NCAR Earth System Laboratory

Investigating the Biogeophysical Impacts of Land Cover Change in CLM 4

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Simulating the Biogeochemical and Biogeophysical Impacts of Transient Land Cover Change and Wood Harvest in the Community Climate System Model (CCSM4) from 1850 to 2100.

Lawrence, P. J., J. J. Feddema, G. B. Bonan, G. A. Meehl, B. C. O'Neill, S. Levis, D. M. Lawrence, K. W. Oleson, E. Kluzek, K. Lindsay, and P. E. Thornton (2012) *Journal of Climate*, In Press

1. Human Land Cover Change and CLM4

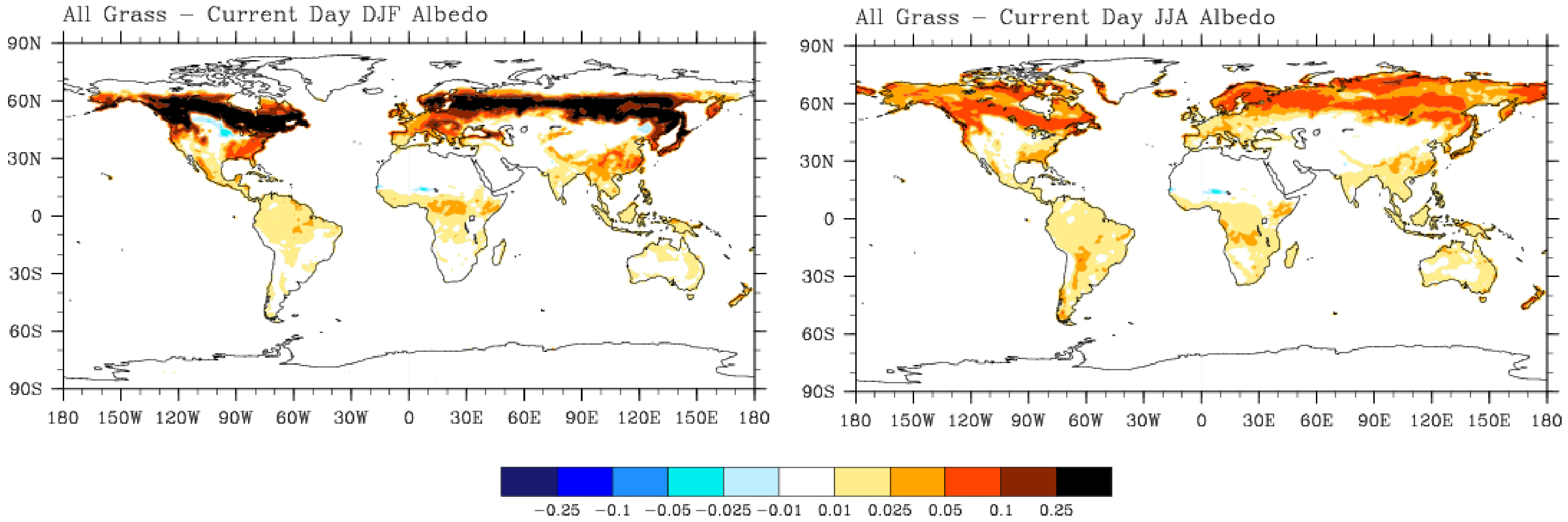
Albedo Impacts of Land Cover Change are Consistently represented in CLM4.

Observed Global Average MODIS Albedo by Biome

Biomes:	DJF	JJA
Tropical Forest	0.13	0.13
Temperate Forest	0.18	0.13
Boreal Forest	0.38	0.12
Savanna	0.17	0.15
Grassland	0.32	0.17
Agriculture	0.24	0.15

(*Lawrence and Chase* 2010)

CLM4 Current Day Vegetation replaced with Grass PFTs



1. Human Land Cover Change and CLM4

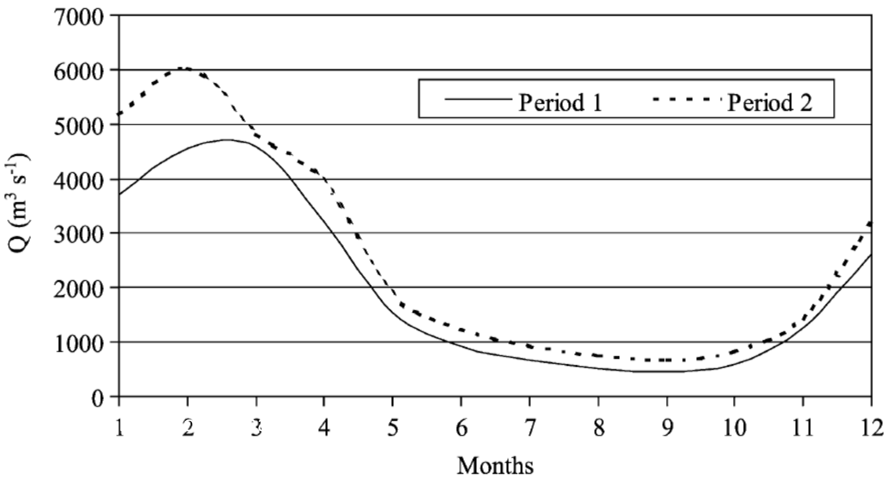
Hydrological Impacts of Land Cover Change are less understood in CLM4.

Observational Catchment Hydrology Studies show Tropical Deforestation and replacement with Agriculture often results in reduced Evapo-Transpiration and increased Runoff

Tocantins River basin, Southeastern Amazonia Study (*Costa et al.* 2003)

Estimates of land used for agricultural purposes in the study area in 1960 and 1995, as a percent of the total study area

	1960	1995
Planted pastures (%)	4.6	22.8
Natural pastures (%)	24.1	22.9
Crops (%)	1.5	3.5
Total land use (%)	30.2	49.2



Long term mean of hydrological variables in the Tocantins River basin upstream of Porto Nacional

Period	*P* (mm/day)	*Q* (m^3/s)	*Q* (mm/day)	ET (mm/day)	*C*
1949–1968	4.22	2055.6	1.00	3.22	0.237
1979–1998	4.35	2532.3	1.24	3.11	0.285

P is precipitation (calculated from the CRU dataset), *Q* is discharge (from the ANEEL records), ET is evapotranspiration ($P - Q$), and *C* is the runoff coefficient (Q/P).

1. Human Land Cover Change and CLM4

Flux Tower studies such as the Large-scale Biosphere-Atmosphere Experiment in the Amazon (LBA) (*von Randow, et al.*, 2004), also found that tropical deforestation resulted in reduced evapo-transpiration with increased sensible heat flux:

- Forested areas had 20% higher evapo-transpiration and 45% lower sensible heat flux than nearby pastures in the wet season

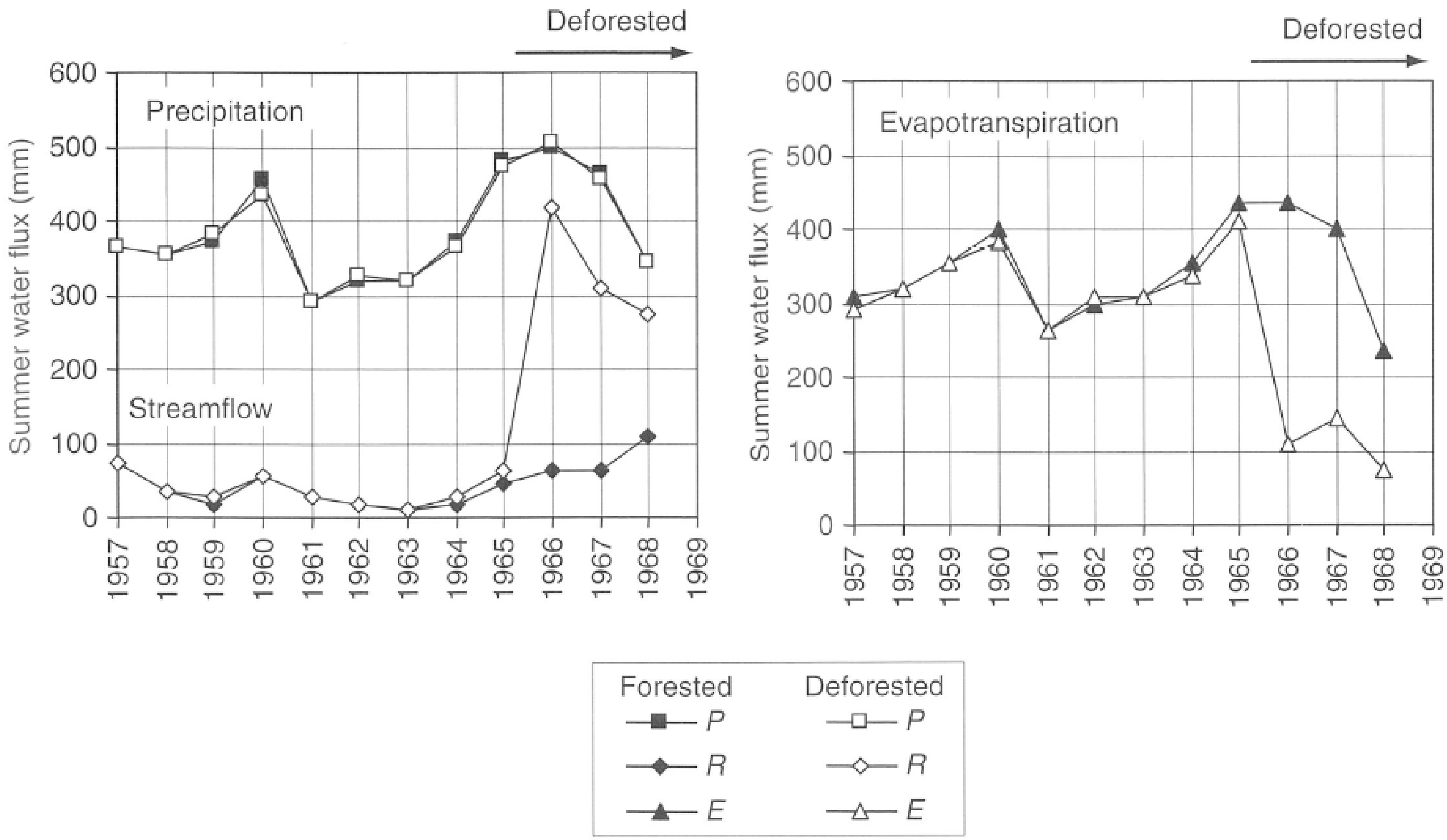
- Forested areas also had 41% higher evapo-transpiration and 28% lower sensible heat flux in the dry season.

- Trees were able to access soil water from deep in the soil profile while the pasture vegetation could only access water from the upper soil layers.

1. Human Land Cover Change and CLM4

Paired Catchment Hydrology Studies also show Temperate Deforestation can result in reduced Evapo-Transpiration and increased Runoff

Hubbard Brook Experimental Forest, New Hampshire Study (*Likens* 2004)



1. Human Land Cover Change and CLM4

Again flux tower studies show mid-latitude deforestation resulted in reduced Evapo-Transpiration was also found in the Duke Forest, Durham, North Carolina (*Juang, et al.*, 2007):

- Compared to hardwood broadleaf forests and pine forests, adjacent pastures were warmer by 2.9 ^{O} C and 2.1 ^{O} C respectively, due to lower evapo-transpiration and reduced surface roughness.

- This dominated smaller cooling from higher albedo of 0.7 ^{O} C and 0.9 ^{O} C.

1. Human Land Cover Change and CLM4

Based on the relationship between Deforestation and Agriculture in 171 catchments, *Zhang et al.* (2001) developed a simplistic vegetation based relationship between Annual Precipitation and Evapo-Transpiration:

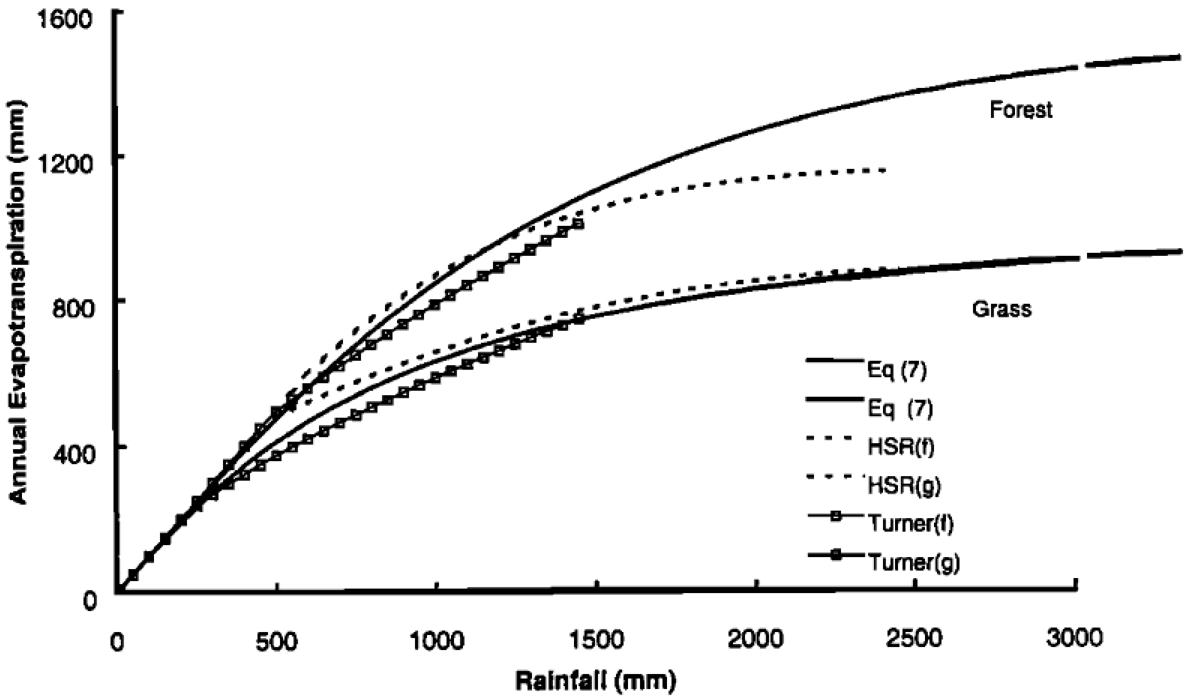


Figure 8. Comparison of equation (8) with the empirical relationships developed by *Holmes and Sinclair* [1986] and *Turner* [1991] for forested and grassed catchments.

- Does not capture physiological differences between tree PFTs or grass PFTs
- Does not account for catchment topography, soils and drainage
- Does not account for net radiation and other climate variables
- But does provide a framework to assess the behavior of trees and grasses in CLM4
- This study is also cited 275 times in the literature

2. Investigate CLM4 under extreme land cover change

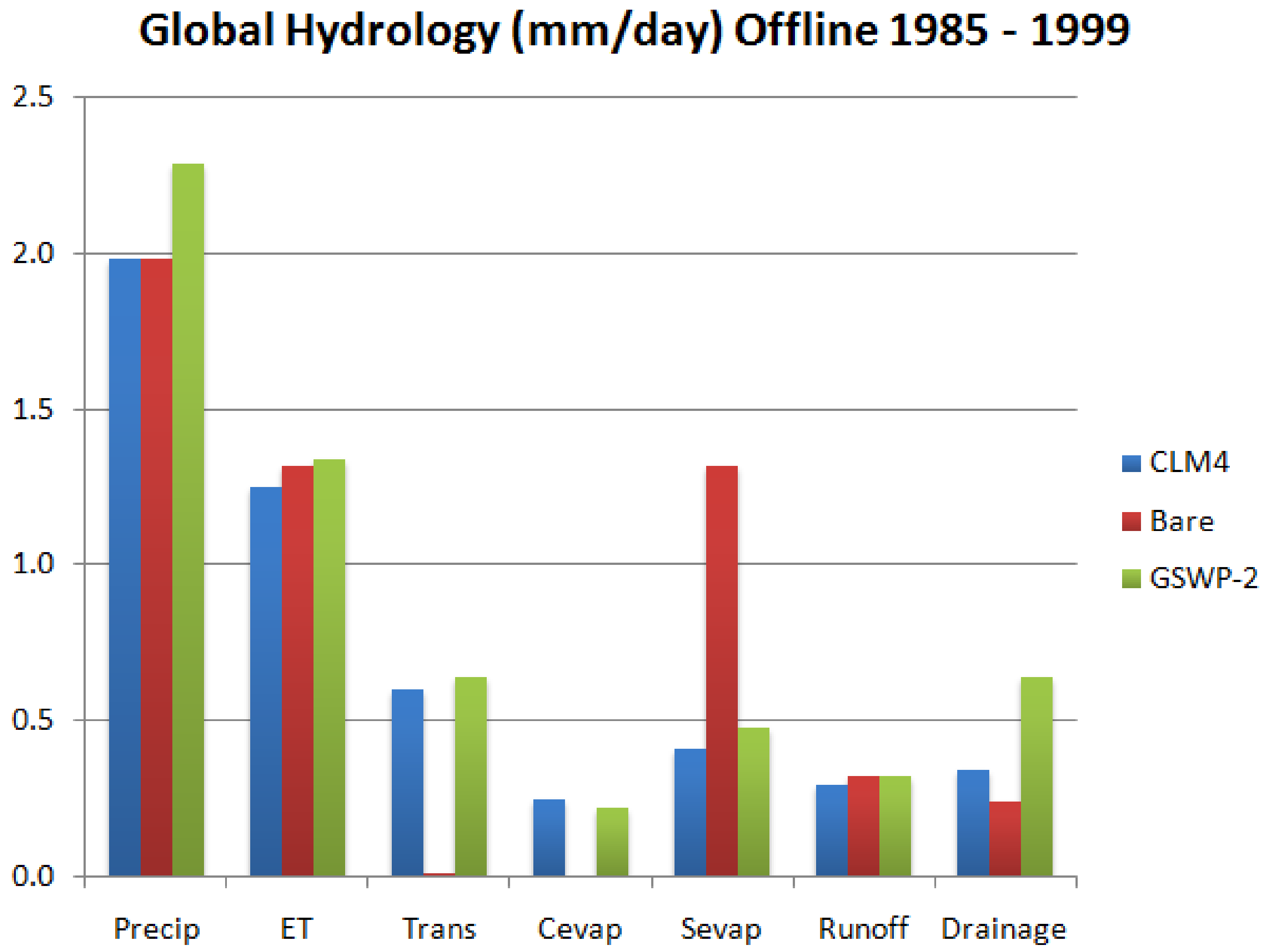
1. Investigate changes in land surface climate of CLM4 with land cover change. All experiments are forced with Qian meteorology for 1970 – 1999 and have monthly satellite phenology (SP) Leaf Area Index.

2. Control: Current day vegetation

3. Vegetation Removal: Global bare soils

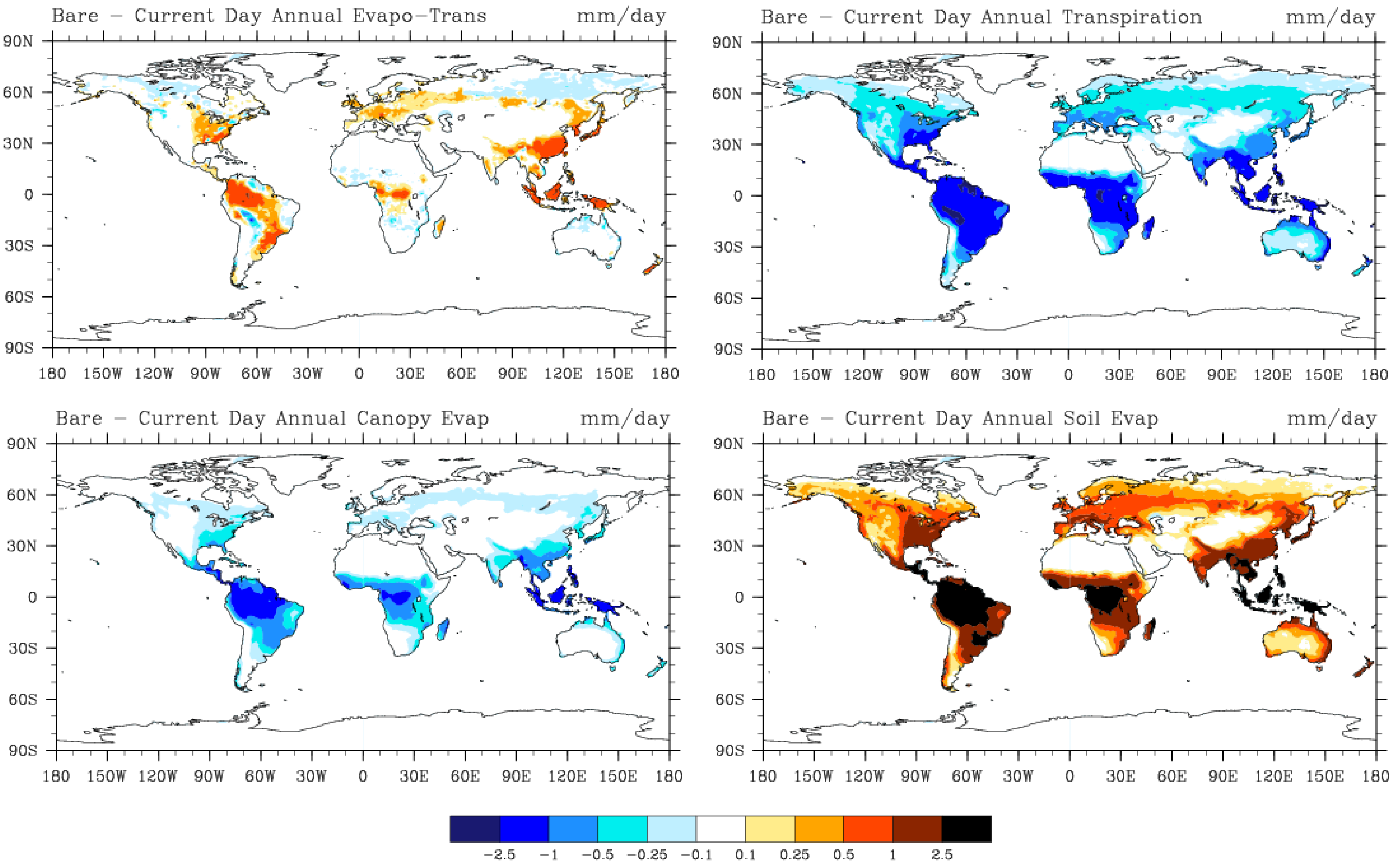
4. All Grass: All current day vegetation replaced with climate appropriate grass PFTs (Bare soil stays at Current Day values)

3. Offline CLM4 – Vegetation Removal – Global Hydro

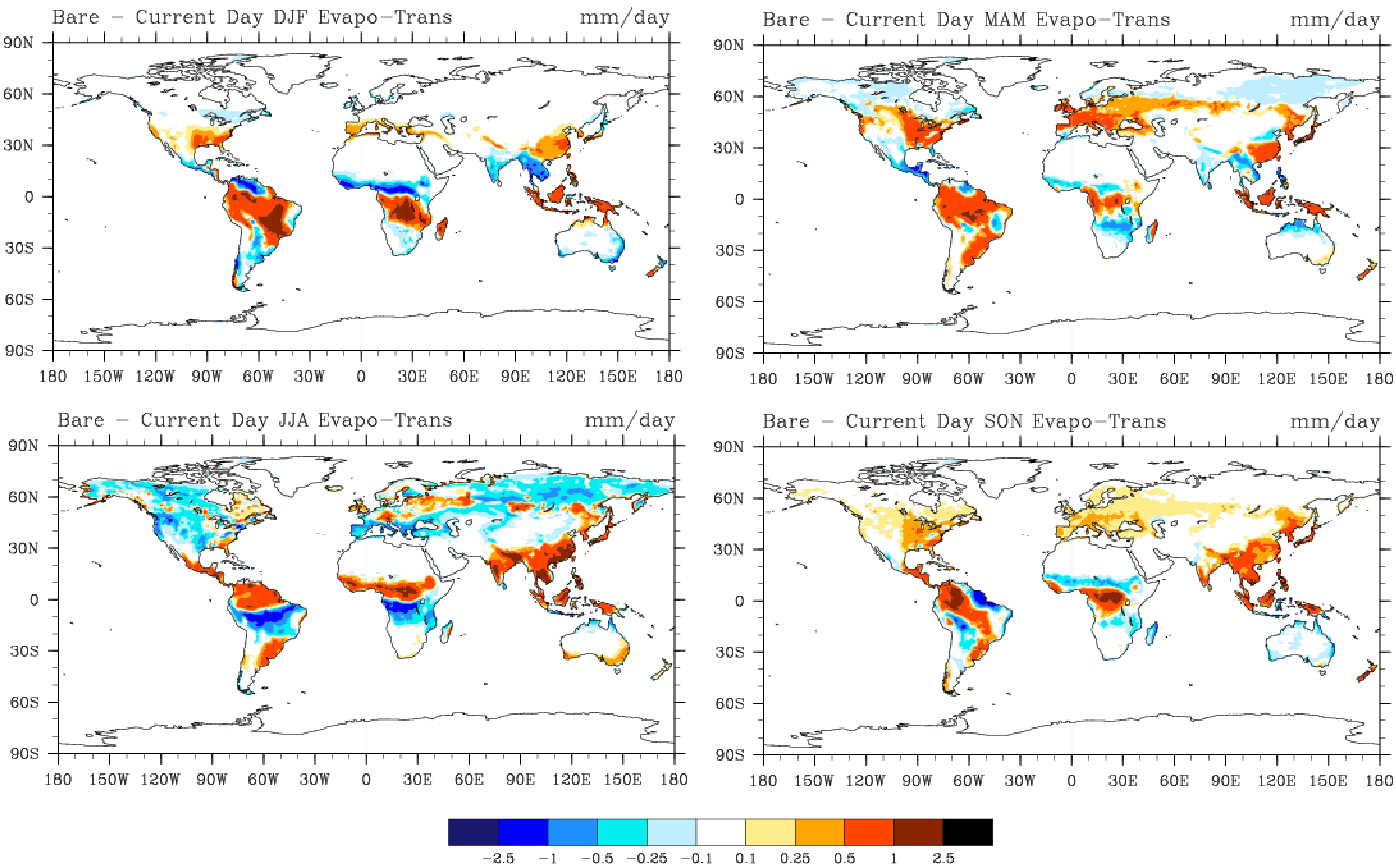


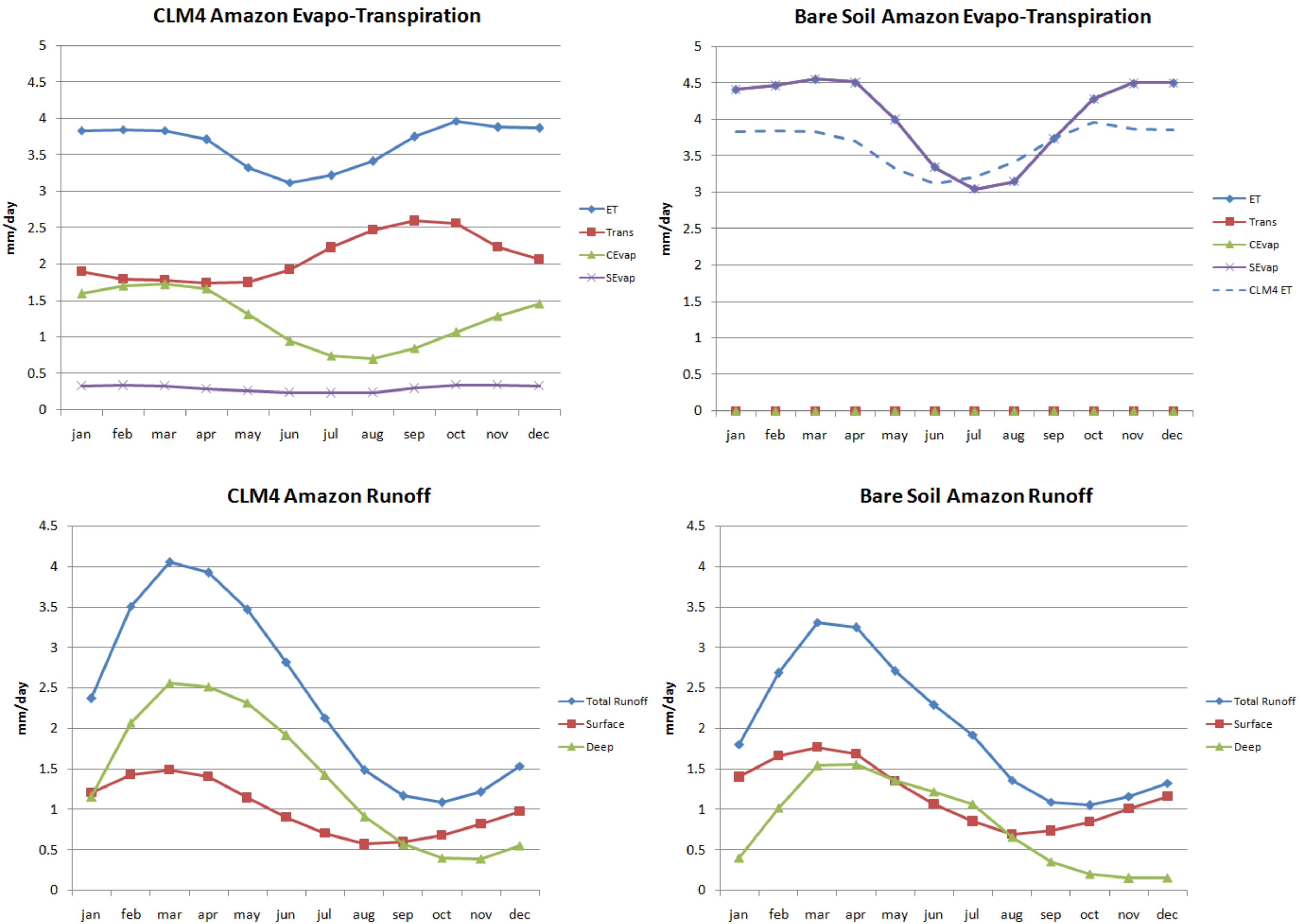
GSWP-2 is Global Soil Wetness Project 2 Global Hydrology used in *Lawrence et al.* (2007)

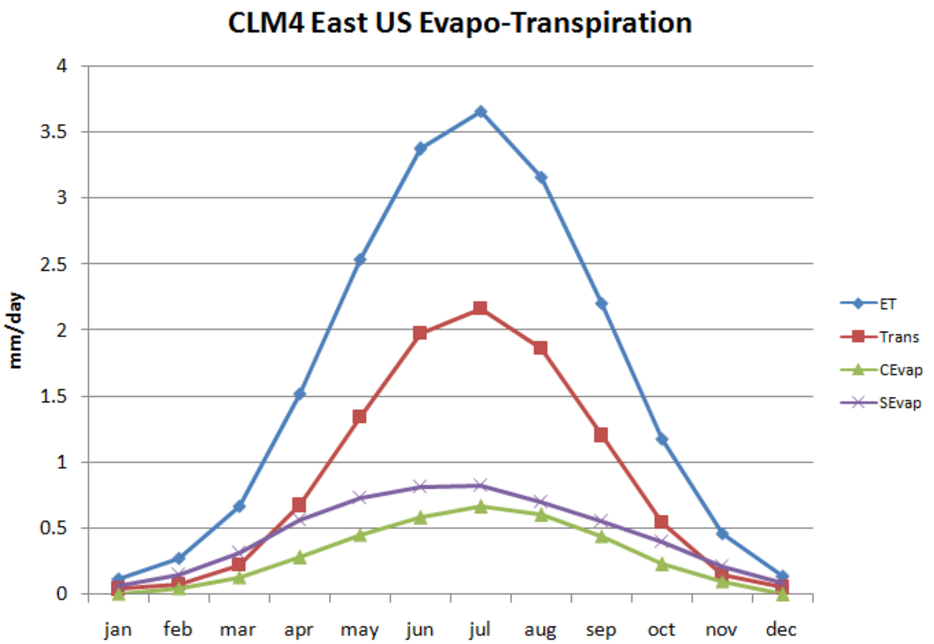
3. Offline CLM4 – Vegetation Removal – Annual ET

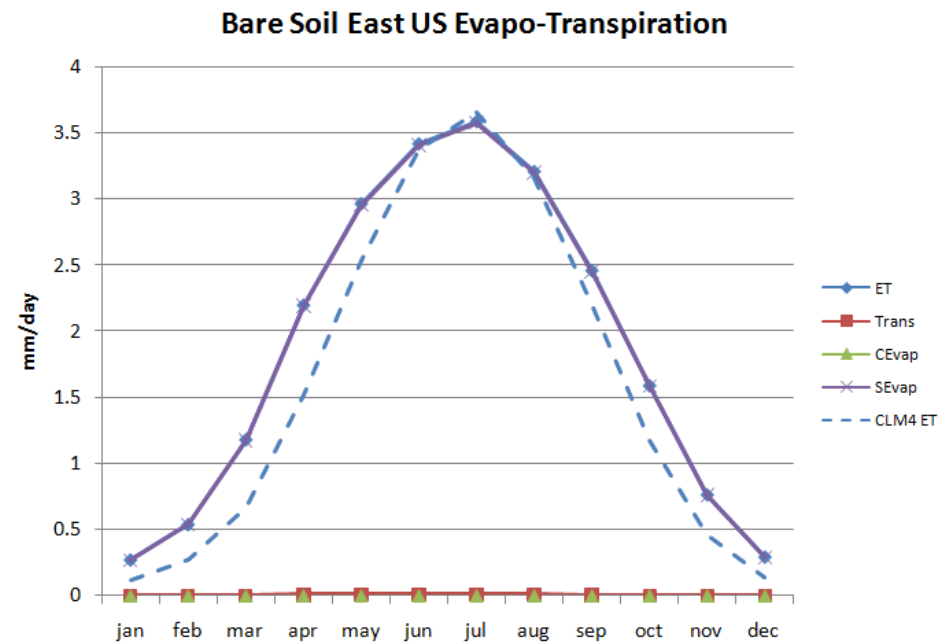


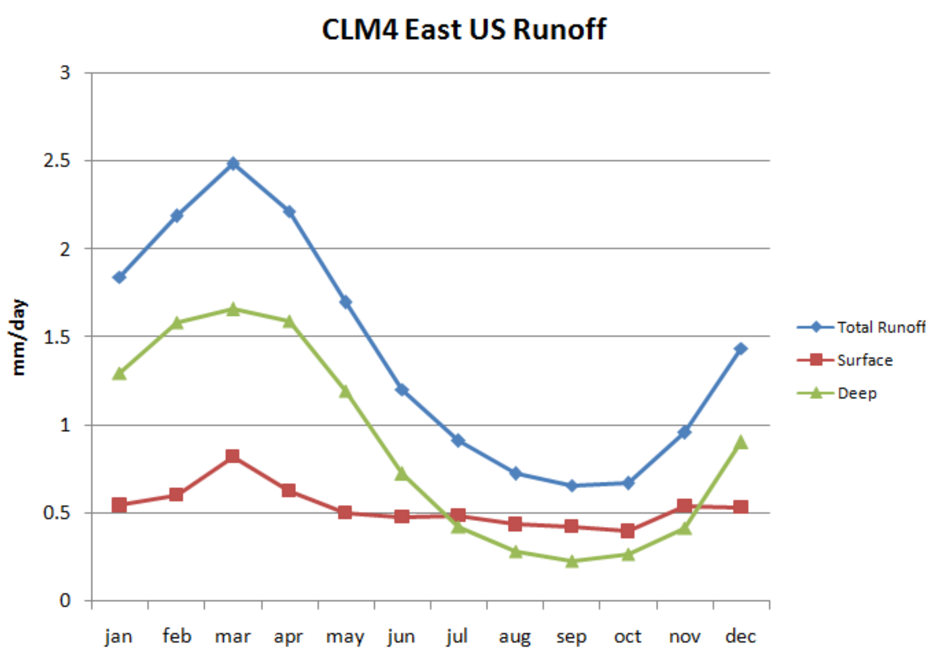
3. Offline CLM4 – Vegetation Removal – Seasonal ET

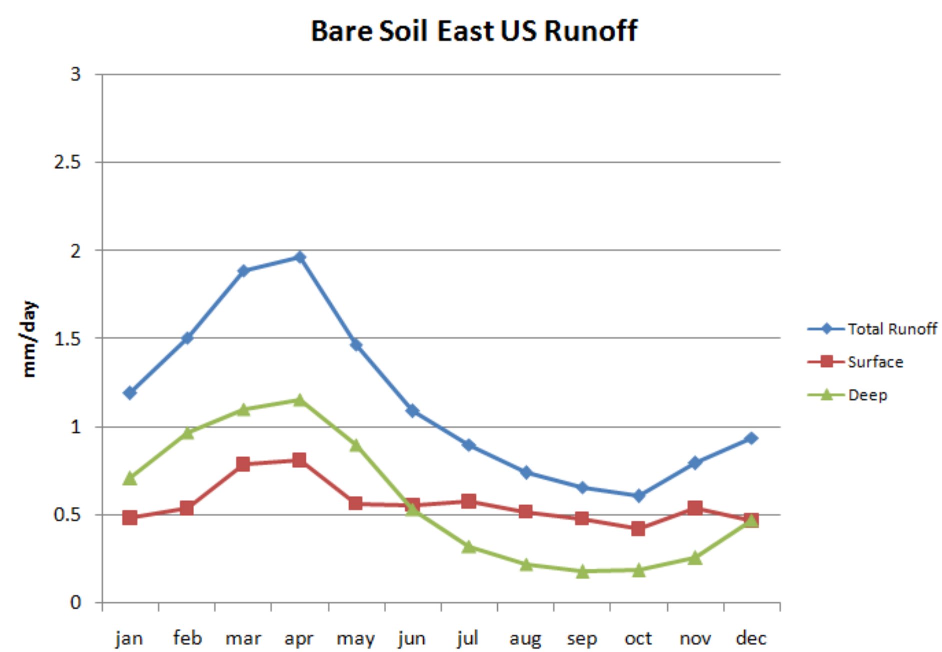



CLM4 Amazon Evapo-Transpiration
mm/day
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
ET
Trans
CEvap
SEvap
Bare Soil Amazon Evapo-Transpiration
mm/day
ET
Trans
CEvap
SEvap
CLM4 ET
CLM4 Amazon Runoff
mm/day
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Total Runoff
Surface
Deep
Bare Soil Amazon Runoff
mm/day
Total Runoff
Surface
Deep

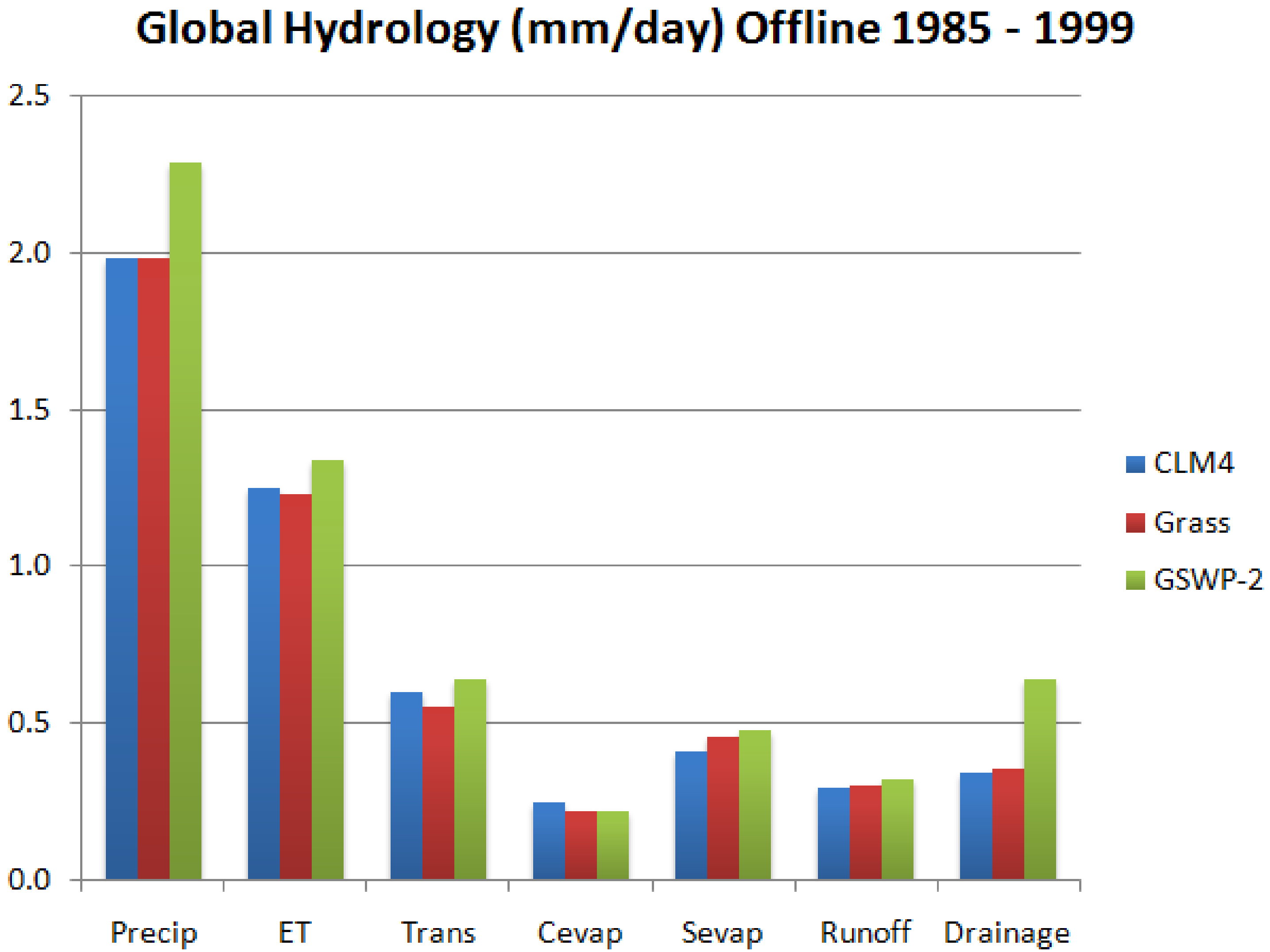

CLM4 East US Evapo-Transpiration
mm/day
4
3.5
3
2.5
2
1.5
1
0.5
0
jan feb mar apr may jun jul aug sep oct nov dec
ET
Trans
CEvap
SEvap


Bare Soil East US Evapo-Transpiration
mm/day
4
3.5
3
2.5
2
1.5
1
0.5
0
jan feb mar apr may jun jul aug sep oct nov dec
ET
Trans
CEvap
SEvap
CLM4 ET


CLM4 East US Runoff
mm/day
3
2.5
2
1.5
1
0.5
0
jan feb mar apr may jun jul aug sep oct nov dec
Total Runoff
Surface
Deep

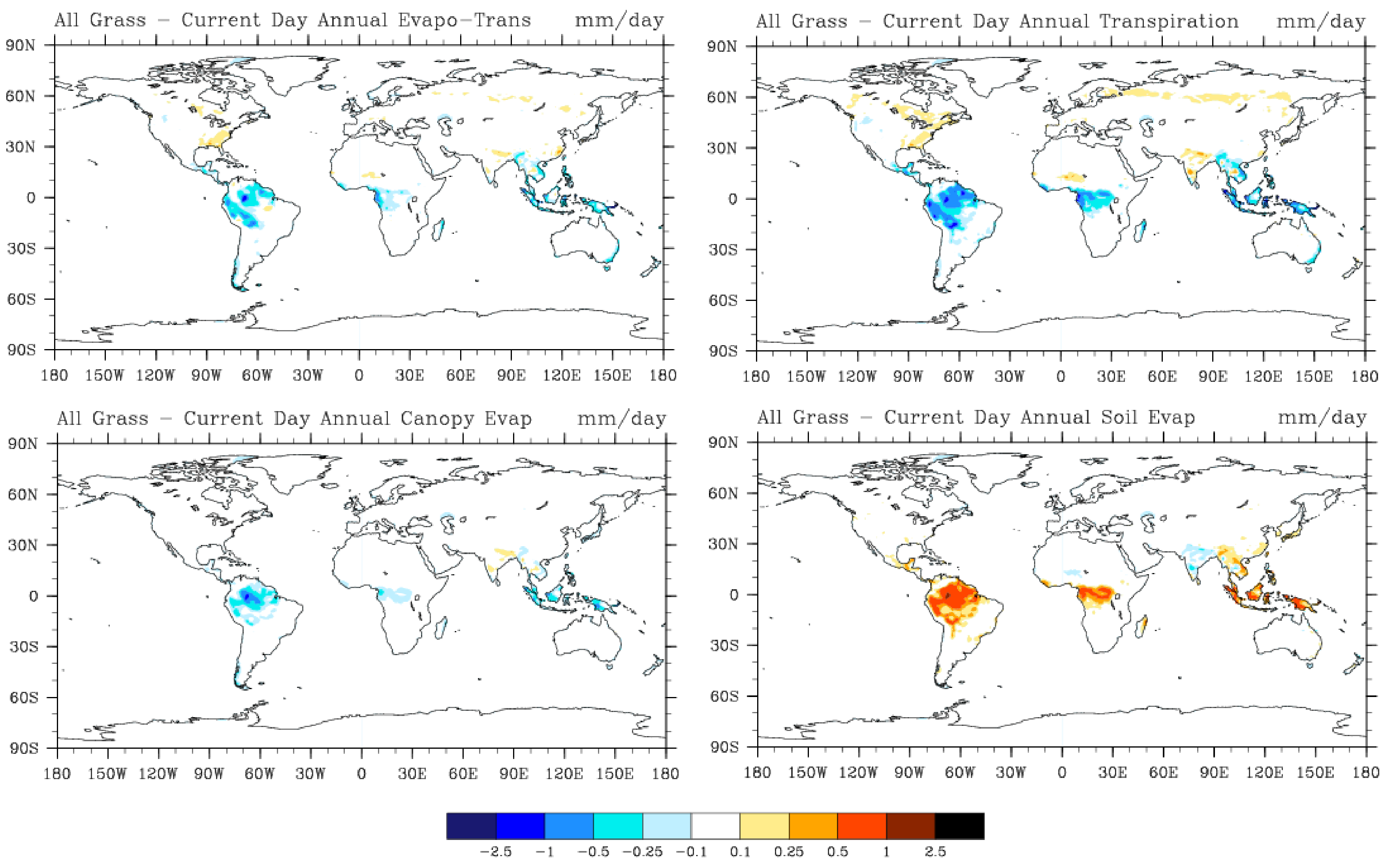

Bare Soil East US Runoff
mm/day
3
2.5
2
1.5
1
0.5
0
jan feb mar apr may jun jul aug sep oct nov dec
Total Runoff
Surface
Deep

4. Offline CLM4 – All Grass – Global Hydro

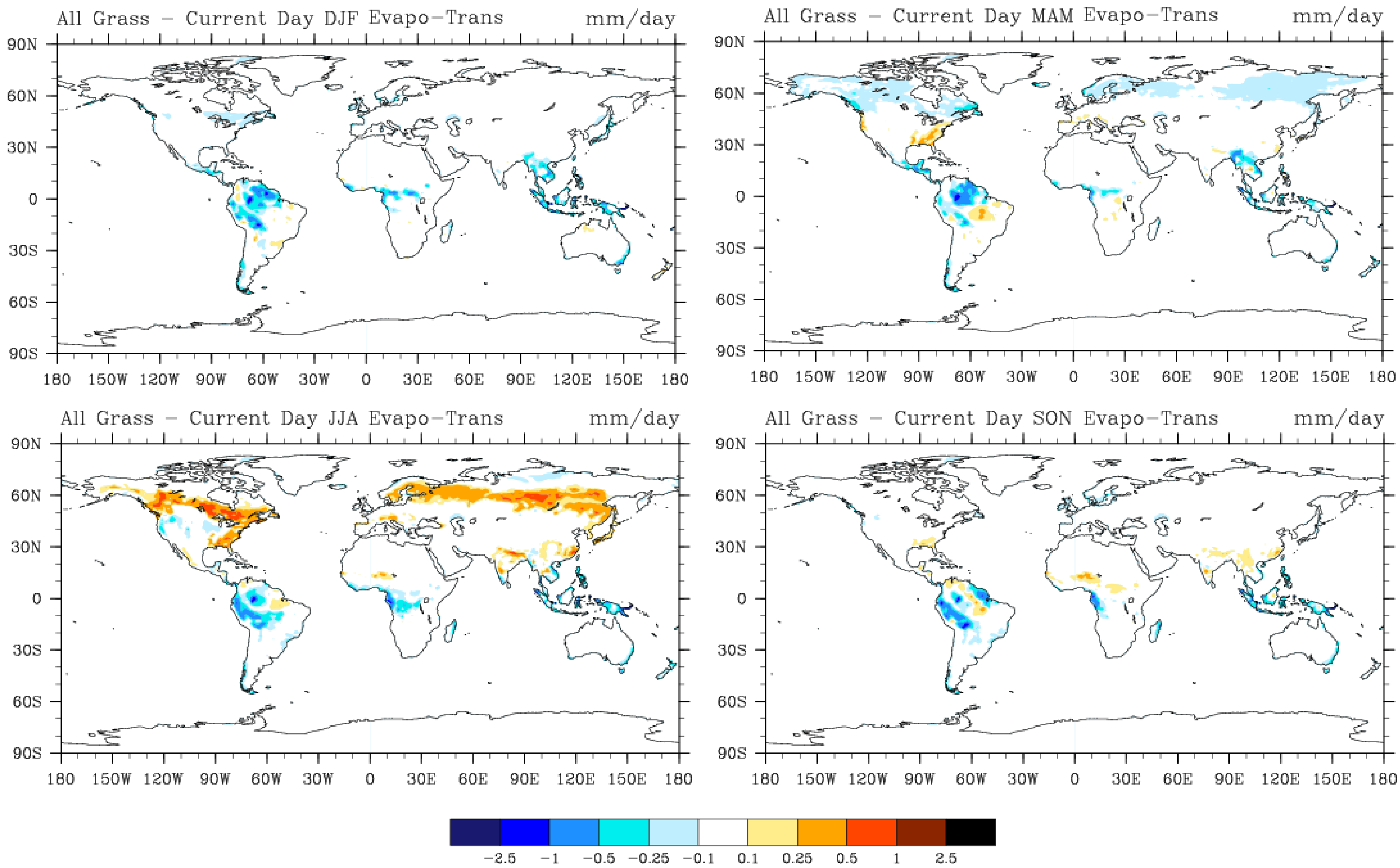


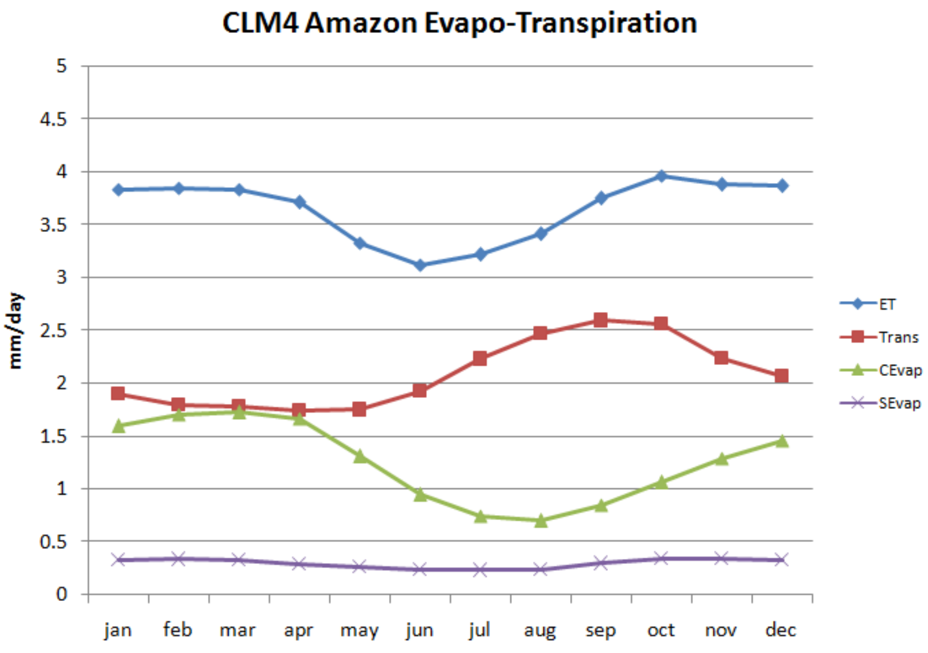
GSWP-2 is Global Soil Wetness Project 2 Global Hydrology used in *Lawrence et al.* (2007)

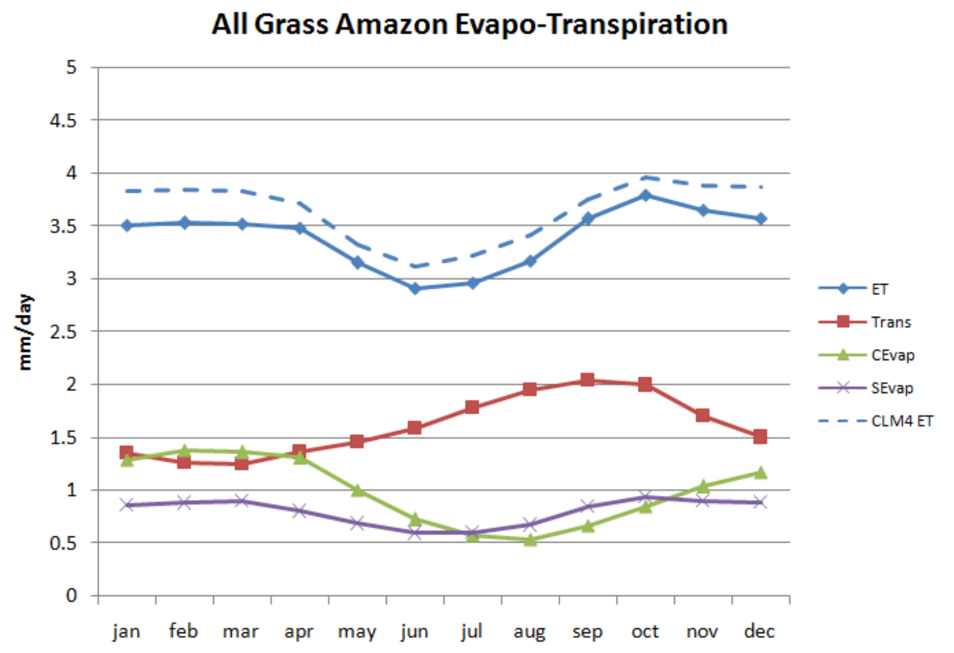
4. Offline CLM4 – All Grass – Annual ET

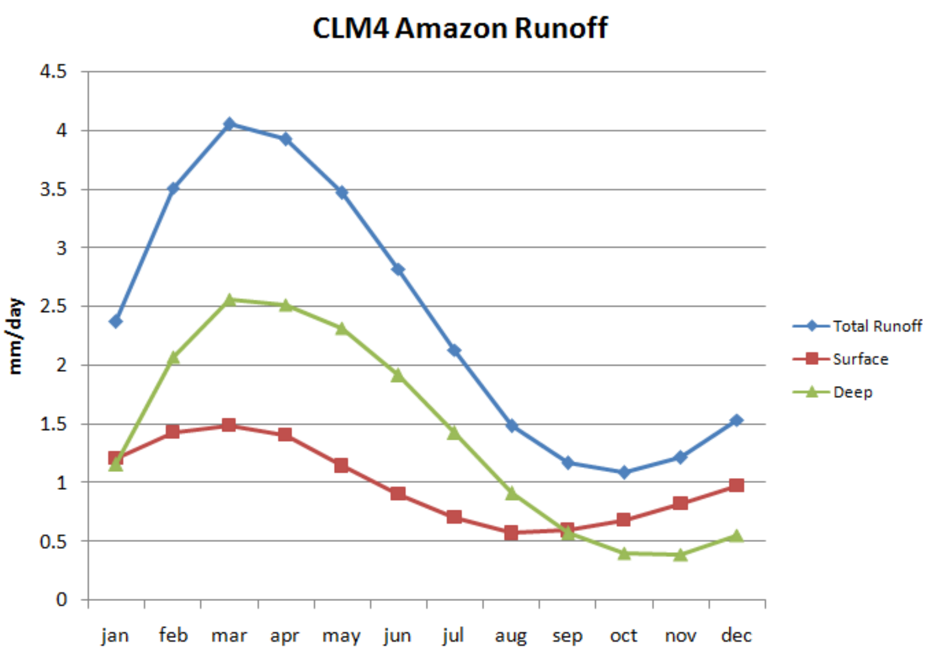


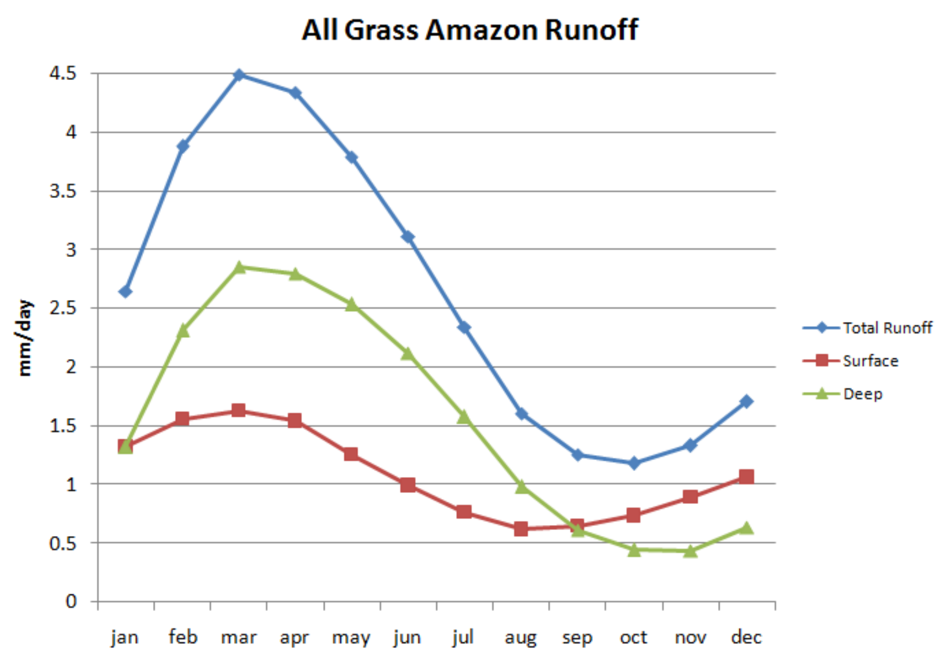
4. Offline CLM4 – All Grass – Seasonal ET

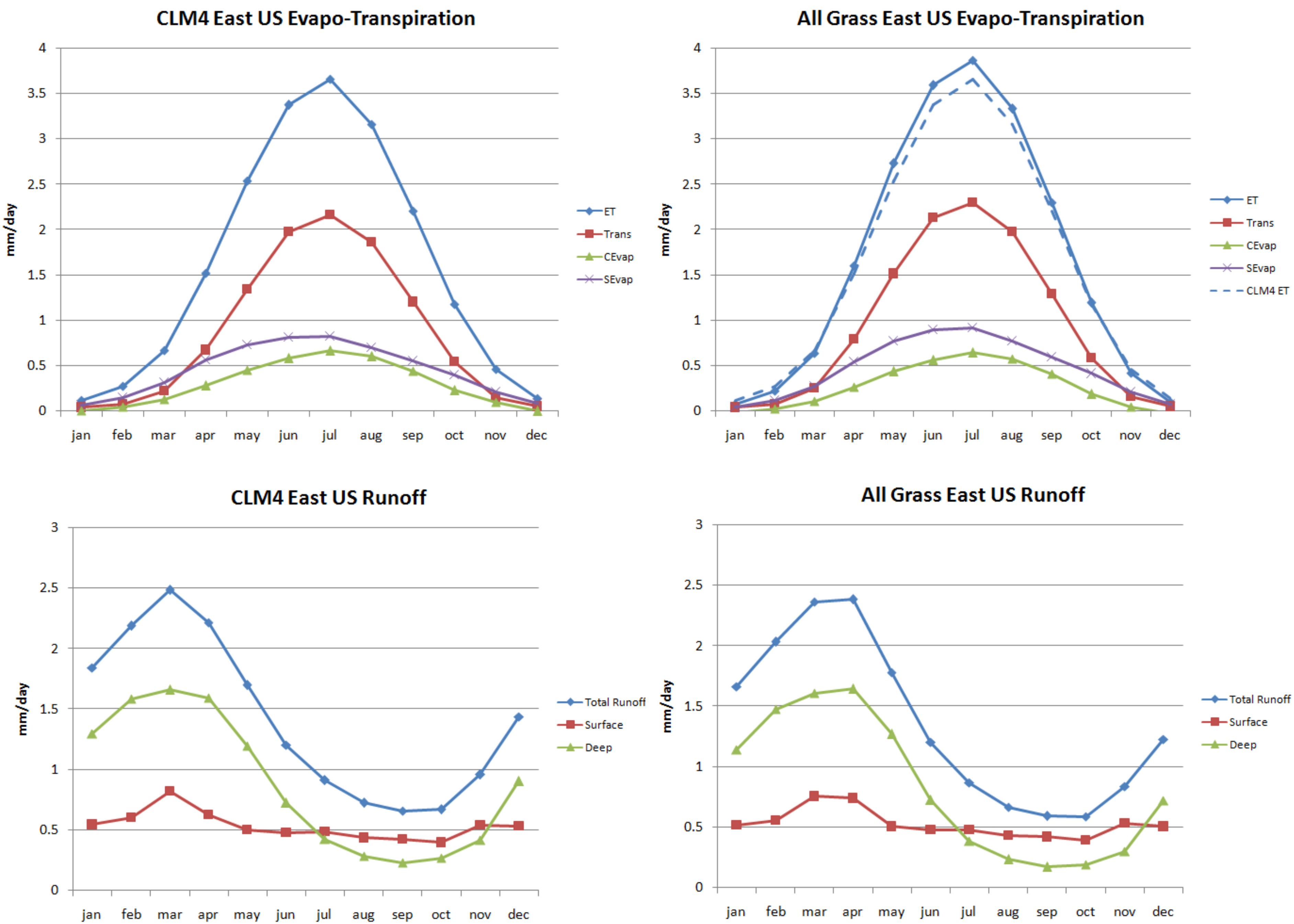



CLM4 Amazon Evapo-Transpiration
mm/day
ET
Trans
CEvap
SEvap
jan feb mar apr may jun jul aug sep oct nov dec


All Grass Amazon Evapo-Transpiration
mm/day
ET
Trans
CEvap
SEvap
CLM4 ET
jan feb mar apr may jun jul aug sep oct nov dec


CLM4 Amazon Runoff
mm/day
Total Runoff
Surface
Deep
jan feb mar apr may jun jul aug sep oct nov dec


All Grass Amazon Runoff
mm/day
Total Runoff
Surface
Deep
jan feb mar apr may jun jul aug sep oct nov dec


CLM4 East US Evapo-Transpiration
mm/day
ET
Trans
CEvap
SEvap
0
0.5
1
1.5
2
2.5
3
3.5
4
jan feb mar apr may jun jul aug sep oct nov dec
All Grass East US Evapo-Transpiration
mm/day
ET
Trans
CEvap
SEvap
CLM4 ET
0
0.5
1
1.5
2
2.5
3
3.5
4
jan feb mar apr may jun jul aug sep oct nov dec
CLM4 East US Runoff
mm/day
Total Runoff
Surface
Deep
0
0.5
1
1.5
2
2.5
3
jan feb mar apr may jun jul aug sep oct nov dec
All Grass East US Runoff
mm/day
Total Runoff
Surface
Deep
0
0.5
1
1.5
2
2.5
3
jan feb mar apr may jun jul aug sep oct nov dec

5. Why Does CLM4 Have Higher Bare Soil Evaporation?

1. The analysis shows that CLM4 with global bare soils has higher global evapo-transpiration than with vegetation.

2. Increases were largest in areas which are most densely vegetated such as the Amazon, South East Asia, Eastern US and Europe.

3. Analysis also shows that changing from trees to grass vegetation had only a small impact on global evapotranspiration.

4. This was the opposite hydrological response that we would have expected for deforestation based on the catchment and flux tower studies.

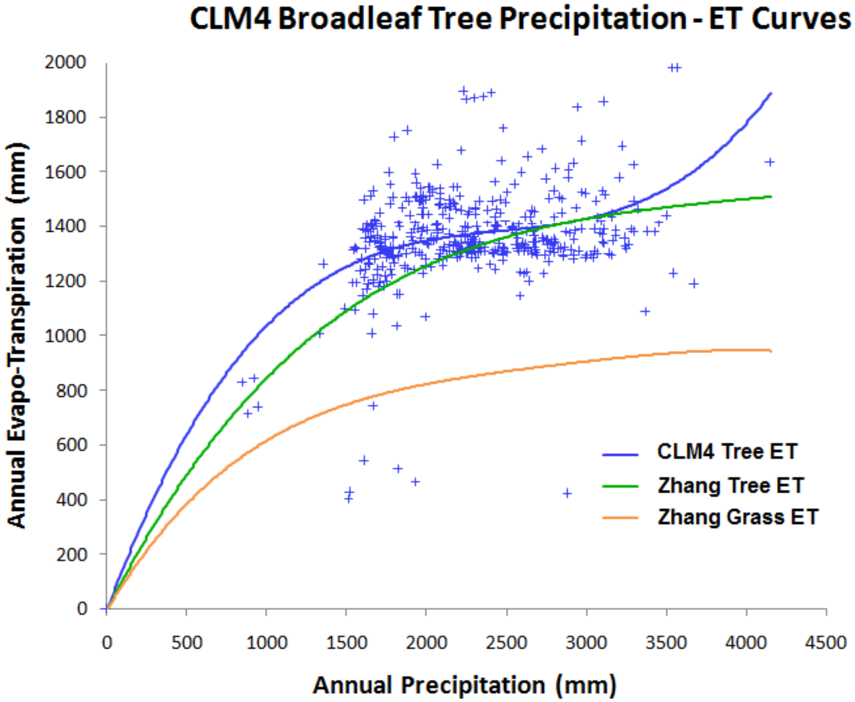
5. Why Does CLM4 Have Higher Bare Soil Evaporation?

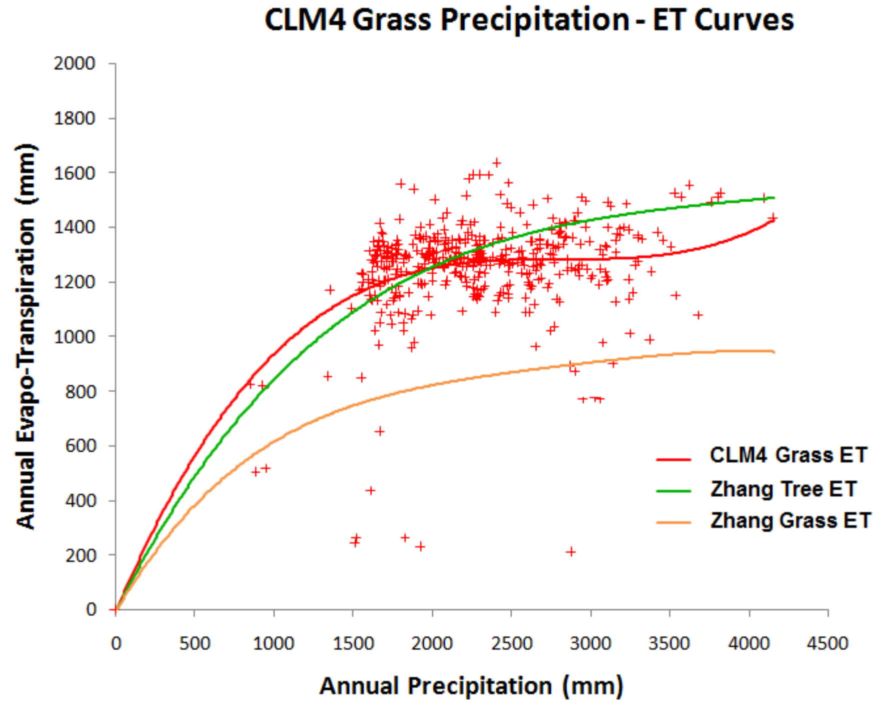
1. To investigate the CLM4 vegetation hydrology relationship further, current day grid cells were selected where the vegetation had 100% tree PFT composition.

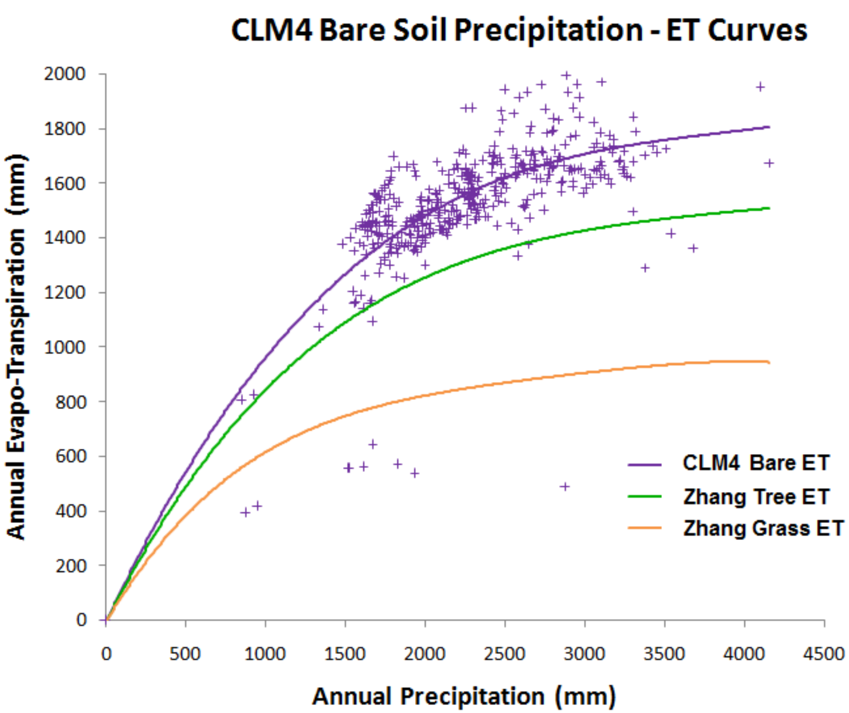
2. These grid cells were analyzed for annual precipitation against evapo-transpiration and compared to the forest evapo-transpiration relationships of Zhang et al. (2001)

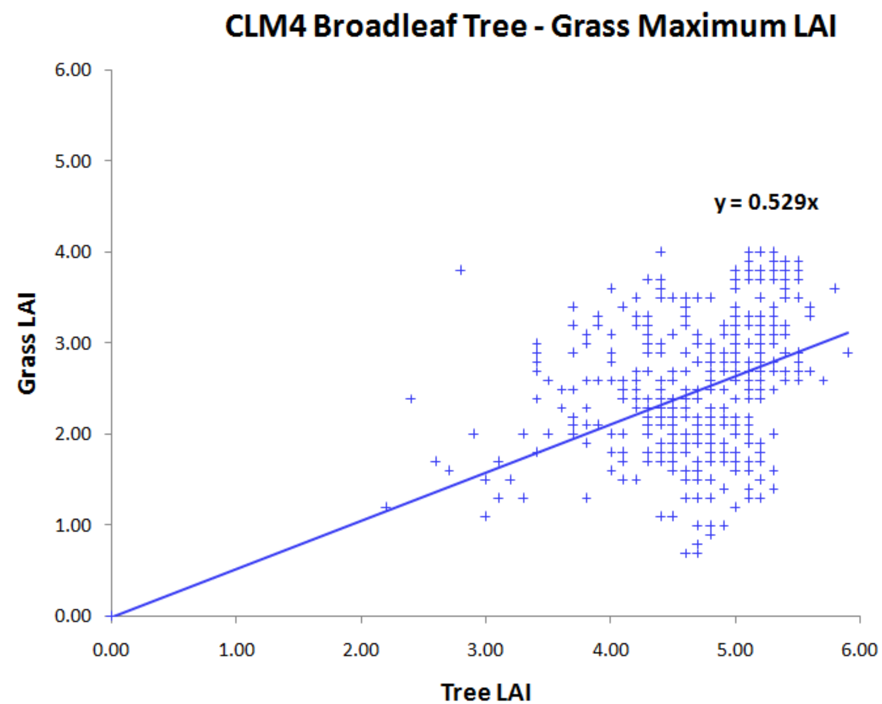
3. These same grid cells were then analyzed for the All Grass and Bare Soil experiments compared to the grass evapo-transpiration relationships of Zhang et al. (2001)

4. This gave relative CLM4 annual precipitation to evapo-transpiration relationships for: trees – grasses – bare soils


CLM4 Broadleaf Tree Precipitation - ET Curves
Annual Evapo-Transpiration (mm)
Annual Precipitation (mm)
CLM4 Tree ET
Zhang Tree ET
Zhang Grass ET
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
500
1000
1500
2000
2500
3000
3500
4000
4500

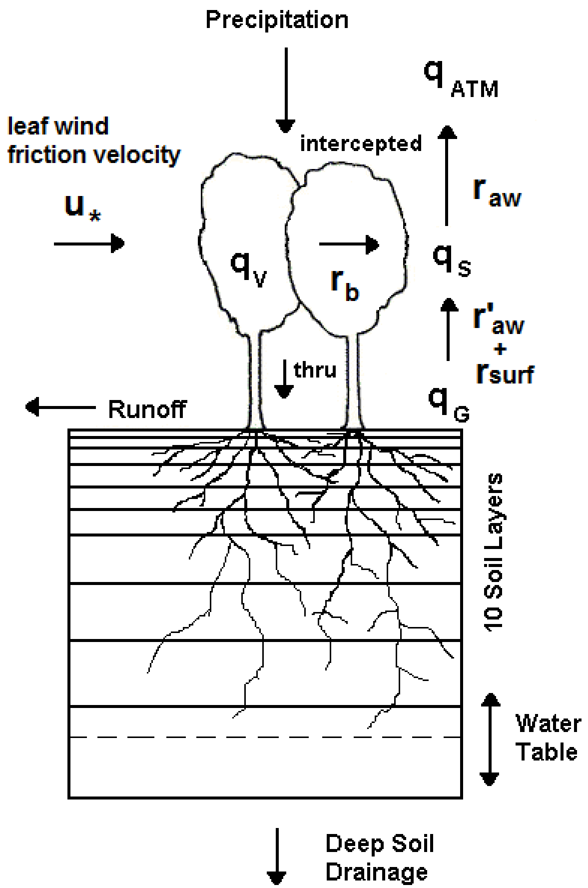

CLM4 Grass Precipitation - ET Curves
Annual Evapo-Transpiration (mm)
Annual Precipitation (mm)
CLM4 Grass ET
Zhang Tree ET
Zhang Grass ET
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
500
1000
1500
2000
2500
3000
3500
4000
4500


CLM4 Bare Soil Precipitation - ET Curves
Annual Evapo-Transpiration (mm)
Annual Precipitation (mm)
CLM4 Bare ET
Zhang Tree ET
Zhang Grass ET
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
500
1000
1500
2000
2500
3000
3500
4000
4500


CLM4 Broadleaf Tree - Grass Maximum LAI
y = 0.529x
Grass LAI
Tree LAI
0.00
1.00
2.00
3.00
4.00
5.00
6.00

5. Why Does CLM4 Have Higher Bare Soil Evaporation?

Soil Evaporation



$$r'_{aw} = \frac{1}{C_S\, u_*}$$ Zeng et al. (2005)

$$q_G = \exp\left(\frac{\Psi_1 g}{1\times10^3 R_{wv} T_G}\right)$$ Philip (1957)

CLM4:

$$E_g = -\rho_{ATM}\beta_{soi}\frac{q_S - q_G}{r'_{aw} + r_{litter}}$$

$$r_{litter} = \frac{1}{0.004\, u_*}\left(1 - e^{-L^{eff}_{litter}}\right)$$

$L^{eff}_{litter} = 0.5$ *Vegetated*

$L^{eff}_{litter} = 0.0$ *Bare Soil*

Sakaguchi and Zeng (2009)

$$\beta_{soi} = 0.25\left[1 - \cos\left(\pi\frac{\theta_1}{\theta_{fc,1}}\right)\right]^2$$

Lee and Pielke (1992)

$$r_{surf} = \frac{(1-\beta_{soi})r'_{aw} + r_{litter}}{\beta_{soi}}$$

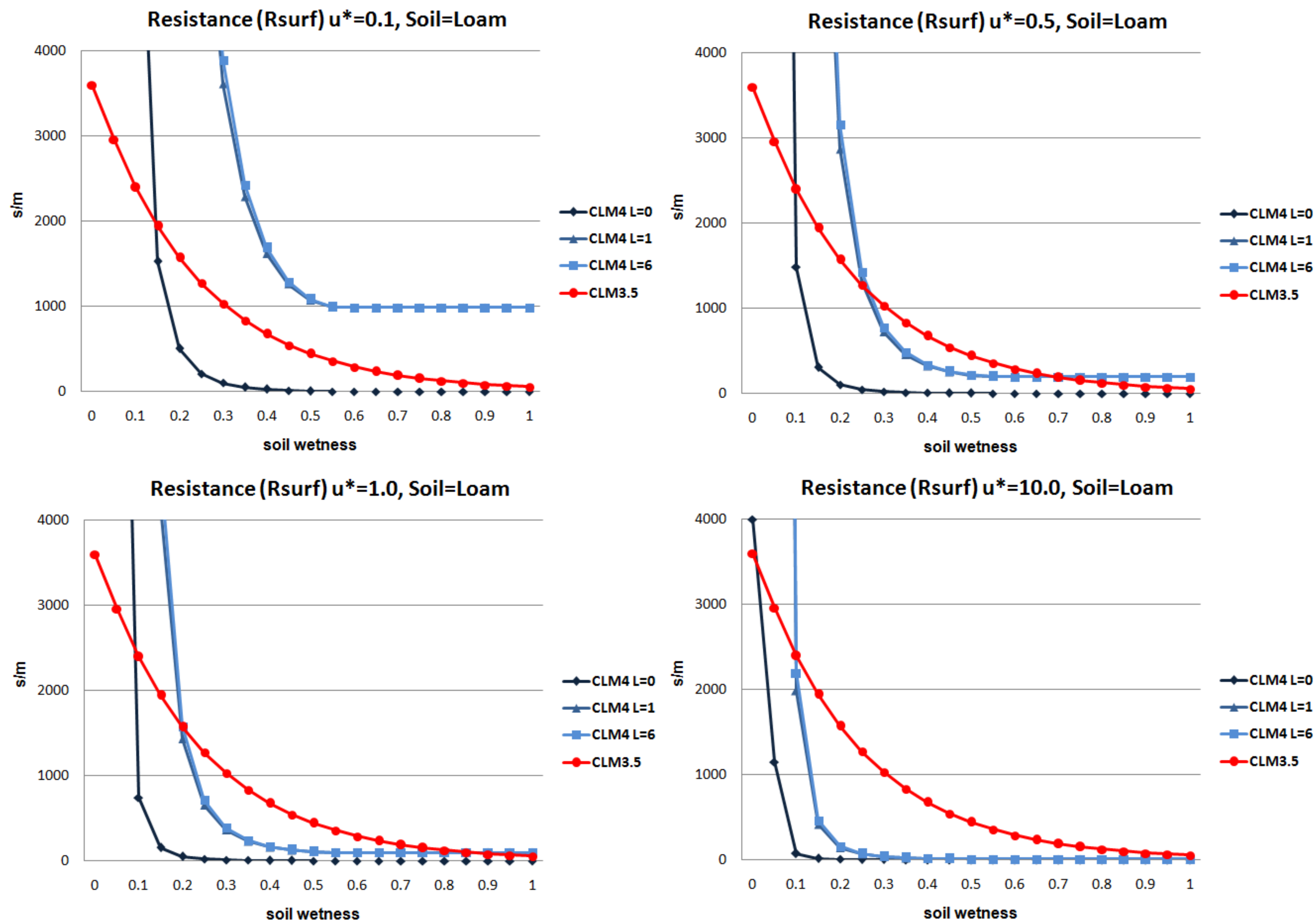
CLM3.5:

$$E_g = -\rho_{ATM}\frac{q_S - q_G}{r'_{aw} + r_{surf}}$$

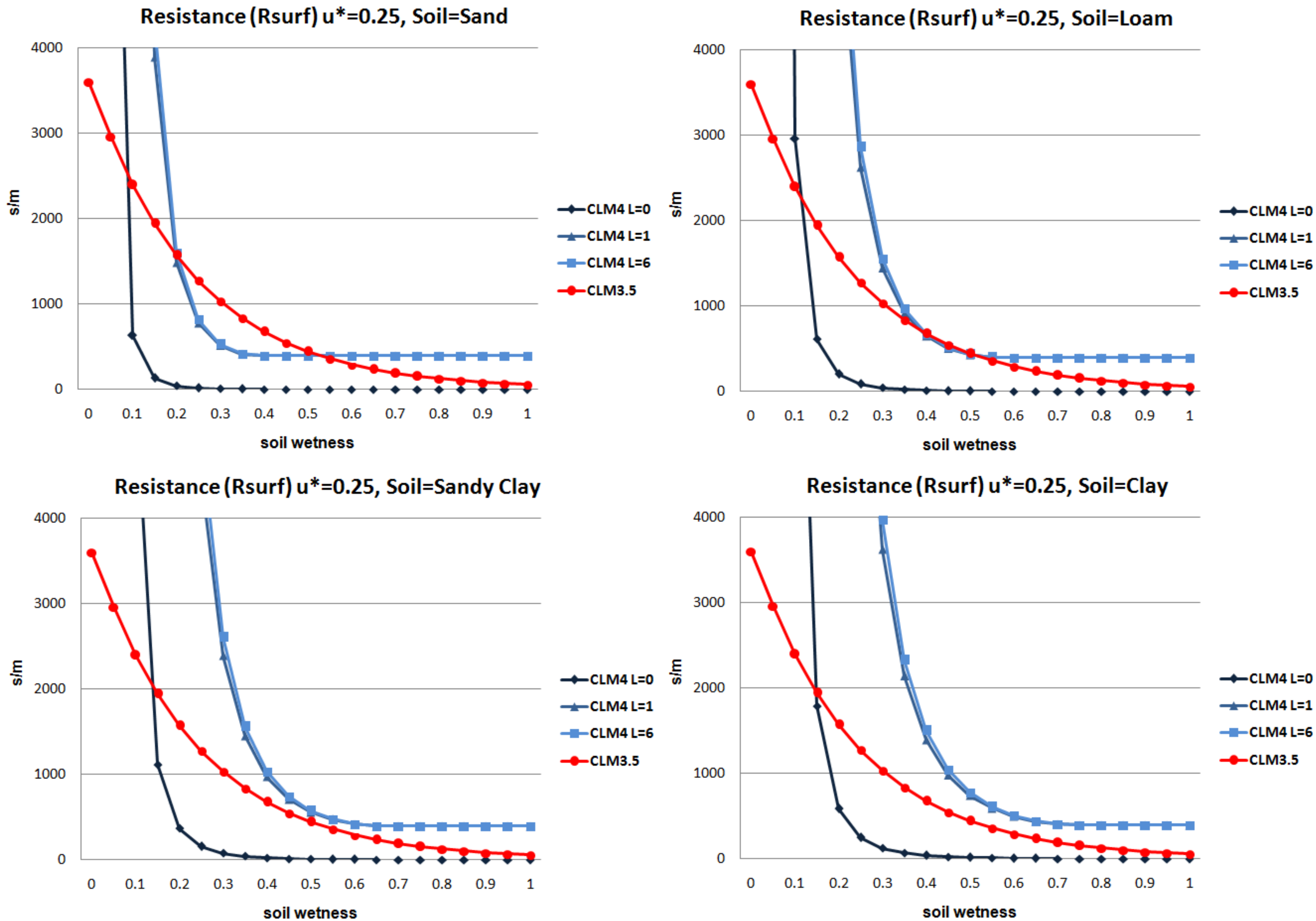
$$r_{surf} = \exp\left(8.206 - 4.255\frac{\theta_1}{\theta_{sat,1}}\right)$$

Sellers et al. (1996)

5. Why Does CLM4 Have Higher Bare Soil Evaporation?



5. Why Does CLM4 Have Higher Bare Soil Evaporation?



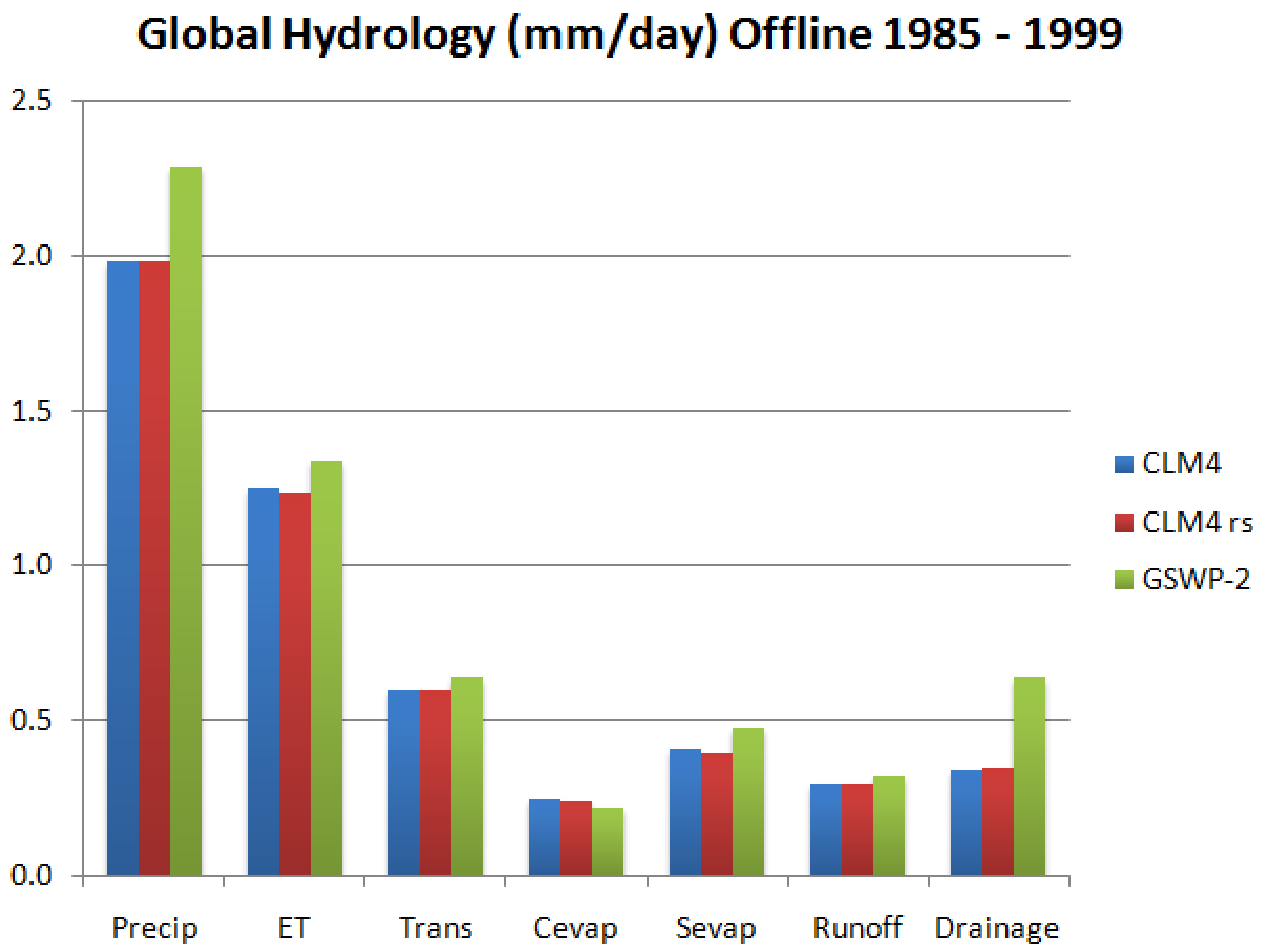
6. Investigating CLM4 Soil Evaporation Parameterization

1. What is the importance of the ground evaporation parameterization on CLM surface climate?

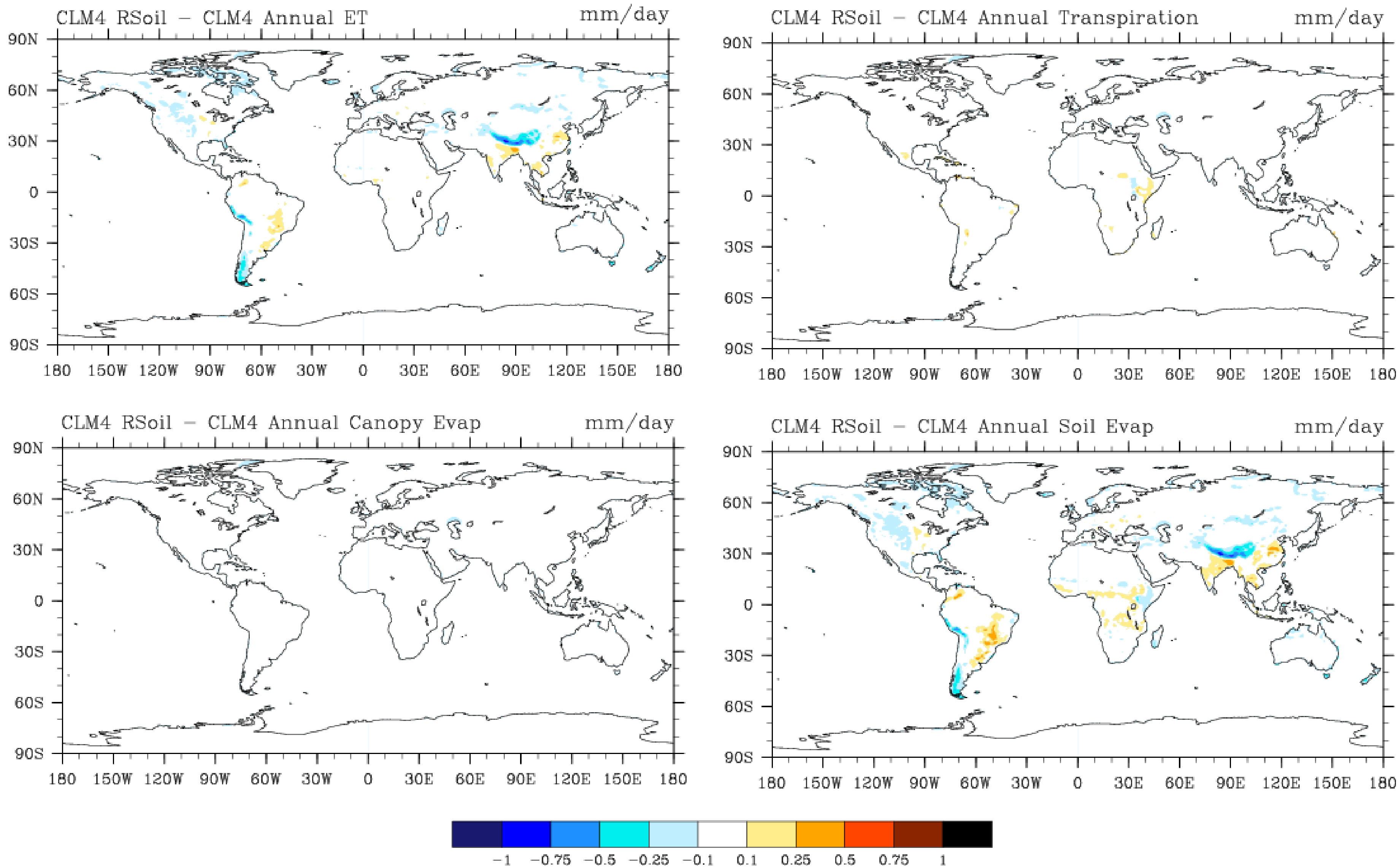
2. Run the CLM4 offline experiments with the with the RSoil of CLM 3.5 from Sellers et al. (1996) replacing the ground evaporation parameterizations of Sakaguchi and Zeng (2009).

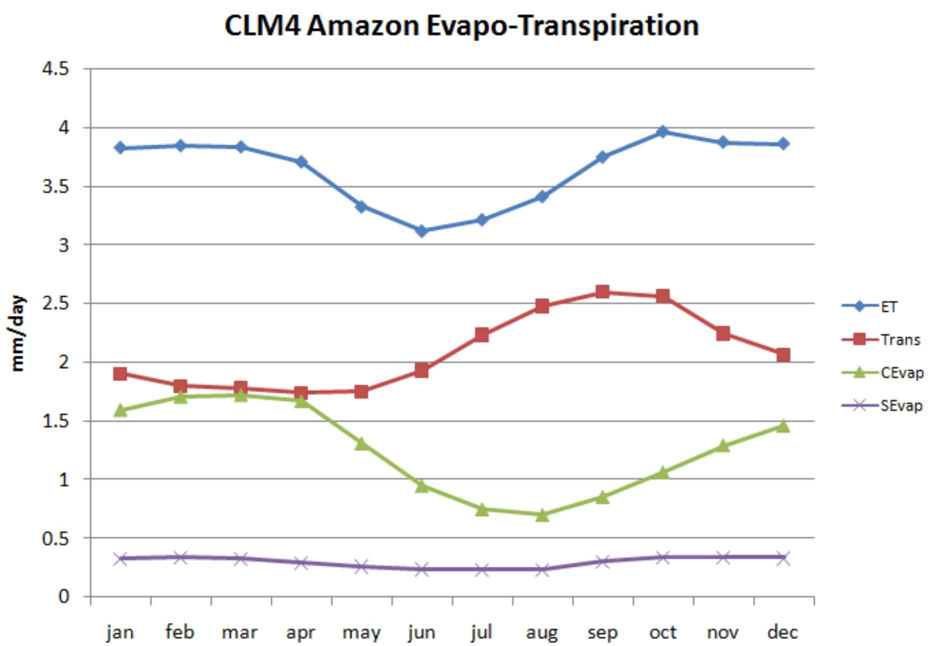
3. Examine differences in surface climate with both parameterizations under Current Day vegetation.

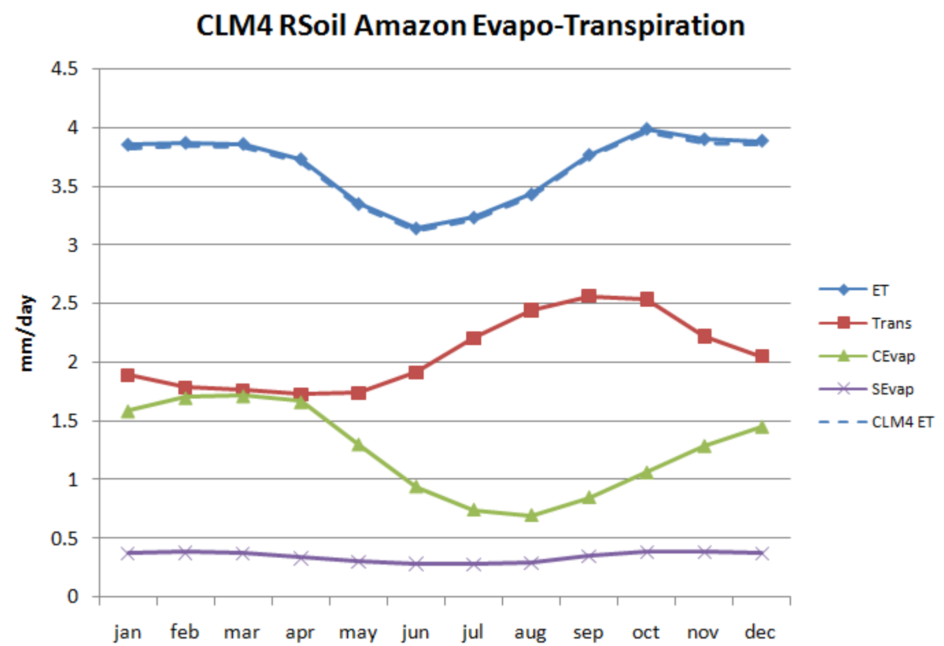
6. Offline CLM4 – CLM4 (RSoil) – Global Hydro

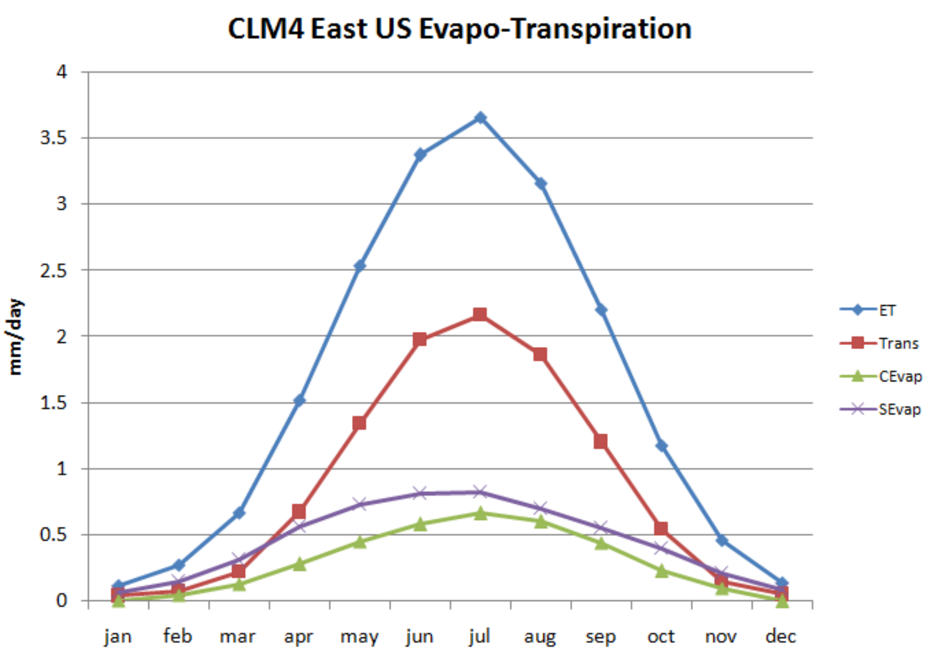


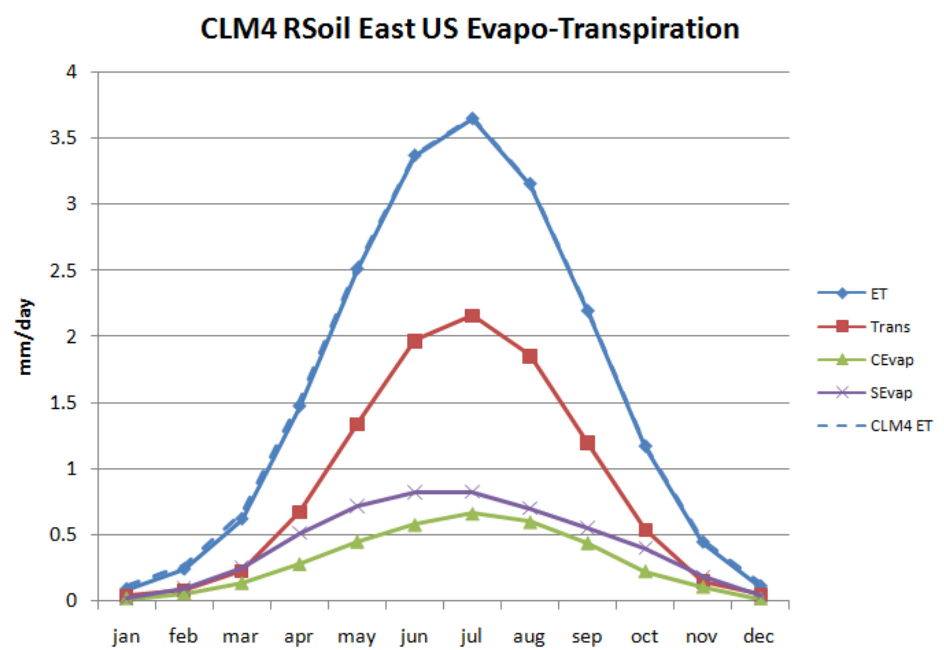
6. Offline CLM4 – CLM4 RSoil – Evapotranspiration

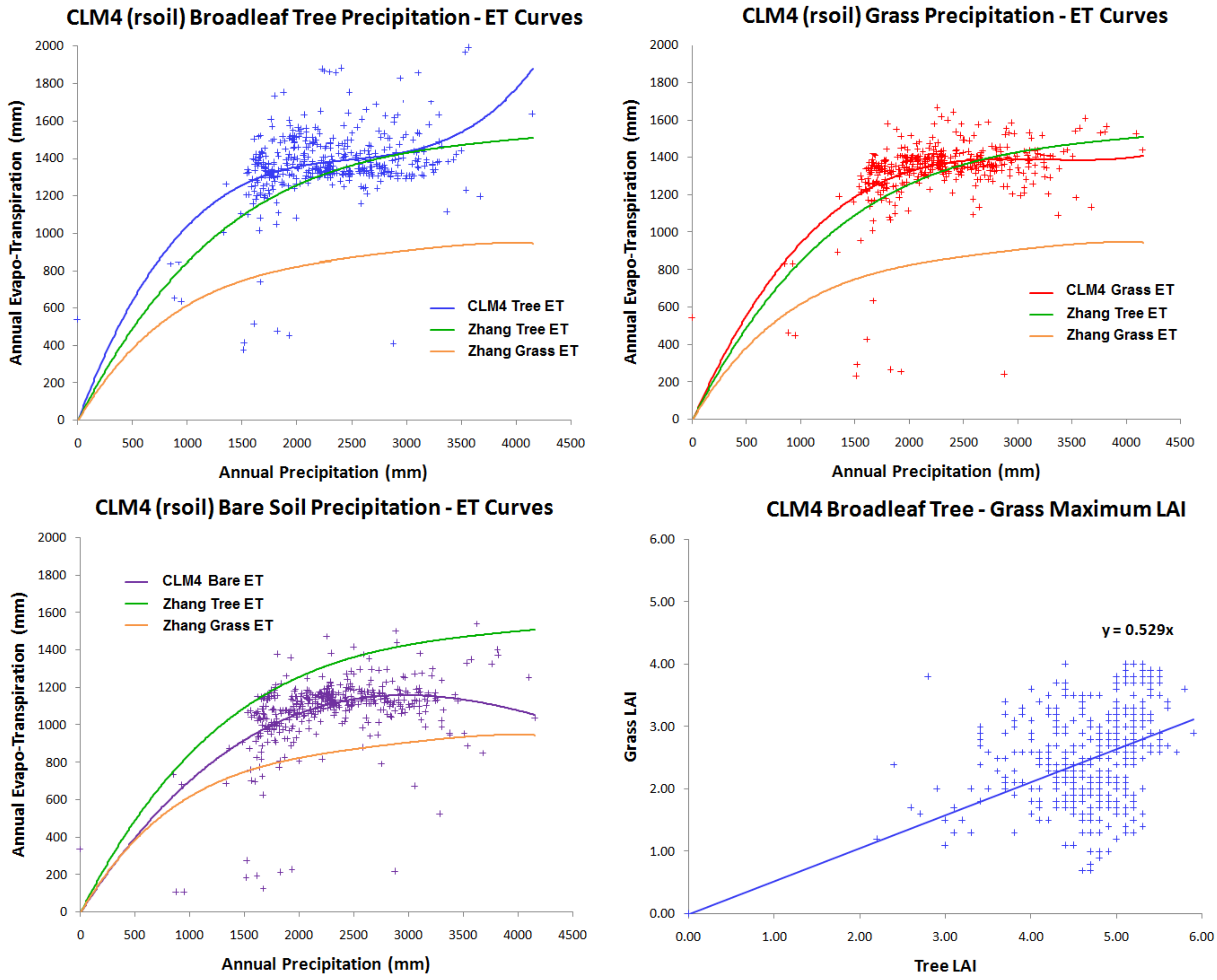



CLM4 Amazon Evapo-Transpiration
mm/day
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
ET
Trans
CEvap
SEvap


CLM4 RSoil Amazon Evapo-Transpiration
mm/day
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
ET
Trans
CEvap
SEvap
CLM4 ET


CLM4 East US Evapo-Transpiration
mm/day
4
3.5
3
2.5
2
1.5
1
0.5
0
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
ET
Trans
CEvap
SEvap


CLM4 RSoil East US Evapo-Transpiration
mm/day
4
3.5
3
2.5
2
1.5
1
0.5
0
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
ET
Trans
CEvap
SEvap
CLM4 ET



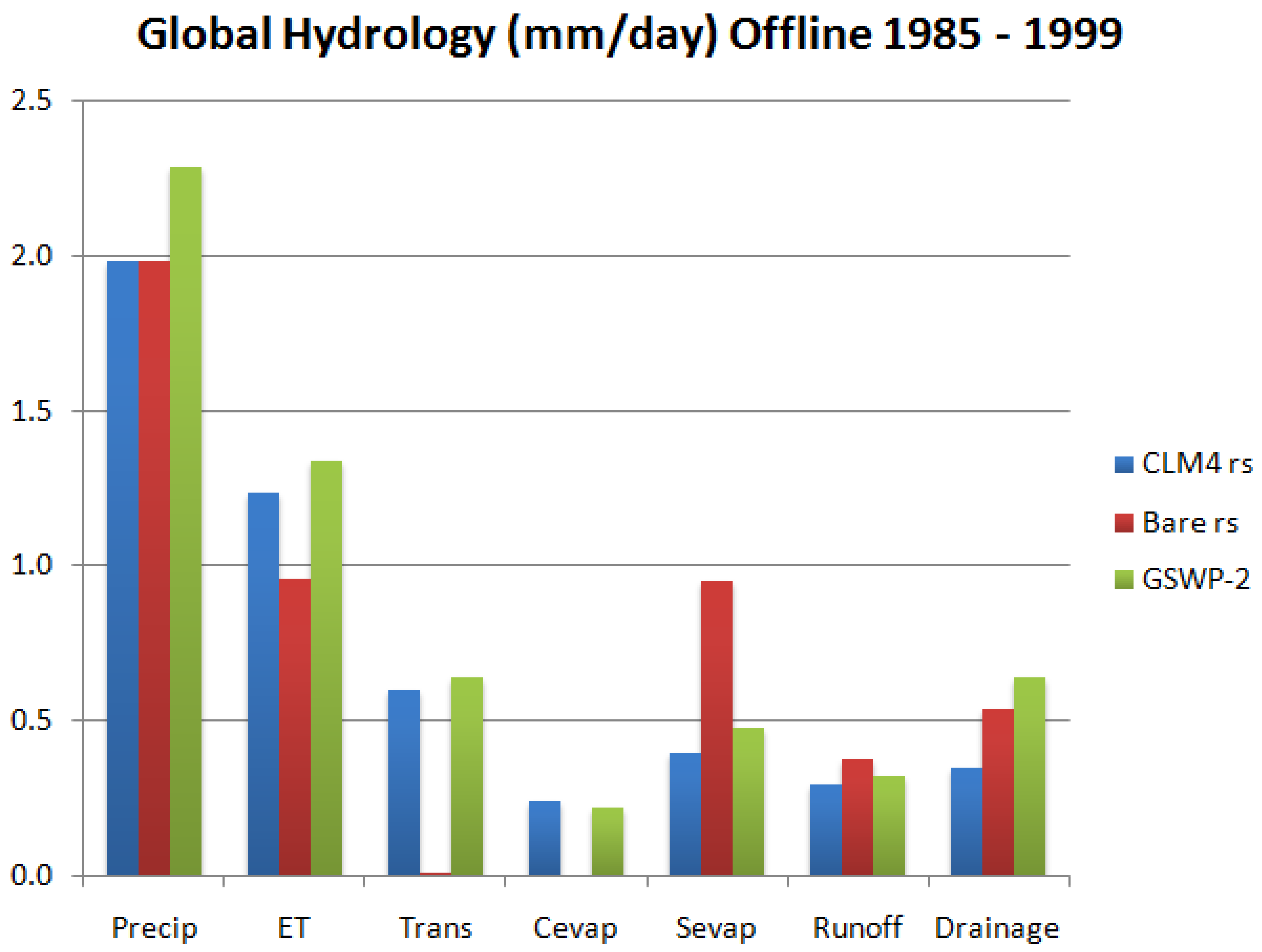
CLM4 (rsoil) Broadleaf Tree Precipitation - ET Curves
Annual Evapo-Transpiration (mm)
Annual Precipitation (mm)
CLM4 Tree ET
Zhang Tree ET
Zhang Grass ET
CLM4 (rsoil) Grass Precipitation - ET Curves
Annual Evapo-Transpiration (mm)
Annual Precipitation (mm)
CLM4 Grass ET
Zhang Tree ET
Zhang Grass ET
CLM4 (rsoil) Bare Soil Precipitation - ET Curves
Annual Evapo-Transpiration (mm)
Annual Precipitation (mm)
CLM4 Bare ET
Zhang Tree ET
Zhang Grass ET
CLM4 Broadleaf Tree - Grass Maximum LAI
y = 0.529x
Grass LAI
Tree LAI

7. Investigate CLM4 RSoil complete vegetation removal

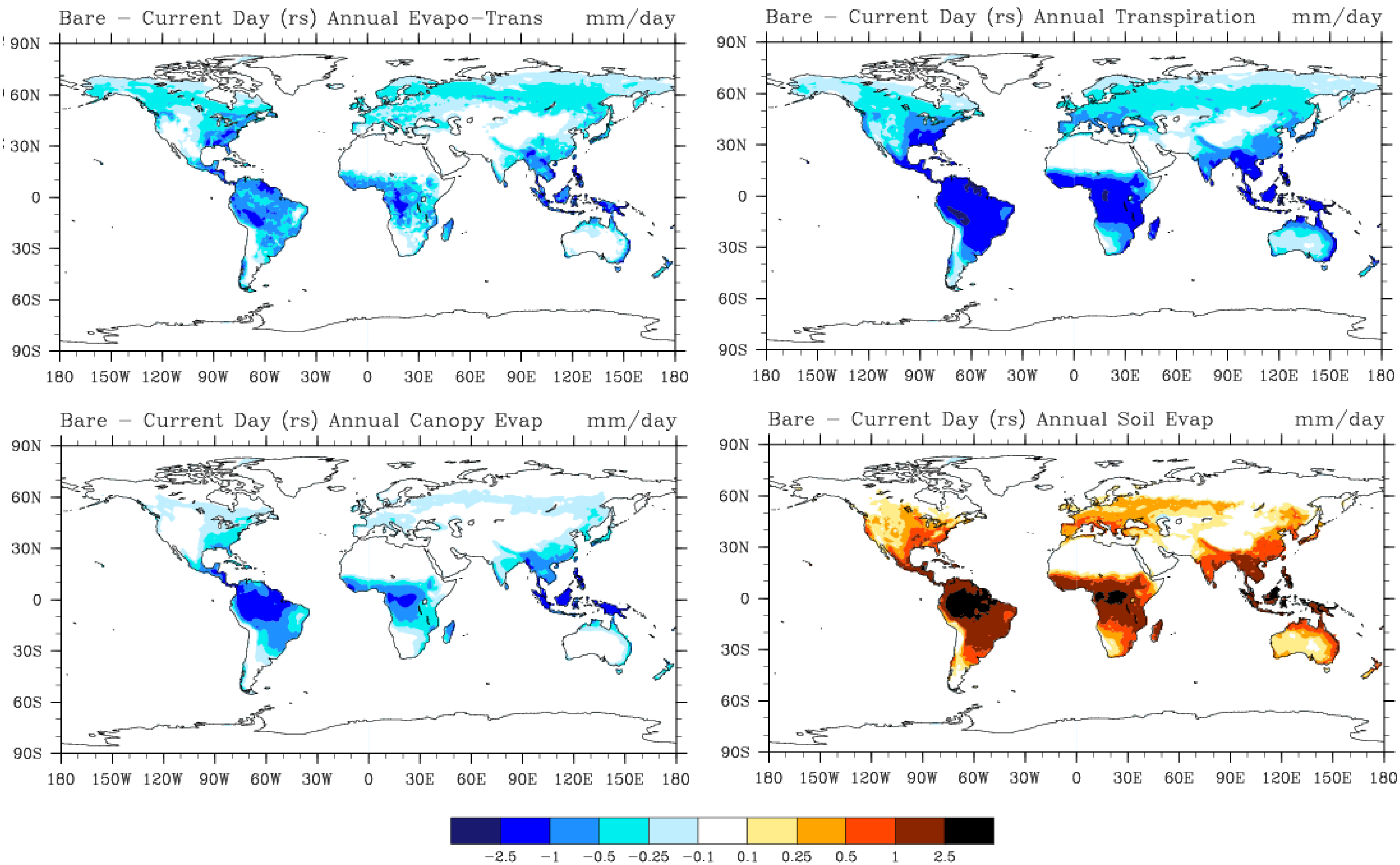
1. Run the CLM4 offline experiments with the with the RSoil of CLM 3.5 from Sellers et al. (1996) replacing the ground evaporation parameterizations of Sakaguchi and Zeng (2009).

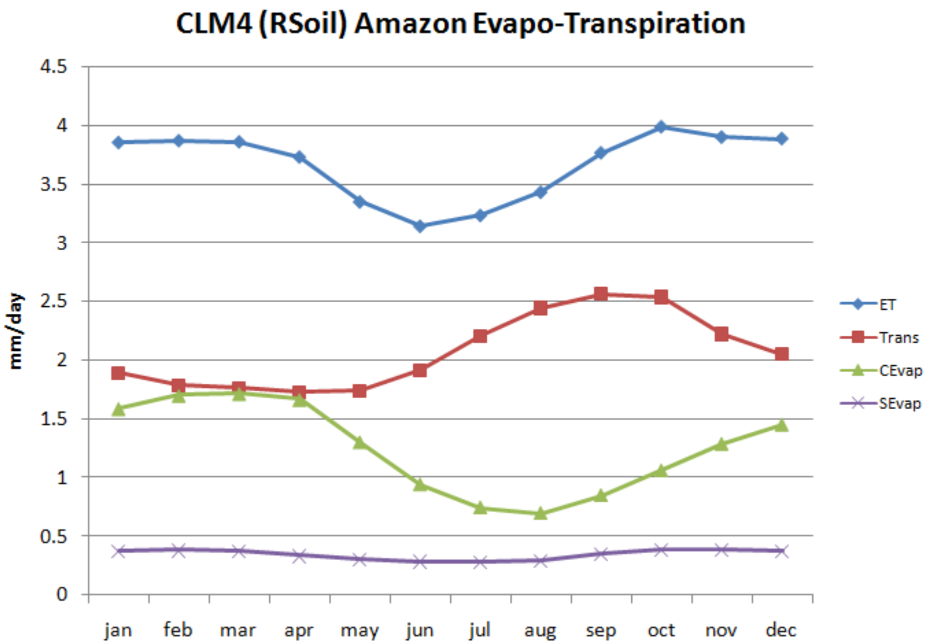
2. Examine impact of removal of all vegetation with both experiments using the RSoil parameterization from CLM 3.5

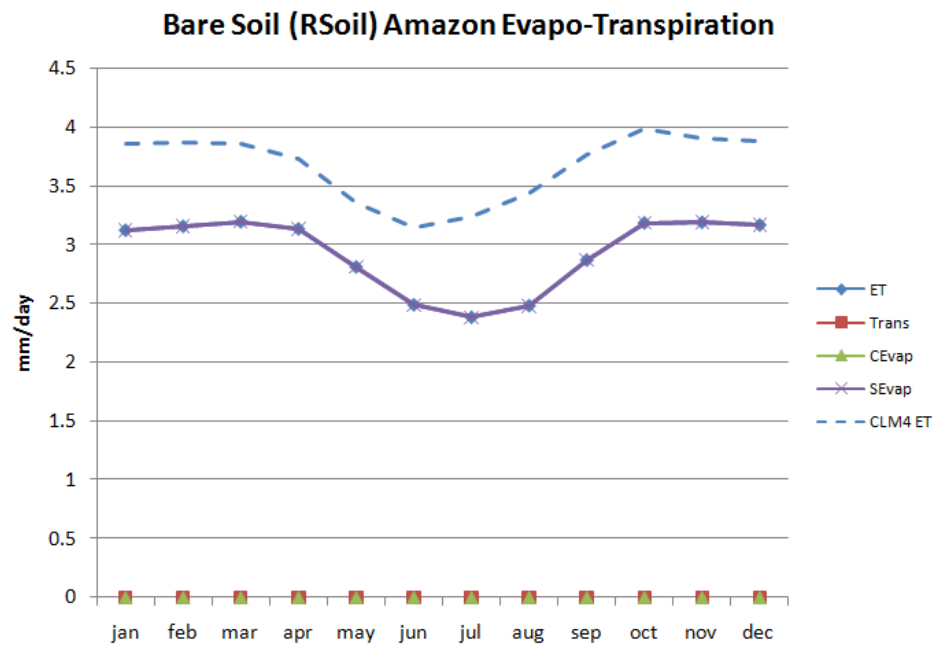
7. CLM4 RSoil – Vegetation Removal – Global Hydro

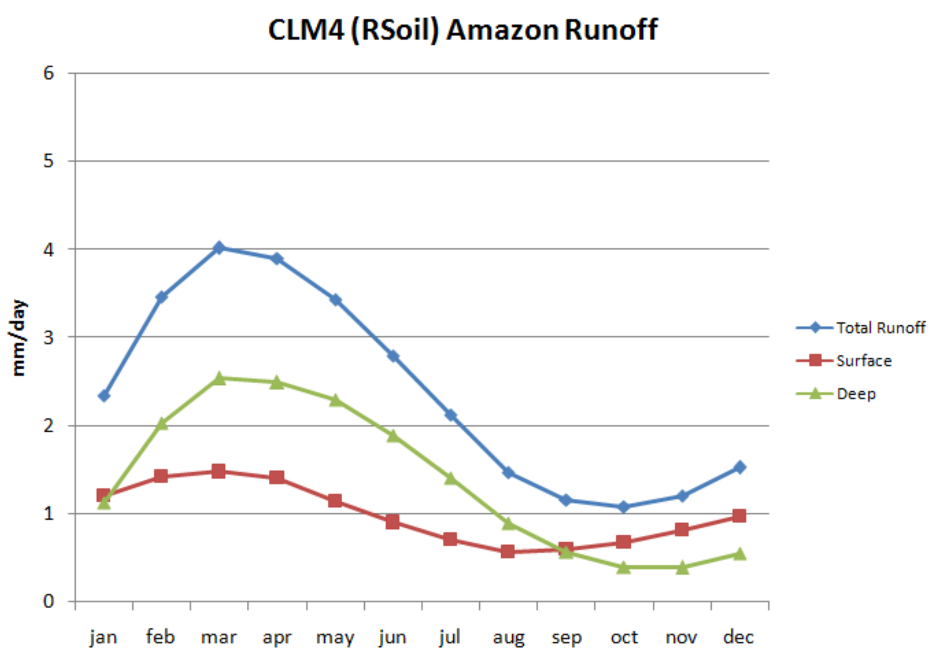


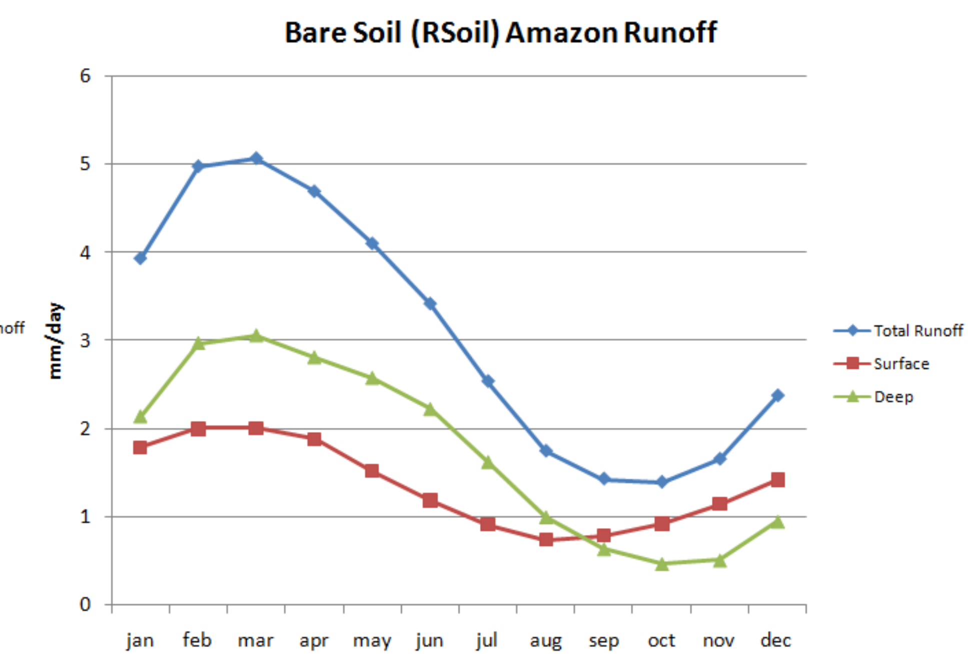
7. Offline CLM4 RSoil – Vegetation Removal – ET

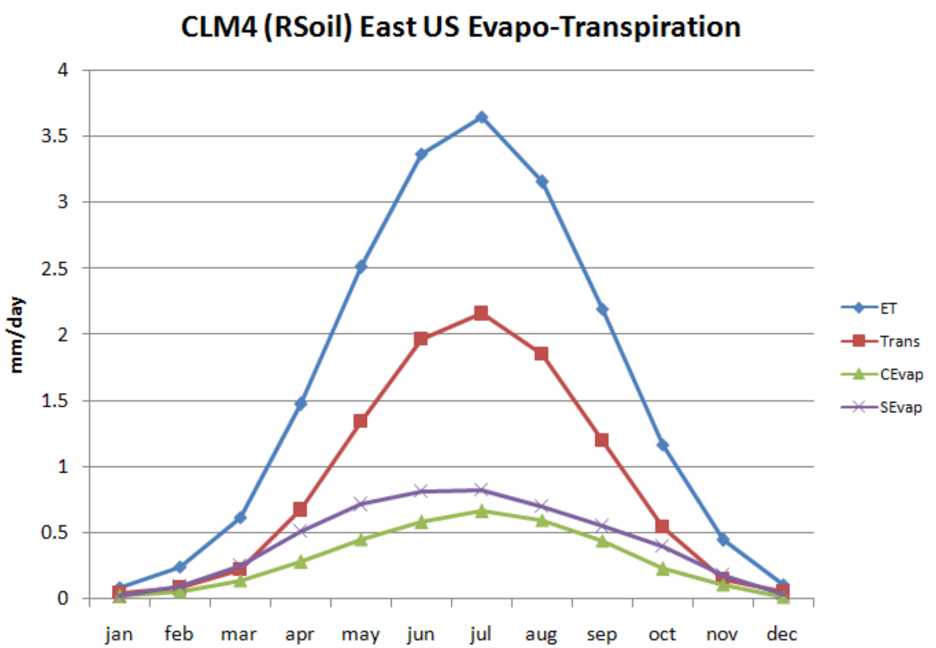


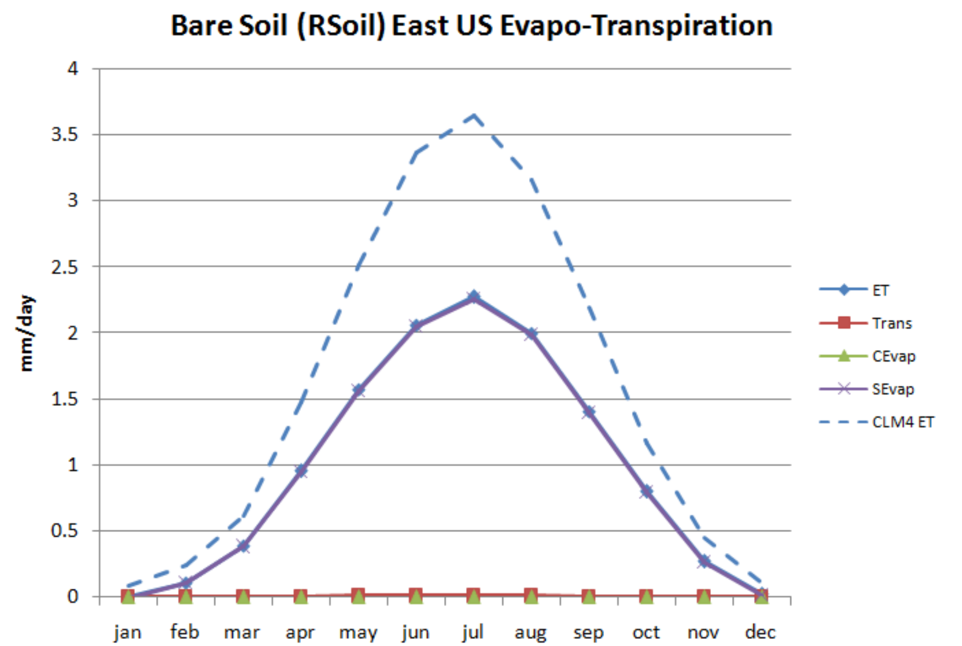

CLM4 (RSoil) Amazon Evapo-Transpiration
mm/day
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
jan feb mar apr may jun jul aug sep oct nov dec
ET
Trans
CEvap
SEvap

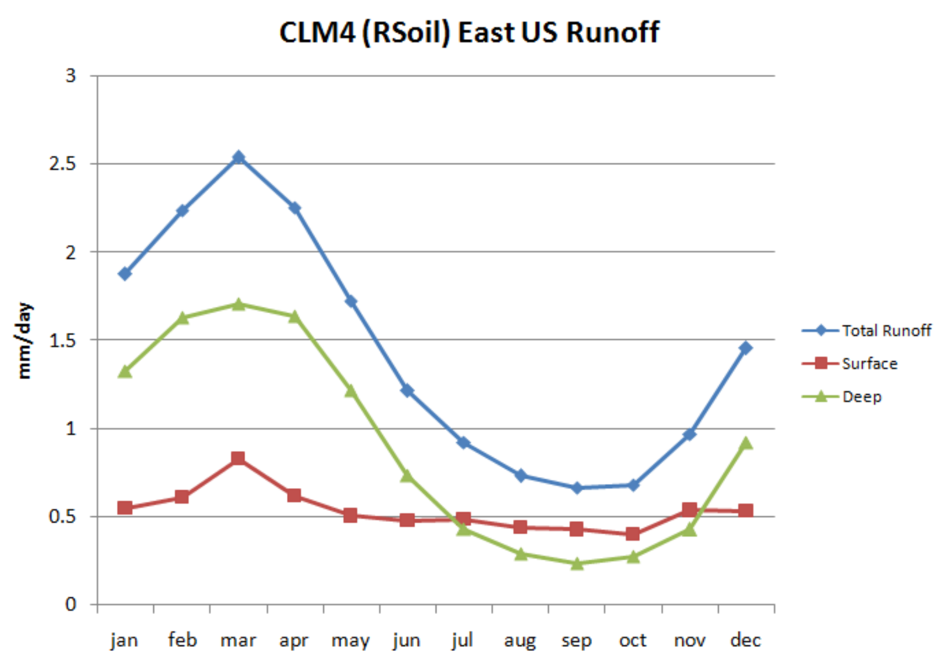

Bare Soil (RSoil) Amazon Evapo-Transpiration
mm/day
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
jan feb mar apr may jun jul aug sep oct nov dec
ET
Trans
CEvap
SEvap
CLM4 ET

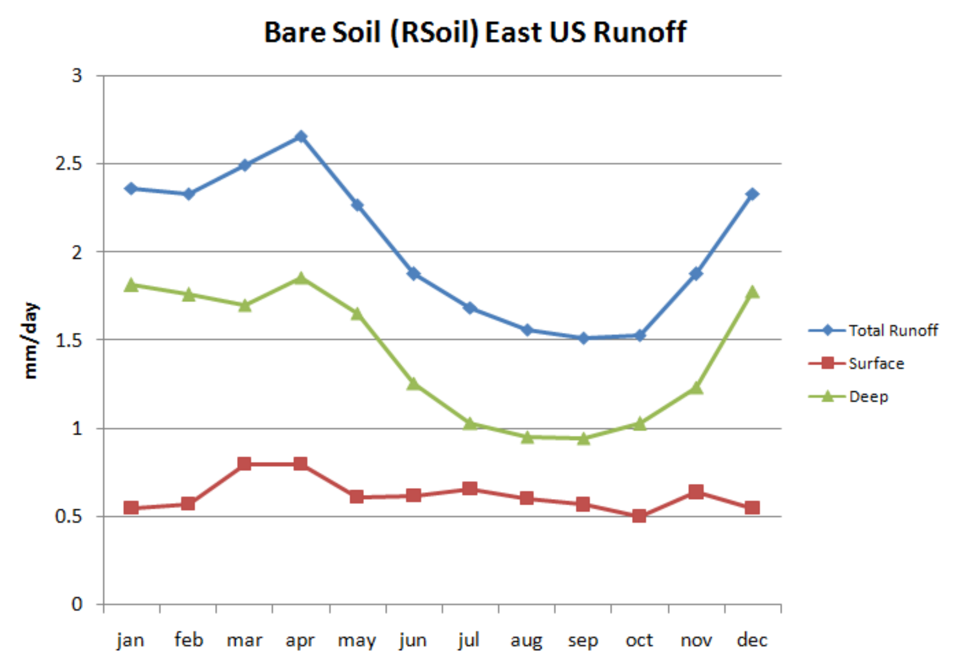

CLM4 (RSoil) Amazon Runoff
mm/day
6
5
4
3
2
1
0
jan feb mar apr may jun jul aug sep oct nov dec
Total Runoff
Surface
Deep


Bare Soil (RSoil) Amazon Runoff
mm/day
6
5
4
3
2
1
0
jan feb mar apr may jun jul aug sep oct nov dec
Total Runoff
Surface
Deep


CLM4 (RSoil) East US Evapo-Transpiration
mm/day
4
3.5
3
2.5
2
1.5
1
0.5
0
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
ET
Trans
CEvap
SEvap


Bare Soil (RSoil) East US Evapo-Transpiration
mm/day
4
3.5
3
2.5
2
1.5
1
0.5
0
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
ET
Trans
CEvap
SEvap
CLM4 ET


CLM4 (RSoil) East US Runoff
mm/day
3
2.5
2
1.5
1
0.5
0
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
Total Runoff
Surface
Deep


Bare Soil (RSoil) East US Runoff
mm/day
3
2.5
2
1.5
1
0.5
0
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
Total Runoff
Surface
Deep

8. Conclusions

1. CLM 4 simulates higher Bare Soil evaporation than Forest evapo-transpiration

2. Grass PFTs behave hydrologically similar to Tree PFTs even with half of the Leaf Area Index

3. The high Bare Soil evaporation can be partially resolved through surface resistance

4. Grass PFT hydrology and Bare Soil evaporation need further investigation

5. Need to look at Surface Hydrology through soil moisture profiles, runoff and drainage

6. Plant physiology through rooting depth and photosynthesis

7. This means that the biogeophysical impacts of land cover change in CLM 4 are uncertain in terms of hydrological response