

# Supplemental Online Material for “The seasonal cycle of satellite chlorophyll fluorescence observations and its relationship to vegetation phenology and ecosystem-atmosphere carbon exchange”

## 1 Additional comparisons between tower, upscaled, and model GPP, GOME-2 $F_{740}$ and MOD15 APAR

The sites highlighted in the main body of the paper were chosen as representative sites for several of the major biomes. Here, we show results from the remaining stations that we examined. Figures 1-12 are similar to figures in the main body of the paper showing seasonal cycles of tower-based and upscaled MPI-BGC GPP, GOME-2  $F_{740}$ , and MODIS-based APAR.

Figures 1-3 (stations in Wisconsin, Ohio, Indiana, Michigan, Missouri, New Hampshire, Maine, and southern Canada in Quebec) confirm that the seasonal cycle of GOME-2  $F_{740}$  is generally in good agreement with that of the tower-based and upscaled MPI-BGC GPP for the respective biomes (dominated by forests and croplands). The MODIS-based APAR, here again, shows a somewhat too lengthy duration of activity as compared with the tower GPP estimates.

Figure 4 shows results for forest-dominated sites located in the southeast US (US-WBW in Tennessee and US-Goo in Mississippi). GOME-2  $F_{740}$  and MPI-BGC GPP indicate a somewhat more narrow period of photosynthetic activity as compared with that displayed by tower-based GPP. The MODIS APAR data show a slightly early springtime rise and later autumn decline at US-WBW as compared with the tower estimates. MODIS APAR does not drop to zero in winter, when the tower GPP data drop to near zero.

An example of heterogeneity within the satellite averaging area is shown in Figure 5 for three Florida stations located within close proximity of each other. APAR declines only to about 60% of its peak values in winter at these sites. In contrast, GPP from the towers and GOME-2  $F_{740}$  both decline to about 20% of peak value in winter for US-SP1 and US-SP2. GPP from MPI-BGC declines to about 40% of its peak value.

Figures 6-7 show that the length of the relatively narrow duration of photosynthesis of US corn and soybean croplands is overestimated by the MODIS-based APAR. Both GOME-2  $F_{740}$  and the MPI-BGC GPP show better agreement with respect to the tower data; this again supports results shown in the main body of the paper.

Figure 8 shows western US stations surrounded by croplands, grasslands, and savannas. The satellite averaging area around these sites is fairly heterogeneous. GOME-2  $F_{740}$  and MPI BGC GPP have show a larger difference with respect to the tower GPP at US-ARM (Fig. 8) as compared with the nearby Shidler Tallgrass Prairie (US-Shd) site shown in the main body of the paper; this appears to be an issue with the heterogeneous nature of the US-ARM site that is located in a winter wheat field that contains grasslands within the satellite averaging area. A similar issue related to spatial heterogeneity may be present at the US-Aud site. All data sets show a late peak in activity around day 230 but with somewhat different widths.

Figure 9 shows that GOME-2  $F_{740}$  has large uncertainties around the US-SO2 site owing to small signal levels. GOME-2  $F_{740}$  uncertainties are smaller for the US-Blo site, and the seasonal cycle is in relatively good agreement with MPI-BGC GPP and the tower data at this site. GPP from the upscaled MPI-BGC shows a somewhat different seasonal variation

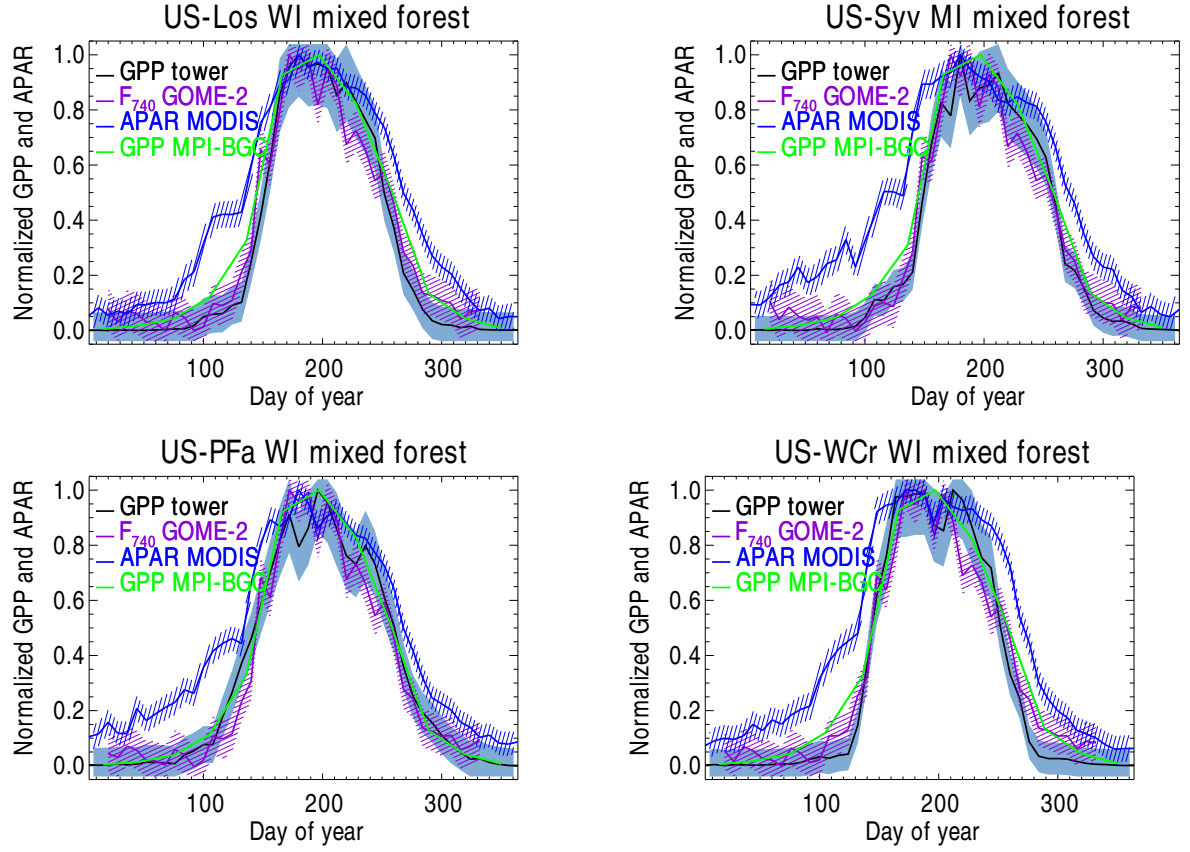


Figure 1: Seasonal cycles of tower-based GPP, APAR derived from MODIS (MOD15), up-scaled GPP from the MPI-BGC product, and GOME-2  $F_{740}$  with corresponding uncertainties (as detailed in the main text) for northern midwest mixed forest sites in Wisconsin and Michigan, US.

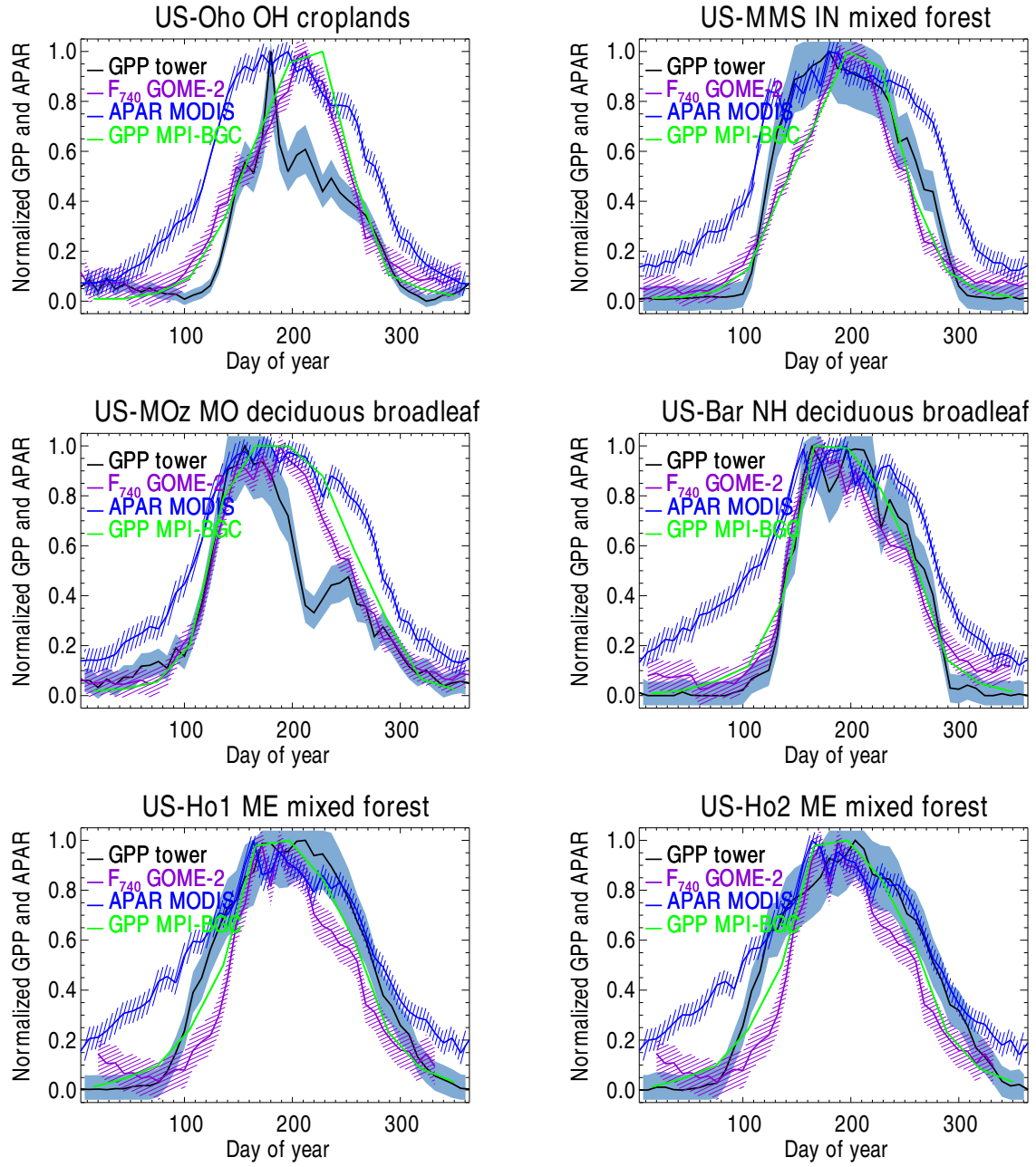


Figure 2: Similar to Fig. 1 showing US forested sites in the midwest (Ohio, Indiana, and Missouri) and northeast (Maine and New Hampshire).

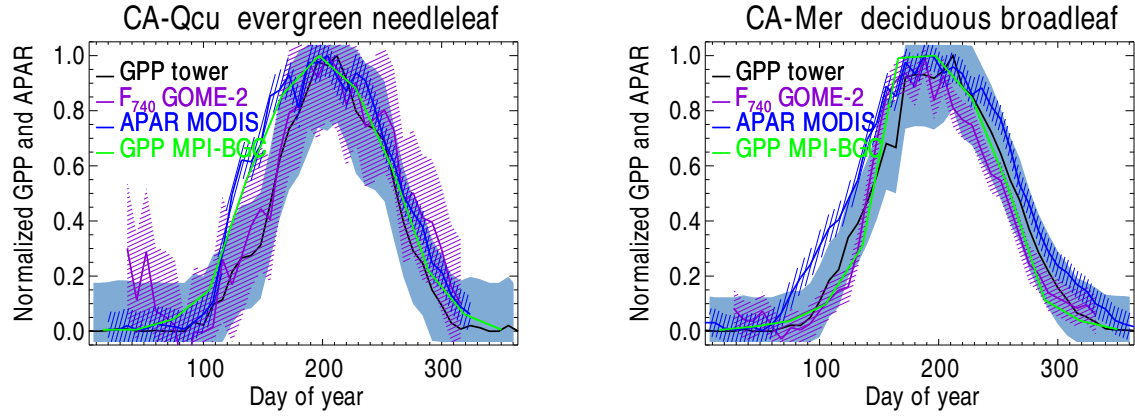


Figure 3: Similar to Fig. 1 showing southern Canadian sites.

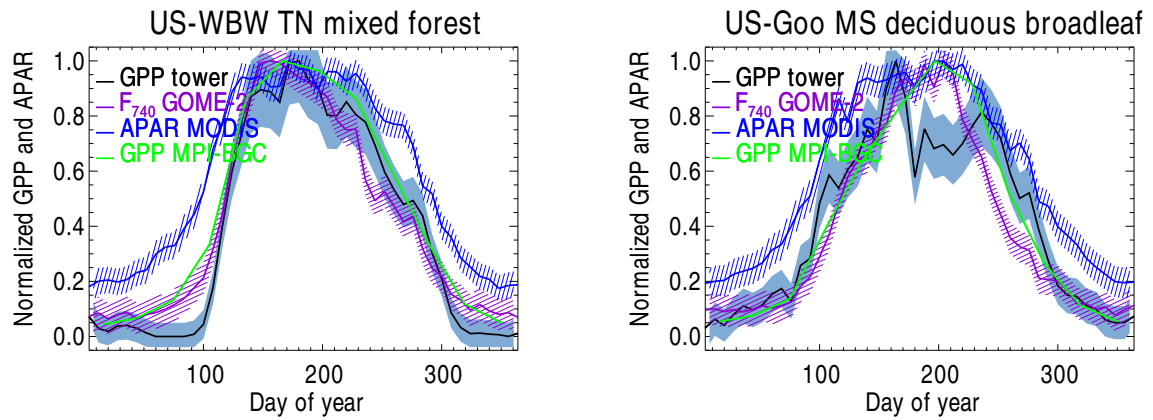


Figure 4: Similar to Fig. 1 but for two US southern mixed forest sites.

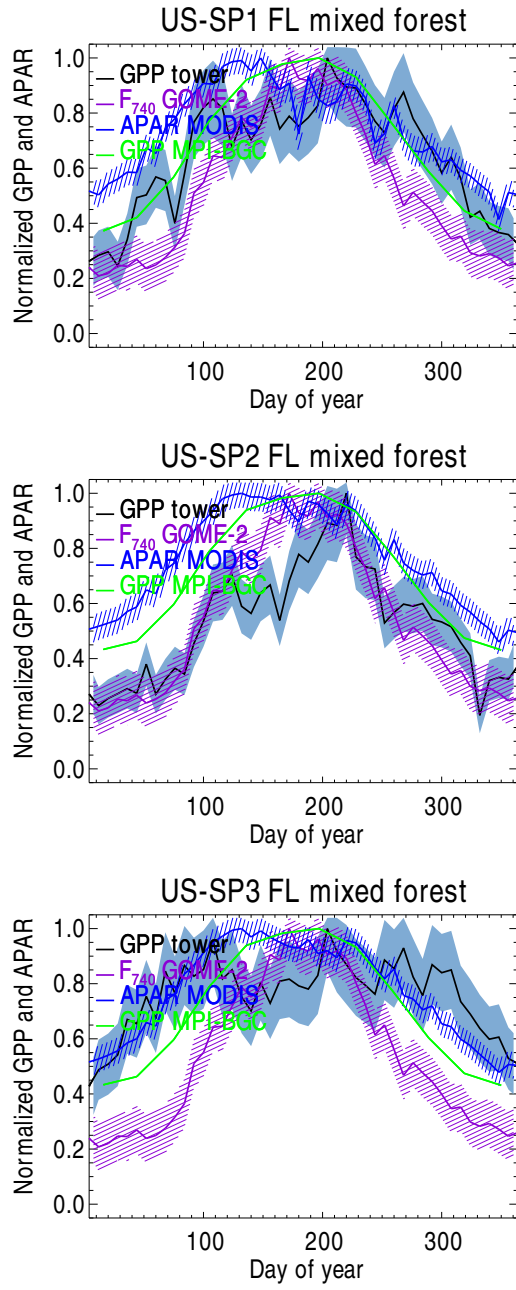


Figure 5: Similar to Fig. 1 but for closely located US Florida sites.

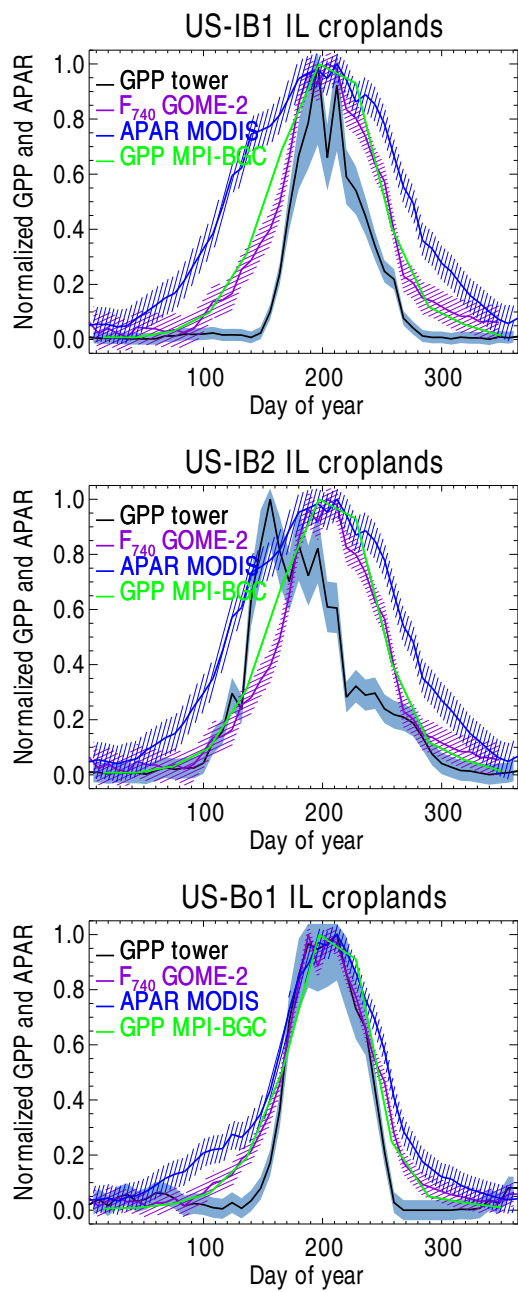


Figure 6: Similar to Fig. 1 but for US midwest agricultural sites in Illinois.

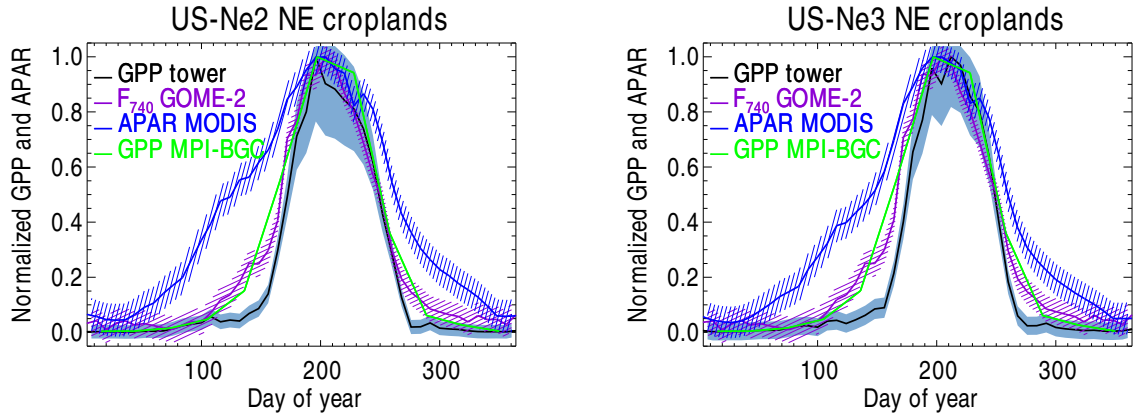


Figure 7: Similar to Fig. 1 but for US midwest agricultural sites in Nebraska.

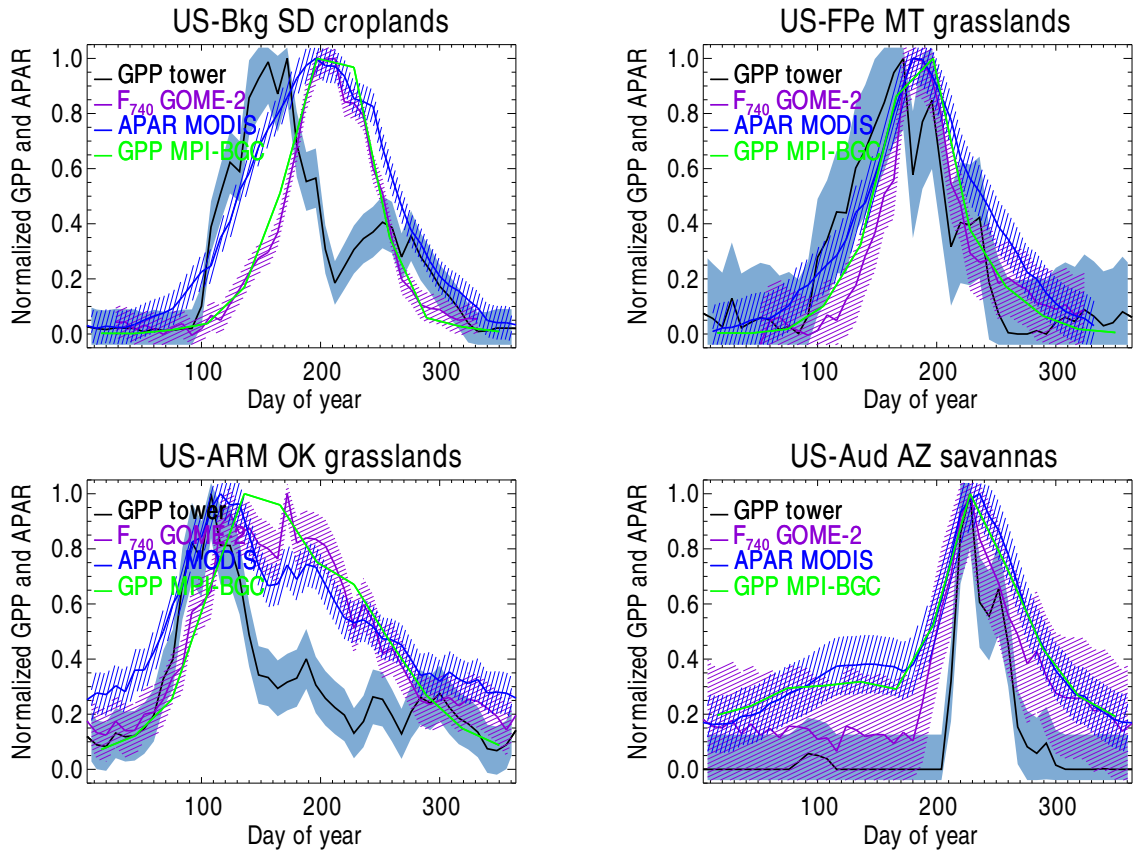


Figure 8: Similar to Fig. 1 but for midwest and western US sites.



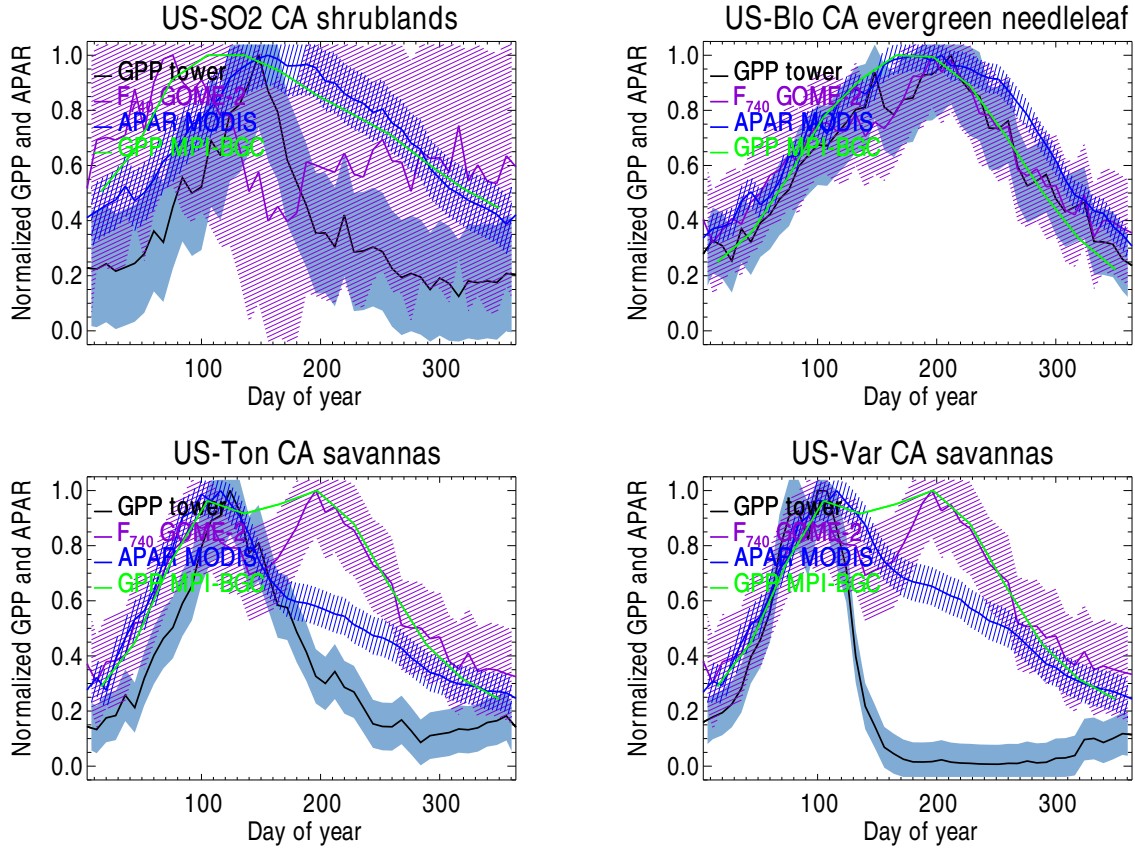


Figure 9: Similar to Fig. 1 but for California US sites.

as compared with tower GPP at the US-Ton and US-Var sites in Fig 9. GOME-2  $F_{740}$  is in reasonably good agreement with upscaled MPI-BGC GPP at these sites.

Figure 10 shows more examples of heterogeneity on small spatial scales for the US-Me2–5 sites. GOME-2  $F_{740}$  data show similar seasonal cycles as compared with GPP from MPI-BGC to within estimated uncertainties for these sites. The tower data show a somewhat more narrow seasonal peak in summer for 3 of the 4 locations. MODIS APAR shows a seasonal cycle most similar to the tower GPP at the US-Me4 site that displays a more wide seasonal peak.

The sites in Africa and Australia in Figure 11 confirm the results shown in paper. Figure 11 also shows results for a site in Israel (IL-Yat). That site is an evergreen needleleaf forest surrounded by shrublands. GOME-2  $F_{740}$  displays low signal levels and therefore large uncertainties, but never-the-less compares well with the tower-based GPP.

The closely located sites in both Italy and the Netherlands shown in Figure 12 show variability in tower-based GPP as compared with the nearby sites shown in the paper. This indicates that these sites are heterogeneous over the satellite averaging area. GOME-2  $F_{740}$  agrees well with upscaled GPP from MPI-BGC for these sites as shown in the paper.

Figures 13–14 display the seasonal cycles of GPP from the multi-model mean of the ensemble for the remaining Ameriflux sites. These figures similarly reinforce the results from the paper; GPP from the multi-model mean overestimates the duration of photosynthesis for most of the midwestern and northeast deciduous and mixed forested sites and agrees better with the tower estimates for the remaining evergreen needleleaf forest site (US-Me2) as shown



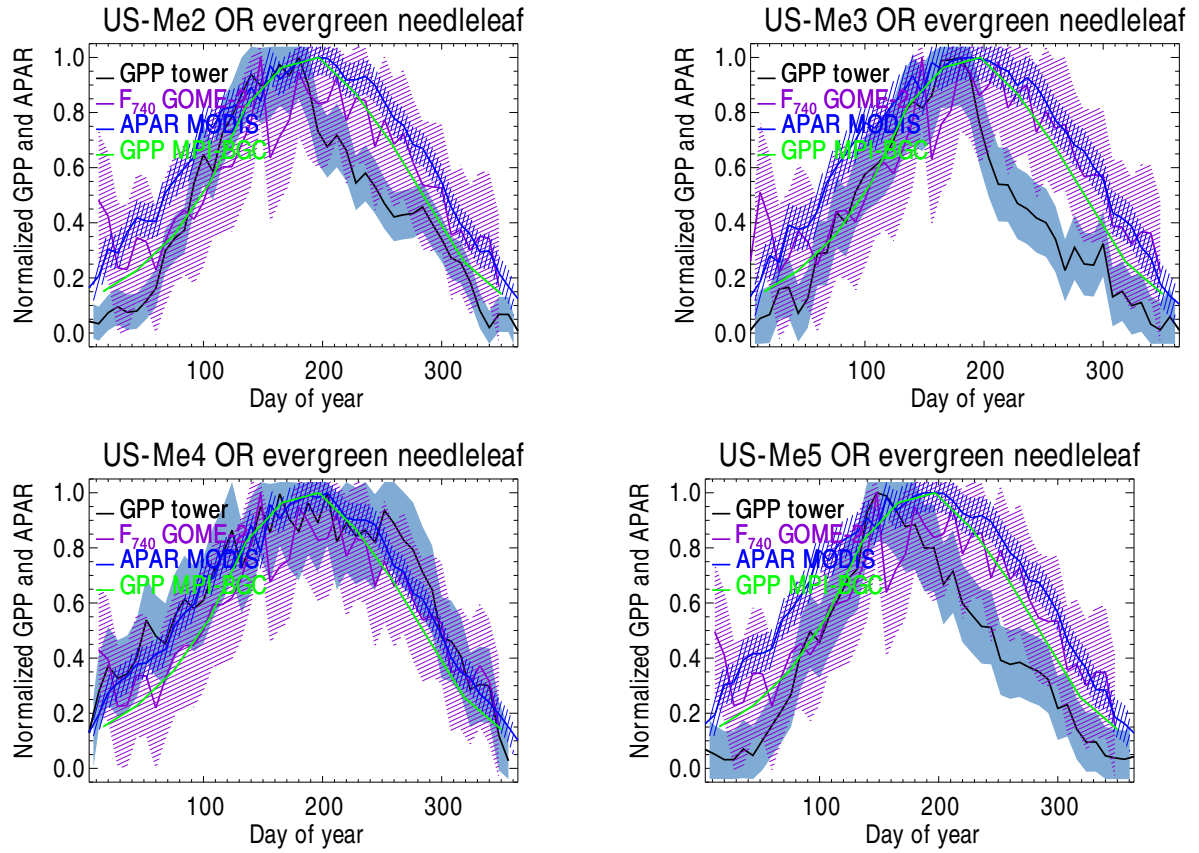


Figure 10: Similar to Fig. 1 but for closely located sites in Oregon surrounded by evergreen needleleaf forests.

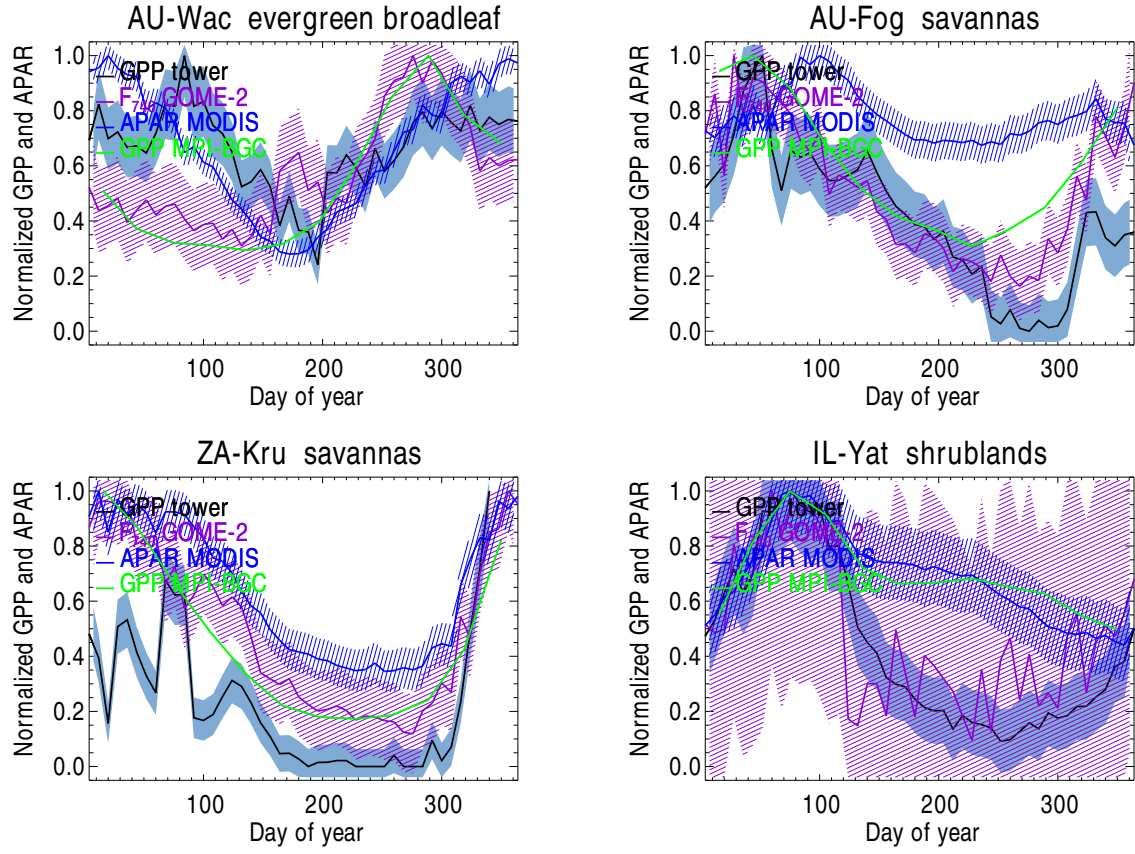


Figure 11: Similar to Fig. 1 but for sites in Australia, Africa, and Israel.

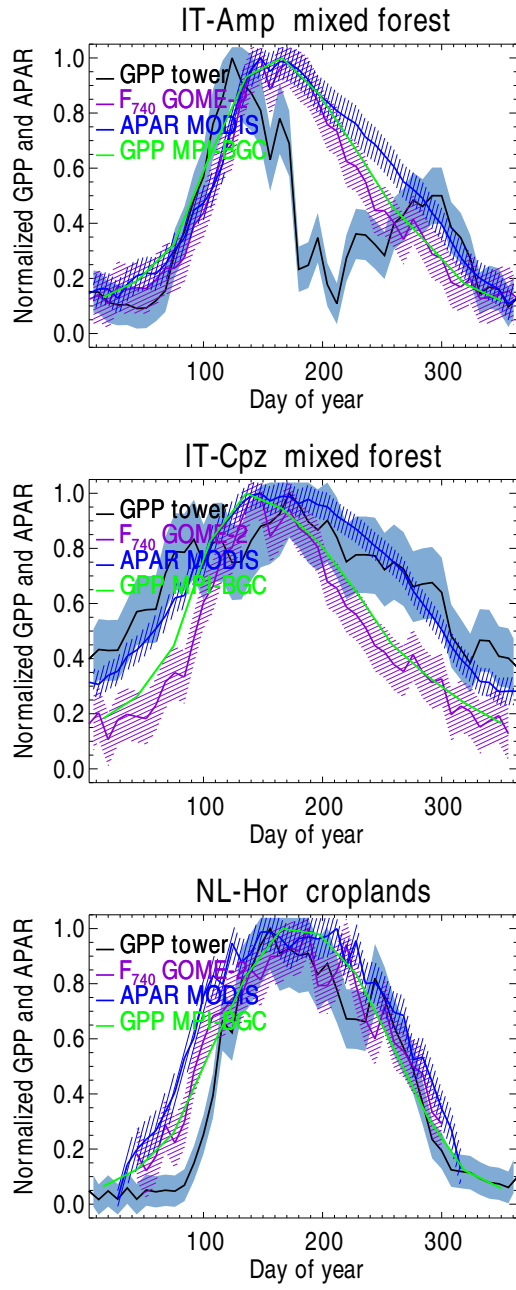


Figure 12: Similar to Fig. 1 but for sites in Italy and the Netherlands.

in Figs. 13–14. The other sites shown have large uncertainties in the observations and a substantial degree of heterogeneity around the sites.

Figure 15 shows the derived inflection points for the different timing indicators as discussed in the text. Similar to the onset of photosynthesis and dormancy, the inflection points show earlier dates in the spring for MODIS APAR particularly for croplands and deciduous and mixed forest sites and later dates in autumn for croplands as compared with GPP estimates and GOME-2  $F_{740}$ . The multi-model mean also shows earlier inflection points in spring for deciduous and mixed forest sites as compared with GPP and GOME-2  $F_{740}$ .

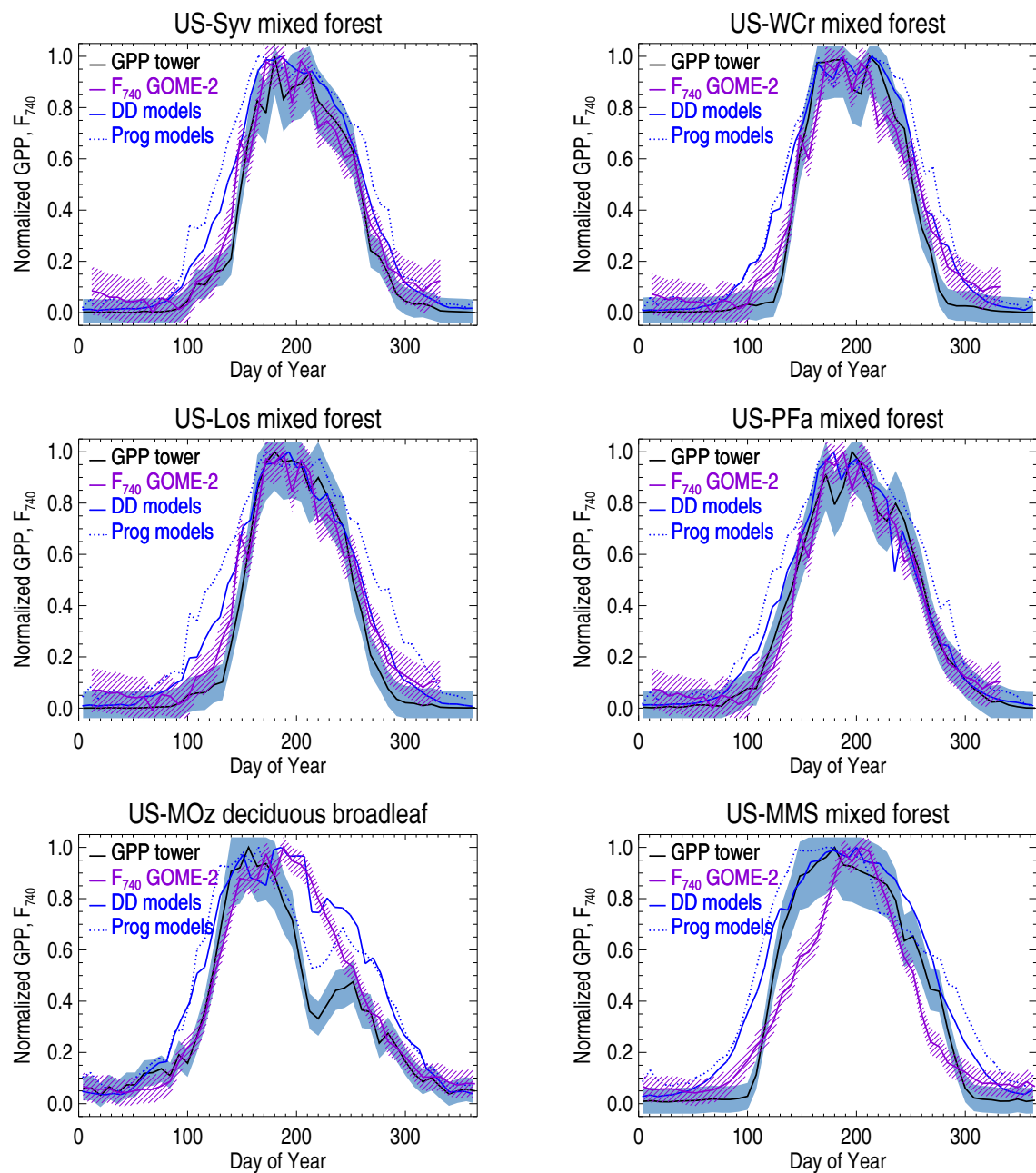


Figure 13: Seasonal cycles of GPP derived from flux tower measurements (black line with blue shaded uncertainties), simulations from a set of prognostic (Prog) and data-driven (DD) models (blue dotted and solid lines, respectively), and fluorescence from GOME-2  $F_{740}$  (purple lines with uncertainties shown as diagonal purple lines).

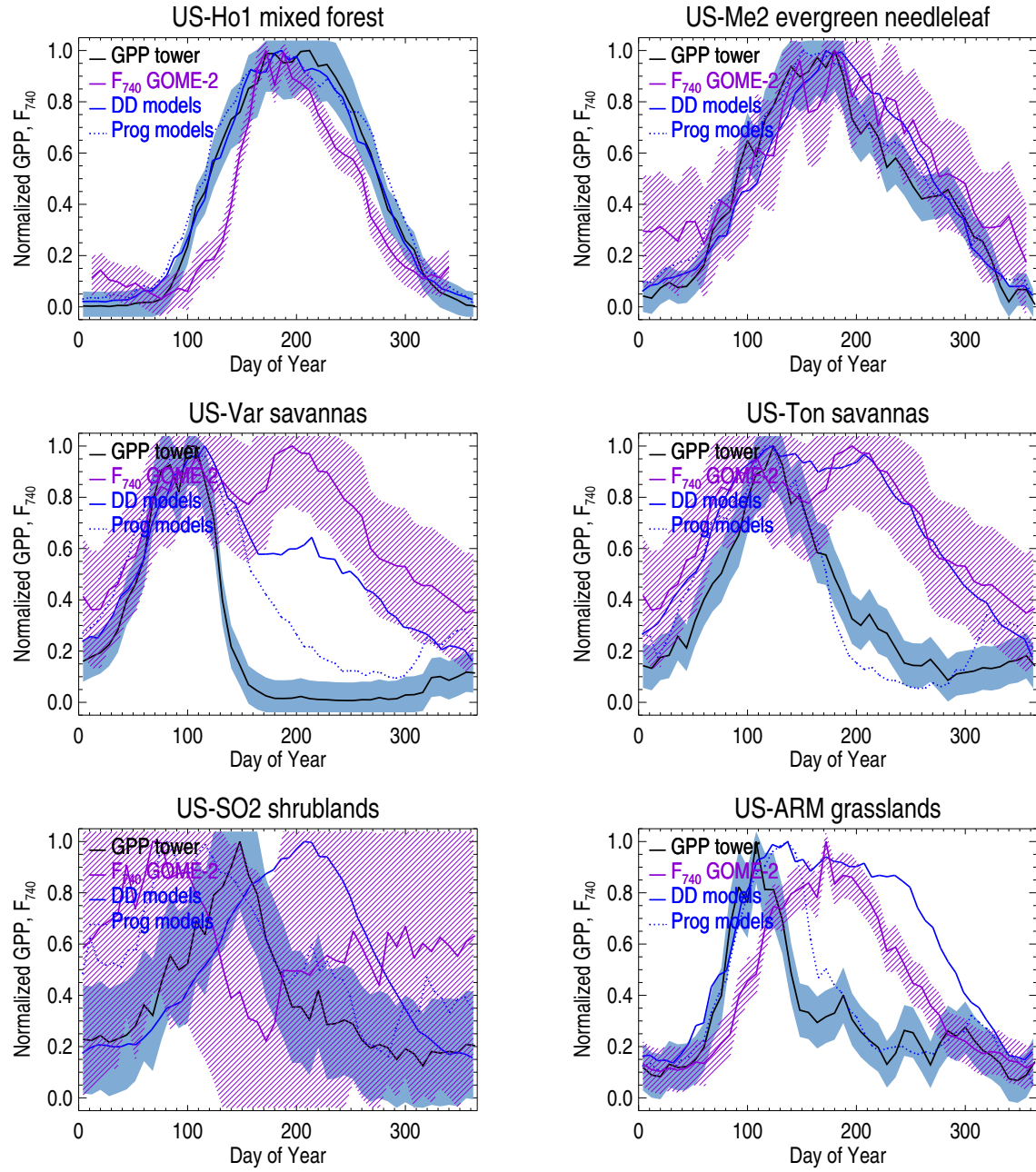


Figure 14: Similar to Fig. 13 but for a different set of US sites.

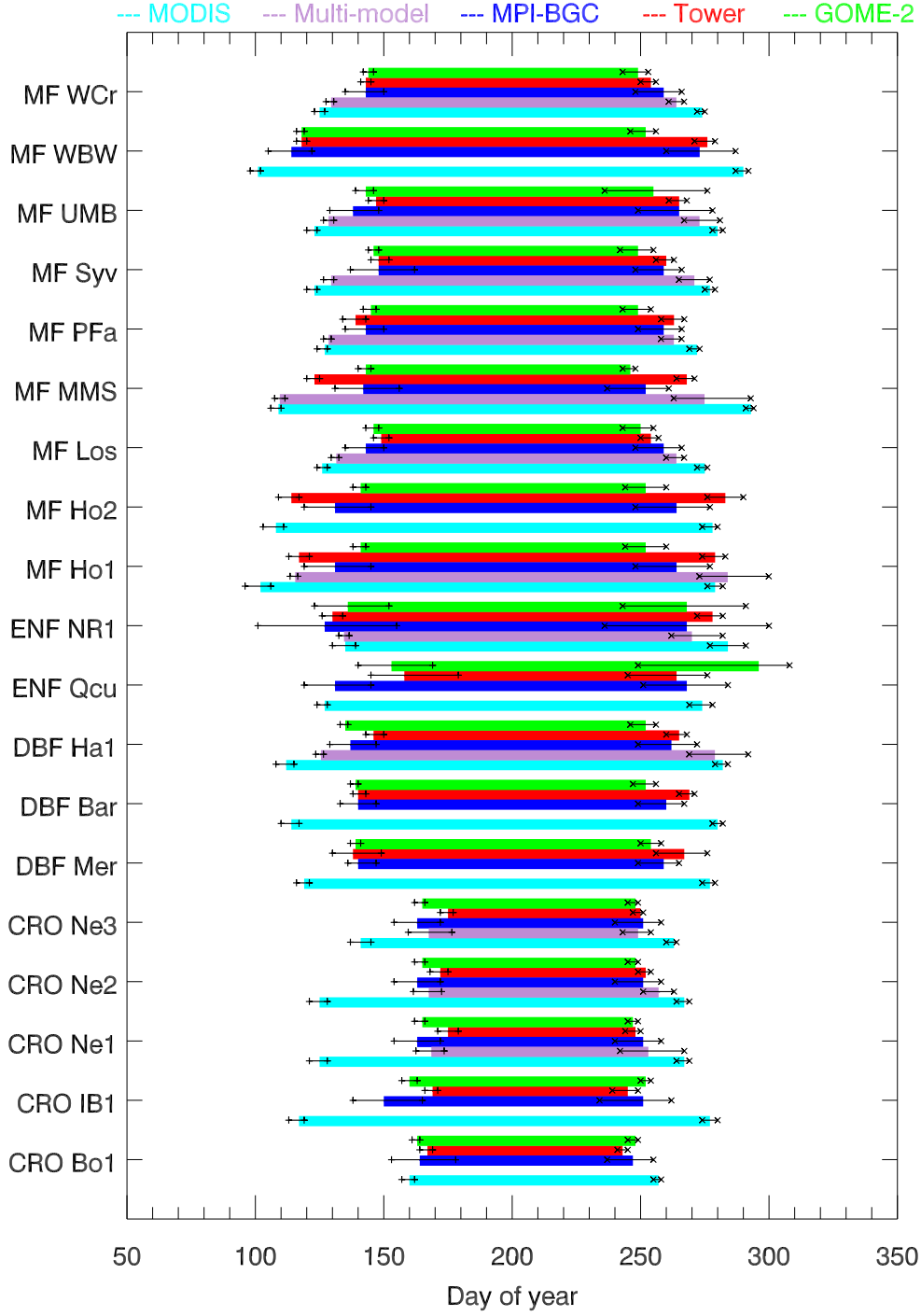


Figure 15: Similar to figures in the main text but showing inflection/stability points (left and right ends of horizontal bars with uncertainties) as discussed in the main text.