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Supplement of

Performance evaluation of UKESM1 for surface ozone across the pan-tropics

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Supplementary

Site descriptions

Congo

The CongoFlux station is located at the Research Centre of Yangambi ("Centre de Recherche de Yangambi" - CRY) in the Congo basin in a mixed semi-deciduous forest. The site is to the right of the Congo river, ~100 km northwest of the city Kisangani (Sibret et al., 2022). The ozone monitor is installed at 56.25 m above ground (Vieira et al., 2023).

Jakarta

The three stations in this area are located within major cities. Two are in Jakarta, the largest city in Indonesia, previously identified as having high air pollution from traffic. The stations are located in central Jakarta at the curbside, and in a commercial area (Suhadi et al., 2005). In the same gridcell, a third ozone monitor is located in Bandung, the third largest city in Indonesia, which also suffers from poor air quality. The city is surrounded by volcanic mountains which can trap air and worsen air quality (Setyawati et al., 2022). The station is on top of a three-storey building near roads with heavy traffic (Komala et al., 1996).

Bukit Koto Tabang

This station is located in remote tropical rainforest as part of the Global Atmospheric Watch (GAW) programme (Utami et al., 2021).

Watukosek

This is a rural station on eastern Java Island in the outskirts of Surabaya, the second largest city in Indonesia. The station is 50 m above mean sea level on the slope of a small hill. The surrounding area includes coast (20 km away) and trees (Komala et al., 1996), and is likely to be influenced by regional biomass burning (Adedeji et al., 2020).

Darwin

These stations are located in Winnellie and in the satellite city of Palmerston. They are primarily to monitor urban air pollution. The city is coastal.

Daintree

This station is located in the James Cook University's Daintree Rainforest Observatory in the Australian Wet Tropics of northeast Queensland. The station is surrounded by rainforest. The surrounding area is coastal and lowland but adjacent to upland rainforest and mountain.

Panama

The station is situated on a 16 km^2 island of Barro Colorado in Panama. The site is surrounded by lowland tropical rainforest.

Bogotá

A network (RMCAB) of stations spanning urban Bogotá. Additionally, 2 stations from Medellín and 1 in Manizales also contribute to the site average (Mura et al., 2020).

Porto Velho

This station is in a forest reserve upwind of Porto Velho city. The site has undergone significant land-use change and experiences seasonal biomass burning. Measurements are taken at 40 m above the ground (~10 m above the canopy).

Amazonas

This site contains a few monitoring stations in the state of Amazonas at different heights. The stations were set up as part of the GOAmazon project (Martin et al., 2017). The site includes a station in Manaus (T1), two stations downwind of Manaus (T2 and T3) as well as upwind locations (T0z, the site of the TT34 flux tower). In the absence of the Manaus city, this is pristine, primary forest with little influence from local biomass burning. However, pollution sources include the area downwind of the Manaus city plume, transport of air masses from Africa and dry season biomass burning. The plume from Manaus first travels to the T2 station ~ 7 km from the city. The T3 station is located ~60 km downwind of the plume, with pollution expected to reach the tower 60 % of the time during dry season. The pristine site T0z is 60 km NW of Manaus and measurements are taken at 40 m above ground level (Martin et al., 2010). The T1 station is on the Manaus University campus.

San Lorenzo

This station is another regional background station set up as part of the GAW monitoring network.

Santarem

This site is an old-growth evergreen tropical rainforest station in the Tapajos National park. The station was established at a flux site (Rice et al., 2004) on a large plateau. The ozone monitoring station is at 65 m above ground (~25 m above the canopy).

São Paulo

A network of 19 stations covering the Metropolitan centre of São Paulo as well as suburban areas. Stations are provided by CETESB (https://cetesb.sp.gov.br/ar/qualar/).

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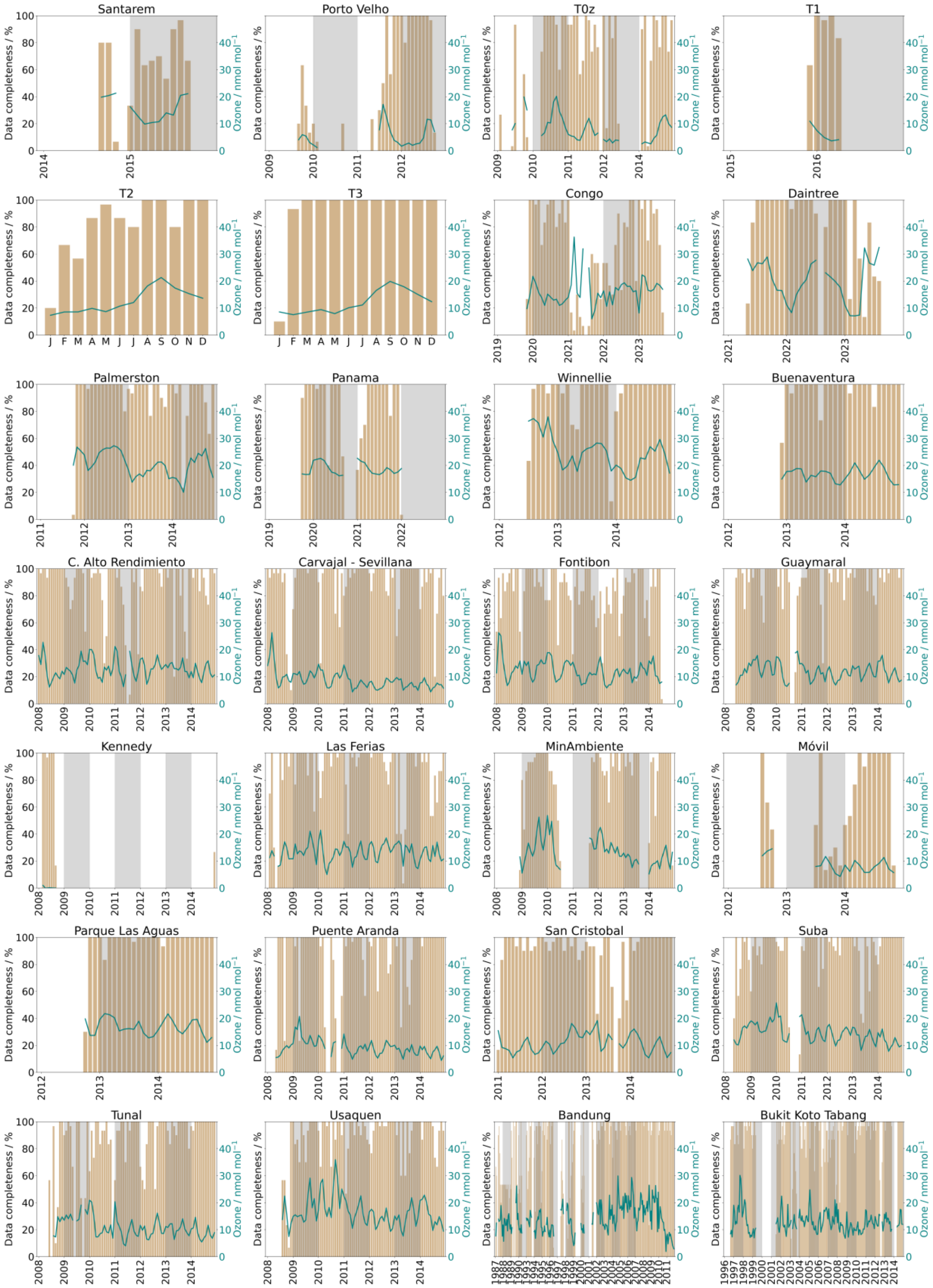
Figures and tables

Table S1: information about individual stations at each site. Stations in the same site are identified by colour.

Station name	Latitude / degrees	Longitude / degrees	Gridcell title	urban	Temporal range
Buenaventura	6.331	-75.569	Bogotá	urban	2013-2014
Parque Las Aguas	6.409	-75.417	Bogotá	urban	2013-2014
C. Alto Rendimiento	4.659	-74.084	Bogotá	urban	2008-2014
Carvajal - Sevillana	4.596	-74.1486	Bogotá	urban	2008-2014
Fontibon	4.670	-74.1416	Bogotá	urban	2008-2014
Guaymaral	4.784	-74.044	Bogotá	urban	2008-2014
Kennedy	4.625	-74.161	Bogotá	urban	2008-2014
Las Ferias	4.691	-74.082	Bogotá	urban	2008-2014
MinAmbiente	4.626	-74.067	Bogotá	urban	2008-2014
Móvil	4.651	-74.061	Bogotá	urban	2013-2014
Puente Aranda	4.632	-74.117	Bogotá	urban	2008-2014
San Cristobal	4.573	-74.084	Bogotá	urban	2011-2014
Suba	4.761	-74.093	Bogotá	urban	2008-2014
Tunal	4.576	-74.131	Bogotá	urban	2008-2014
Usaquen	4.710	-74.03	Bogotá	urban	2008-2014
Bukit Koto Tabang	-0.2	100.32	Bukit Koto	remote	1996-2014
Bandung	-6.894	107.587	Jakarta	urban	1987-2011
Gambir	-6.1831	106.8354	Jakarta	urban	1997-1999
Kemayoran	-6.1558	106.842	Jakarta	urban	2000-2014
Watukosek	-7.5647	112.6781	Watukosek	urban	1987-2011
San Lorenzo	-25.3667	-57.55	San Lorenzo		1997-2007
Cubato-centro	-23.8791	-46.4179	Sao Paulo	urban	1998-2014
Parelheiros	-23.7763	-46.697	Sao Paulo	urban	2007-2014

Diadema	-23.6859	-46.6116	Sao Paulo	urban	1998-2014
Ibirapuera	-23.5918	-46.6607	Sao Paulo	urban	1998-2014
Ipen	-23.5663	-46.7374	Sao Paulo	urban	2007-2014
Itaquera	-23.58	-46.4667	Sao Paulo	urban	2007-2014
Mauã	-23.6686	-46.4653	Sao Paulo	urban	1998-2014
Mooca	-23.5497	-46.6004	Sao Paulo	urban	1998-2014
Nossa Senhora do ó	-23.4801	-46.6921	Sao Paulo	urban	2004-2014
Osasco	-23.5267	-46.7921	Sao Paulo	urban	1998-2002
Parque D.Pedro II	-23.5448	-46.6277	Sao Paulo	urban	1998-2014
Pinheiros	-23.5615	-46.702	Sao Paulo	urban	1998-2014
S.Andrã-Capuava	-23.6398	-46.4916	Sao Paulo	urban	2000-2014
Santana	-23.506	-46.629	Sao Paulo	urban	1998-2014
Santo Amaro	-23.655	-46.71	Sao Paulo	urban	2002-2014
São Caetano	-23.6184	-46.5564	Sao Paulo	urban	1998-2014
São Josã dos Campos	-23.1885	-45.8734	Sao Paulo	urban	2000-2014
São Miguel Paulista	-23.4985	-46.4448	Sao Paulo	urban	1998-2005
Sorocaba	-23.5024	-47.479	Sao Paulo	urban	2000-2014
CongoFlux	0.48	24.3	Yangambi	remote	2019-2023
DRO Daintree	-16.1	145.4	Daintree	remote	2020 -2023
Panama	8.5	-80.78	Barro Colorado	remote	2020-2022
T1	-3.1002	-59.977	Amazonas	urban	2016
T2	-3.139	-60.132	Amazonas	remote	2014
T3	-3.213	-60.598	Amazonas	remote	2014
T0z (K34)	-2.59	-60.21	Amazonas	remote	2009-2014
Porto Velho	-8.687	-63.869	Porto Velho	remote	2009-2012
Santarem	-2.85	-54.967	Santarem	remote	2015
Winnellie	-12.42	130.87	Darwin	urban	2012-2014
Palmerston	-12.48	130.98	Darwin	urban	2011-2014



Santarem
Porto Velho
T0z
T1
T2
T3
Congo
Daintree
Palmerston
Panama
Winnellie
Buenaventura
C. Alto Rendimiento
Carvajal - Sevillana
Fontibon
Guaymaral
Kennedy
Las Ferias
MinAmbiente
Móvil
Parque Las Aguas
Puente Aranda
San Cristobal
Suba
Tunal
Usaquen
Bandung
Bukit Koto Tabang
Data completeness / %
Ozone / nmol mol^{-1}
J F M A M J J A S O N D

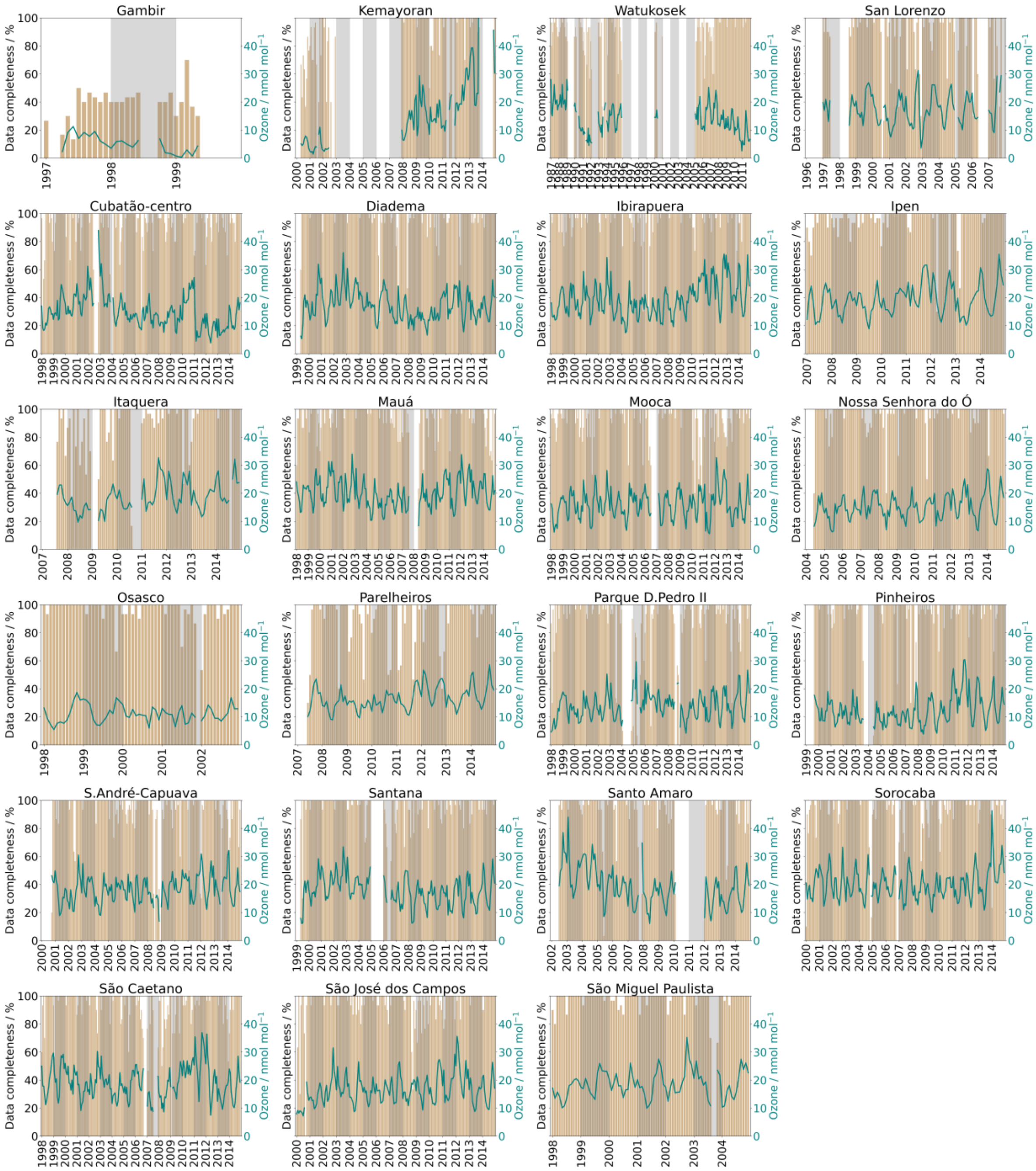


Figure S1: Data completeness for individual stations in each month (gold bars) using daily data. Data is considered 100 % complete if there is data present for every day in a month. Grey shading covers every other year to help distinguish different years. The monthly mean ozone concentration is shown as a blue solid line.

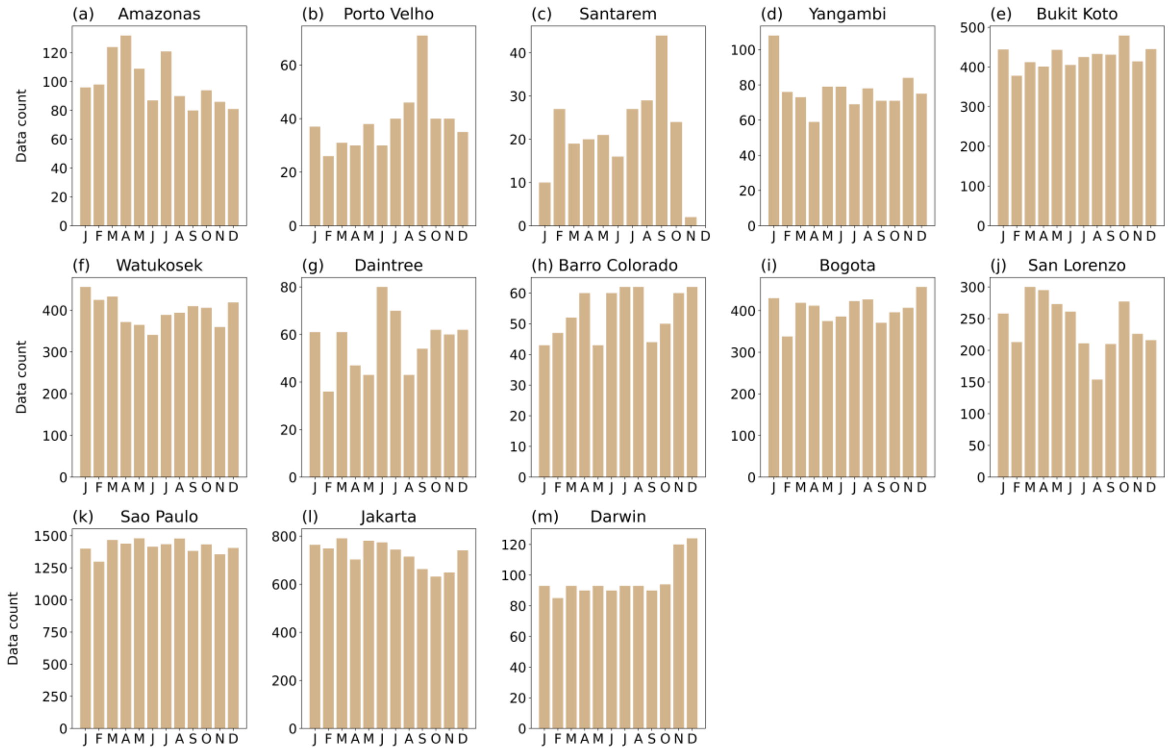
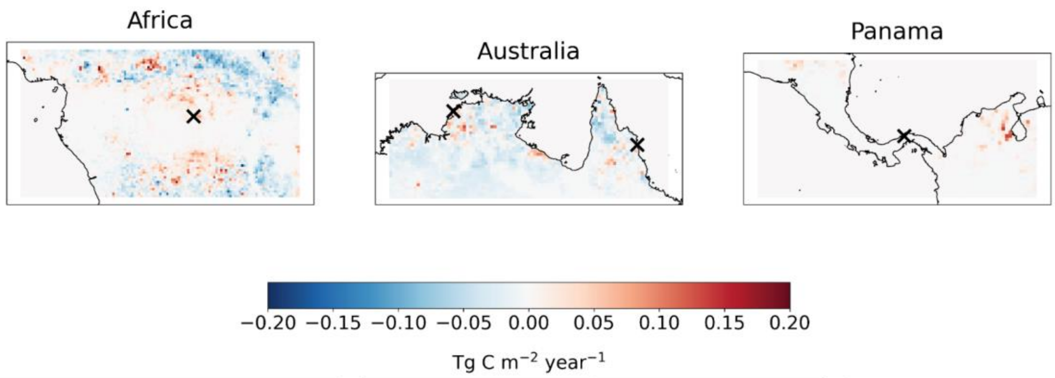


Figure S2: The total number of days of data for each month at each site. This includes data from different years as well as different stations within each site.



	Yangambi	
	Mean temp (K)	Mean ppt (mg m^{-2} s^{-1})
2005 - 2014	298.33	60
2019 - 2022	298.57	60
UKESM 2005-2014	300.56	61

Darwin		Daintree	
Mean temp (K)	Mean ppt (mg m^{-2} s^{-1})	Mean temp (K)	Mean ppt (mg m^{-2} s^{-1})
300.22	60	298.73	42
300.95	59	299.52	42
300.91	63	298.07	31

Barro Colorado	
Mean temp (K)	Mean ppt (mg m^{-2} s^{-1})
299.33	76
299.44	75
300.01	89

Figure S3: The change in fire emissions between 2005 – 2014 and 2019 – 2022 in the area around the Congo site, the Darwin and Daintree sites and the Panama site. Tables below show the mean temperatures and precipitation rates for the grid cells containing each site using CRU-JRA reanalysis at the same resolution as UKESM1 and UKESM1 for the period 2005 – 2014.

Table S2: The gridcell mean and standard deviation in temperature for the period 2005 – 2014 from UKESM1 and CRU-JRA reanalysis. The final column given the difference between model and observations.

Site	CRUJRA mean	UKESM1 mean	CRUJRA std	UKESM1 std	Difference (UKESM1 – CRUJRA)
	°C	°C	°C	°C	°C
Porto Velho	20.9	22.0	0.2	0.6	1.1
Amazonas	22.1	23.4	0.2	0.6	1.3
Santarem	21.9	23.1	0.1	0.7	1.3
Yangambi	19.3	21.6	0.1	0.4	2.2
Bukit Koto	20.9	21.1	0.2	0.2	0.2
Watukosek	20.5	21.6	0.2	0.3	1.1
Daintree	19.7	19.0	0.4	0.3	-0.7
Barro Colorado	20.3	21.1	0.2	0.3	0.8
Bogota	13.9	14.7	0.3	0.4	0.8
San Lorenzo	17.4	16.8	0.4	0.8	-0.6
Sao Paulo	13.9	14.3	0.3	0.3	0.4
Jakarta	20.4	21.6	0.1	0.2	1.2
Darwin	21.2	21.9	0.6	0.4	0.7

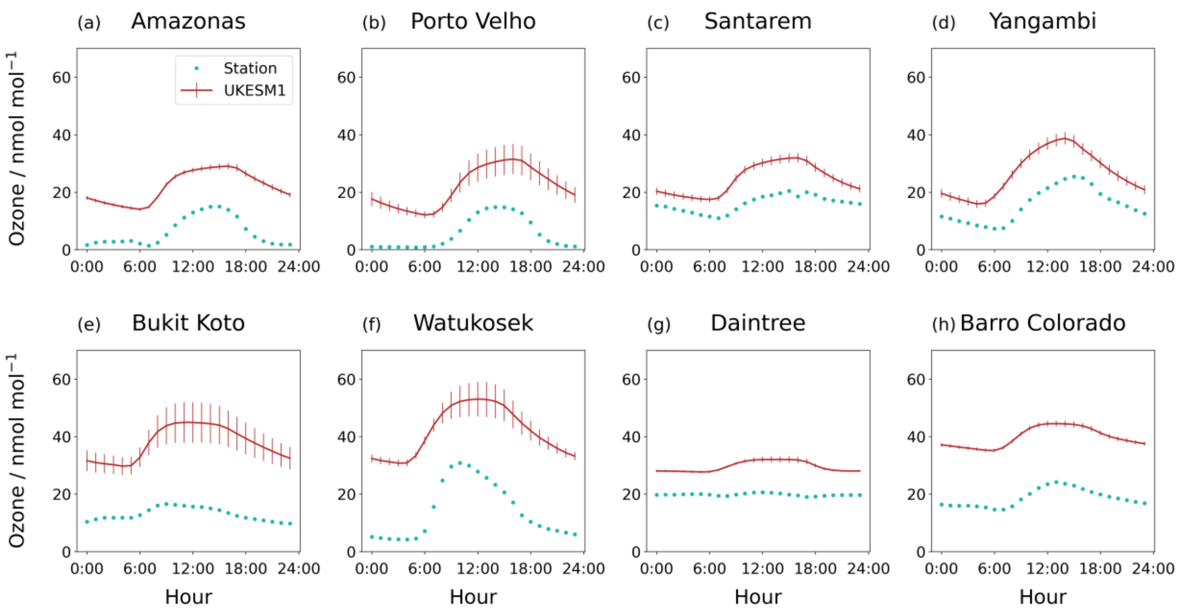


Figure S4: Annual mean hourly ozone concentration at each site (blue dots) compared to in the corresponding gridcell of UKESM1 (red solid line). Vertical bars represent 1 standard deviation using annual diurnal cycles in UKESM1 to indicate interannual variability. Assessment of interannual variability was not possible for the observational datasets.

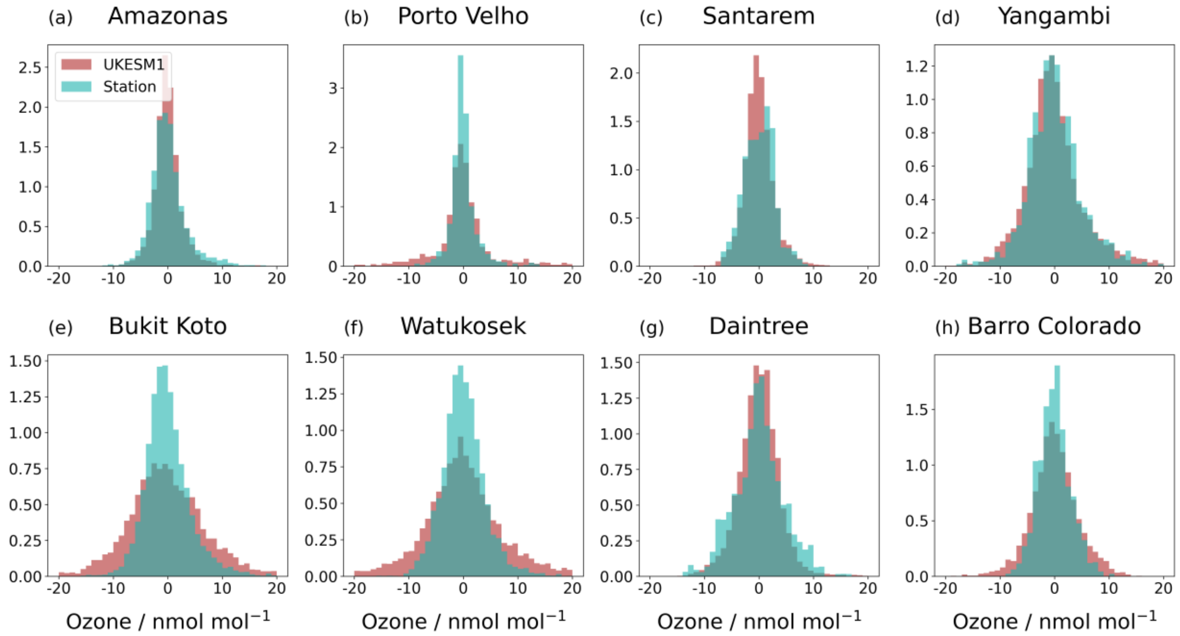


Figure S5: Density plots showing the daily anomaly compared to the monthly mean for all months at each station (blue) compared to UKESM1 (red). Y-axis is the proportion of days such that the bars for each month sum to 1 (i.e. total bars sum to 12).

Table S3: Features of the distribution of daily anomaly compared to the monthly mean. Remote sites are shaded grey. Features that are underestimated by UKESM1 by more than 50% are shaded blue, features that are overestimated by more than 50% are shaded red. Features within this range are shaded green.

Gridcell name	kurtosis	Kurtosis UKESM	skew	Skew UKESM	Standard deviation	Standard deviation UKESM
Bogota	2.4	1.8	0.6	0.5	3.1	4.0
Jakarta	27.5	1.1	0.9	0.4	7.0	8.9
Bukit Koto	3.8	2.0	1.0	0.5	4.3	7.4
Watukosek	1.9	1.7	0.4	0.2	4.0	7.5
San Lorenzo	6.6	8.2	1.3	1.1	6.7	5.7
Sao Paulo	0.7	2.8	0.4	0.7	5.5	9.3
Yangambi	1.9	2.3	0.2	0.8	5.3	5.6
Daintree	0.7	3.5	-0.1	0.4	4.8	3.8
Barro Colorado	0.2	0.9	0.2	-0.1	2.9	4.2
Amazonas	3.1	6.3	1.0	1.0	3.3	2.7
Porto Velho	5.2	7.9	1.3	0.3	2.8	7.3
Santarem	0.1	1.9	0.1	0.5	2.9	2.7
Darwin	1.7	4.9	0.4	1.0	4.9	5.7

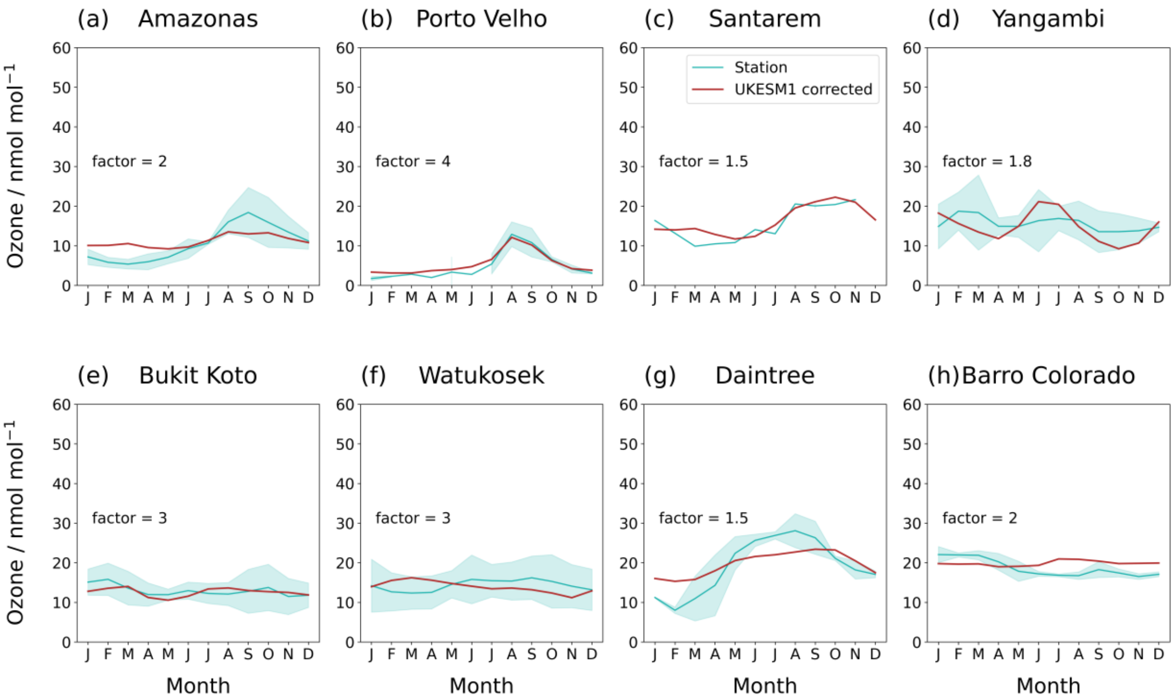


Figure S6: Mean monthly ozone concentration at each station (blue solid line) compared to the corresponding gridcell of UKESM1 after bias correcting by a factor (red solid line). Shading covers 1 standard deviation using the observations to show interannual variability. The factor used in each bias correction is stated on each panel.

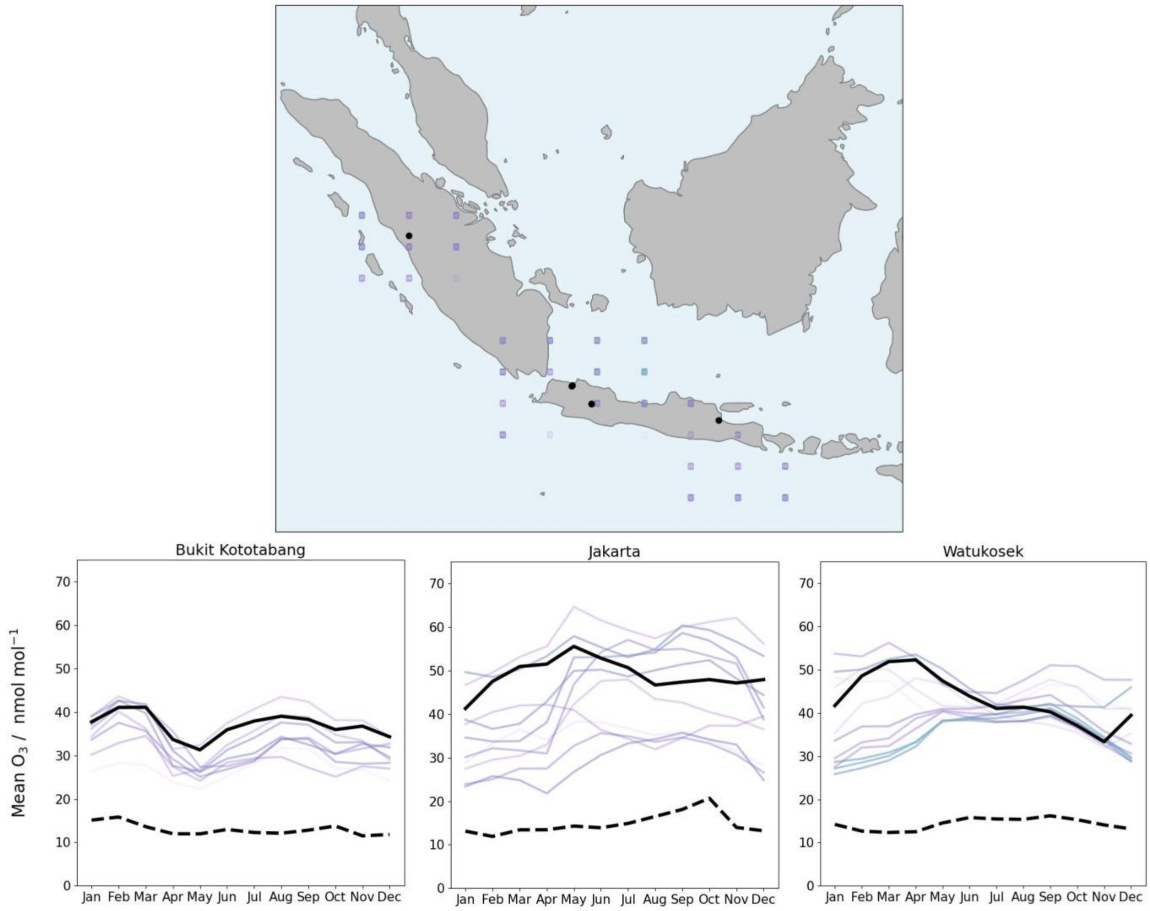


Figure S7: Seasonal cycle of ozone concentrations from observations (black dashed line), at the gridcell containing the station (black solid line), and for the surrounding gridcells (solid coloured lines) for the three S. E. Asia sites in the study. Map above shows the station locations (black dots), and gridcells used in the analysis below (coloured squares) with gridcells coloured based on correlation with observations. The highest correlation are darker in tone and more blue.

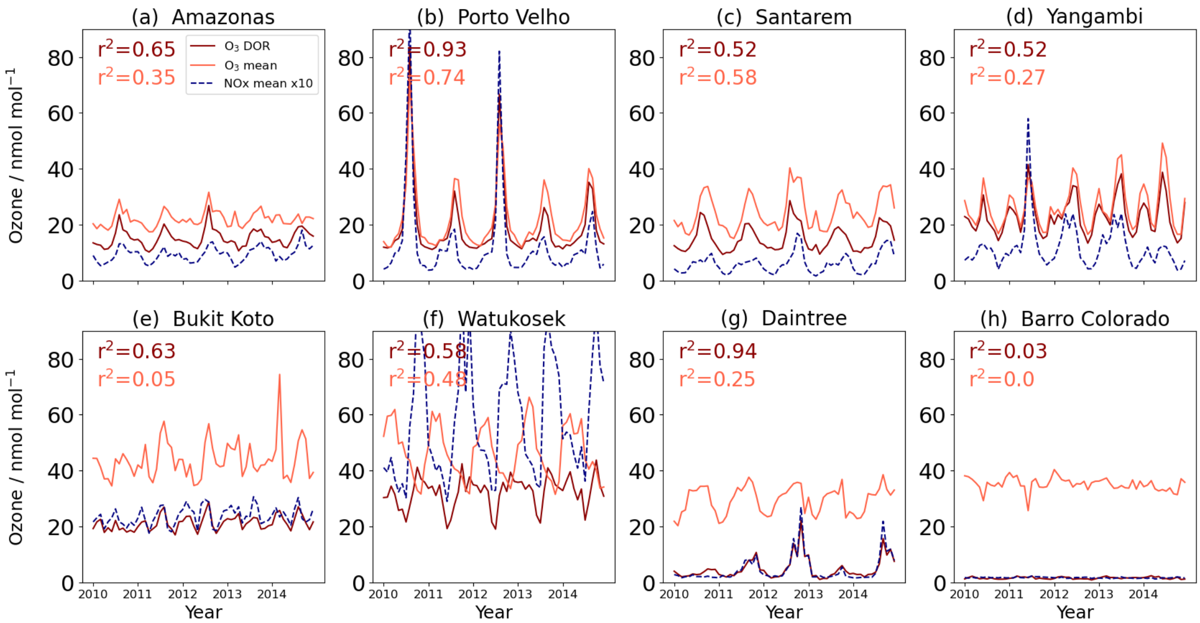


Figure S8: Monthly mean data between 2010 – 2014 showing patterns in ozone concentrations (orange solid line), the DOR (red solid line) and NOx concentrations (x10, blue dashed line). r^2 values in the upper left corner gives the correlation between NOx and the DOR (red) or NOx and ozone (orange).

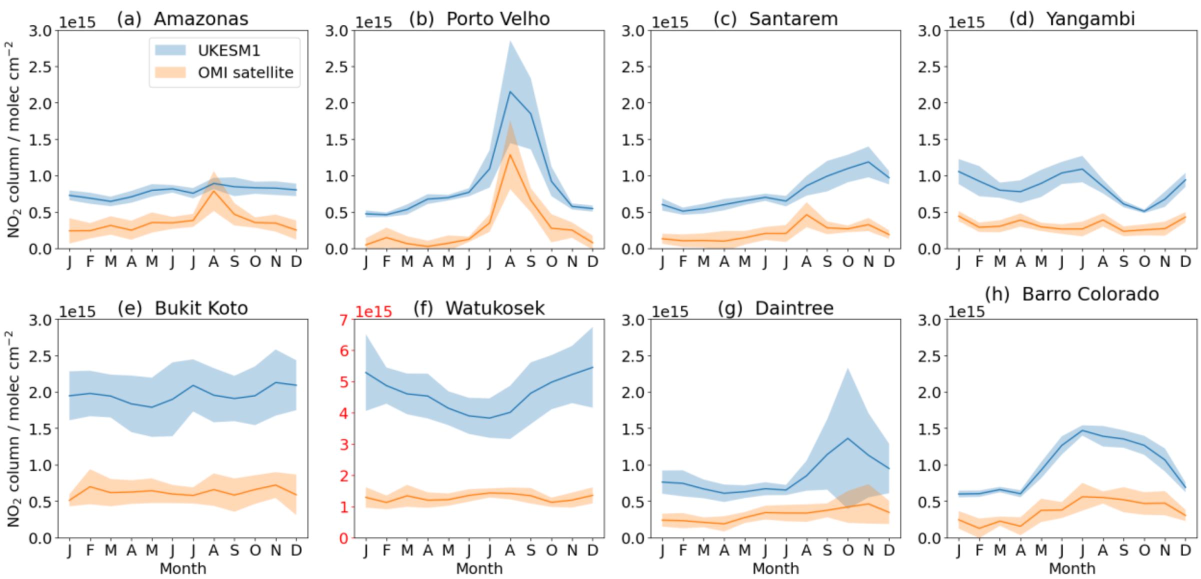


Figure S9: Monthly mean tropospheric NO_2 columns between 2005 – 2014 at each site for UKESM1 (blue solid line) and OMI satellite (orange solid line). Shading covers 1 standard deviation using monthly means to represent interannual variability. Note the different scale used for Watukosek to improve readability.

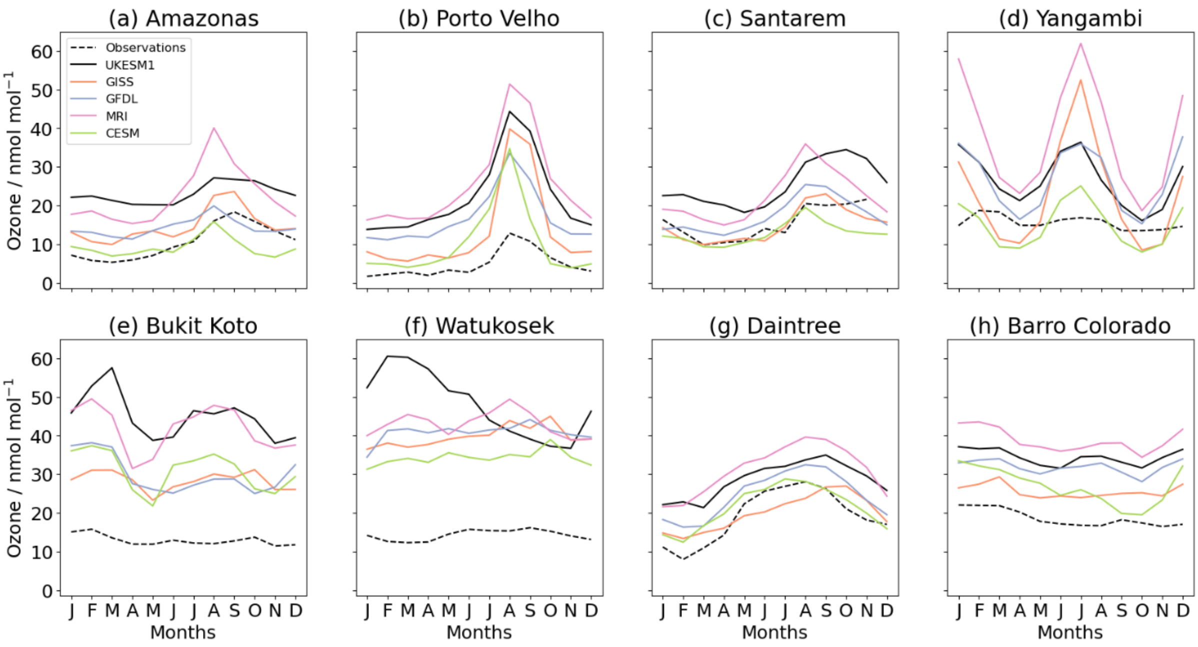


Figure S10: Monthly mean ozone for the period 2005 – 2014 at each remote site for five Earth system models for comparison to UKESM1 (solid black line) and observations (black dashed line).

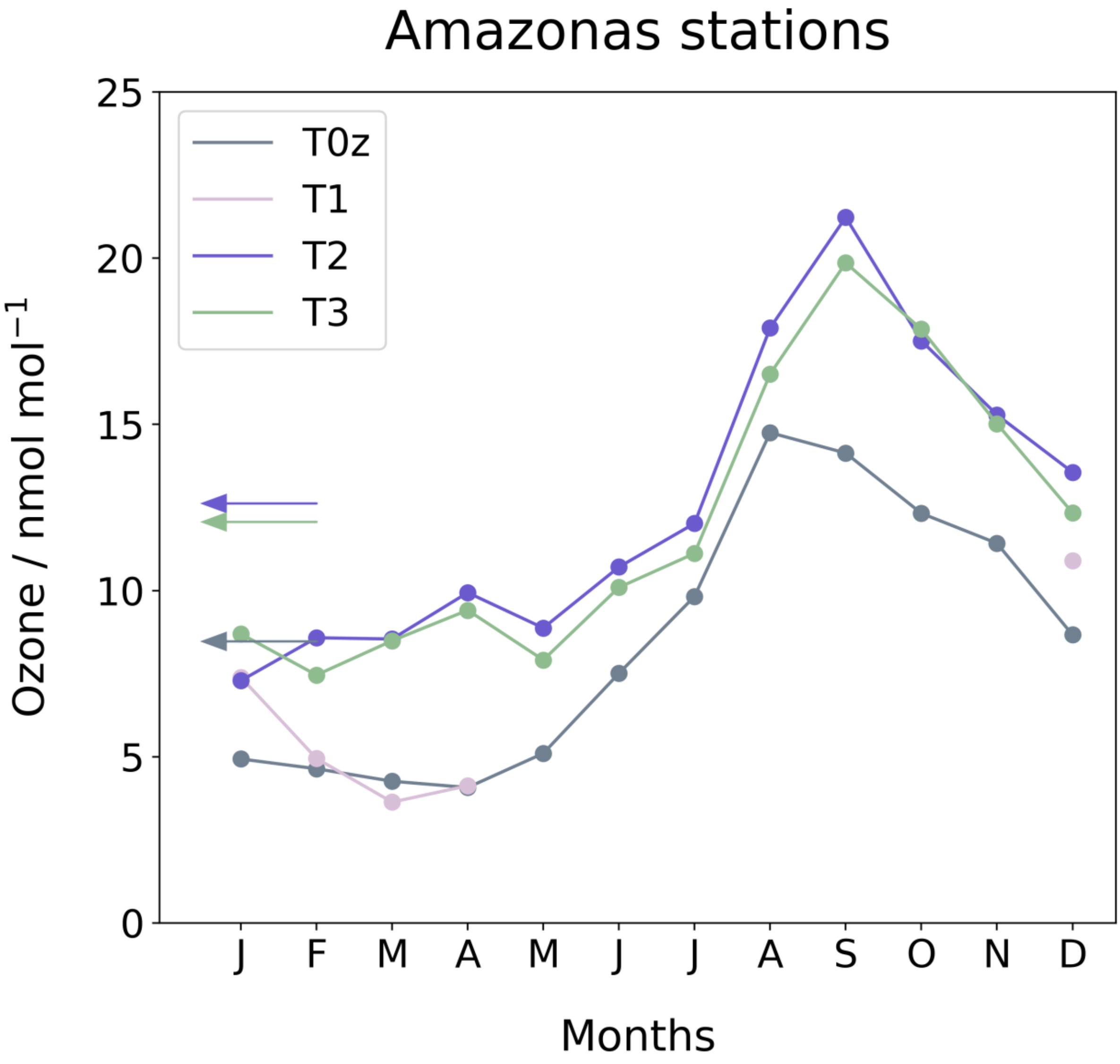


Figure S11: Monthly mean ozone concentrations (solid lines) and annual mean ozone concentrations (arrows) from individual stations at the Amazonas site.