Supplementary Information to "Detection of signals linked to climate change, land-cover change and climate oscillators in Tropical Montane Cloud Forests"

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Table S1: Assessment of the accuracy of the Random Forest classification; the confusion matrix shows the results using the MERRA2 T_{2m} and Z_C products. The out-of-bag (OOB) estimate of error rate is 5.72 %. The column '% Error' shows the classification error per class, 'r MODIS' shows the correlation between the class probability estimated by the Random Forest Classifier and the % cover of the same class in the aggregated MODIS classification (Friedl et al., 2010; Sulla-Menashe et al., 2019), and '% Area' shows the percentage area per class as estimated by the Random Forest Classifier. (EBL = Evergreen broadleaf forest; DBL = Deciduous broadleaf forest; see also Table 2.

		Predicted Class										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	% Error	r MODIS	% Area
Actual Class	1. TMCF	350	59	17	12	1	17	7	2	25		4.4
	2. EBL	39	950	10	0	0	0	0	0	5	0.94	20.4
	3. DBL	9	13	945	31	0	0	1	0	5	0.78	8.0
	4. SAV	5	1	31	935	0	15	12	0	6	0.82	20.6
	5. Shrub	0	0	0	0	963	29	0	4	2	0.87	5.5
	6. Grass	1	0	0	11	17	943	28	0	6	0.84	20.9
	7. Crop	1	0	0	35	0	28	936	0	6	0.71	5.3
	8. Barren	0	0	0	0	0	0	0	999	0	0.98	14.7

Table S2: Summary statistics, by country and continent, for cells where TMCFs are the dominant land-cover class. Statistics are calculated for 8 countries with the largest TMCF surface area in a continent. Area is the surface area of these TMCF cells, P(TMCF) is the average probability that TMCFs occurs in these cells, T is the average ERA5 2 m temperature, T_d the average ERA5 2 m dewpoint temperature, Z_C is the average cloud-base height, P is the average annual TRMM precipitation amount (excluding occult precipitation), h is the average elevation, Δh the average relief (the difference between minimum and maximum altitude for each $0.1^\circ \times 0.1^\circ$ cell), h/D is the mean slope (β_1) from the regression equation $h = \beta_0 + \beta_1 D$ with D being the distance and h the elevation, D_{coast} is the average distance to the coast, V is the average NDVI value, σ_V is the mean spatial standard deviation in NDVI, and Ag is the % cropland indicated by the MODIS land-cover classification. A small difference between the land-sea mask used for data analysis and the country boundaries explains the difference in the total of TMCF area for each continent.

Country / Region	Area	P(TMCF)	T	T_d	Z_C	P	h	Δh	$\Delta h/\Delta D$	D_{coast}	V	σ_V	Ag
	10^3km^2	10^3km^2	°C	°C	m	mm	m a.s.l.	m	m/km	km	-	-	%
Colombia	232	0.77	16.9	14.0	364	2280	1896	1235	0.3	214	0.74	0.002	1.6
Peru	172	0.72	13.3	10.4	362	1376	2487	1465	-14.6	251	0.66	0.004	1.2
Mexico	163	0.64	17.7	12.7	623	1350	1617	1204	18.8	126	0.70	0.003	3.4
Ecuador	98	0.72	14.9	12.5	303	1288	2137	1109	10.4	115	0.68	0.004	3.3
Venezuela	88	0.67	20.5	17.2	403	1897	1281	1082	6.4	219	0.74	0.004	0.3
Bolivia	66	0.67	13.9	10.8	398	1126	2300	1212	-26.2	503	0.66	0.005	0.2
Brazil	41	0.49	21.2	17.6	452	1719	729	593	13.1	366	0.73	0.007	0.0
Guatemala	37	0.67	18.1	14.5	452	2191	1531	1239	6.9	106	0.72	0.003	2.4
Americas – Other	115	0.62	21.2	17.9	419	1889	906	1102	16.5	76	0.76	0.002	1.3
Americas – All	1015	0.69	17.1	13.7	418	1700	1771	1200	3.2	202	0.71	0.003	1.7
Ethiopia	72	0.52	16.2	10.5	710	1365	2215	876	-2.7	715	0.67	0.002	18.5
Kenya	40	0.56	16.6	10.6	758	1129	2146	686	8.3	536	0.66	0.004	7.3
DR Congo	39	0.57	18.5	14.4	518	1207	1780	787	3.3	1140	0.73	0.002	0.1
Madagascar	39	0.51	18.4	15.1	408	1839	1098	609	16.7	85	0.71	0.004	0.1
Tanzania	36	0.57	18.5	13.4	637	1027	1538	943	11.1	386	0.65	0.007	1.5
Uganda	12	0.56	18.9	13.9	616	1161	1738	795	-1.3	1018	0.72	0.003	35.4
Cameroon	12	0.55	21.8	18.9	368	2099	1006	902	20.9	110	0.73	0.002	3.9
Angola	10	0.46	23.1	19.5	448	940	479	374	20.1	60.5	0.69	0.004	0.0
Africa – Other	46	0.52	20.5	16.0	560	1332	1153	775	16.5	469	0.68	0.005	11.4
Africa – All	309	0.54	18.3	13.5	596	1332	1642	784	8.7	554	0.69	0.004	8.7
Indonesia	255	0.64	21.0	18.7	290	2635	1086	1095	25.1	54	0.78	0.002	5.9
Papua New Guinea	98	0.73	17.8	16.0	231	2665	1667	1266	28.0	96	0.79	0.001	0.9
Viet Nam	90	0.57	20.8	17.7	393	1973	795	1133	7.7	176	0.76	0.002	2.3
Philippines	89	0.60	23.3	20.7	333	2497	6314	1051	21.3	25	0.76	0.002	11.0
China	62	0.59	18.8	14.8	502	1563	1185	1144	6.6	409	0.73	0.002	2.3
Laos	48	0.53	20.7	17.2	442	1928	944	1010	-1.6	267	0.78	0.002	0.2
Malaysia	34	0.60	23.0	20.6	306	2843	720	1070	16.7	79	0.81	0.002	0.4
Myanmar	29	0.53	19.8	15.0	609	1679	1195	1323	0.3	310	0.77	0.002	0.2
Australasia – Other	83	0.57	22.2	18.3	487	1679	751	1056	26.2	85	0.78	0.003	2.5
Australasia – All	793	0.61	20.9	18.0	358	2299	994	1111	19.2	124	0.78	0.002	3.9

Table S3: Same as Table S2 but for MERRA-2 classification and temperature T, T_d and cloud-base height (Z_C) fields. The ranking of 8 countries with highest TMCF surface area is differs from that show in Table S2.

Country / Region	Area	fc * A	T	T_d	Z_C	P	h	Δh	$\Delta h/\Delta d$	d	V	σ_V	Ag
	10^3km^2	10^3km^2	°C	°C	m	mm	m a.s.l.	m	m/km	km	-	-	%
Colombia	236	0.74	19.6	16.0	449	2314	1857	1231	1.5	211	0.74	0.002	1.3
Peru	156	0.69	15.6	10.4	644	1351	2501	1478	-13.2	252	0.66	0.005	1.3
Mexico	140	0.62	20.0	13.7	797	1329	1629	1259	19.6	121	0.70	0.003	2.8
Venezuela	91	0.66	23.7	19.2	569	1852	1217	1063	7.4	207	0.74	0.004	0.3
Ecuador	88	0.73	17.3	13.1	524	1266	2291	1184	12.5	116	0.67	0.004	1.8
Bolivia	53	0.63	14.9	9.0	734	1119	2375	1262	-27.8	493	0.66	0.005	0.2
Brazil	39	0.46	23.3	19.3	492	1854	603	556	12.2	477	0.72	0.010	0.0
Honduras	36	0.62	23.1	18.7	560	1507	944	1116	7.0	78	0.75	0.002	0.6
Americas – Other	134	0.61	23.7	19.2	558	2037	946	1062	18.1	68	0.75	0.003	2.9
Americas – All	962	0.68	20.0	15.2	583	1725	1695	1185	5.3	193	0.71	0.004	1.5
Ethiopia	60	0.52	18.8	12.1	835	1386	2109	960	-2.0	734	0.68	0.003	12.9
Kenya	40	0.56	19.2	12.4	846	1125	2122	712	8.9	538	0.65	0.004	8.9
DR Congo	38	0.58	20.1	15.3	600	1224	1774	853	5.7	1176	0.73	0.002	0.12
Tanzania	32	0.57	21.2	15.2	756	1000	1509	1019	15.5	381	0.65	0.007	2.3
Madagascar	31	0.49	20.1	17.2	361	1840	1056	691	20	82	0.71	0.005	0.0
Uganda	14	0.53	21.6	15.4	770	1164	1649	772	-3.4	1027	0.72	0.006	34.6
Cameroon	13	0.55	23.3	20.0	410	2092	1072	955	18.1	128	0.72	0.002	4.6
Rwanda	9	0.59	19.2	14.0	643	1056	1920	737	1.7	1105	0.66	0.008	34.9
Africa – Other	30	0.59	23.0	17.1	735	1271	1044	990	28.1	377	0.67	0.005	9.2
Africa – All	265	0.55	20.4	14.8	696	1324	1656	870	1.0	602	0.69	0.004	8.7
Indonesia	296	0.62	24.3	21.4	358	2537	867	968	26.0	43	0.78	0.003	5.4
Philippines	114	0.61	25.8	22.6	401	2513	520	940	22.6	21	0.78	0.002	10.6
Papua New Guinea	108	0.70	21.6	18.9	335	2683	1517	1210	30.4	84	0.79	0.002	0.8
Viet Nam	81	0.55	22.5	18.5	492	1992	765	1137	8.3	161	0.75	0.002	3.0
China	60	0.55	19.5	15.0	560	1566	1173	1170	6.6	423	0.72	0.002	2.2
Malaysia	37	0.57	24.9	22.5	293	2802	561	861	17.2	53.8	0.78	0.003	2.7
Laos	30	0.51	22.3	17.2	647	1987	906	1075	-3.2	258	0.78	0.002	0.2
Thailand	27	0.53	24.8	20.1	595	1777	635	937	6.4	184	0.78	0.003	2.3
Australasia – Other	101	0.56	24.5	19.4	637	1744	734	1068	26.4	104	0.76	0.003	2.7
Australasia – All	794	0.57	23.9	20.4	435	2329	812	968	22.7	94	0.77	0.003	4.0

Table S4: Trends in climatic and environmental variables over 8 land cover classes (see table for explanation of classes) as well as locations of TMCFs used for training the classification (indicated by column 'TMCF') identified by Aldrich et al. (1997). Zero trends and trend with significance of $p > 0.05$ are indicated by a '-'.

	Sites	TMCF	EBL	DBL	SAV	Shrub	Grass	Crop	Barren
MERRA T_{2m} ($10 \times$ K y^{-1}): 1980—2019									
Tropics	0.22	0.19	0.31	0.27	0.31	0.13	0.23	0.22	0.32
Americas	0.25	0.20	0.31	0.23	0.32	0.10	0.26	0.31	-
Africa	0.24	0.20	0.43	0.36	0.33	0.16	0.27	0.31	0.33
Asia	0.18	0.16	0.18	0.17	0.15	-	-	0.16	-
MERRA $T_{d,2m}$ ($10 \times$ K y^{-1}): 1981–2019									
Tropics	0.23	0.24	0.17	0.18	0.12	0.35	0.23	0.30	0.37
Americas	0.11	0.14	0.10	-	-	-	-	0.11	-
Africa	0.37	0.40	0.28	0.14	0.21	0.48	0.28	0.25	0.39
Asia	0.31	0.30	0.30	0.36	0.33	-	0.28	0.37	0.44
MERRA Z_C (m y^{-1}): 1980–2019									
Tropics	-	-0.65	1.57	1.10	2.34	-	-	-	-
Americas	1.64	0.80	2.59	2.07	4.24	3.14	3.03	2.48	2.01
Africa	-1.66	-2.48	1.92	2.56	-	-3.41	-	-	-
Asia	-1.71	-1.80	-1.75	-2.35	-2.26	-	-	-2.58	-
MODIS NDVI ERA $\times$ 1000 (- y^{-1}): 2000–2019									
Tropics	0.78	0.92	0.44	0.72	0.55	-	-	1.35	-
Americas	0.91	1.05	0.35	-	-	-	-	0.94	0.35
Africa	-	-	0.62	0.79	0.54	-	-	-	-
Asia	0.878	0.98	0.54	0.97	1.80	-	-	2.19	0.90
MEaSUREs Tree cover (% y^{-1}): 1982–2016									
Tropics		0.20	-	-	-	-	-	0.04	-
Americas		0.22	-	-0.11	-0.19	-	-	0.08	-
Africa		-	-	-	-	-	-	-	-
Asia		0.24	0.14	0.15	0.10	-	-	0.05	-
Area with positive secular trend in tree cover (km$^2 \times 1000$)									
Tropics	-	1610	5080	1910	4480	360	4560	19200	80
Americas	-	790	2690	440	1520	30	670	240	30
Africa	-	130	830	730	2290	190	3200	390	50
Asia	-	710	1550	740	680	110	740	1230	2
Area with negative secular trend in tree cover (km$^2 \times 1000$)									
Tropics	-	560	5160	2060	5880	1570	4510	790	30
Americas	-	220	3500	650	2920	40	970	110	10
Africa	-	130	1050	1070	2530	450	2470	350	20
Asia	-	210	610	340	330	1080	1070	330	0

Table S5: TMCF surface area (1000× km^2) affected by either a positive or a negative trend over time in cloud-base height. Column 'Area' shows the total TMCF area, subscripts E and M indicate ERA5 and MERRA-2 products, respectively. Up arrows indicate areas where the cloud-base increases, and down arrows where they decrease.

Area (km^2)	TMCF	$Z_{C,\mathrm{E}}\uparrow$	$Z_{C,\mathrm{M}}\uparrow$	$Z_{C,\mathrm{E}}\downarrow$	$Z_{C,\mathrm{M}}\downarrow$
Drift correction					
Tropics	2120	405	440	735	830
Americas	1010	390	400	250	170
Africa	310	10	5	120	170
Asia	790	0	40	590	480
No correction					
Tropics		870	410	190	580
Americas		520	280	260	230
Africa		240	50	130	40
Asia		110	70	150	310

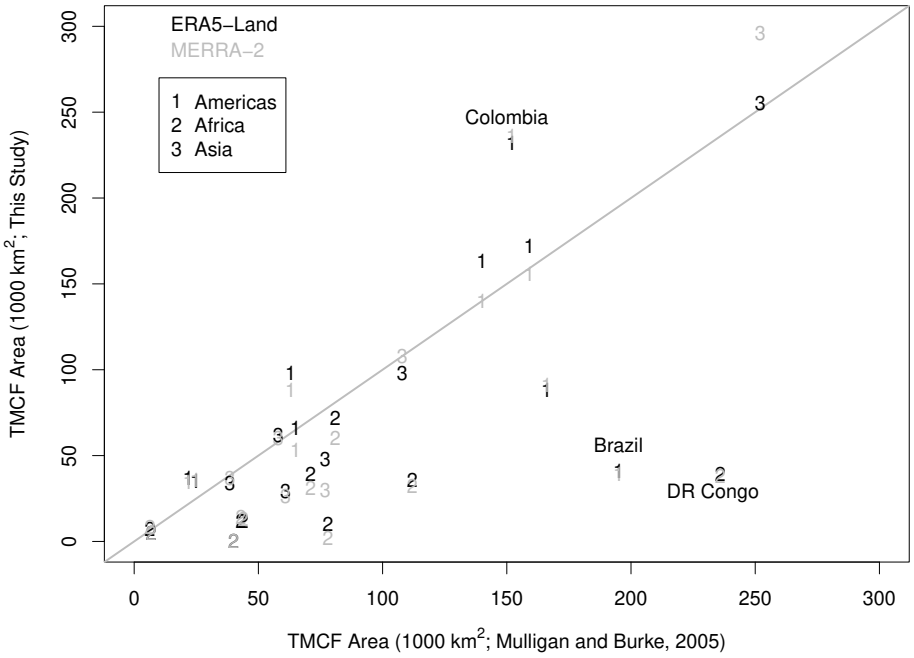

Figure S1: Comparison of TMCF area estimates for 25 countries from Mulligan and Burke (2005) with those from the present study. Country names (Brazil, Democratic Republic of the Congo and Colombia) for three outliers are indicated. The estimates of Brazil are not comparable because Mulligan and Burke (2005) consider all of Brazil and the present study is limited to that part of Brazil located in the tropics (r = 0.65, RMSE = 64.7 10^3 km^2 (ERA5-Land) and r = 0.66, RMSE =62.7 10^3 km^2 (MERRA-2) for 25 countries; and r = 0.71, RMSE = 54.5 10^3 km^2 (ERA5-Land) and r = 0.72, RMSE =57.5 10^3 km^2 (MERRA-2) when data for Brazil are removed. The mean bias is largest for Africa (-12.5 10^3 km^2 (ERA5-Land) and -5.4 10^3 km^2 (MERRA-2) for the Americas without Brazil, 48.6 10^3 km^2 and 51.5 10^3 km^2 for Africa, 11.5 10^3 km^2 and 6.3 10^3 km^2 for Asia).

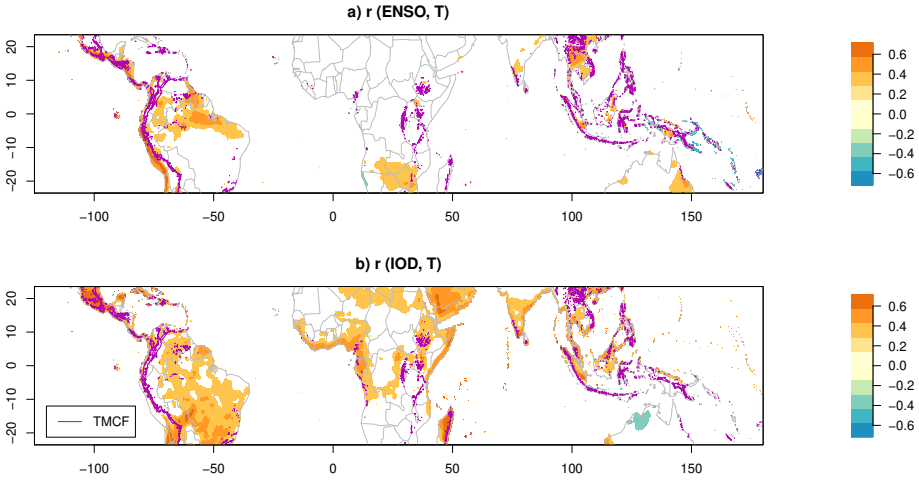

Figure S2: Same as Fig. 5 but for MERRA-2 surface-air temperature.

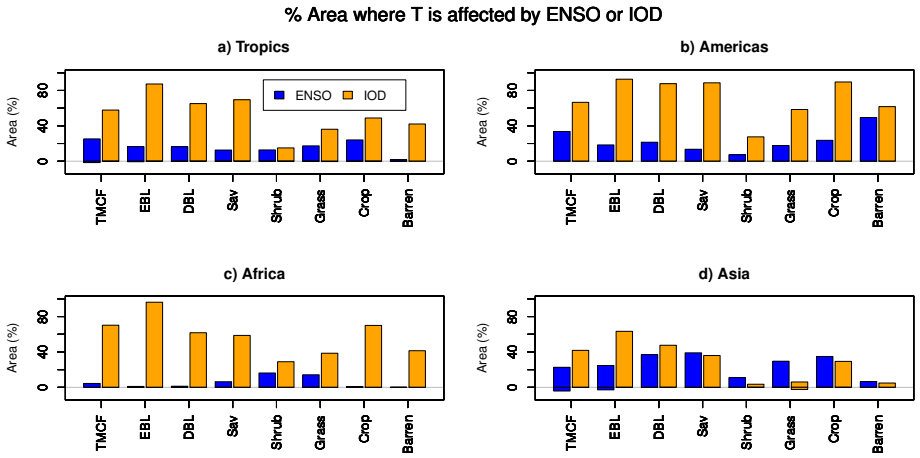

Figure S3: Percentage area of each of the eight land-cover classes (using the ERA5-Land based classification) where ENSO or IOD is significantly correlated with ERA5-Land mean annual surface temperature. a) Tropics b) Americas, c) Africa d) Asia.

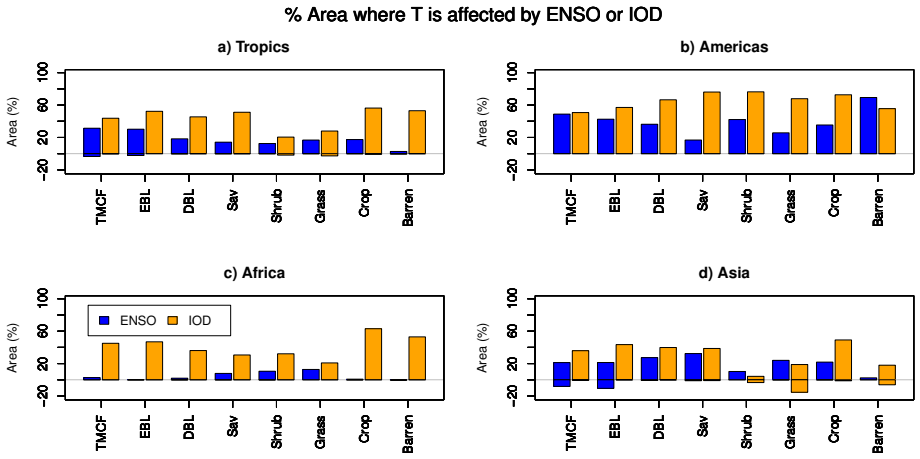

Figure S4: Same as Fig. S3 but for MERRA-2 surface air temperature.

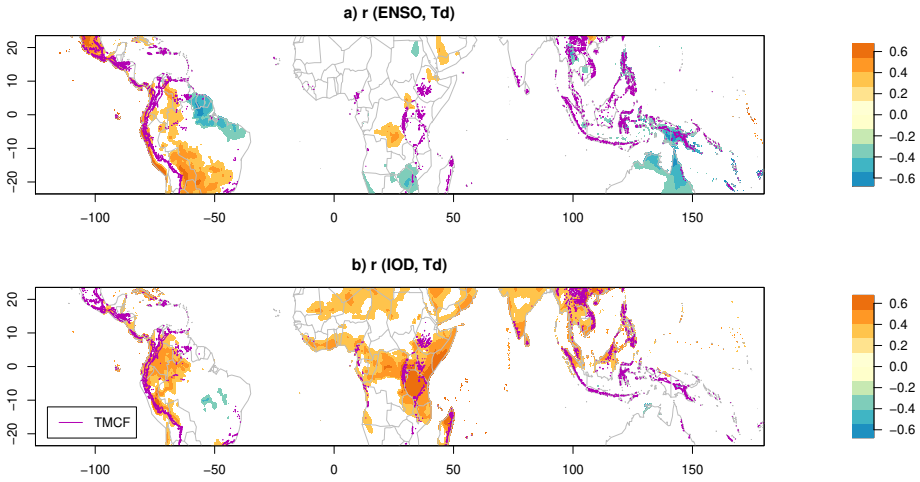

Figure S5: Same as Fig. 5 but for MERRA-2 dewpoint temperature.

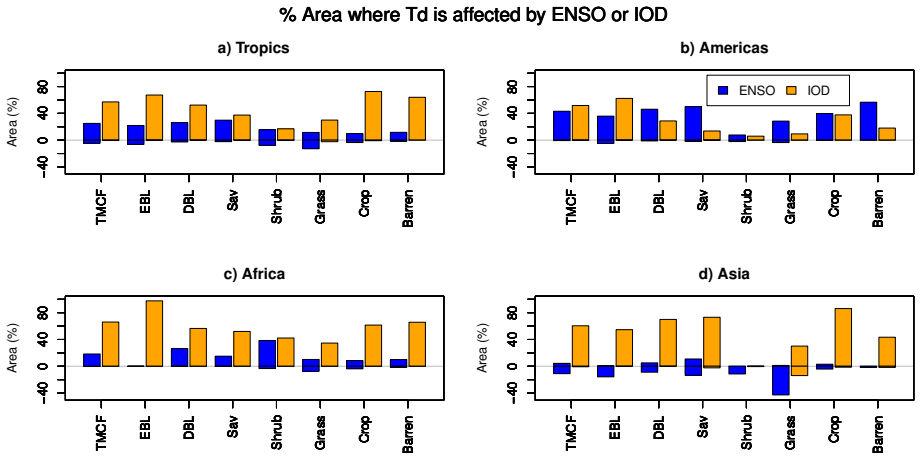

Figure S6: Same as Fig. S3 but for ERA5-Land dew-point temperature.

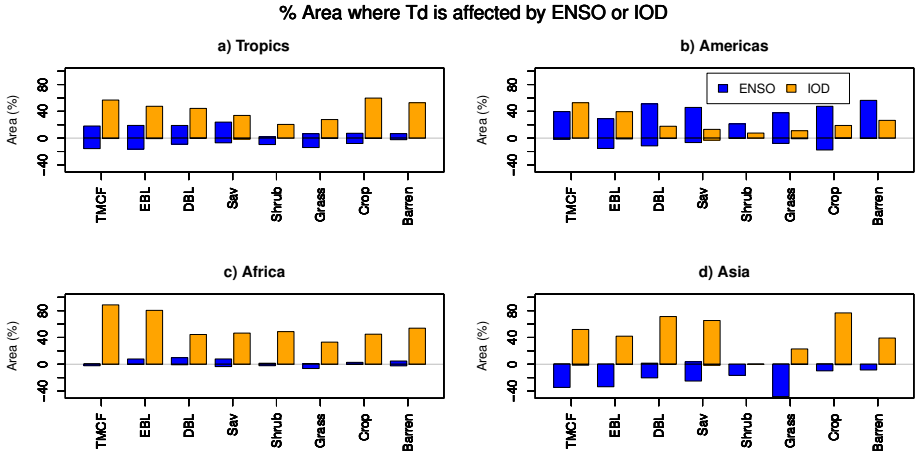

Figure S7: Same as Fig. S3 but for MERRA-2 dew-point temperature.

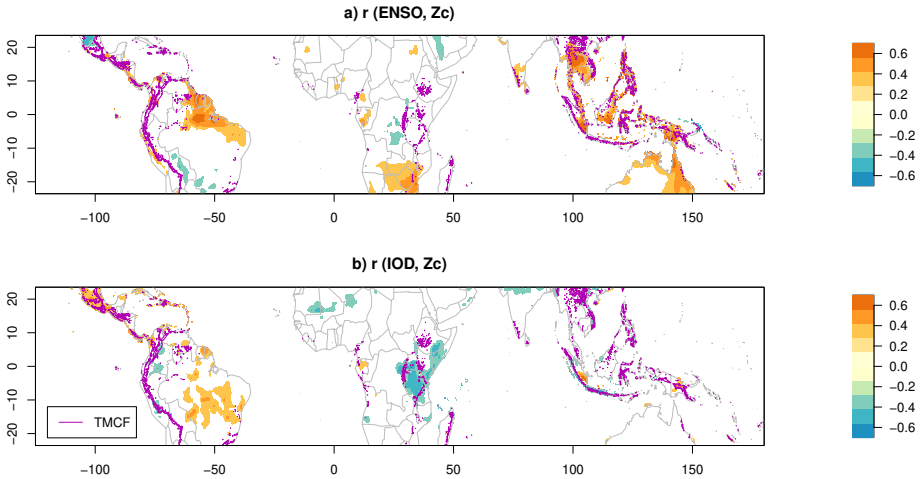

Figure S8: Same as Fig. 5 but for MERRA-2 cloud-base height.

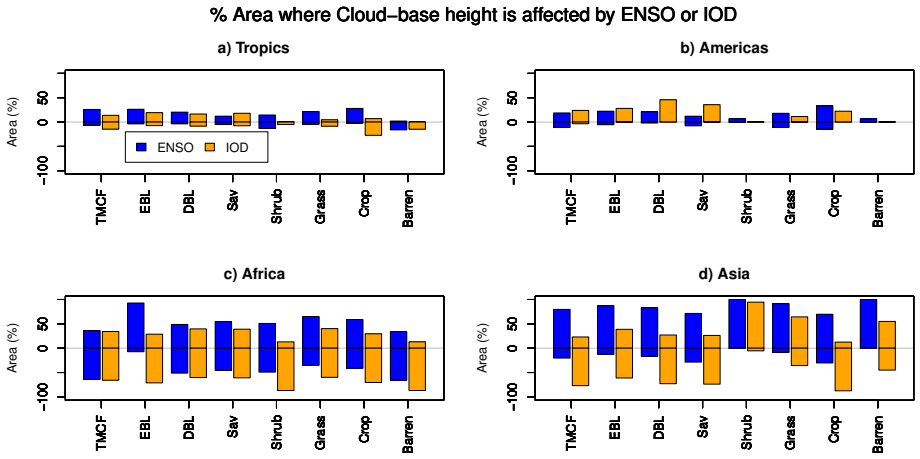

Figure S9: Same as Fig. S3 but for ERA5-Land cloud-base height.

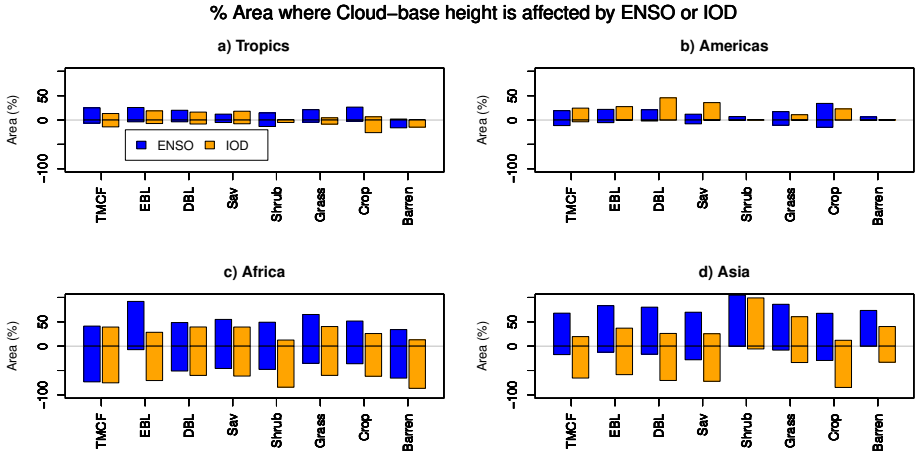

Figure S10: Same as Fig. S3 but for MERRA-2 cloud-base height.

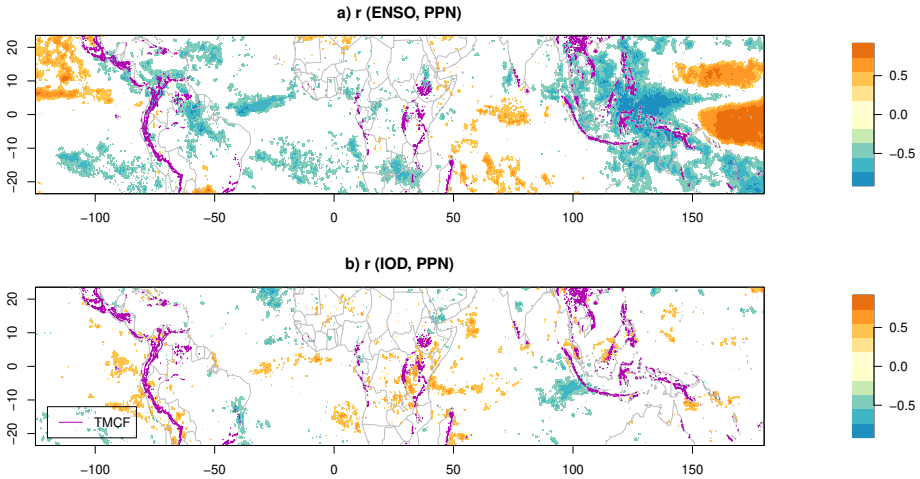

Figure S11: Same as Fig. 5 but for TRMM precipitation.

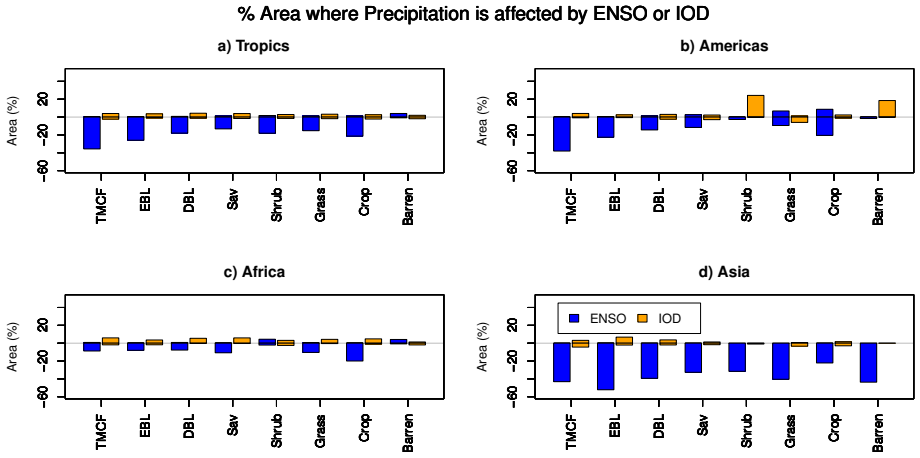

Figure S12: Same as Fig. S3 but for TRMM precipitation.

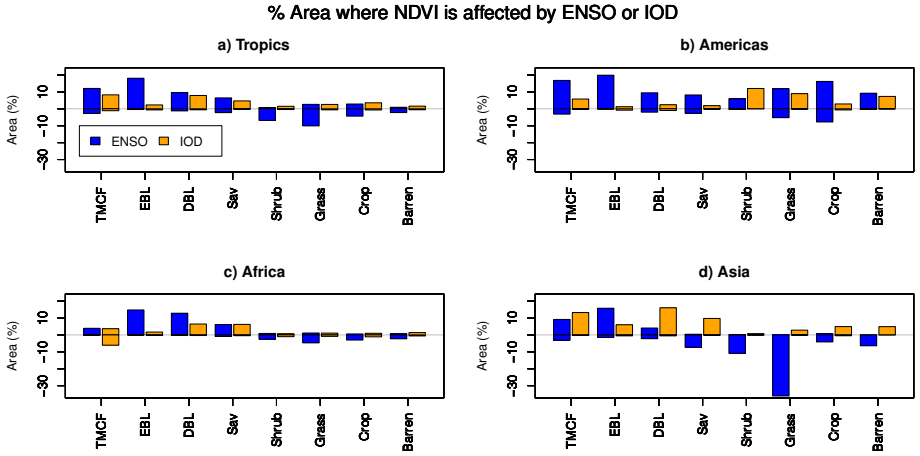

Figure S13: Same as Fig. S3 but for NDVI.

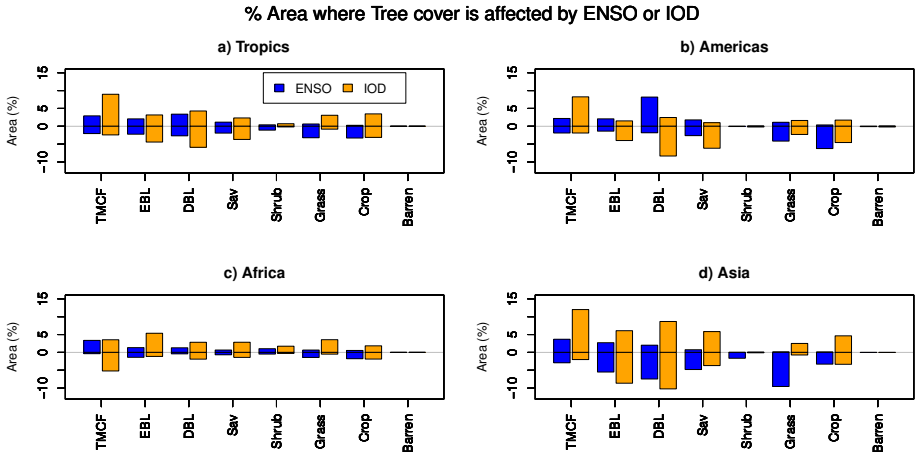

Figure S14: Same as Fig. S3 but for tree cover.

References

Aldrich, M., Billington, C., Edwards, M., Laidlaw, R., 1997. Tropical montane cloud forests: An urgent priority for conservation. WCMC Biodiversity Bulletin 2.

Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., Huang, X.M., 2010. MODIS collection 5 global land cover: Algorithm refinements and characterization of new datasets. Remote Sens. Environ. 114, 168–182.

Mulligan, M., Burke, S., 2005. DFID FRP Project ZF0216 Global cloud forests and environmental change in a hydrological context. Final Report. Technical Report. United Kingdom Department for International Development. http://www.ambiotek.com/cloudforests/cloudforest_finalrep.pdf.

Sulla-Menashe, D., Gray, J.M., Abercrombie, S.P., Friedl, M.A., 2019. Hierarchical mapping of annual global land cover 2001 to present: The modis collection 6 land cover product. Remote Sens. Environ. 222, 183–194, doi: 10.1016/j.rse.2018.12.013.