axis is time, in years; *y* axis is water equivalent thickness, in mm.

W01413 SWENSON ET AL.: GRACE ESTIMATES OF GROUNDWATER VARIABILITY IN OKLAHOMA W014

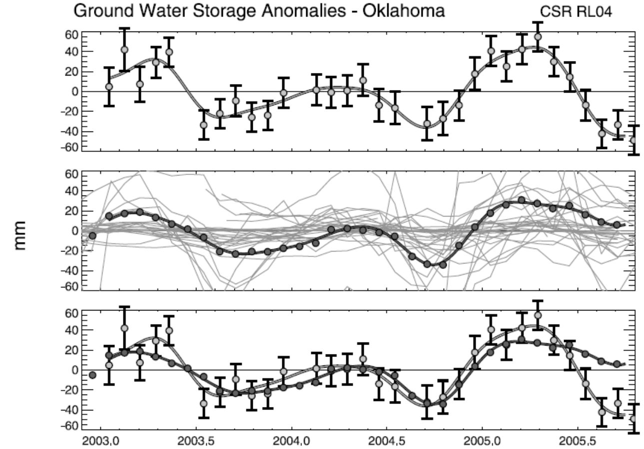


Figure 10. Top panel: regional average time series of residual groundwater storage anomalies, computed by subtracting scaled OM time series from GRACE time series. Circles represent monthly values, line represents seasonally varying values. Middle panel: monthly groundwater anomalies, computed from USGS well level observations. Thin gray lines represent individual wells, thick gray line represents regional average. Bottom panel: comparison of GRACE-OM and USGS groundwater time series. *X* axis is time, in years; *y* axis is water equivalent thickness, in mm.

Oklahoma Case

Swenson et al., 2008, WRR

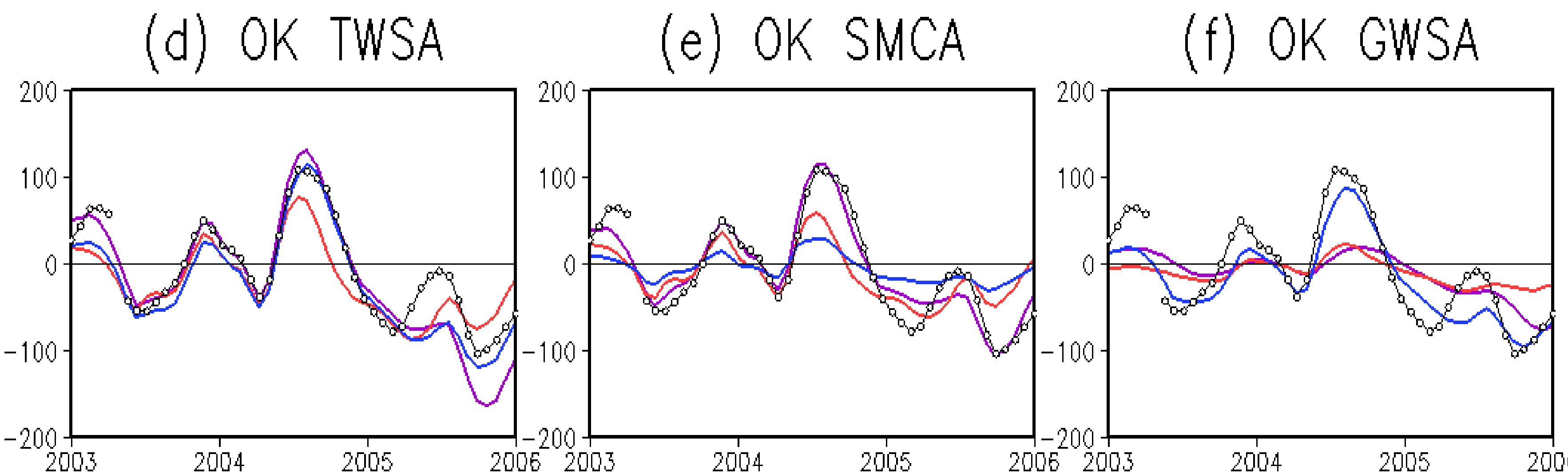


Figure 11: A visual comparison for Oklahoma.

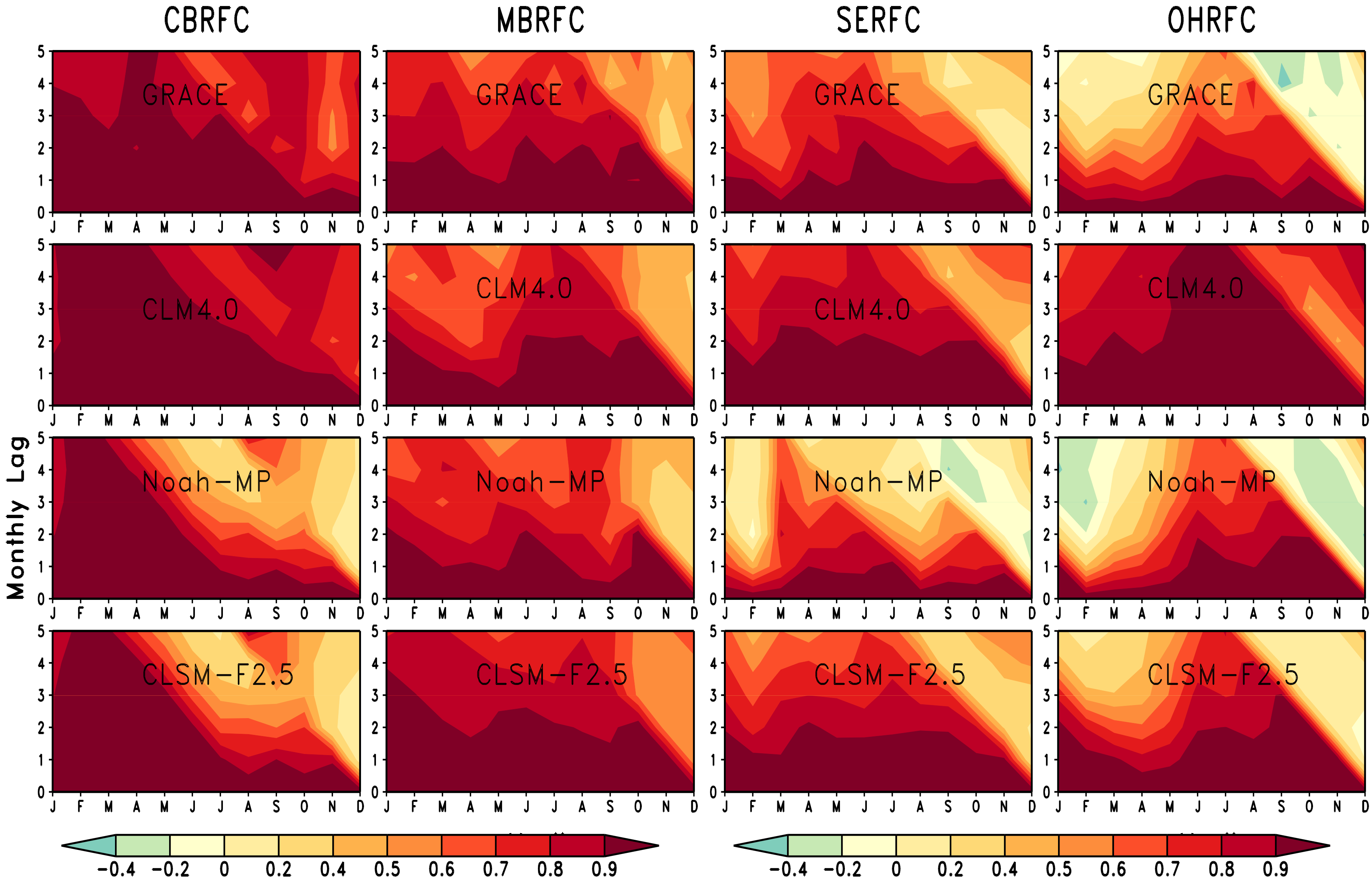


Figure 12: Seasonal dependence of observed and simulated TWSA persistence (month to month autocorrelation) for 2013-2014 over the four RFCs.

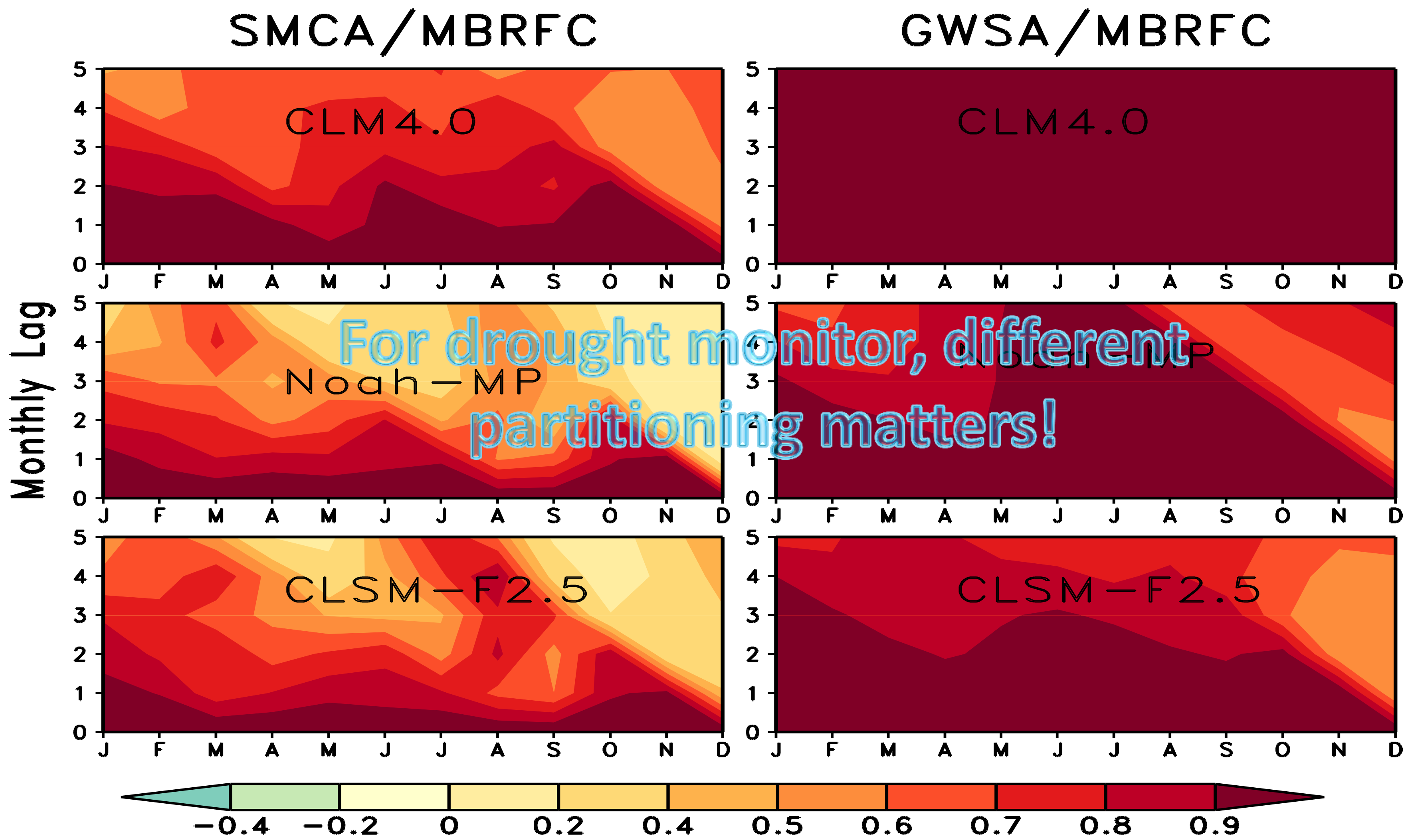


Figure 13: Seasonal dependence of simulated SMCA (left) and GWSA (right) persistence (month to month autocorrelation) for 2003-2014 at MBEFC. Initial month is along the X axis, and the lag to the target month along the y axis. Observations from GRACE and three models (CLM4.0, Noah-MP, and CLSM-F2.5) are shown from the top to the bottom.

3.2. USGS Ground Water Storage Anomaly

CLM4.0 and Noah-MP:

Simple Ground Water Model [*Niu and Yang, 2007*]

CLSM-F2.5: Simple shallow water table [*Koster et al.*, *2000*]

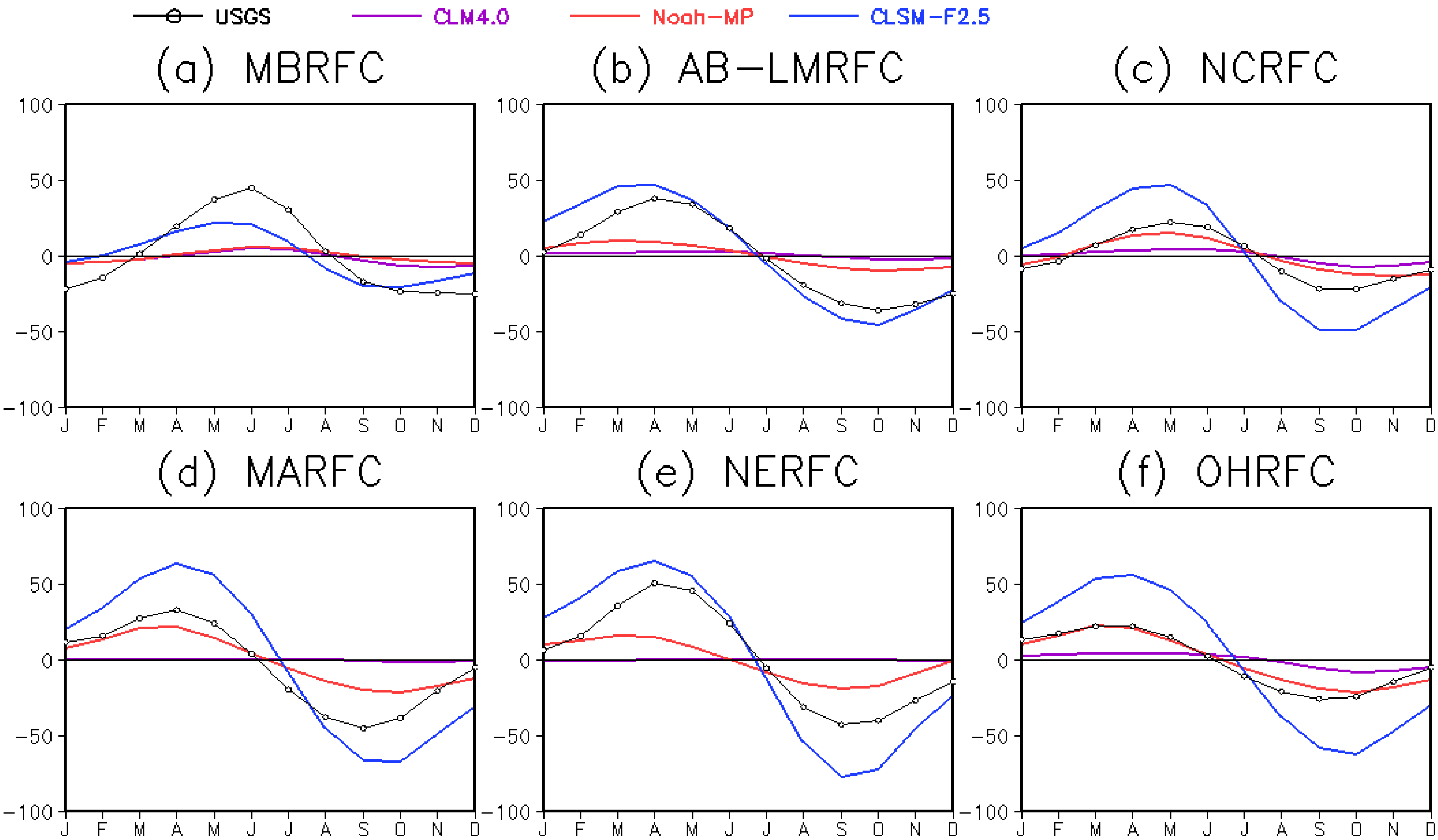


Figure 14: Mean seasonal cycle of USGS observed and model-simulated ground water storage anomaly (mm) at six RFCs. It should be noted that Pennsylvania and New Jersey is for MARFC, and Massachusetts and New York is for NERFC.

Irrigation effect?

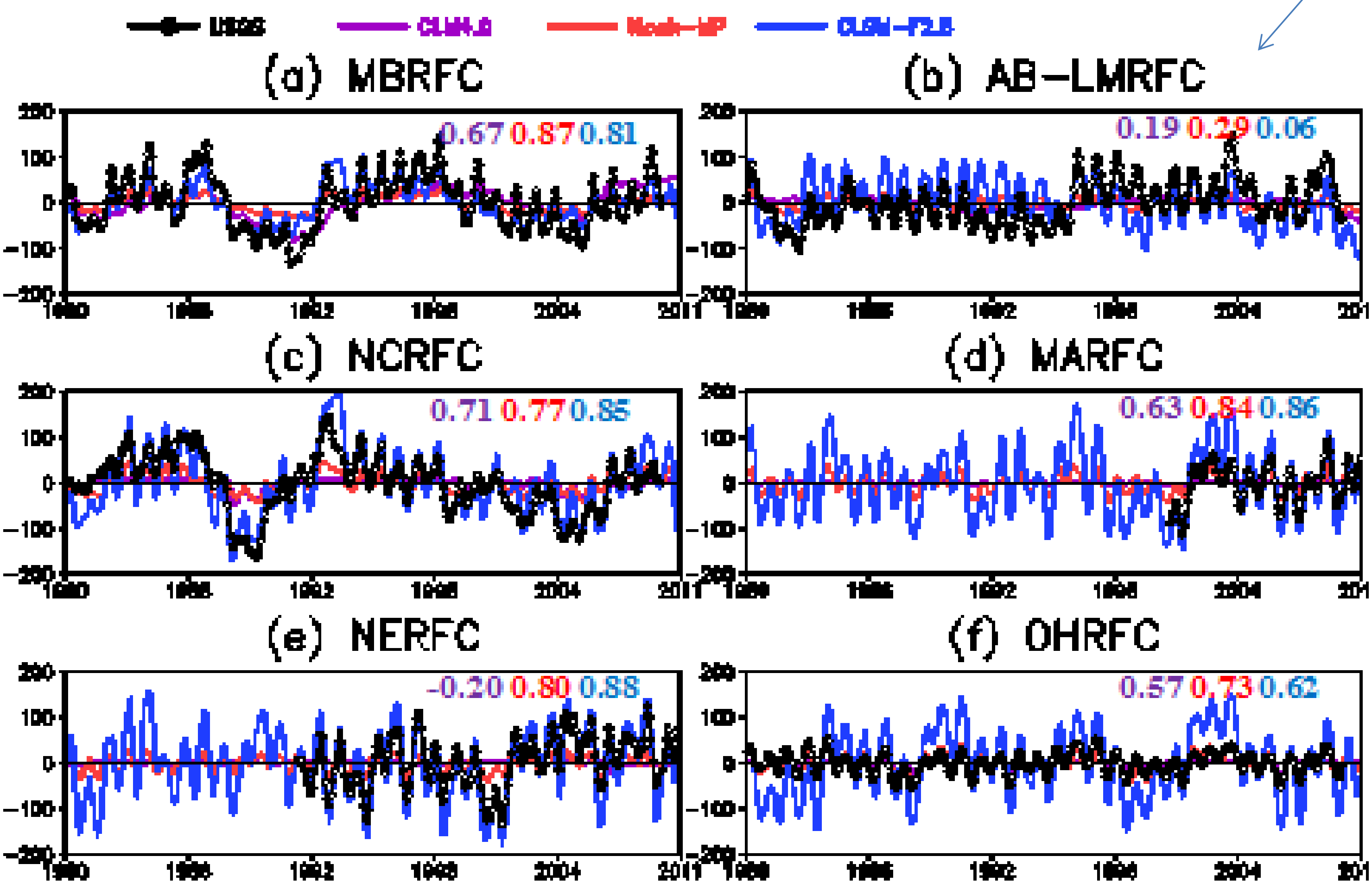


Figure 15: USGS observed and model-simulated ground water storage anomaly from 1980 to 2011 (mm) at six RFCs

3.3. Snow Water Equivalent (SWE)

CLM4.0: 5-layer snow model

Noah-MP: 3-layer snow model; CLASS albedo

CLSM-F2.5: 3-layer snow model

Snowfall, snowmelt and sublimation are compared for Noah-MP and CLSM-F2.5 model

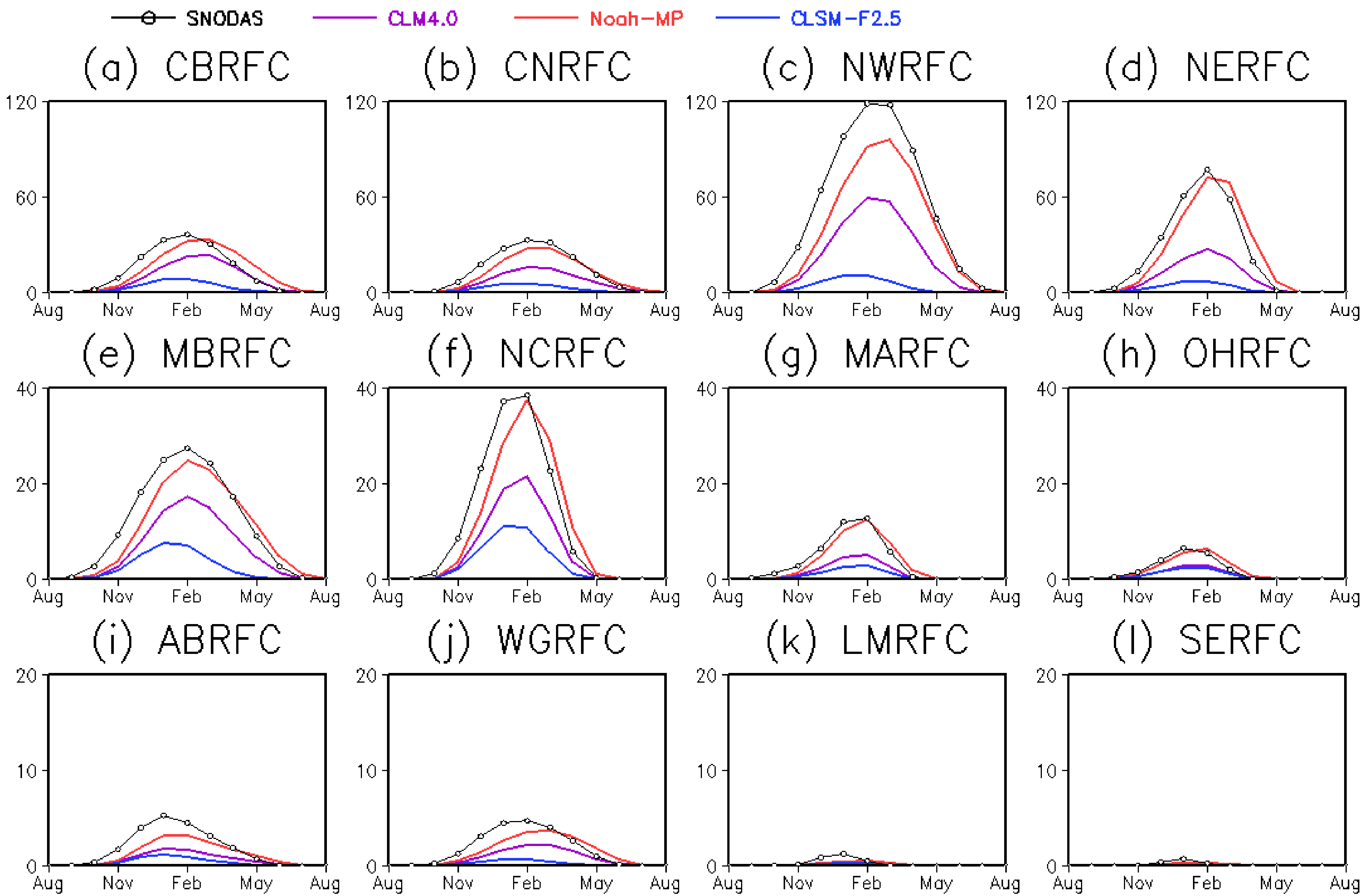


Figure 16: Comparison of 11-year (2004-2014) mean seasonal cycle of SNODAS and model-simulated SWE (mm) at 12 RFCs

Table 2: Anomaly correlation between SNODAS SWE and Simulated SWE by the three models for 12 NWS RFCs when mean seasonal cycle is removed.

RFC Name	CLM4.0	Noah-MP	CLSM-F2.5
CBRFC	0.70	0.67	0.68
CNRFC	0.79	0.79	0.79
WGRFC	0.60	0.62	0.54
MBRFC	0.61	0.58	0.62
ABRFC	0.20	0.25	0.36
NCRFC	0.80	0.80	0.78
NWRFC	0.85	0.75	0.61
MARFC	0.66	0.55	0.81
SERFC	0.17	0.13	0.22
NERFC	0.73	0.70	0.63
LMRFC	0.20	0.13	0.23
OHRFC	0.45	0.47	0.62
Mean	0.56	0.54	0.57

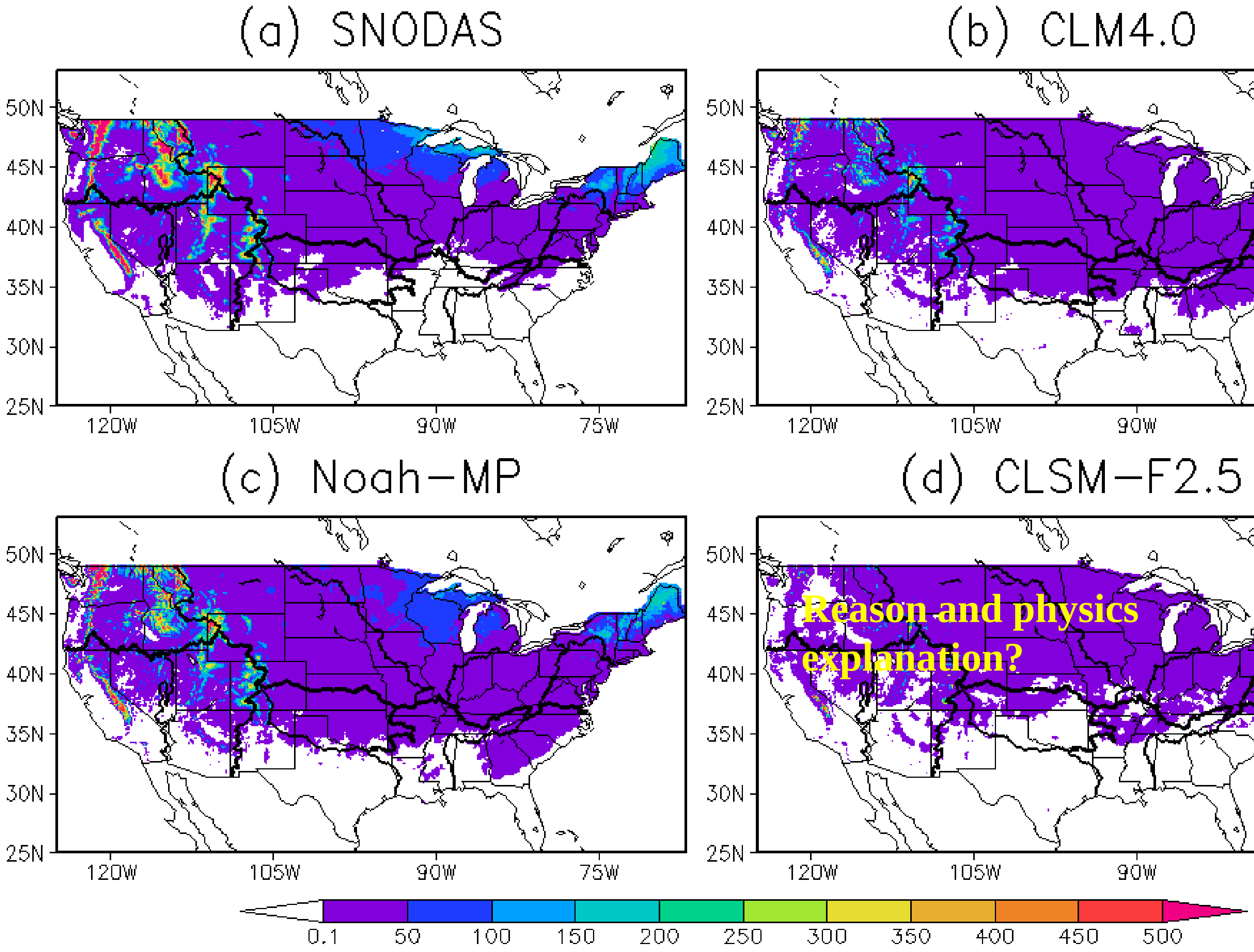


Figure 17: Comparison of spatial 11-year averaged SWE in February (mm) : (a) SNODAS, (b) CLM4.0, (c) Noah-MP, and (d) CLSM-F2.5.

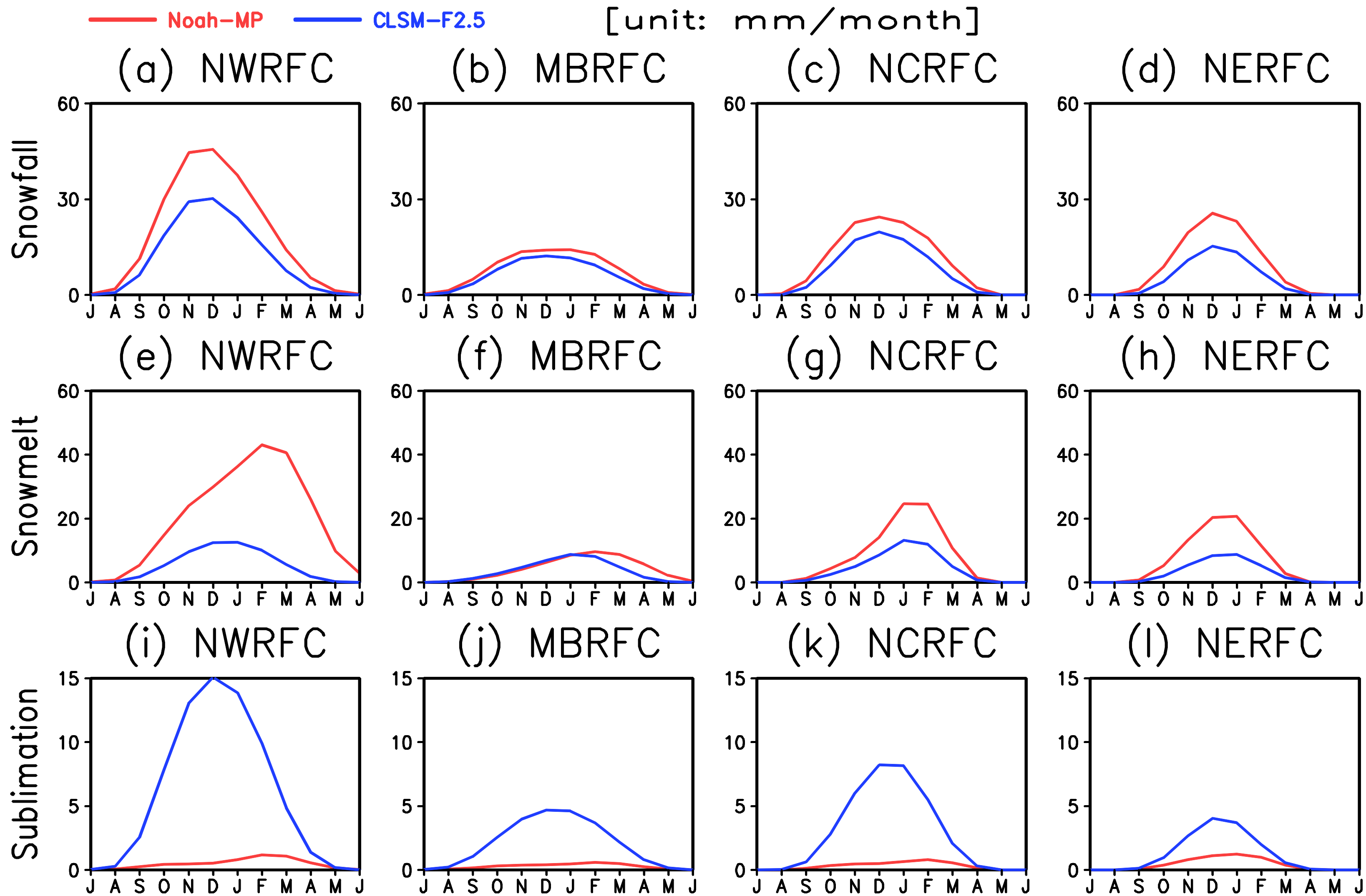


Figure 19: Mean annual cycle of monthly mean snowfall, snowmelt and sublimation (unit: mm) for four selected RFCs calculated from 35-year (1980-2014) monthly model output (red line – Noah-MP, blue line – CLSM-F2.5).

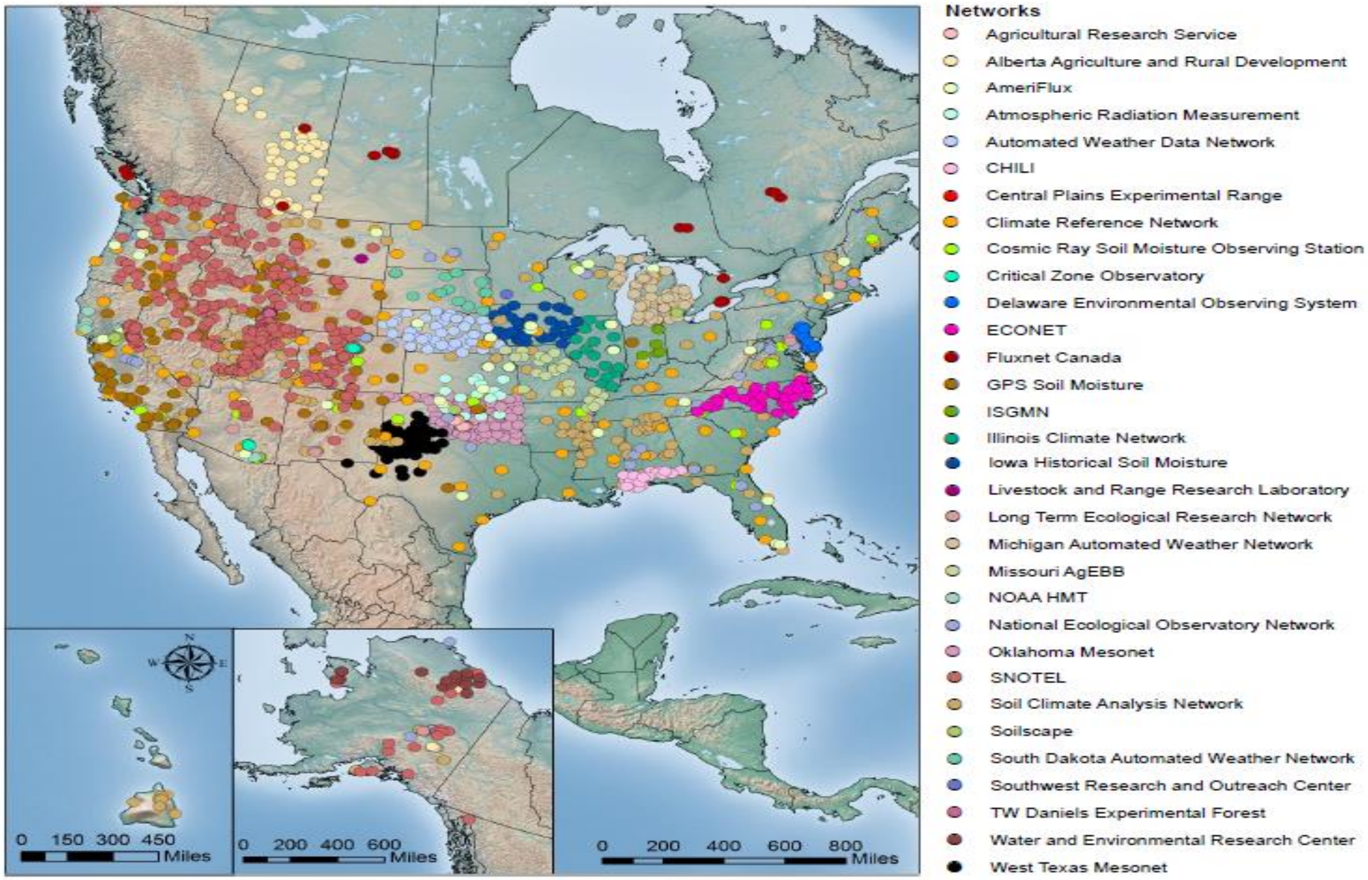
3.4. Top 1m Soil Moisture Content Anomaly

Top 1m soil layer:

Model: CLM4.0, Noah-MP, CLSM-F2.5
OBS: Alabama, Illinois, Oklahoma, West Texas

Data quality – quality controlled:
Illinois [*Robock et al.*, 2000, BAMS]
AL, OK, and WTX [*Xia et al.*, 2015, JAMC]

The work is ongoing ……



Quality control [*Xia et al., 2015*, JAMC]

TAMU North American Soil Moisture Database (NASMD) - http://soilmoisture.tamu.edu/

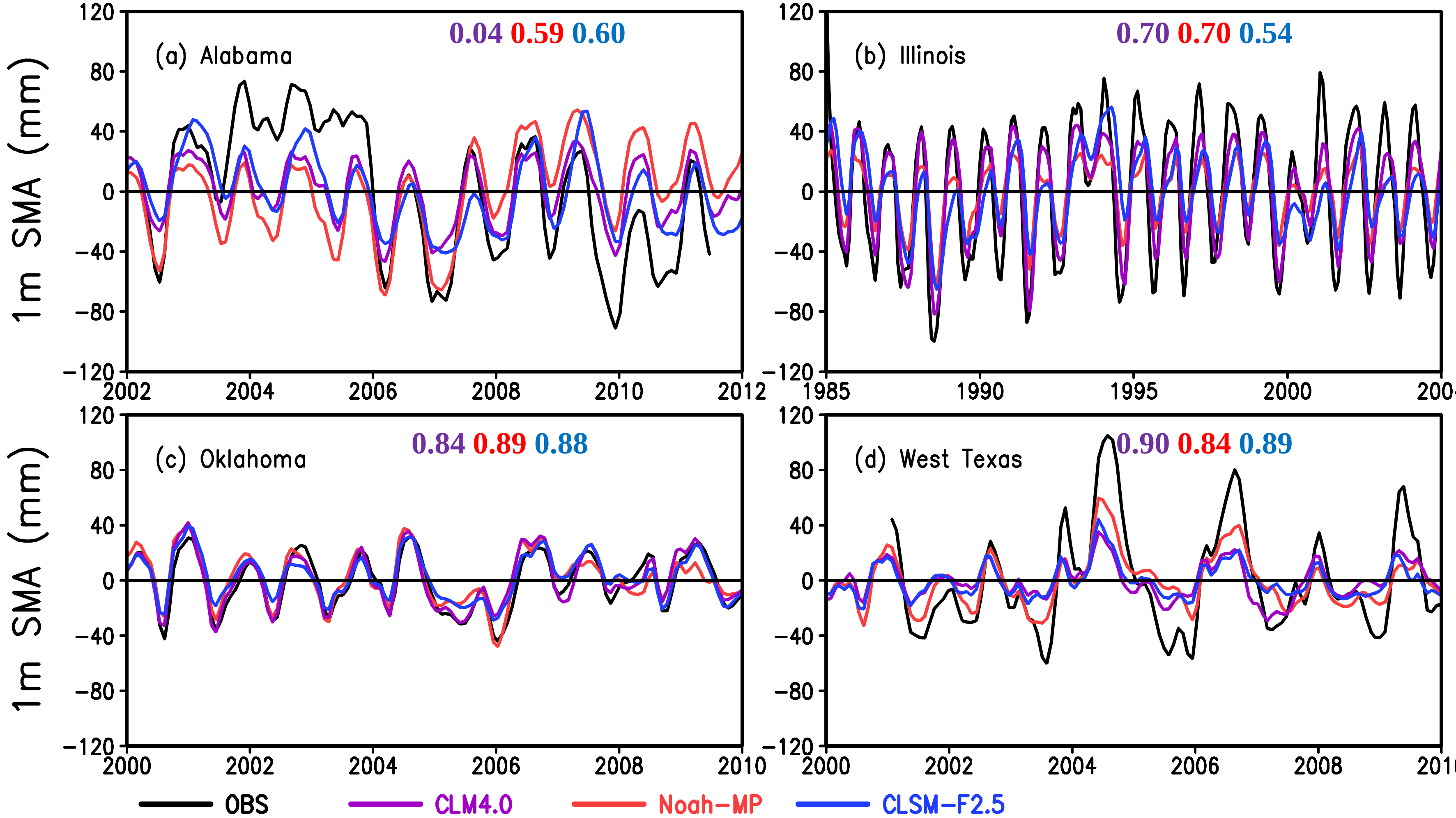


Figure 20: Comparison of multi-year (from 11 to 20 years) time series of top 1-m monthly soil moisture content anomaly (SMCA, unit: mm) spatially averaged over each of four regions from the three models and their corresponding AC values

Variance Ratio and Error Estimation

To evaluate modeled data anomaly using observed data anomaly, mean square error (E^2) can be decomposed as (Gupta et al. 2009):

$$E^2 = E_p^2 + E_m^2 \quad (1a)$$

$$E_p^2 = (1 + \gamma^2 - 2\gamma AC_0)\sigma_O^2 \quad (1b)$$

$$\gamma = \frac{\sigma_S}{\sigma_O} \quad (1c)$$

$$E_m^2 = (\bar{S} - \bar{O})^2 \quad (1d)$$

$$\sigma_S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{i=N}(S_i - \bar{S})^2},\ \sigma_O = \sqrt{\frac{1}{N-1}\sum_{i=1}^{i=N}(O_i - \bar{O})^2} \quad (1e)$$

$$AC_0 = \frac{\sum_{i=1}^{i=N}(S_i' - \overline{S'})(O_i' - \overline{O'})}{\sum_{i=1}^{i=N}(S_i' - \overline{S'})^2 \sum_{i=1}^{i=N}(O_i' - \overline{O'})^2}\text{, where } S_i' = S_i - \bar{S},\ O_i' = O_i - \bar{O} \quad (1f)$$

where σ_S and σ_O are standard deviation for modeled and observed data, respectively. S_i and O_i (i=1, N) are model and observation data time series. S_i' *and* O_i' are model and observation data anomaly time series. N is total number of months. The AC_0 is anomaly correlation when long-term mean seasonal cycles are not removed, and $\bar{S}$ and $\bar{O}$ are mean modeled and observed data, respectively. $\overline{S'}$ *and* $\overline{O'}$ are the long − term anomaly mean. γ is a ratio between modeled and observed standard deviation.

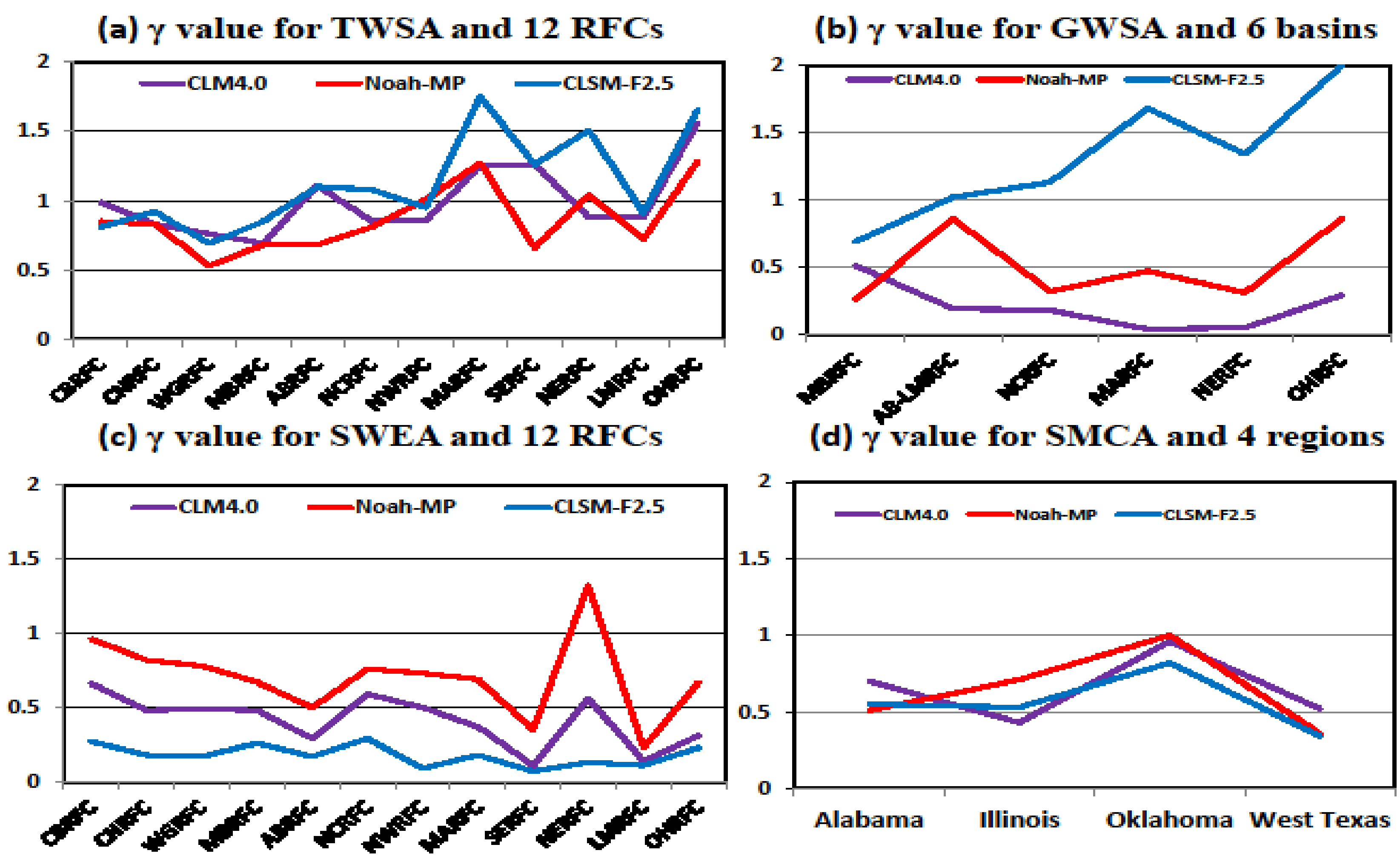


Figure 21: γ values (ratio between observed and simulated standard deviation) calculated from simulated and observed and (a) TWSA for 12 RFCs, (b) GWSA for 6 basins, (c) SWEA for 12 RFCs, and (d) SMCA for 4 regions. The γ value represents a ratio between simulated and observed standard deviation.

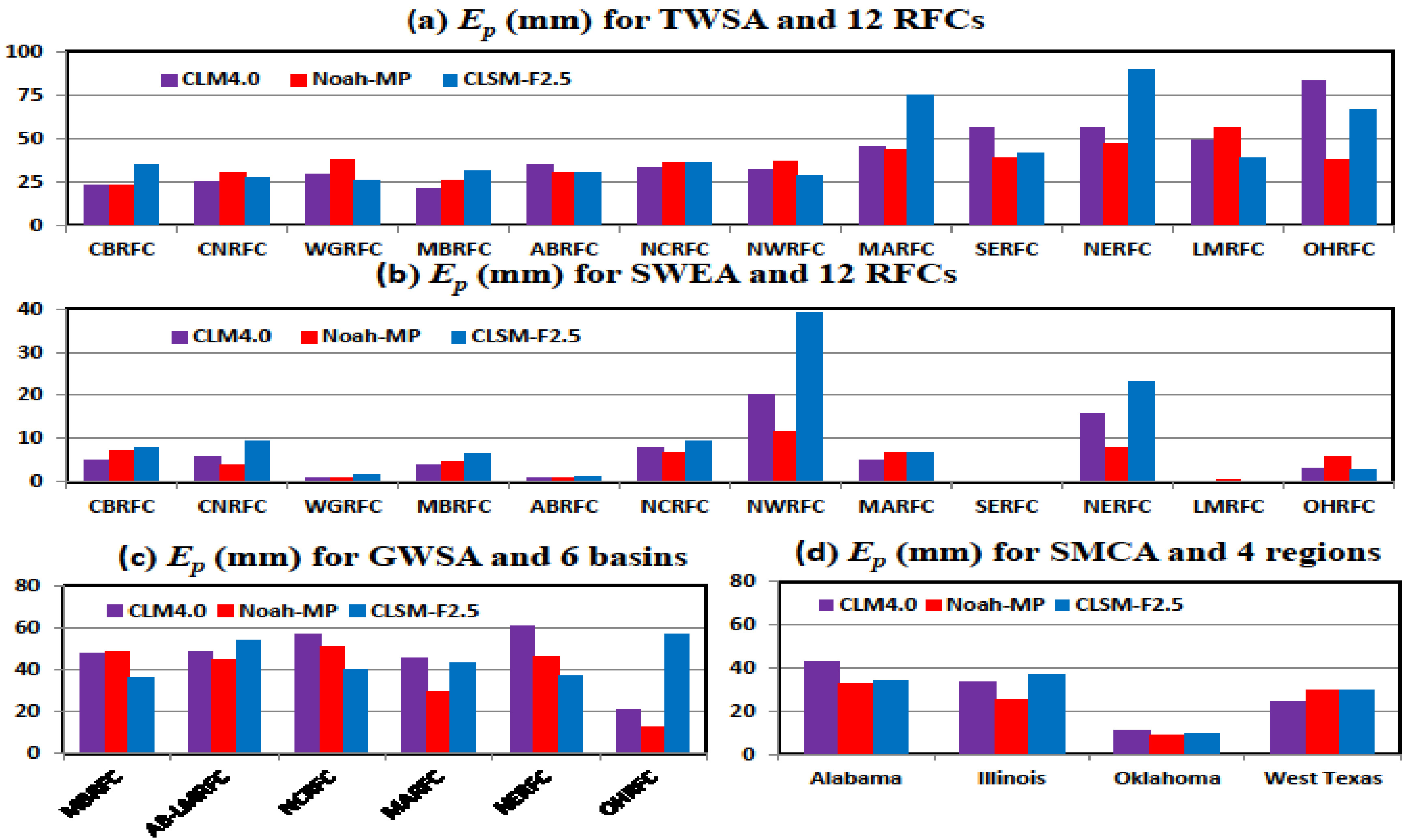


Figure 22: The E_p values calculated from simulated and observed/referred and (a) TWSA for 12 RFCs, (b) SWEA for 12 RFCs, (c) GWSA for 6 basins, and (d) SMCA for 4 regions. The error is caused from anomaly pattern

4. Water storage depletion in CBRFC, CNRFC and WGRFC

How well can the models capture ground water storage depletion at three RFCs?

What part mainly contributes to the large depletion?

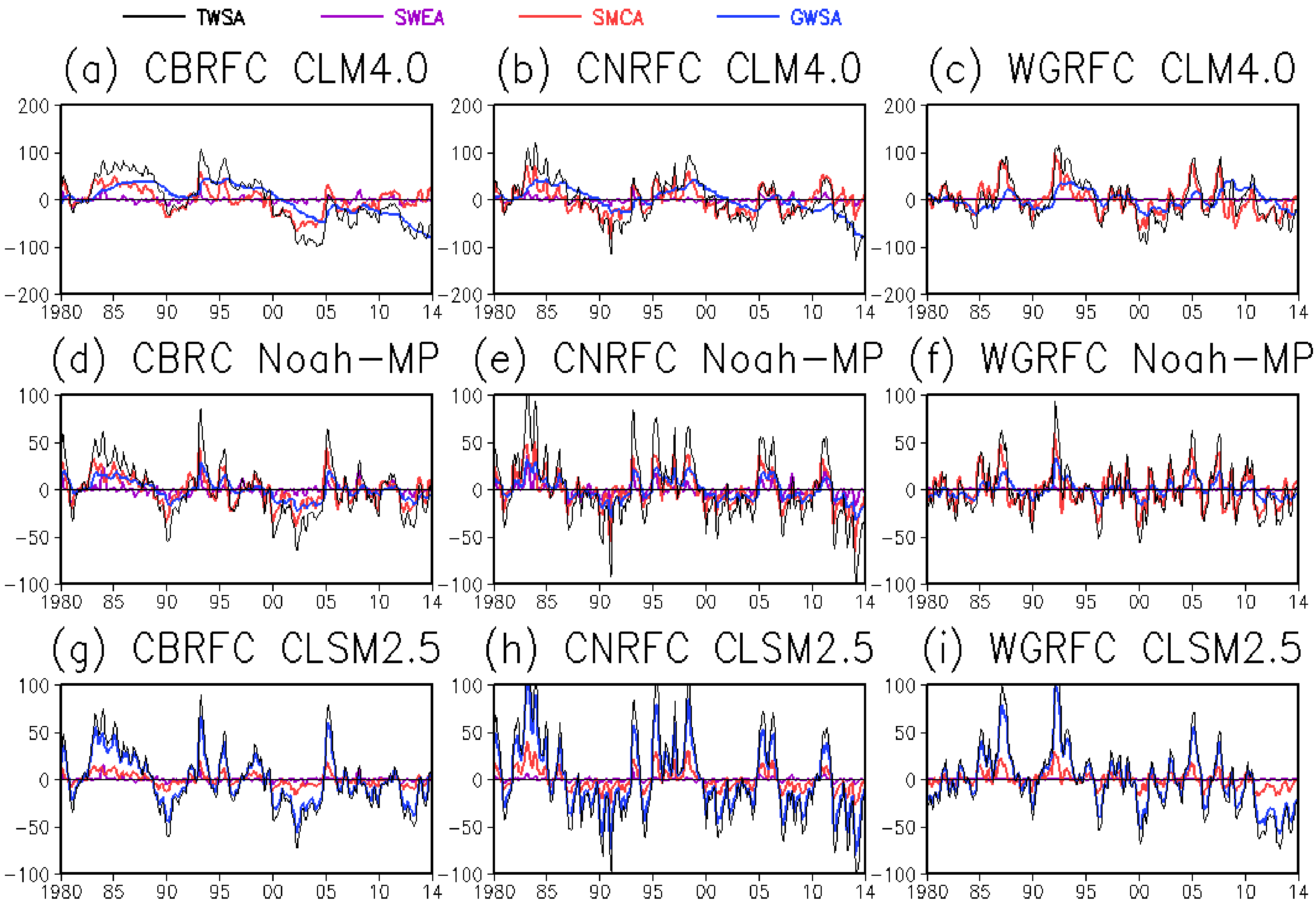


Figure 23: 35-year water storage anomaly (mm) for three models and NWS RFCs when mean seasonal cycle is removed.

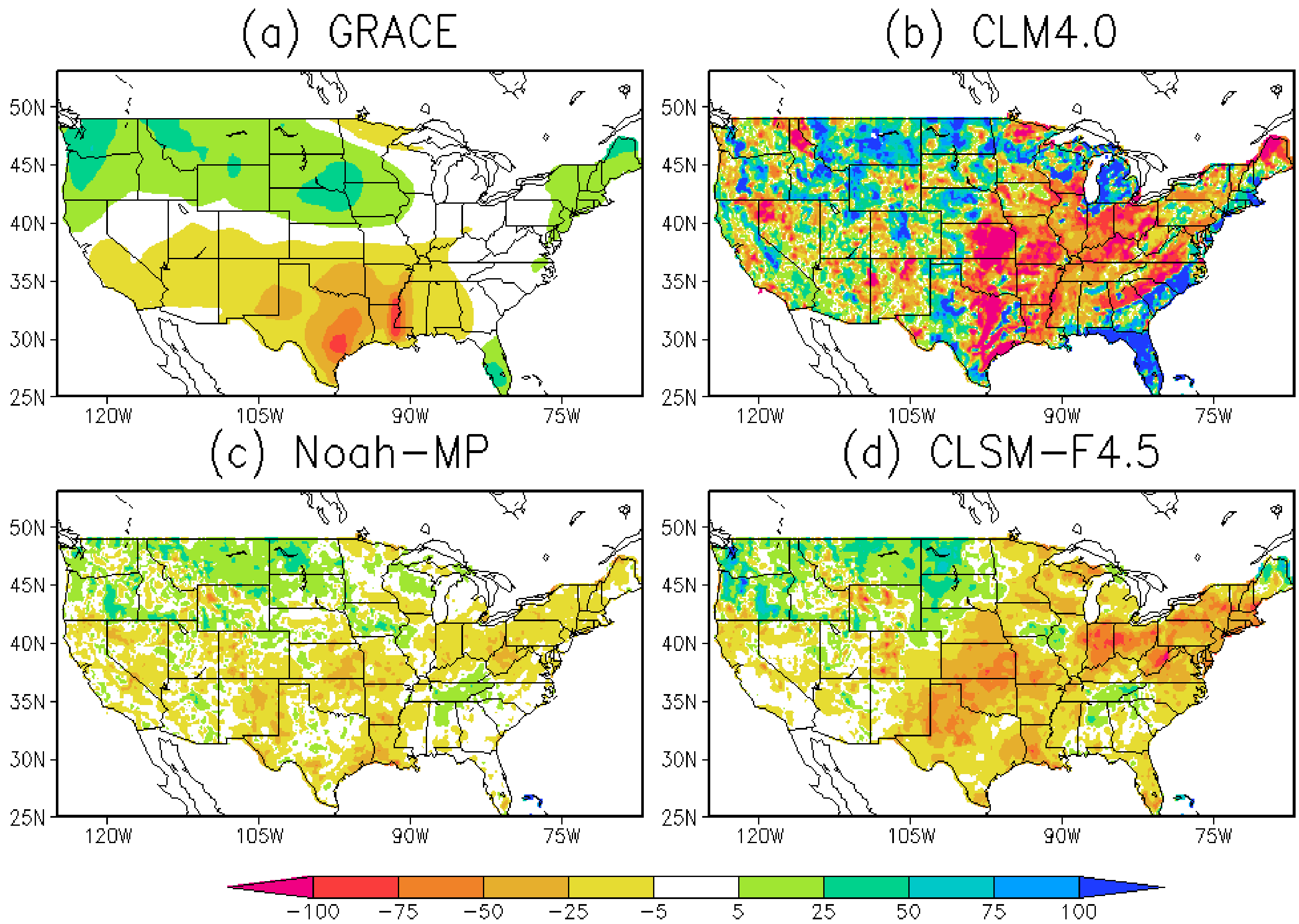


Figure 24: Recent 10-year (2005-2014) mean total water storage anomaly depletion rate (mm/year) calculated by the three models and with a 35-yr climatology (1980-2014). GRACE climatology is calculated from 2004-2009.

Swenson and Lawrence, 2015, WRR

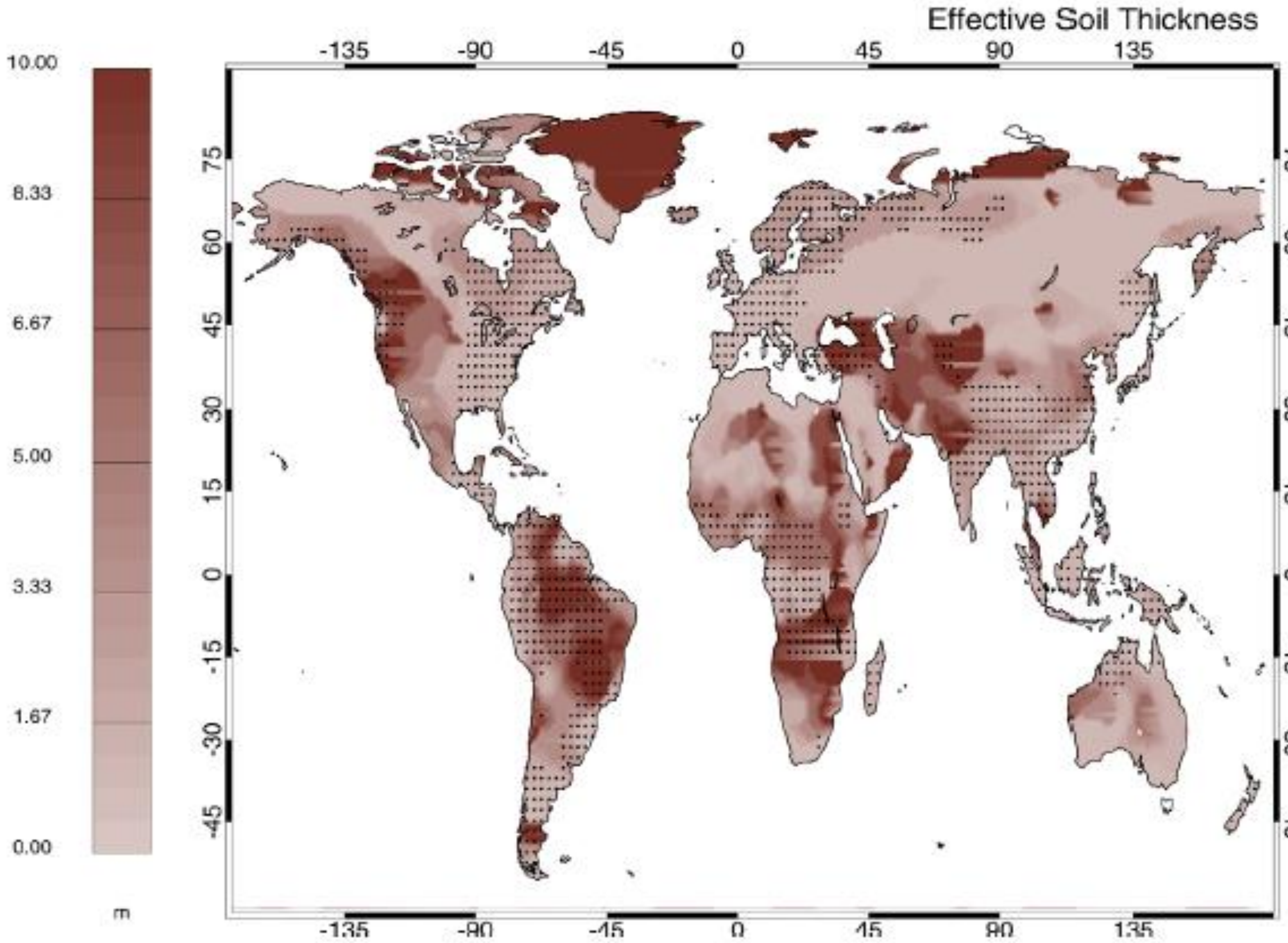


Figure 25: Optimal CLM soil thickness parameter (m). Value at each grid cell is taken from the ZBOT simulation rmsd between GRACE and CLM TWS.

Take away messages from this analysis:

a. Estimates of total water storage anomalies are just okay for all three models although anomaly correlation is relatively high. However, the amplitudes are different.

b. Noah-MP has quite good performance for SWE simulation when compared with SNODAS product. The fair performance can be seen for CLSM-F2.5. The reason comes from both precipitation partitioning and sublimation differences.

c. CLM4.0 captures quite well for ground water depletion observed in USGS wells. Noah-MP and CLSM-F2.5 fairly capture this phenomena.

d. CLSM-F2.5 (CLM4.0 and Noah-MP) shows too strong (weak) amplitude and signals in wet RFCs when compare USGS wells. All models have fair performance when compared with USGS OBS. This may need more efforts to work together to move forward.

e. Differences of TWSA and its components have implications how water is stored in surface, soil and ground on drought analysis and monitoring. It matters!

f. Grid cell dependent (rather than uniform) soil depth may need a further investigation in future