Supplementary Material for Comprehensive evaluation on the robustness of deep learning based rainfall-runoff models under climate change scenarios

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Structure of this supplementary report:

- **Section S1. Selected catchments and model skill**: .
- **Section S2. SAC-SMA + Snow-17 internal states**: Mean snow water equivalent ($\overline{\mathrm{SWE}}$), mean potential evapotranspiration ($\overline{\mathrm{PET}}$), and mean fractional change ($\Lambda^{\mu}_{\delta_P,\delta_T}$) for the perturbation grid of precipitation and temperature for SAC-SMA + Snow17 benchmark. The star indicates the position of $\Lambda^{\mu}_{\delta_P,\delta_T} = 1$ ($\delta_P = 1$ and $\delta_T = 0$).
- **Section S3. Fractional change $\Lambda^{\mu}_{\delta_P,\delta_T}$ across models**: One panel per model on a shared color scale. The star marks the reference forcing ($\delta_P = 1,\ \delta_T = 0$), where $\Lambda^{\mu} = 1$.
- **Section S4. Response transects**: Transects of the perturbation of each factor with the other one fixed at normal conditions ($\delta_P = 1$ and $\delta_T = 0$). The origin on the dotted lines axes indicates the position of $\Lambda^{\mu}_{\delta_P,\delta_T} = 1$ ($\delta_P = 1$ and $\delta_T = 0$). The dashed line represents the precipitation perturbation in the same plot as a way to facilitate the comparison with the streamflow change.
- **Section S5. Day-of-year climatology divergence**: Day-of-year fractional change (Λ^{doy}) and divergence from SAC-SMA PBIAS^{doy} for the lowest emissions scenario (SSP1-2.6) and first period (2015–2045) and the highest emissions scenario (SSP5-8.5) and the last period (2071-2100).

Section S1 Selected catchments and model skill

The perturbation experiment was run over all the available catchments, and here we present the results for the catchment with the highest Kling–Gupta efficiency (KGE), in order to avoid results that could arise from catchments with processes that are not well represented, of each HUC2 hydrologic region, so the sample spans the continental United States while keeping every site at the top of its region's KGE distribution.

Table S1. KGE of every model over the CAMELS test period for the catchments of the dual-factor perturbation experiment. Mean column represents the average over the six models. The best model of each catchment is set in bold. Rows are ordered by HUC2 region.

HUC2	Gauge	SAC-SMA	LSTM	minLSTM	minGRU	MLP-Mixer	Transformer	Mean
01	01031500	0.895	**0.925**	0.922	0.872	0.859	0.915	0.898
02	02016000	0.876	**0.913**	0.865	0.835	0.869	0.885	0.874
03	02177000	**0.945**	0.896	0.900	0.883	0.868	0.917	0.902
04	04256000	0.853	**0.895**	0.858	0.808	0.856	0.892	0.860
05	03164000	0.901	**0.943**	0.849	0.876	0.887	0.925	0.897
06	03498500	0.813	0.928	0.877	0.927	0.939	**0.947**	0.905
07	05507600	0.768	0.848	0.795	0.828	**0.869**	0.813	0.820
08	07290650	0.886	0.908	0.863	0.917	0.878	**0.924**	0.896
09	05131500	0.842	0.764	0.839	0.547	0.611	**0.886**	0.748
10	06919500	0.879	**0.916**	0.833	0.908	0.885	0.902	0.887
11	07056000	0.792	0.861	0.835	0.812	0.700	**0.901**	0.817
12	08025500	0.819	0.821	0.780	0.874	0.737	**0.885**	0.819
13	08271000	**0.868**	0.826	0.860	0.782	0.848	0.842	0.838
14	09081600	0.849	**0.920**	0.912	0.902	0.806	0.835	0.871
15	09510200	0.649	0.677	0.661	0.726	0.795	**0.893**	0.733
16	10316500	0.869	0.776	**0.893**	0.821	0.888	0.792	0.840
17	14301000	0.899	**0.956**	0.954	0.901	0.936	0.912	0.926
18	11532500	0.801	0.923	0.908	0.795	0.891	**0.949**	0.878
	Median	0.860	0.902	0.861	0.854	0.869	0.897	0.872

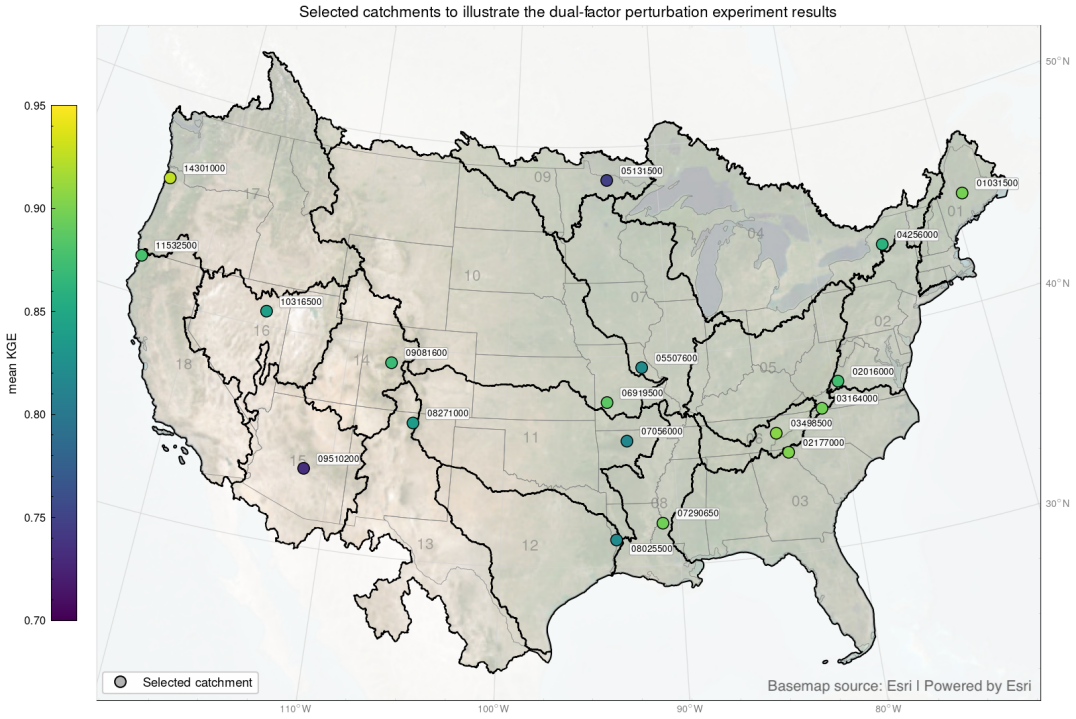


Figure S1. Location of the selected catchments. Each point is labeled with its gauge id; the color represents the KGE value. Black outlines are the HUC2 hydrologic regions. Sources: US Census Bureau, USGS, ESRI World Imagery.

Section S2 SAC-SMA + Snow-17 internal states

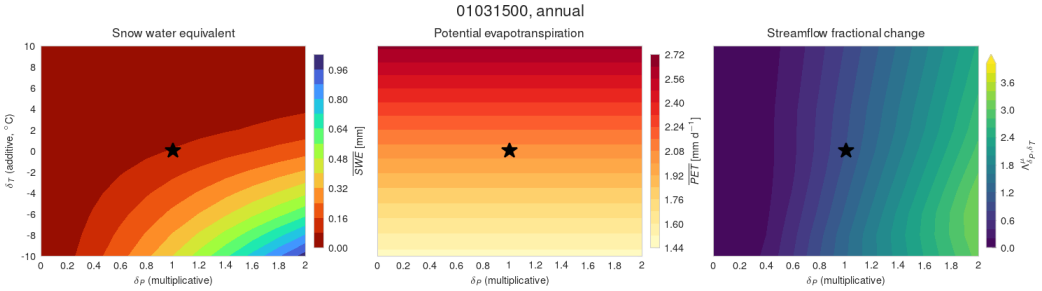


Figure S2. HUC 01: Catchment 01031500, mean KGE 0.90. Annual.

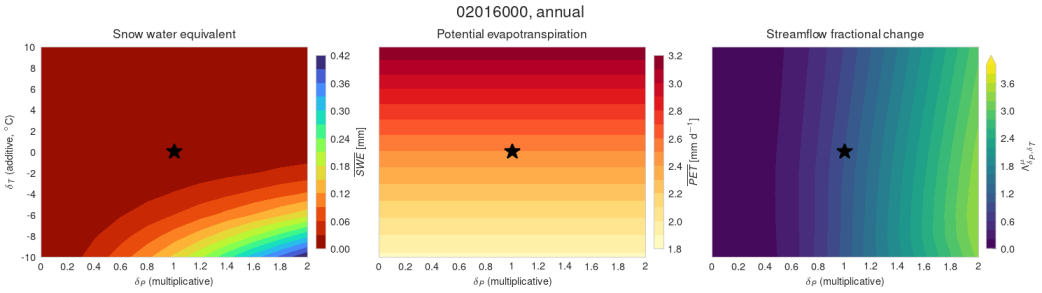


Figure S3. HUC 02: Catchment 02016000, mean KGE 0.87. Annual.

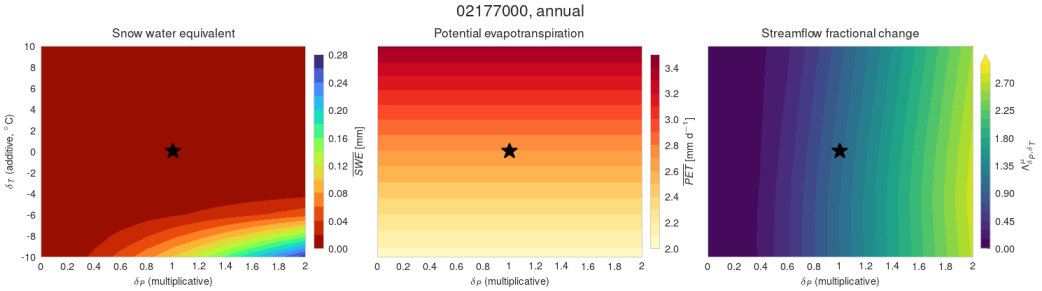


Figure S4. HUC 03: Catchment 02177000, mean KGE 0.90. Annual.

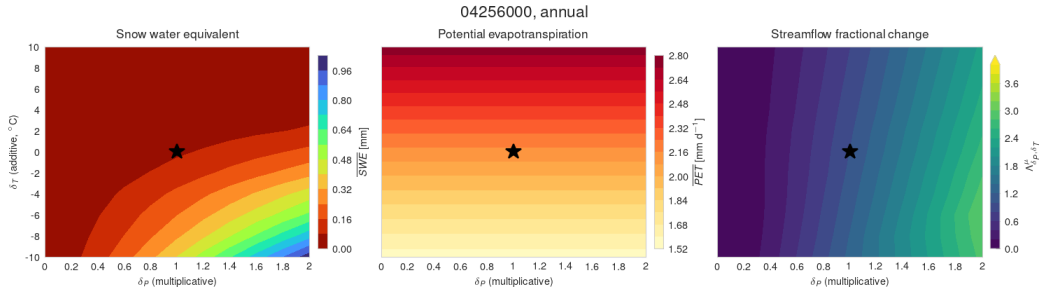


Figure S5. HUC 04: Catchment 04256000, mean KGE 0.86. Annual.

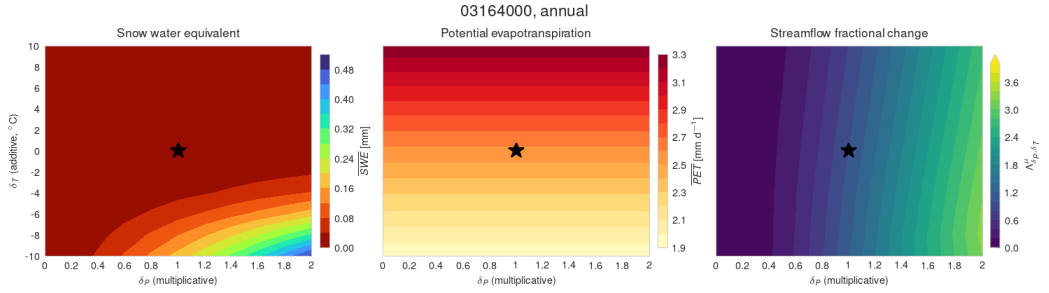


Figure S6. HUC 05: Catchment 03164000, mean KGE 0.90. Annual.

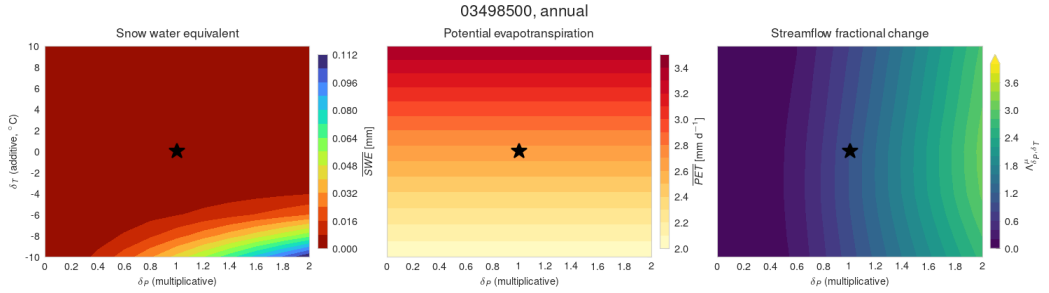


Figure S7. HUC 06: Catchment 03498500, mean KGE 0.91. Annual.

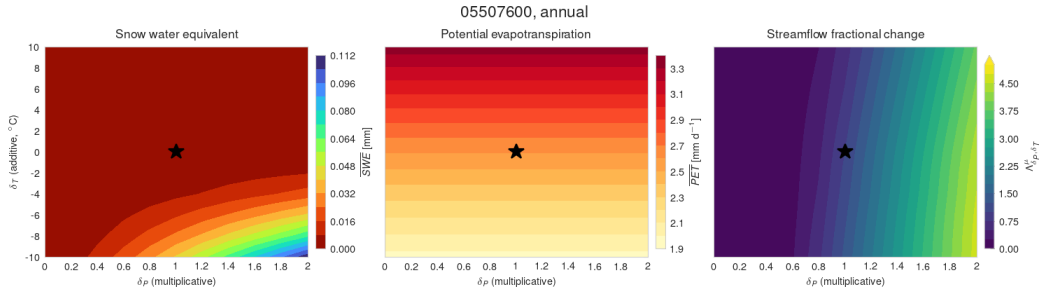


Figure S8. HUC 07: Catchment 05507600, mean KGE 0.82. Annual.

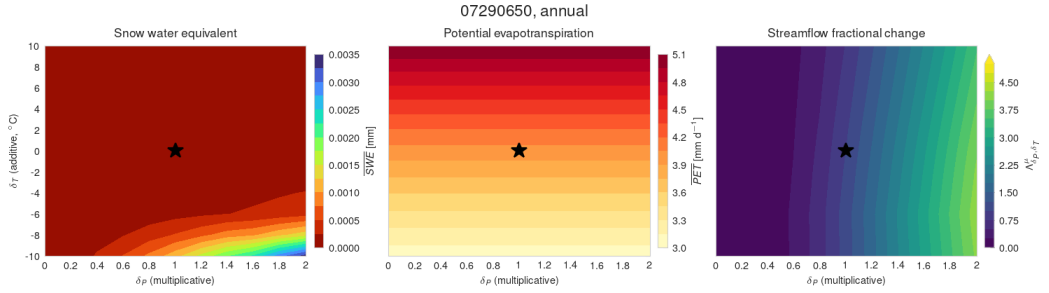


Figure S9. HUC 08: Catchment 07290650, mean KGE 0.90. Annual.

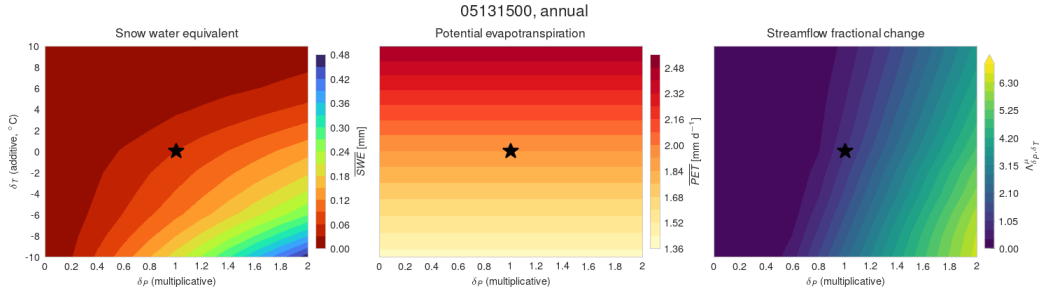


Figure S10. HUC 09: Catchment 05131500, mean KGE 0.75. Annual.

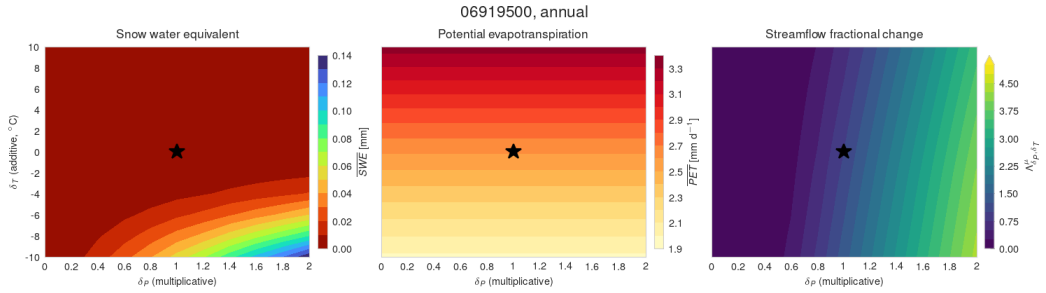


Figure S11. HUC 10: Catchment 06919500, mean KGE 0.89. Annual.

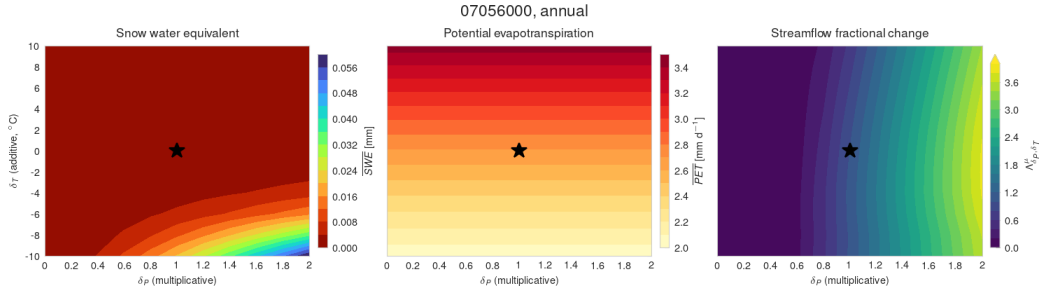


Figure S12. HUC 11: Catchment 07056000, mean KGE 0.82. Annual.

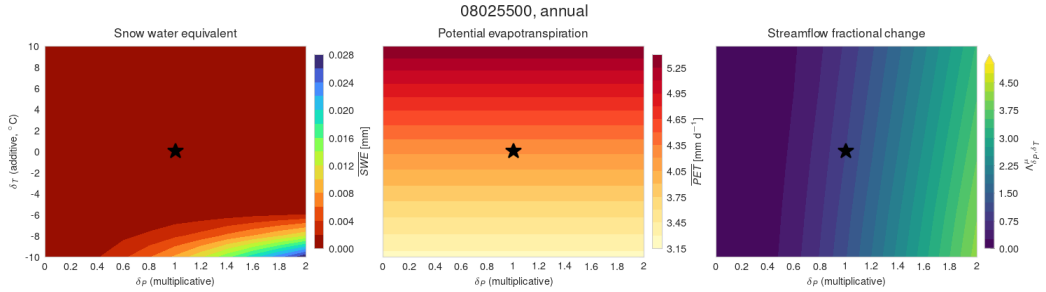


Figure S13. HUC 12: Catchment 08025500, mean KGE 0.82. Annual.

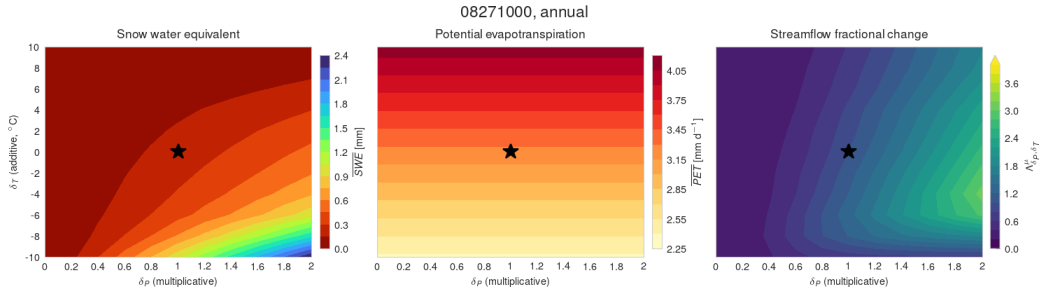


Figure S14. HUC 13: Catchment 08271000, mean KGE 0.84. Annual.

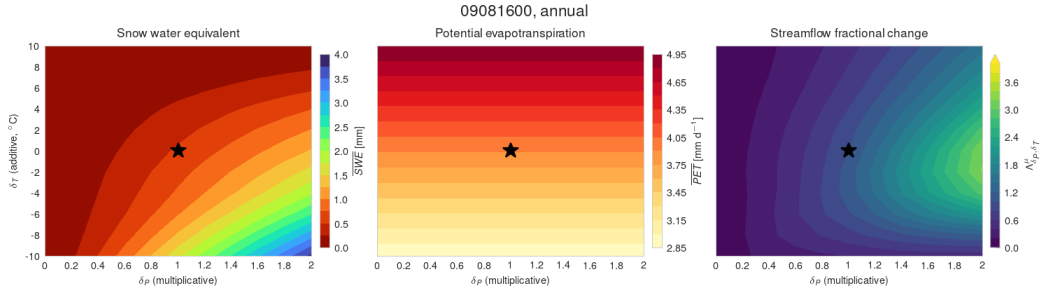


Figure S15. HUC 14: Catchment 09081600, mean KGE 0.87. Annual.

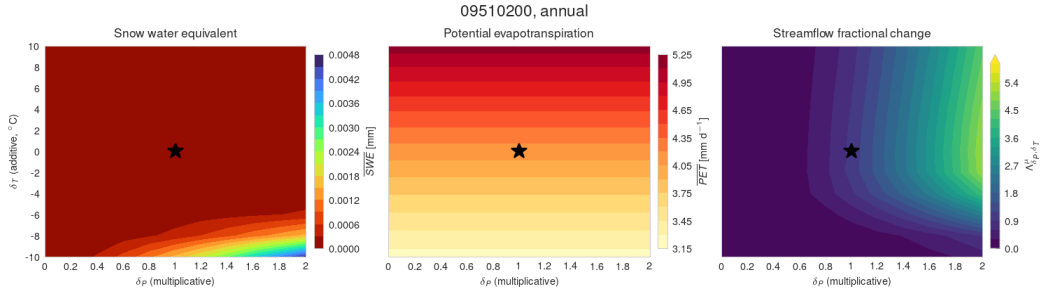


Figure S16. HUC 15: Catchment 09510200, mean KGE 0.73. Annual.

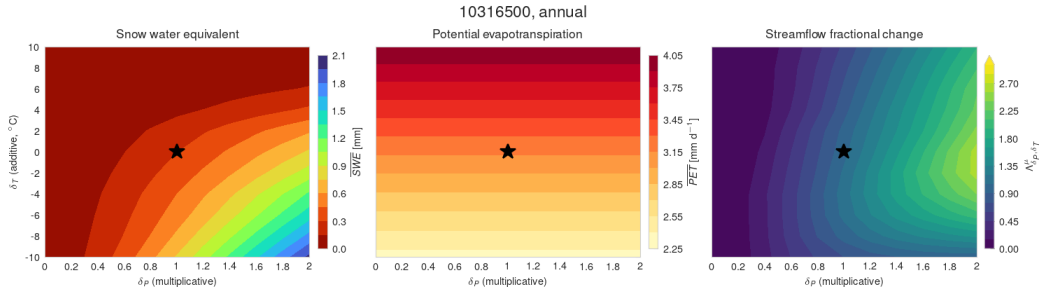


Figure S17. HUC 16: Catchment 10316500, mean KGE 0.84. Annual.

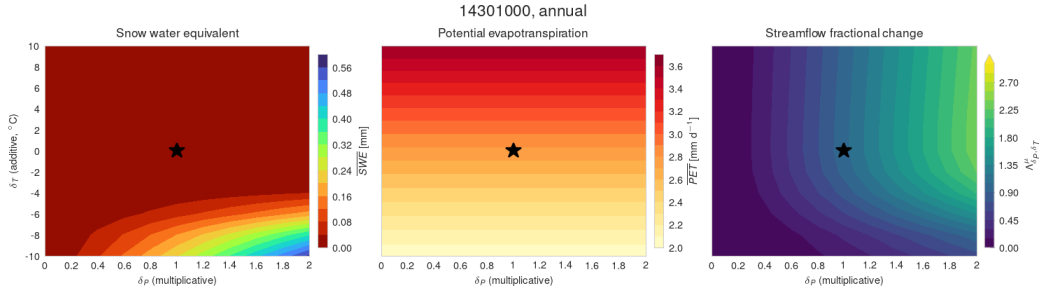


Figure S18. HUC 17: Catchment 14301000, mean KGE 0.93. Annual.

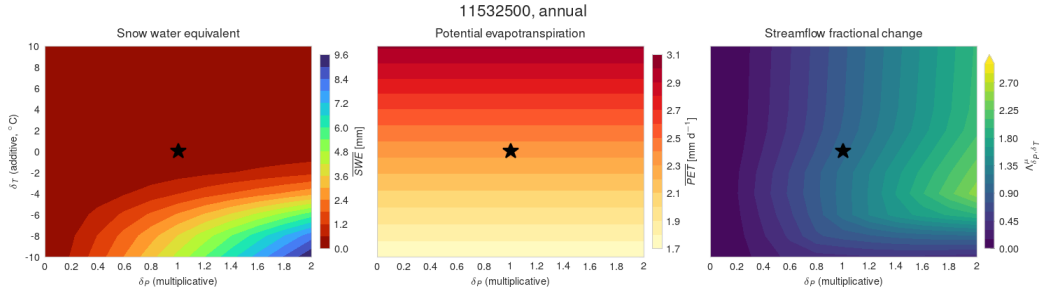


Figure S19. HUC 18: Catchment 11532500, mean KGE 0.88. Annual.

Section S3 Fractional change $\Lambda^{\mu}_{\delta_P,\delta_T}$ across models

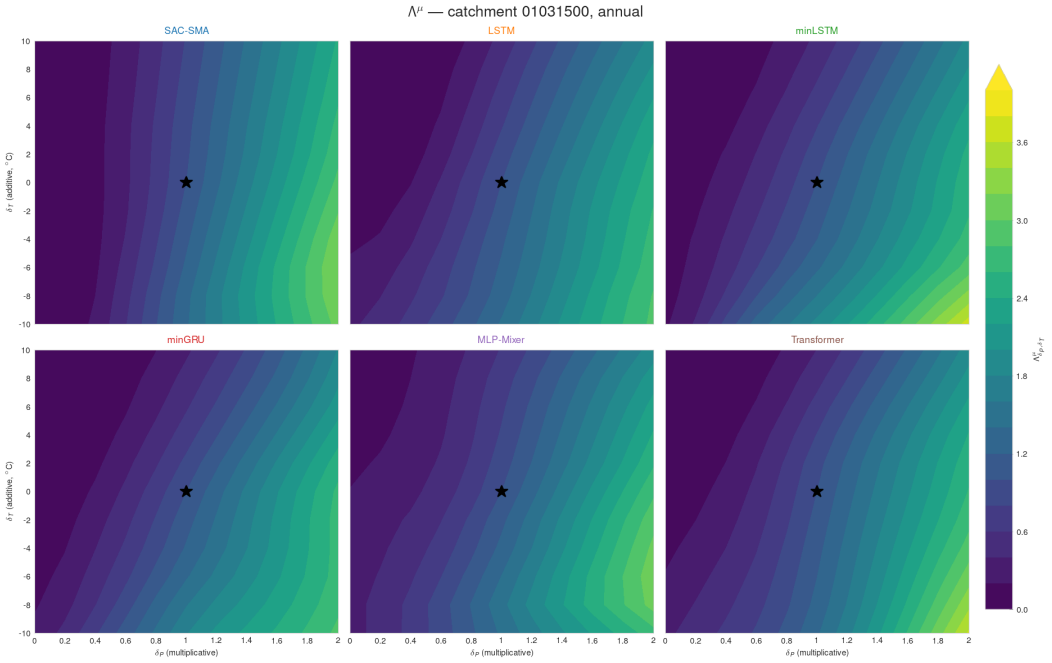


Figure S20. HUC 01: Catchment 01031500, mean KGE 0.90. Annual.

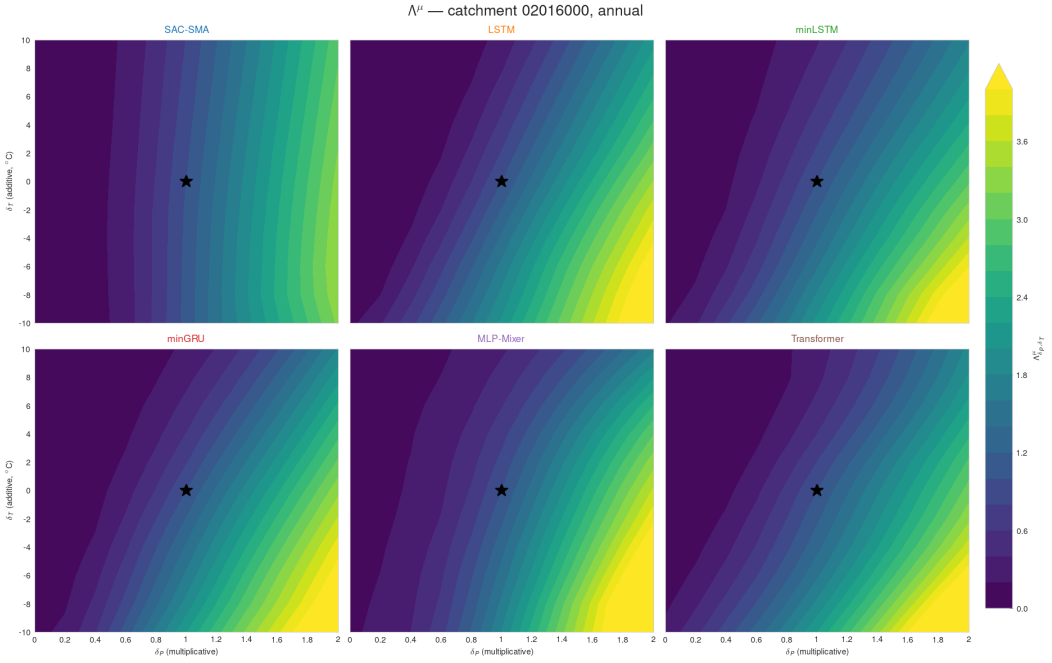


Figure S21. HUC 02: Catchment 02016000, mean KGE 0.87. Annual.

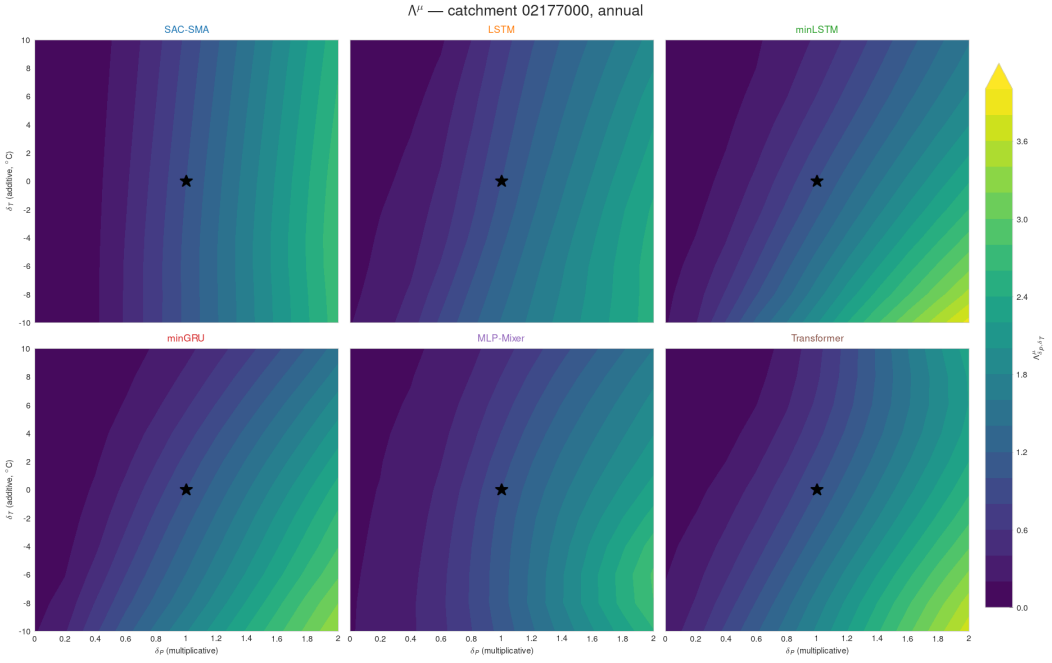


Figure S22. HUC 03: Catchment 02177000, mean KGE 0.90. Annual.

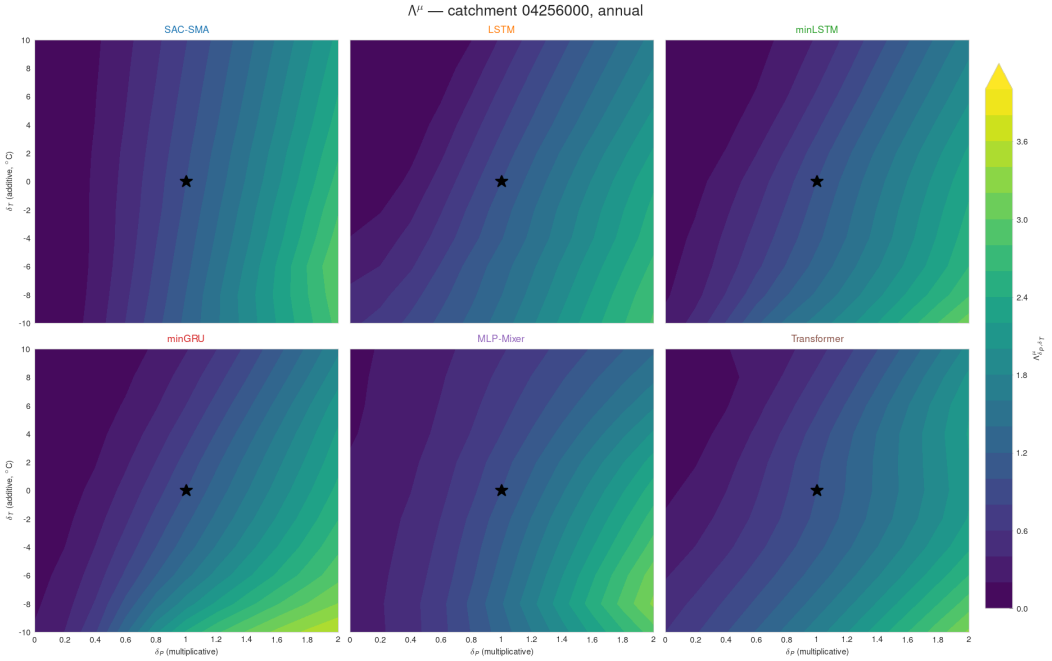


Figure S23. HUC 04: Catchment 04256000, mean KGE 0.86. Annual.

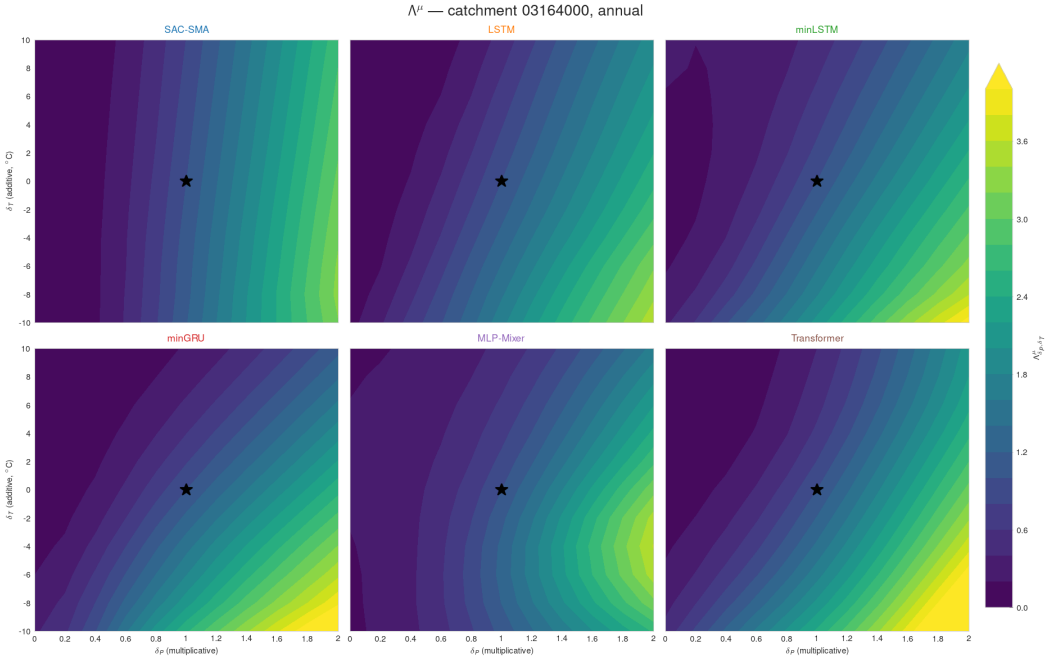


Figure S24. HUC 05: Catchment 03164000, mean KGE 0.90. Annual.

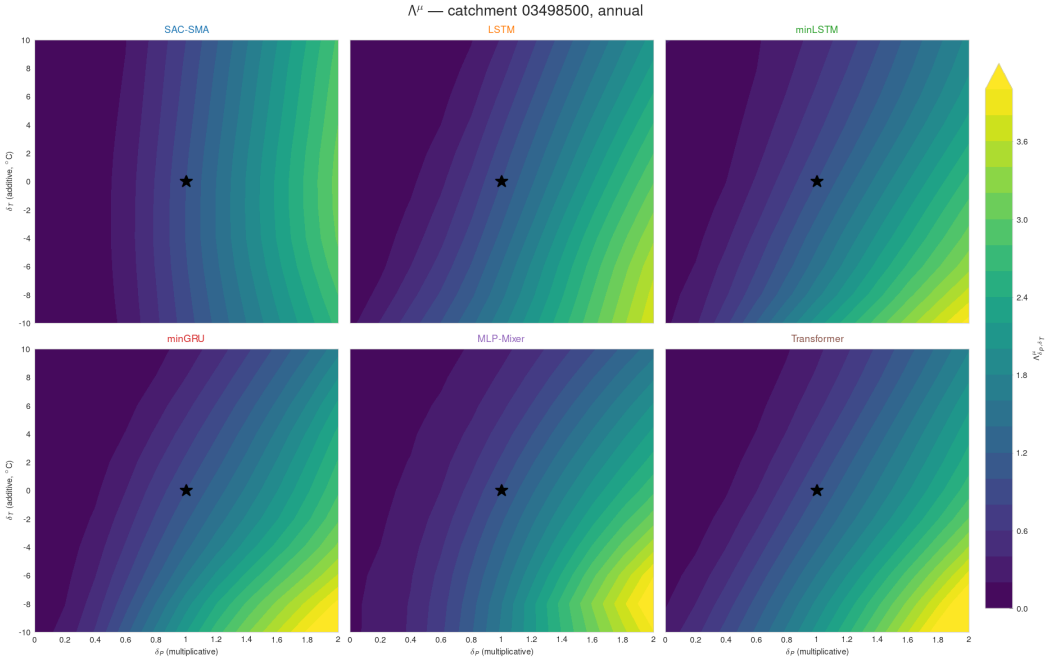


Figure S25. HUC 06: Catchment 03498500, mean KGE 0.91. Annual.

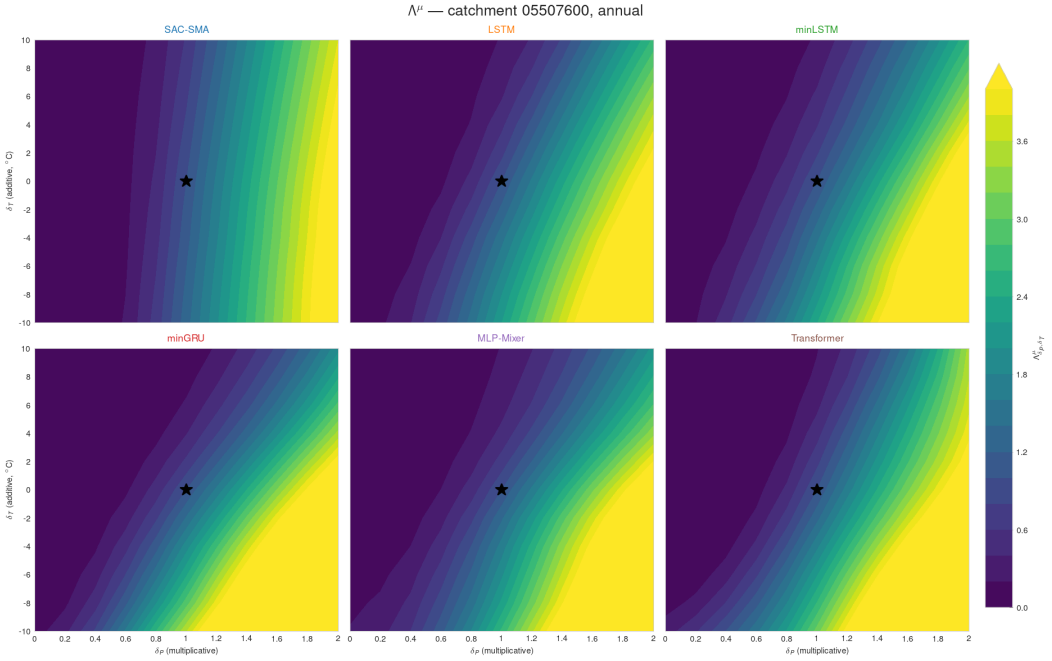


Figure S26. HUC 07: Catchment 05507600, mean KGE 0.82. Annual.

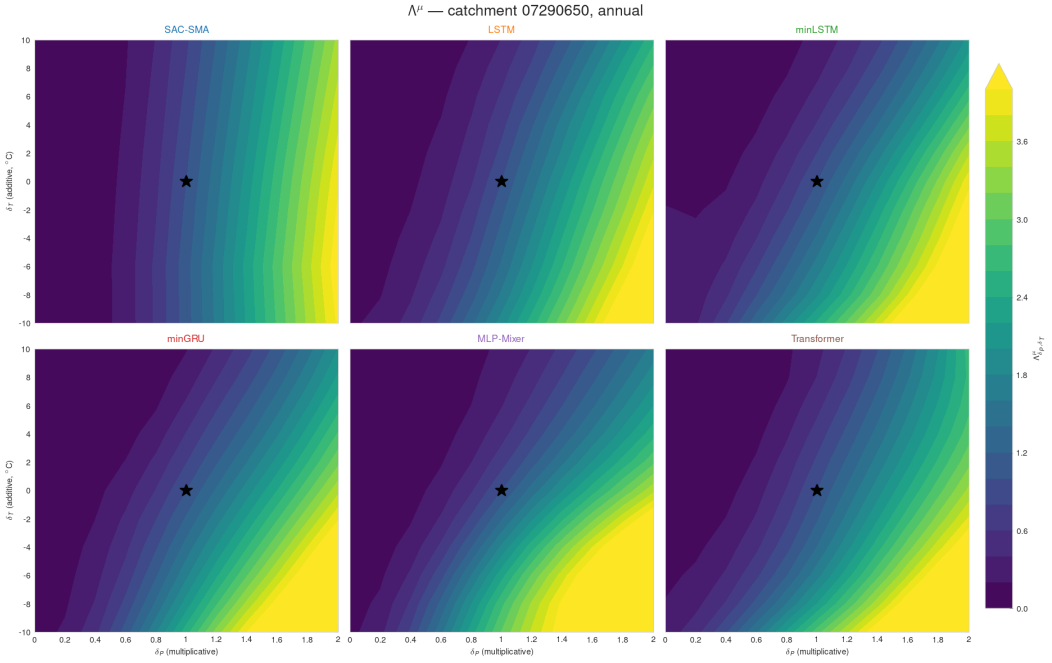


Figure S27. HUC 08: Catchment 07290650, mean KGE 0.90. Annual.

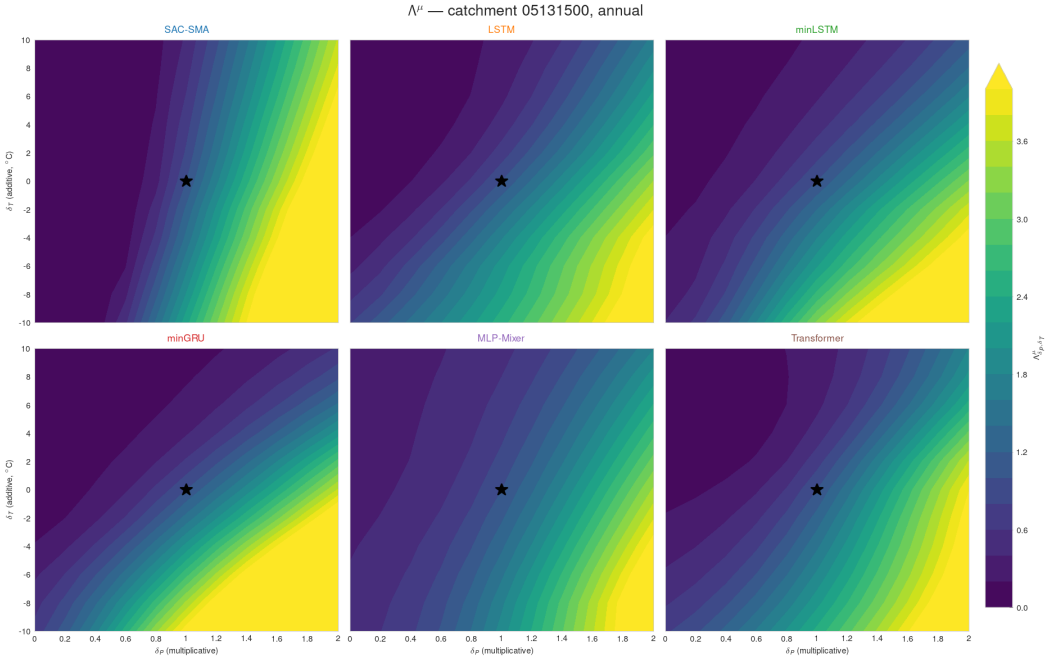


Figure S28. HUC 09: Catchment 05131500, mean KGE 0.75. Annual.

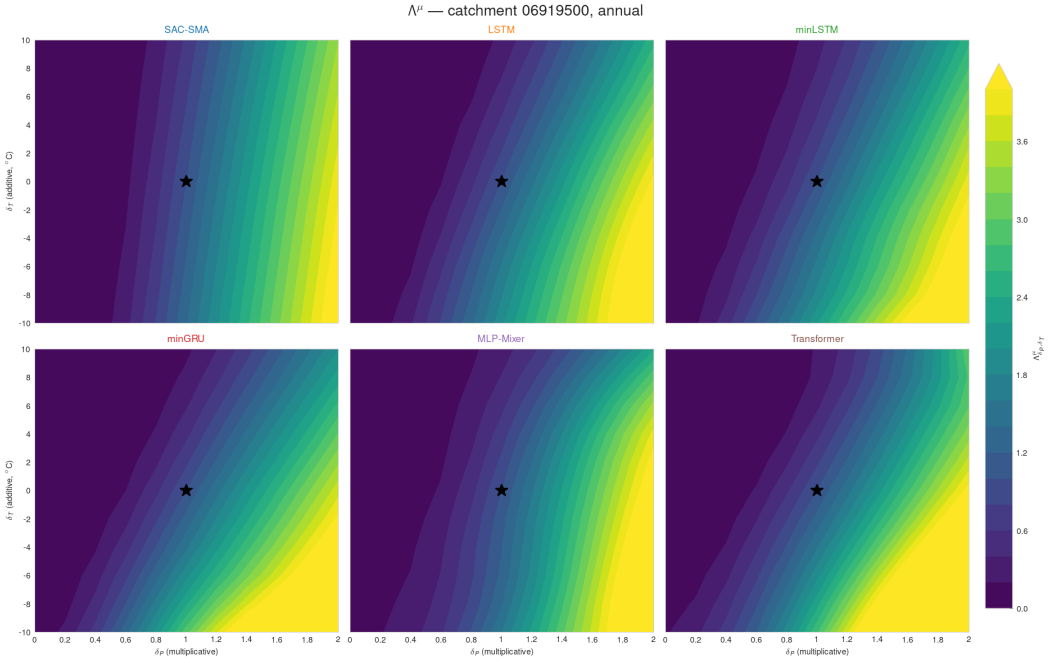


Figure S29. HUC 10: Catchment 06919500, mean KGE 0.89. Annual.

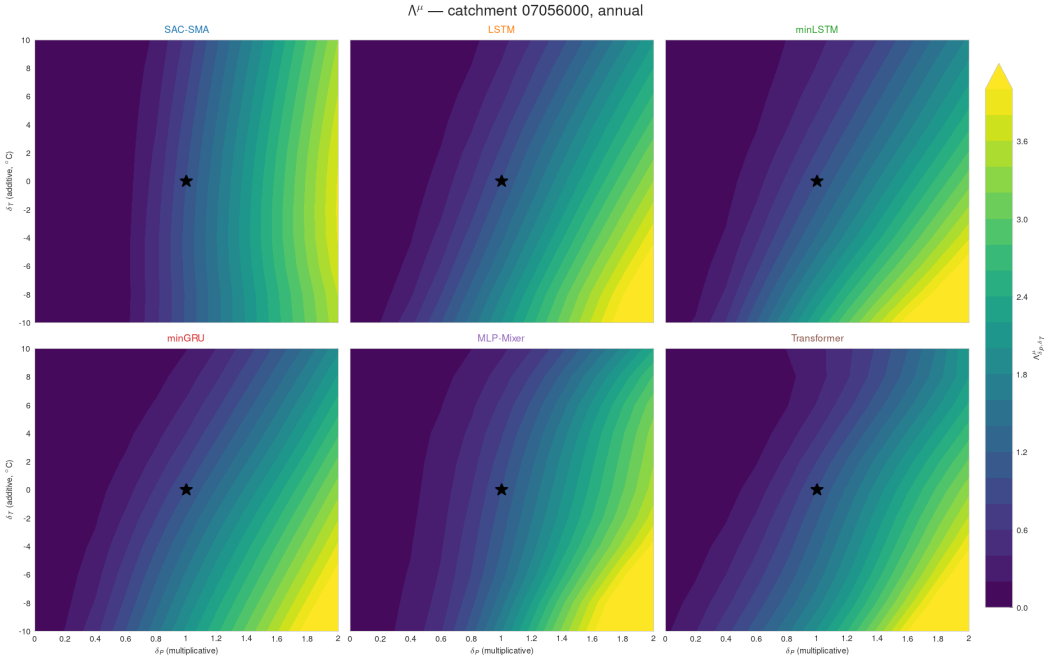


Figure S30. HUC 11: Catchment 07056000, mean KGE 0.82. Annual.

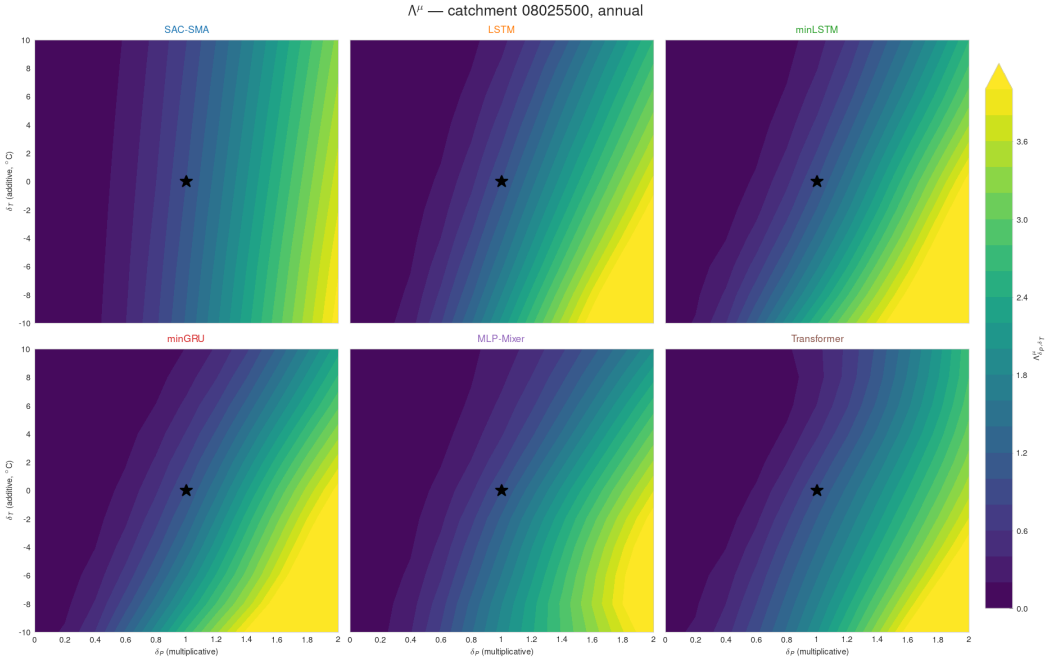


Figure S31. HUC 12: Catchment 08025500, mean KGE 0.82. Annual.

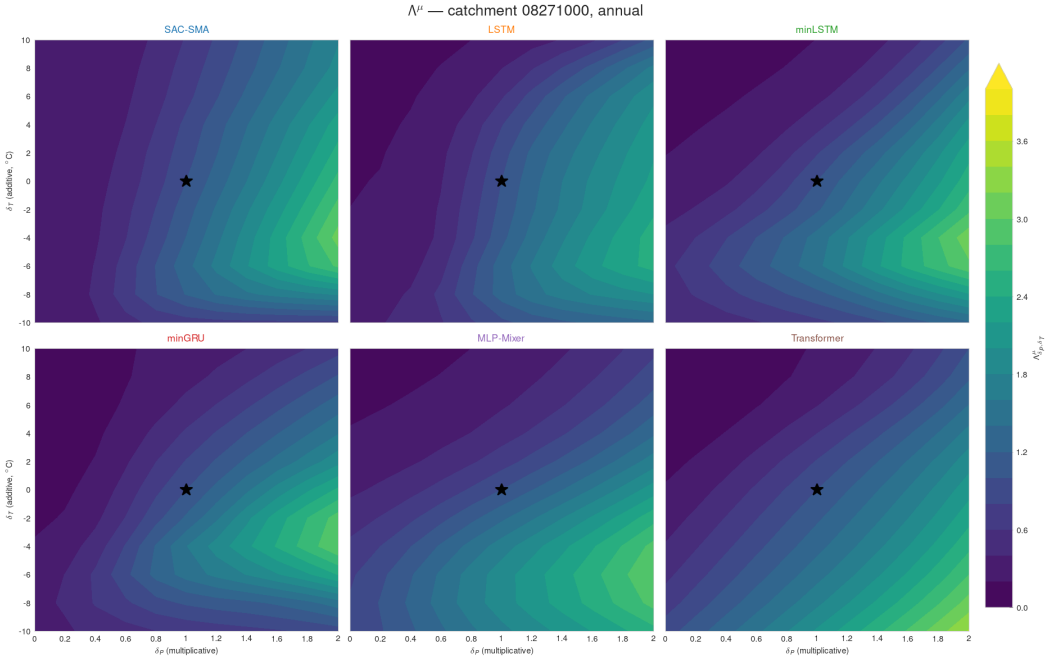


Figure S32. HUC 13: Catchment 08271000, mean KGE 0.84. Annual.

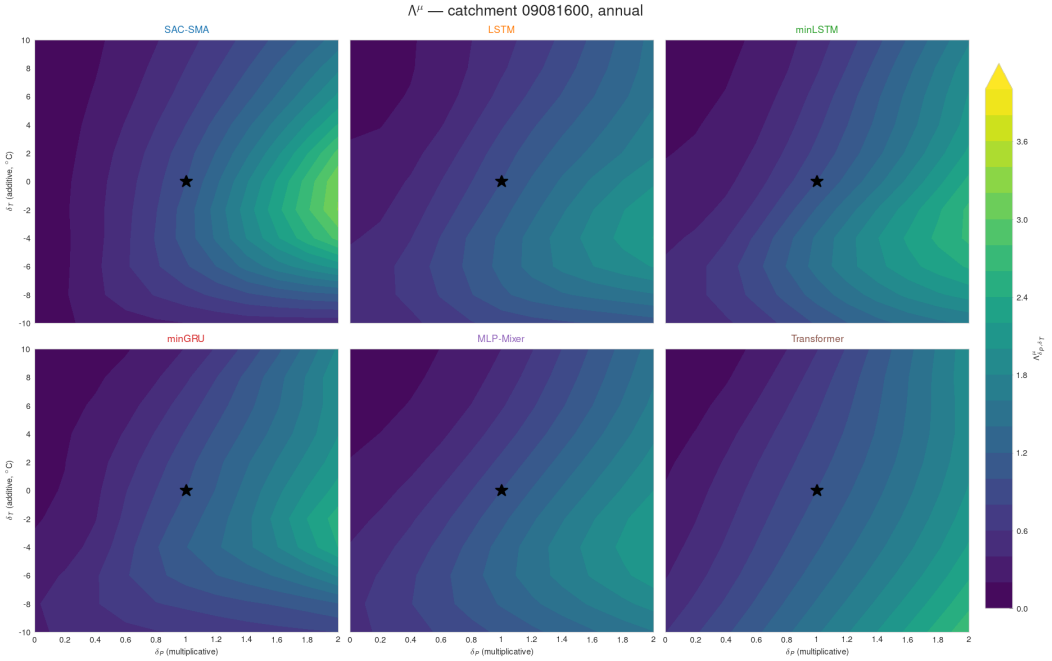


Figure S33. HUC 14: Catchment 09081600, mean KGE 0.87. Annual.

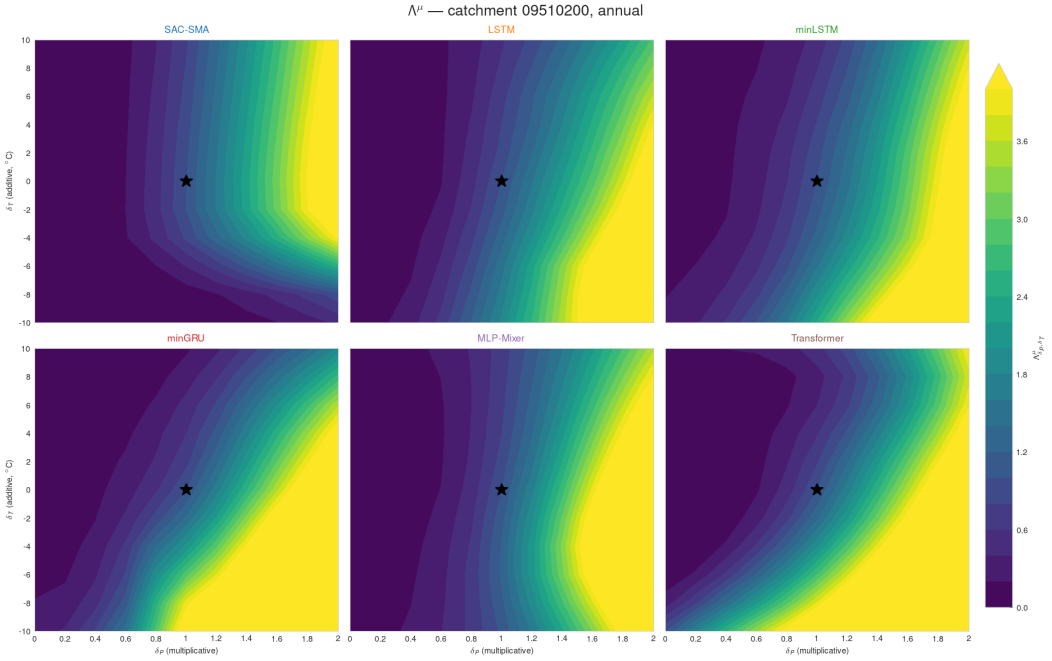


Figure S34. HUC 15: Catchment 09510200, mean KGE 0.73. Annual.

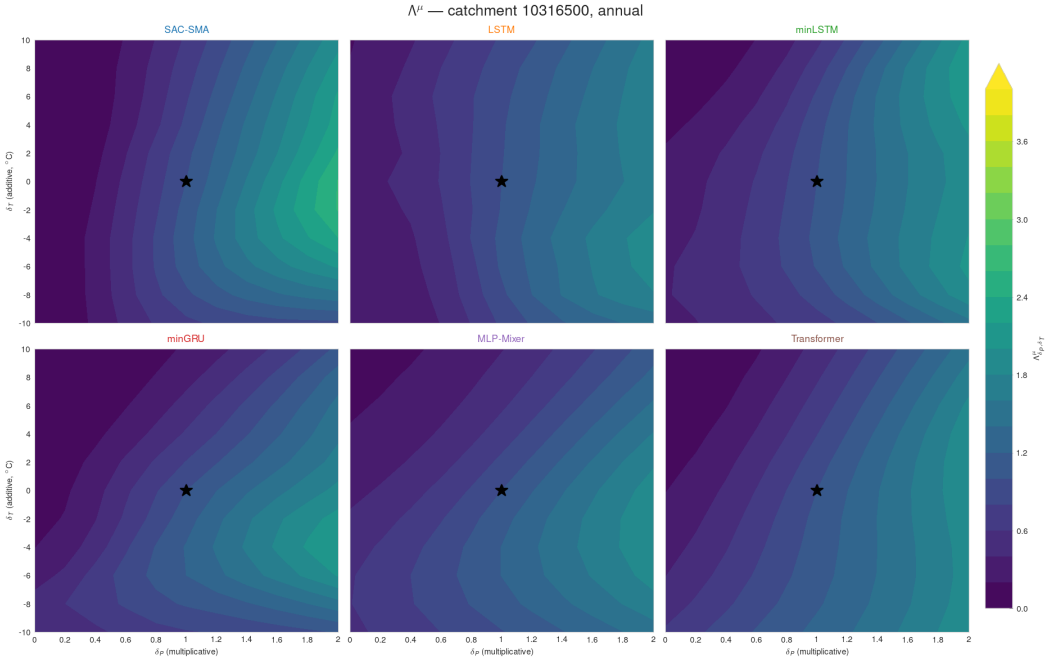


Figure S35. HUC 16: Catchment 10316500, mean KGE 0.84. Annual.

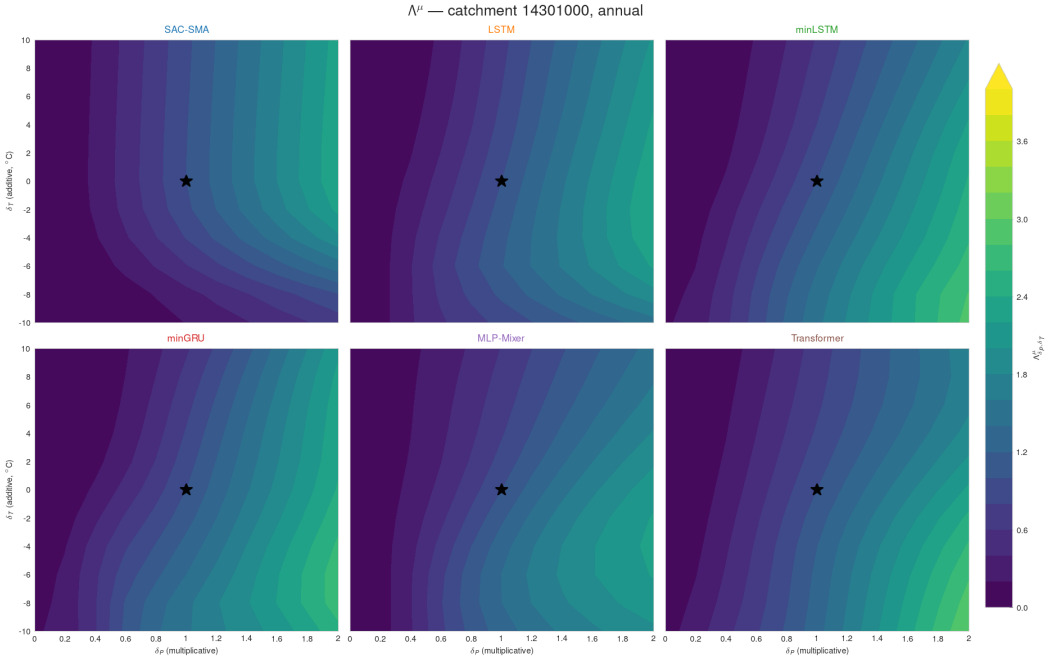


Figure S36. HUC 17: Catchment 14301000, mean KGE 0.93. Annual.

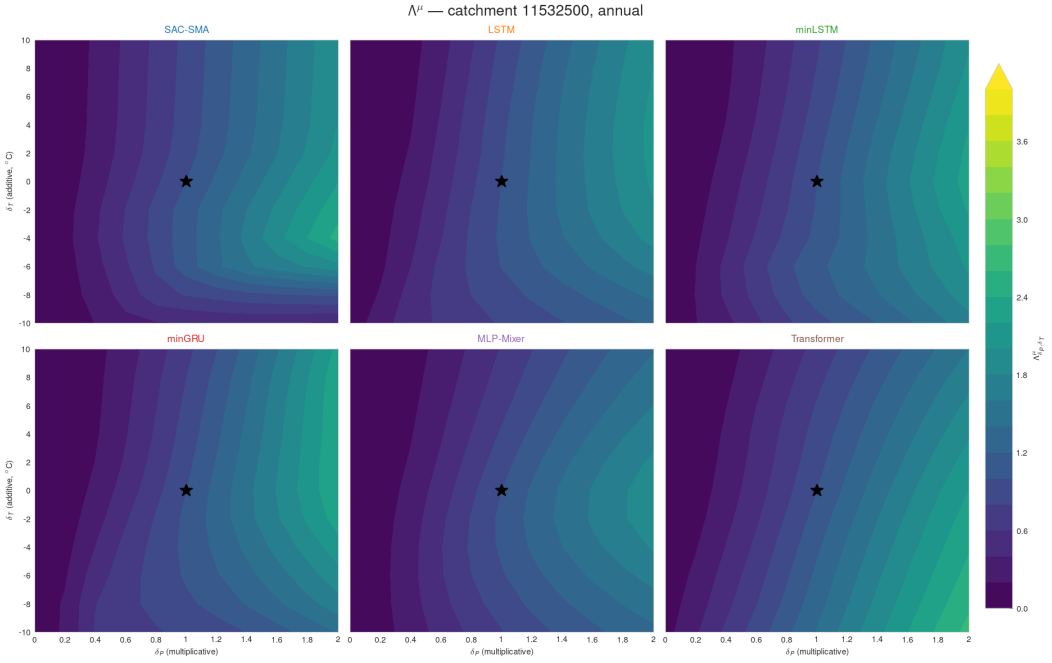


Figure S37. HUC 18: Catchment 11532500, mean KGE 0.88. Annual.

Section S4 Response transects

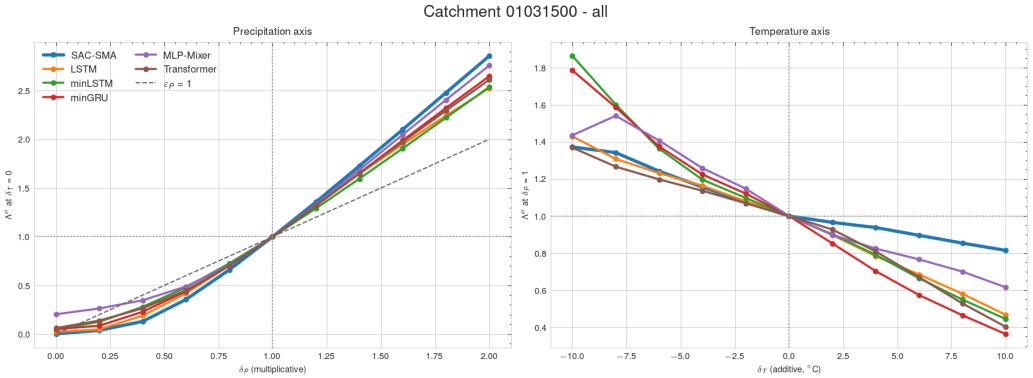


Figure S38. HUC 01: Catchment 01031500, mean KGE 0.90. Annual.

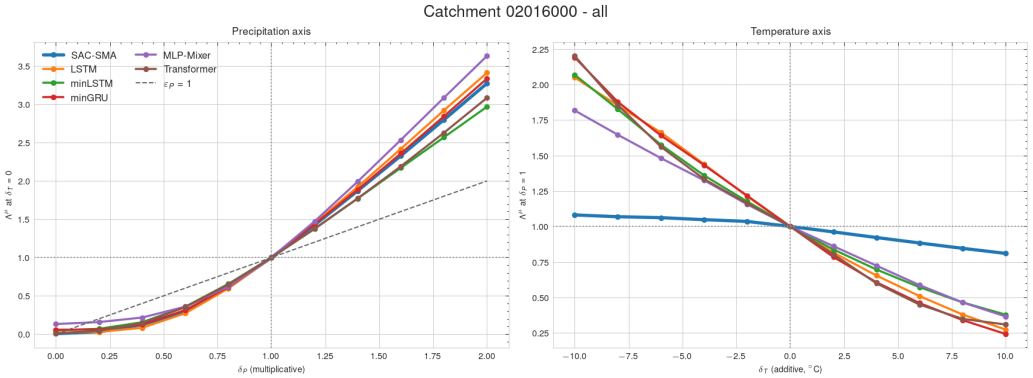


Figure S39. HUC 02: Catchment 02016000, mean KGE 0.87. Annual.

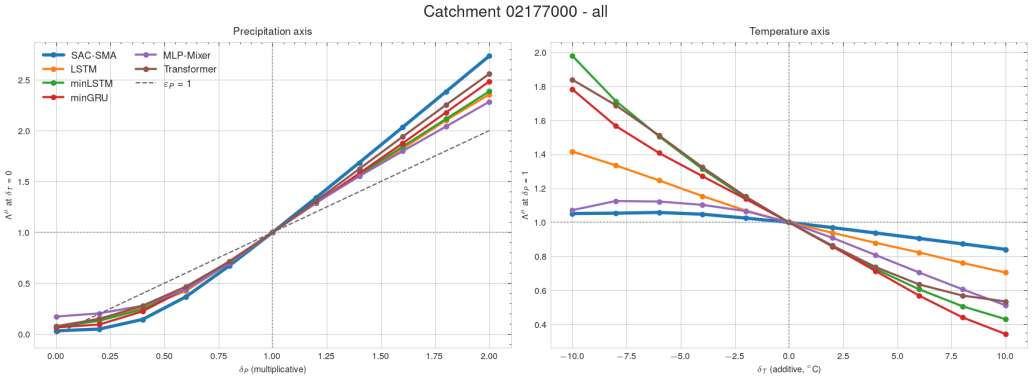


Figure S40. HUC 03: Catchment 02177000, mean KGE 0.90. Annual.

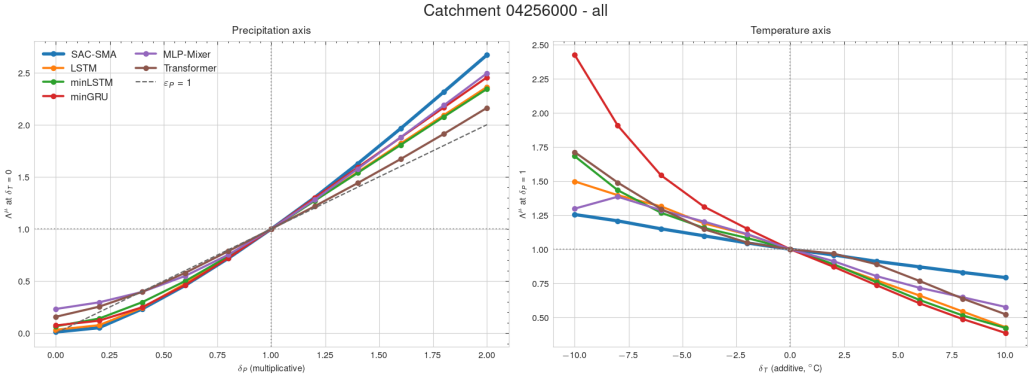


Figure S41. HUC 04: Catchment 04256000, mean KGE 0.86. Annual.

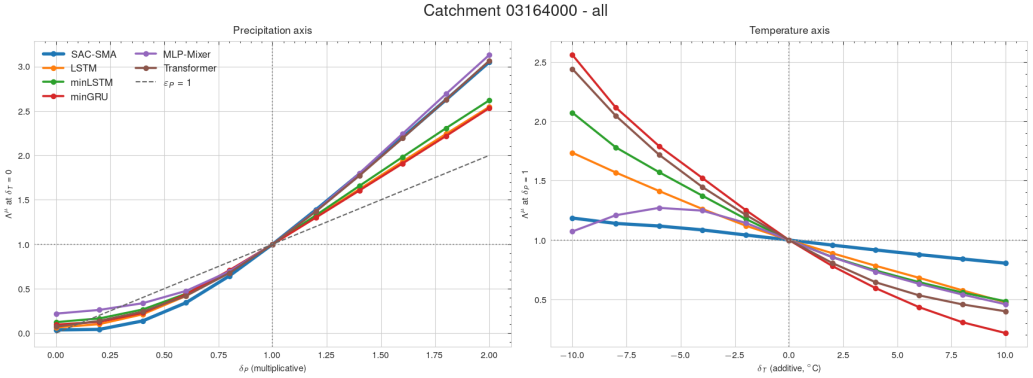


Figure S42. HUC 05: Catchment 03164000, mean KGE 0.90. Annual.

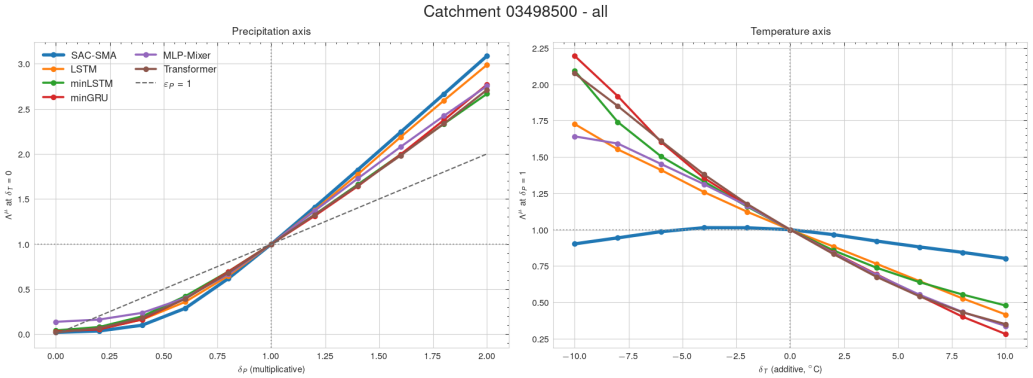


Figure S43. HUC 06: Catchment 03498500, mean KGE 0.91. Annual.

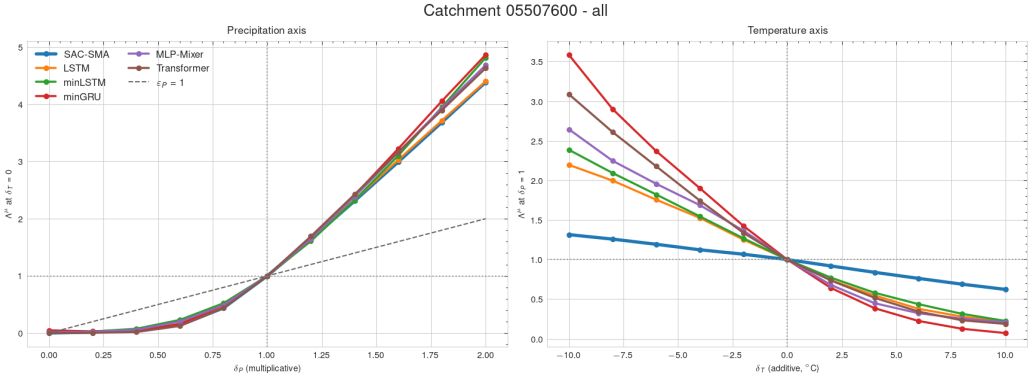


Figure S44. HUC 07: Catchment 05507600, mean KGE 0.82. Annual.

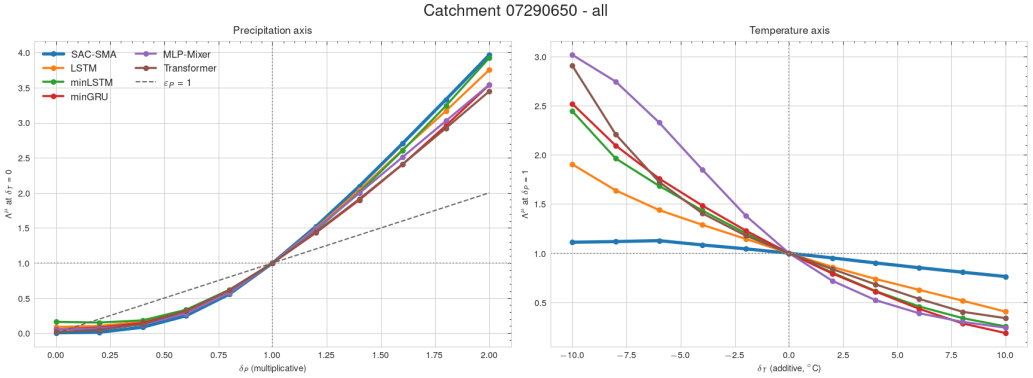


Figure S45. HUC 08: Catchment 07290650, mean KGE 0.90. Annual.

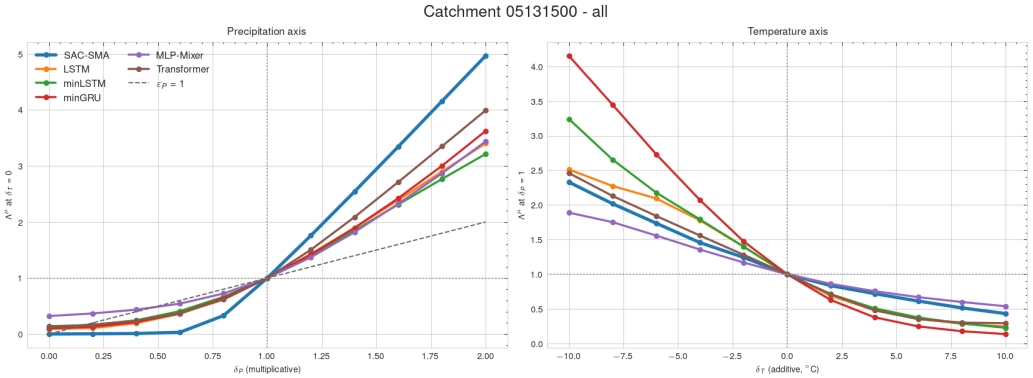


Figure S46. HUC 09: Catchment 05131500, mean KGE 0.75. Annual.

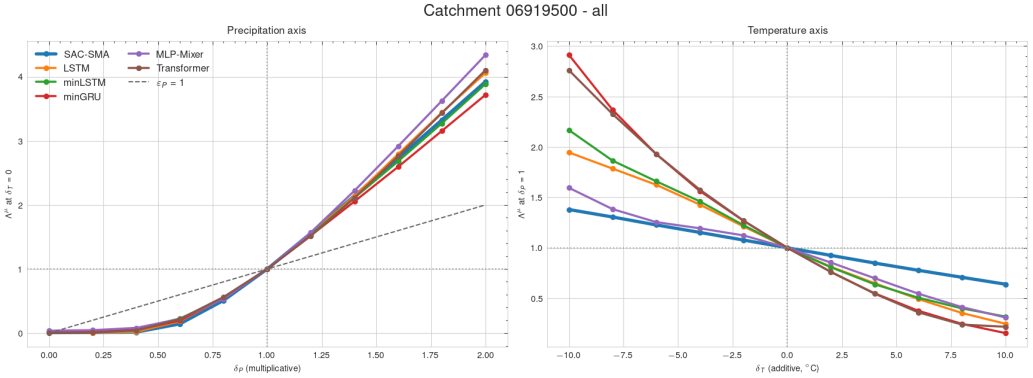


Figure S47. HUC 10: Catchment 06919500, mean KGE 0.89. Annual.

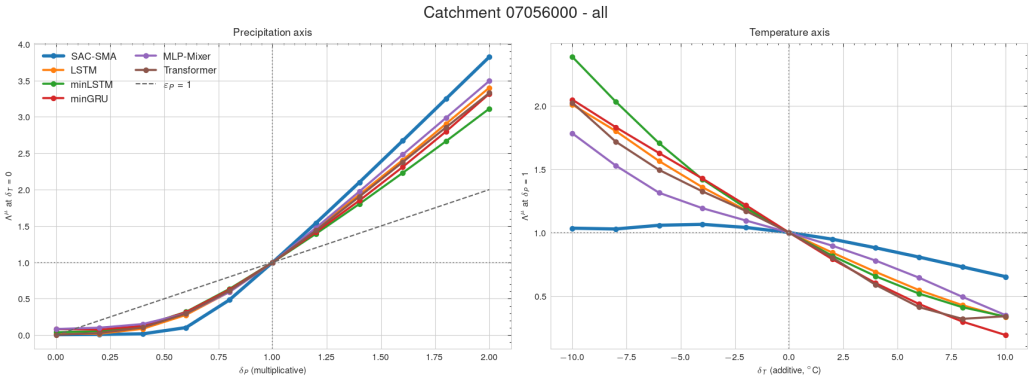


Figure S48. HUC 11: Catchment 07056000, mean KGE 0.82. Annual.

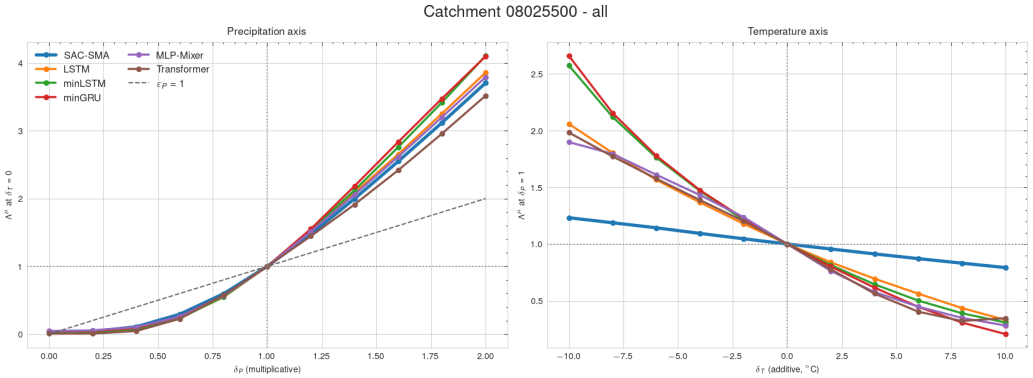


Figure S49. HUC 12: Catchment 08025500, mean KGE 0.82. Annual.

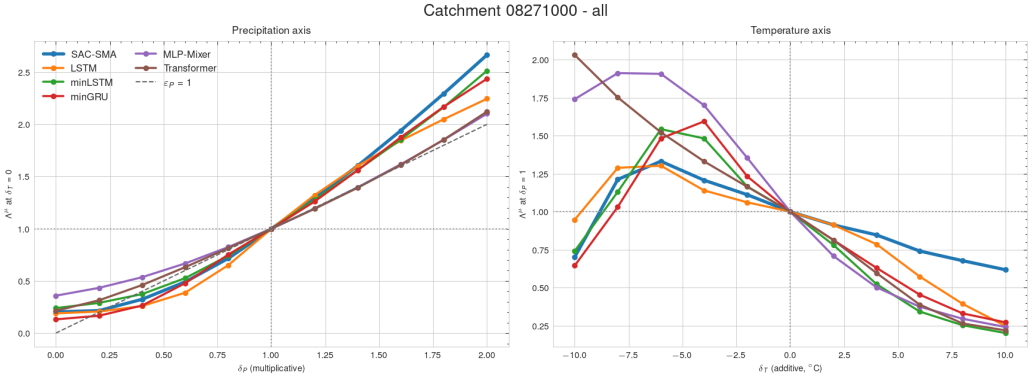


Figure S50. HUC 13: Catchment 08271000, mean KGE 0.84. Annual.

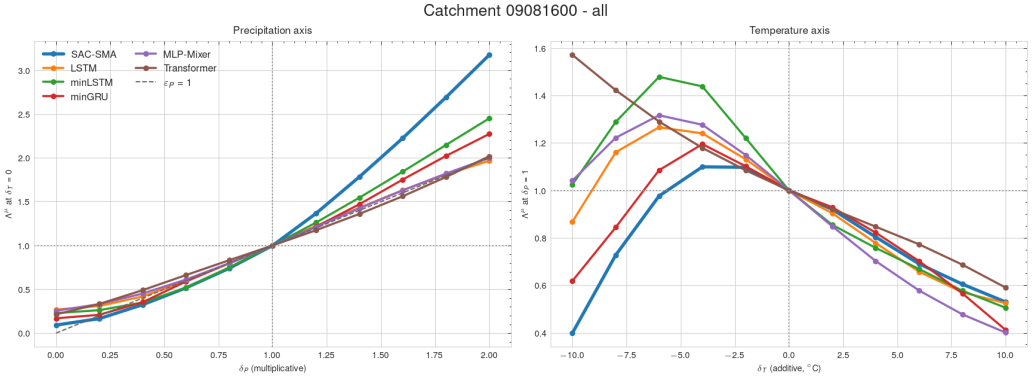


Figure S51. HUC 14: Catchment 09081600, mean KGE 0.87. Annual.

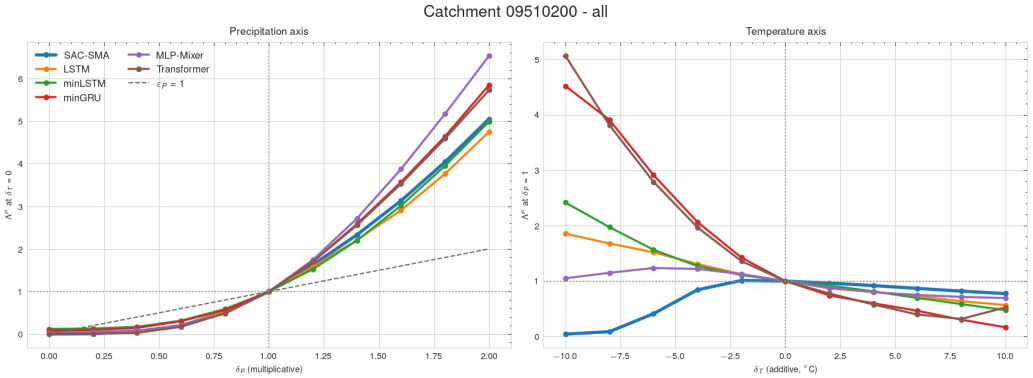


Figure S52. HUC 15: Catchment 09510200, mean KGE 0.73. Annual.

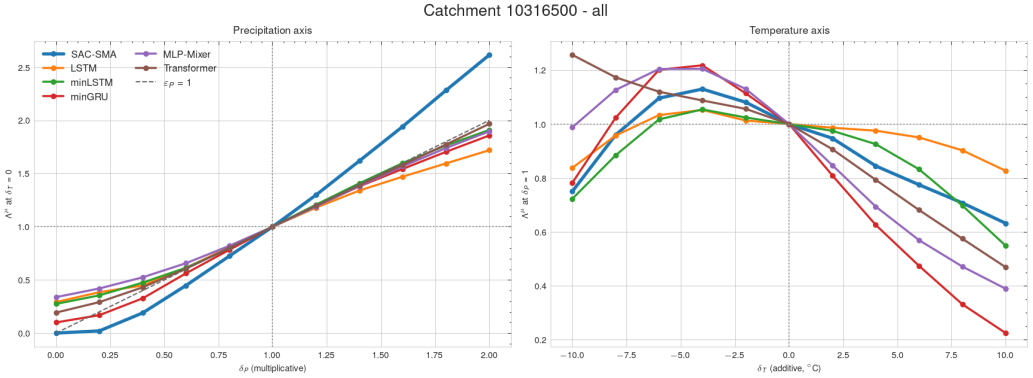


Figure S53. HUC 16: Catchment 10316500, mean KGE 0.84. Annual.

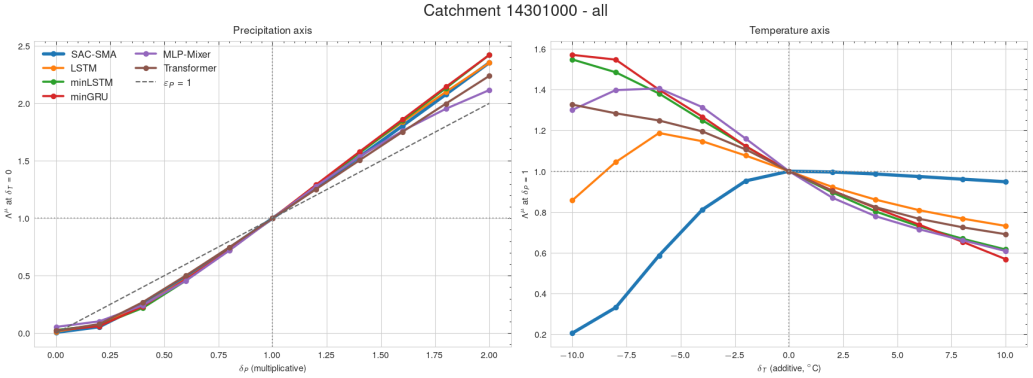


Figure S54. HUC 17: Catchment 14301000, mean KGE 0.93. Annual.

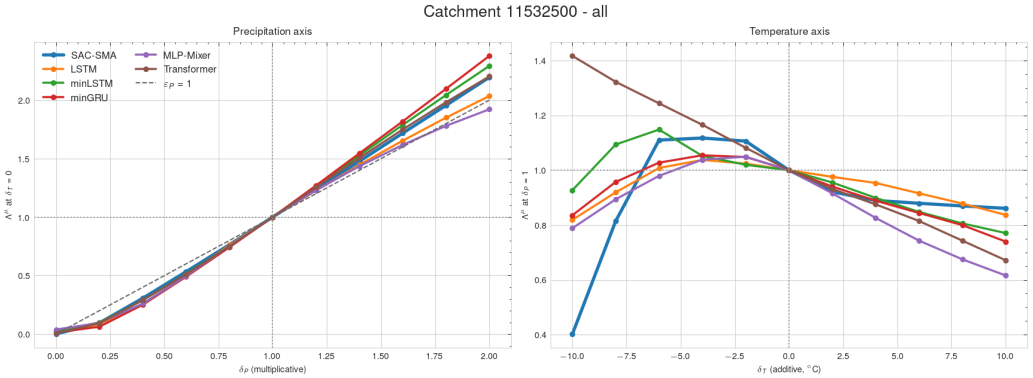


Figure S55. HUC 18: Catchment 11532500, mean KGE 0.88. Annual.

Section S5 Day-of-year climatology divergence

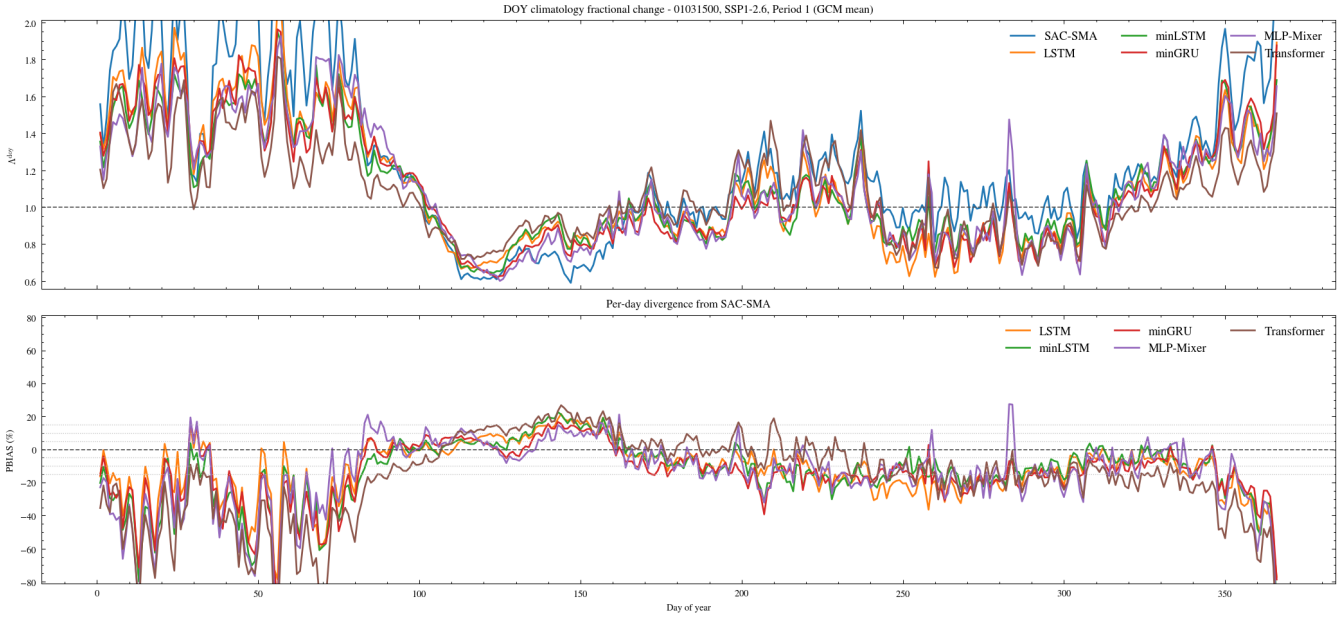


Figure S56. HUC 01: Catchment 01031500, scenario SSP1-2.6, period 2015–2045

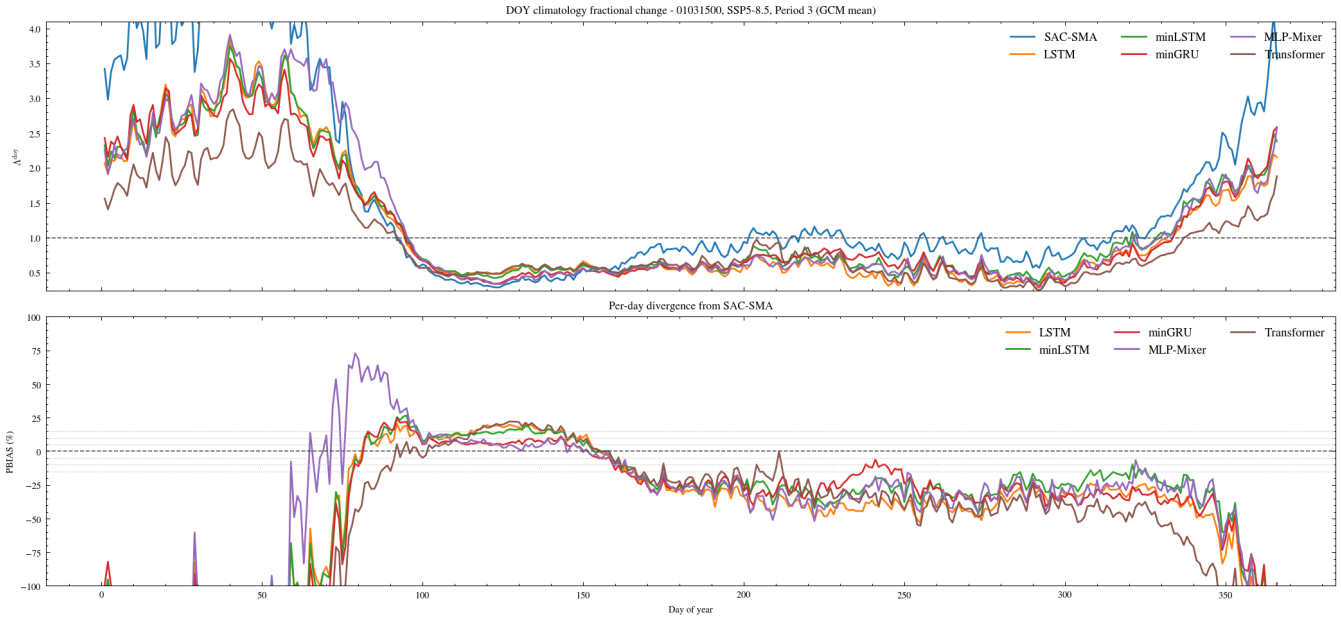


Figure S57. HUC 01: Catchment 01031500, scenario SSP5-8.5, period 2071-2100

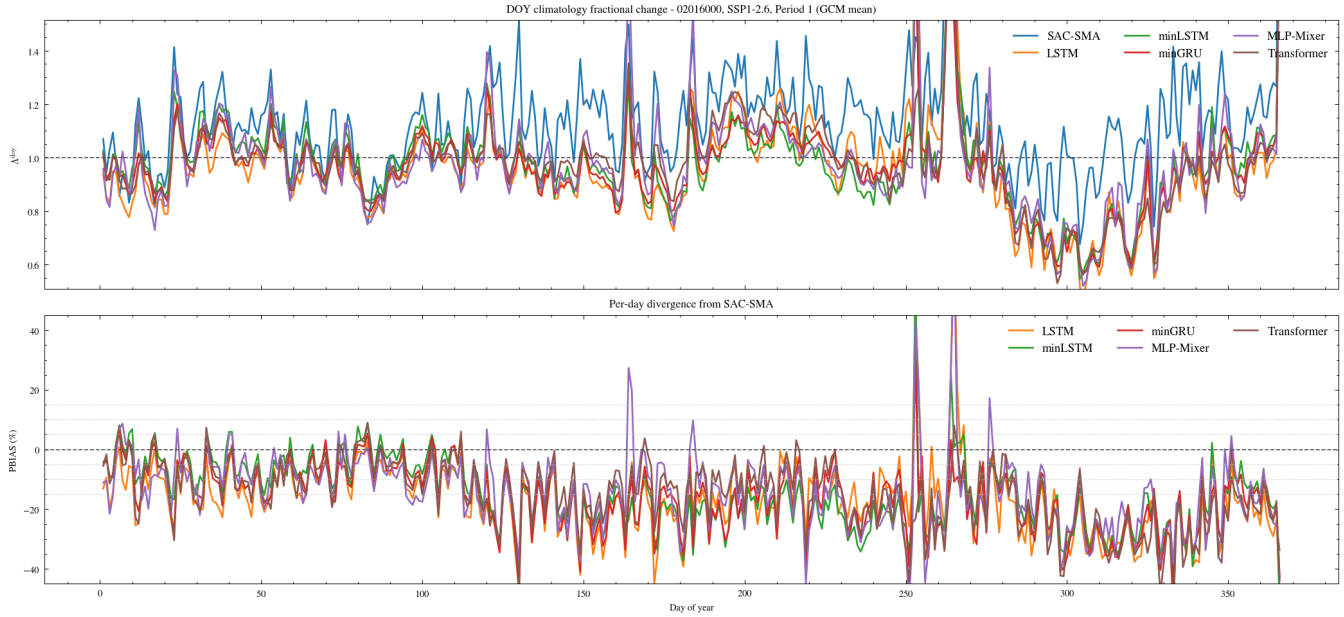


Figure S58. HUC 02: Catchment 02016000, scenario SSP1-2.6, period 2015–2045

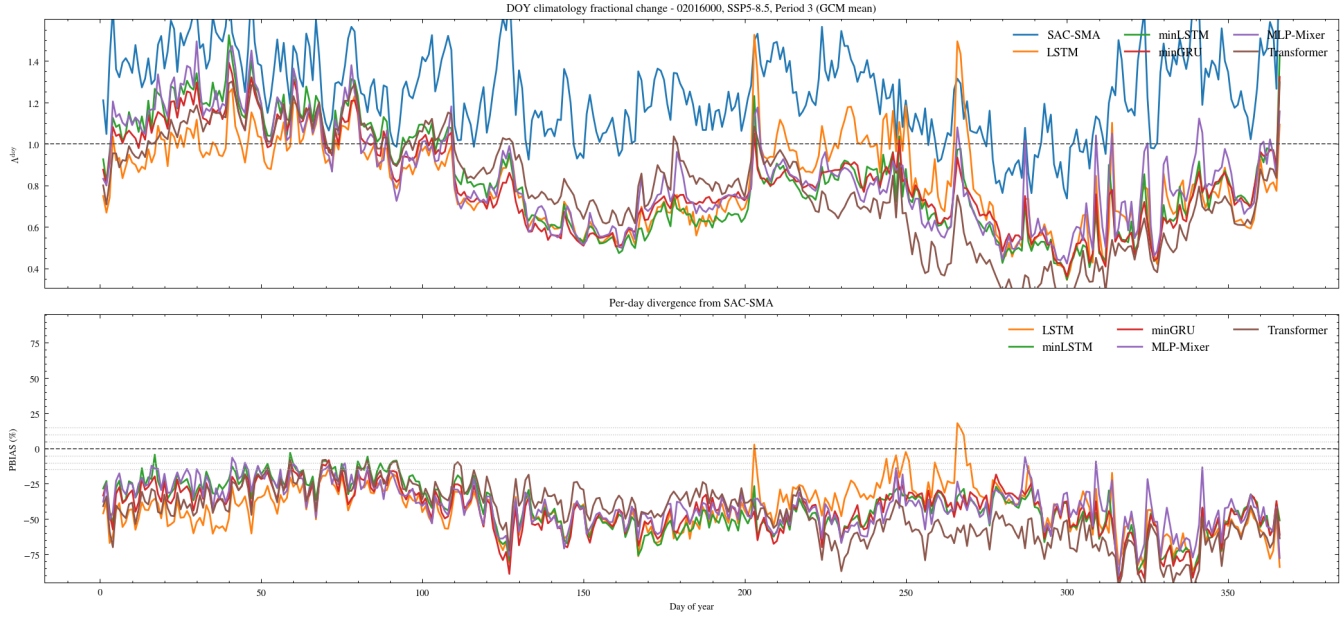


Figure S59. HUC 02: Catchment 02016000, scenario SSP5-8.5, period 2071-2100

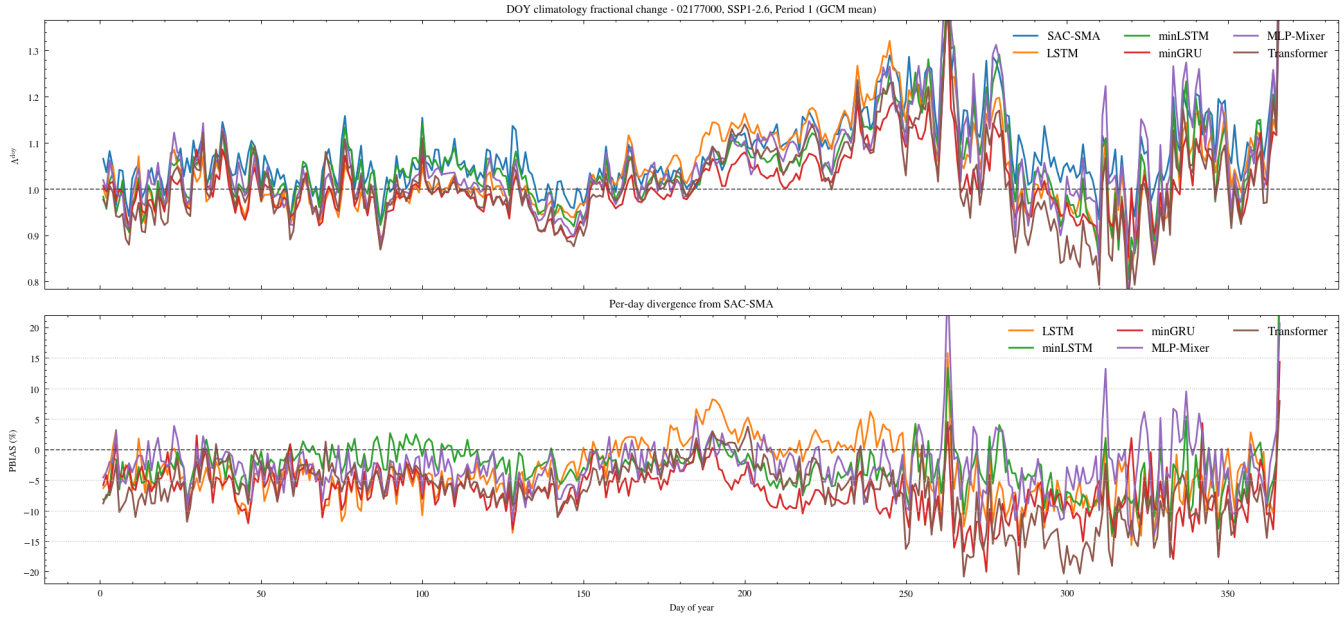


Figure S60. HUC 03: Catchment 02177000, scenario SSP1-2.6, period 2015–2045

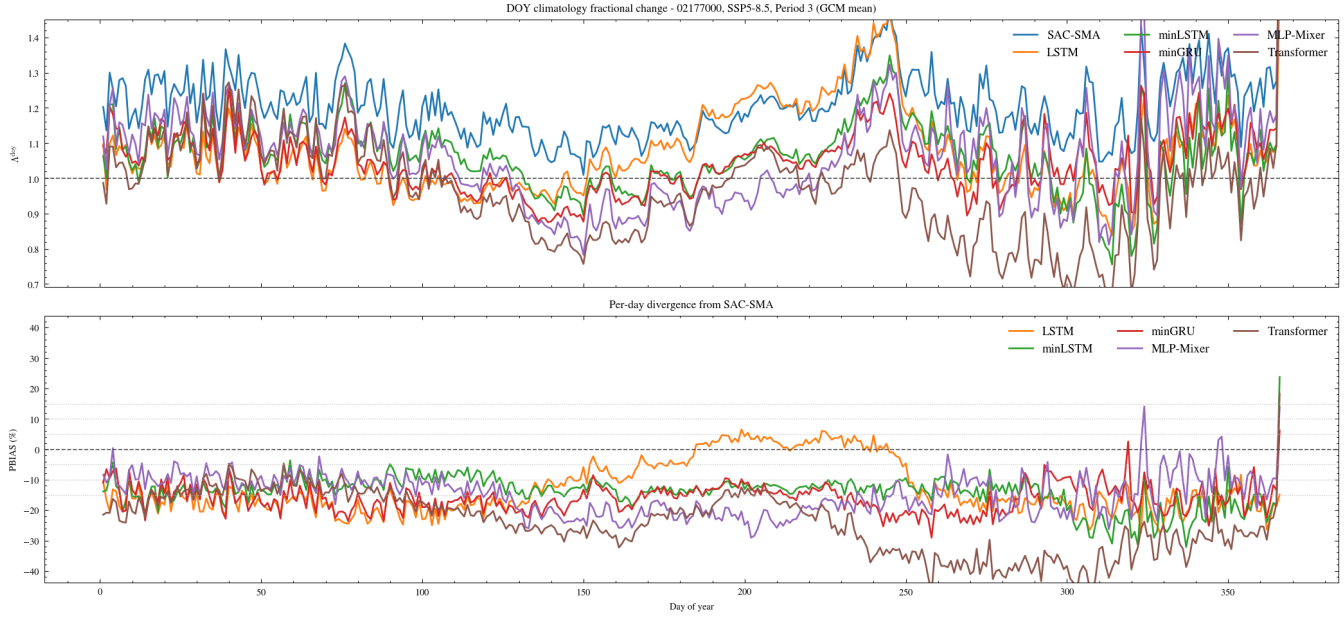


Figure S61. HUC 03: Catchment 02177000, scenario SSP5-8.5, period 2071-2100

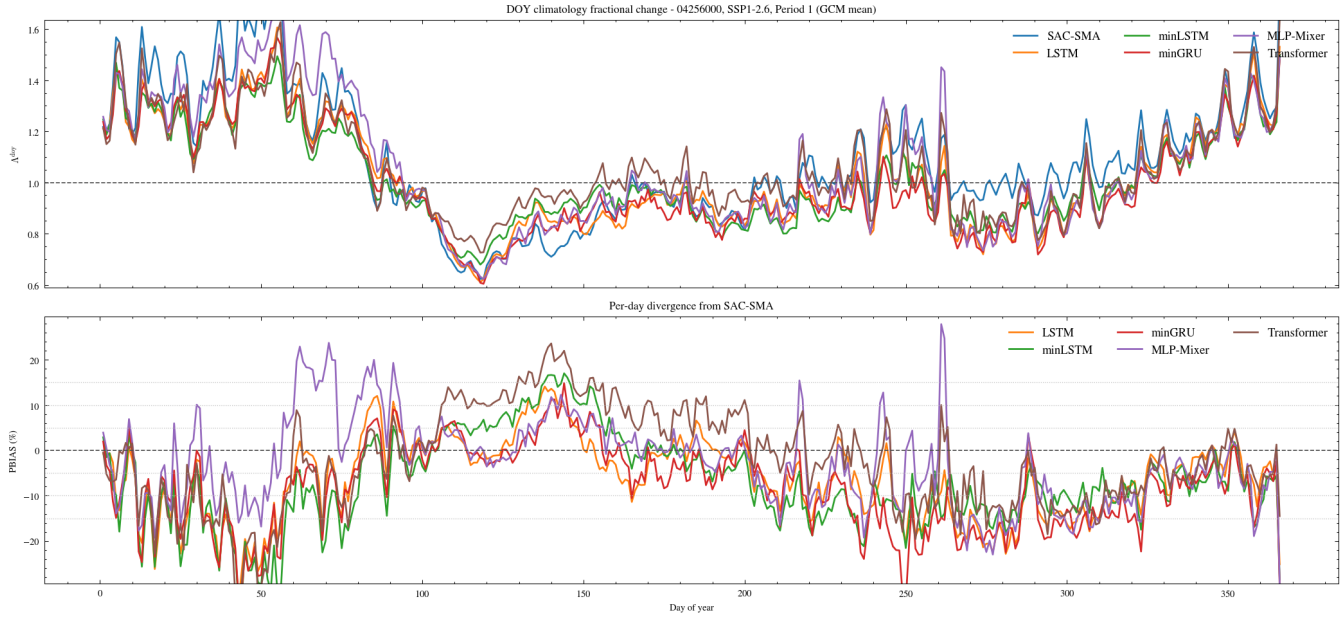


Figure S62. HUC 04: Catchment 04256000, scenario SSP1-2.6, period 2015–2045

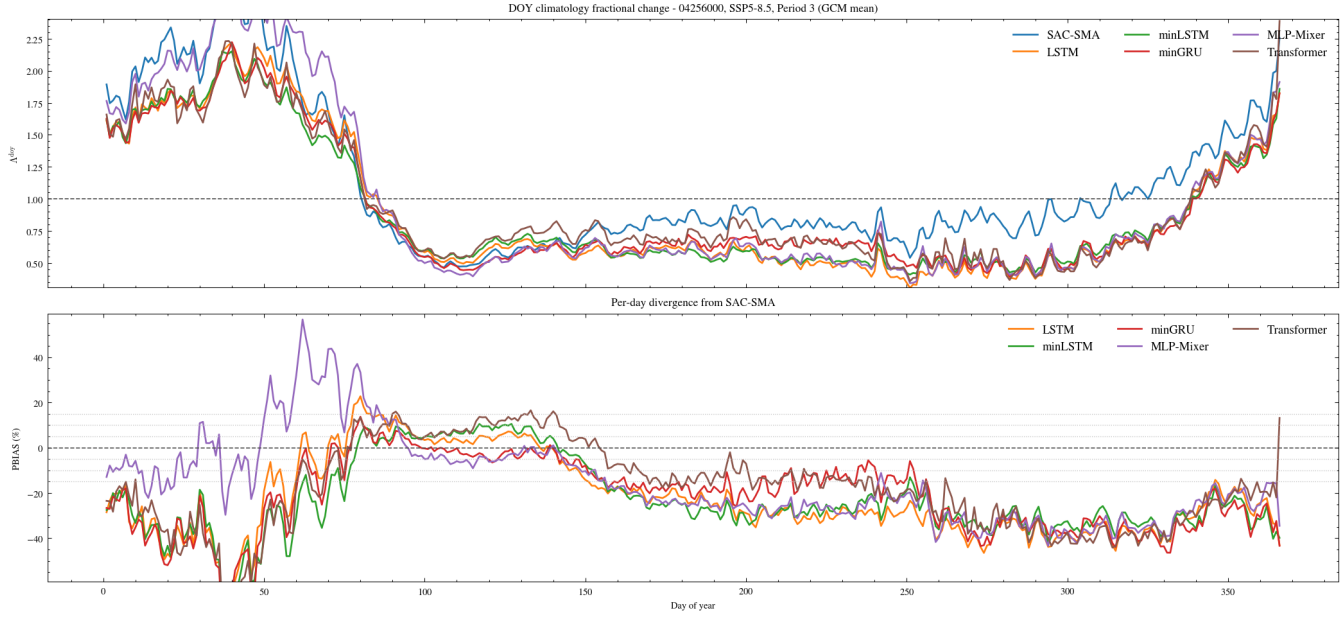


Figure S63. HUC 04: Catchment 04256000, scenario SSP5-8.5, period 2071-2100

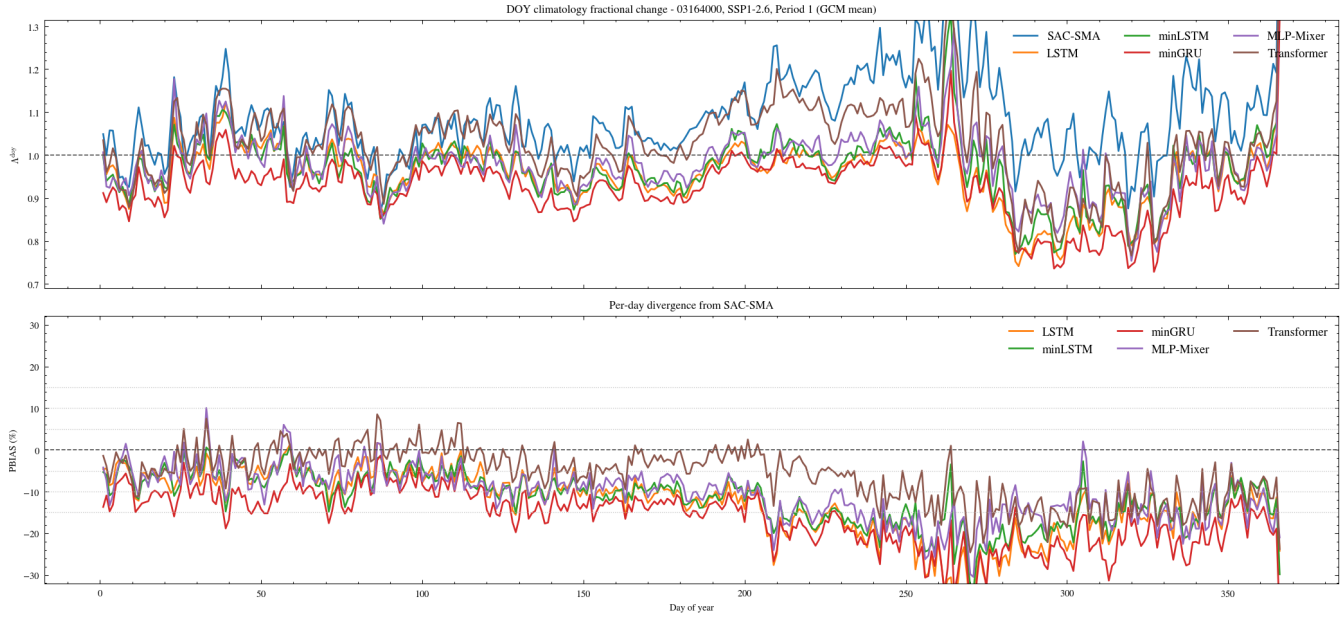


Figure S64. HUC 05: Catchment 03164000, scenario SSP1-2.6, period 2015–2045

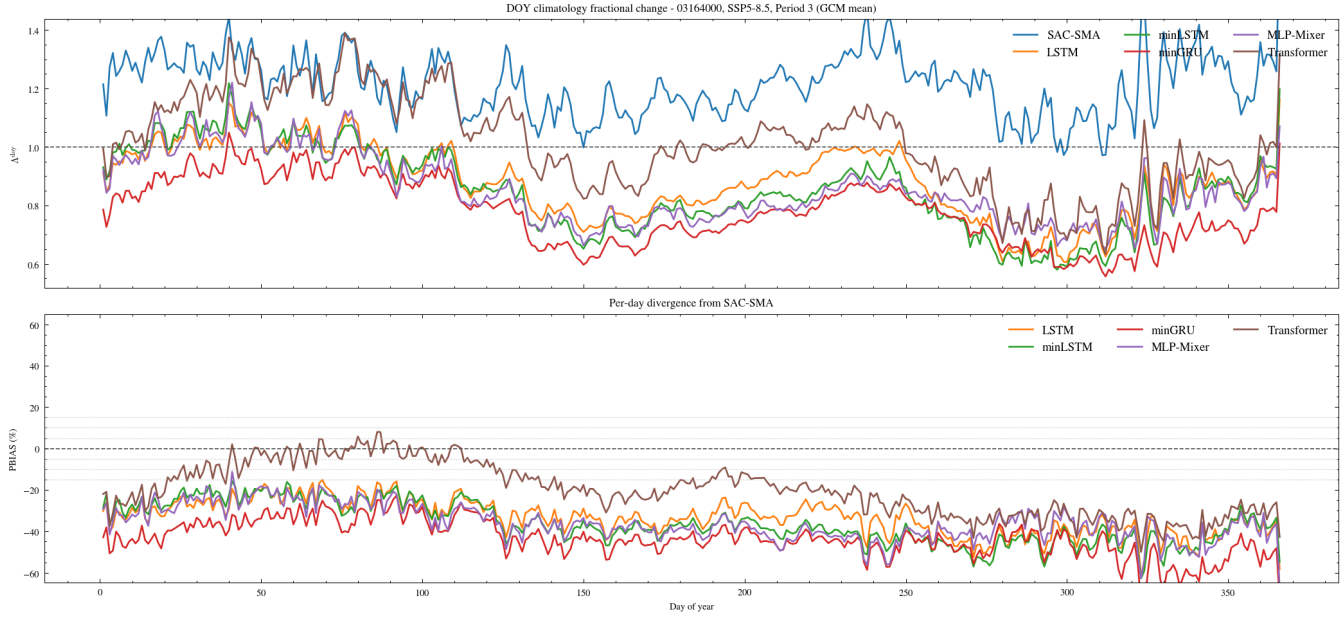


Figure S65. HUC 05: Catchment 03164000, scenario SSP5-8.5, period 2071-2100

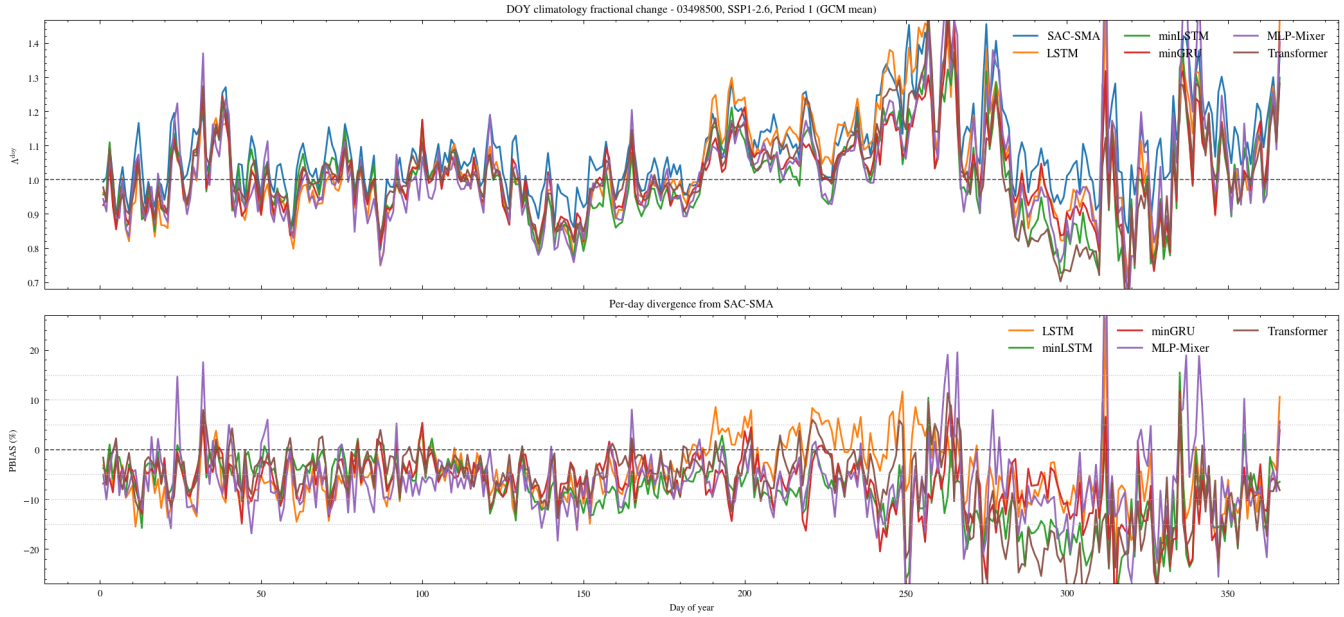


Figure S66. HUC 06: Catchment 03498500, scenario SSP1-2.6, period 2015–2045

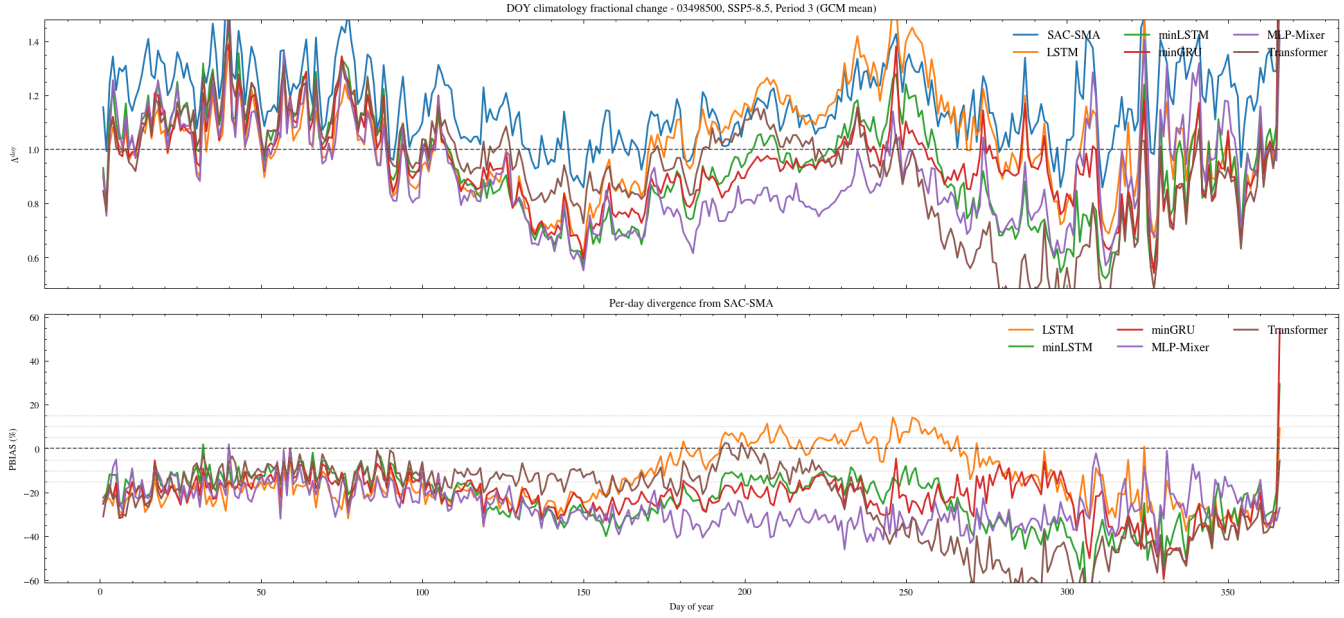


Figure S67. HUC 06: Catchment 03498500, scenario SSP5-8.5, period 2071-2100

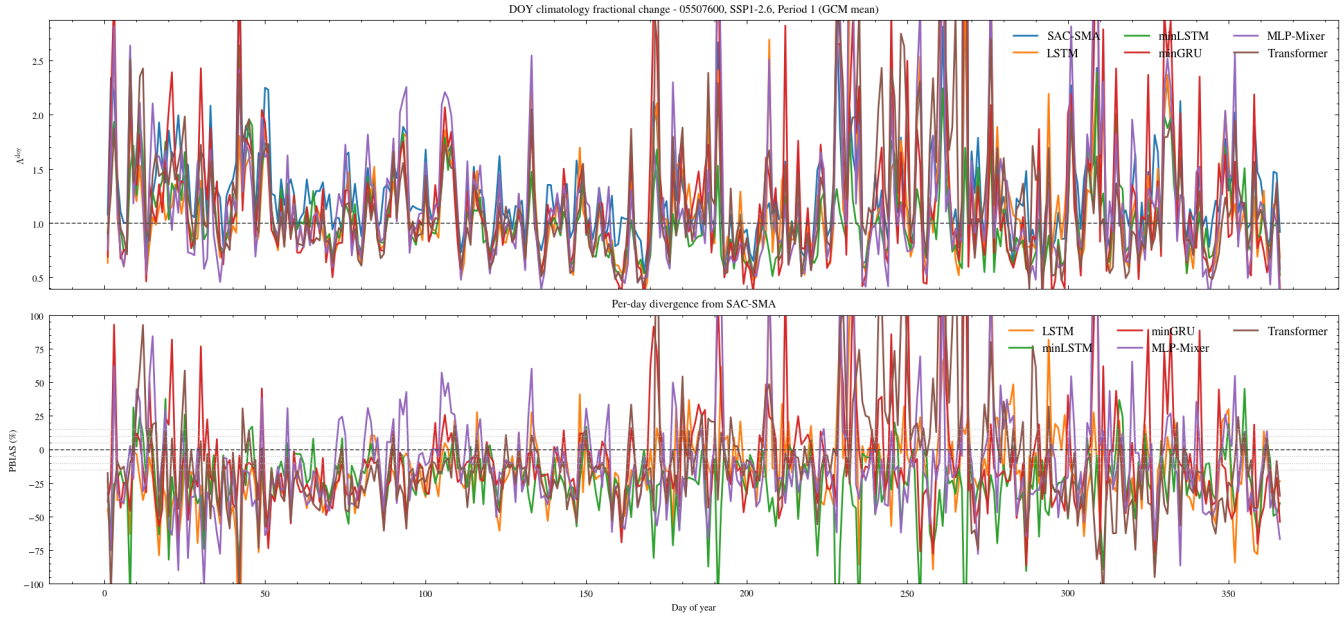


Figure S68. HUC 07: Catchment 05507600, scenario SSP1-2.6, period 2015–2045

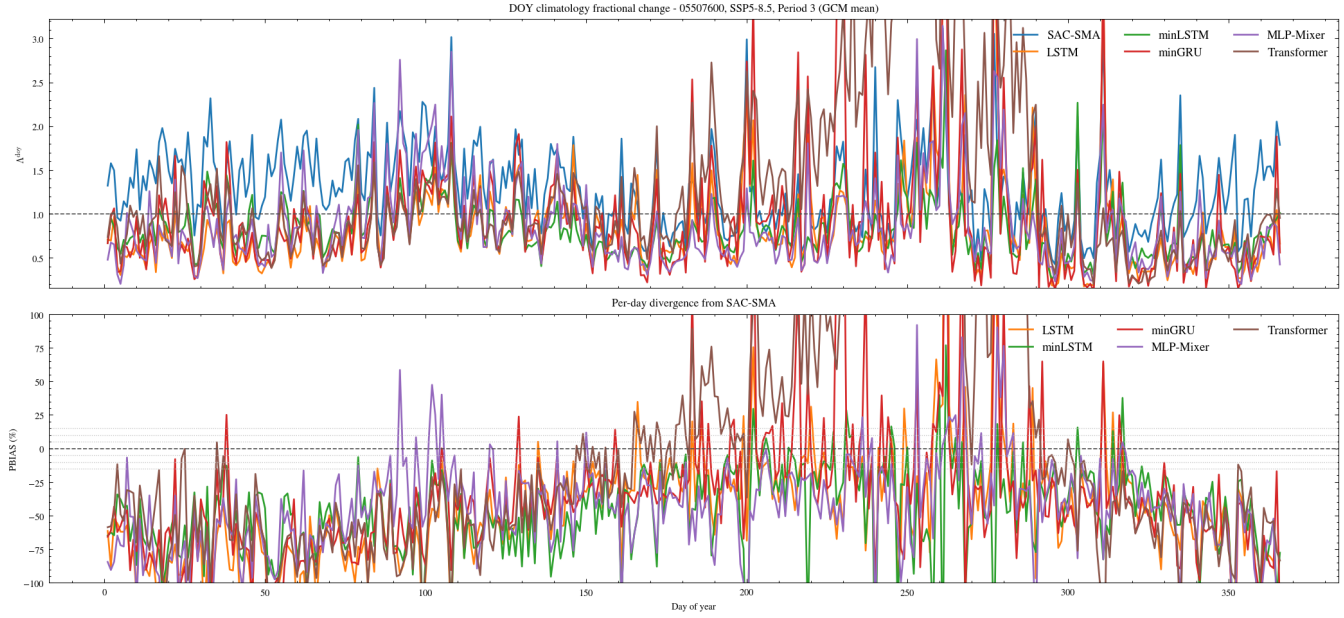


Figure S69. HUC 07: Catchment 05507600, scenario SSP5-8.5, period 2071-2100

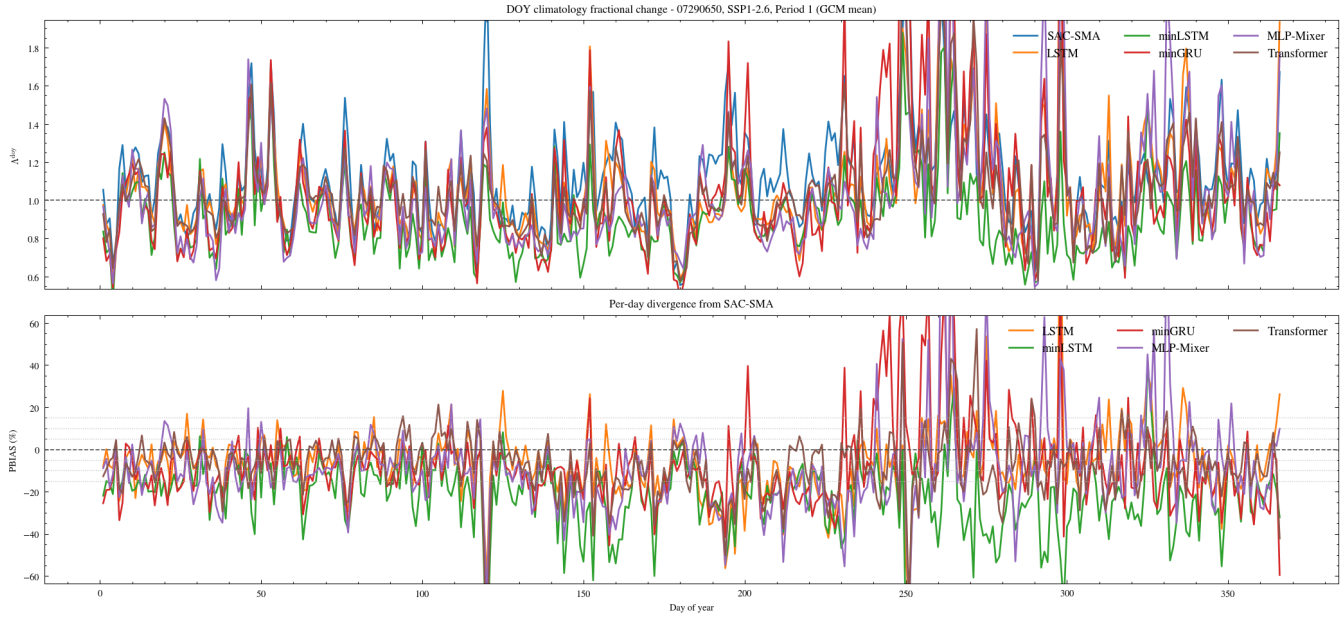


Figure S70. HUC 08: Catchment 07290650, scenario SSP1-2.6, period 2015–2045

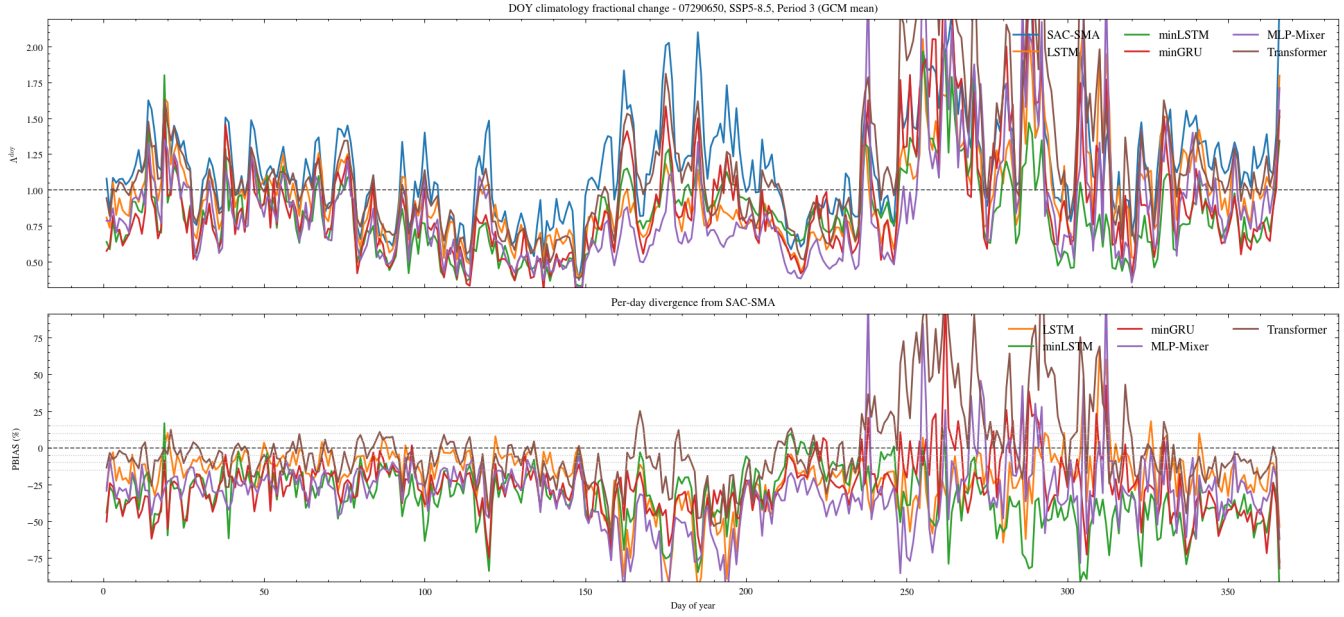


Figure S71. HUC 08: Catchment 07290650, scenario SSP5-8.5, period 2071-2100

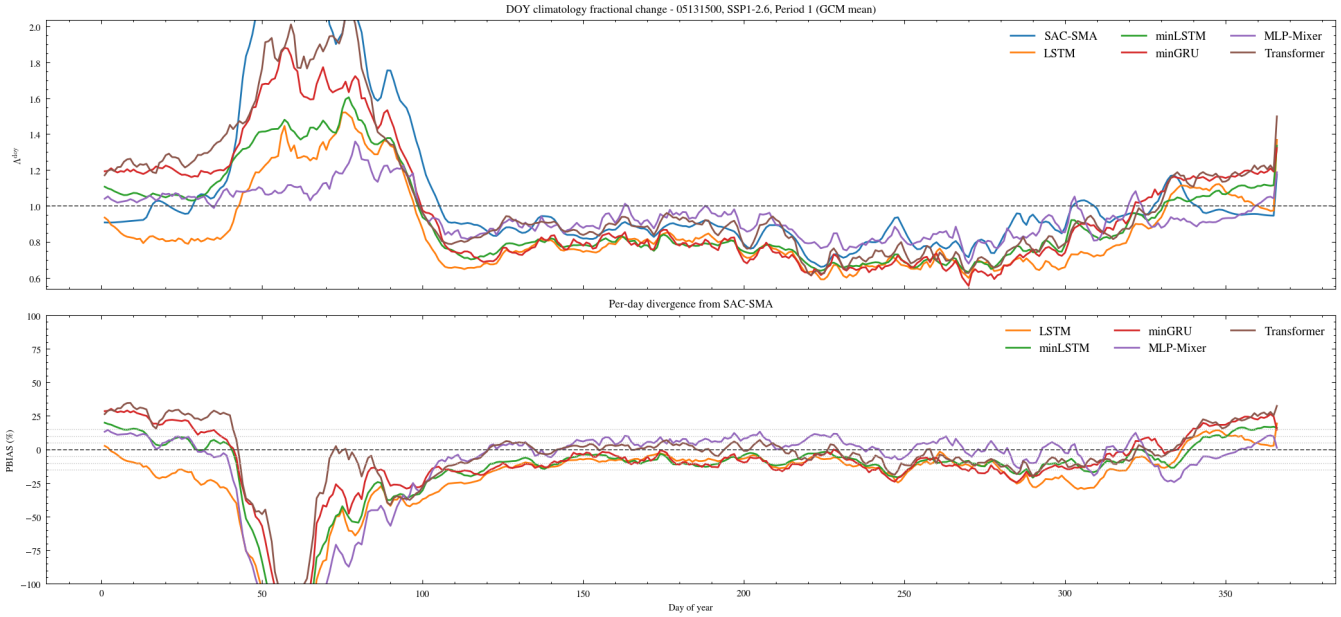


Figure S72. HUC 09: Catchment 05131500, scenario SSP1-2.6, period 2015–2045

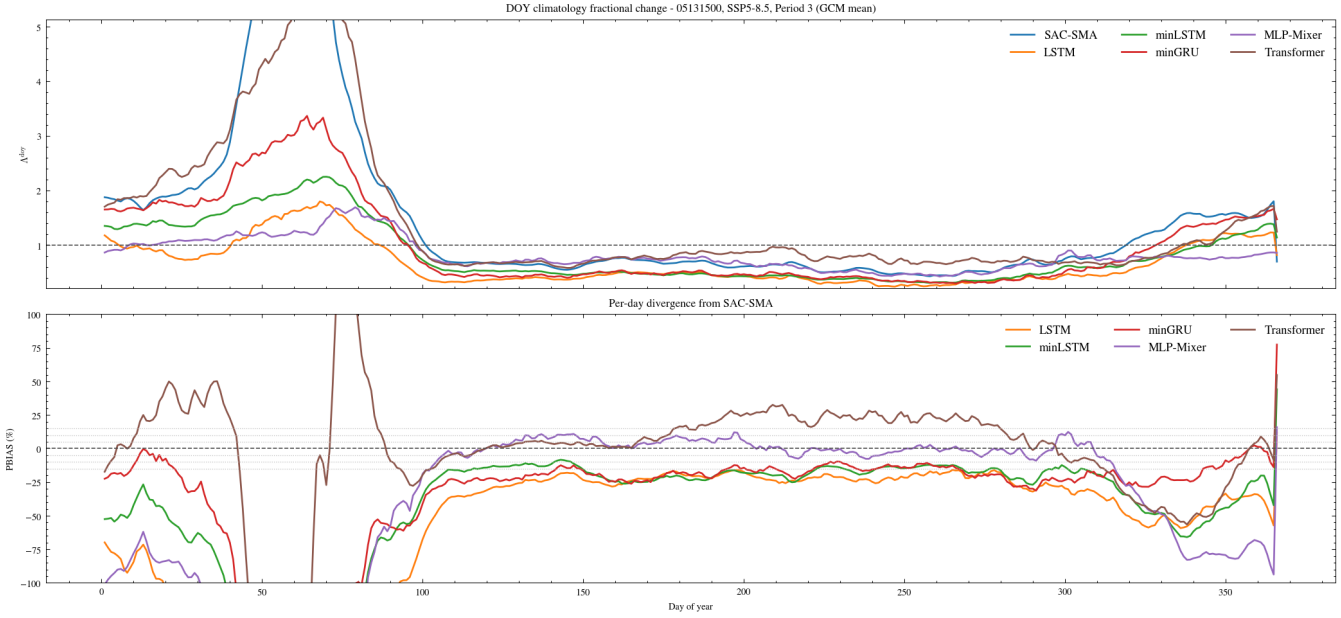


Figure S73. HUC 09: Catchment 05131500, scenario SSP5-8.5, period 2071-2100

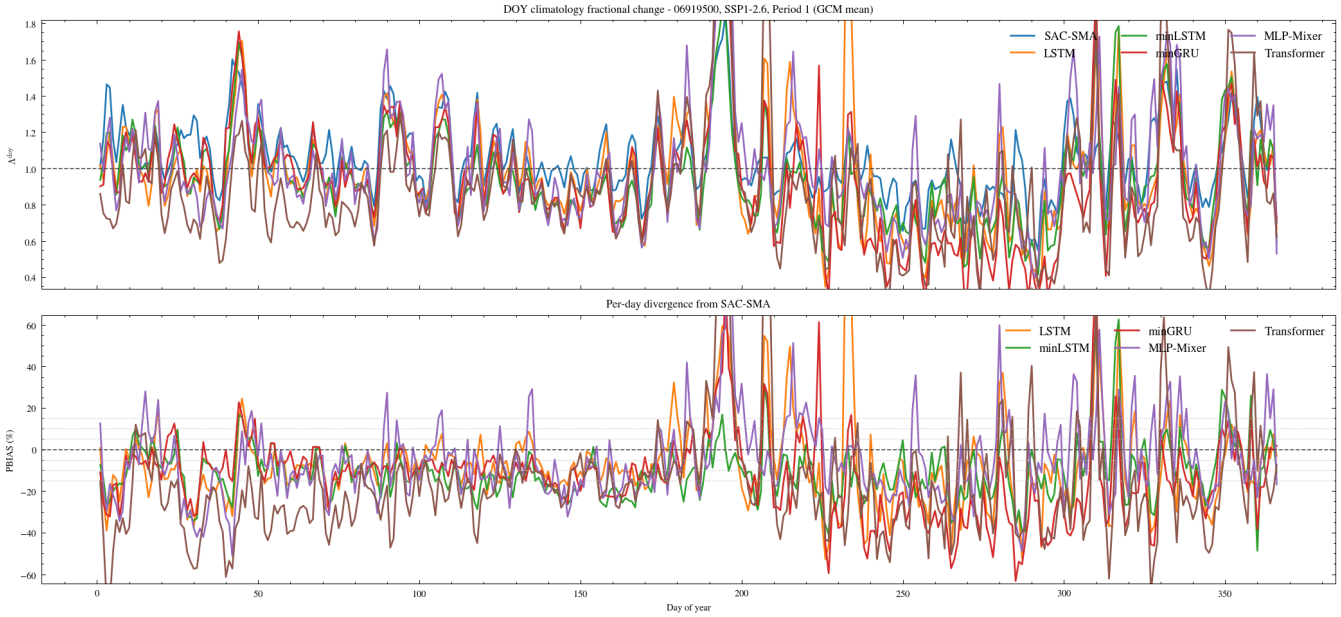


Figure S74. HUC 10: Catchment 06919500, scenario SSP1-2.6, period 2015–2045

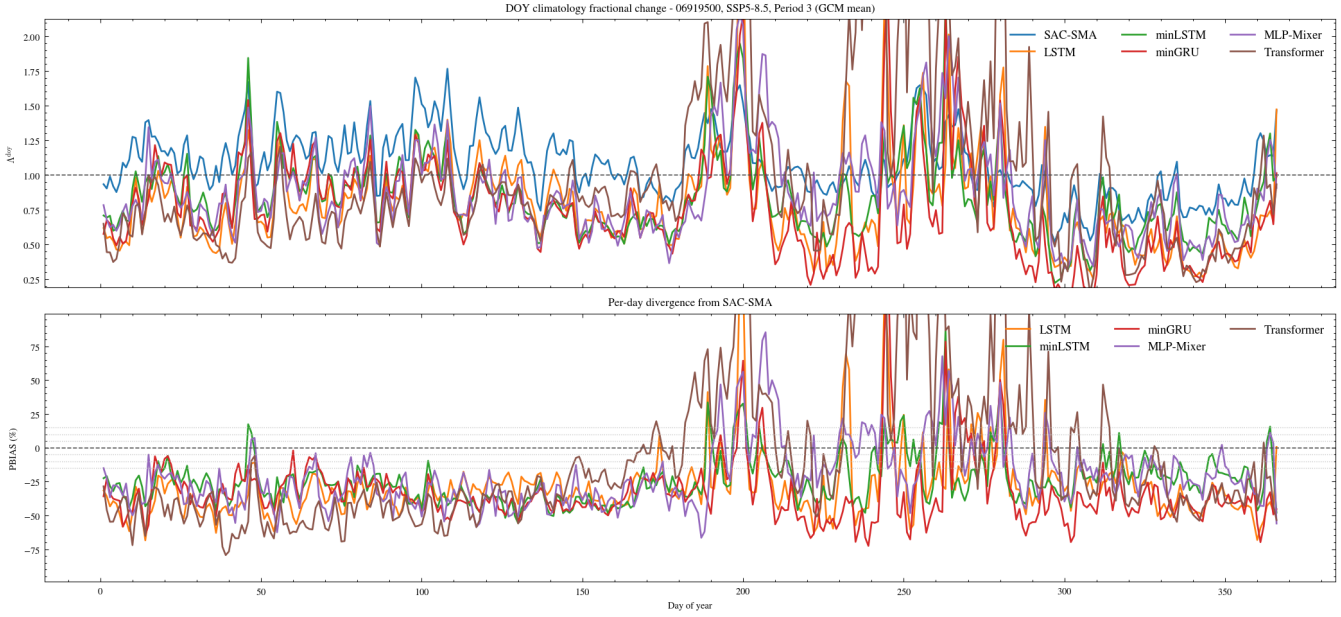


Figure S75. HUC 10: Catchment 06919500, scenario SSP5-8.5, period 2071-2100

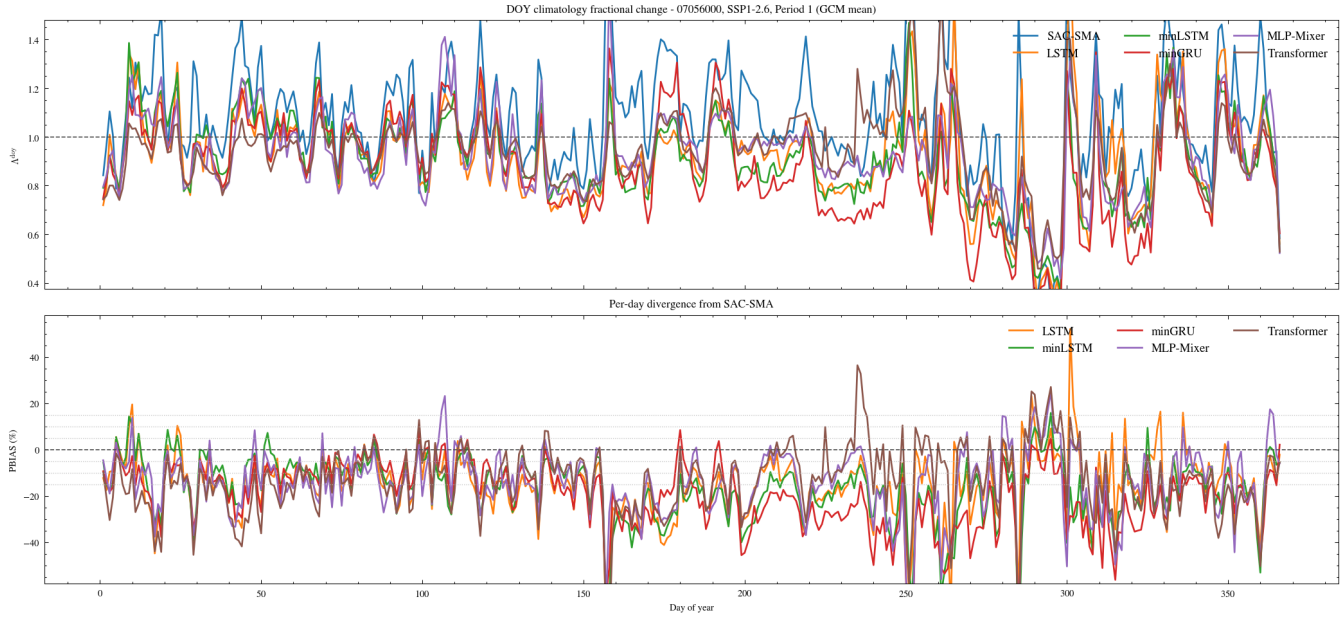


Figure S76. HUC 11: Catchment 07056000, scenario SSP1-2.6, period 2015–2045

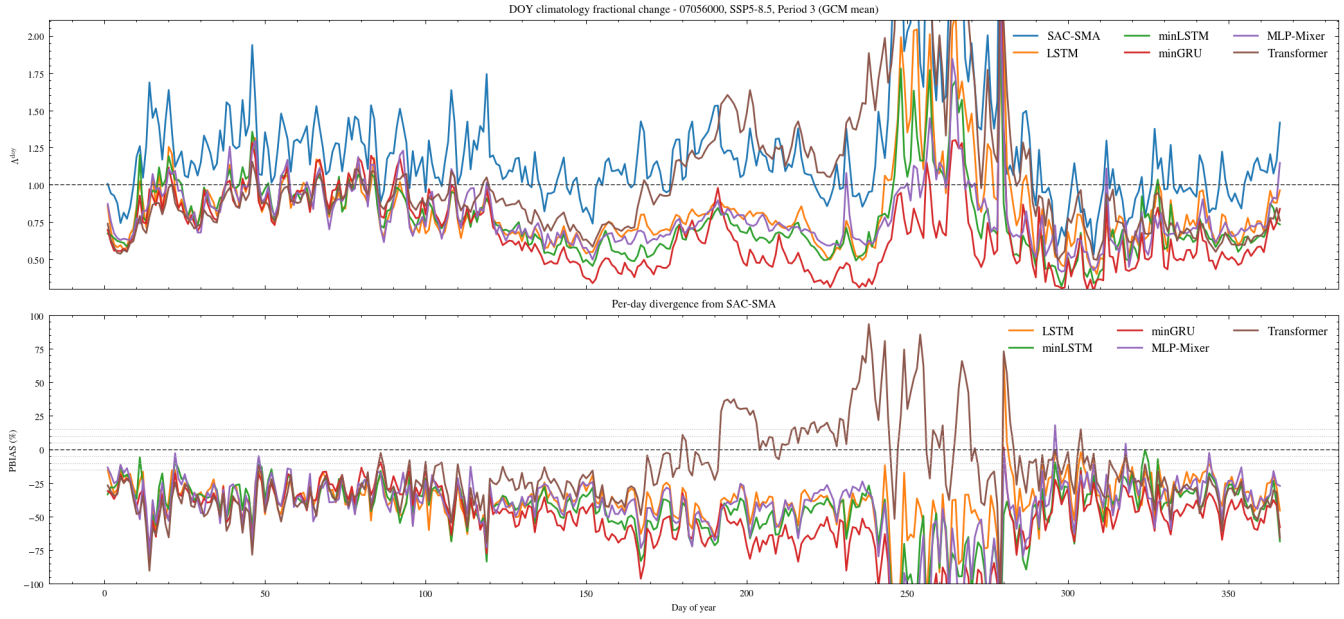


Figure S77. HUC 11: Catchment 07056000, scenario SSP5-8.5, period 2071-2100

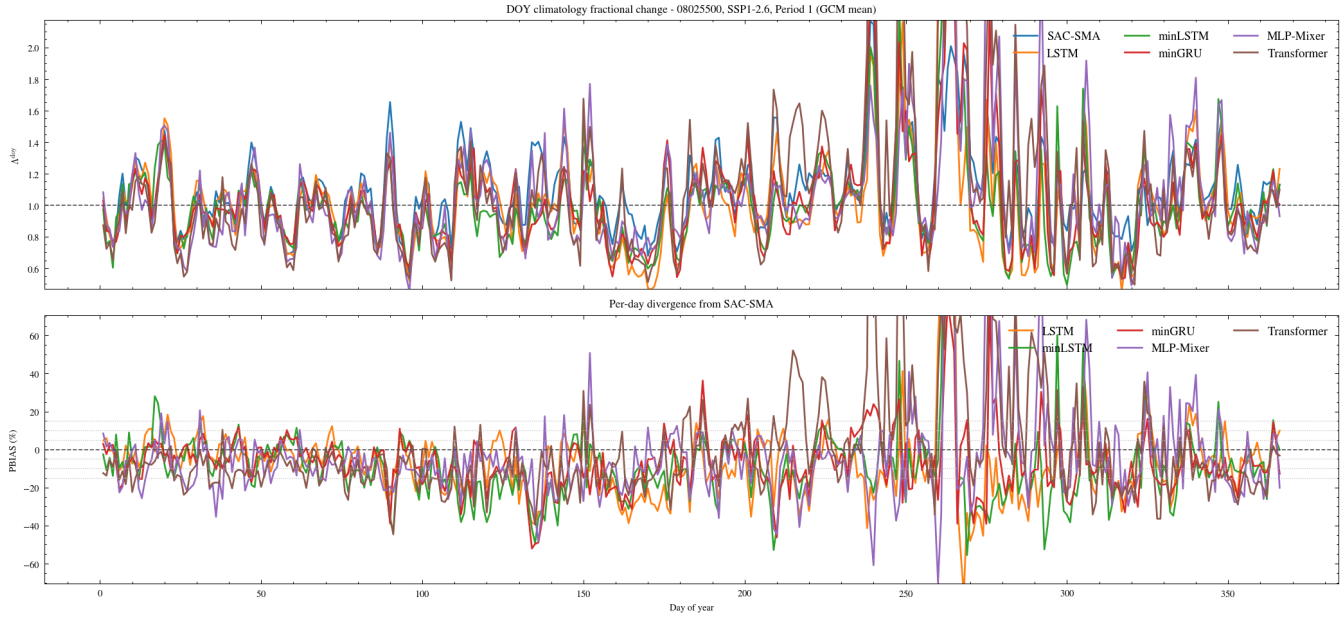


Figure S78. HUC 12: Catchment 08025500, scenario SSP1-2.6, period 2015–2045

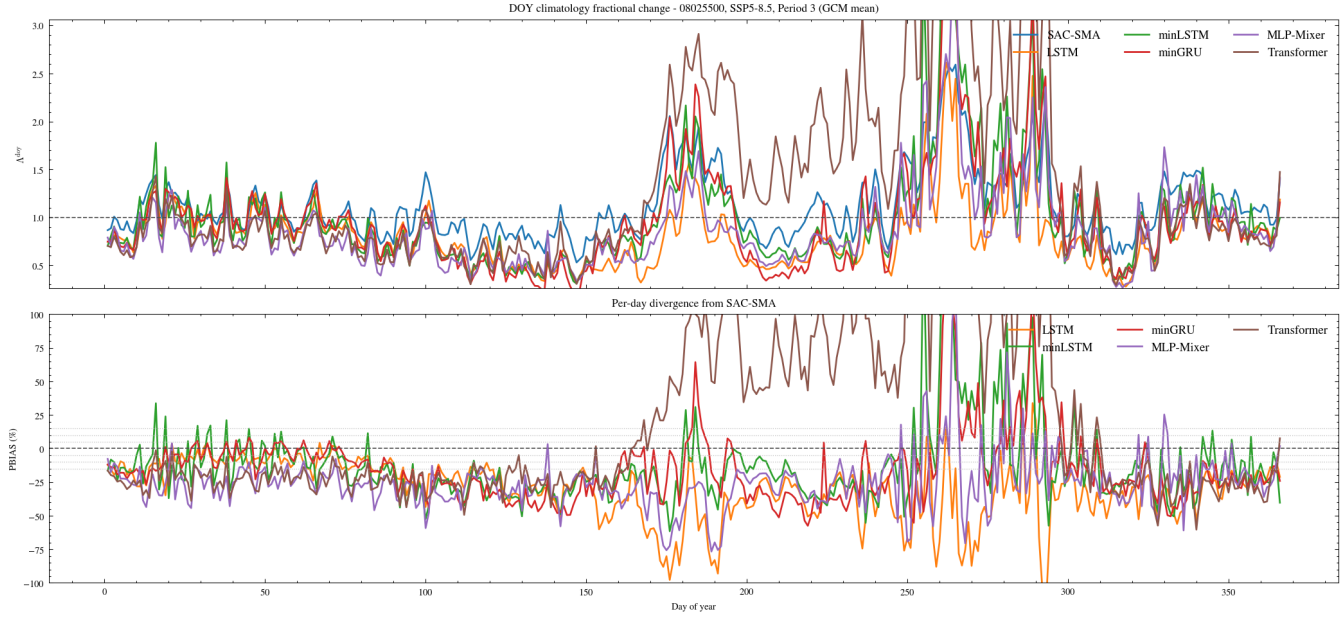


Figure S79. HUC 12: Catchment 08025500, scenario SSP5-8.5, period 2071-2100

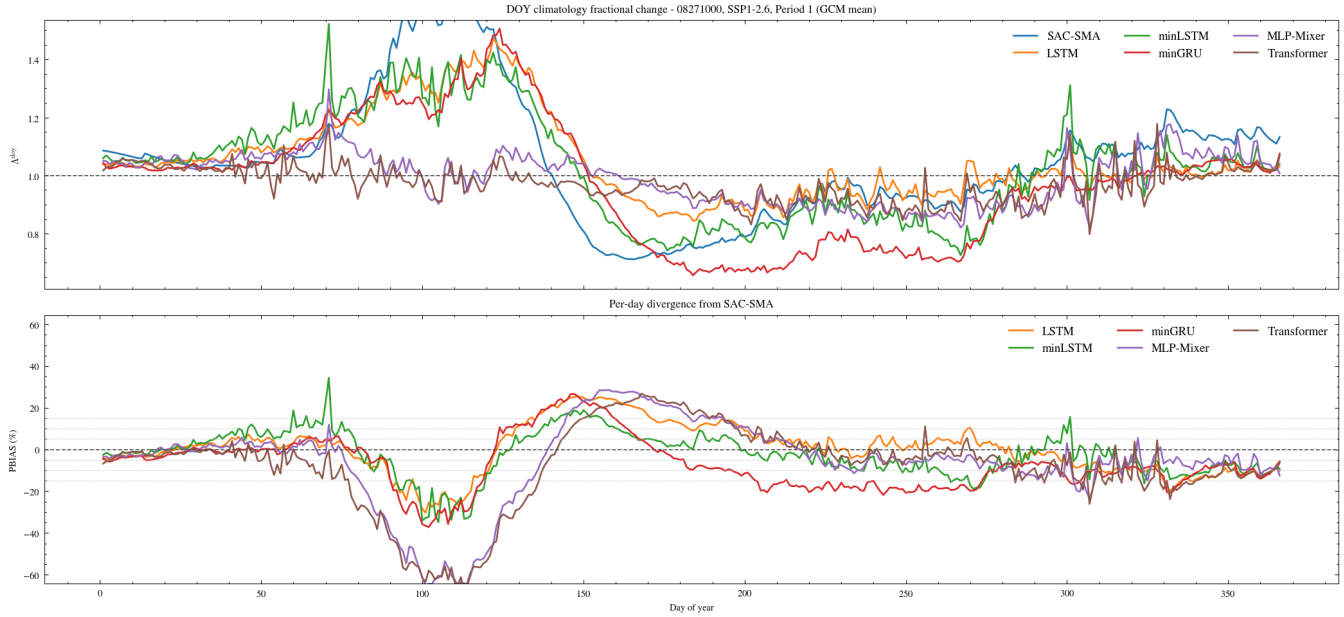


Figure S80. HUC 13: Catchment 08271000, scenario SSP1-2.6, period 2015–2045

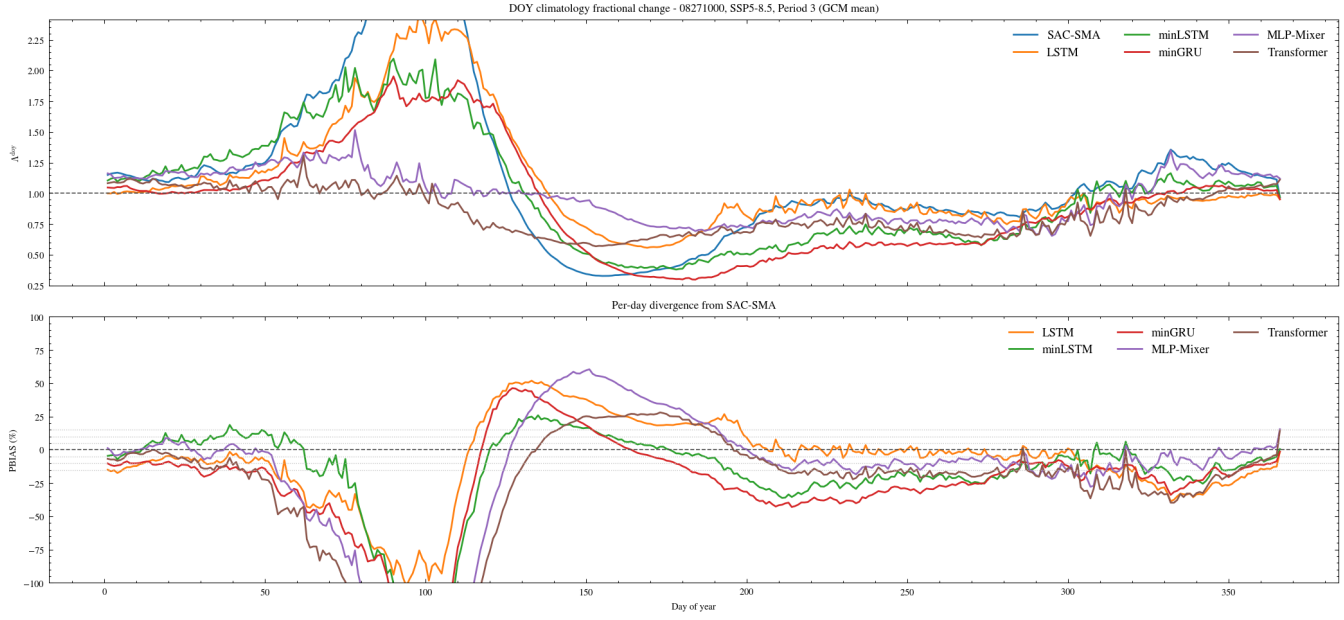


Figure S81. HUC 13: Catchment 08271000, scenario SSP5-8.5, period 2071-2100

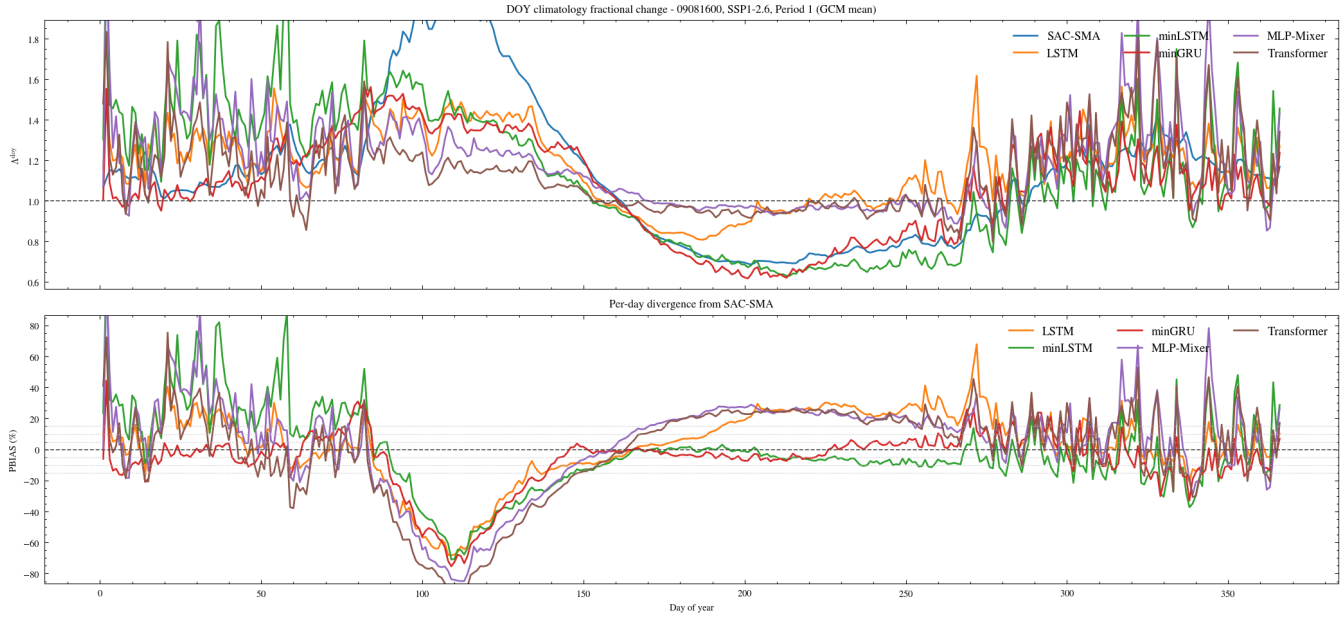


Figure S82. HUC 14: Catchment 09081600, scenario SSP1-2.6, period 2015–2045

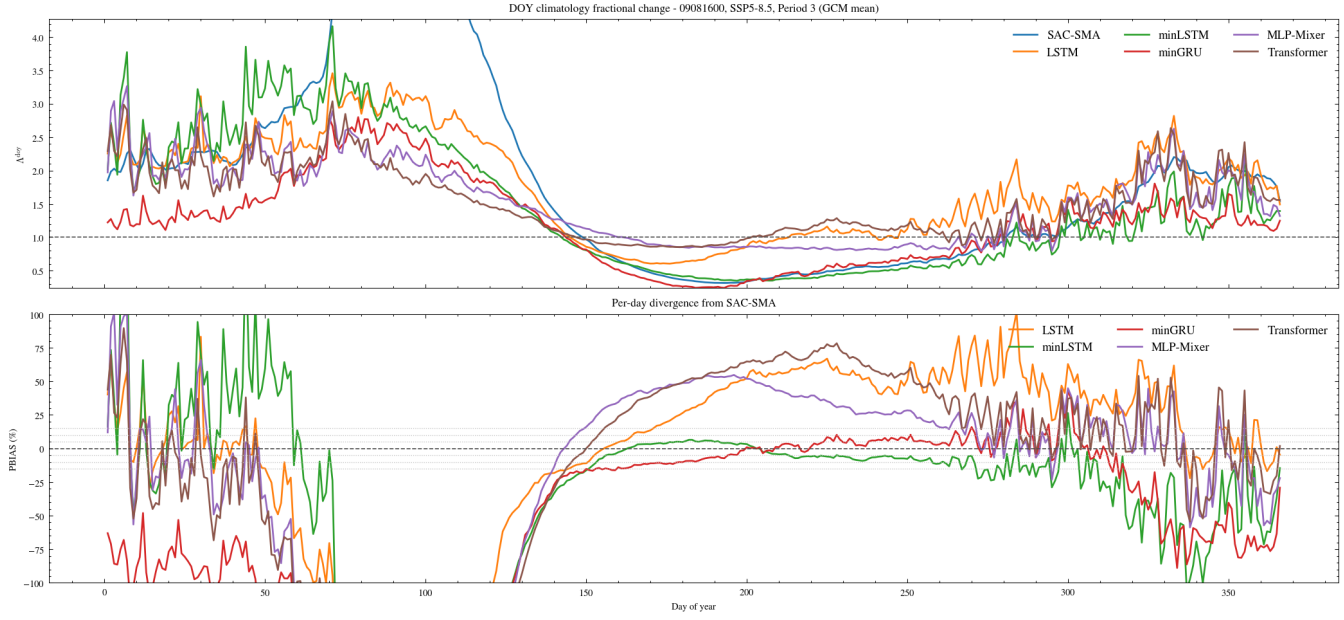


Figure S83. HUC 14: Catchment 09081600, scenario SSP5-8.5, period 2071-2100

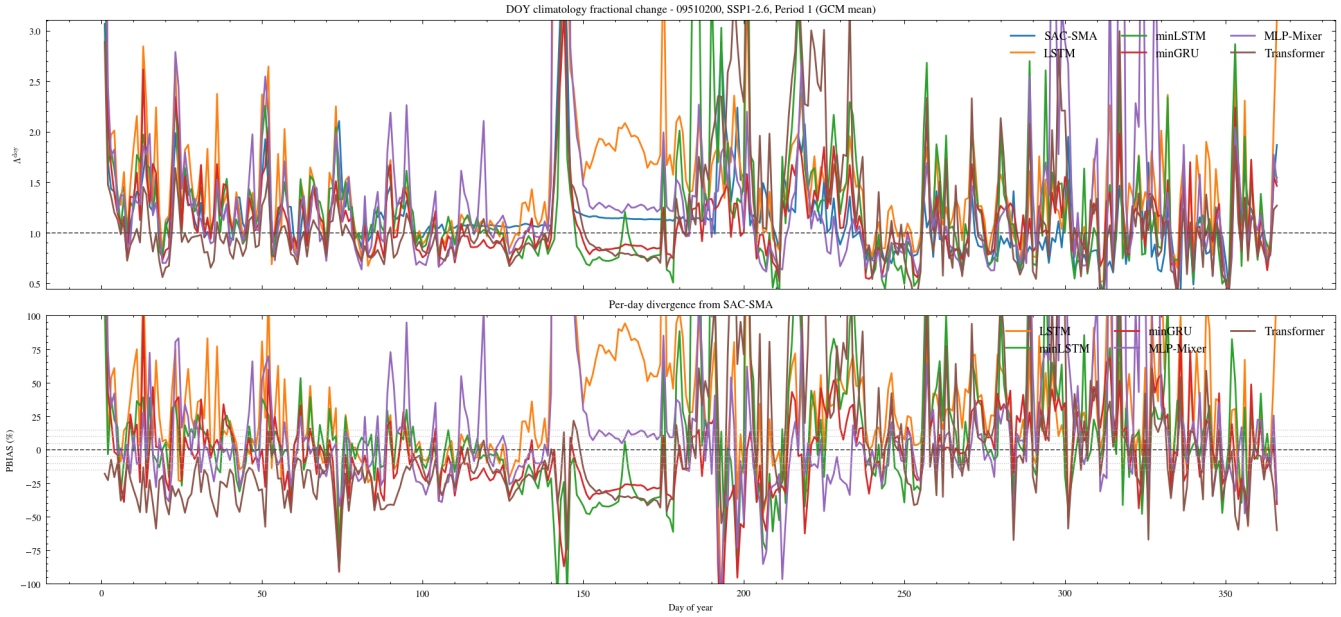


Figure S84. HUC 15: Catchment 09510200, scenario SSP1-2.6, period 2015–2045

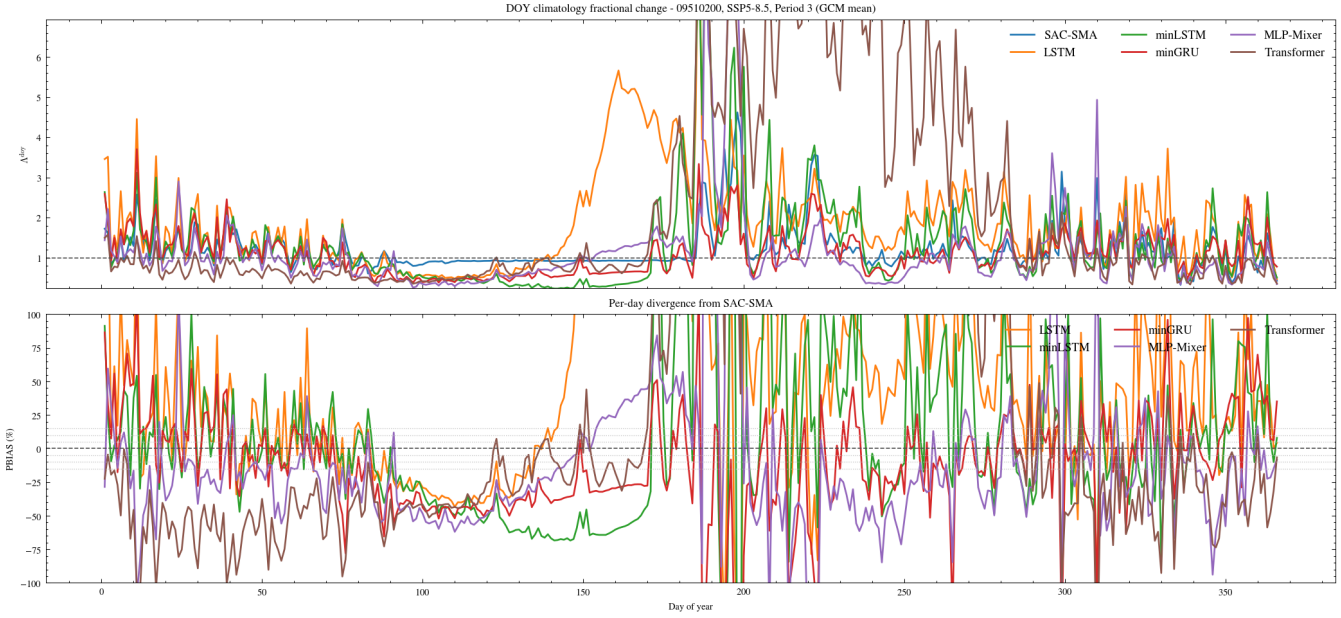


Figure S85. HUC 15: Catchment 09510200, scenario SSP5-8.5, period 2071-2100

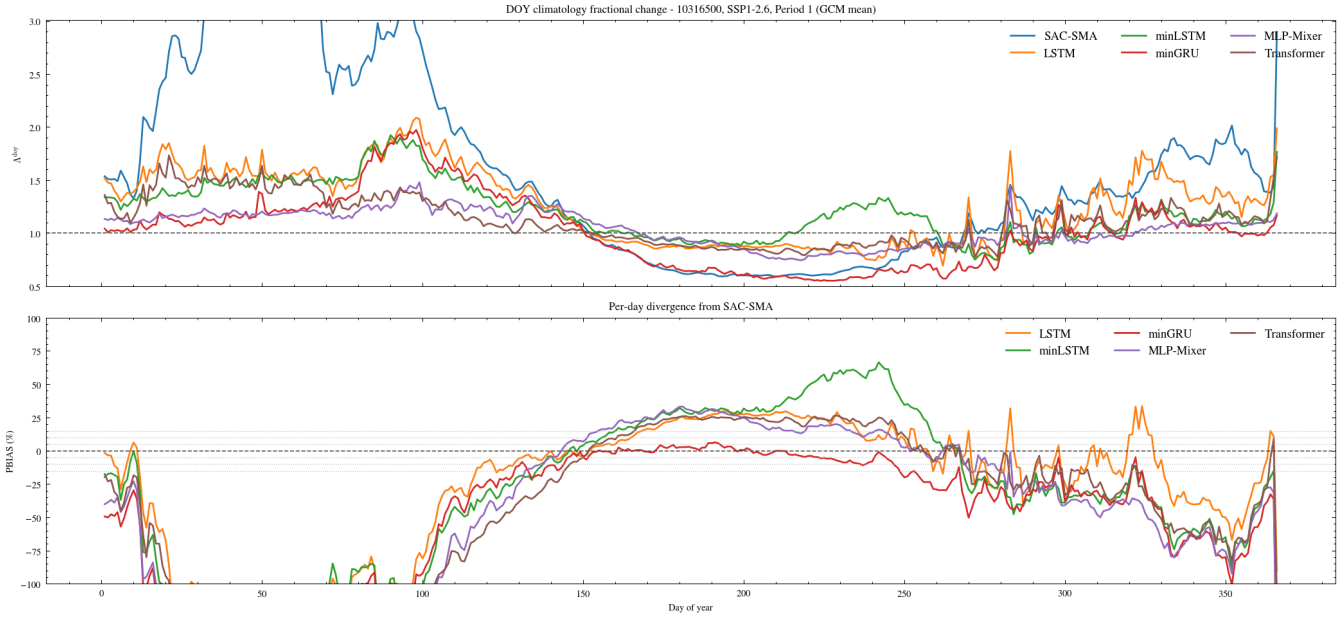


Figure S86. HUC 16: Catchment 10316500, scenario SSP1-2.6, period 2015–2045

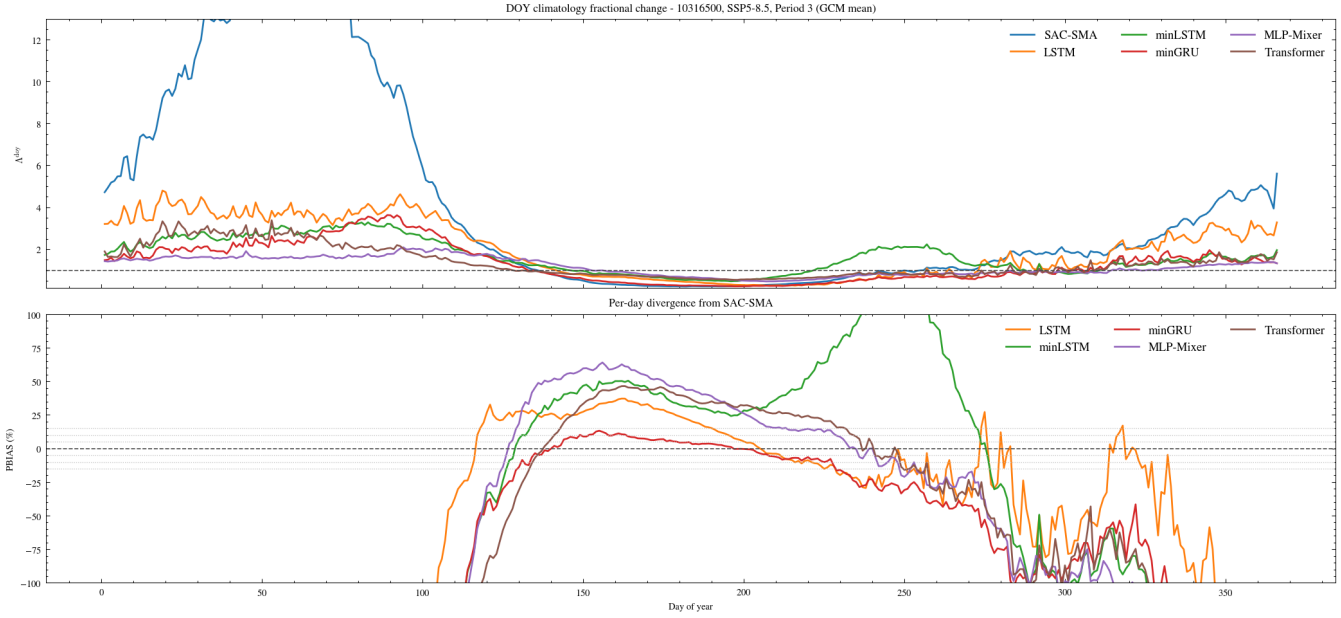


Figure S87. HUC 16: Catchment 10316500, scenario SSP5-8.5, period 2071-2100

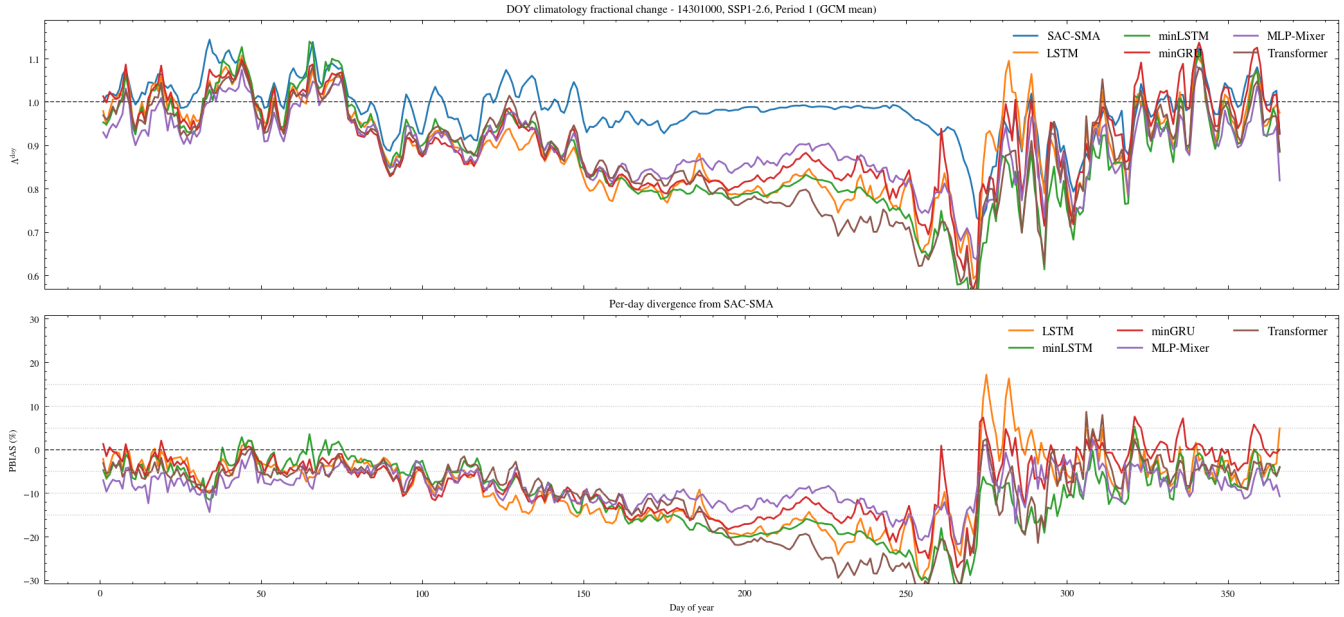


Figure S88. HUC 17: Catchment 14301000, scenario SSP1-2.6, period 2015–2045



Figure S89. HUC 17: Catchment 14301000, scenario SSP5-8.5, period 2071-2100

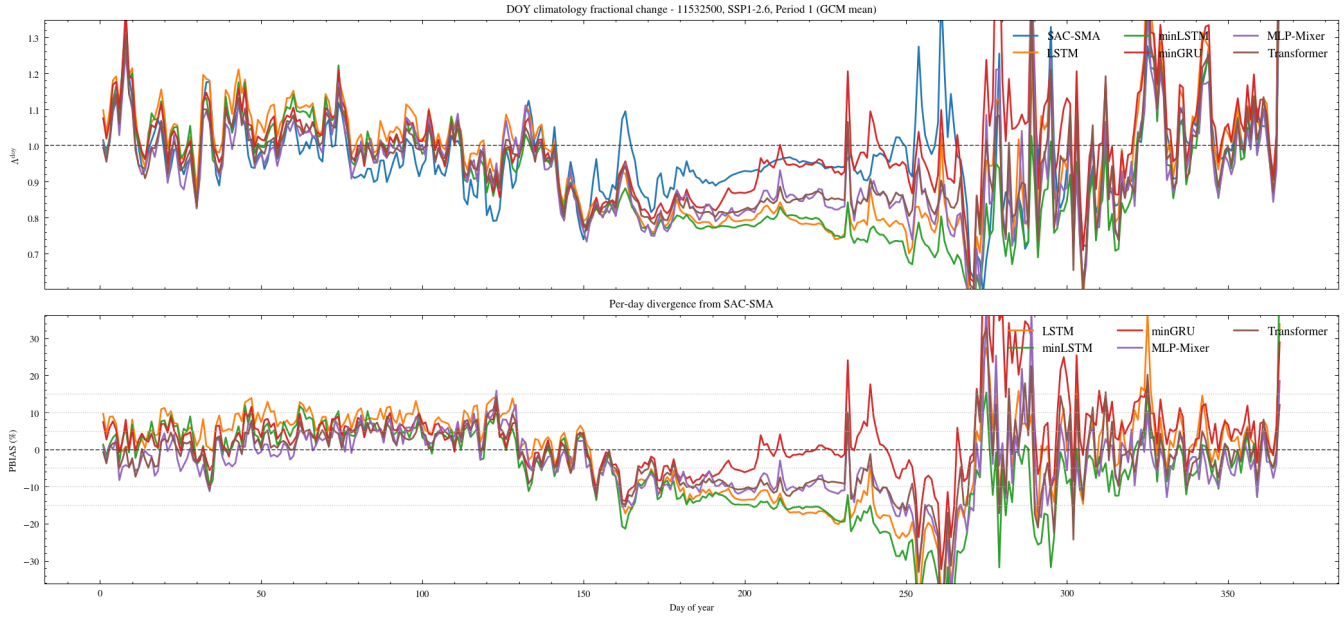


Figure S90. HUC 18: Catchment 11532500, scenario SSP1-2.6, period 2015–2045



Figure S91. HUC 18: Catchment 11532500, scenario SSP5-8.5, period 2071-2100