A "Make a Difference" Experiment to Assess the Value of ARM Data in Carbon Cycle Models

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Introduction

Atmospheric Radiation Measurement (ARM) Program data include many of the measurements needed by carbon modelers to predict carbon dynamics in terrestrial ecosystems. How much difference, if any, would using ARM measurements rather than any of several synthetic climate generators typically used by carbon modelers make in estimates of respiration and productivity predicted by carbon models? We designed a "make a difference" simulation experiment to compare differences in carbon flux predictions based on synthetic input data with predictions based on historical measurements taken from the ARM archive. The experimental design used alternative data sources that an intelligent carbon modeler might employ in the absence of ARM measurements. Because "true" carbon fluxes are unknown, our experiment examined only the magnitude of differences created when the same carbon model, Biome-BGC, was driven with synthetic climate rather than actual ARM measurements. The position of ARM-derived measurements within a population distribution of synthetic records provided a non-parametric test of significance.

Two widely used weather generators, MtClim and Generation for weather Elements for Multiple applications (GEM) U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS), were used to produce artificial weather input streams in the absence of ARM measurements. MtClim 4.3 was originally developed by Running et al. (1987), and version 4.3 has been substantially modified by Dr. Peter Thornton, currently at the National Center for Atmospheric Research (NCAR). MtClim "adjusts" temperature, vapor pressure, and solar radiation values supplied at a "base" location to values appropriate for a "site" at a different location, based on latitude, elevation, and mean yearly precipitation. MtClim is commonly used as a first step in running the Biome-BGC model, and its output is designed to match the input format needed by Biome-BGC.

GEM was developed from the basic internal structure of USCLIMATE (Hanson et al. 1994) and WGEN models (Richardson 1981, Richardson and Wright 1984), but includes significant improvements. We used version 6 of GEM designed for use with the Shaw water quality model. The GEM6-Shaw generator used in this study, obtained from Dr. William Frymire at USDA-ARS in Boise, Idaho, is endorsed as the weather generation tool recommended by the USDA NRCS and ARS.

Methods

We reviewed the data requirements for Biome-BGC, a popular carbon model, and identified meteorology and radiation measurements from the Southern Great Plains (SGP) ARM Central Facility (CF) that were needed to run the model. We simulated a wheat crop growing at the ARM CF for a 5-year period from 1996 to 2000. The parameters for c^3 grasses used in White et al. (2000) were employed, except that the frequency of wildfire was set to zero, and the initial soil nitrogen was set to 0.01 and 0.05 kgN/m^2 for litter and mineral soil nitrogen, respectively. No attempt was made to simulate the wheat harvest with the Biome-BGC model. The "make a difference" comparison was performed for both the input to Biome-BGC model and the output from the model.

Before ARM measurements could be used as input, we needed to identify outliers, fill gaps in the data record using imputation methods, and summarize the measurements at an appropriate temporal scale. Daily means were prepared from ARM Surface Meteorological Observing Station (SMOS) and Solar Infrared Station (SIRS) data. Maximum and minimum temperatures were selected as maxima and minima from hourly summaries to limit extreme values. Mean daylight temperature and mean daylight vapor pressure deficit (VPD) were calculated using sunrise and sunset calculations based on the location of the CF.

Different strategies were used to produce populations of synthetic climate data from the two climate generators (Figure 1). GEM is a stochastic generator. Using coefficients derived from the 30-year Climate Normals (1960 to 1990) at the Oklahoma City airport, along with a unique set of random number seeds, we produced 30 stochastic replicates of climate for the CF for the 5-year simulation period.

Since MtClim is a deterministic model, we used a spatial technique to obtain a population of 5-year climate estimates. Measurements from 1996 to 2000 from the 30 Oklahoma MESONET stations closest to the CF were used to drive MtClim. MtClim was used to "adjust" the climates from each of the MESONET station locations to the CF location.

Finally, we used a combination of GEM followed by MtClim. In the GEM-only pathway, it was assumed that the climate at the Oklahoma City airport was not substantially different from that at the CF. In the combined pathway, MtClim was used to "adjust" each of the 30 GEM-supplied climates to the exact location of the CF.

Biome-BGC was "spun-up" to equilibrium initial conditions using the 30-year Climate Normals from the Oklahoma City airport. The model took 1080 years to reach an equilibrium (residual trend = 0.000014), and these steady-state initial conditions were used to start each of the simulation pathways in the "make a difference" experiment. Stochastic or spatial variability were used to produce a population of artificial data for the SGP from each of the synthetic weather generators.

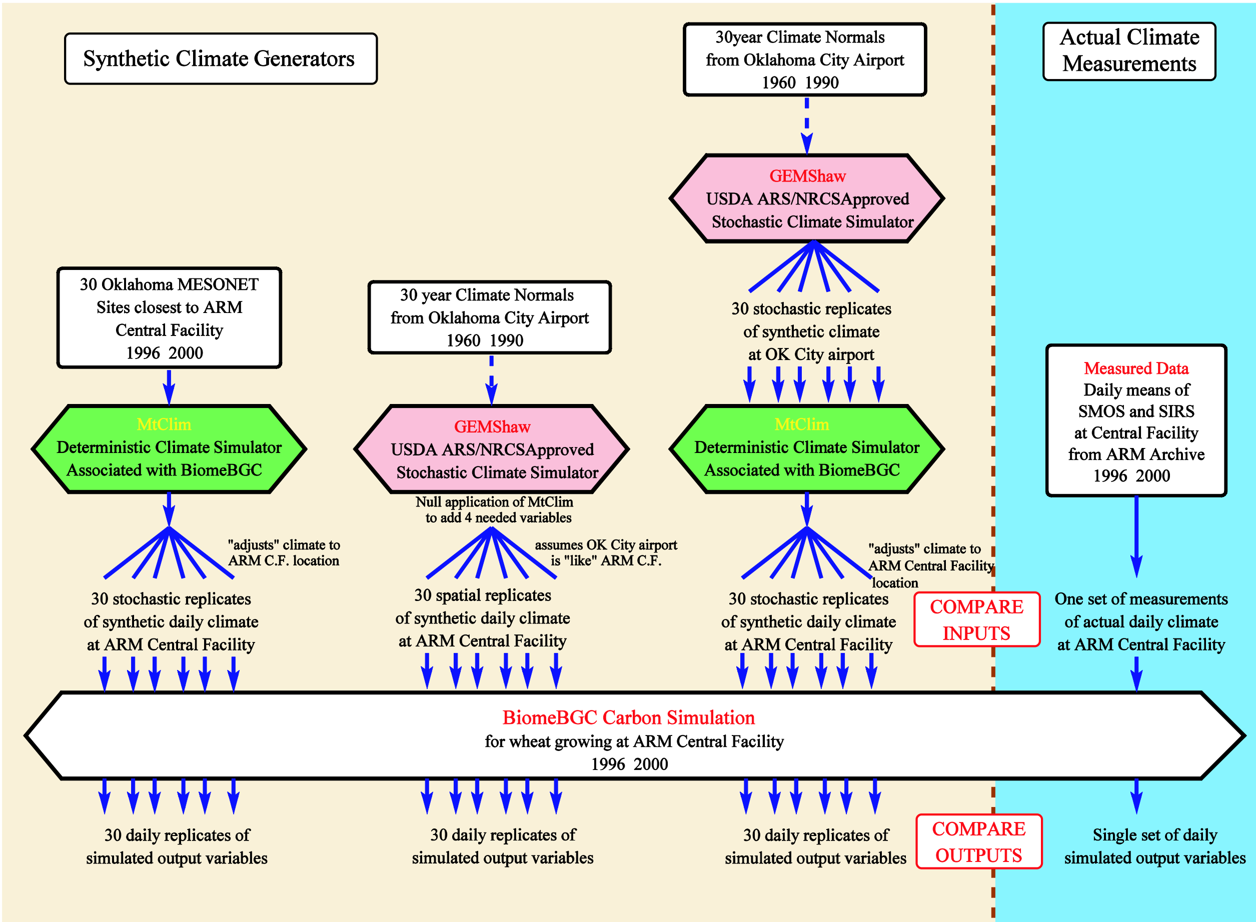

Figure 1. In a "make a difference" experiment, inputs and outputs from a carbon flux simulation, Biome-BGC, were compared when the model was driven using synthetic climate versus actual ARM measurements. The three pathways shown in the yellow portion represent synthetic climate produced by MtClim, GEM, and a combination of GEM and MtClim. The pathway shown in the blue portion shows actual ARM measurements taken at the CF. The Biome-BGC model was used to simulate wheat growing at the CF over a 5-year period from 1996 to 2000.

Filling Data Gaps

Biome-BGC, like most simulation models, cannot tolerate missing data or input gaps. For all input variables except precipitation, we fit linear regressions with all spatial neighbors. To interpolate values for missing dates, we drove the regression with data from the neighboring site with the highest r2 that had data for that date. EF-9 had the strongest predictive relationship for temperatures at the CF (all r2 > 0.98). The EF-15 site had the strongest relationship for shortwave radiation and VPD with the CF.

Site-to-site correlations for precipitation were low (r2 < 0.3). We used a weighted average of precipitation at surrounding sites as the best predictor for missing precipitation values. EF-9 and EF-15 were used for the CF, while the 30 closest MESONET sites were used for the MtClim pathway.

Results

Comparison of Inputs

Figures 2 and 3 compare the 5th to 95th percentile ranges of cumulative synthetic precipitation for each of the three climate generator pathways with precipitation measurements from ARM on a per-year basis and over the duration of the simulation, respectively. Precipitation was highly variable across all 5-simulation years. The ARM measurement of precipitation was within the range of the synthetic estimates, but was often close to the extremes, and changed from being overestimated in 1996 to being underestimated during the four years that followed. The timing of precipitation events was found to be critical to simulated photosynthesis, particularly in late summer.

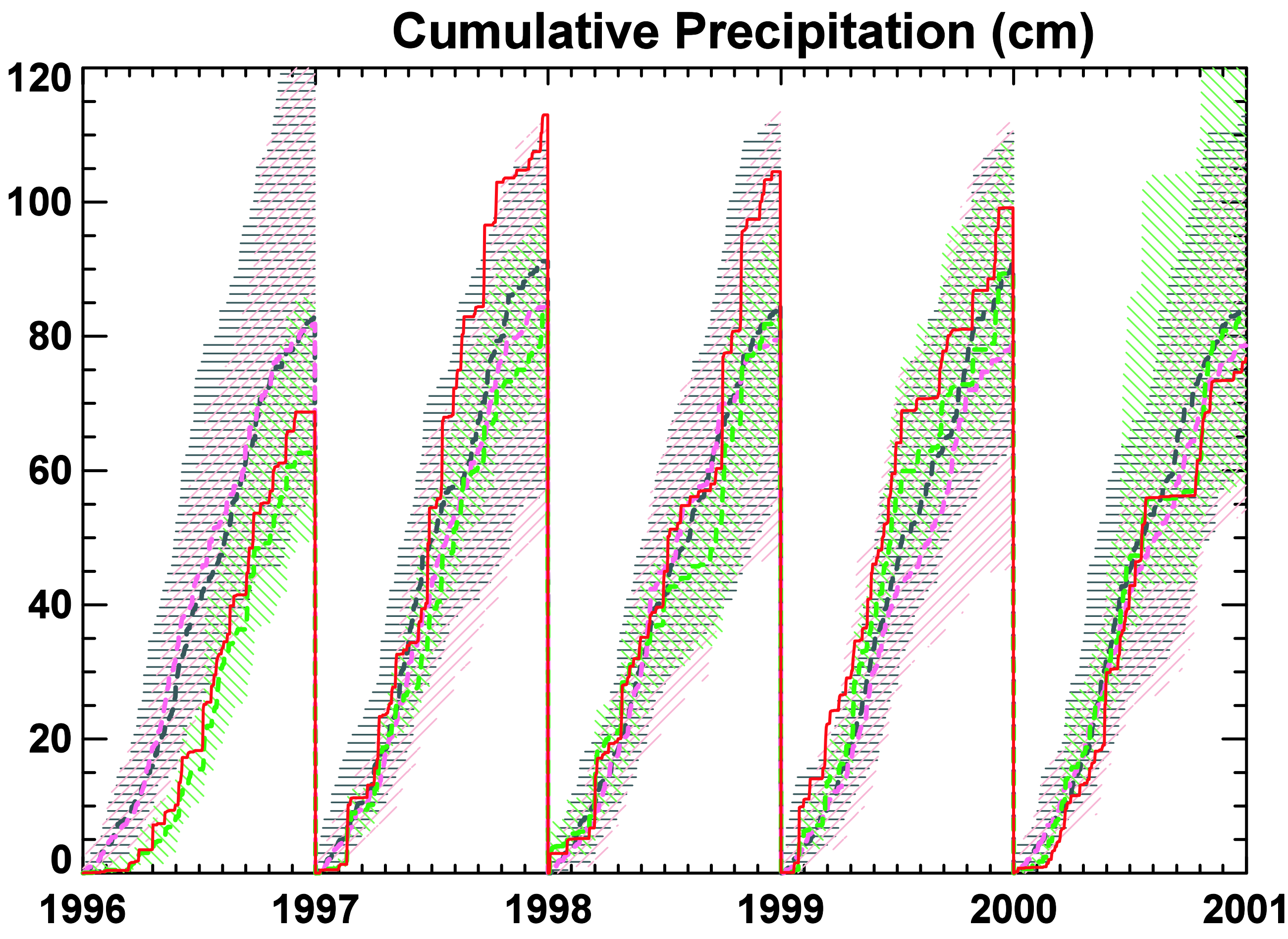

Figure 2. Estimates of cumulative yearly precipitation from the three synthetic climate pathways compared to ARM measurements. The 5th to 95th percentiles of 30 replicates are shown for each of the synthetic generators. Precipitation estimates from the MtClim population and median are shown in green, from the GEM population and median are shown in pink, and from the GEM-MtClim combined pathway population and median are shown in gray. ARM measurements of actual precipitation are shown as a solid red line.

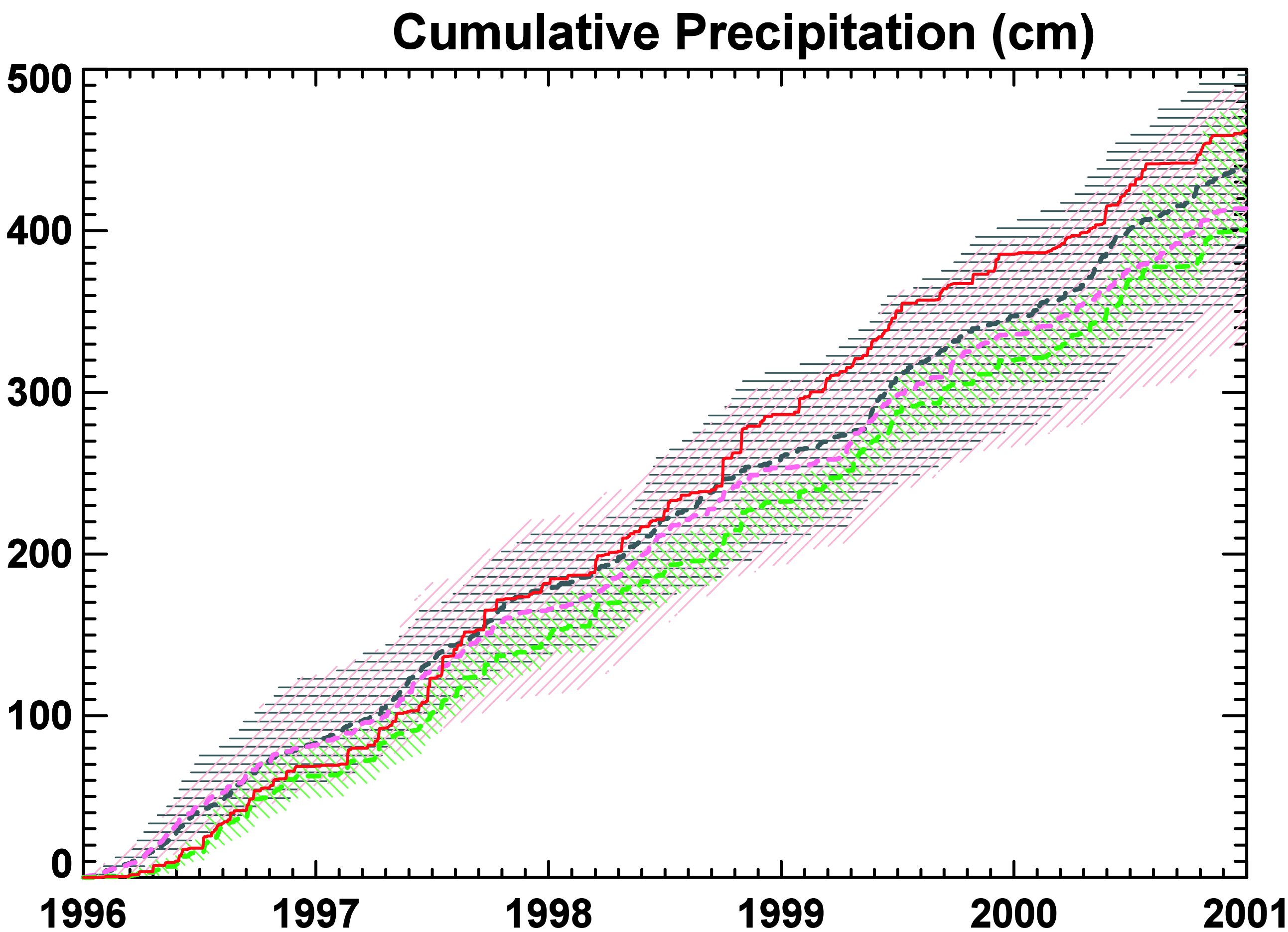

Figure 3. Estimates of cumulative precipitation from the three synthetic climate pathways compared to ARM measurements across the 5-year duration of the simulation. Colors for each synthetic pathway are the same as explained in Figure 2. The ARM measurement is within cumulative precipitation estimates, but is highly variable across years.

Figure 4 compares median yearly values for VPD, while Figure 5 shows cumulative values for the simulation period. VPD was generally overestimated by the climate generators, but was underestimated for a critical period in the late summer. Maximum, minimum, and mean daylight temperatures were slightly overestimated, contributing to this overestimate of VPD. The ARM measurement falls at the lower limit of the range in the cumulative plot (Figure 5).

Daylight average shortwave radiation (Figures 6 and 7) was consistently and significantly underestimated by all of the synthetic climate generators. Both the yearly median and the cumulative measurements fell outside the 5th-to-95th percentile ranges for most simulated days. Underestimates in shortwave radiation may have contributed to underestimates of photosynthetic production as compared to ARM measurements.

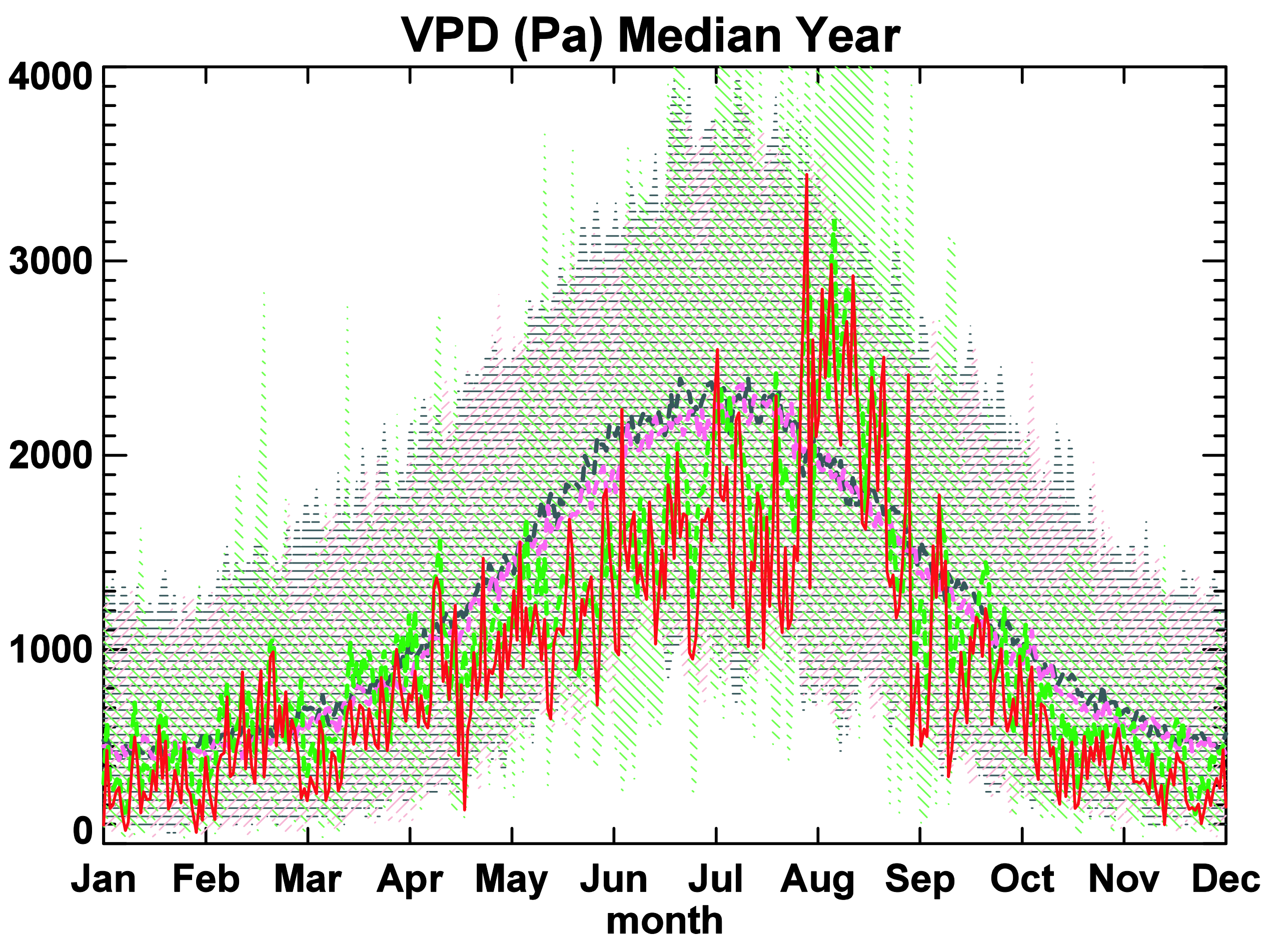

Figure 4. Median yearly VPD, as estimated from the three synthetic climate pathways compared to ARM measurements for an average year. Colors for each synthetic pathway are the same as explained in Figure 2. Each day was considered to have 150 replicates (30 replicates x 5 years) in this plot. VPD is generally overestimated.

Comparison of Outputs

Hot, dry conditions in late summer caused increased maintenance respiration (Figure 8) and inhibited simulated estimates of Net Primary Productivity (NPP) (Figure 9). The increase in maintenance respiration was underestimated by all climate generators except MtClim. NPP simulated by ARM measurements was overestimated during these brief but important hot, dry periods in late summer.

Climate forcings from all of the synthetic generator pathways led to underestimates of leaf-level carbon assimilation (Figure 10). Cumulative carbon in the leaf litter pool was also underestimated (Figure 11). Soil carbon, however, was overestimated, possibly because the transfer of carbon from litter to soil during decomposition was overestimated due to temperature overestimates.

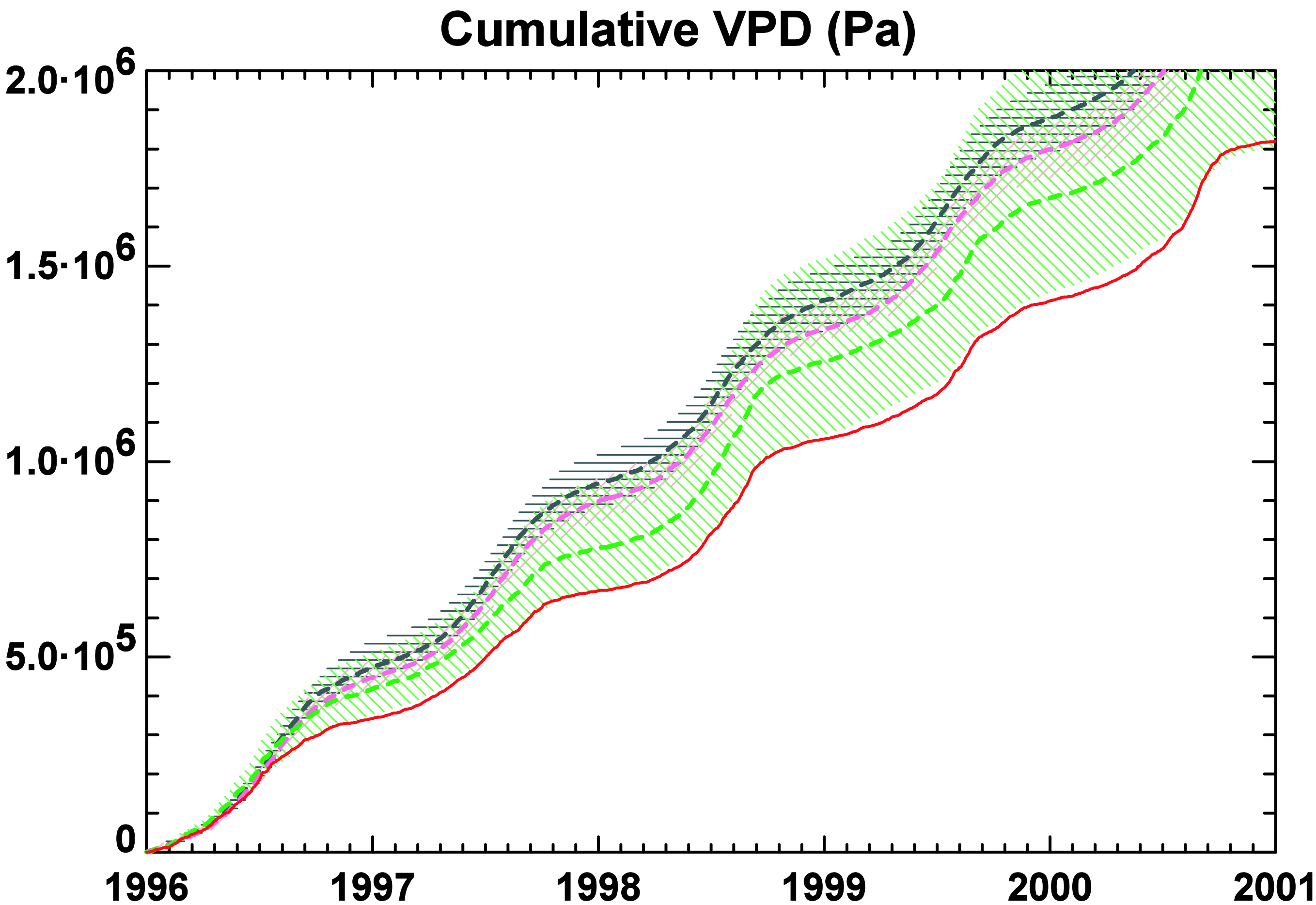

Figure 5. Cumulative VPD across the 5-year duration of the simulation. Colors for each synthetic pathway are the same as explained in Figure 2. The ARM measurement is at the lower limit of the range.

Net Ecosystem Productivity (NEP) estimates were highly variable, especially in the late summer (Figure 12). The variable nature of NEP from year-to-year is shown in Figure 13. In some years, the median NEP is always positive, but in other years it dips far below the zero line. Although such variations are shown in the populations from the synthetic climate estimators, the trajectory of NEP in any single year is strongly dependent on the exact sequence of hot, dry days occurring in late summer.

Differences in the specific late-summer climate trajectory accumulate and are often significant throughout the 5-year simulation (Figure 14). Model estimates of NEP generated from MtClim matched those from ARM measurements most closely, but still significantly underestimated NEP most of the time (Figure 14).

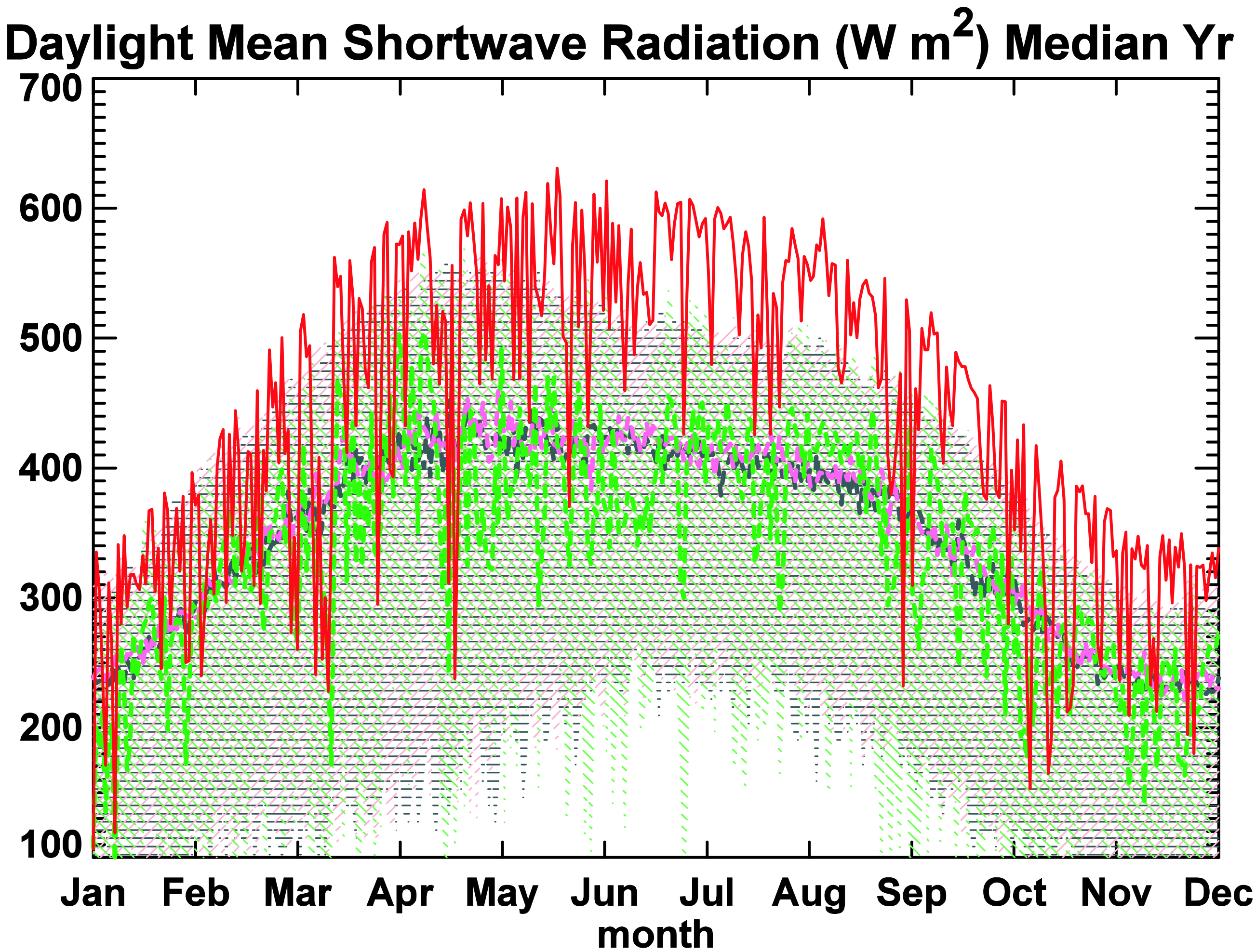

Figure 6. Median yearly daylight average shortwave radiation, as estimated from the three synthetic climate pathways compared to ARM measurements for an average year. Colors for each synthetic pathway are the same as explained in Figure 2. Shortwave radiation is consistently underestimated by all synthetic climate generators.

Conclusions

In some cases, differences in the input drivers were propagated through the Biome-BGC model, and were visible in the output estimates. Effects of temperature overestimation on decomposition rates, and the subsequent imbalance of carbon pools in litter versus soil have already been discussed. Cumulative yearly estimates of transpiration (Figure 15) and NPP (Figure 16) can be seen to mirror patterns of cumulative yearly precipitation (Figure 2).

The climate simulators, both alone and together, did a good job of simulating the conditions of an average year, as reported elsewhere (Johnson et al. 1996), but failed to capture the variation present in the measured climate. Wheat is limited in the Biome-BGC model by nitrogen, high temperature, and precipitation. These results are consistent with those reported for Biome-BGC in a published sensitivity analysis (White et al. 2000). Simulated photosynthesis shuts down during hot, dry periods, while

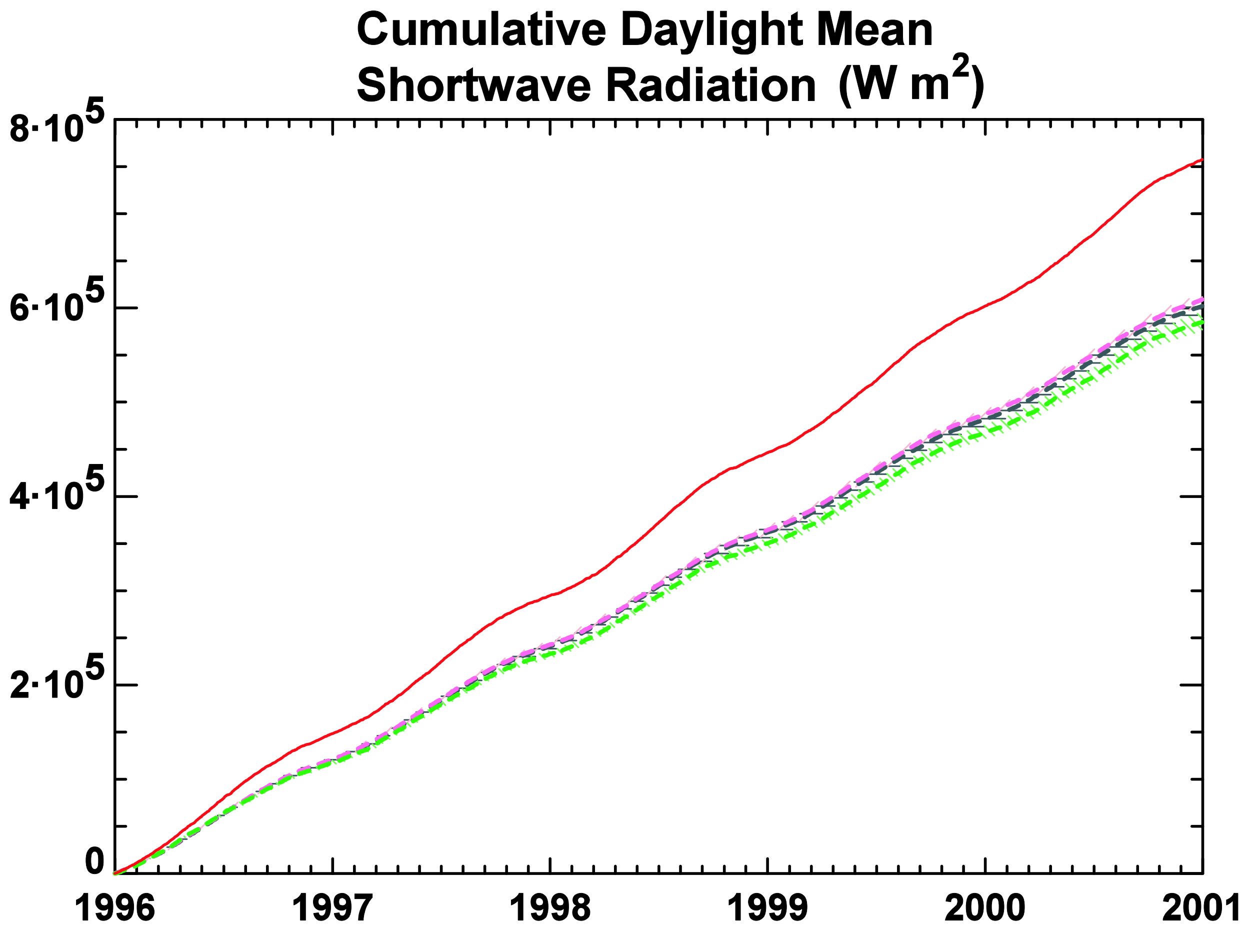

Figure 7. Estimates of cumulative daylight average shortwave radiation from the three synthetic climate pathways compared to ARM measurements. Colors for each synthetic pathway are the same as explained in Figure 2. Underestimates in shortwave radiation may be responsible for underestimates in photosynthesis.

maintenance respiration increases, causing simulated NPP and NEP to go strongly negative. The particular timing of these hot, dry periods, especially in late summer, has large effects on the magnitude of the carbon flux estimates produced by Biome-BGC.

Estimates of leaf area index and vegetation carbon were about the same for all pathways. Estimates of these pools were not so temporally variable, so the "average" behavior of the climate generators produced estimates of these equal to estimates produced from the ARM measurements. However, there were large differences in estimates for NEP, litter carbon, and leaf-level assimilation, and the differences in carbon pools tended to grow and accumulate throughout the 5-year simulation period.

The temporal scale used for comparing results in the "make a difference" experiment is important. Comparison of annual means show few differences, in most cases (but see NEP, Figure 12), since the climate generators perform well, on average. Comparison of particular actual years, comparison of seasons (especially late summer), and multi-year comparisons typically show that the use of ARM measurements makes a large difference in carbon flux estimates.

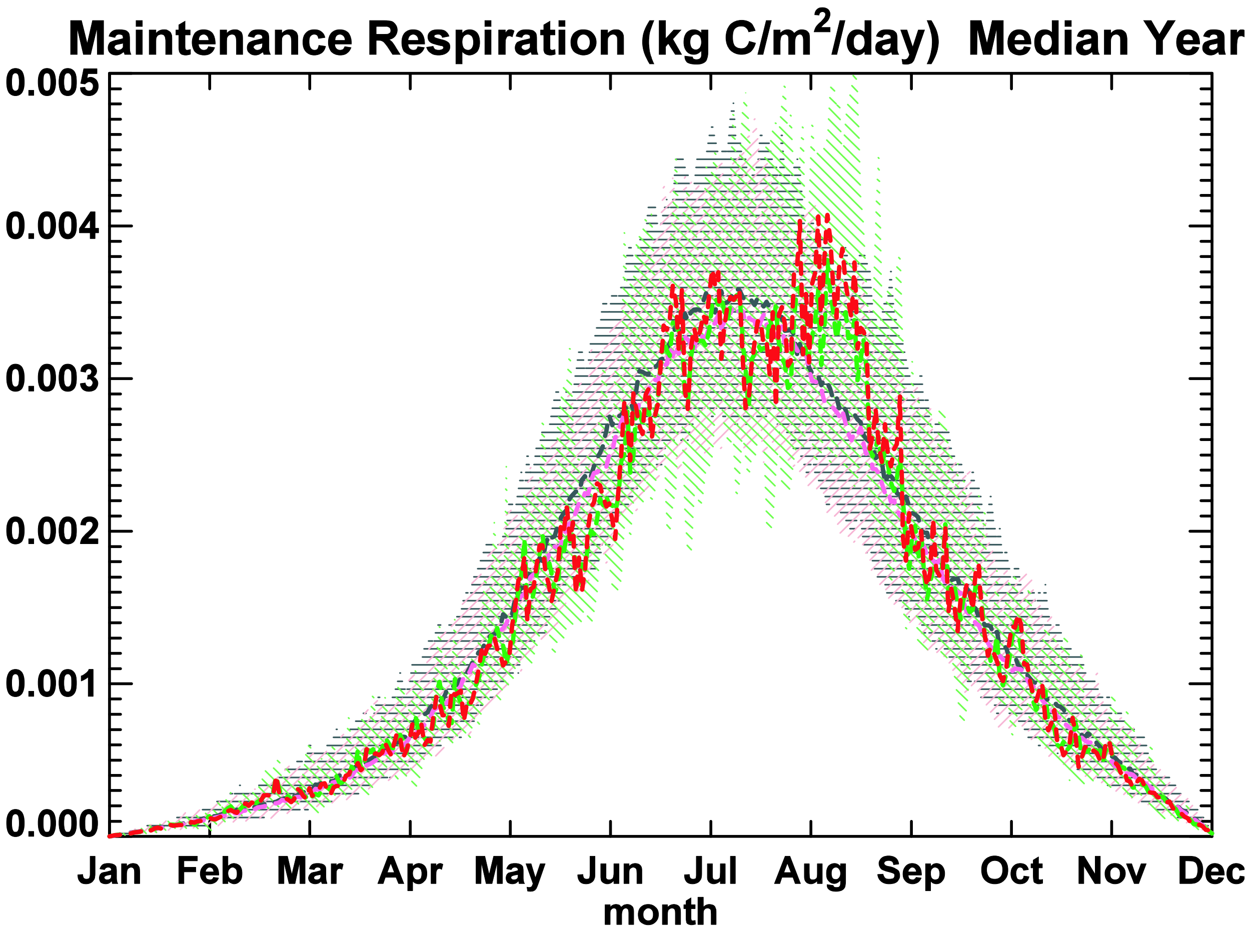

Figure 8. Median yearly maintenance respiration, as estimated from the three synthetic climate pathways compared to ARM measurements for an average year. Colors for each synthetic pathway are the same as explained in Figure 2. Maintenance respiration increases during hot, dry periods in late summer.

Next Steps

We plan to repeat the "make a difference" experiment using another carbon model, SiBD (Sellers et al. 1996). The SiBD model has greater emphasis on carbon fluxes rather than pools. It requires more detailed input data at a higher temporal frequency, including downward longwave radiation. The emphasis on fluxes may favor a "no differences" result, but the increased temporal frequency and reliance on radiometric inputs may make a "difference" in the comparison.

Gap-filling and the imputation of missing measurement values continues to be a central issue when using ARM measurements in simulation models. We are planning a sister experiment to determine whether different gap-filling techniques "make a difference" in carbon model outputs. We will perform a "hole-punching" experiment to produce artificial gaps of varying lengths in different parameters through different seasons, and will then use a jackknife approach to compare estimates with those produced using the originally removed measurements.

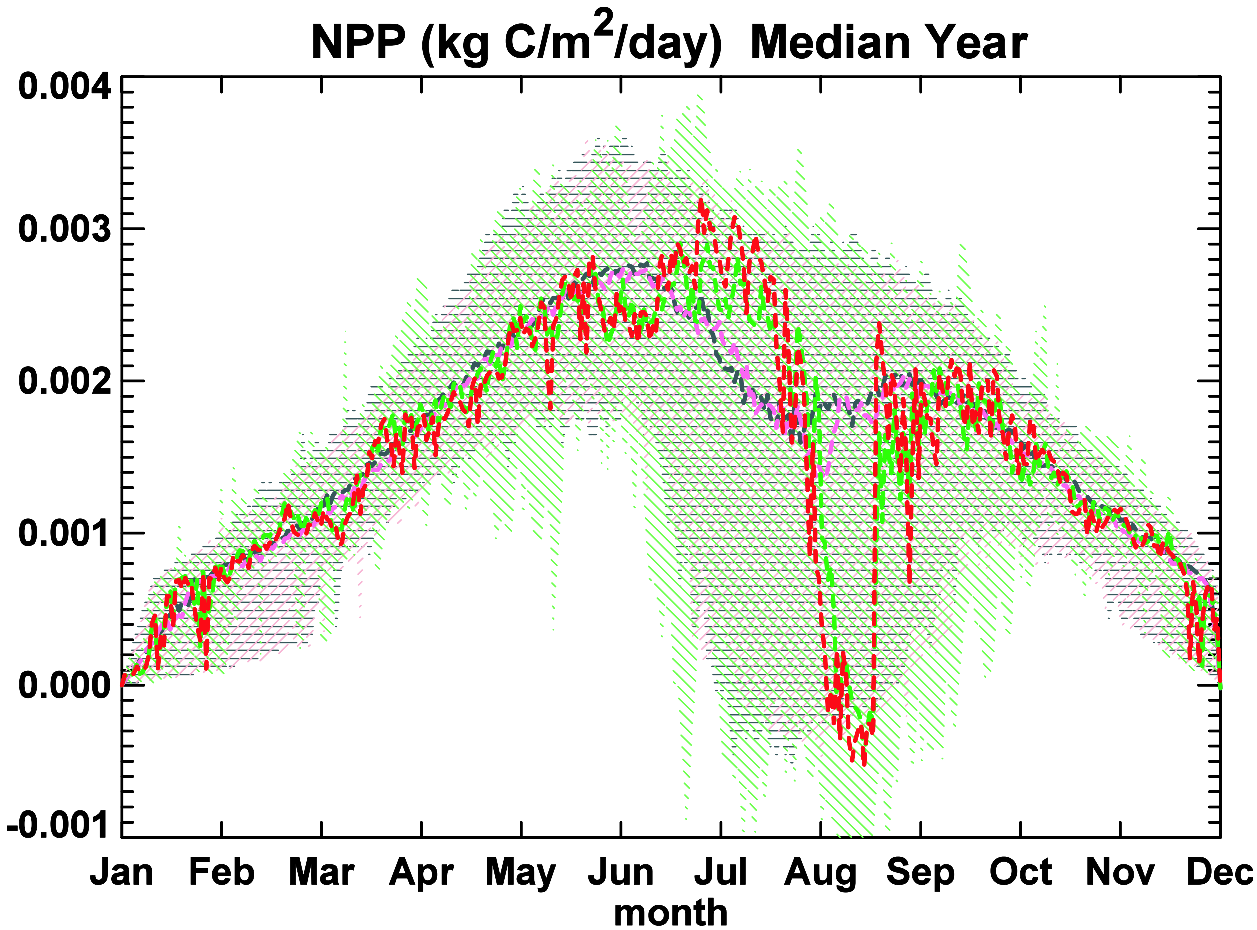

Figure 9. Median yearly NPP, as estimated from the three synthetic climate pathways compared to ARM measurements for an average year. Colors for each synthetic pathway are the same as explained in Figure 2. NPP drops, and is underestimated during dry periods in late summer.

We believe that the "make a difference" design presented here may provide a template that is generally useful for quantifying the value added by ARM data for many different alternative uses. The use of ARM measurements to force climate models may be particularly productive. We intend to continue to foster and facilitate alternative uses for ARM data, both within the carbon modeling community and elsewhere.

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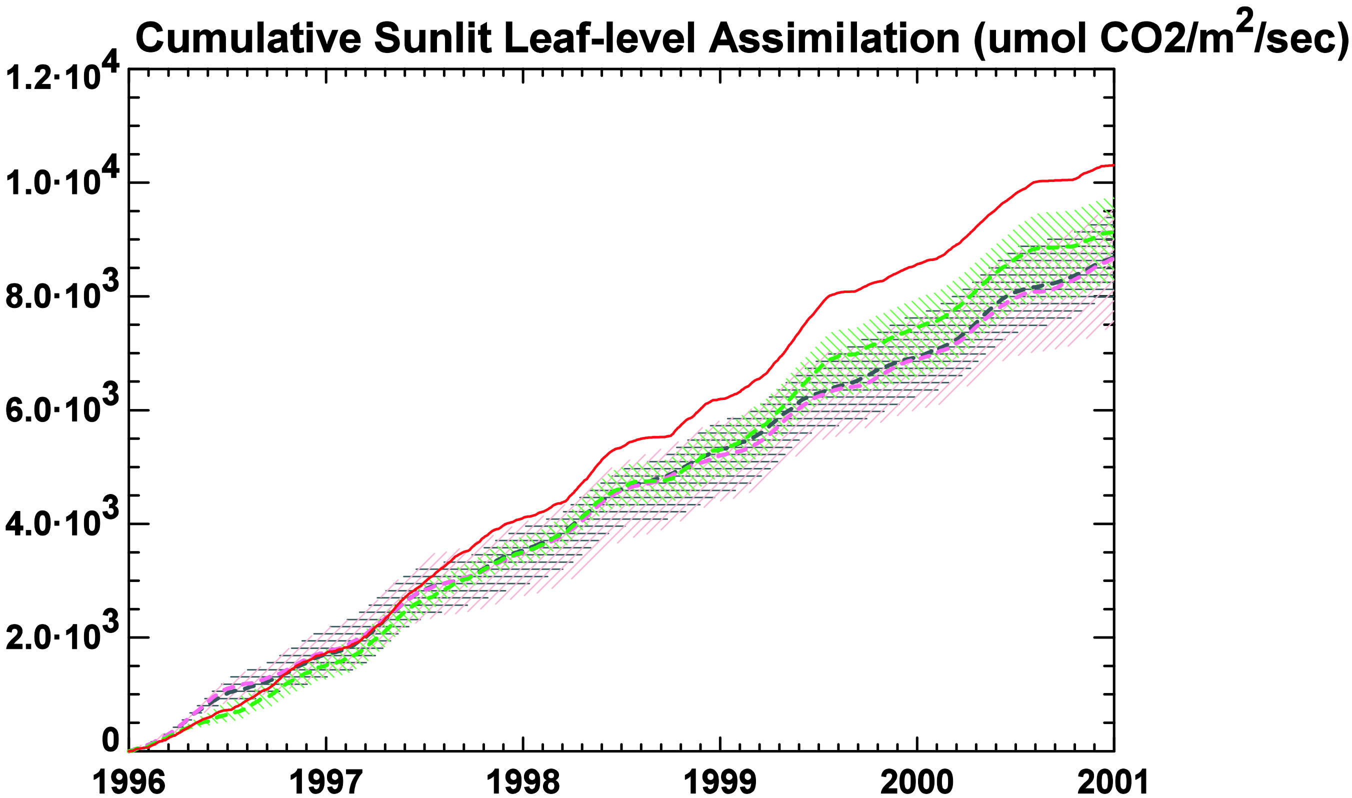

Figure 10. Estimates of cumulative leaf-level carbon assimilation from the three synthetic climate pathways compared to ARM measurements across the 5-year duration of the simulation. Colors for each synthetic pathway are the same as explained in Figure 2. Leaf-level carbon assimilation is underestimated by all three synthetic pathways.

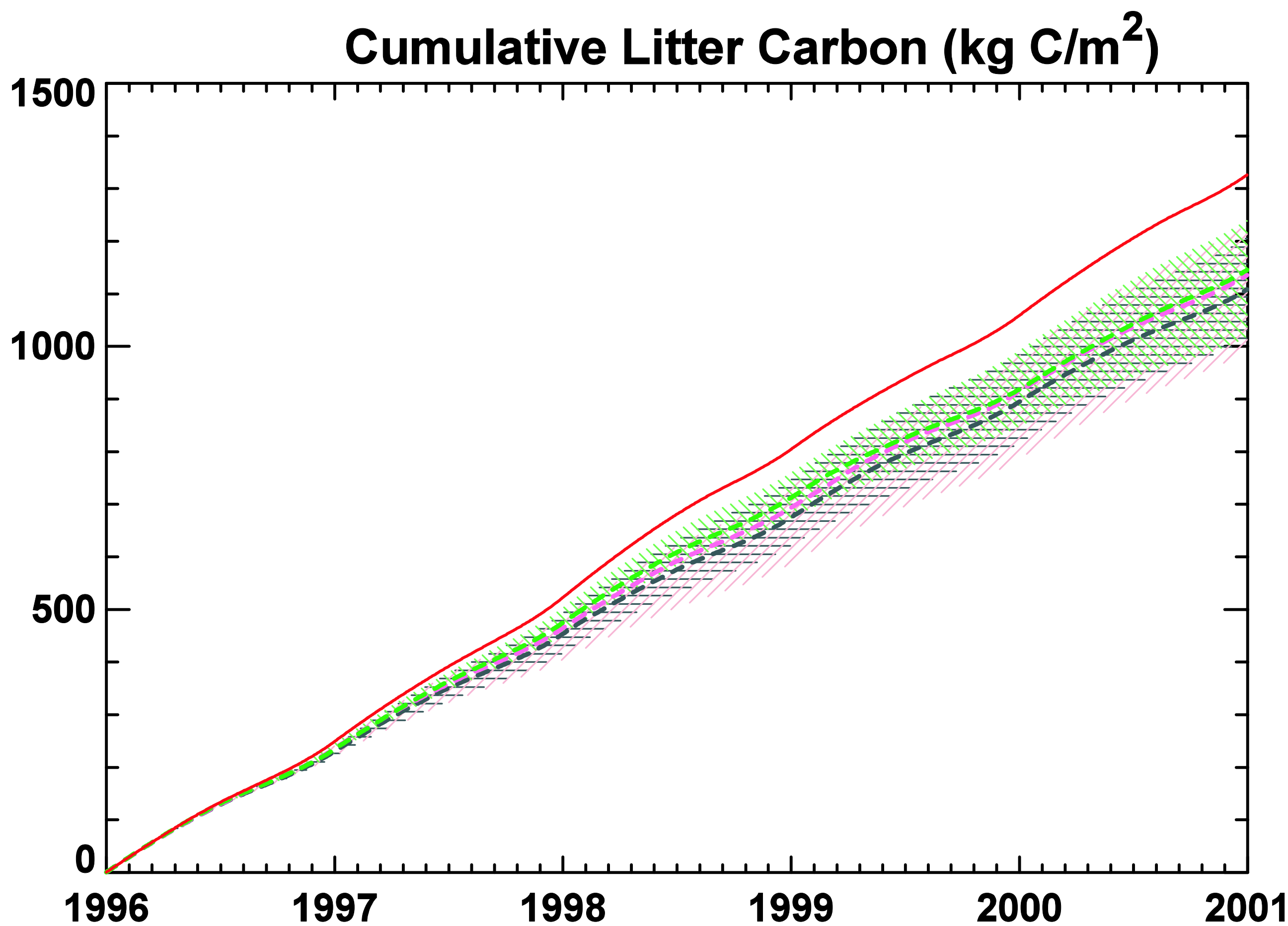

Figure 11. Estimates of cumulative litter carbon from the three synthetic climate pathways compared to ARM measurements across the 5-year duration of the simulation. Colors for each synthetic pathway are the same as explained in Figure 2. Litter carbon is underestimated, and soil carbon is overestimated by all three synthetic pathways, possibly because decomposition rates are overestimated.

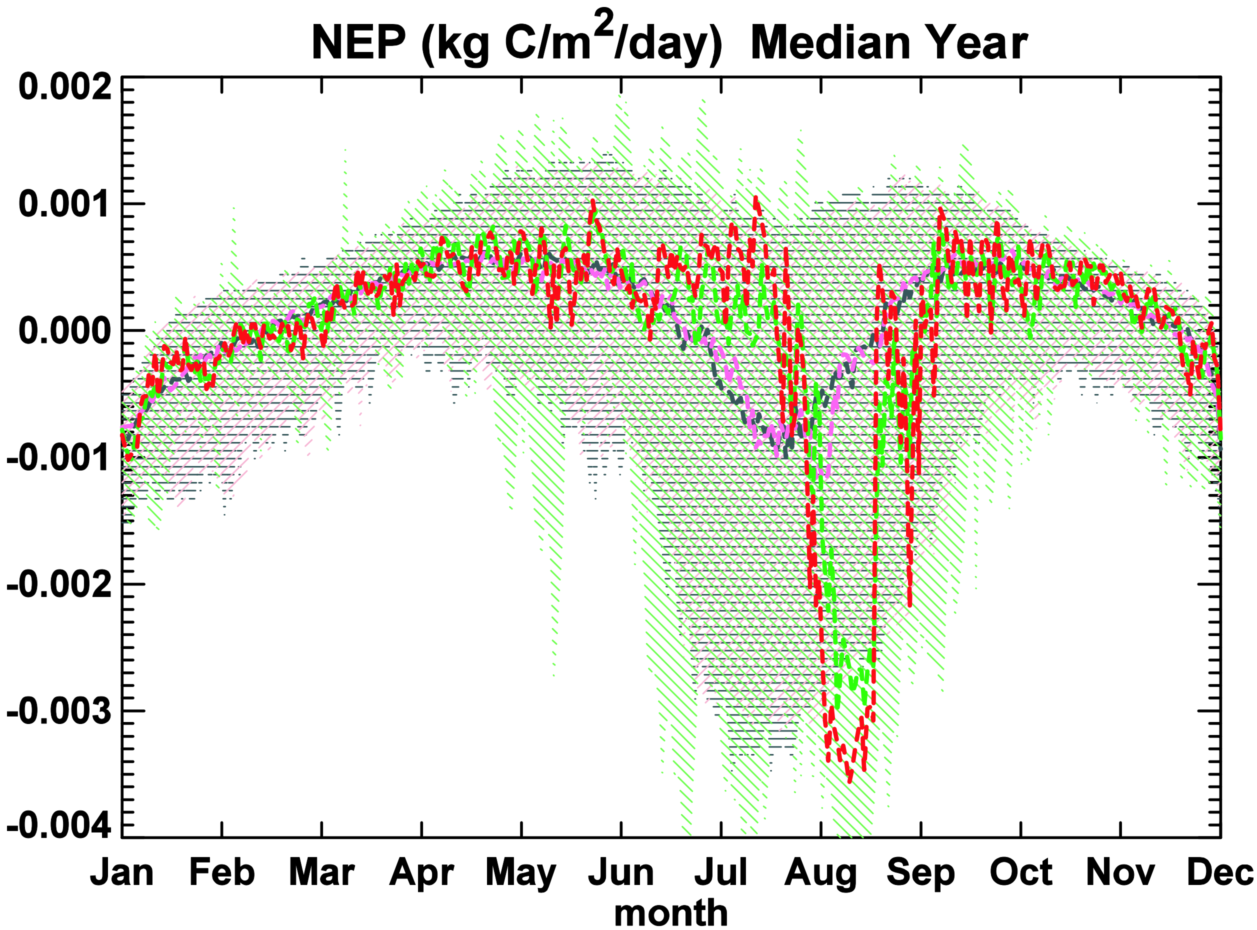

Figure 12. Median yearly NEP, as estimated from the three synthetic climate pathways compared to ARM measurements for an average year. Colors for each synthetic pathway are the same as explained in Figure 2. NEP is variable, and depends on the occurrence of hot, dry days in late summer.

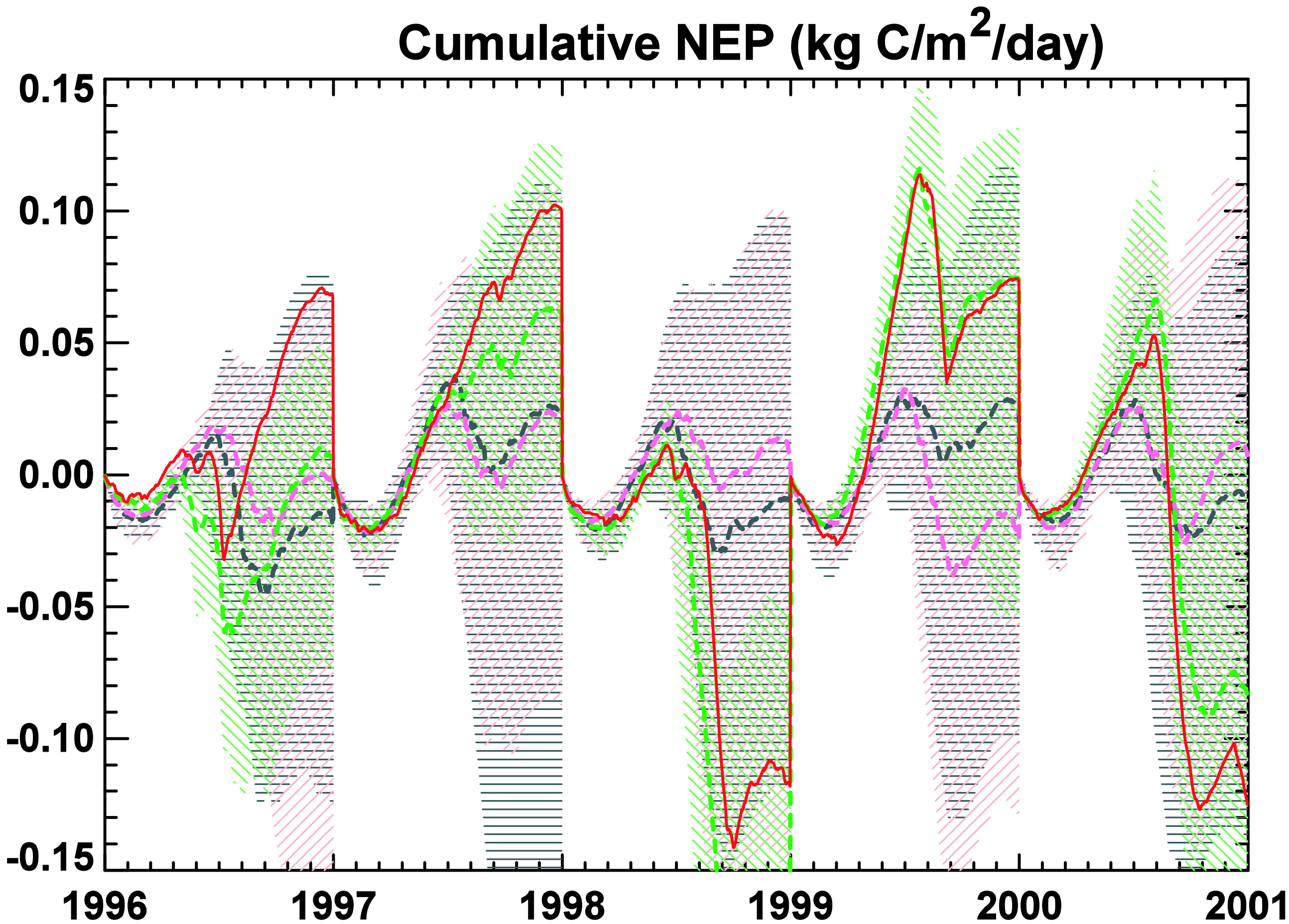

Figure 13. Estimates of cumulative yearly NEP from the three synthetic climate pathways compared to ARM measurements. Colors for each synthetic pathway are the same as explained in Figure 2. NEP estimated from ARM measurements is seen to swing both above and below zero in some years. The sign of NEP depends on the occurrence of hot, dry days in late summer.

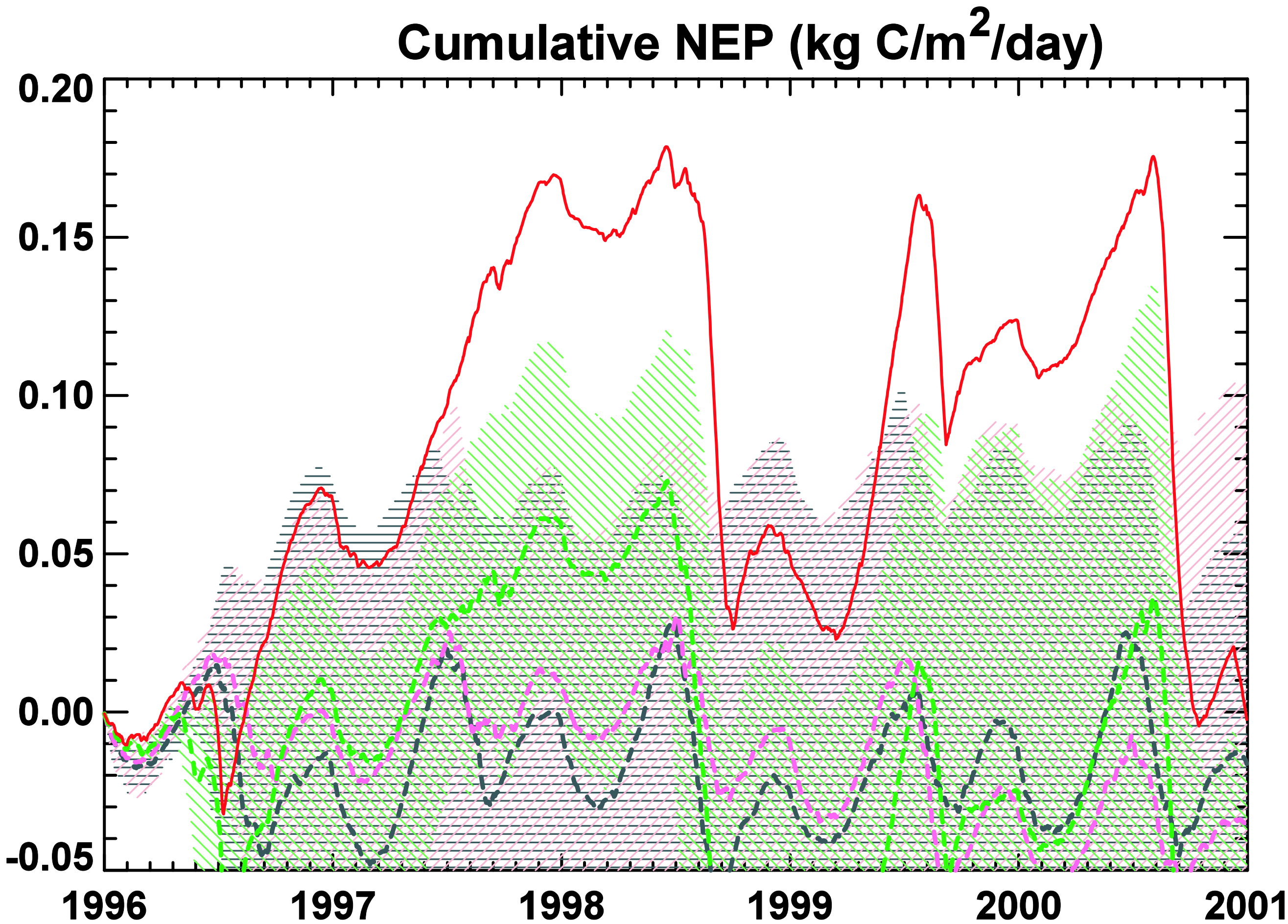

Figure 14. Estimates of cumulative NEP from the three synthetic climate pathways compared to ARM measurements across the 5-year duration of the simulation. Colors for each synthetic pathway are the same as explained in Figure 2. The comparison of total cumulative NEP from synthetic versus measured climate is significantly different over most of the simulated period.

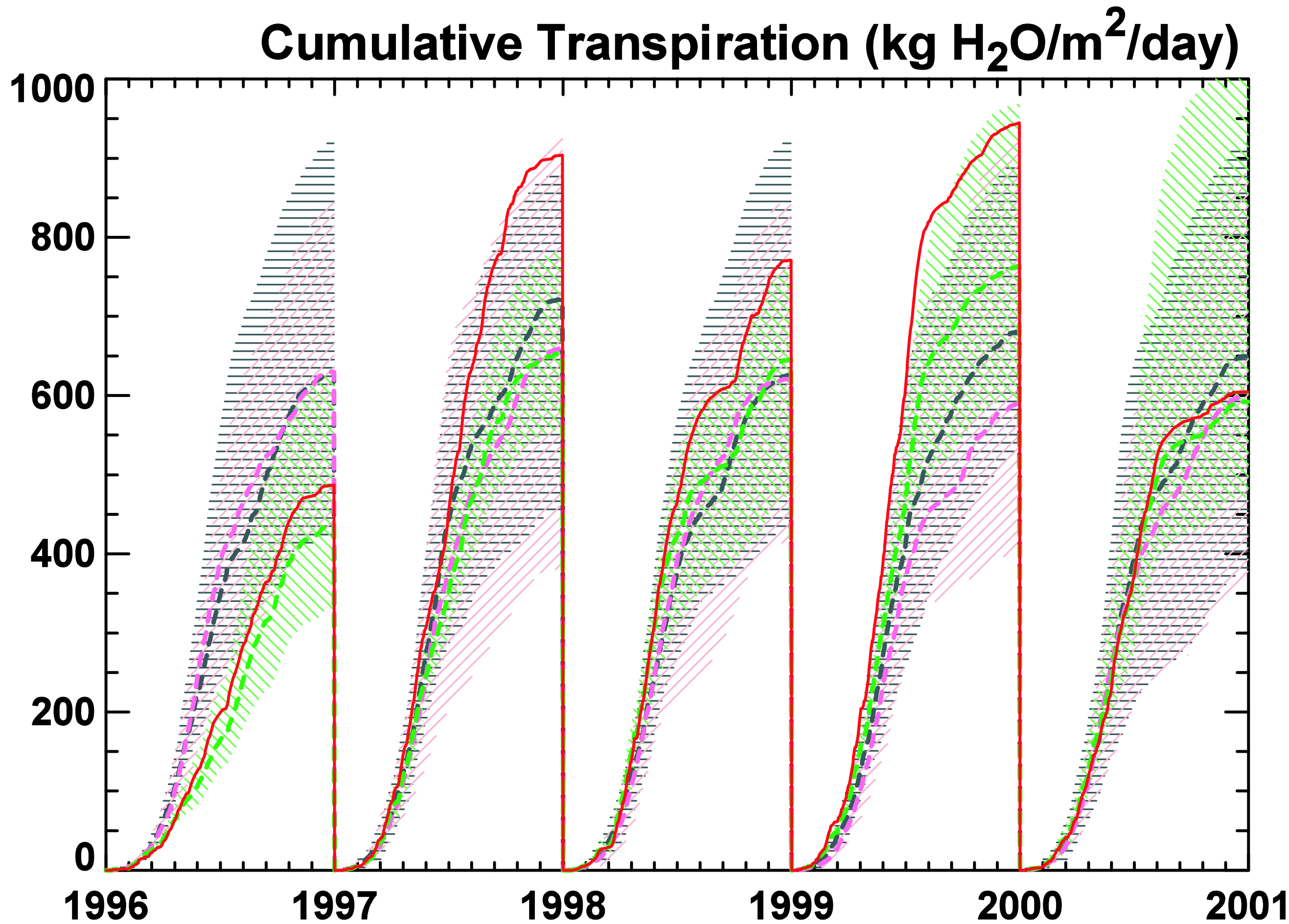

Figure 15. Estimates of cumulative transpiration from the three synthetic climate pathways compared to ARM measurements. Colors for each synthetic pathway are the same as explained in Figure 2. The pattern of cumulative transpiration is similar to the pattern of cumulative precipitation shown in Figure 2.

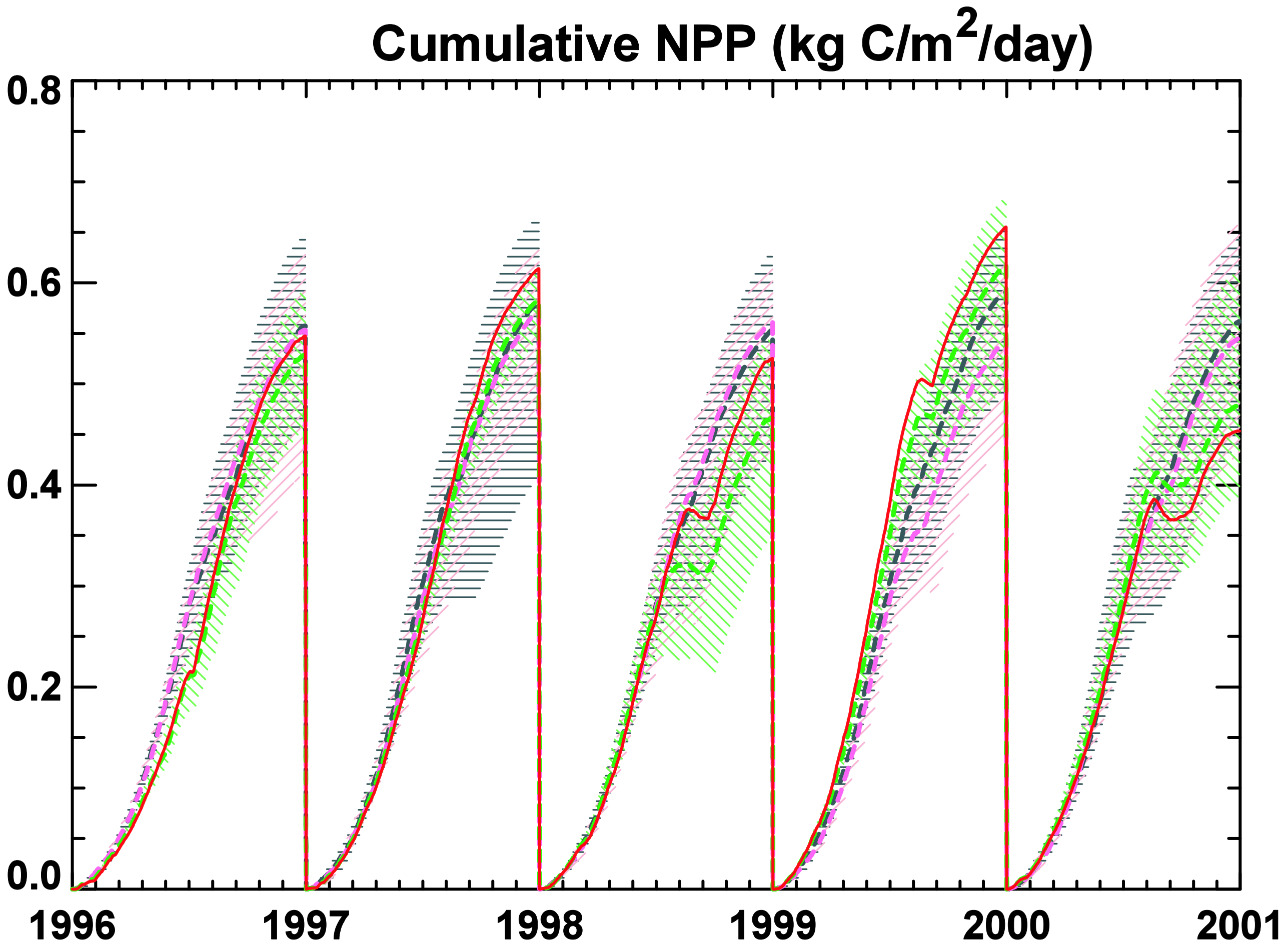

Figure 16. Estimates of cumulative NPP from the three synthetic climate pathways compared to ARM measurements. Colors for each synthetic pathway are the same as explained in Figure 2. The pattern of cumulative NPP is similar to the pattern of cumulative precipitation shown in Figure 2, and the pattern of cumulative transpiration shown in Figure 15.