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Evapotranspiration in the Amazon: spatial patterns, seasonality, and recent trends in observations, reanalysis, and climate models

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Table S1 – River-gauge station data. Data for the eleven river-gauge stations used in the study.

River catchment	Part of Amazon drained	Area (km^2)	Station name	Station code	Degrees E (°)	Degrees N (°)	Years of data
Amazon	77% of basin	4,694,100	Óbidos	17050001	–55.51	–1.91	1968–2019
Aripuanã	S	134,100	Prainha Velha	15830000	–60.66	–7.17	2002–2016
Branco	N	130,800	Caracaraí	14710000	–61.13	1.81	1967–2018
Japura	NW	207,100	Villa Bittencourt	12845000	–69.42	–1.49	1980–2020
Jari	NE	48,900	São Francisco	19150000	–52.56	–0.57	1968–2014
Madeira	S/SW	1,006,200	Porto Velho	15400000	–63.92	–8.76	1967–2020
Negro	N	290,400	Serrinha	14420000	–64.80	–0.43	1977–2018
Purus	S	227,600	Lábrea	13870000	–64.79	–7.23	1931–2017
Solimões	W	1,192,200	São Paulo de Olivença	11400000	–68.79	–3.46	1973–2020
Tapajós	SE	462,700	Buburé	17710000	–56.32	–4.59	2004–2019
			Itaituba	17730000			
Xingu	SE	463,200	Altamira	18850000	–52.21	–3.20	1968–2014

Table S2 – Seasonal variation in Amazon catchment-balance error estimates. Absolute uncertainties (in mm) in precipitation (σ_P), river runoff (σ_R), change in groundwater storage ($\sigma_{\frac{dS}{dt}}$), and evapotranspiration (σ_{ET}), and the relative uncertainty (in %) in evapotranspiration (υ_{ET}). σ_P was estimated as the random error (σ_{P_random}) plus the systematic error (σ_{P_bias}), combined in quadrature. σ_{P_random} was calculated following Eq. (4), from Huffman (1997): $\sigma_{P\_random} = \overline{r}\left[\frac{H-p}{pN}\right]^{\frac{1}{2}}$ where $\overline{r}$ is the climatological mean precipitation over the basin, H is a constant (1.5), p is the frequency of non-zero rainfall and N is the number of independent precipitation samples (defined as the number of Amazon pixels with finite P measurements in each month). For σ_{P_bias}, we used the value of –3.6 % from Table 4 in Paredes-Trejo et al. (2017). σ_R was estimated as 5% of monthly river flow (Dingman, 2015). Uncertainty in groundwater storage was quantified by combining GRACE measurement errors and leakage errors in quadrature. For these, we used Amazon-specific values from the literature (6.1 and 0.9 mm for measurement and leakage errors, see Table 1 in Wiese et al. (2016)). Since $\frac{dS}{dt}$ values were calculated using data from two consecutive months, groundwater error values were multiplied by $\sqrt{2}$ to obtain $\sigma_{\frac{dS}{dt}}$ (e.g. Maeda et al., 2017). σ_{ET} was estimated using $\sigma_{ET} = \sqrt{{\sigma_P}^2 + {\sigma_R}^2 + {\sigma_{\frac{dS}{dt}}}^2}$, and $\upsilon_{ET} = \frac{\sigma_{ET}}{ET}$ x 100. For further details please see the main paper. The Amazon region considered for this analysis is indicated by blue hatching in Figure 1.

	σ_P,	σ_R	$\sigma_{\frac{dS}{dt}}$	σ_{ET}	υ_{ET}
Jan	8.98	3.91	8.72	13.15	14.82
Feb	8.70	4.59	8.72	13.17	20.83
Mar	9.84	5.54	8.72	14.30	16.78
Apr	8.43	6.19	8.72	13.64	23.03
May	7.21	6.66	8.72	13.14	20.78
Jun	4.91	6.57	8.72	11.99	25.05
Jul	4.08	6.23	8.72	11.48	18.08
Aug	3.67	5.41	8.72	10.92	11.32
Sep	4.25	4.13	8.72	10.58	8.79
Oct	5.74	3.11	8.72	10.91	8.85
Nov	6.98	2.81	8.72	11.50	10.67
Dec	8.35	3.23	8.72	12.43	13.53
Mean	6.76	4.87	8.72	12.27	16.04

Table S3 – Details of the 13 CMIP5 models analysed in this study. Models that provided historical simulations of evapotranspiration, precipitation, surface radiation and leaf area index over the historical period were selected.

	Modelling centre	Model	Native resolution (°)
1	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	ACCESS1-3	1.875 x 1.25
2	Beijing Climate Centre, China Meteorological Administration	bcc-csm1-1	2.8125 x 2.8125
3	College of Global Change and Earth System Science, Beijing Normal University	BNU-ESM	2.8125 x 2.8125
4	Canadian Centre for Climate Modelling and Analysis	CanESM2	2.8125 x 2.8125
5	National Centre for Atmospheric Research	CCSM4	1.25 x 0.9375
6	Community Earth System Model Contributors	CESM1-BGC	1.25 x 0.9375
7	The First Institute of Oceanography, SOA, China	FIO-ESM	2.8125 x 2.8125
8	Met Office Hadley Centre	HadGEM2-CC	1.875 x 1.25
9		HadGEM2-ES	1.875 x 1.25
10	Institute for Numerical Mathematics	inmcm4	2 x 1.5
11	Institut Pierre-Simon Laplace	IPSL-CM5A-LR	3.75 x 1.875
12	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-ESM-LR	1.875 x 1.875
13	Norwegian Climate Centre	NorESM1-M	2.5 x 1.875

Table S4 – Details of the 10 CMIP6 models analysed in this study. Models that provided historical simulations of evapotranspiration, precipitation, surface radiation and leaf area index were selected.

	Modelling centre	Model	Native resolution (°)
1	Commonwealth Scientific and Industrial Research Organization (CSIRO)	ACCESS-ESM1-5	1.875 x 1.25
2	Beijing Climate Centre, China Meteorological Administration	BCC-CSM2-MR	1.125 x 1.125
3		BCC-ESM1	2.8125 x 2.8125
4	Community Earth System Model Contributors	CESM2	1.25 x 0.9375
5		CESM2-WACCM	1.25 x 0.9375
6	NASA Goddard Institute for Space Studies	GISS-E2-1-G	2.5 x 2
7	Met Office Hadley Centre	HadGEM3-GC31-LL	1.875 x 1.25
8		HadGEM3-GC31-MM	0.833 x 0.556
9	Seoul National University, Seoul, South Korea	SAM0-UNICON	1.25 x 0.9375
10	Met Office Hadley Centre	UKESM1-0-LL	1.875 x 1.25

Table S5 – Data for the six LBA flux tower sites used in the study.

Site code	Site name	Latitude	Longitude	Land cover type	Years of data
BAN	Bananal, Tocantins State	-9.82	-50.15	Seasonally flooded ecotone	2003–2006
K34	km 34, Manaus	-2.61	-60.21	Forest	1999–2017
K67	km 67, Santarém	-2.85	-54.97	Primary forest	2002–2006
K83	km 83, Santarém	-3.05	-54.93	Selectively logged forest	2000–2004
RJA	Reserva Jaru Tower A, Rondônia State	-10.08	-61.93	Tropical dry forest	1999–2002
PDG	Reserva Pé-de-Gigante, São Paulo State	-21.62	-47.63	Cerrado/ savanna	2002–2003

Table S6 – Sensitivity of K34 seasonal correlations to changing data-inclusion thresholds. Testing the sensitivity of seasonal correlations between K34 and gridded ET datasets to changing the data-inclusion thresholds for the K34 dataset. The left-hand column indicates the minimum number of hours of flux-tower measurements required in each day, and the minimum number of days required in each month, to compute monthly-mean ET values.

	Dataset	MODIS	P-LSH	GLEAM	ERA5	CMIP5	CMIP6
0hrs_0days	**r**	**0.77**	**0.67**	0.16	0.55	-0.31	-0.06
	p	0.00	0.02	0.62	0.07	0.32	0.84
0hrs_10days	**r**	**0.78**	**0.67**	0.31	0.54	-0.28	-0.1
	p	0.00	0.02	0.33	0.07	0.37	0.75
0hrs_21days	**r**	**0.77**	**0.61**	0.23	0.47	-0.21	0
	p	0.00	0.04	0.46	0.12	0.52	0.99
18hrs_0days	**r**	**0.8**	**0.71**	0.1	**0.59**	-0.43	-0.09
	p	0.00	0.01	0.75	0.04	0.16	0.79
18hrs_10days	**r**	**0.77**	**0.72**	0.34	**0.61**	-0.36	-0.16
	p	0.00	0.01	0.29	0.04	0.25	0.62
18hrs_21days	**r**	**0.67**	0.51	0.12	0.43	-0.32	0.03
	p	0.02	0.09	0.7	0.17	0.31	0.93
21hrs_0days	**r**	**0.8**	**0.71**	0.21	**0.59**	-0.44	-0.08
	p	0.00	0.01	0.5	0.04	0.16	0.81
21hrs_10days	**r**	**0.74**	**0.72**	0.3	**0.65**	-0.4	-0.21
	p	0.01	0.01	0.35	0.02	0.19	0.52
21hrs_21days	**r**	**0.7**	0.56	0.03	0.5	-0.44	-0.04
	p	0.01	0.06	0.92	0.1	0.15	0.91

Table S7 – Table of catchment-mean ET estimates. The climatological annual and interannual standard deviation (σ) in ET over each catchment for each of the ET data sources in this study (mm year^{-1}). Correlations between catchment-balance ET and other ET estimates are shown. All data are from 2003–2013, apart from the CMIP5 data, which are from 1994–2004. These data are shown in a scatter plot in Figure S7.

	Catchment-balance	MODIS	P-LSH	GLEAM	ERA5	CMIP5	CMIP6
Catchment	**Mean ± σ**	**Mean ± σ**	**Mean ± σ**	**Mean ± σ**	**Mean ± σ**	**Mean ± σ**	**Mean ± σ**
Amazon	1083.1±36.5	1298.7±27.2	1266.8±16.5	1480.8±16.4	1279.7±8.0	1244.0±16.8	1298.7±15.9
Aripuanã	1403.3±81.0	1409.1±32.4	1348.4±29.0	1500.4±36.8	1239.1±33.6	1236.2±33.8	1293.7±31.5
Branco	1087.2±117.0	1187.2±24.1	1247.5±14.7	1472.0±61.9	1213.5±39.7	1049.2±45.8	1066.3±47.9
Japura	1217.0±158.4	1339.4±51.4	1263.2±19.8	1632.9±24.7	1340.0±17.5	1421.9±26.8	1386.9±24.8
Jari	1487.0±107.3	1501.0±36.4	1439.9±16.2	1793.2±62.8	1074.4±68.9	1032.6±59.1	1002.8±72.4
Madeira	1011.4±43.2	1185.8±27.1	1131.1±14.1	1196.4±38.1	1198.6±18.4	1063.2±22.1	1154.9±24.9
Negro	1206.1±85.3	1338.4±51.9	1361.5±16.9	1727.7±25.1	1367.3±14.8	1429.1±31.8	1448.6±28.0
Purus	1248.0±109.1	1406.1±46.4	1336.1±30.9	1538.8±38.3	1305.6±18.8	1224.8±32.8	1340.8±26.2
Solimões	966.6±138.9	1239.6±39.7	1209.7±17.2	1436.1±15.1	1239.4±10.6	1245.1±18.6	1269.0±18.4
Tapajós	1180.7±96.7	1291.2±31.2	1265.6±38.2	1382.6±44.5	1238.8±28.5	1178.1±30.4	1256.9±33.2
Xingu	1445.0±130.9	1336.2±27.3	1306.9±40.9	1414.8±39.3	1238.0±21.2	1173.2±33.1	1226.7±32.3
Correlation with catchment-balance ET		r=0.84, p=0.00	r=0.82, p=0.00	r=0.51, p=0.11	r=-0.28, p=0.41	r=-0.06, p=0.85	r=-0.14, p=0.69

Figures

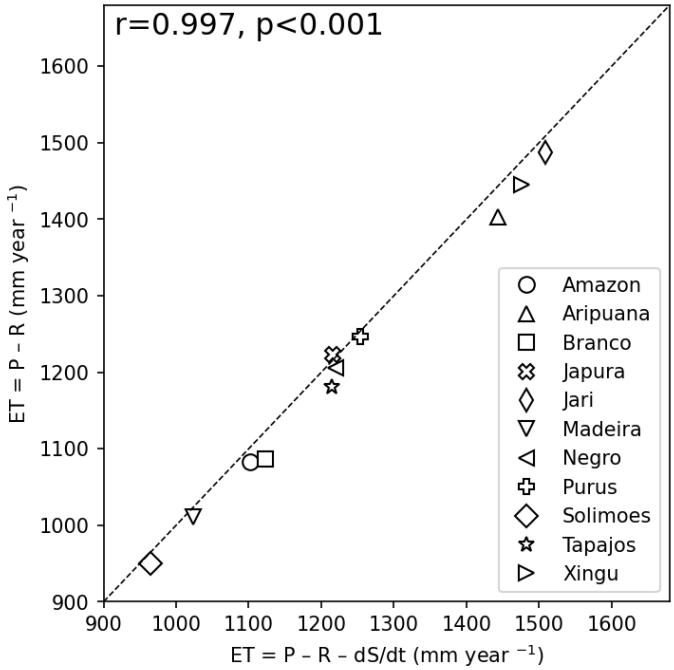

Figure S1 – Comparing ET estimates based on water-budget analysis. Relationship between climatological annual mean ET estimated from precipitation (P), runoff (R), and change in terrestrial water storage (dS/dt), and ET estimated from P and R only, over the Amazon and ten sub-catchments. Data are from 2003–2013.

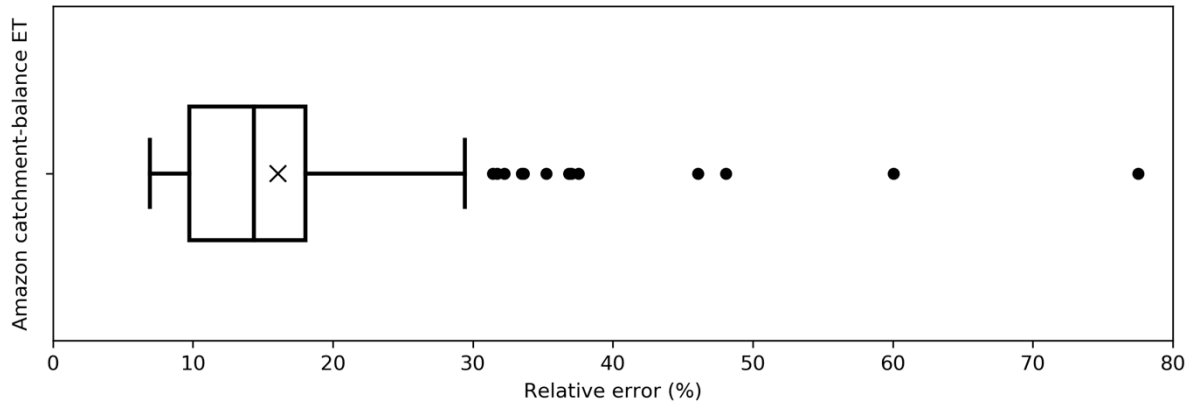

Figure S2 – Relative uncertainty in Amazon catchment-balance ET estimates. Distribution of relative errors in monthly Amazon catchment balance ET from 2003–2013.

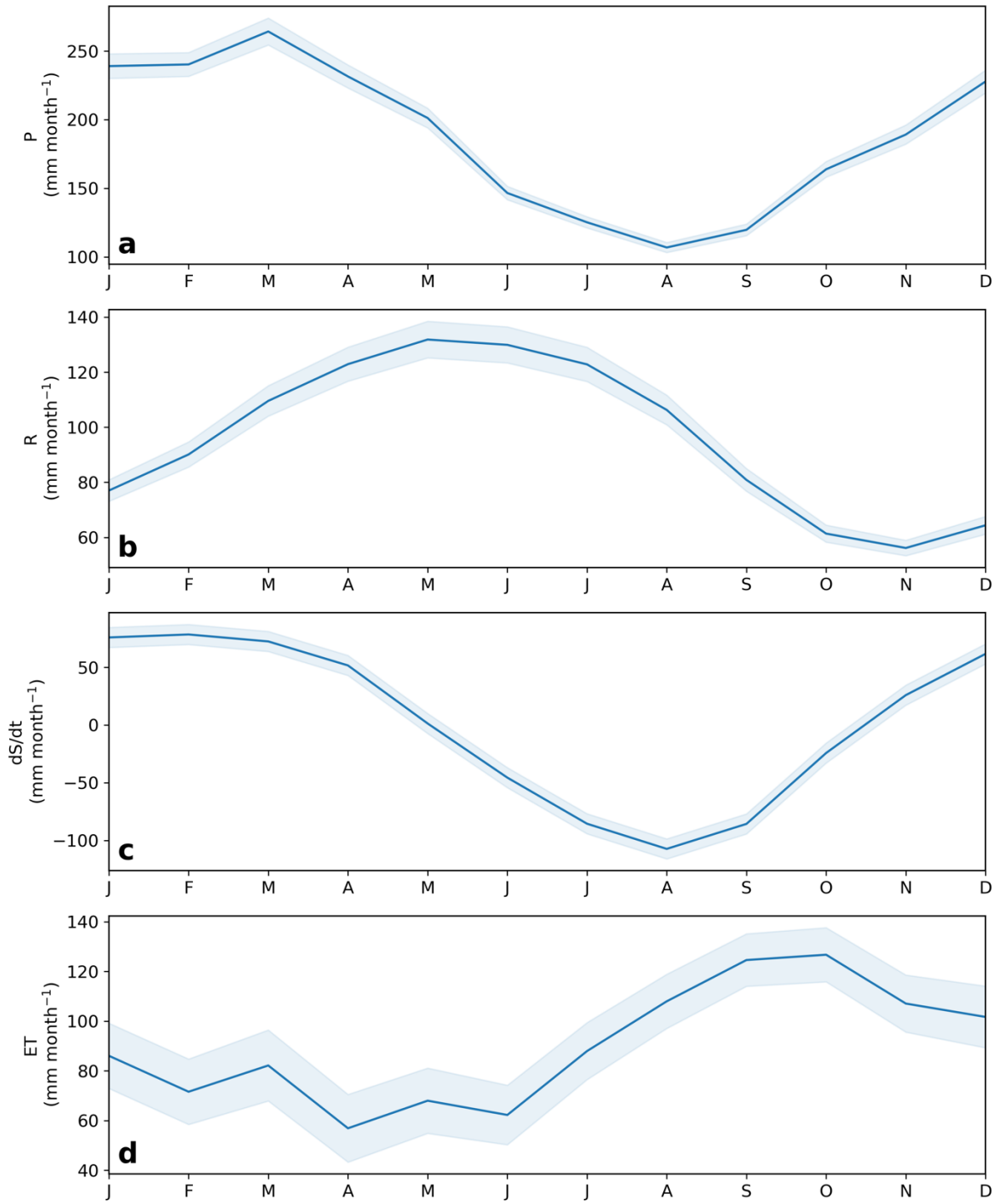

Figure S3 – Seasonal variation in components of the water-budget equation. a) Precipitation (P); b) river runoff (R); c) change in groundwater storage (dS/dt); and d) evapotranspiration (ET). Shading represents the mean absolute error in each month.

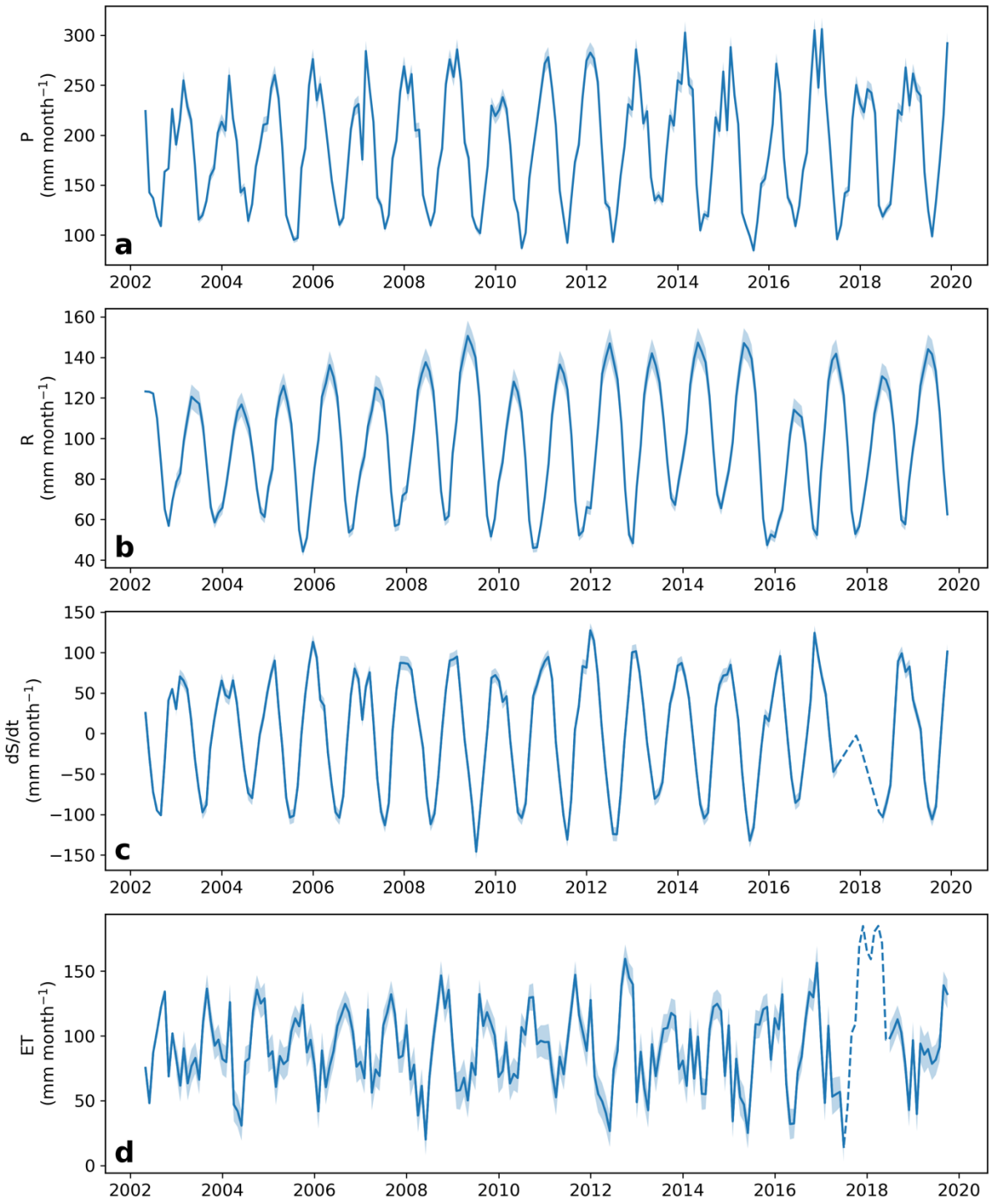

Figure S4 – Interannual variation in components of the water-budget equation. a) Precipitation (P); b) river runoff (R); c) change in groundwater storage (dS/dt); and d) evapotranspiration (ET). Shading represents the absolute error in each month. Dashed lines indicate data that were removed due to doubts over reliability.

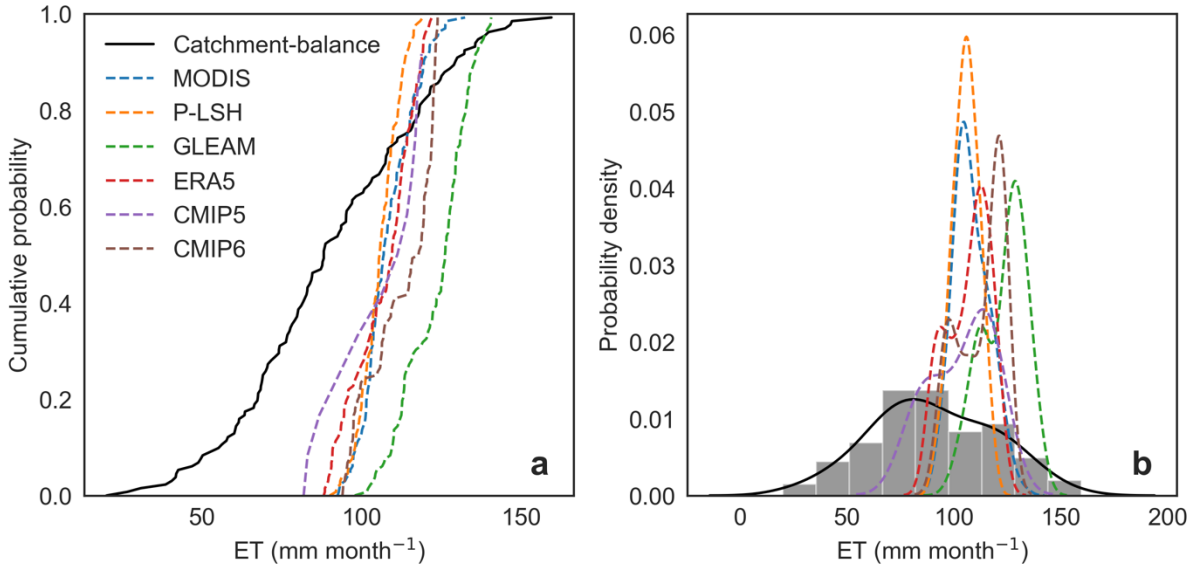

Figure S5– Kolmogorov-Smirnov analysis. The cumulative probability (a) and probability density (b) functions for monthly Amazon ET from catchment-balance, satellites (MODIS, P-LSH, GLEAM), ERA5 reanalysis, and climate models (CMIP5 and CMIP6) from 2003 to 2013. Dashed lines indicate the data come from a statistically different distribution from the catchment-balance data (determined using a two-sample Kolmogorov-Smirnov test).

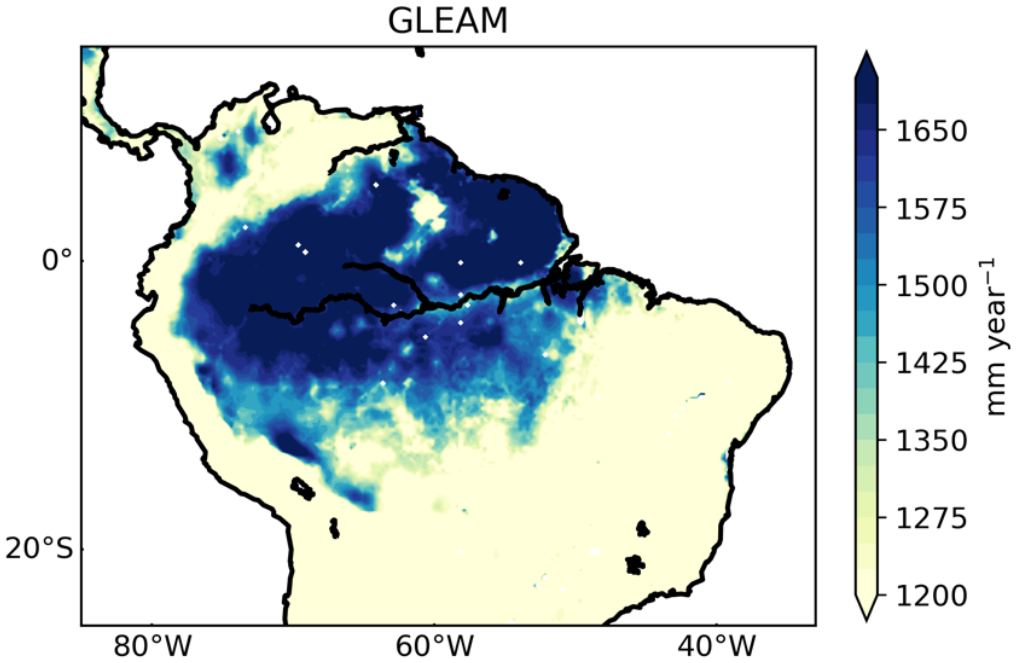

Figure S6 – Climatological mean annual ET from GLEAM (2003–2013).

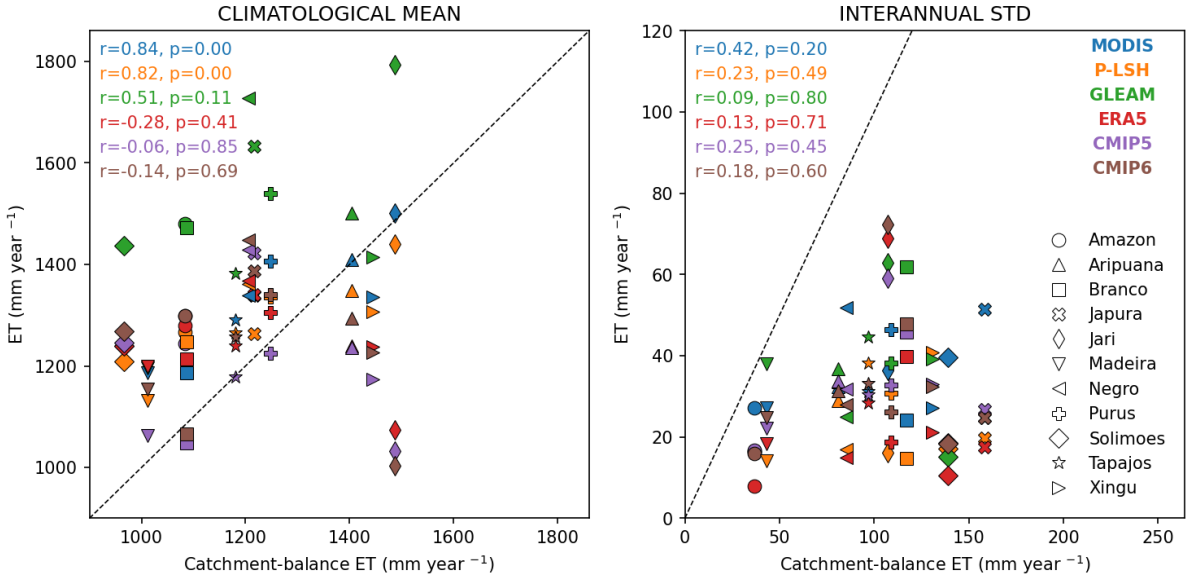

Figure S7 – Comparing catchment-mean ET estimates. The climatological annual means (left panel) and standard deviations (right panel) of catchment-balance ET estimates plotted against ET estimates from six gridded products. All data are from 2003–2013, apart from the CMIP5 data, which are from 1994–2004. Catchment locations are shown in Figure 1.

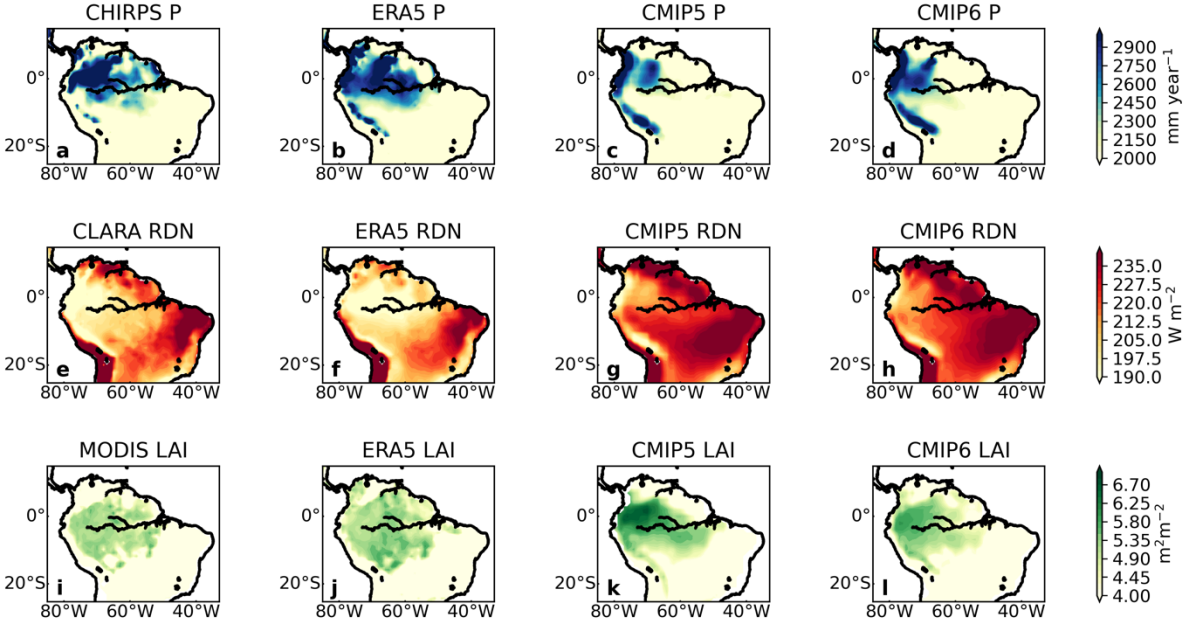

Figure S8 – Climatological annual precipitation, radiation and leaf area index. Mean annual precipitation (P, a–d), radiation (RDN, e–h) and leaf area index (LAI, i–l) from satellites (column 1), reanalysis (column 2) and climate models (columns 3 & 4) over the period 2003–2013. References for each dataset are provided in the main paper.

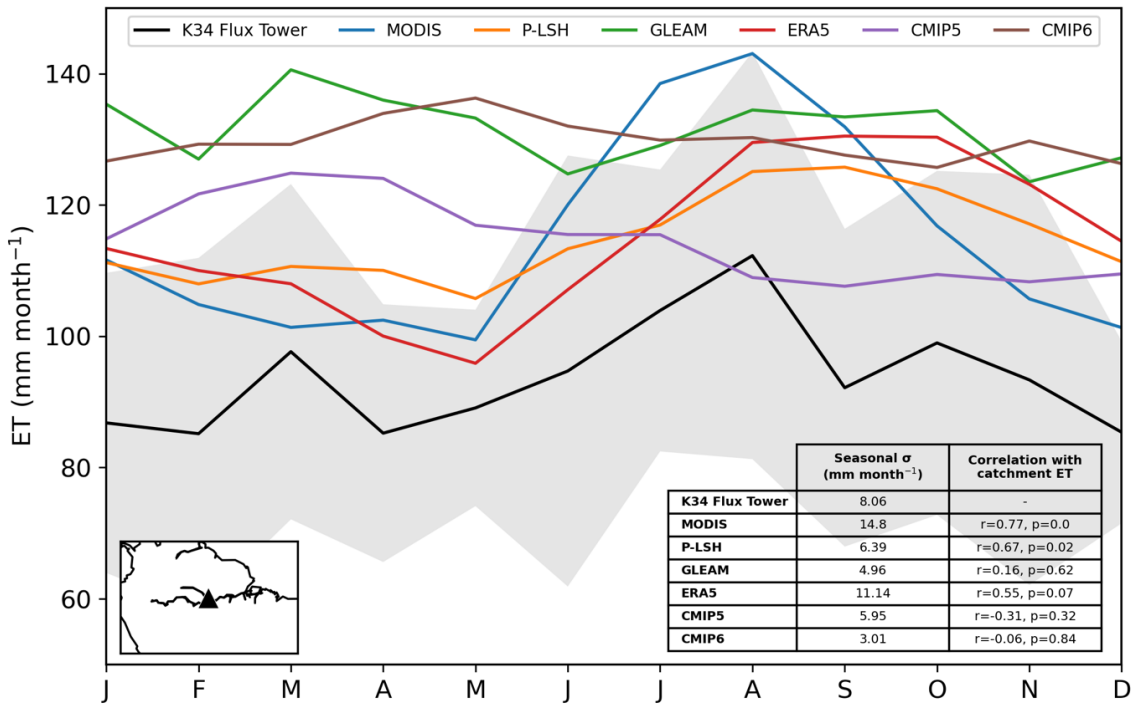

Figure S9 – Climatological seasonal cycle in ET at the K34 flux tower site. Lines indicate the seasonal time series in ET from the K34 flux tower (black), satellites (dark blue), ERA5 reanalysis (light blue) and climate models (green). The location of the K34 tower is indicated in the inset map. Data for satellite and reanalysis products were taken from a 0.25° grid cell containing the tower, and model data were from a 1° grid cell. Shading represents the standard deviation in flux-tower ET (see Methods). The inset table records the seasonal variation (standard deviation, σ) in ET for each dataset, and the correlations between each dataset and flux-tower ET. ET data from the K34 tower are from 1999–2017, data for all other products are from 2003–2013. Note that the y-axis does not start at zero.

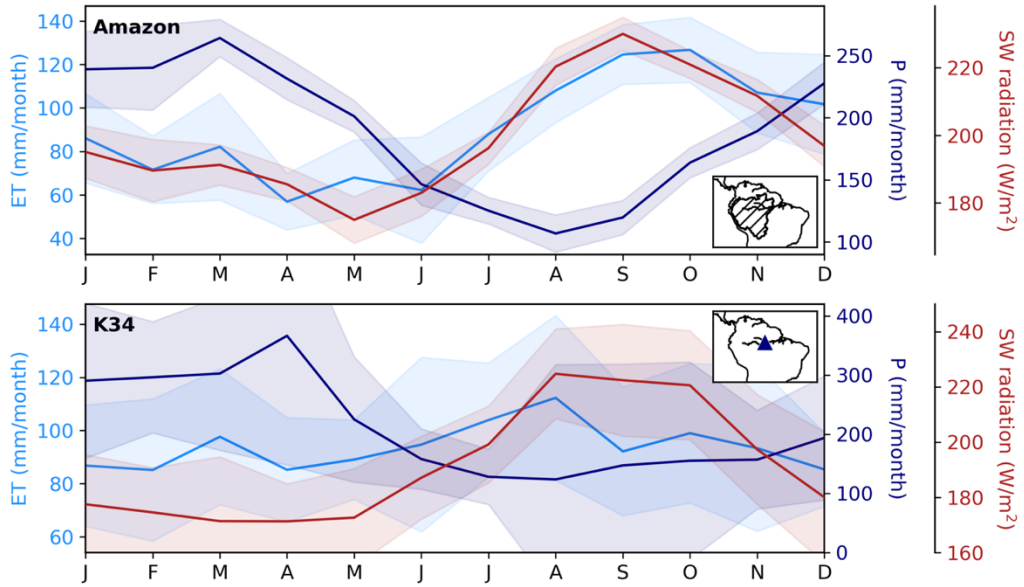

Figure S10 – Seasonal variation in controls on ET. Climatological seasonal cycles in ET (light blue), precipitation (P, dark blue) and shortwave radiation (red) averaged over the Amazon (catchment-balance data from 2003–2013, top panel) and measured at the K34 flux tower site (bottom panel, data from 1999–2017). P and radiation data for the Amazon basin are area-weighted basin-means of CHIRPS and CLARA-A1 data, respectively. Confidence intervals indicate the interannual standard deviation in each month. Note that y-axes do not all start at zero.

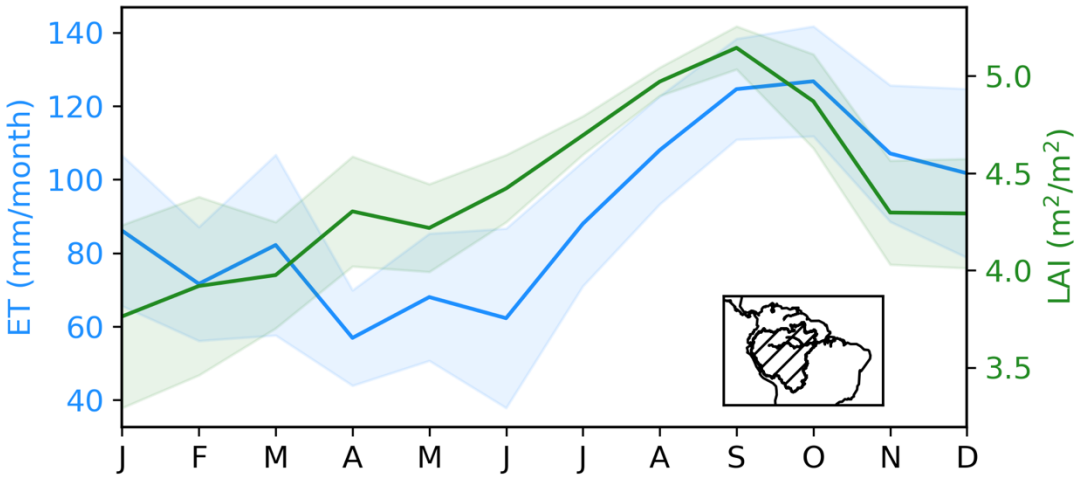

Figure S11 – Seasonal variation in leaf area index over the Amazon. Climatological seasonal cycles in catchment-balance ET (light blue) and MODIS MOD15A2H Collection 6 LAI (green) averaged over the Amazon region shown in the inset map (area-weighted mean using data from 2003–2013). Confidence intervals indicate the interannual standard deviation in each month. Note that y-axes do not start at zero.

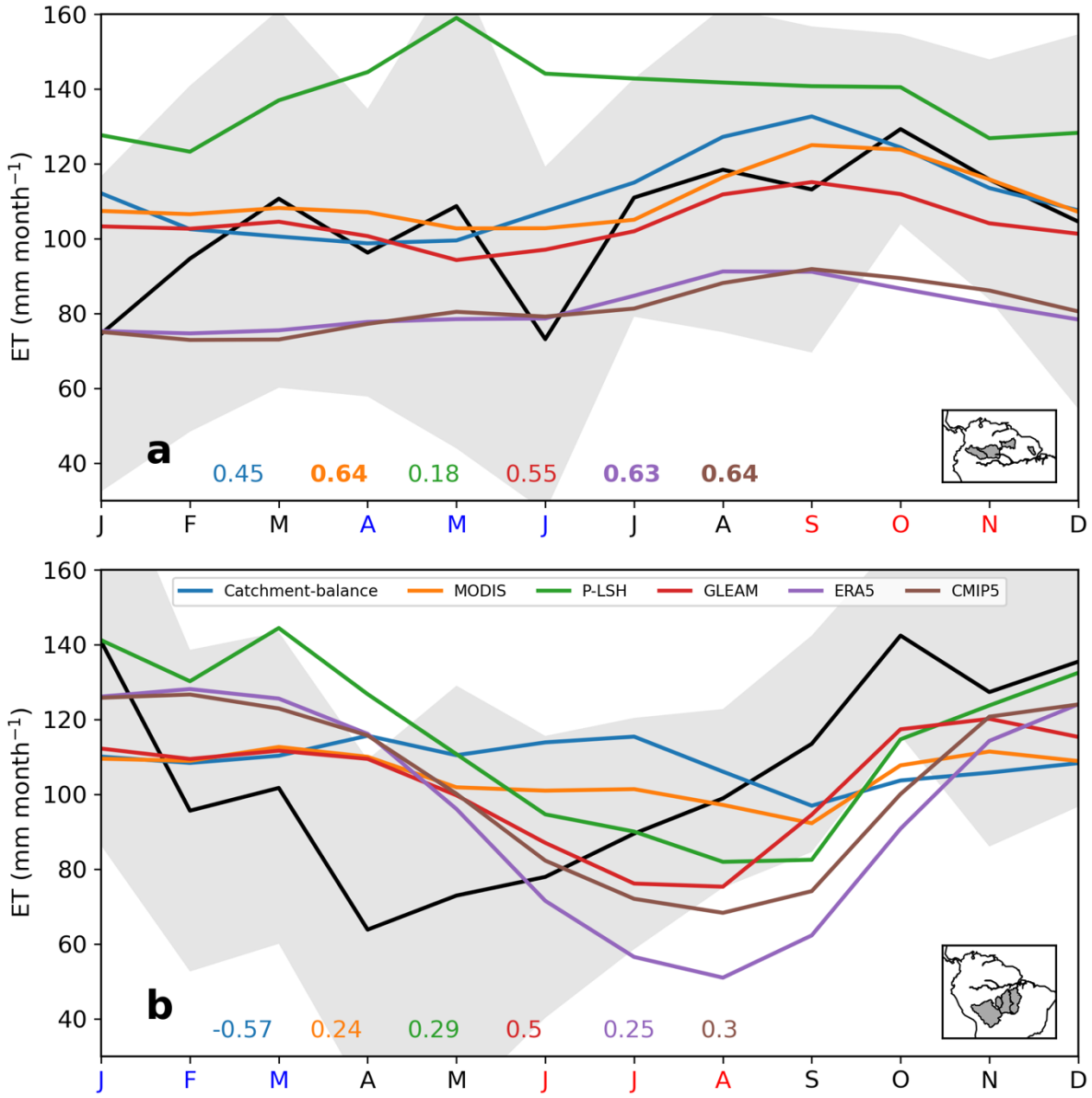

Figure S12 – Climatological seasonal cycles in evapotranspiration over the northern and southern Amazon. Mean seasonal cycle in ET from catchment balance, satellites (MODIS, P-LSH, GLEAM), ERA5 reanalysis and climate models (CMIP5 and CMIP6) over the northern Amazon basins (a) and southern Amazon basins (b). The regions used in each analysis are indicated in the inset maps. Shading represents absolute uncertainty in catchment-balance ET (see Methods). Correlations with catchment-balance ET are shown on each panel, with bold numbers indicating statistical significance ($p<0.05$). Data are from 2003 to 2013, with the exception of CMIP5, where the data are from 1994–2004. On the x-axis of each panel, the three wettest months are indicated in blue and three driest months are indicated in red. Note that the axes do not start at zero.

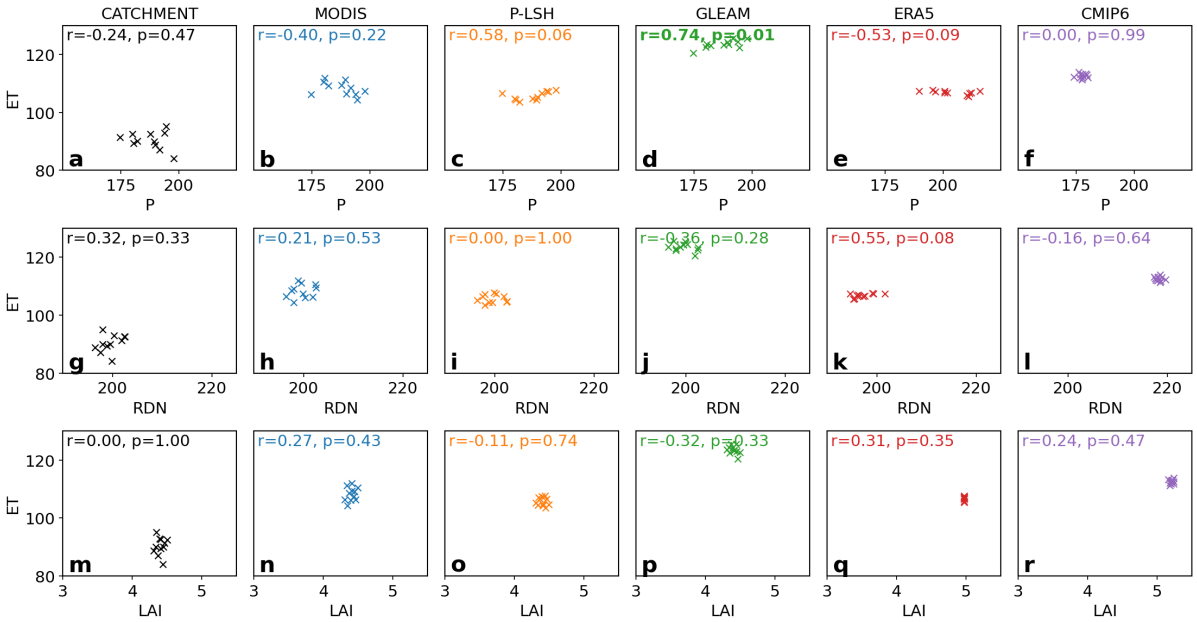

Figure S13 – Controls on interannual variation in Amazon ET. Interannual ET (in units of mm month^{-1}) for the Amazon (Fig. 1) from catchment-balance, satellites (MODIS, P-LSH, GLEAM), ERA5 reanalysis and CMIP6 plotted against (a–f) precipitation (P, mm month^{-1}); (g–l) surface shortwave radiation (RDN, W m^{-2}); and (m–r) leaf area index (LAI, m^2 m^{-2}). Satellite ET data are plotted against P from CHIRPS, RDN from CLARA-A1 and LAI from MODIS; ERA5 and CMIP6 ET are plotted against ERA5 and CMIP6 P, RDN and LAI, respectively. All data are from 2003 to 2013. Note that the axes do not start at zero.

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